Title: Dark matter searches with quantum computing systems

Speakers: Roni Harnik

Collection/Series: Charting the Future Symposium

Subject: Cosmology, Particle Physics, Strong Gravity

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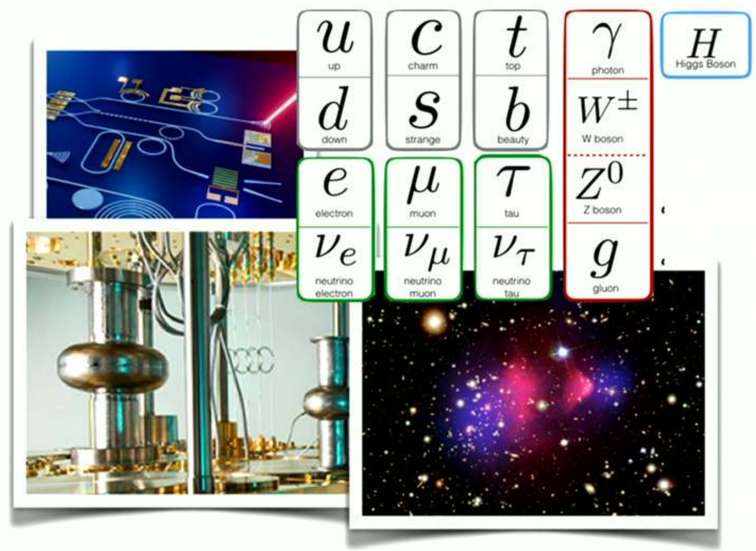
Dark Matter Searches with QuantumComputing Systems

Roni Harnik

Fermilab Quantum Theory Department
and
SQMS NQI Center

PI@25: Charting the Future

Work with Arushi Bodas, Sohitri Ghosh, Yao Lu, and Friends



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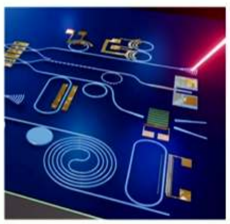
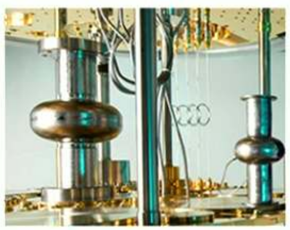
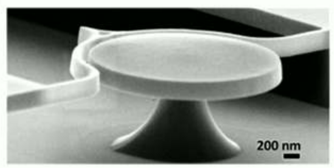
Quantum Information Science

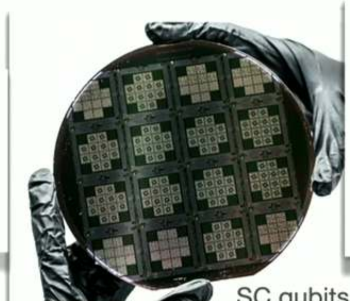
- In the past 25 years we drastically improved the ability to control and read out the quantum state of systems.
- In the coming 25 years we will process and sense information in quantum ways.
- The field spans many cool technologies.

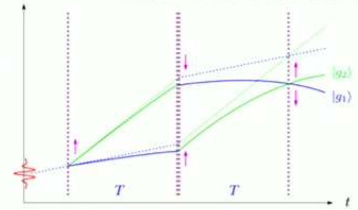

Integrated photonics

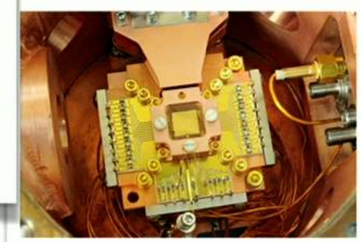

SC cavities



Optomechanical sensors

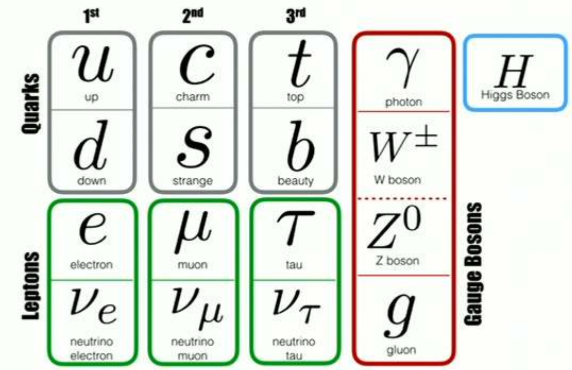

SC qubits


Atom interferometers


Ion traps

This endeavor is entangled with particle physics, both in its roots and its future.

Quantum Field Theory



- The SM is a QFT. Every particle is a quantized field.
- What does this mean?

  Expand the field. We get to pick the modes. Something like -

$$\phi(x_\mu) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2\omega}} \left(a_{\vec{k}} u_{\vec{k}}(\vec{x}) e^{i\omega t} + a^\dagger_{\vec{k}} u_{\vec{k}}{}^*(\vec{x}) e^{-i\omega t} \right)$$

Quantize: a, $a^\dagger$ are operators. Create and annihilate modes.

Satisfy: $[a_k, a_{k'}^\dagger] = \delta_{kk'}$ $\cdots$ and $|\phi(x)\rangle = \phi(x)\,|\Omega\rangle$

- This is sometimes referred to as "second quantization". For us its first!

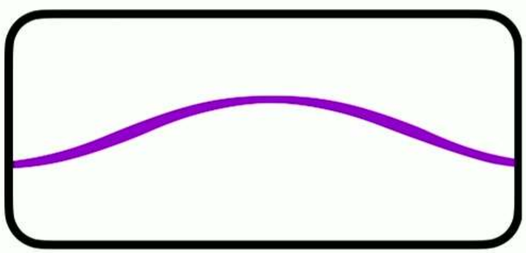
Quantum Fields in Small Devices

- Fields live everywhere, but sometimes they get localized to a finite regions. Either "naturally" or in a lab.

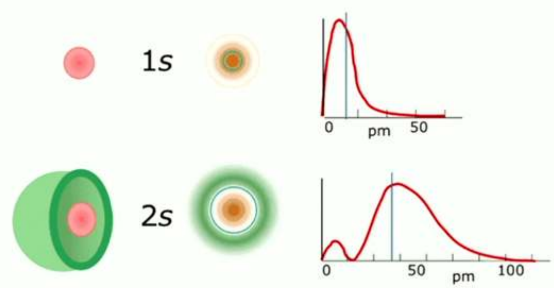
$$\phi(x_\mu) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2\omega}} \left(a_{\vec{k}} u_{\vec{k}}(\vec{x}) e^{i\omega t} + a^\dagger_{\vec{k}} u_{\vec{k}}{}^*(\vec{x})(e^{-i\omega t} \right)$$

$$+ \sum_j \frac{1}{\sqrt{2\omega}} \left(a_j u_j(\vec{x}) e^{i\omega t} + a^\dagger_j u_j{}^*(\vec{x})(e^{-i\omega t} \right)$$

Only a discretum satisfies boundary conditions.



or

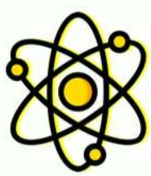


Quantum Fields in Small Devices

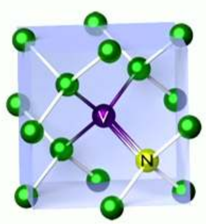
- Consider the low energy EFT of the discretum. Often in terms of a, $a^\dagger$

$$\phi_j(x_\mu) = \frac{1}{\sqrt{2\omega}}\left(a_j u_j(\vec{x})e^{i\omega t} + a_j^\dagger u_j{}^*(\vec{x})(e^{-i\omega t}\right)$$

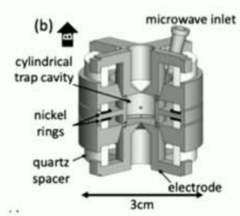
- In these EFTs, modes separate from the continuum, Quantum Mechanics shines:



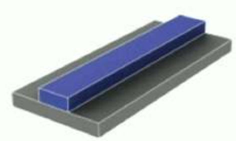
Atoms



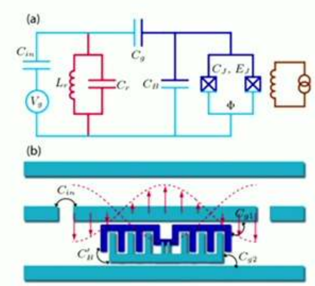
Defects



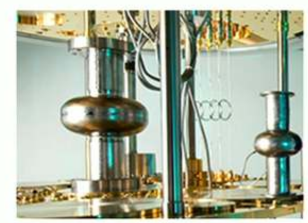
Artificial Atoms (particle in trap)



Optical waveguide



Superconducting circuits



Electromagnetic Cavities

The main challenge:
These states are very sensitive to the environment! :-(

On the flip side:
These states are very sensitive to the environment!!! :-)

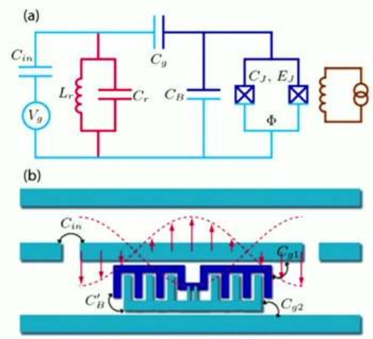
Sensors!

Outline

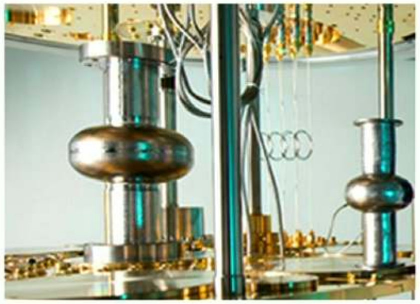
- An example: **cavities and qubits.**
  - Generalities
  - State of the art system at Fermilab
- **Wave-like DM**
- **DM searches with cavities & qubits**
  - Photon counting
  - Stimulated signals
  - N sensors
  - Towards N^2

Example:

Photons in confined spaces

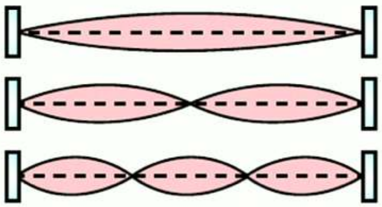


Superconducting circuits

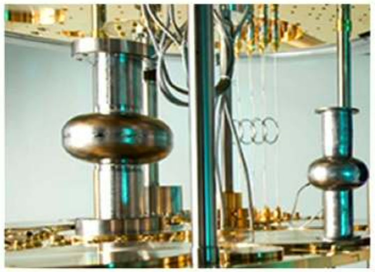


Electromagnetic Cavities

Superconducting Cavities & Circuits

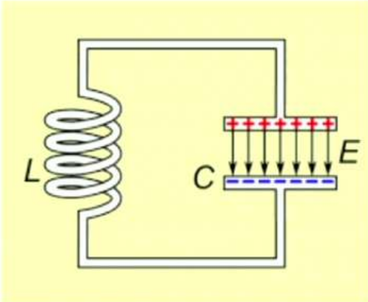


- <u>Cavities</u>: Light in a box. A discretum of states.



- Separation from the continuum is parametrized by Q.

  $Q \sim 10^{10}$ is now routine. (Thank you accelerators!)



- <u>LC Circuits</u>: quantized current/flux.
- Control frequency with L & C, $(\omega^2 = 1/LC)$.

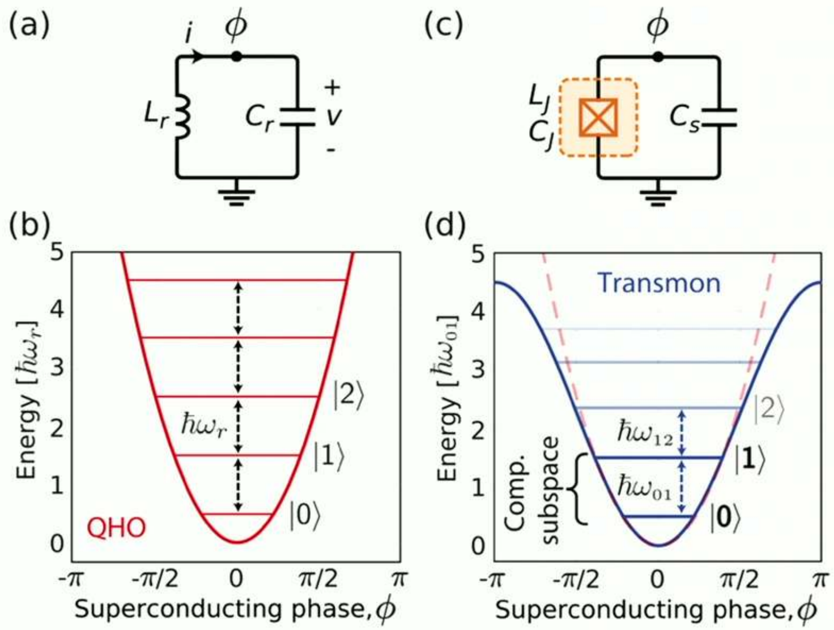
Both are harmonic. Equally spaced levels. $H_{mode} = \hbar\omega(a^\dagger a + ½)$

Nonlinear Devices

- We can arrange for a UV cutoff with higher dim operators, e.g. $\frac{1}{\Lambda^4}\left(F^{\mu\nu}F_{\mu\nu}\right)^2$
- Operationally making L a function of $a^\dagger a$, gives

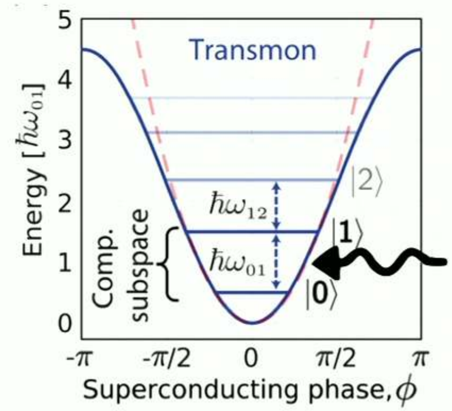
$$H = \hbar\omega(a^\dagger a + 1/2) + \kappa(a^\dagger a)^2$$

- Level spacing is nonuniform.
- Generically, $\kappa < \omega$. ("Naturalness" :-)
- This allows for control of individual levels of a given mode!

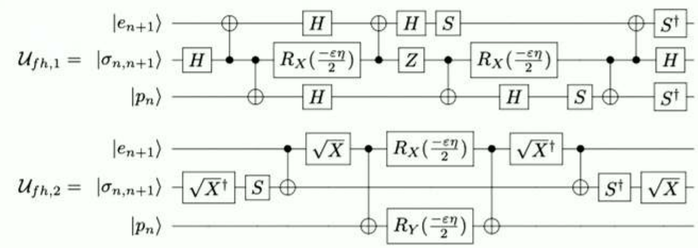


Quantum Control

- Within the device EFT, we can control the quantum state.
- Pluses of light can induce oscillation between states
- Occupation number, say, can store information & be read out.



Qubit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



Or Qudit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle \cdots$

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- A limiting factor for superconducting qubits is loss (finite Q) & decoherence.

  e.g. prepare a qubit, $\alpha|0\rangle + \beta|1\rangle$, after a while $|1\rangle \longrightarrow |0\rangle$
  For modern qubits, a while ~ msec

- We (royal we) already developed ultra-high-Q cavities to accelerate particles! Lifetimes of O(sec)!

- The SQMS center is bringing this expertise to QIS.

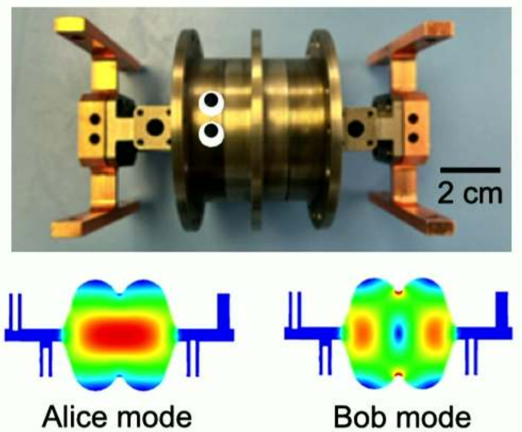
- A big(ish) effort in materials science, devices, QIS and fundamental physics.

Kim et al 2506.03286 [quant-ph]

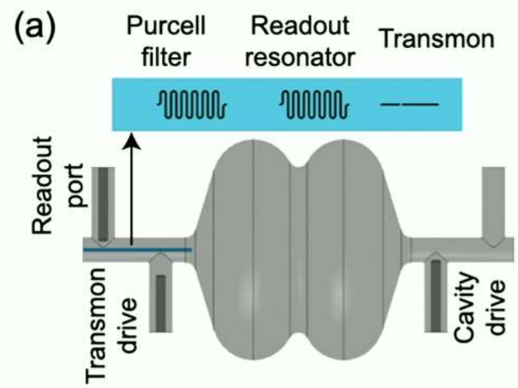
SQMS Cavity-Qubit system

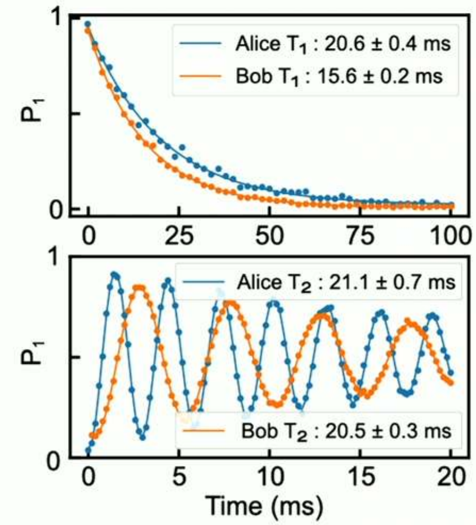
A single photon can live in the cavity for 20 sec! (A world record)

A two-mode Nb cavity



With an inserted qubit

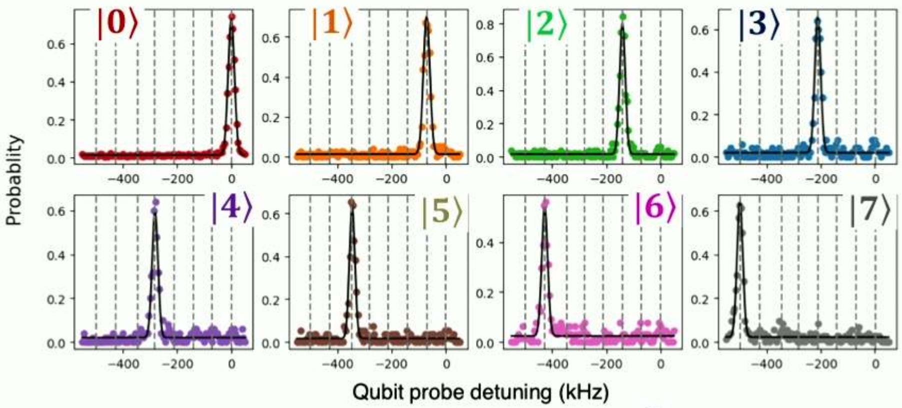




For comparison, leading transom qubits have T_1 ~ 1 msec

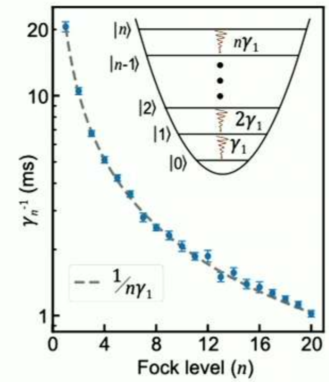
Kim et al 2506.03286 [quant-ph]

SQMS Cavity-Qubit system

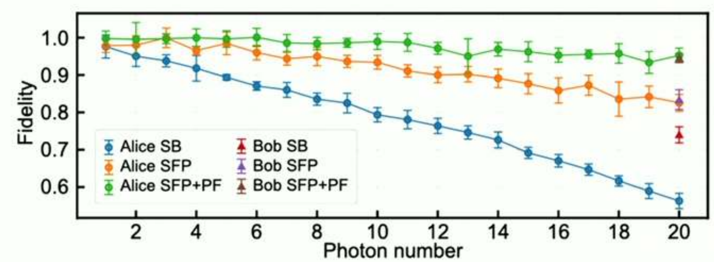


Qubit frequency is sensitive to # of photons in the cavity. We can count photons precisely!

20 Photon state lives for a msec!



High fidelity control up to 20 photons



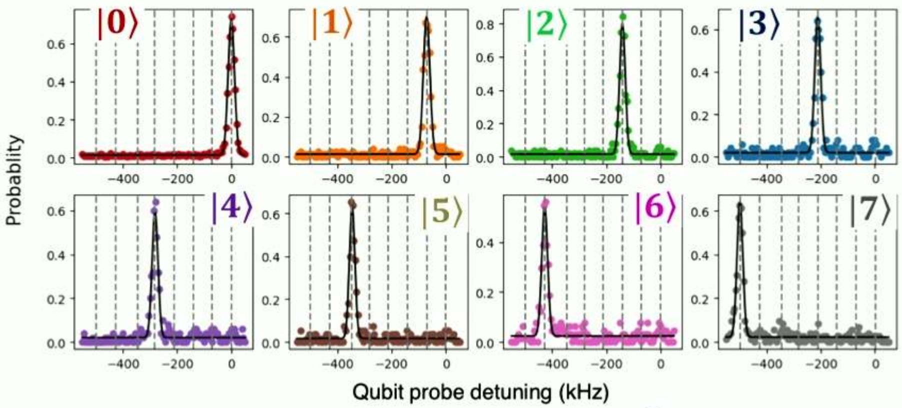
A promising building block for a qudit based quantum computer!

A great start!

Can we use it as a sensor?

Kim et al 2506.03286 [quant-ph]

SQMS Cavity-Qubit system



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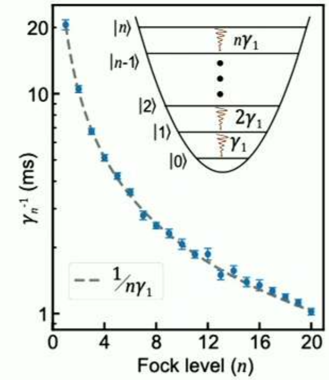
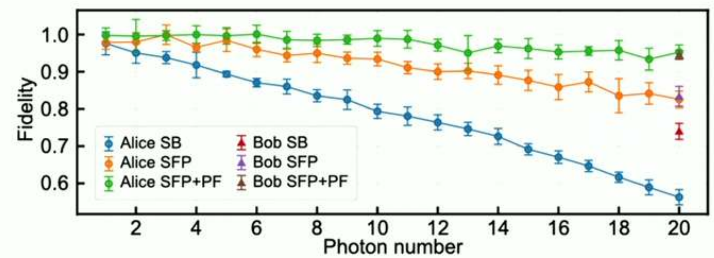


High fidelity control up to 20 photons



A promising building block for a qudit based quantum computer!

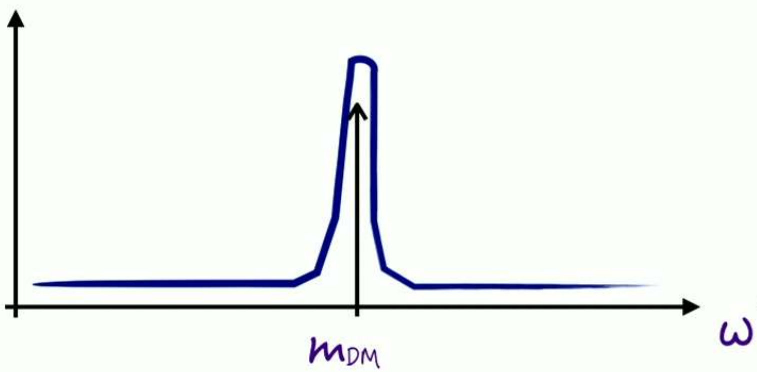
Wavelike DM as a Benchmark

- Hypothesis: DM is has high occupation number, more wave-like that particle like.
- DM is a light field which is non relativistic:

$$\chi_{DM} = A \cos [k\cdot x - \omega t + \phi]$$

with $k \ll \omega \rightarrow \omega \simeq m_{DM} \, (1 + O(v^2))$ and $v \sim 10^{-3}$

(At GHz, DM coherence time is ~ msec)

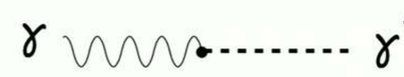


m_{DM} is unknown!
A resonant search requires scanning.
The "scan rate" is key.

Dark Photon and Axion DM

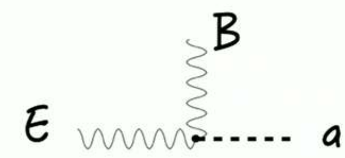
- Wavelike DM which couples to photons:
  - Dark Photon – a linear extension of QED:

$$\mathcal{H} \supset \mathcal{H}_{QED} + \varepsilon\, \vec{E}\cdot\vec{E}' + \vec{B}\cdot\vec{B}'$$



  - Axion (-like particle) – a nonlinear extension of QED:

$$\mathcal{L} \supset \frac{a}{f} F^{\mu\nu}\tilde{F}_{\mu\nu} = \frac{a}{f}\vec{E}\cdot\vec{B}$$



DM = monochromatic source of photons in devices, w/ unknown frequency.

An effective DM current lives everywhere, J_{eff}

Fine print: you need a background B field in the axion case.

Fine print: direction of $\mathbf{J}_{\text{eff}}$ is random.

Fine print: …..

Low energy EFT

- The low energy EFT of the cavity/qubit system and the mode is

$$H \;=\; \omega\left(a^\dagger a + \frac{1}{2}\right) + g\cos\left(m_{A'}t + \phi(t)\right)a^\dagger + \text{h.c.}$$

For a cavity $\qquad g = \epsilon\,\sqrt{2G\rho_{\rm DM}V_{\rm cav}\,\omega}$

For a 2D SC qubit $\qquad g = \epsilon\sqrt{2\kappa^2\rho_{\rm DM}V_{\rm eff}\omega}$

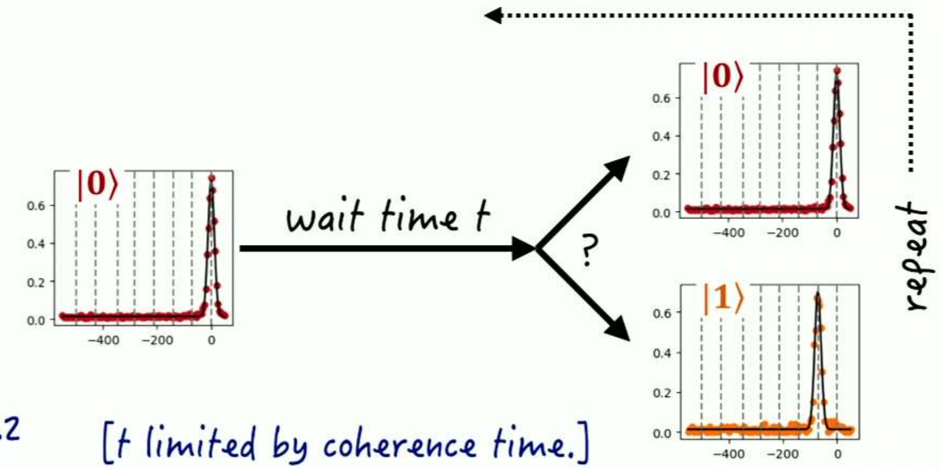
$\Rightarrow$ Cavity has a parametric advantage.

with an effective volume $\qquad V_{\rm eff} = d^2C$

(G and κ are order one geometric factors)

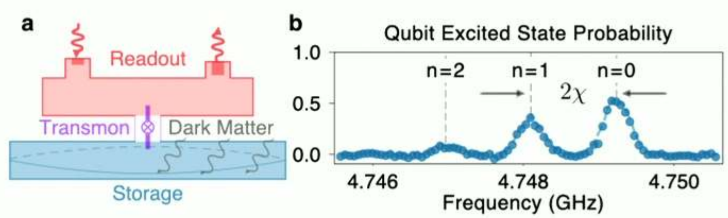
Photon Counting

- DM can deposit photons in an empty cavity:

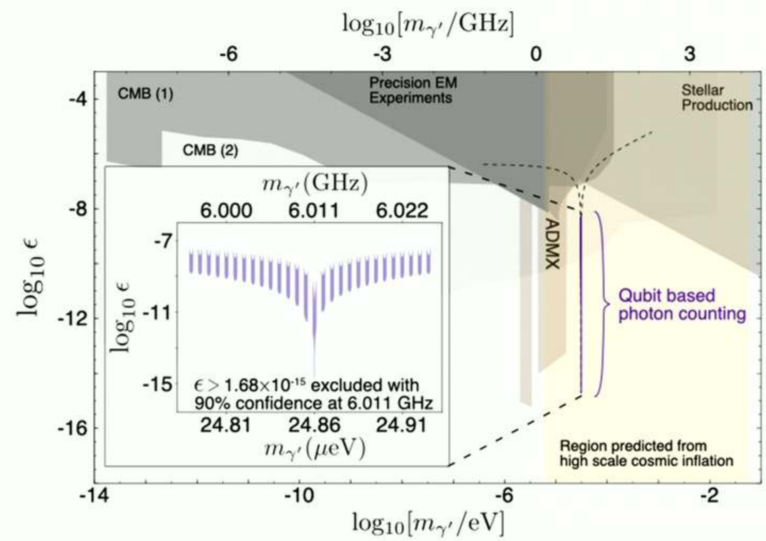


Per-shot signal probability: $P_1 \sim g^2 t^2$ [t limited by coherence time.]

- Demonstrated by Schuster at a single frequency:



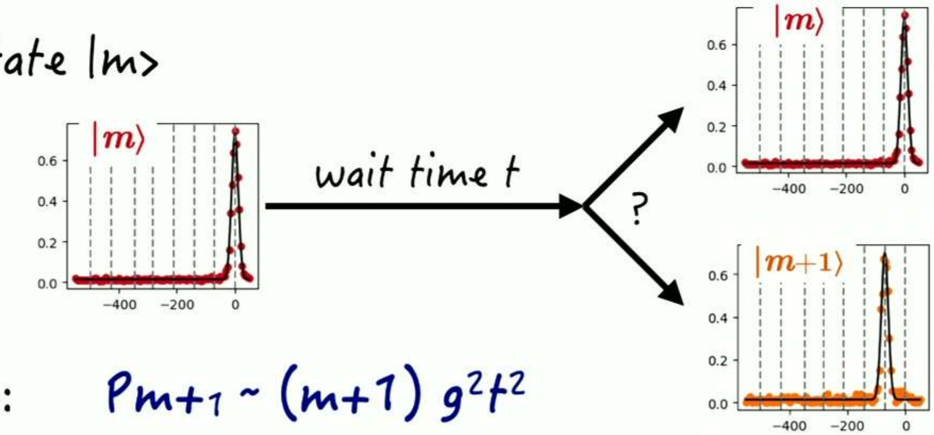
Dark count of ~ 1 Hz.
SQMS system will improve on this.



Phys.Rev.Lett. 126 (2021) 14, 141302

Stimulated Emission

- Stimulate the signal by preparing a Fock state |m>



Per-shot signal probability: $P_{m+1} \sim (m+1)\, g^2 t^2$

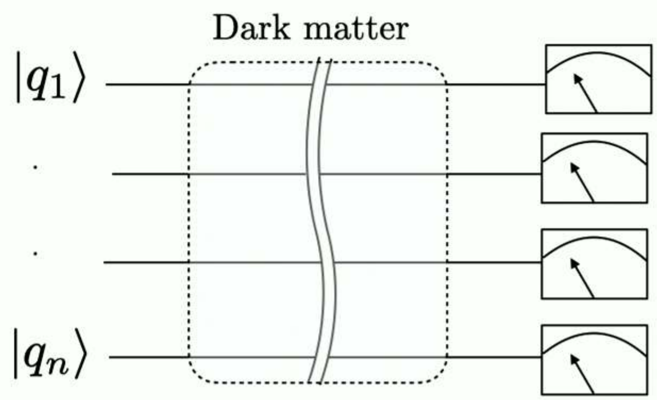
- Note: this stimulates the thermal noise as well! useful in the noiseless era.
- This was attempted by Schuster et al with m=4, but limit not improved.

We will attempt m = 20 with SQMS system.

Phys.Rev.Lett. 132 (2024) 14, 140801

N Cavities

- Can we scale this to an array of N cavities? 1 mode -> N modes
- Simplest thing: replicate the system, including readout



Rate scales as N.

Noise scales as $\sqrt{N}$.

- Signal-to-noise ratio $\mathrm{SNR} \propto \sqrt{N}$
- We can do better.

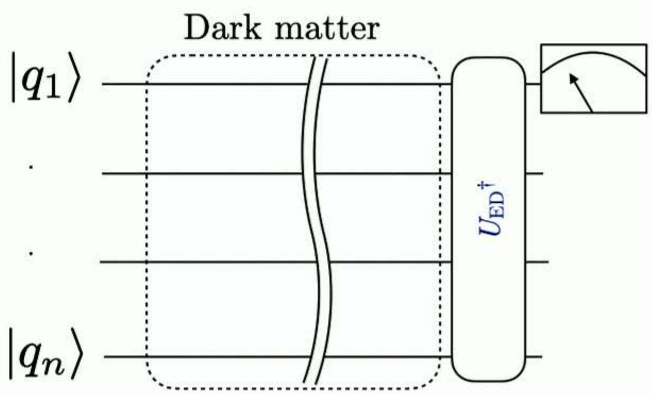
In preparation with Ben Freiman and Yao Lu

N Cavities

- Dark matter couples to the symmetric combination $H_{\text{int}} \supset g e^{i\Delta t + \delta\phi(t)} \sum_{n=1}^{N} a_n^\dagger + \text{h.c.}$
- With quantum control, we can to a unitary transformation:

$$U_{\text{ED}}^{-1} \sum_{n=1}^{N} \hat{a}_n^\dagger U_{\text{ED}} = \sqrt{N} \hat{a}_1^\dagger$$

(transfer symmetric mode to cavity 1)



Coherent signal: scales with N

Incoherent noise: only $1/N$ of noise will be in symmetric mode. Noise $\propto N^0$!

$\text{SNR} \propto N$

Towards N^2

- The N scaling so far is the usual scaling of signal with total effective volume V.

- On general grounds of energy conservation (Poynting), the amount of power drawn from DM scales linearly with volume

Work done by DM

$$\int d^3x\,(\vec{E}\cdot\vec{J}_{\rm eff})$$

Loss $\quad \dfrac{\omega}{Q}\displaystyle\int d^3x\,|\vec{E}|^2$

Readout

Optimizing one finds $P_{\rm readout} \propto V$

- To go beyond N scaling, we had better not read out power!

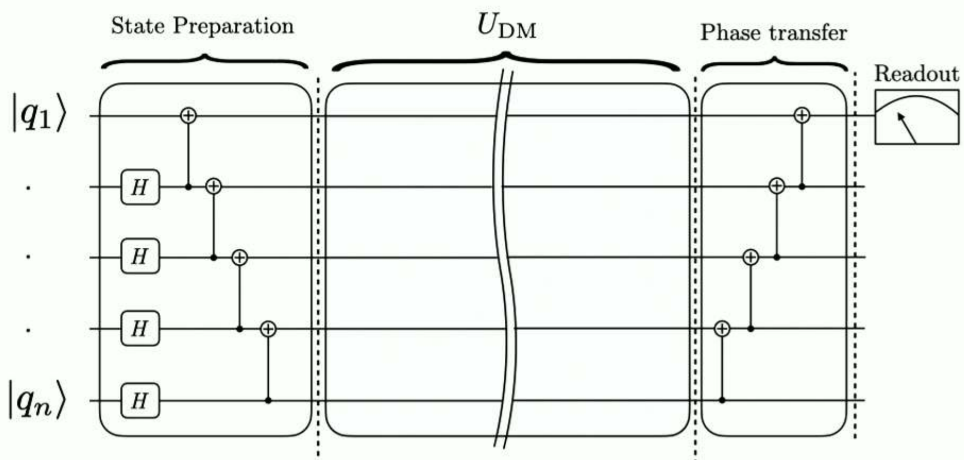
An Entanglement Protocol

Chen, Moroi, et al *Phys.Rev.Lett.* 133 (2024)
Kitano et al *JHEP* 02 (2024) 124
Bodas, Ghosh, RH - in preparation

- Back to qubits: The states $|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$ are eigenstates of DM time evolution

$$\boxed{U_{\rm DM}\,|\pm\rangle = e^{\pm i\delta}\,|\pm\rangle}$$

"Spin-precesion-like".



$$\frac{1}{\sqrt{2}}\left[|+\rangle^{\otimes n_q} + |-\rangle^{\otimes n_q}\right]$$

"GHZ state"

$$\frac{1}{\sqrt{2}}\left[e^{in_q\delta}|+\rangle^{\otimes n_q} + e^{-in_q\delta}|-\rangle^{\otimes n_q}\right]$$

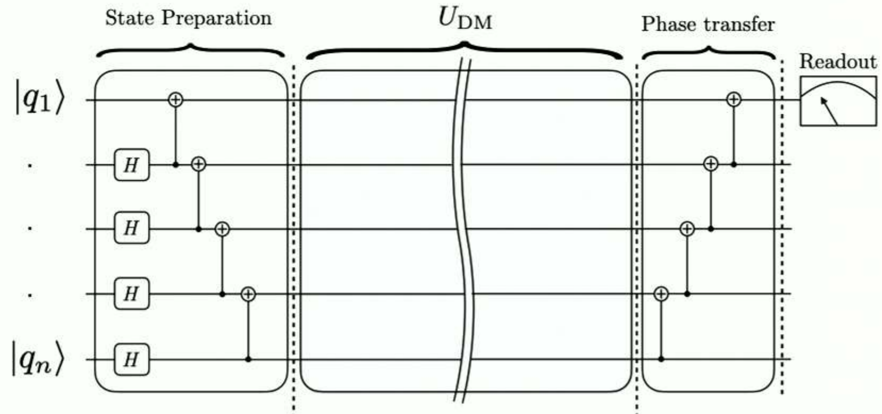
"rotated" GHZ

For a different N^2 story see Arvanitaki, Dimopoulos, Galanis *Phys.Rev.D* 111 (2025) 5, 055015

An Entanglement Protocol

- This protocol satisfies Poynting.

Read out information, not power.

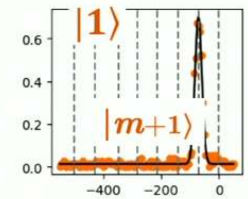


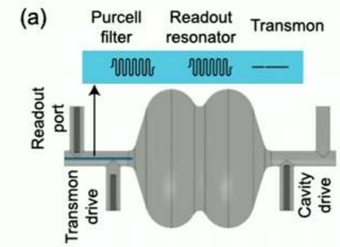
$\Delta E = 0$

$$\frac{1}{\sqrt{2}}\left[|+\rangle^{\otimes n_q} + |-\rangle^{\otimes n_q}\right] \longrightarrow \frac{1}{\sqrt{2}}\left[e^{in_q\delta}|+\rangle^{\otimes n_q} + e^{-in_q\delta}|-\rangle^{\otimes n_q}\right]$$

- However, the protocol has higher requirements for coherence and error rates⋯.

Outlook





- We can leverage the era of quantum control to sense new physics! After all we are explorers.

- **Example**: Cavity and qubit systems
  - Exciting recent results with 20 sec coherence and high fidelity
  - Dark matter search demonstrations this year
  - Interesting scaling with Fock number and number of sensors.
  - Prospects for N^2 scaling

- Many challenges ahead:
  - Error correction
  - Frequency tuning
  - Magnetic field resilience