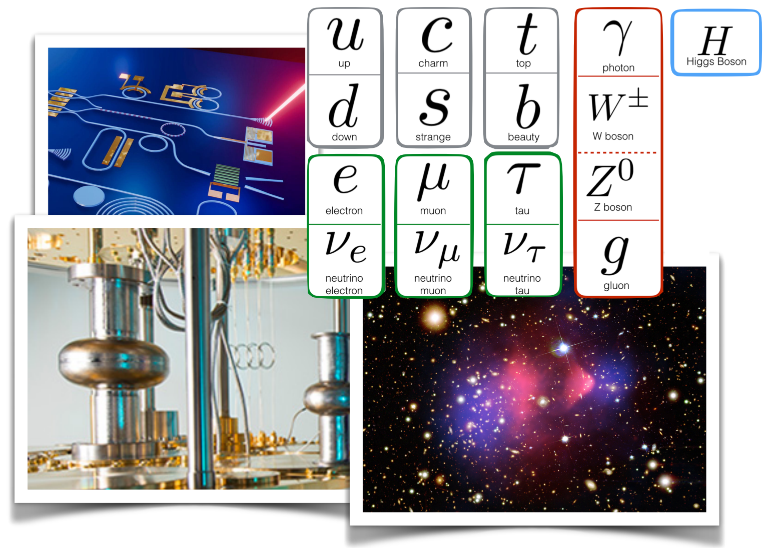
Quantum Sensing for Fundamental Physics

Roni Harnik,
Fermilab Quantum Theory Department
and SQMS



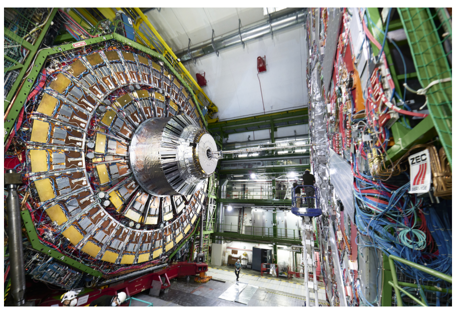
Fermilab

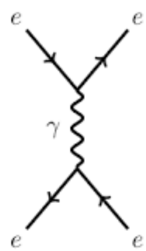
SQMS
SUPERCONDUCTING QUANTUM
MATERIALS & SYSTEMS CENTER

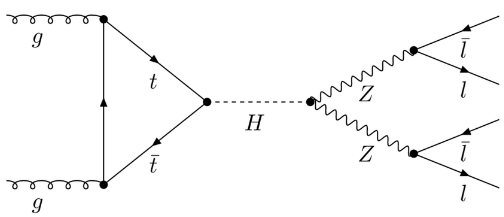
3061

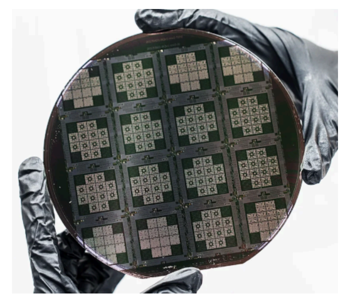
HEP - Quantum Interface

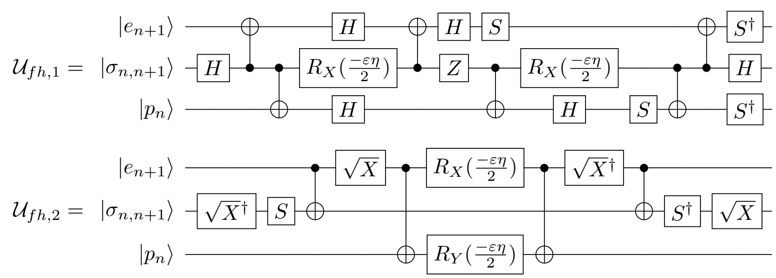
- Particle physics was always inherently quantum. Duh.
- A new field of Quantum physics is rapidly emerging, QIS.
- The interface is growing, but still small -





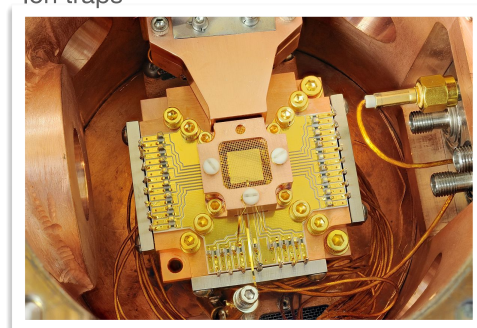




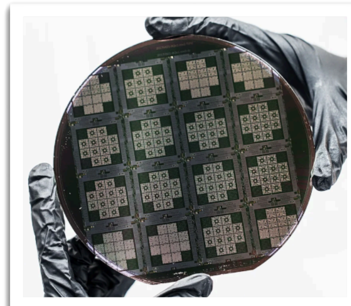


QIS spans many technologies.
Very sensitive (and cool) devices!
The goal is to manipulate information in quantum ways.

Ion traps

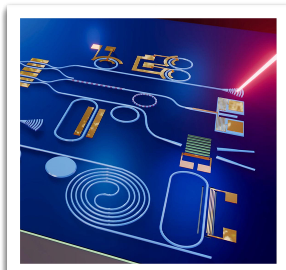


SC qubits

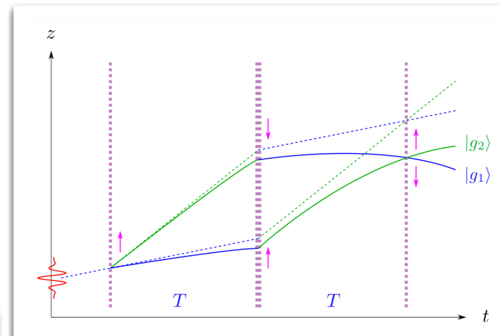


SC cavities

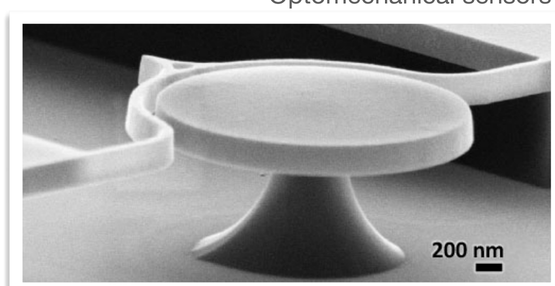
Integrated photonics

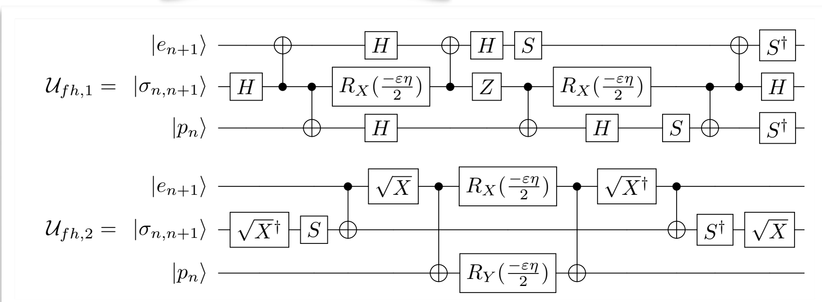


Atom interferometers



Optomechanical sensors





Quantum algorithms

Takeway and Plan

Takeaway: we can bridge the gap b/w these fields

- HEP, QIS share a common foundation - **Quantum Field Theory.**
  These fields are not as distant as we sometimes think.

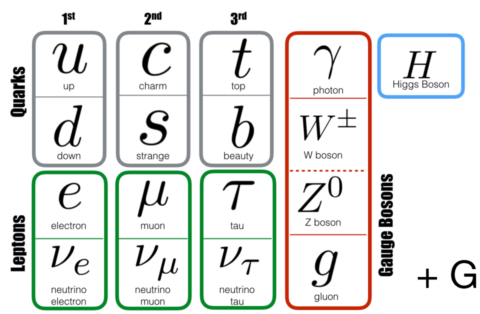
- We have new opportunities to explore Nature with quantum technology.

Plan:

- Talk about quantum devices in HEP language. (EFT)
  - Examples.
- Talk about BSM models in a QIS language.
  - Examples
- Examples of searches for BSM with sensors

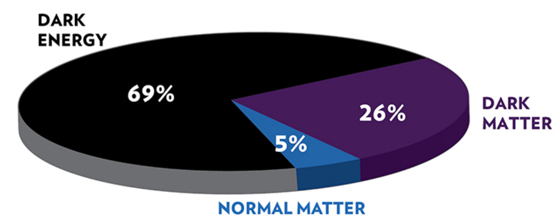
Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



+ Gravity

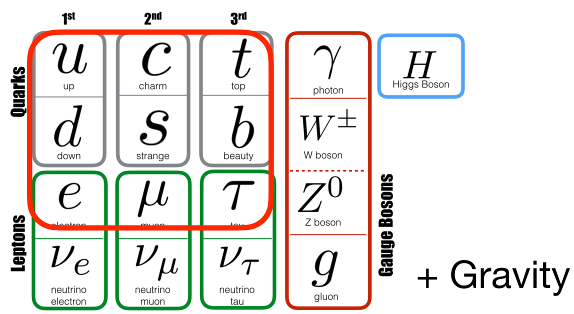
+



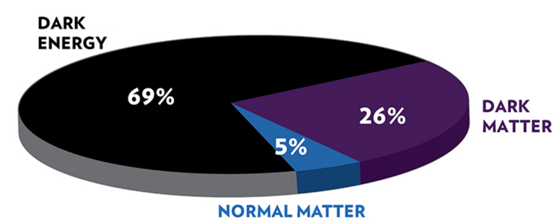
+ a whole lot of mysteries.

Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



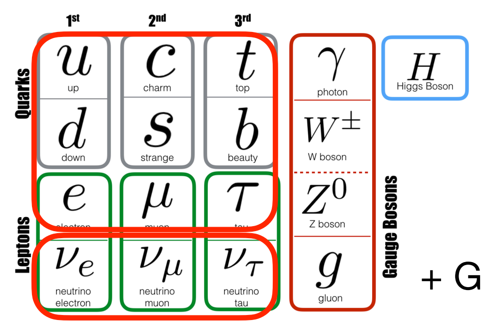
+



+ a whole lot of mysteries.

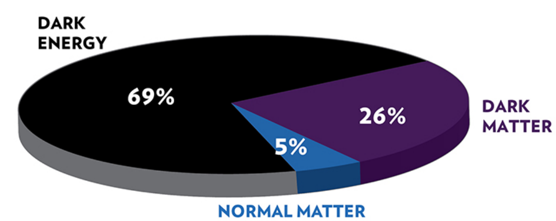
Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



+ Gravity

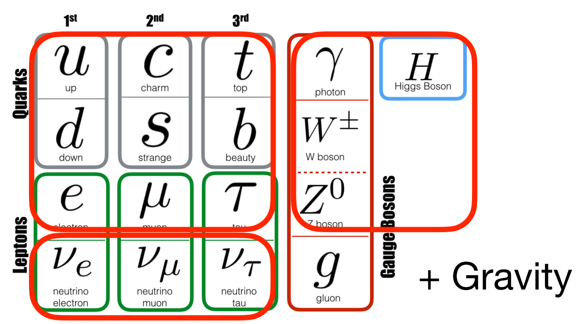
+



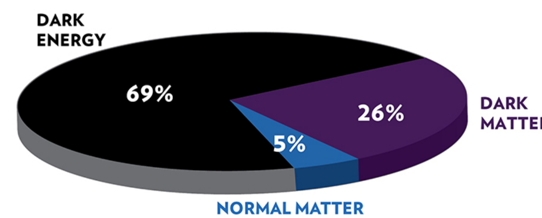
+ a whole lot of mysteries.

Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



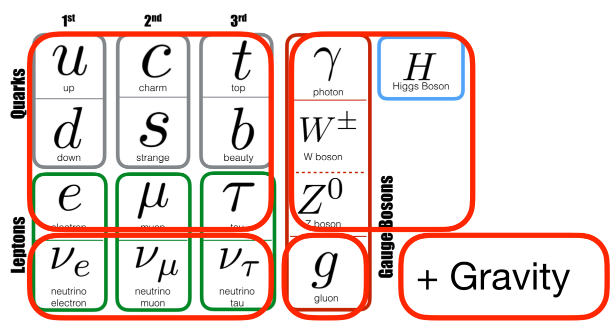
+



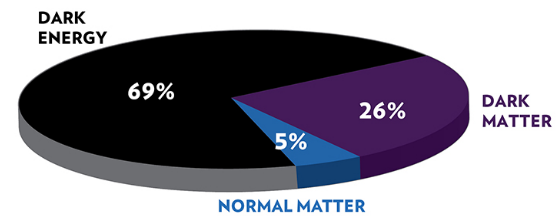
+ a whole lot of mysteries.

Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



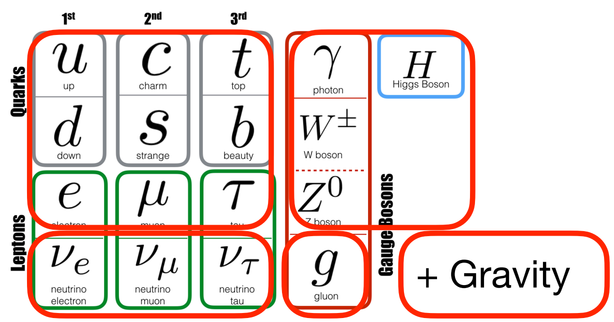
+



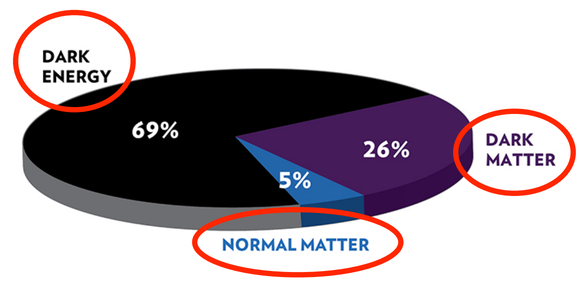
+ a whole lot of mysteries.

Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



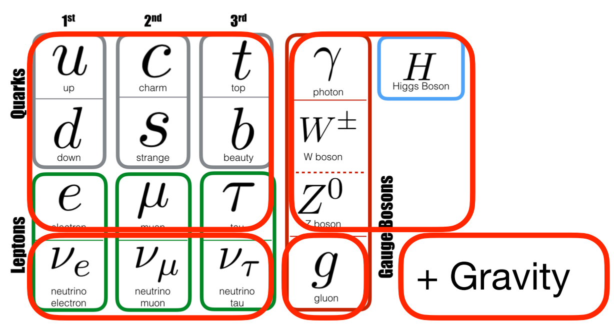
+



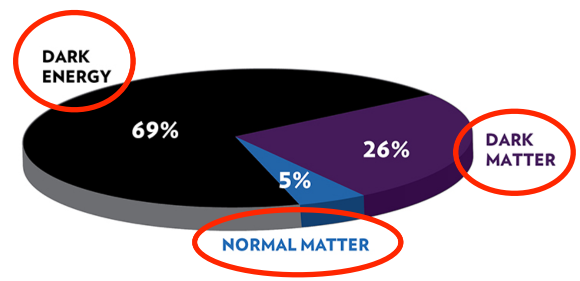
+ a whole lot of mysteries.

Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



+

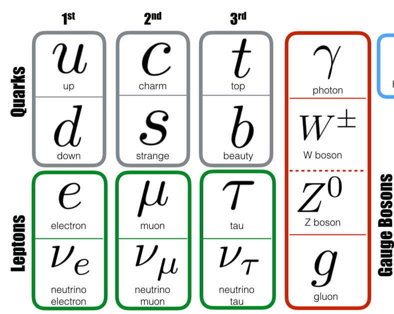


+ a whole lot of mysteries.

There is more. **BSM**. More fields! We'll get back to that!

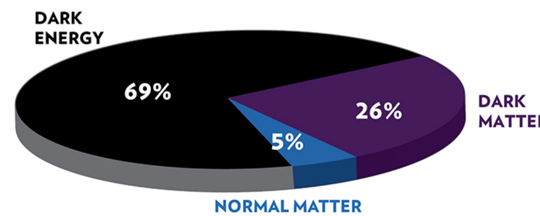
Particle physics and its mysteries:

- The Standard model(s): a menu of particles & interactions + an energy budget,



+ Gravity

+



Particle physics and its mysteries:

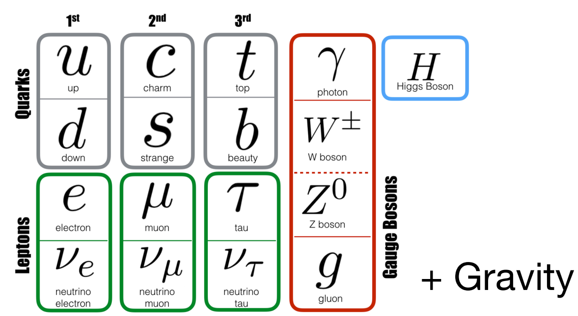
- The Standard model(s): a menu of particles & interactions + an energy budget,

QFT:

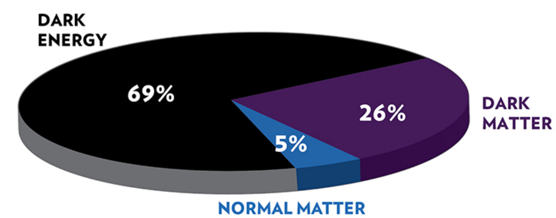
$|\psi(x)\rangle = \psi(x)\,|\Omega\rangle$

$\mathcal{L} = \cdots$

+



+



Every particle is a Field

QFT is continuum of interacting fields. All frequencies.

Quantum Field Theory

- At the heart of QFT is a mode expansion.
  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.

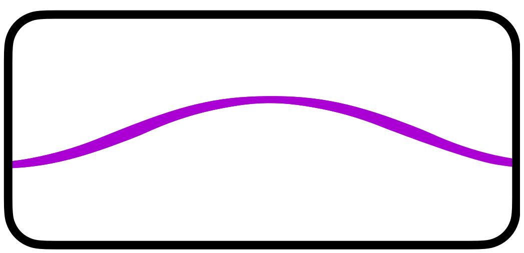
Statify: $[a_k, a_{k'}^\dagger] = \delta_{kk'}$

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

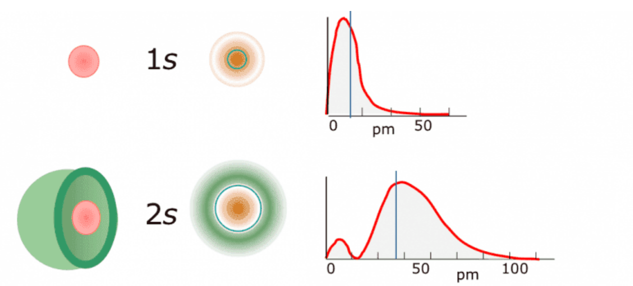
Quantum Fields in Small Devices

- In this big Universe, fields sometimes get localized to a finite regions. Either "naturally" or in a lab.

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



or



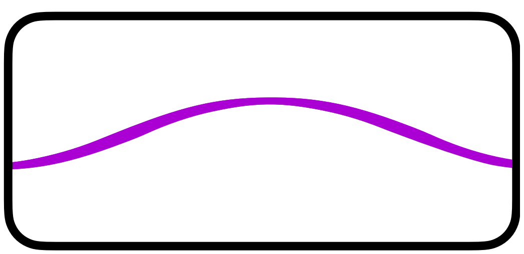
Quantum Fields in Small Devices

- In this big Universe, fields sometimes get localized to a finite regions. Either "naturally" or in a lab.

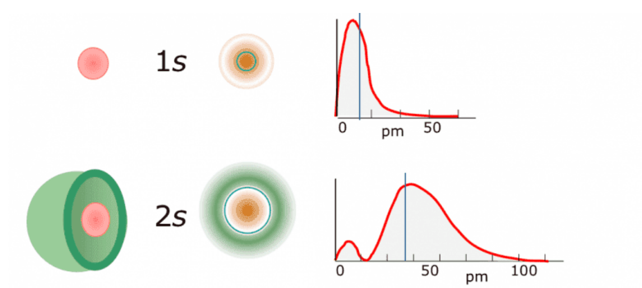
$$\phi(x_\mu) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2\omega}} \left(a_{\vec{k}} u_{\vec{k}}(\vec{x}) e^{i\omega t} + a^\dagger_{\vec{k}} u_{\vec{k}}{}^*(\vec{x})(e^{-i\omega t} \right)$$

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

Only a discretum satisfies boundary conditions.



or

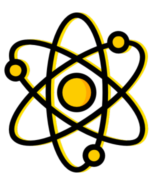


Quantum Fields in Small Devices

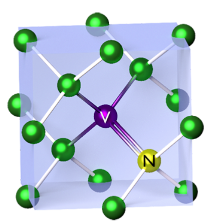
- Consider the low energy EFT of the discretum. Often in terms of a, a†

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

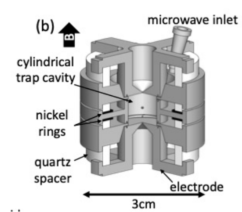
- In these EFTs, modes separate from the continuum, Quantum Mechanics shines:



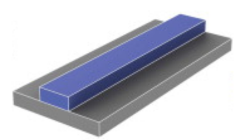
Atoms



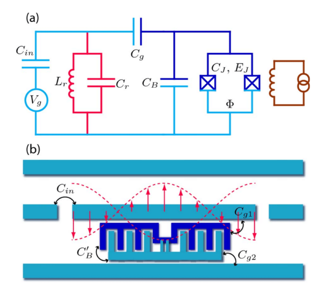
Defects



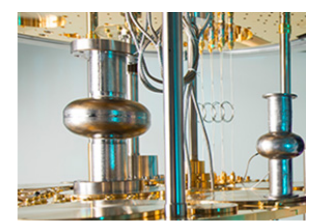
Artificial Atoms (particle in trap)



Optical waveguide



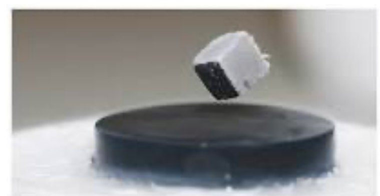
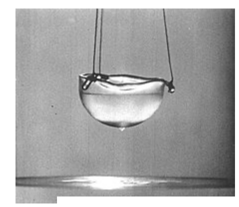
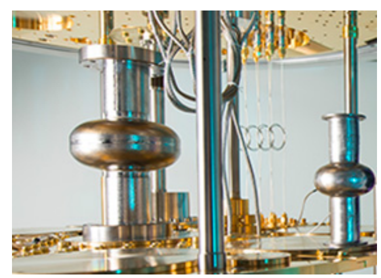
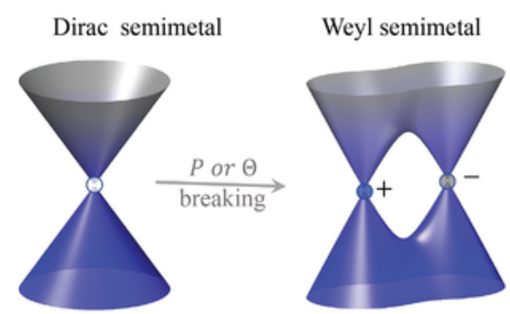
Superconducting circuits



Electromagnetic Cavities

New phases

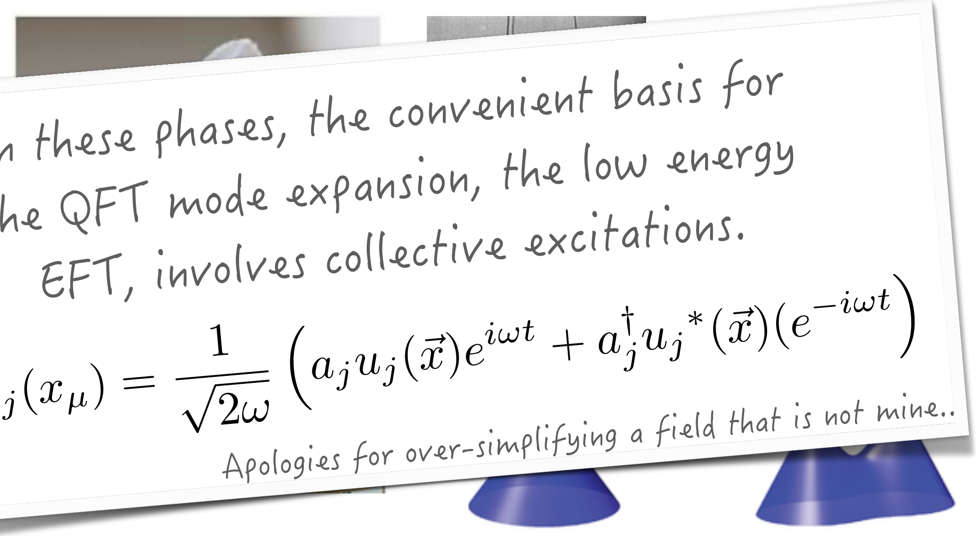
- BTW: interesting quantum effects sometimes happen even without boundary conditions
- New phases, gaps, band structures, nontrivial dispersion⋯ :
  - Superconductors
  - Superfluids
  - Semiconductors
  - Semi-metals
  - Spin glasses
  - Topological phase
  - ⋯

Of course, these phases are sometimes used to impose boundary conditions, and ⋯

New phases

- BTW: interesting quantum effects sometimes happen even without boundary conditions
- New phases, gaps, band structures, nontrivial dispersion$\cdots$:
  - Superconductors
  - Superfluids
  - Semiconductors
  - Semi-metals
  - Spin glasses
  - Topological phase
  - $\cdots$



In these phases, the convenient basis for the QFT mode expansion, the low energy EFT, involves collective excitations.

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

Apologies for over-simplifying a field that is not mine..

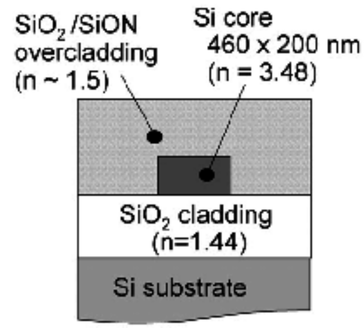
Of course, these phases are sometimes used to impose boundary conditions, and $\cdots$

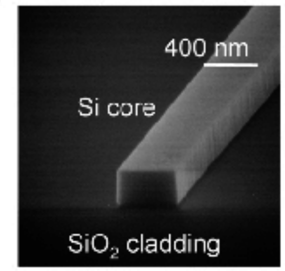
Examples

Optical Devices (e.g. integrated optics)

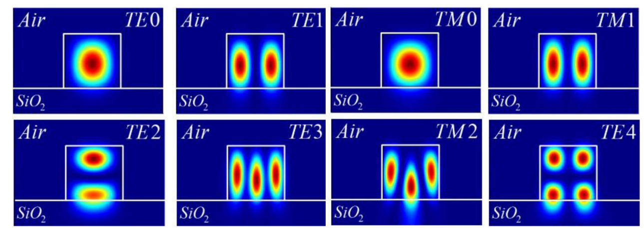
Superconducting circuits and cavities

Optical Devices

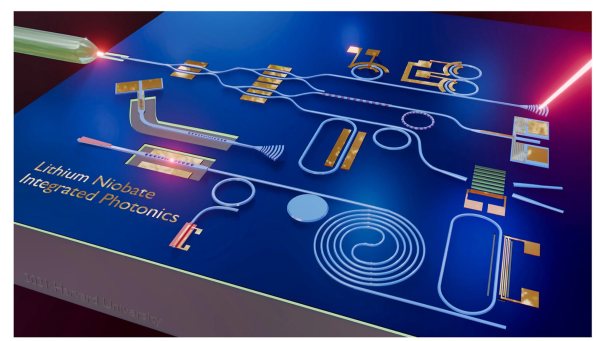




- Optics is the low energy EFT of light in matter.
- We can control the dispersion relation: $k = n\omega$.
  Useful for localization.



- A waveguide admits a 1D EFT w/ modes quantized in transverse direction.
- Transverse wave function affects longitudinal dispersion relation (a la KK modes!)



"Integrated photonics"

Linear Optics: $H = E^2 + B^2 = \Sigma\, \hbar\omega(a^\dagger a + 1/2)$

Nonlinear Devices

- Like any EFT, in a quantum device there is a UV cutoff.
- We can add higher dim operators. For example, in optics

Dim-6: $$H_{\mathrm{SPDC}} = \int_{\mathrm{crystal}} d^3\vec{x} \left(\chi^{(2)}_{jkl} E_j E_k E_l \right)$$

Dim-8: $$H_{\mathrm{4\text{-}wave}} = \int_{\mathrm{crystal}} d^3\vec{x} \left(\chi^{(3)}_{jkl} E_j E_k E_l E_m \right)$$

Nonlinear Devices

- Like any EFT, in a quantum device there is a UV cutoff.
- We can add higher dim operators. For example, in optics

Dim-6: $$H_{\text{SPDC}} = \int_{\text{crystal}} d^3\vec{x} \left(\chi^{(2)}_{jkl} E_j E_k E_l\right)$$

Dim-8: $$H_{\text{4-wave}} = \int_{\text{crystal}} d^3\vec{x} \left(\chi^{(3)}_{jkl} E_j E_k E_l E_m\right)$$

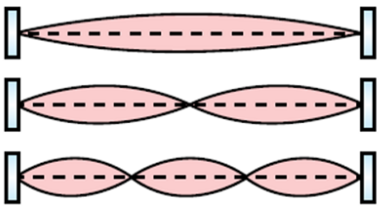
[We can estimate χ's in naive dimensional analysis:

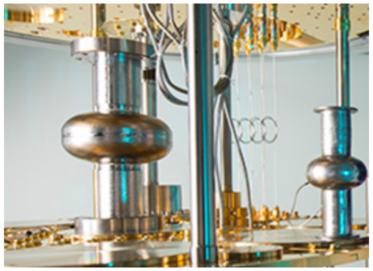
When the field is set to that in an atom, we set (Dim-4 ~ Dim-6 ~ Dim-8):

$$E_{\text{atom}} \sim e/4\pi a_0^2 \qquad \chi^{(2)} \sim \frac{\sqrt{4\pi}}{\alpha^{5/2} m_e^2} \qquad \chi^{(3)} \sim \frac{4\pi}{\alpha^5 m_e^4}$$

(by comparison, in vacuum $\chi^{(2)} = 0$, $\chi^{(3)} = \frac{2\alpha^2}{45 m_e^4}$)]

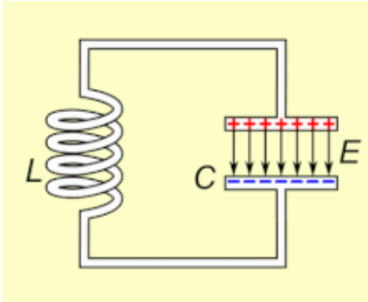
Superconducting Cavities & Circuits





- **Cavities**: 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!)



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

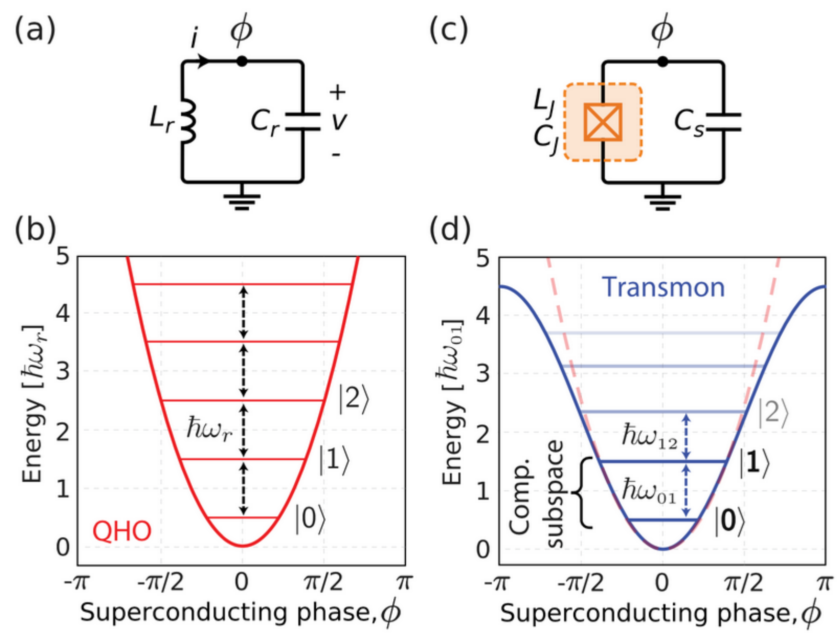
Both are harmonic. Equally spaced levels. $H_{mode} = \hbar\omega(a^\dagger a + 1/2)$

Nonlinear Devices

- Here too, we can arrange for a UV cutoff with higher dim operators,
- e.g. making L a function of $a^\dagger a$.

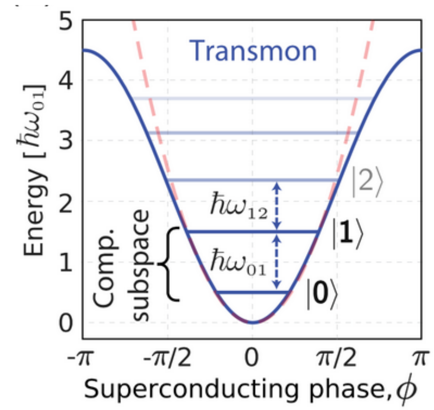
$$H = \hbar\omega(a^\dagger a + 1/2) + \kappa(a^\dagger a)^2$$

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

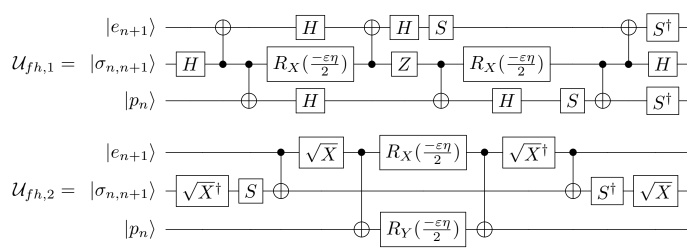


Quantum Control

- 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.

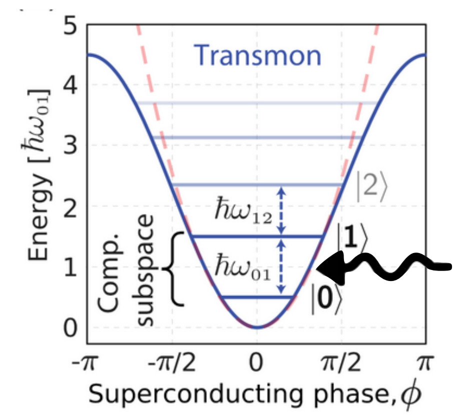


Qubit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

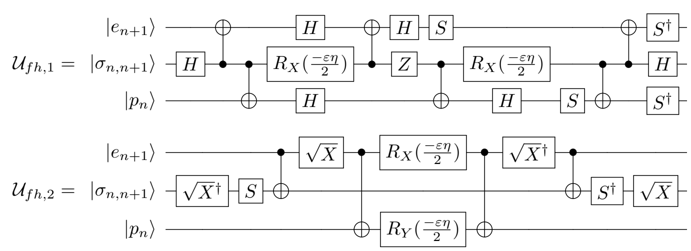


Quantum Control

- 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.

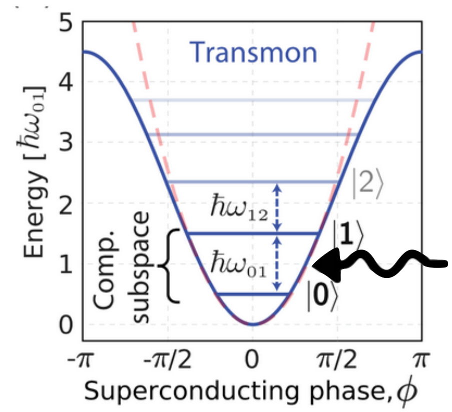


Qubit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

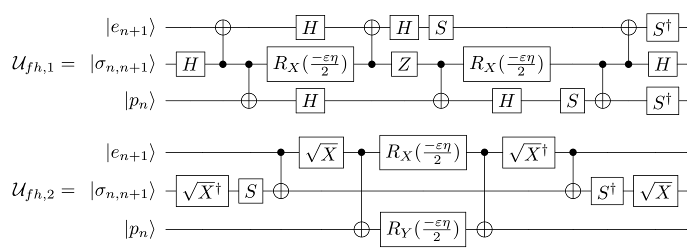


Quantum Control

- 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.

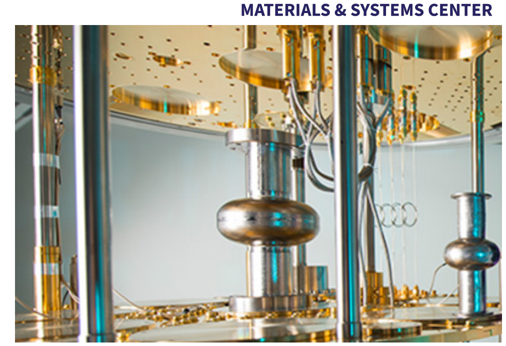


Qubit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



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

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



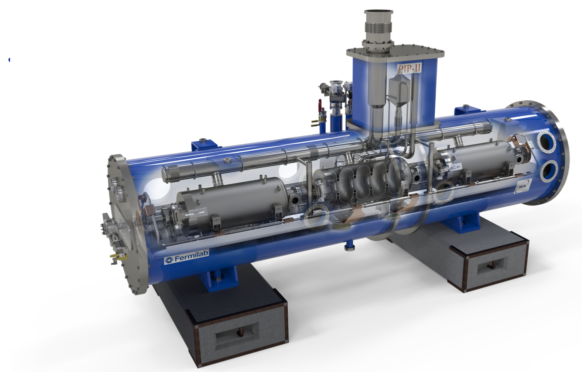
By the way … (

SQMS

- Superconducting devices are a central player in QIS.
- A limiting factor in their performance is loss (finite Q) & decoherence.

  e.g. prepare a qubit, $\alpha|0\rangle + \beta|1\rangle$, after a while $|0\rangle \longrightarrow |1$

  For modern qubits, a while ~ msec



- Fermilab, and other labs, had already developed ultra-high-Q cavities to accelerate particles! Lifetimes of O(sec)!
- The SQMS center is using this technology and materials know-how for QIS.
- Achieving record coherence times in 2D and 3D systems, and understanding decoherence effects.

)

Quantum Simulation


The New York Times
Tuesday, March 3, 2020 | Today's Paper | Personalize Your WeatherPersonalize Your Weather
OPINION BUSINESS TECH SCIENCE HEALTH SPORTS ARTS FASHION & STYLE CROSSWORD TIMES INSIDER
Google unveils new "Quantum Computer"

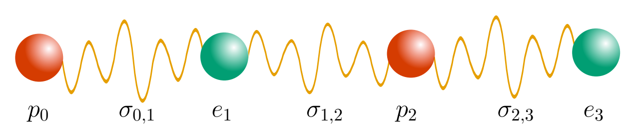
- Famously, control of quantum states change the game. Quantum computers! (Shor's algorithm, etc).

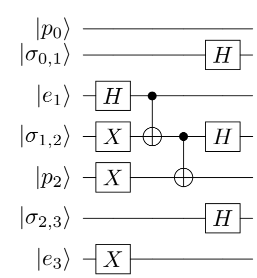
- For HEP, quantum computers may tackle open computational challenges:

- Real-time simulation of HEP (e.g. of hadronization) on classical computers converge prohibitively slowly due to rapidly rotating phases (sign problem).

- But, even if quantum computers were fault tolerant today, we are not ready!

- Identifying efficient mappings of a lattice QFT to a QC, and the algorithm for simulation is an active area of research!

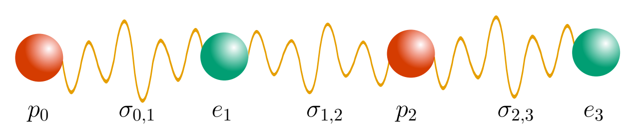


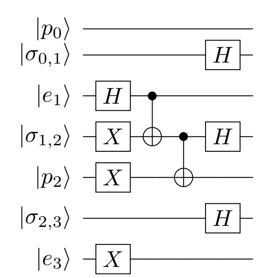


Quantum Simulation

- Famously, control of quantum states change the game. **Quantum computers!** (Shor's algorithm, etc).
- For HEP, quantum computers may tackle open computational challenges:
- Real-time simulation of HEP (e.g. of hadronization) on classical computers converge prohibitively slowly due to rapidly rotating phases (sign problem).
- But, even if quantum computers were fault tolerant today, we are not ready!
- Identifying efficient mappings of a lattice QFT to a QC, and the algorithm for simulation is an active area of research!

But not the focus of my talk.

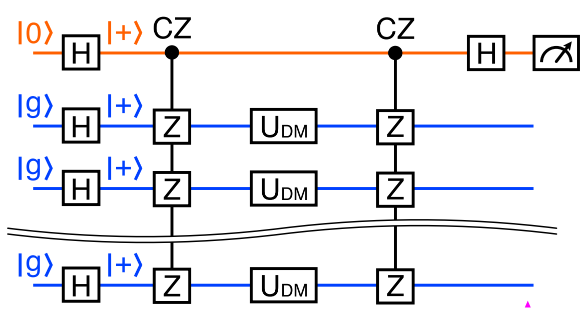


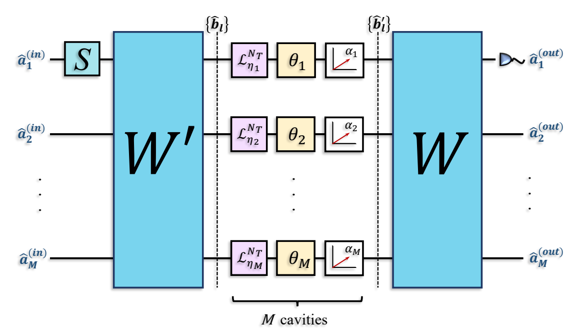


Quantum Sensing

- The isolation of modes, and the ability to control them enables feeble effects to lead to dramatic consequences:
  - Appearance of mode occupation (Haloscope, light shining though wall)
  - Removal of mode occupation/phase transitions (TES, Nanowires: SC to normal)
  - Time evolution of ultra sensitive (entangled?) states

Chen et al, 2311.10413
Ito et al 2311.11632

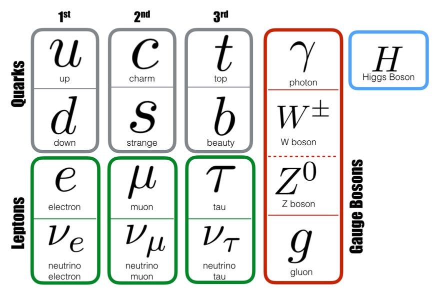




Distributed squeezing: Brady, RH, et al, *PRX Quantum* 3 (2022) 3, 030333

BSM - for Quantum Mechanics

New Physics ⟶ New Fields



+ Something new.

Ok. For concreteness,

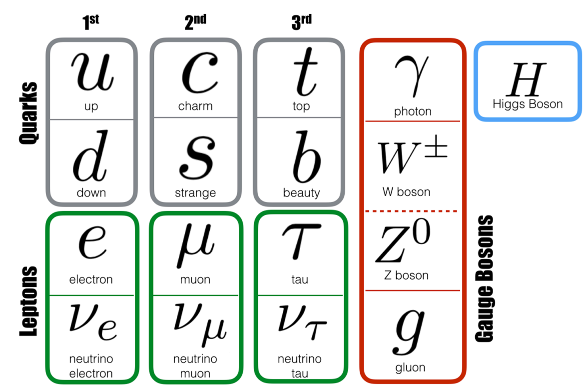
(and because QIS is often about controlling light)

lets assume the new field couples to photons.

Linear or nonlinear?

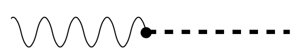
Dark Photons - a Linear Extension

- If something mixes linearly with the photon, it must have the same quantum numbers:



- The dark Photon effective Hamiltonian:

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

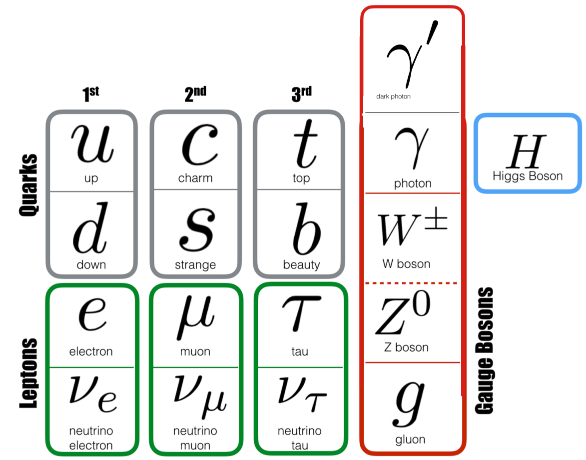


(and dark photon also has a mass, and a longitudinal polarization!)

(OFC, a dark photon, if it exists, would teach us profound lessons! New force of nature. Grand Unification, etc.)

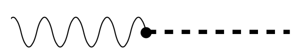
Dark Photons - a Linear Extension

- If something mixes linearly with the photon, it must have the same quantum numbers:



- The dark Photon effective Hamiltonian:

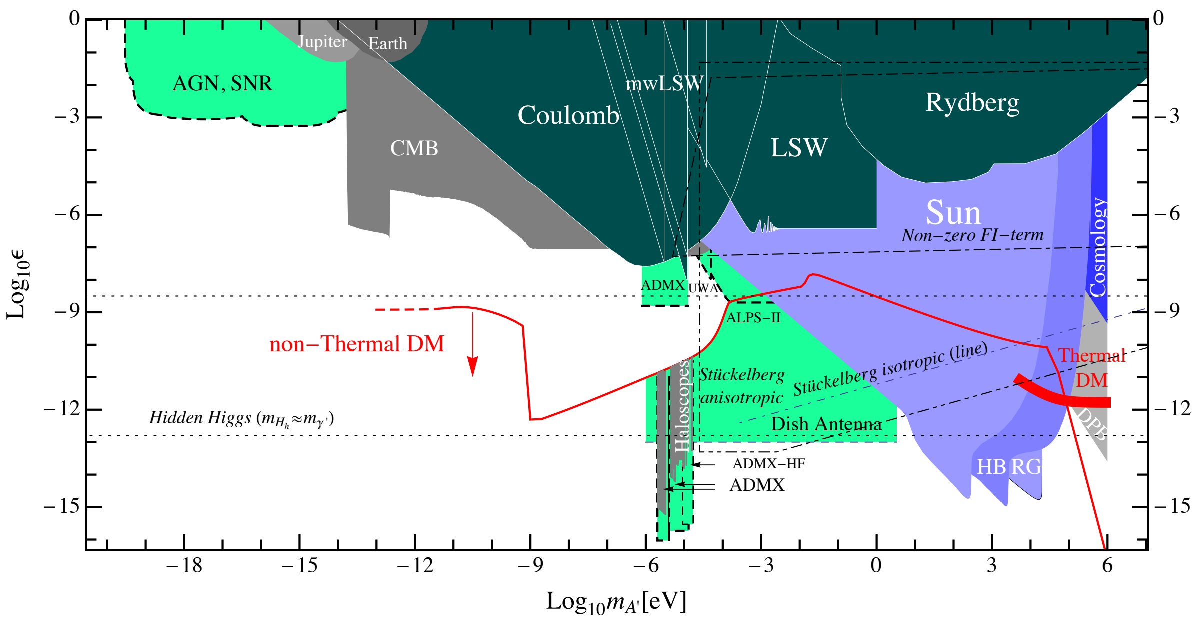
$$\mathcal{H} \supset \mathcal{H}_{QED} + \varepsilon\, \vec{E}\cdot\vec{E}' + \vec{B}\cdot\vec{B}'$$

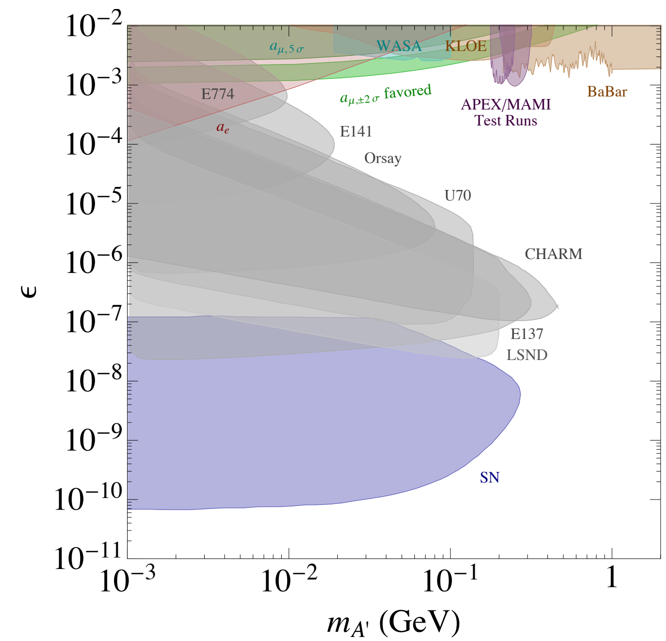


(and dark photon also has a mass, and a longitudinal polarization!)

(OFC, a dark photon, if it exists, would teach us profound lessons! New force of nature. Grand Unification, etc.)

Dark Photons - a Linear Extension



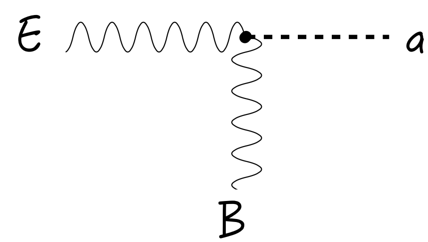


Pecci and Quinn (77)

Axions - A nonlinear extension of QED

- A nonlinear interaction, naively, would involve 2 photons & 1 new field.

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

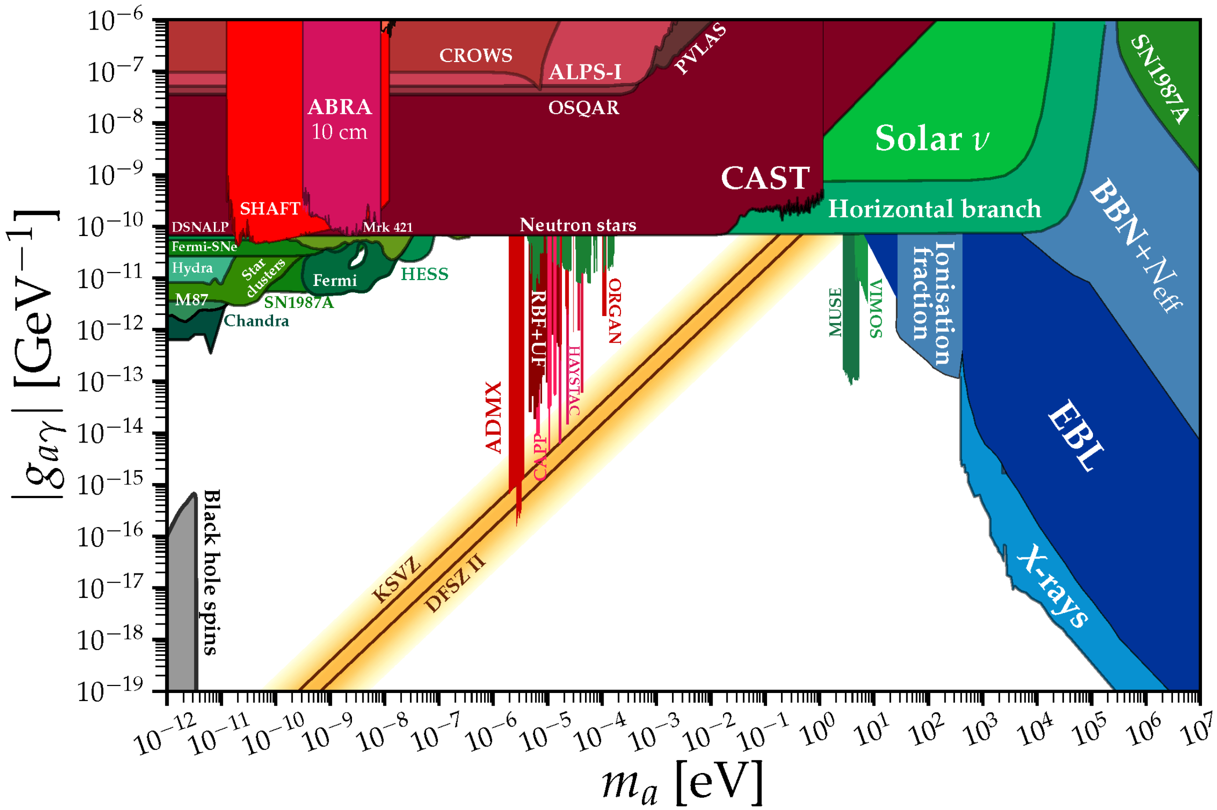


- Axion phenomenology:
  - Axion mixing w/ photons polarized along background B field. [Sikivie]
  - Axion can be absorbed by photon -> up conversion. [Berlin et al (2019)] [Gao, RH (2020)]
  - Axion exchange -> photon nonlinearity in vacuum. [PVLAS] [e.g. Bogorad, Hook, Kahn, Soreq (2020)]

(Of course, the discovery of an axion will be a profound insight! Strong CP. etc.)

Pecci and Quinn (77)

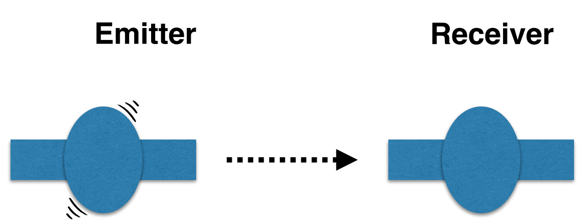
Axions - A nonlinear extension of QED



New Particle vs Dark Matter Searches

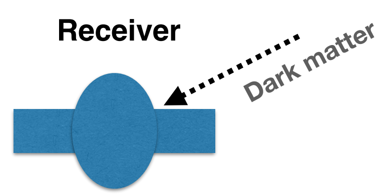
- We can test two distinct hypotheses:
  - Axion/Dark photons are new fields we can source in a lab.
  - They also make up the (cold) dark matter of the Universe.

<u>Lab search</u>



e.g. Light Shining through wall.
Frequency is known.

<u>DM search</u>



Frequency is set by DM mass and is unknown. Need to scan!

Examples

Cavities

Optics

Qubits

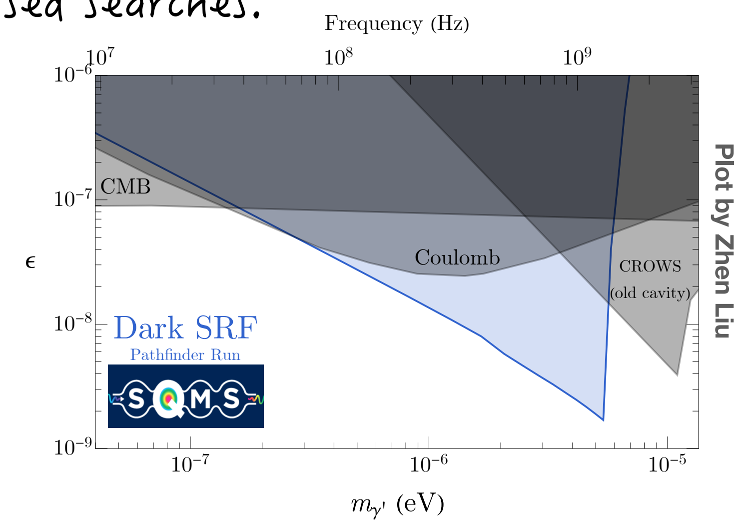
Atoms

I probably have more example than we have time for…

Dark SRF: cavity-based search for the Dark Photon

Look for linear model with linear devices:
A light-shining-through-wall experiment.

Phase 1: Pathfinder run in LHe.
Demonstrated enormous potential for SRF based searches.

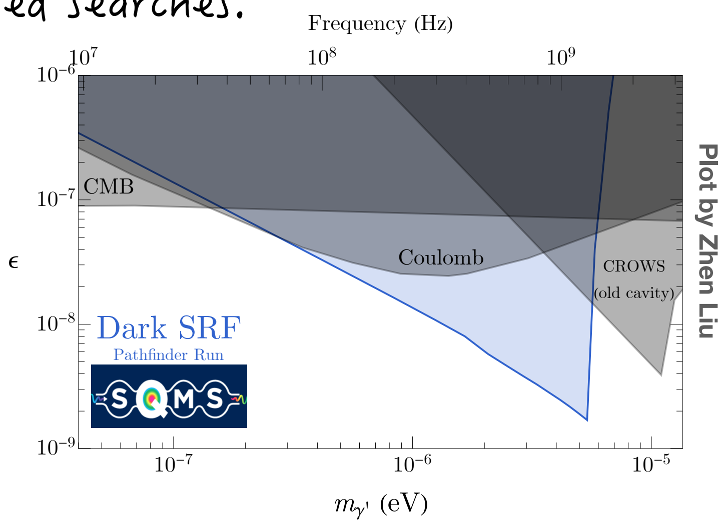


Romanenko et al., *Phys.Rev.Lett.* 130 (2023) 26, 261801

Dark SRF: cavity-based search for the Dark Photon

Look for linear model with linear devices:
A light-shining-through-wall experiment.

Phase 1: Pathfinder run in LHe.
Demonstrated enormous potential for SRF based searches.

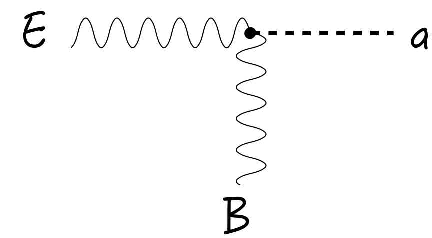


Phase 2: in DR, receiver at ~mk, in quantum regime. Improved frequency stability. Photon counting and/or phase sensitive readout.

Increased reach.

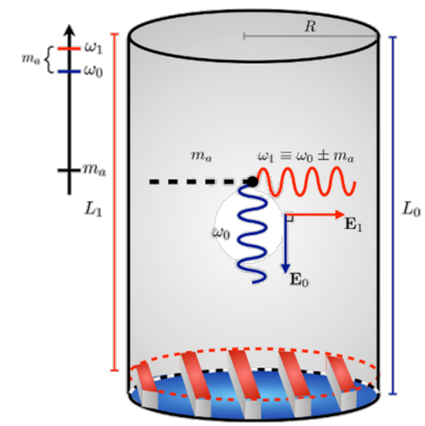
Romanenko et al., *Phys.Rev.Lett.* 130 (2023) 26, 261801

Axion searches with Cavities



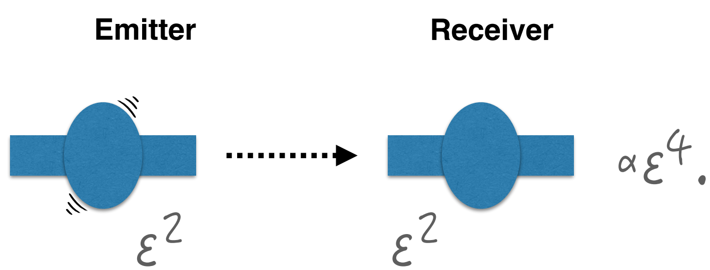
- We can look for nonlinear effects.
  - **DM search**: Turn on a B field*, or up conversion of pump mode photon into a nearby signal mode. [Sikivie] [Berlin et al (2019)]
  - **Lab search**: look for nonlinearity between modes (e.g. 2 pumps, one signal. [e.g. Bogorad, Hook, Kahn, Soreq (2020)]
- Condensed matter connection: In many cases, the inherent nonlinearity of SC, nonlinear-Meinser.

  [J. A. Sauls, Prog. Theor. Exp. Phys. 2022, 033I03 (2022)]
- A double cavity setup likely needed. [Gao, RH (2020)]

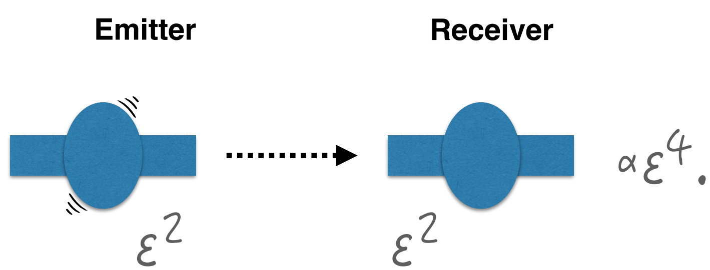


* Turning one a strong B field in a SC cavity and keeping high Q is an open research challenge.

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

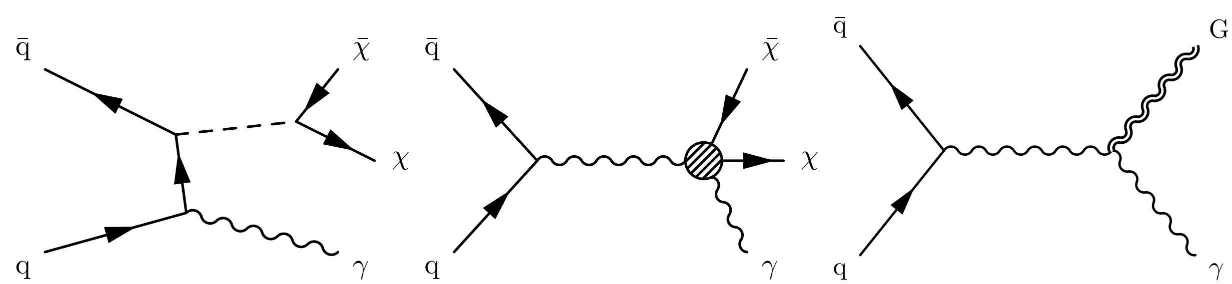


Can we do better?



Can we do better?

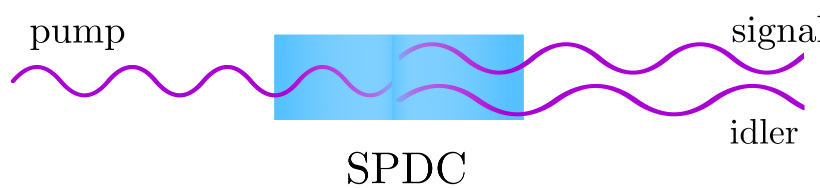
CMS, ATLAS:



Estrada et al. *PRX Quantum* 2 (2021) 3, 030340
RH in prepration.

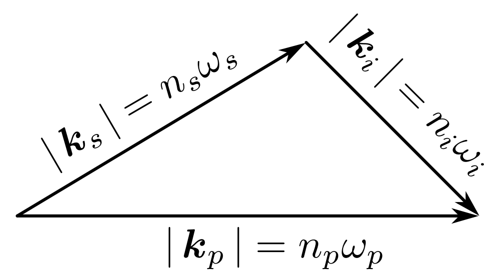
Nonlinear Optics with Dark States

- SPDC: a workhorse in quantum optics.
- Pump -> signal + idler (a "decay")
- A particle physicist may think such a decay has not phase space.
- Recall: pump, signal and idler can have different n's!



$$\omega_p = \omega_s + \omega_i$$

and

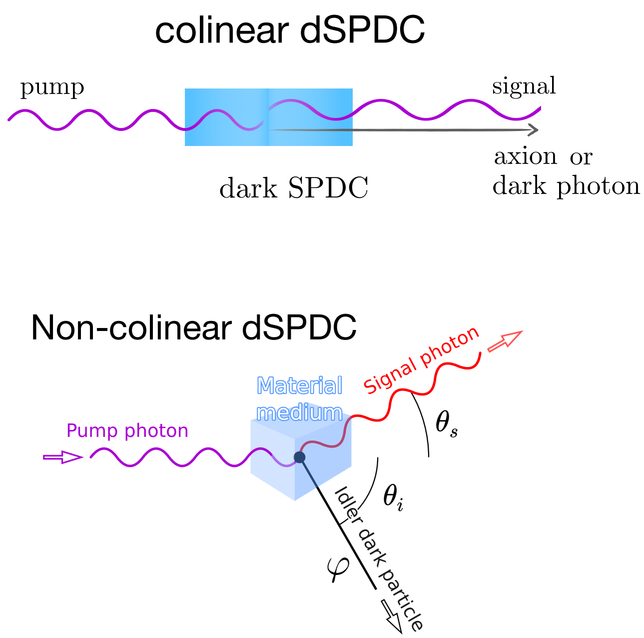


- Presence of idler is **inferred**. Might as well be invisible!

Estrada et al. *PRX Quantum* 2 (2021) 3, 030340
RH in prepration.

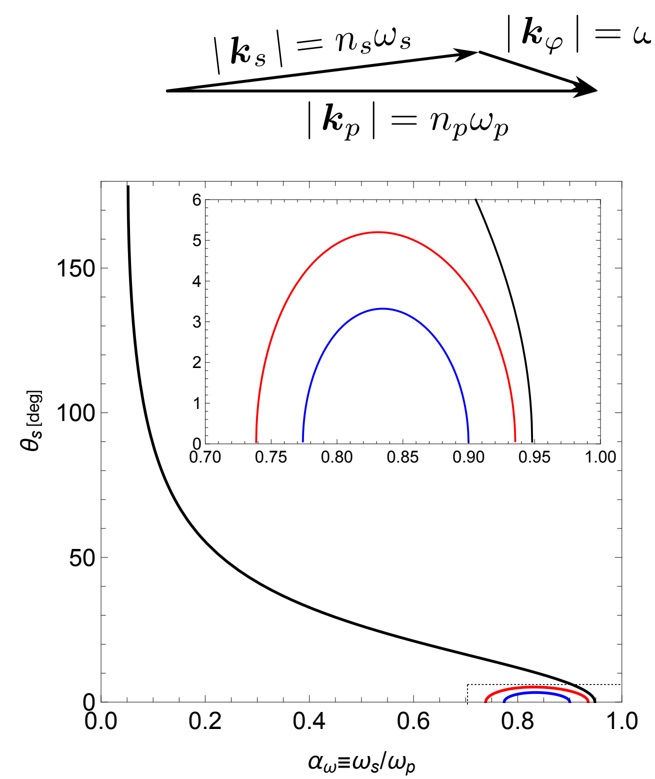
Nonlinear Optics with Dark States

- Dark SPDC: Pump -> signal + axion or dark photon. Rate ∝ ε^2 (vs ε^4 for LSW)



Note: the axion or dark photon have index of refraction of 1 (and a mass).

dSPDC has significantly different phase matching conditions. Different kinematics.

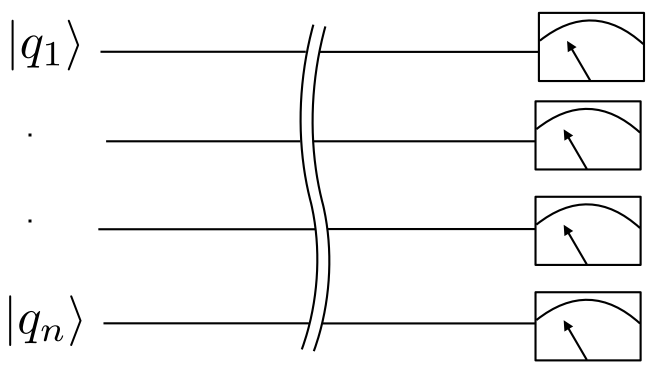


Experimental design in progress with Niel Sinclair

Quantum Advantage with Qubits

Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

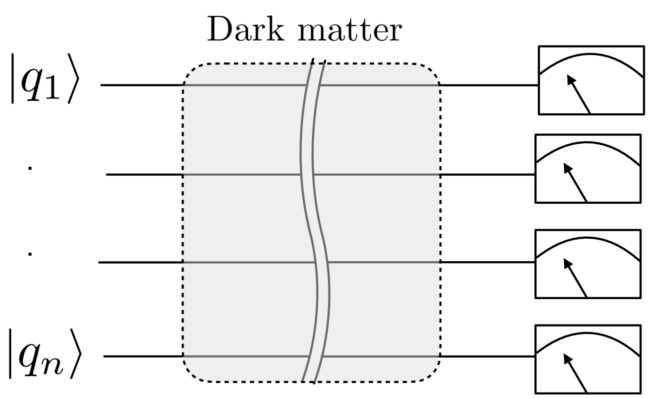
- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:



Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

Quantum Advantage with Qubits

- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:

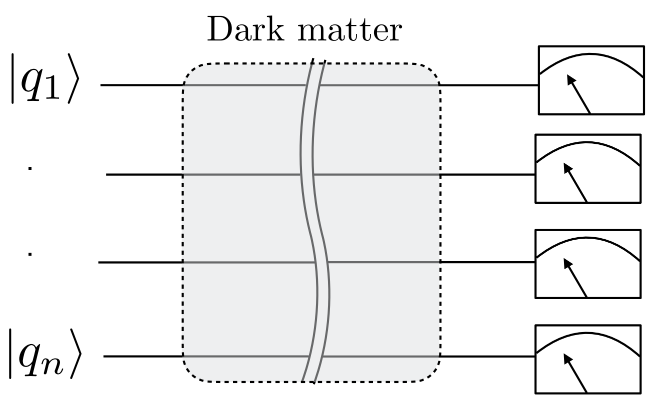


Rate scales as n.

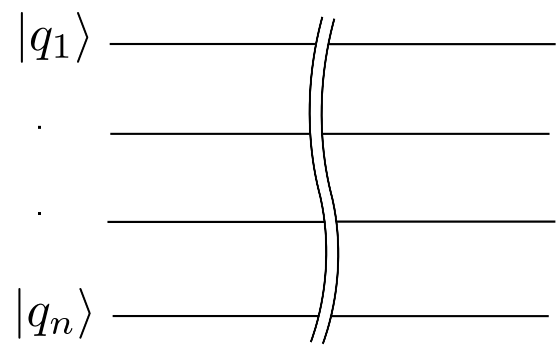
Quantum Advantage with Qubits

Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:



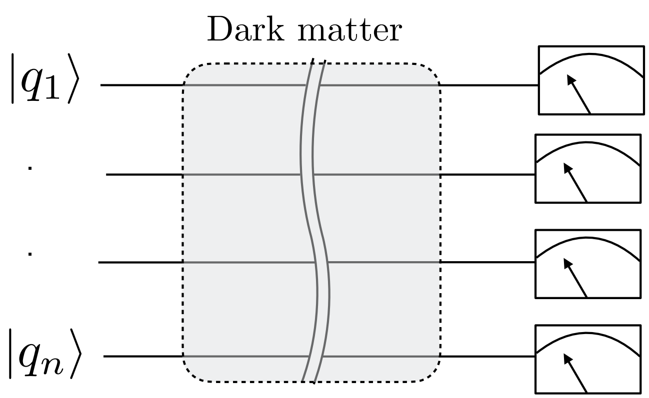
Rate scales as n.



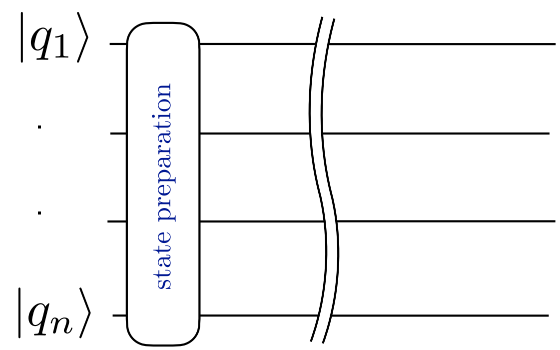
Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

Quantum Advantage with Qubits

- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:



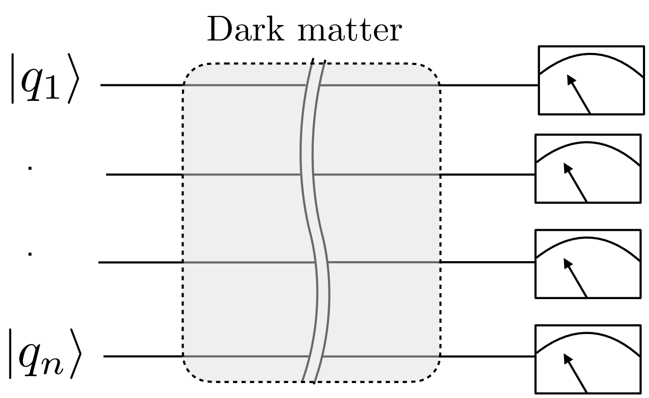
Rate scales as n.



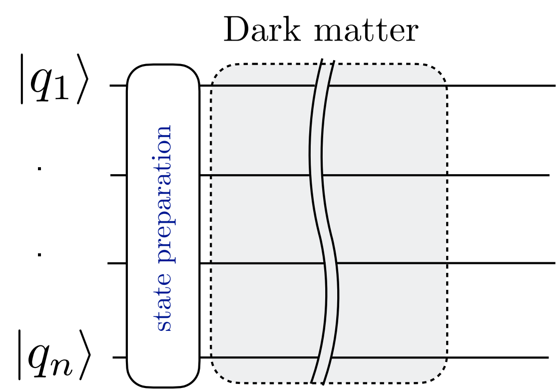
Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

Quantum Advantage with Qubits

- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:



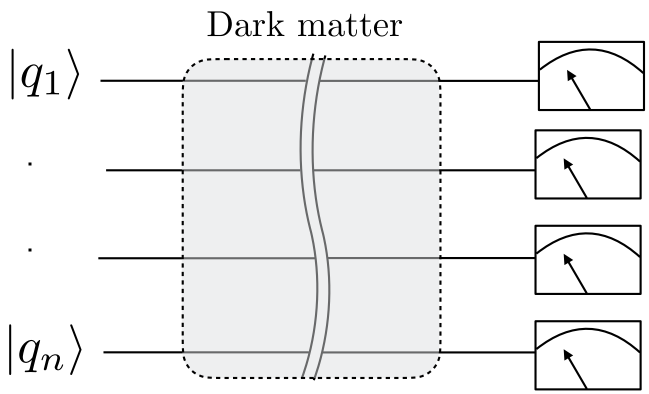
Rate scales as n.



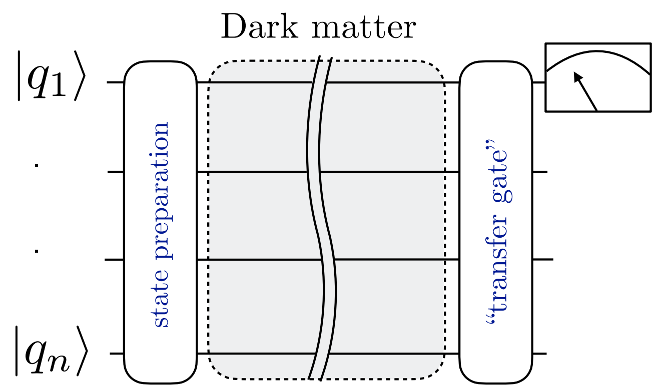
Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

Quantum Advantage with Qubits

- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:



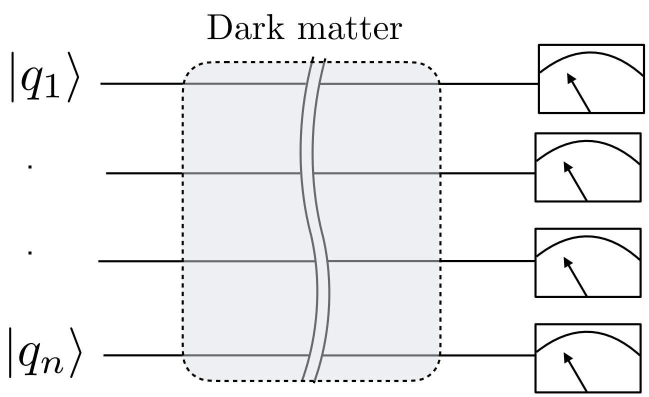
Rate scales as n.



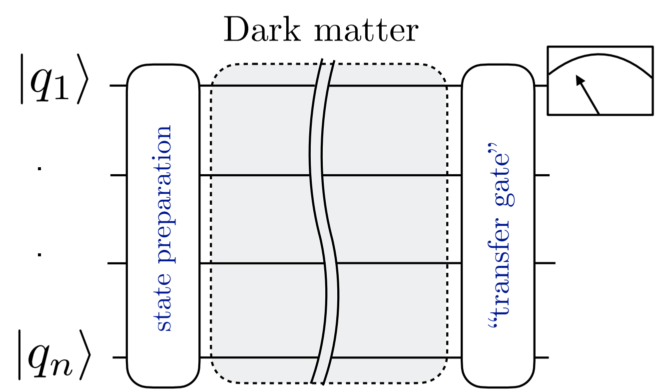
Chen et al, 2311.10413
Ito et al 2311.11632
Bodas, Ghosh, RH, in prep

Quantum Advantage with Qubits

- Can we get quantum speed-up in DM detection? Consider n qubits interacting with DM:



Rate scales as n.



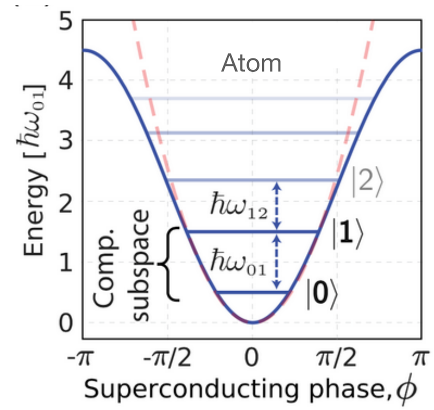
Which qubit interacted?
<u>Amplitude</u> scales as n.
Rate scales as n^2 !!

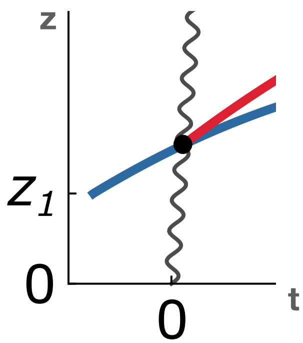
- A variety of algorithms for sensing (e.g. quantum phase estimation, work in progress).

Quantum Control in Free Space

- Imagine we take a qubit in **free space** and induce a transition:

- We give the atom some energy, but also momentum!

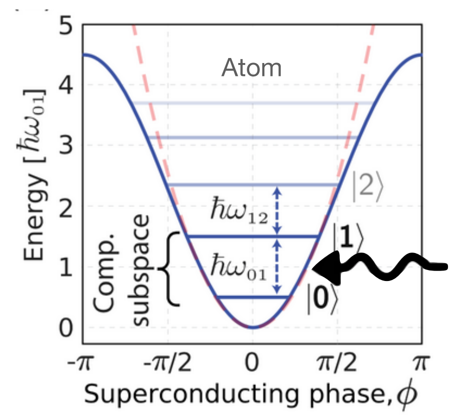


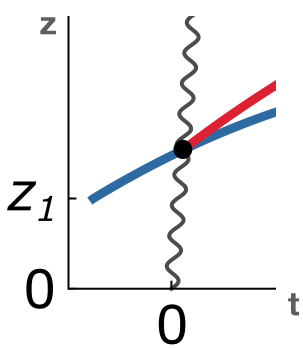


Quantum Control in Free Space

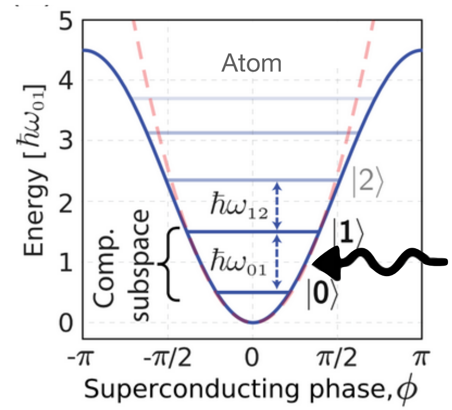
- Imagine we take a qubit in **free space** and induce a transition:

- We give the atom some energy, but also momentum!



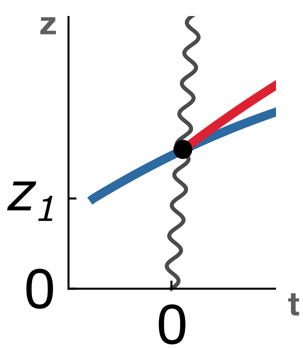


Quantum Control in Free Space

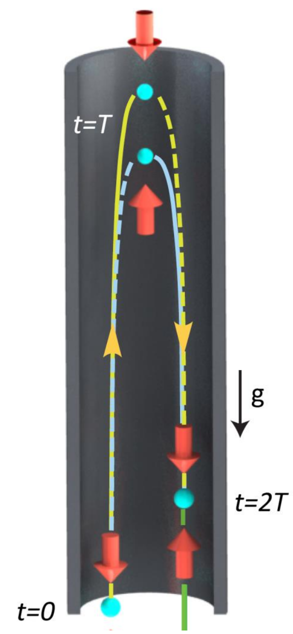


- Imagine we take a qubit in **free space** and induce a transition:

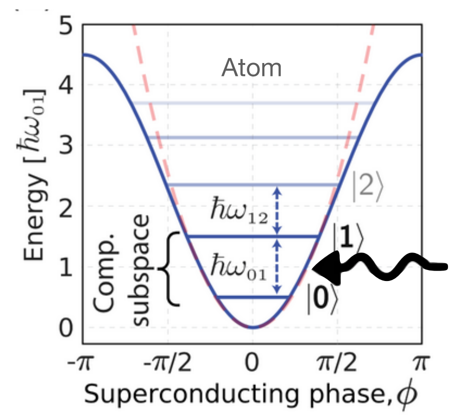
- We give the atom some energy, but also momentum!



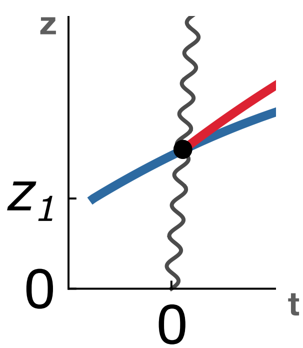
Wait …



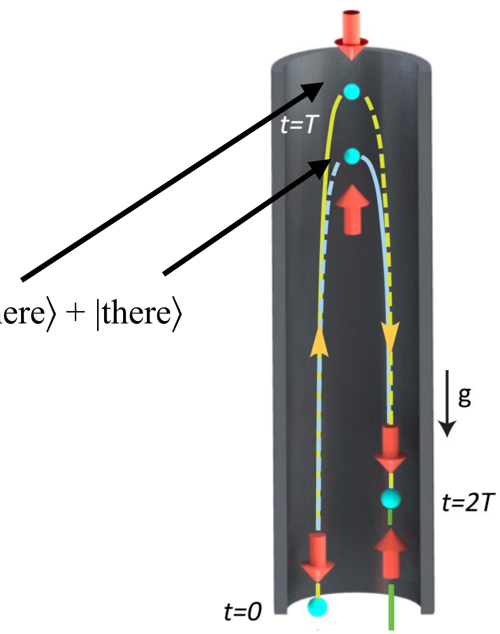
Quantum Control in Free Space



- Imagine we take a qubit in free space and induce a transition:
- We give the atom some energy, but also momentum!



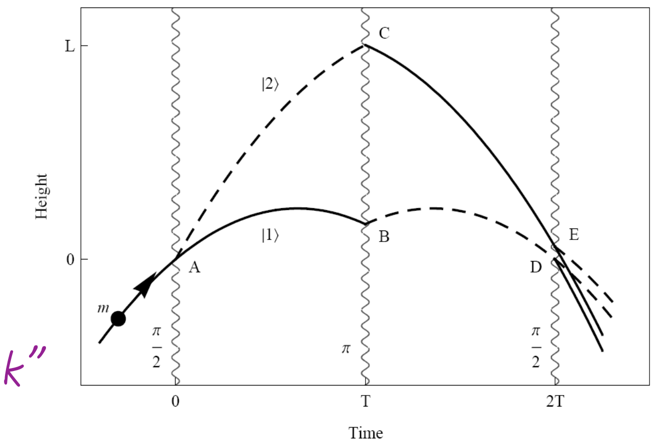
Wait …



$|\text{atom}\rangle = |\text{here}\rangle + |\text{there}\rangle$

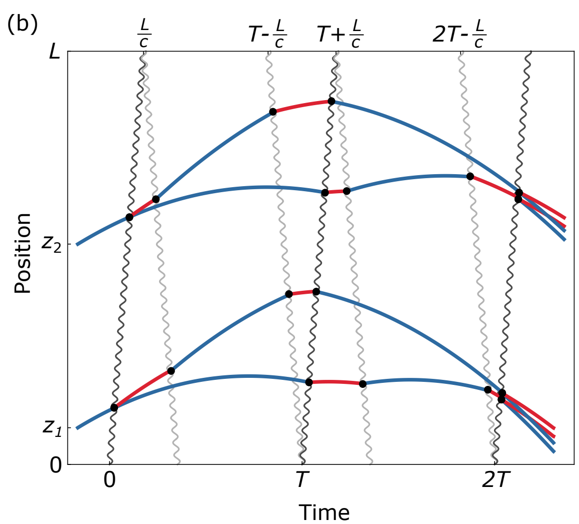
MAGIS 100

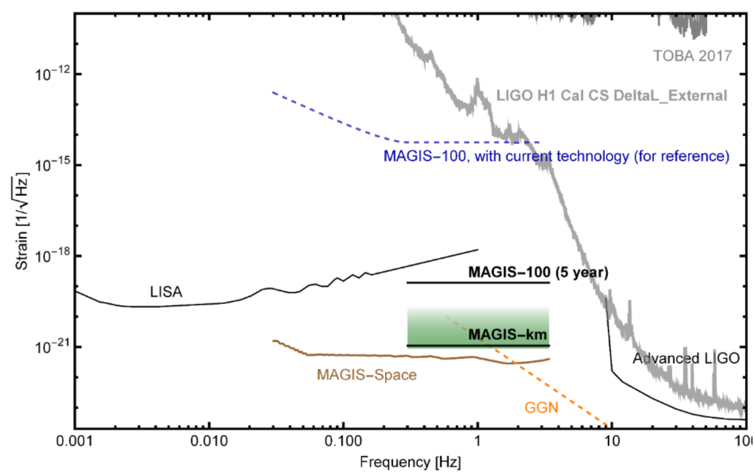
- Now we can do cool things!   Interferometry:



"A freely falling clock"

- MAGIS 100:





MAGIS-100 is under construction in Fermila's MINOS shaft.   :-)

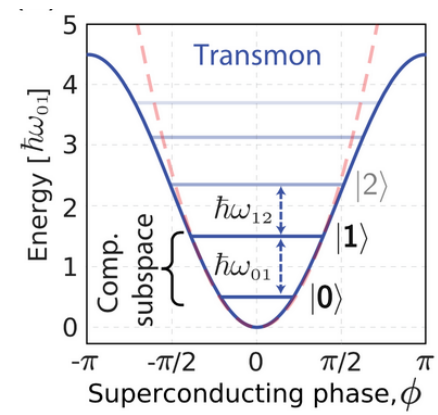
Summary

- Quantum Field theory extends into today's quantum devices!
- The interface of HEP and QIS is growing!
  - Quantum simulation of HEP (exciting, but not today's topic)
  - Quantum sensing
- Quantum sensors can probe new hypotheses in HEP

3061

Fermilab

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



Deleted Scenes

Rates:

$$\Gamma_{\text{SPDC}} \sim \frac{P_p {\chi_{\text{eff}}^{(2)}}^2 \omega_s \omega_i L}{\pi n_p n_s n_i A_{\text{eff}}}$$

Motivates long crystals too.

Rates:

$$\Gamma_{\rm SPDC} \sim \frac{P_p {\chi^{(2)}_{\rm eff}}^2 \omega_s \omega_i L}{\pi n_p n_s n_i A_{\rm eff}}$$

Motivates long crystals too.

$$\Gamma^{(A'_L)}_{\rm dSPDC} \sim \epsilon^2 \frac{m^2_{A'}}{\omega^2_{A'}} \frac{P_p {\chi^{(2)}_{A'_L}}^2 \omega_s \omega_{A'} L}{n_p n_s A_{\rm eff}}$$

$$\Gamma^{(\rm axion)}_{\rm dSPDC} \sim \frac{P_p g^2_{a\gamma\gamma} \omega_s L}{\omega_{\rm axion} n_p n_s A_{\rm eff}}$$

$$N^{(A'_L)}_{\rm events} \sim 10^{21} \left(\epsilon^2 \frac{m^2_{A'}}{\omega^2_{A'}}\right) \left(\frac{P_p}{\rm Watt}\right) \left(\frac{L}{\rm m}\right) \left(\frac{t_{\rm int}}{\rm year}\right)$$

$$N^{(\rm axion)}_{\rm events} \sim 40 \left(\frac{g_{a\gamma}}{10^{-6}\ {\rm GeV}^{-1}}\right)^2 \left(\frac{P_p}{\rm Watt}\right) \left(\frac{L}{\rm m}\right) \left(\frac{t_{\rm int}}{\rm year}\right)$$

	Dark Photon ($m_{A'} = 0.1$ eV)	Axion-like particle ($m_a = 0.1$ eV)
Current lab limit	$\epsilon < 3 \times 10^{-7}$	$g_{a\gamma} < 10^{-6}$ GeV^{-1}
Example dSPDC setup	$P_p = 1$ W	$P_p = 1$ kW
	$L = 1$ cm	$L = 10$ m
	$\Gamma = 10/\text{day}$	$\Gamma = 10/\text{day}$
Current Solar limit	$\epsilon < 10^{-10}$	$g_{a\gamma} < 10^{-10}$ GeV^{-1}
Example dSPDC setup	$P_p = 1$ W	$P_p = 100$ kW
	$L = 10$ m	$L = 100$ m
	$\Gamma = 10/\text{year}$	$\Gamma = 10/\text{year}$

Gravity Waves - A nonlinear extension

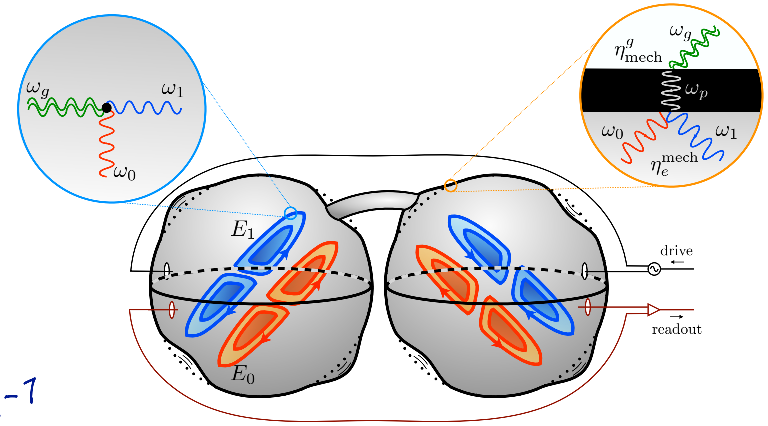
- A gravity wave also interacts w/ two photons

$$\mathcal{L} \supset F^{\mu\nu}F_{\mu\nu} \sim h(B\cdot B + E\cdot E) + \cdots$$

- But often more important:

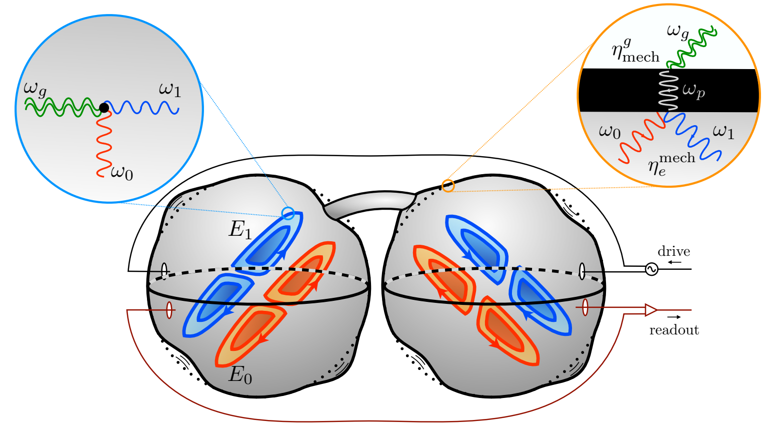
$$H = \hbar\omega(a^\dagger a + 1/2) \quad \text{with} \quad \omega \sim (1+h)L^{-1}$$

- Axion-like phenomenology:
  - GW mixing w/ photons in background B field.
  - GW can be absorbed by photon -> up conversion.

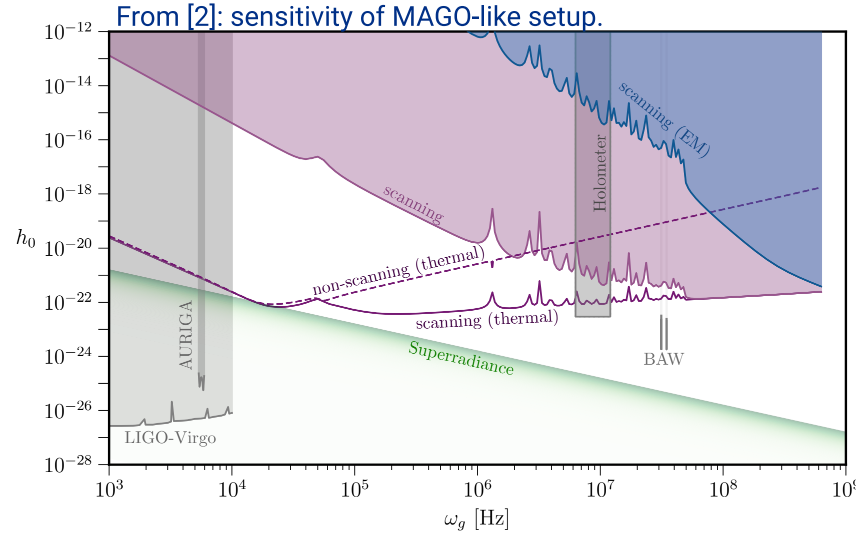


Gravitational waves

- Photon up-conversion due to GW.
- Current axion experiments have sensitivity to GHz Gravity waves [1].
- A dedicated cavity experiment, e.g. MAGO, has significant reach at MHz [2].
- MAGO traveled from INFN to DESY to Fermilab for testing
- **A Fermilab KEK collaboration to design new dedicated broadband cavity.**



From [2]: sensitivity of MAGO-like setup.

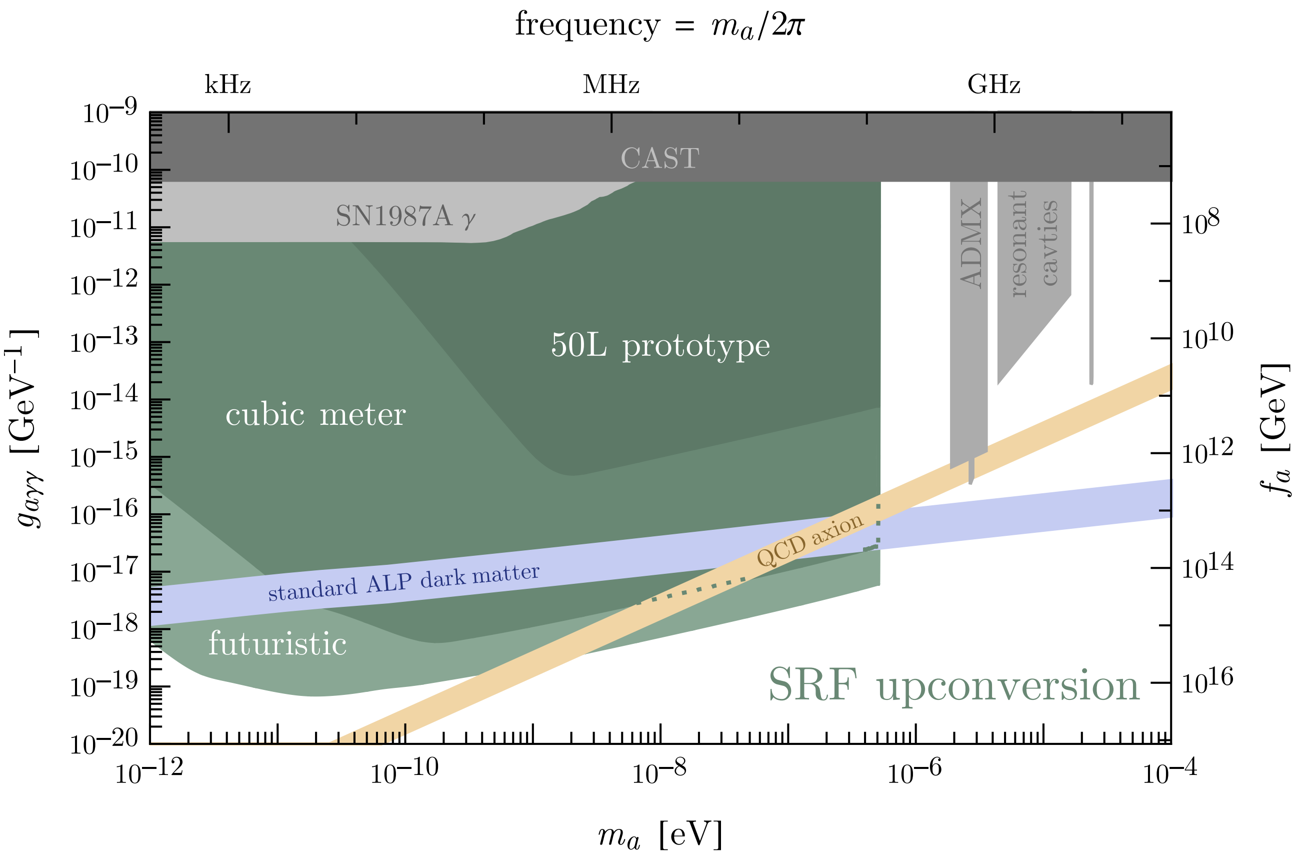


MAGO (INFN)

[1] *Phys.Rev.D* 105 (2022) 11, 116011
[2] *Phys.Rev.D* 108 (2023) 8, 084058

Multimode searches

Berlin, et al., JHEP, DOI:10.1007/JHEP07 (2020) 088
Berlin, et al., arXiv:2203.12714, Snowmass WP (2022)
Giaccone, et al., arXiv:2207.11346 (2022)

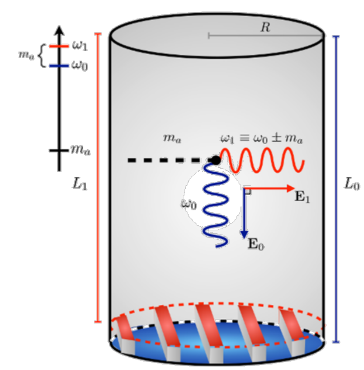


Snowmass name:

SRF-m³

Asher's proposal:

SuperRAD

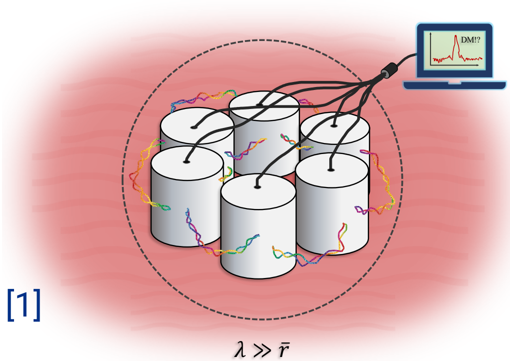


Contacts: Asher Berlin, Bianca Giacone

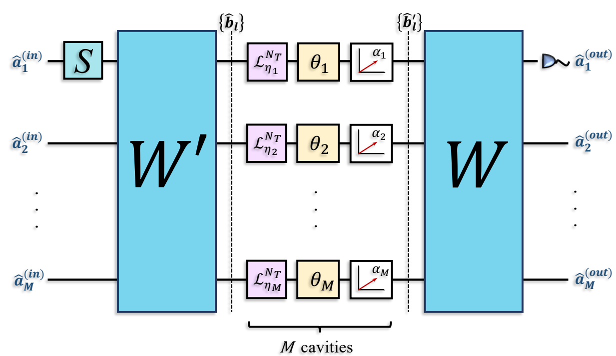
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Dark Matter - Quantum Sensor Network

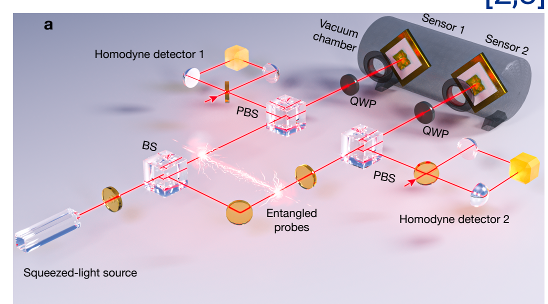
- A network of cavities can be used to enhance the sensitivity to dark matter.
- How should we distribute quantum resources in the network?
- **A distributed quantum sensing protocol for DM searches allows for enhanced scan rate for DM.**



[1]



[2,3]

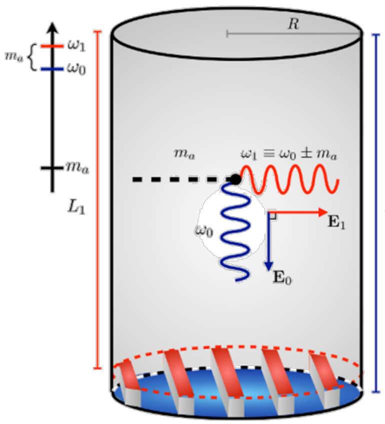


A new collaboration of HEP and QIS experts from across SQMS:

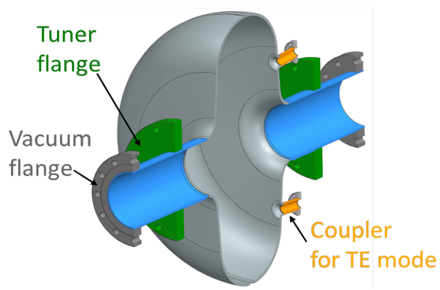
[1] ***PRX Quantum* 3 (2022) 3, 030333**
[2] 2210.07291 [quant-ph]
[3] 2210.16180 [quant-ph] **(in review by Nature Photonics)**

Multimode searches

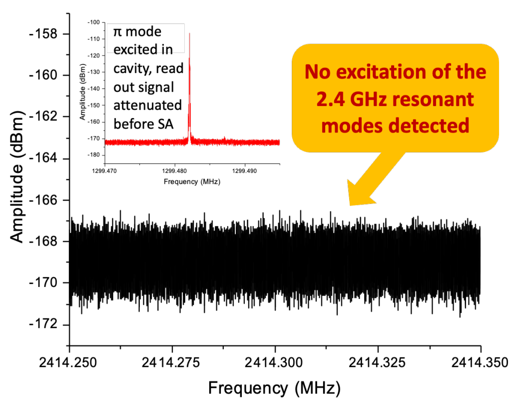
Bogorad, et al., PRL, DOI:10.1103/PhysRevLett.123.021801
Berlin, et al., JHEP, DOI:10.1007/JHEP07 (2020) 088
Gao & Harnik, JHEP, DOI:10.1007/JHEP07 (2021) 053
Berlin, et al., arXiv:2203.12714, Snowmass WP (2022)
Sauls, PTEP, DOI:10.1093/ptep/ptac034 (2022)
Giaccone, et al., arXiv:2207.11346 (2022)



Axion DM search concept



Experimental design for MHz Axion search

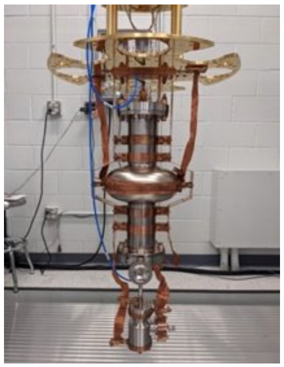


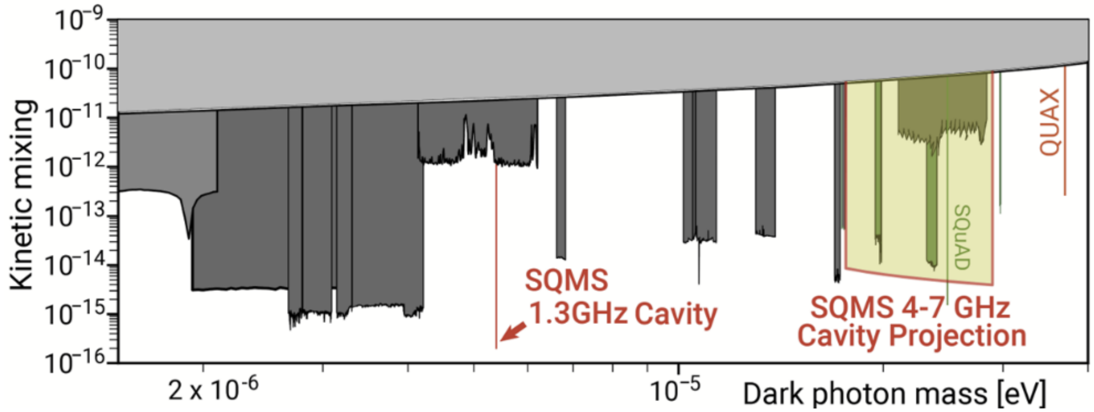
- **Axion DM** search based on the heterodyne detection scheme: cavity design is finalized, contract for cavity fabrication placed (cavity arrival: Fall 2023)
- In preparation for search:
  - Working on RF experimental set up and read out system
  - Addressing experimental challenges such as passive dampening of vibrations in LHe facility
  - Multimode feasibility study

Contacts: Asher Berlin, Bianca Giacone

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

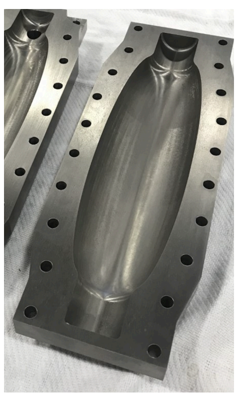
Ultrahigh Q for Dark Matter

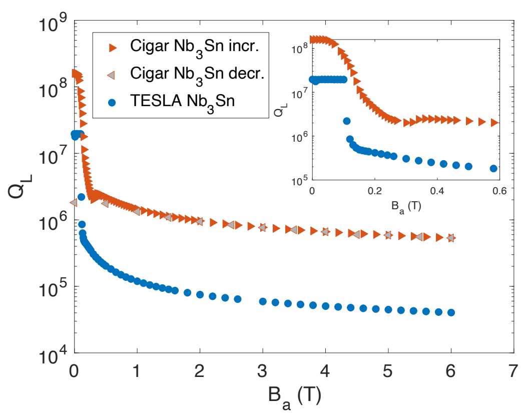




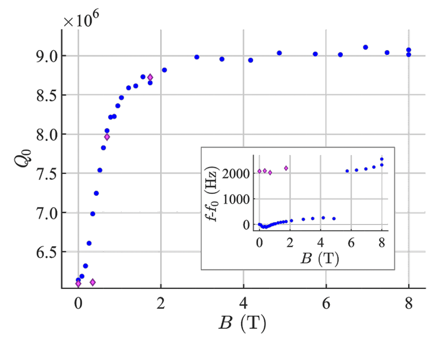
Cervantes et al., arxiv:2208.03183, in review in Phys. Rev. Lett.

No B-Field: Q>10^{10}





Superconducting Nb_3Sn cavity (FNAL): Posen et al., arxiv:22014.10733, in review in Phys Rev Applied

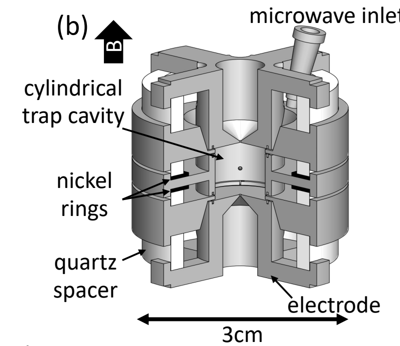


Hybrid copper-dielectric cavity (INFN): Di Vora et al., PhysRevApplied.17.054013

With B-Field: Q ≥ 10^{5-7}

Single Particle Qubit

- The most precise theory-experiment comparison in physics:

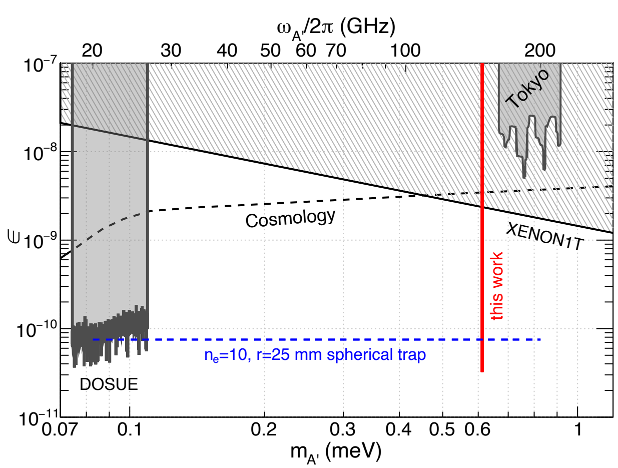


Electron magnetic moment $(g\text{-}2)_e$:
The quantum state of a single electron in a trap is monitored via a **QND measurement**.

$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1.001\,159\,652\,180\,59\,(13) \quad [0.13\ \text{ppt}]$$

Phys. Rev. Lett. 130, 071801 (2023)
Editors choice!

- SQMS joined the effort, contributed to understanding loss sources.

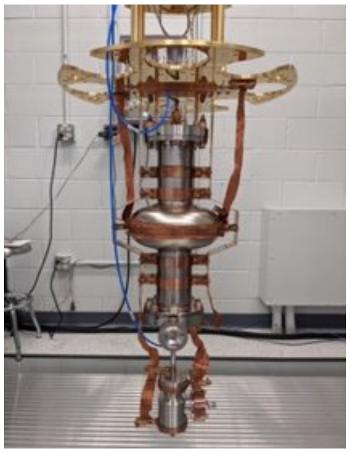


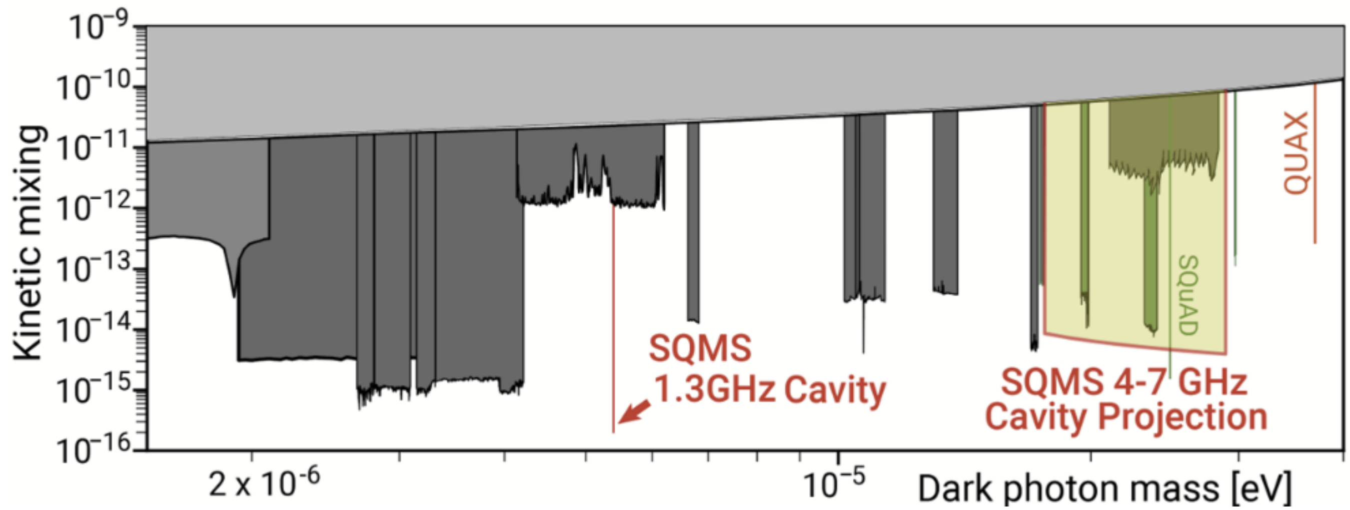
- **SQMS bonus:** We also found that a single-electron qubit is a sensitive DM search in a challenging frequency range!
- Theory + proof-of-concept!

Phys.Rev.Lett. **129 (2022) 26, 261801**
(a new NU-Stanford-Fermilab collaboration)

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Ultrahigh Q for Dark Matter





Cervantes et al., arxiv:2208.03183, in review in Phys. Rev. Lett.

DPDM search with 1.3 GHz cavity with $Q_L \approx 10^{10}$.

Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

- Tunable DPDM search from 4-7 GHz. (“low hanging fruit”)
- Implement photon counting to subvert SQL noise limit.

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER