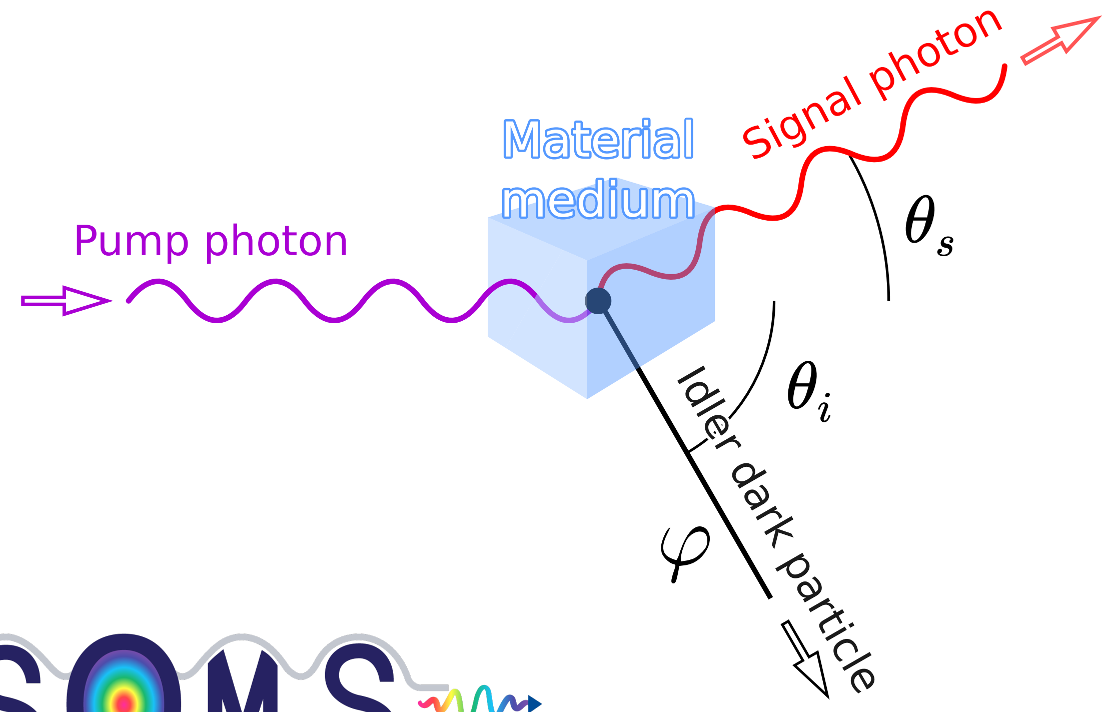
Quantum Sensing for HEP

Roni Harnik,
Fermilab Quantum Theory Department
SQMS Science Thrust Lead



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Some more talks….

Quantum Sensing for Fundamental Physics
Anthony Brady
David Lawrence Hall 121, University of …
14:00 - 14:30

Radiation Sensing with Superconducting Transmon Qubits
Tanay Roy

Quantum Measurement for Axion Da Matter Searches
Saptarshi Chaudhuri

MagLev for Dark Matter *Zhen Liu*

Probing (ultra-) light Dark Matter Using Mössbauer Spect…
Abhishek Banerjee

Electron Trap as a meV Axion and Dark Photon Dark Mat
Yawen Xiao

Atom interferometer detection of dark matter *Yufeng Du*

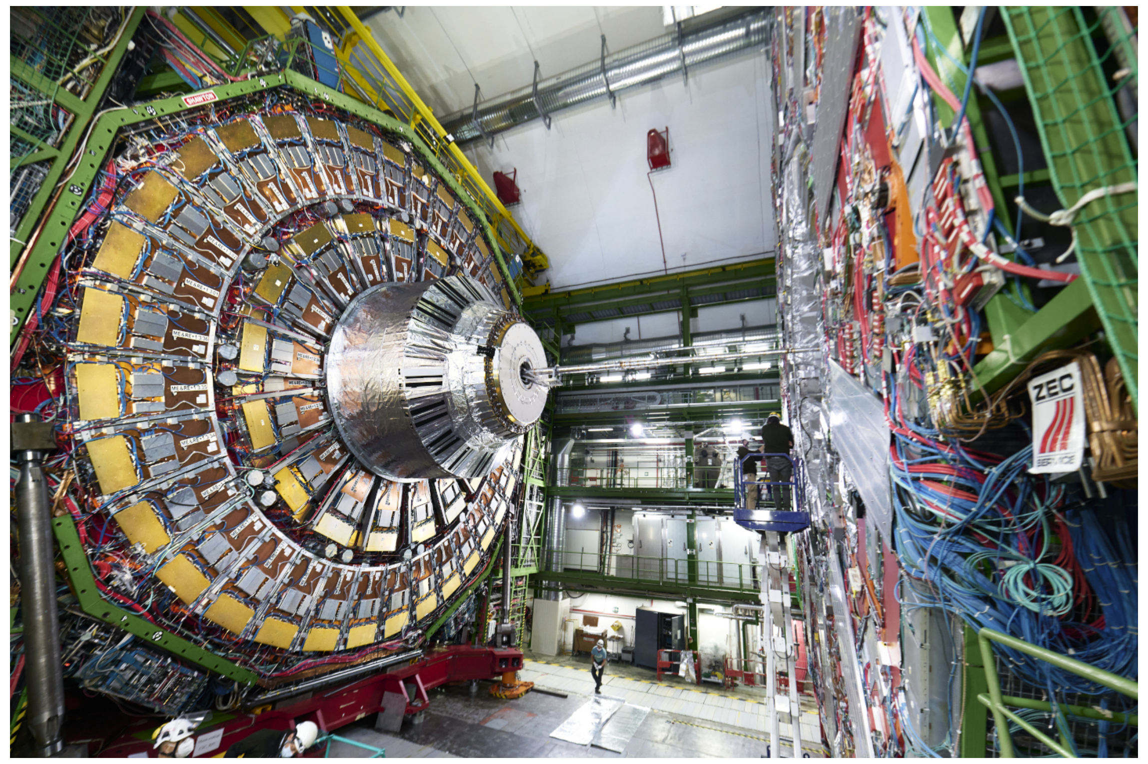
Dark Matter Searches on a Photonic Chip *Christina Gao*
David Lawrence Hall 120, University of Pittsburgh 14:00 - 14:15

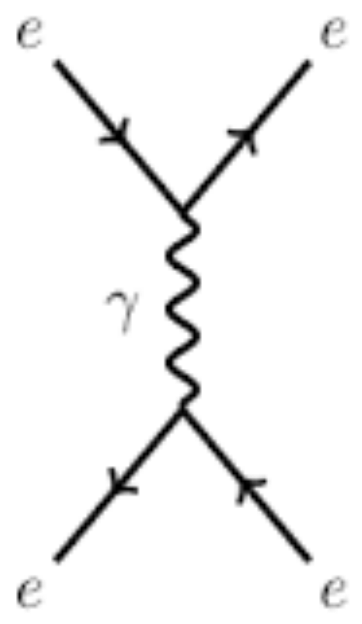
QCD and Quantum Computing *Christian Walter Bauer*
David Lawrence Hall 121, (overflow in David Lawrence Hall 120), University of Pittsburgh 11:30 - 12:00

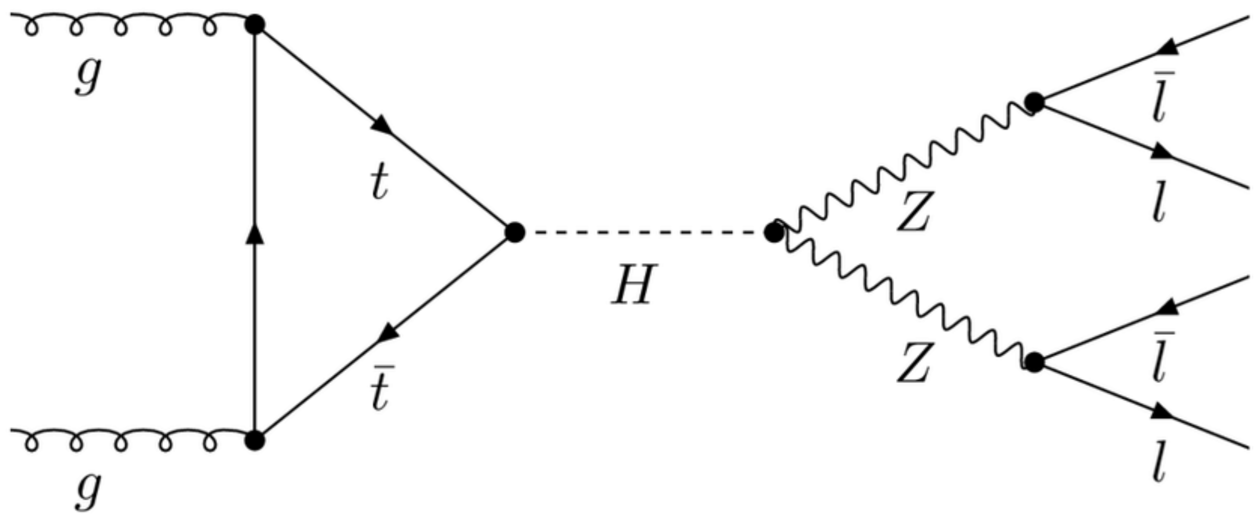
At the HEP-QIS interface.

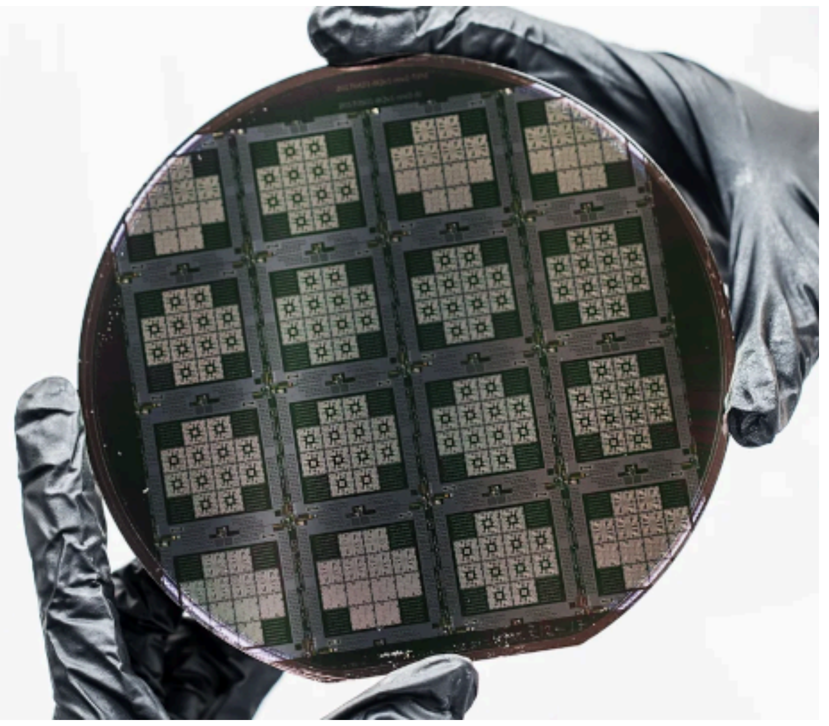
HEP - Quantum Interface

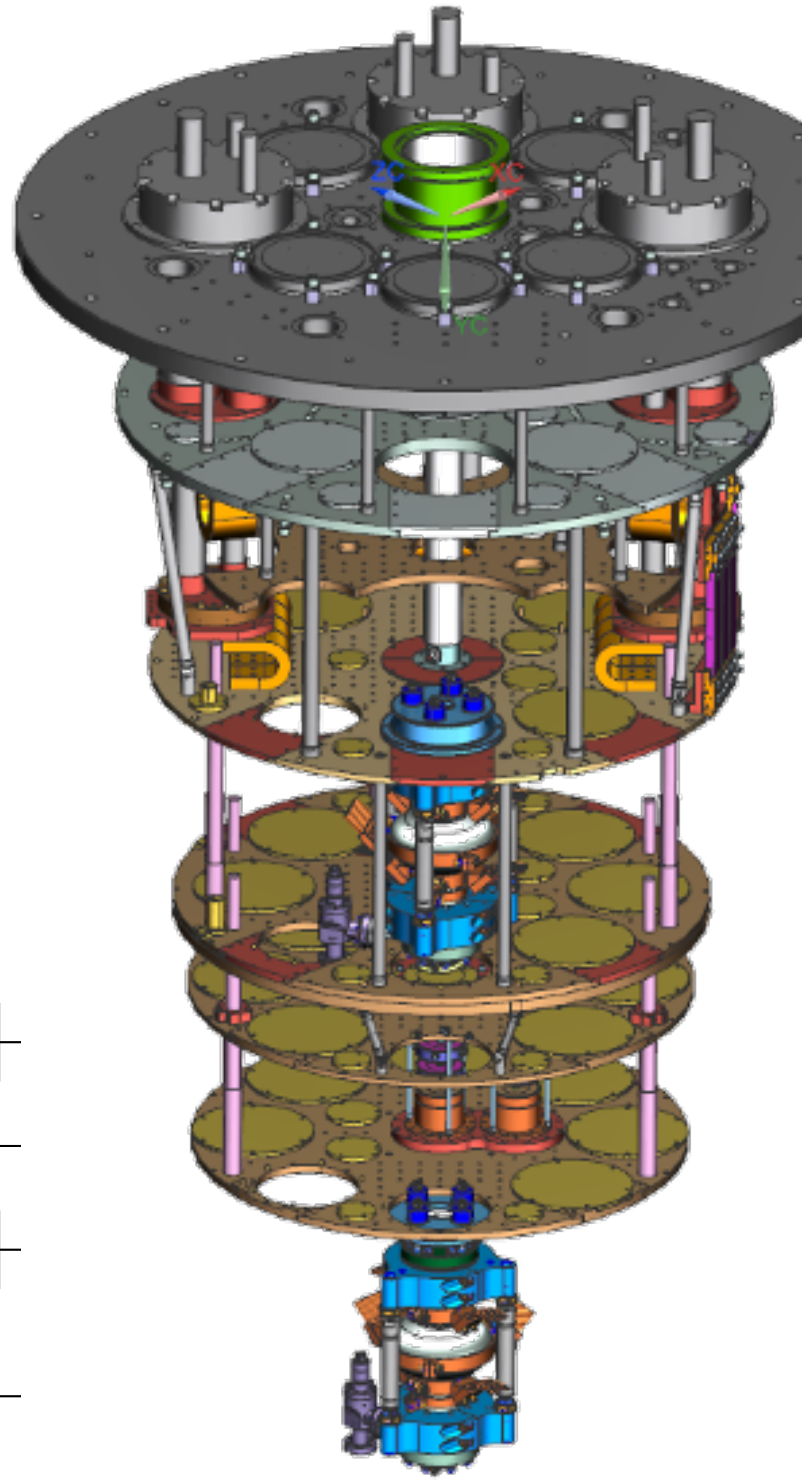
- We are DPF!! Particle physics was always inherently quantum. Duh.
- A new field of Quantum physics is rapidly emerging, QIS.
- The interface is growing, but still small -

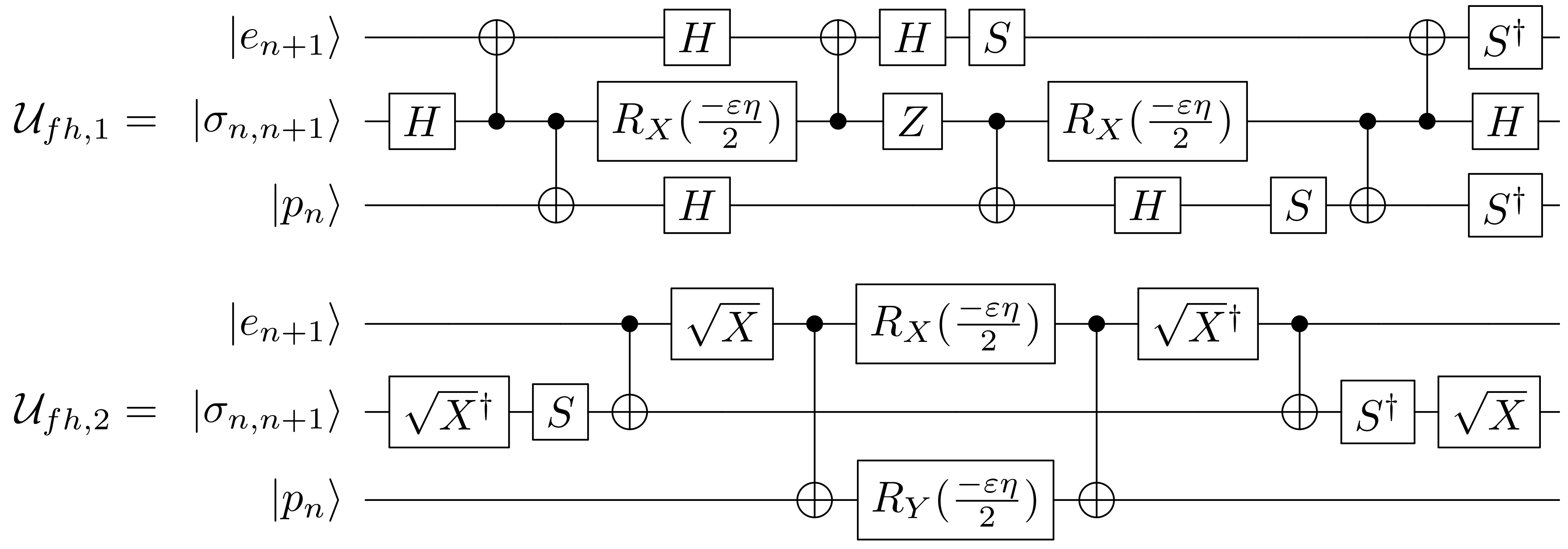












Overview

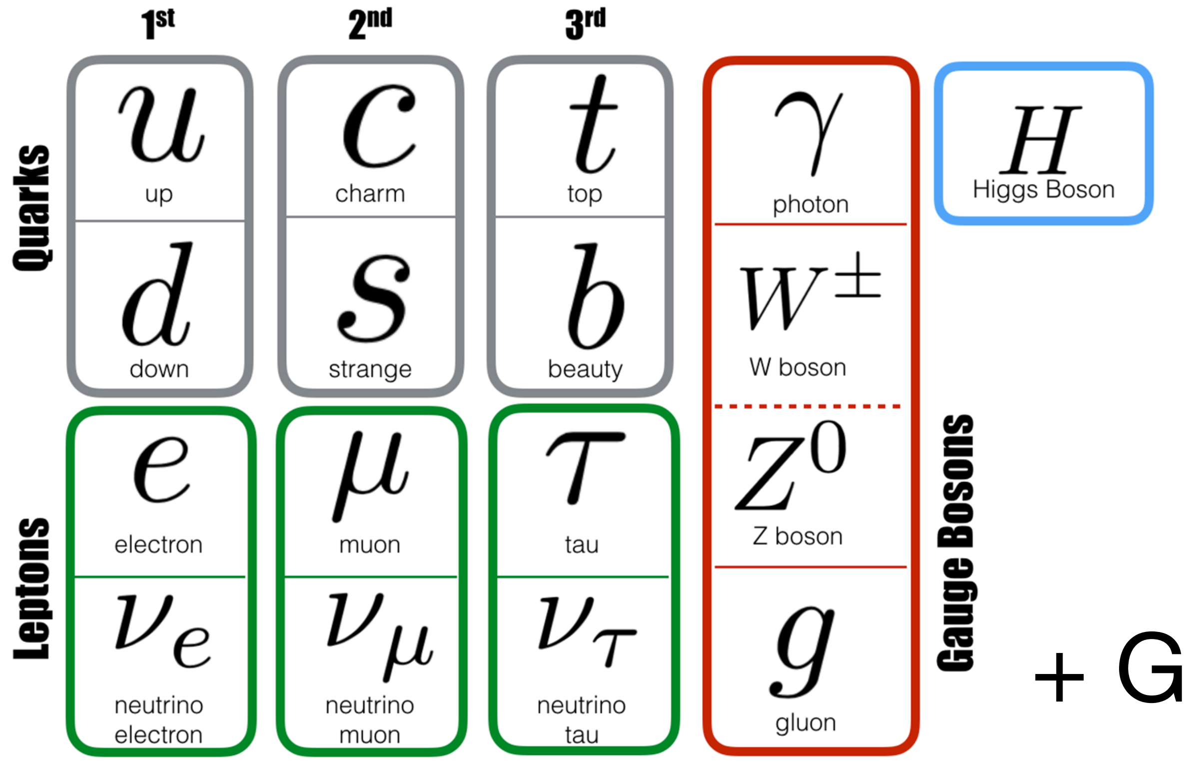
- In this talk,
  - Try bridging the divide,
  - see some examples of BSM searches with Quantum Sensing

Plan:

- Talk about quantum devices in HEP language.
- Talk about BSM models in a QIS language.
- Examples: Cavities, Optics,⋯

HEP - Quantum Fields in a Big Universe

- The instant recipe for particle physics:



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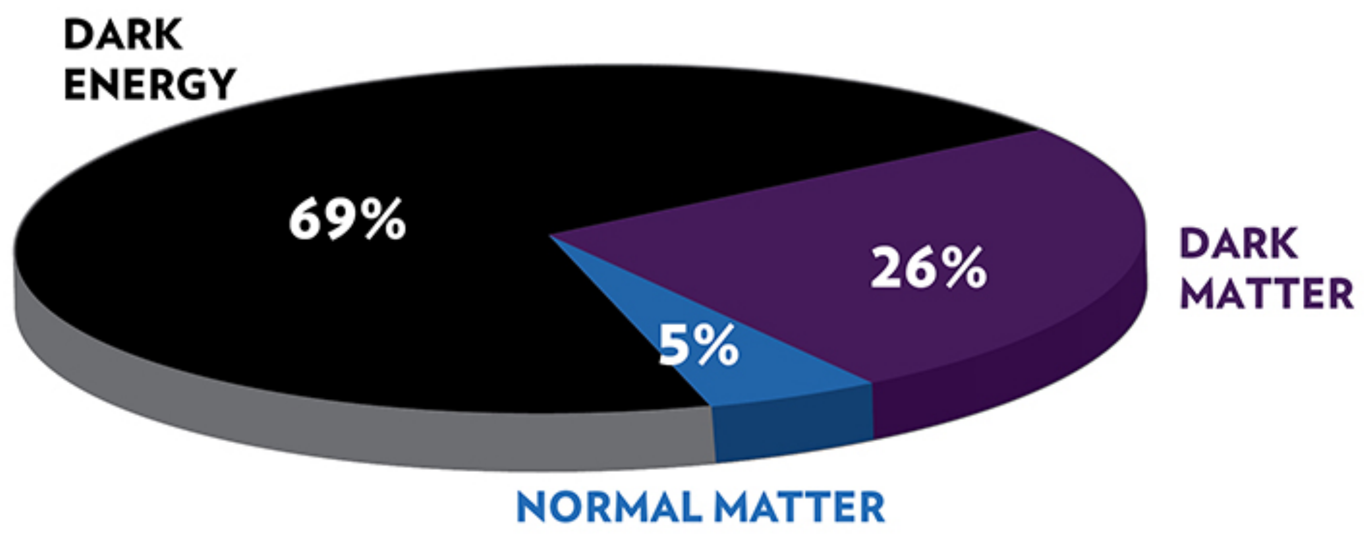

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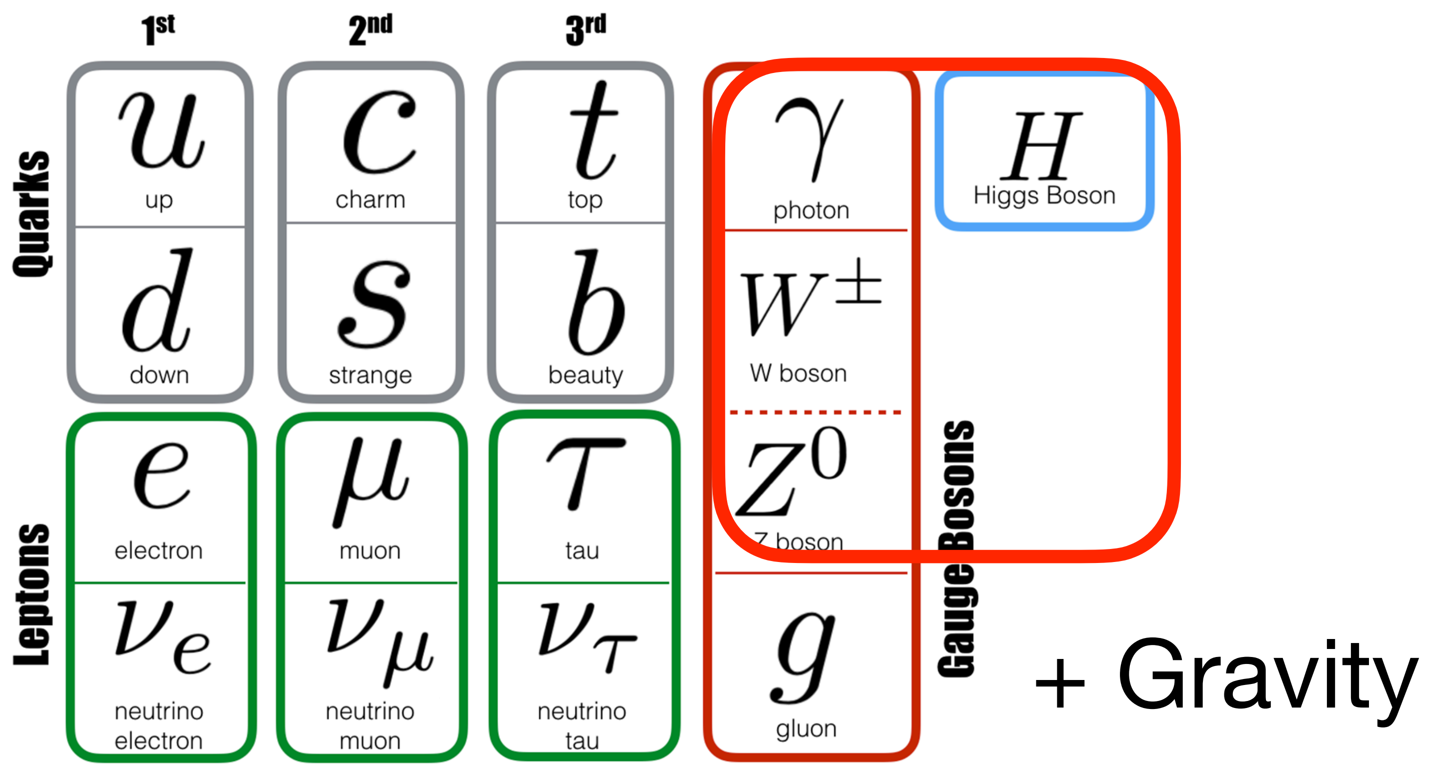

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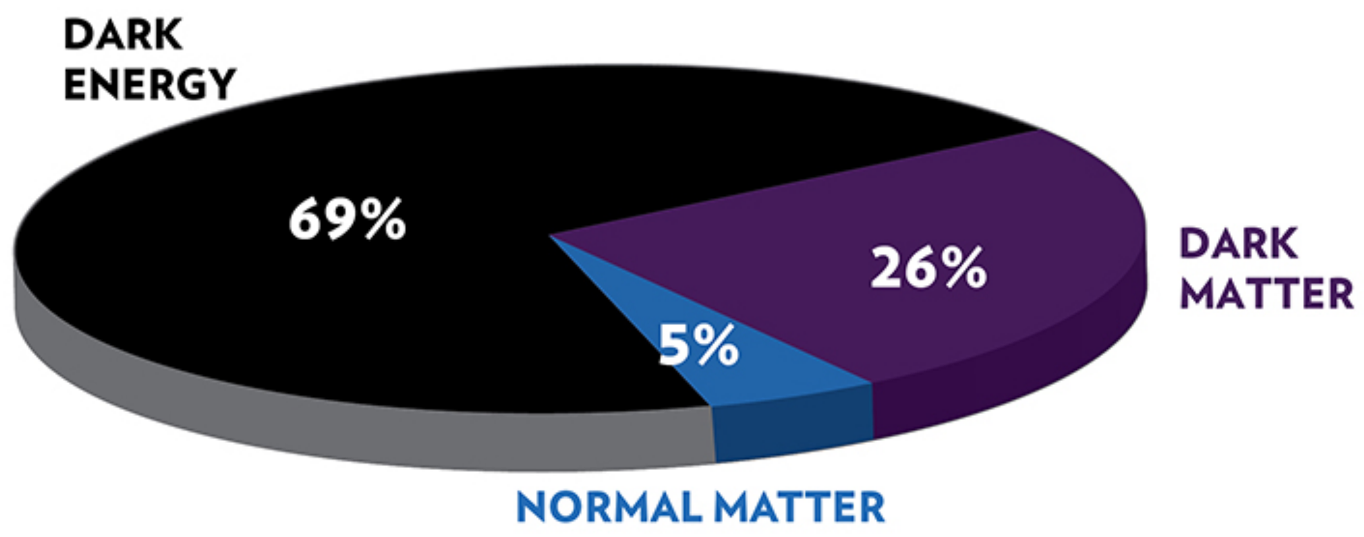

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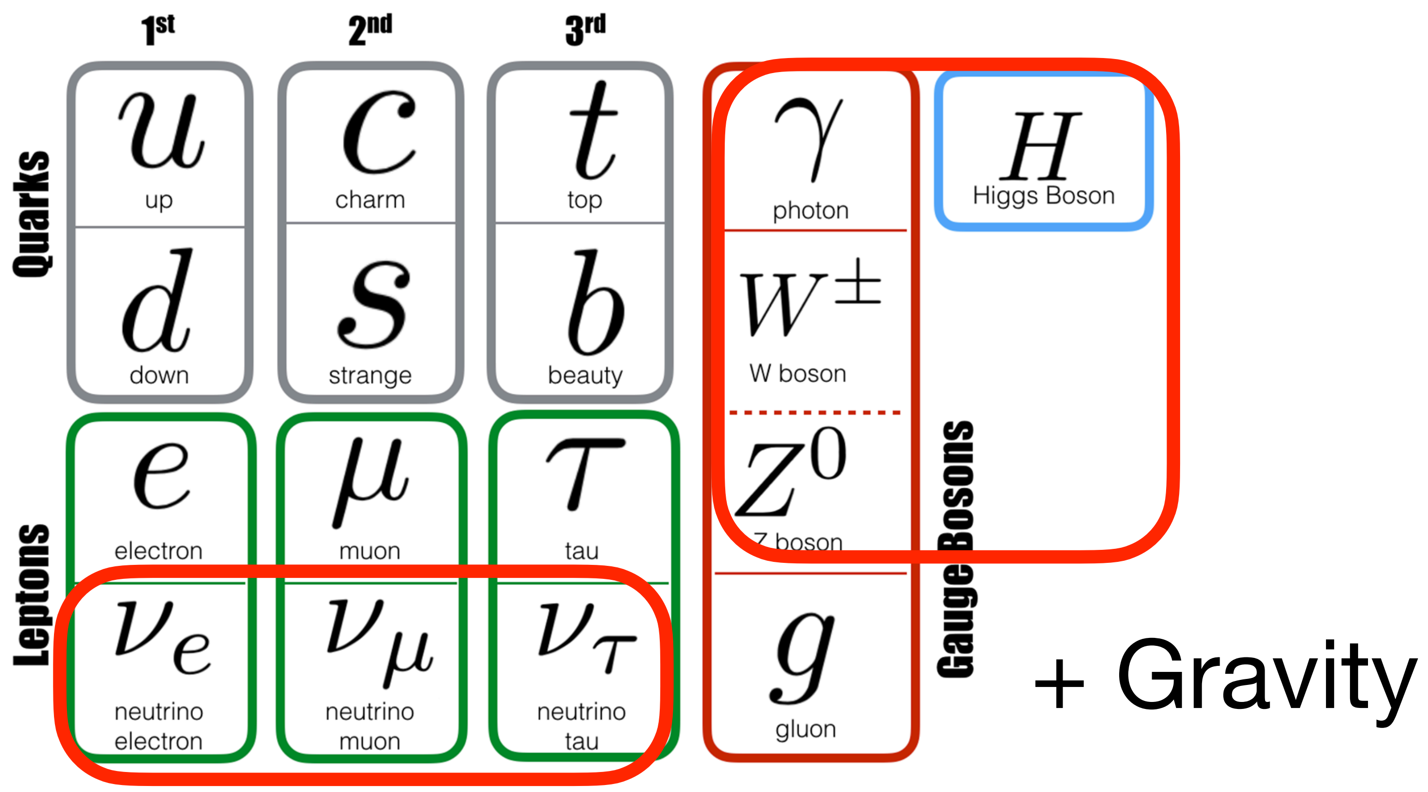

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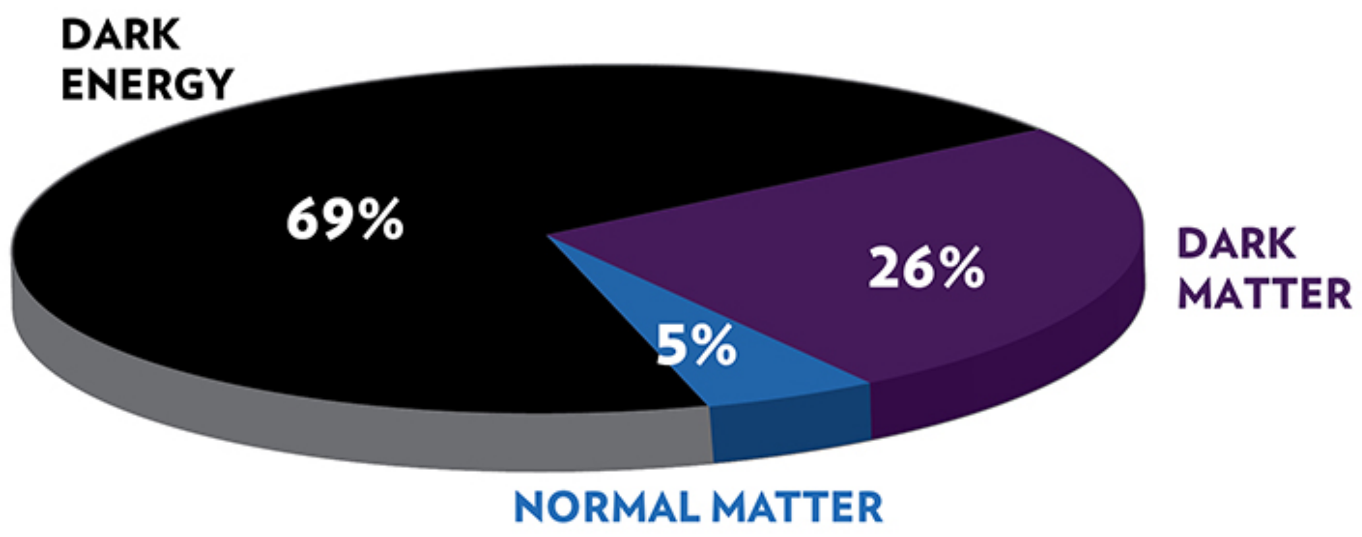

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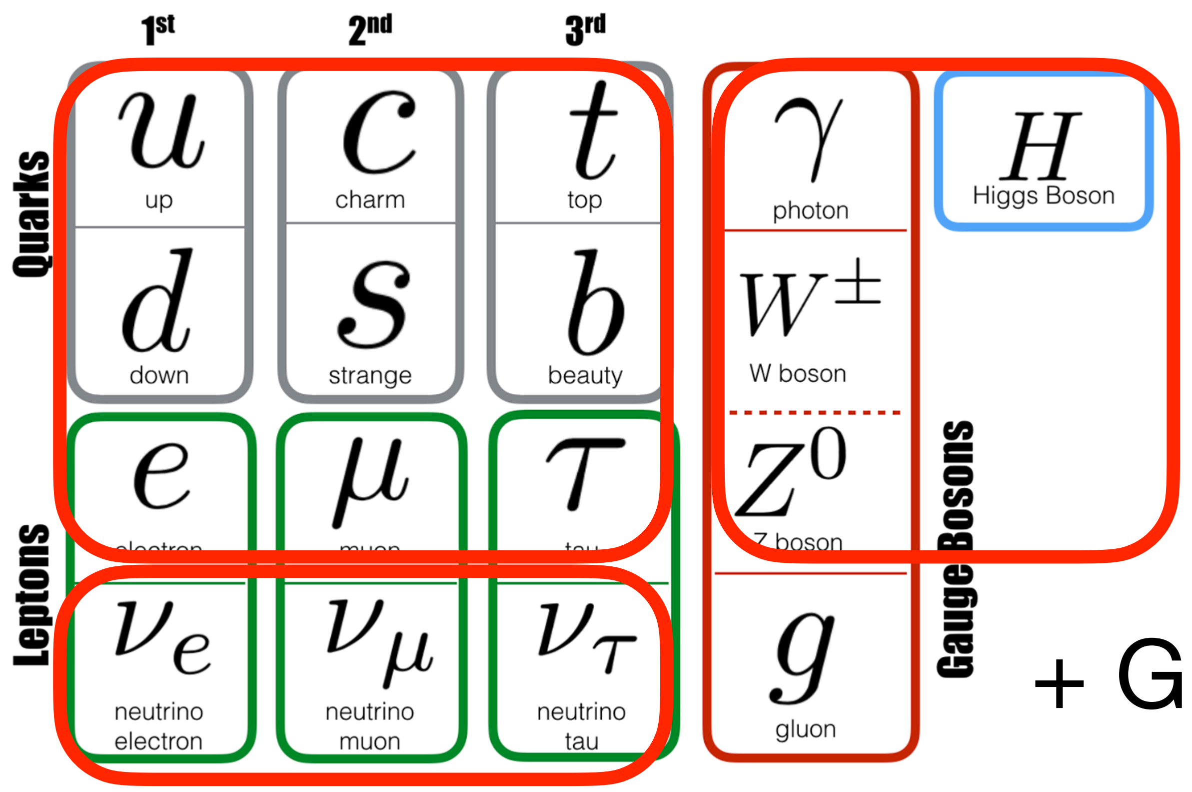

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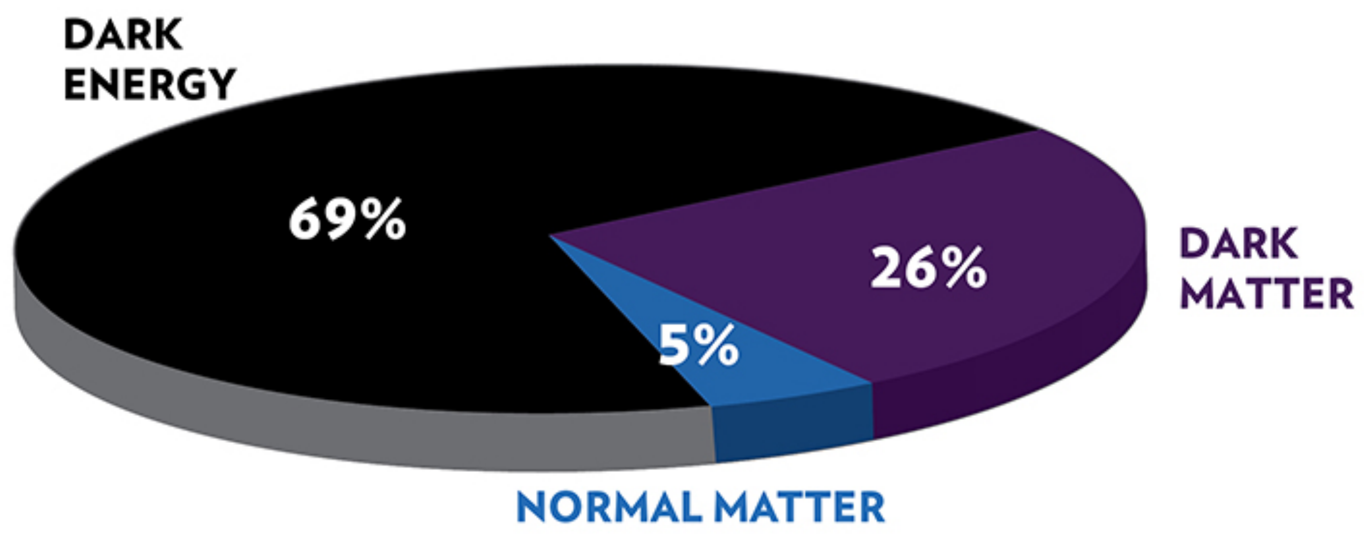

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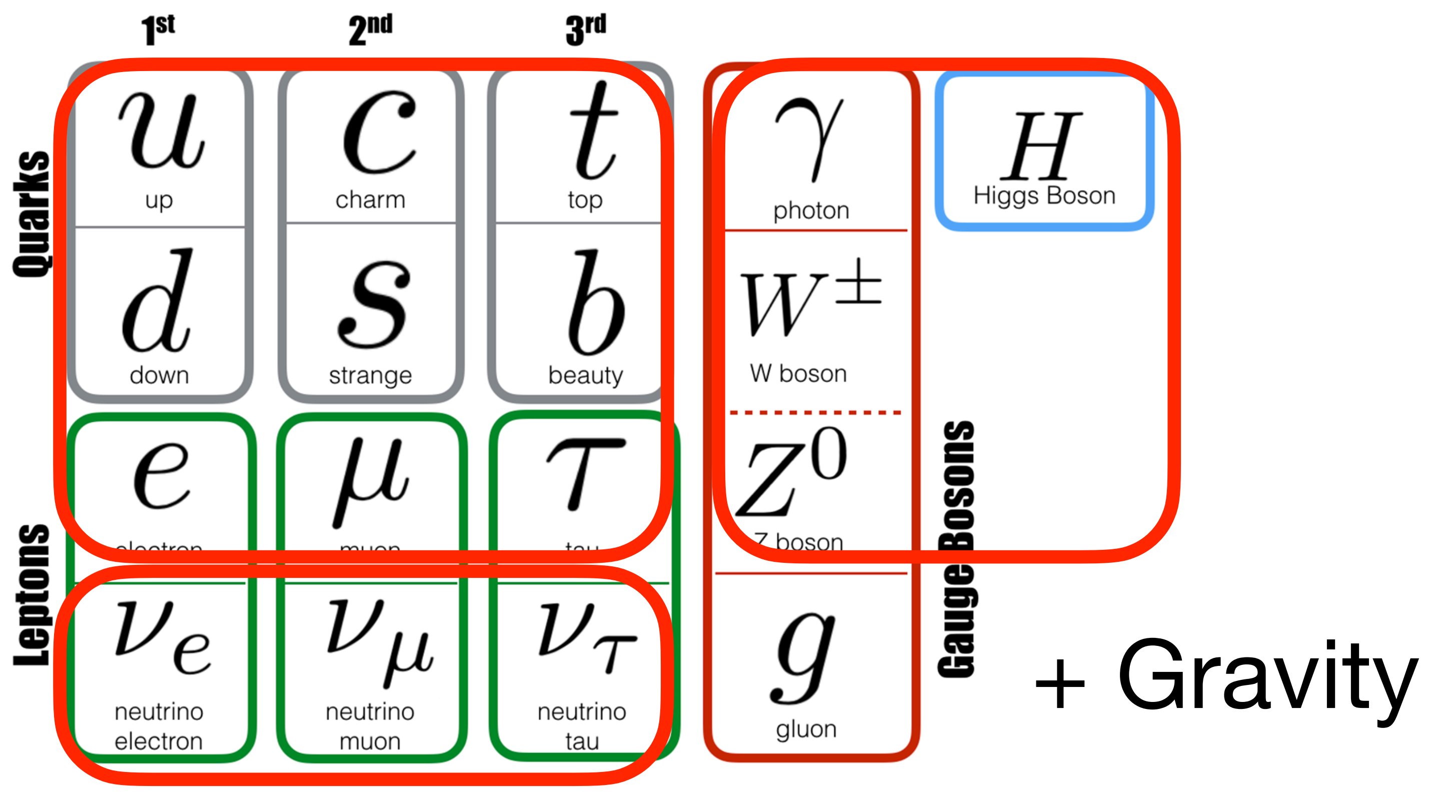

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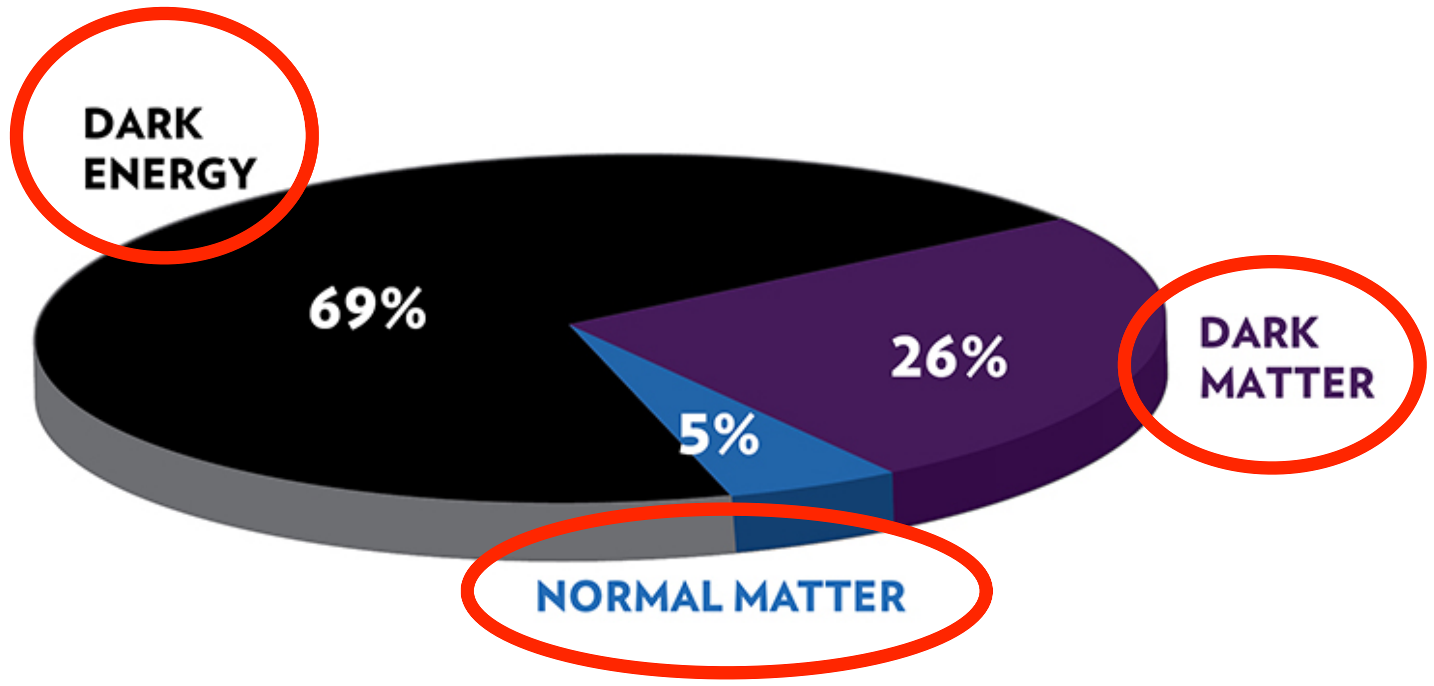

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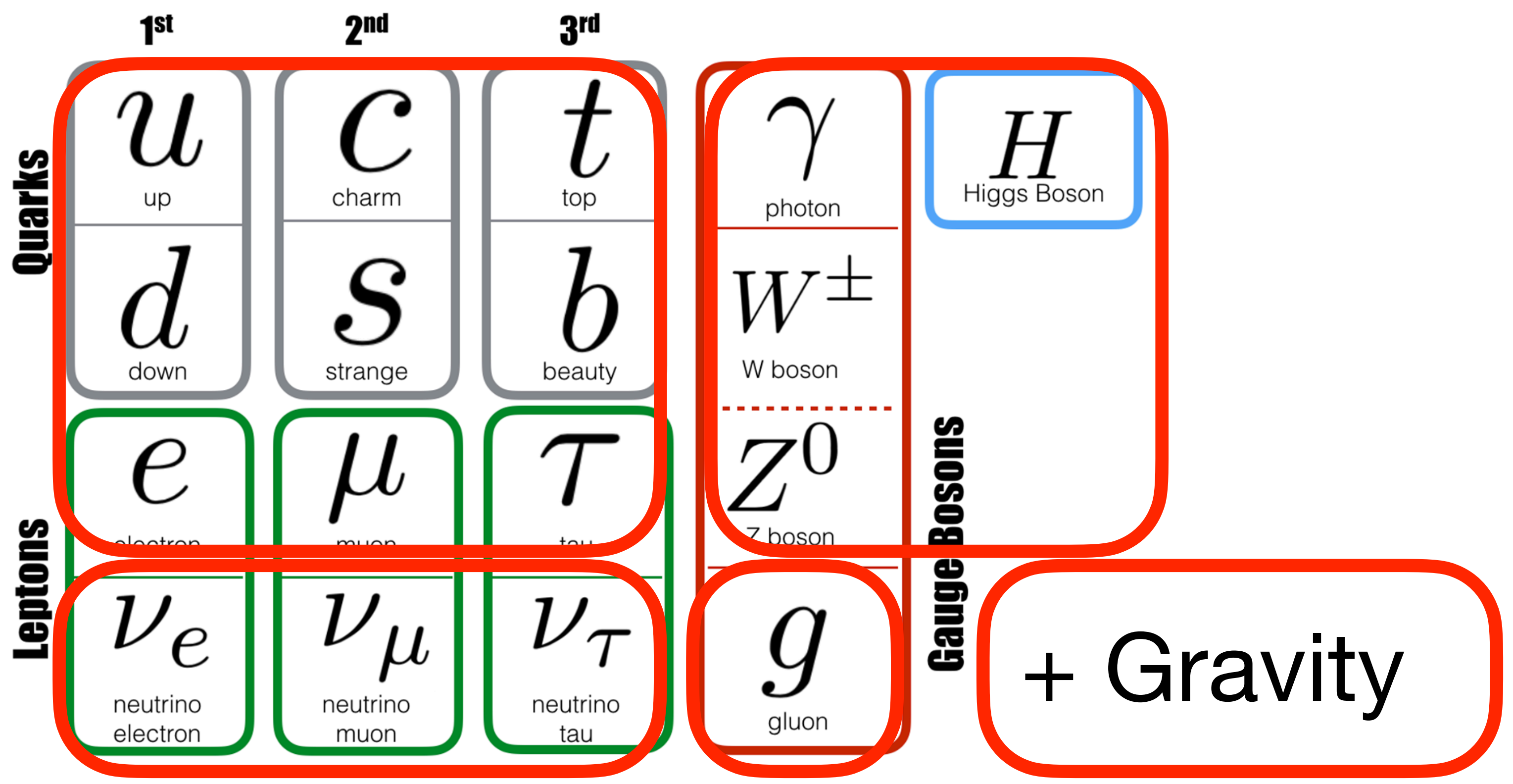

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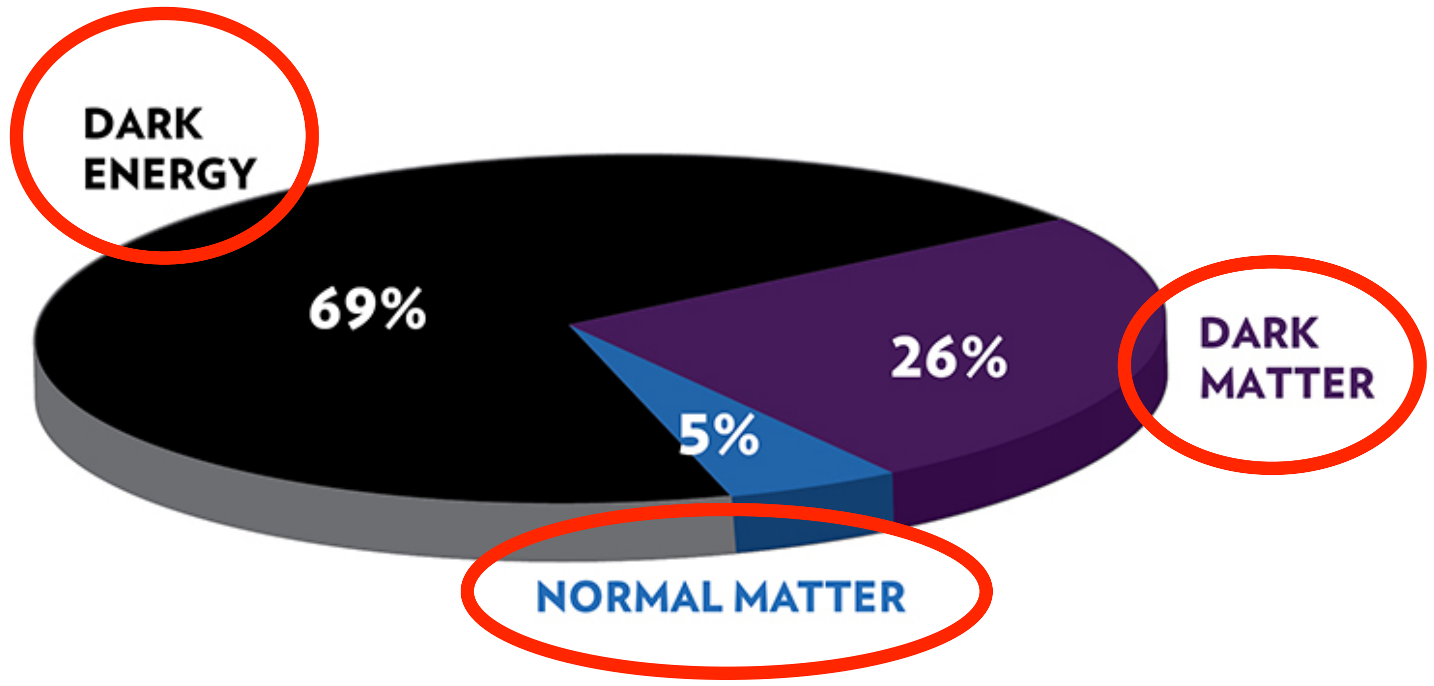

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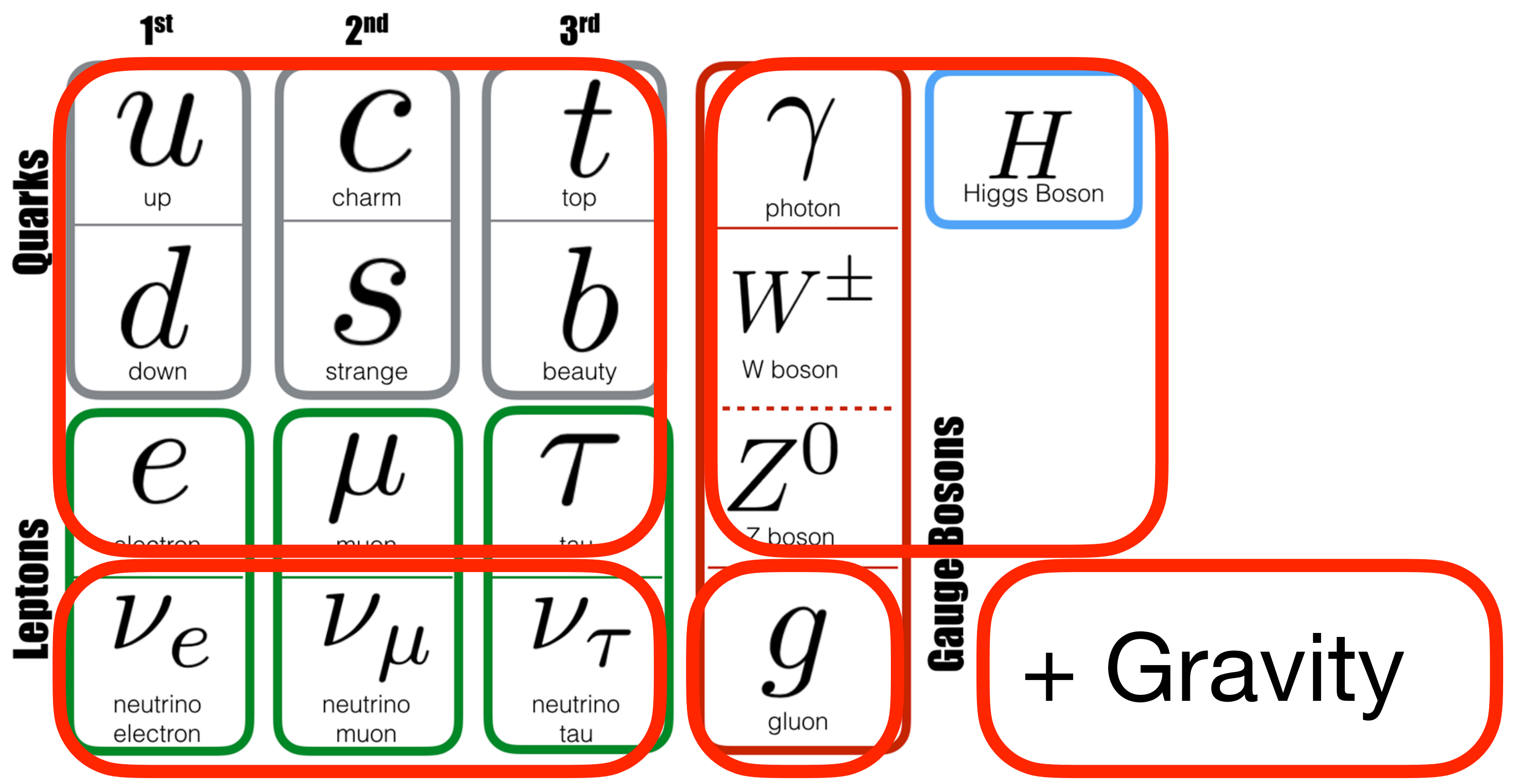

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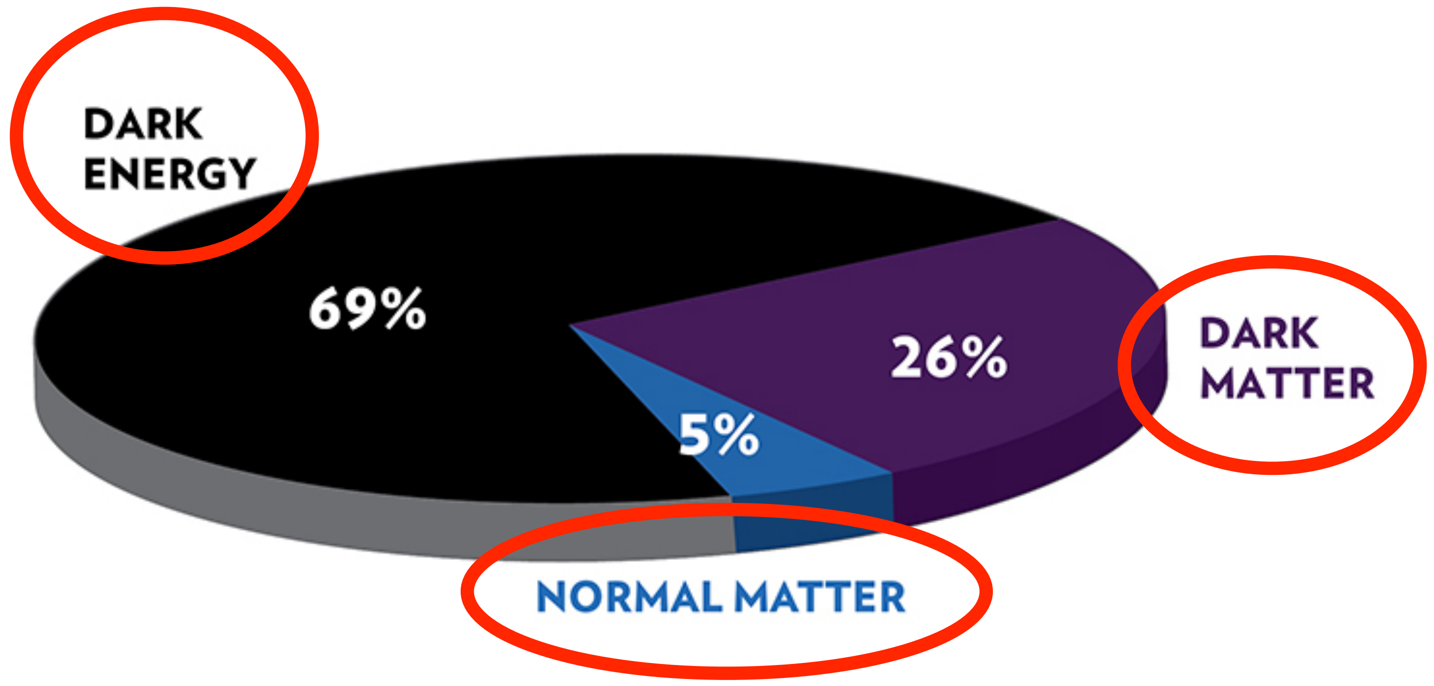


There is more. **BSM**. More fields! We'll get back to that!

HEP - Quantum Fields in a Big Universe

- The instant recipe for particle physics:

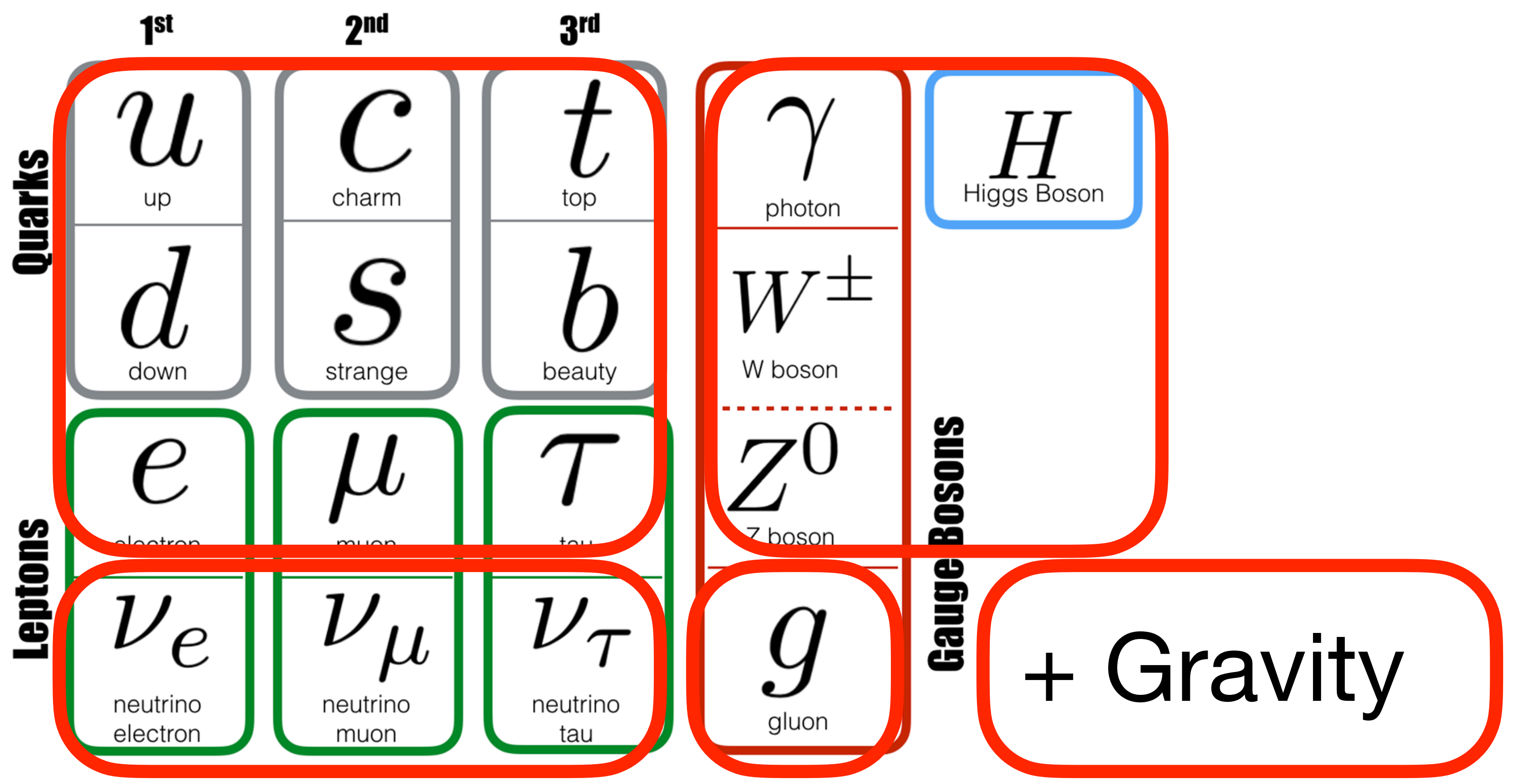
QFT:

$$|\psi\rangle = \psi |\Omega\rangle$$

$$\psi \sim \sum a_k e^{ikx} + h.c.$$

$$\mathcal{L} = \cdots$$

+



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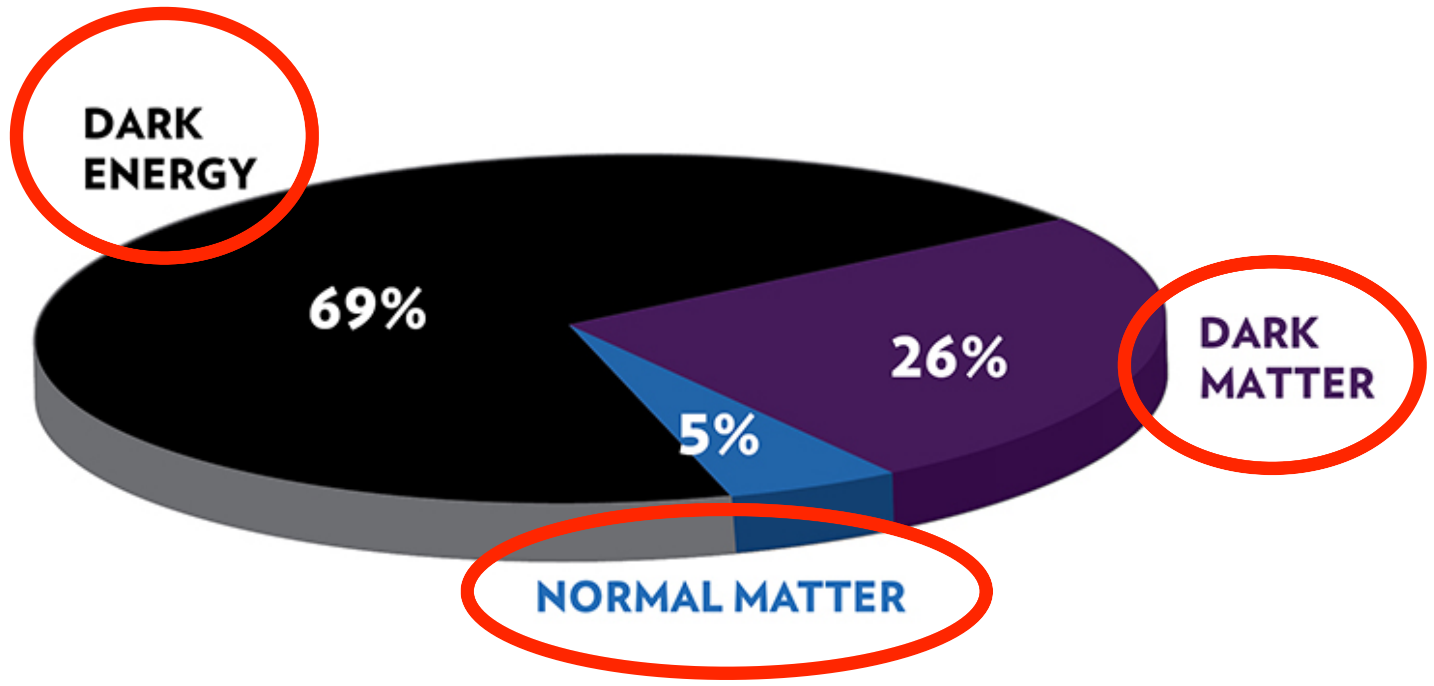

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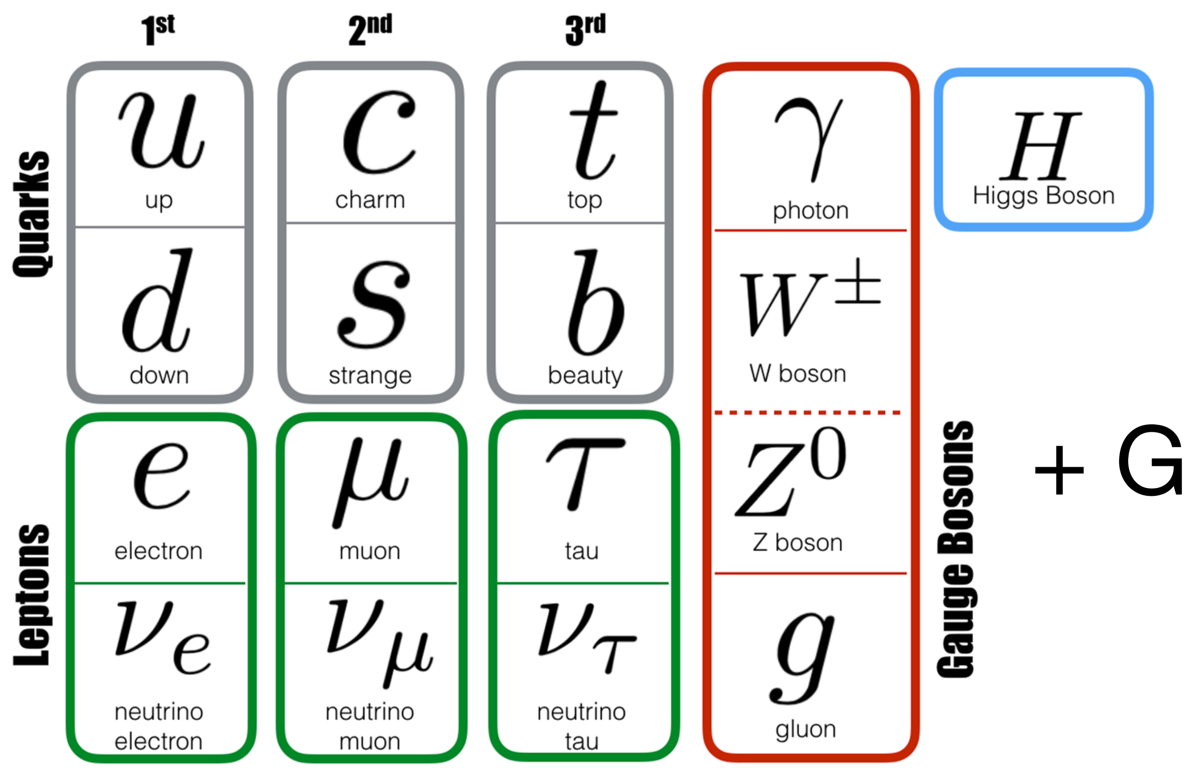

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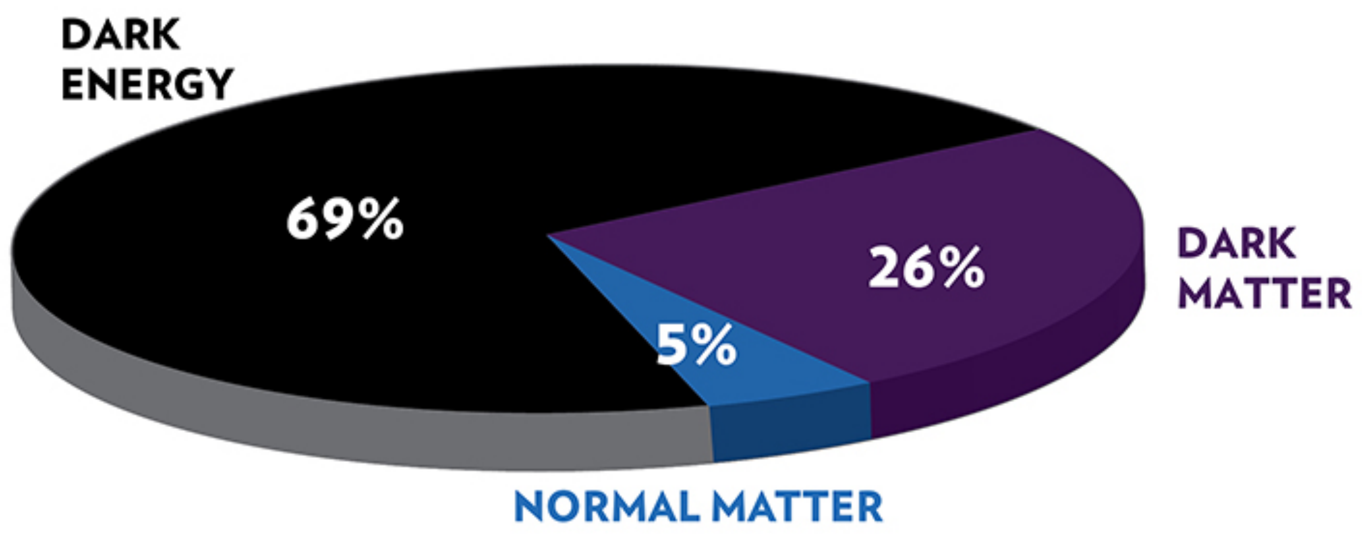

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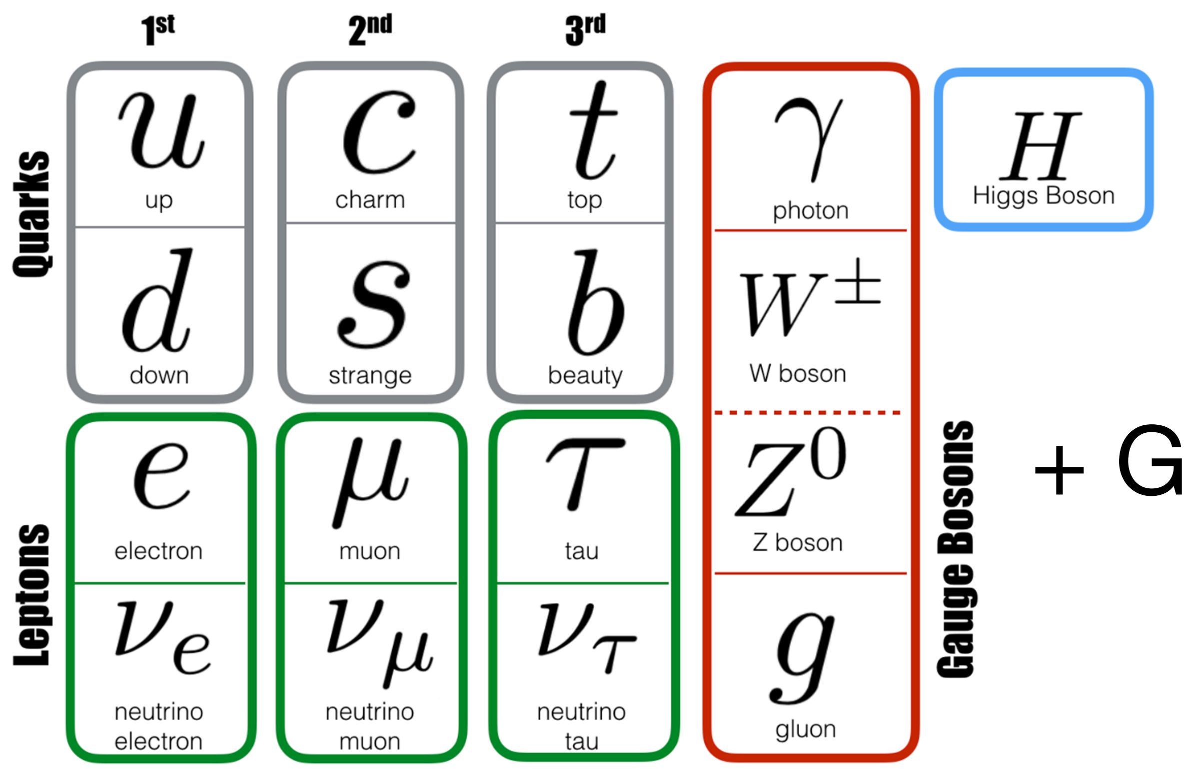

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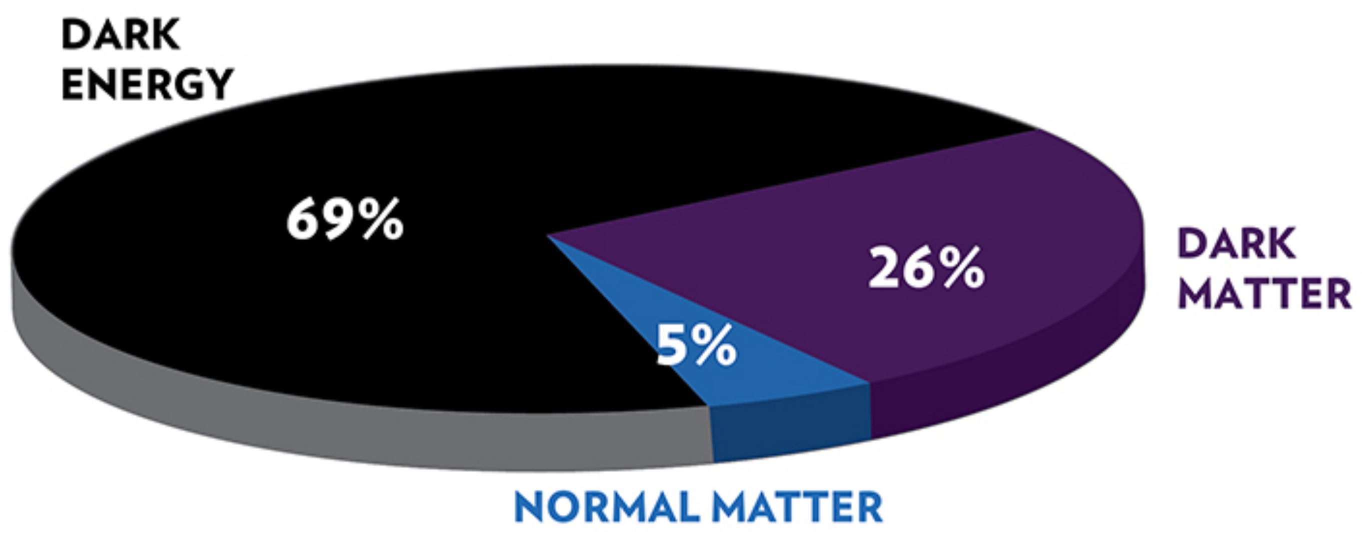


We are the DPF: **Every particle is a Field**

QFT is **continuum** of interacting fields. All frequencies.

Quantum Fields

- 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.

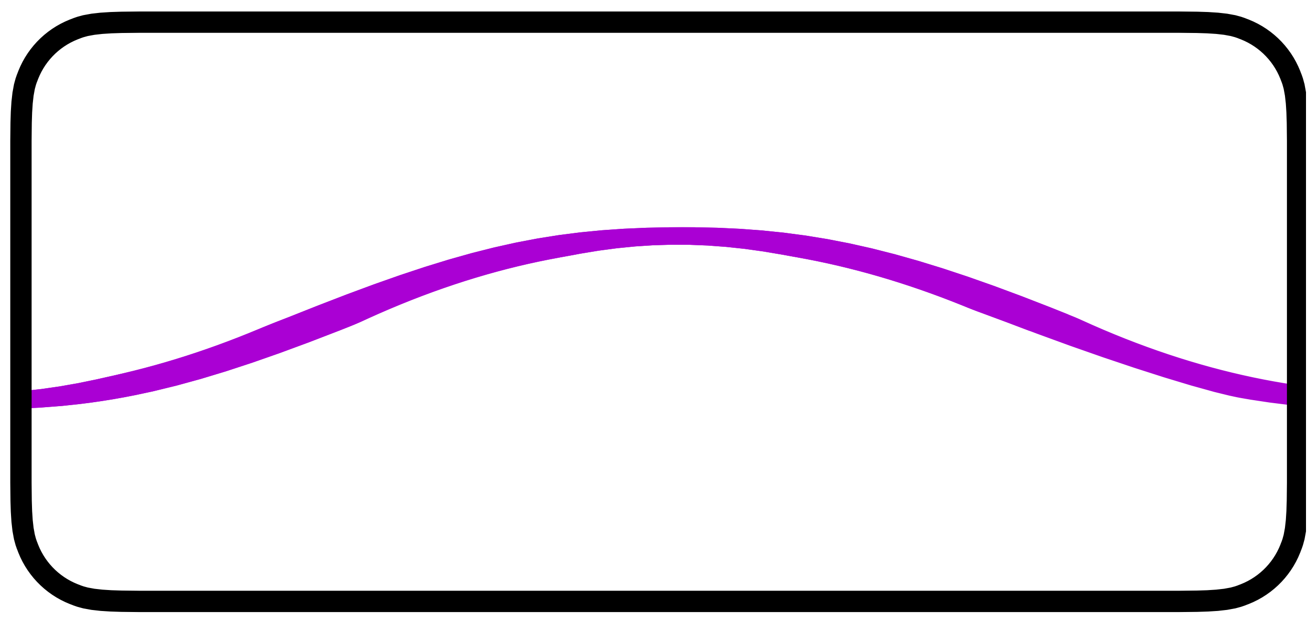
Statify: $[a_k, a_{k'}^\dagger] = \delta_{kk'}$

- This is sometimes referred to as "second quantization". For DPF 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.

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



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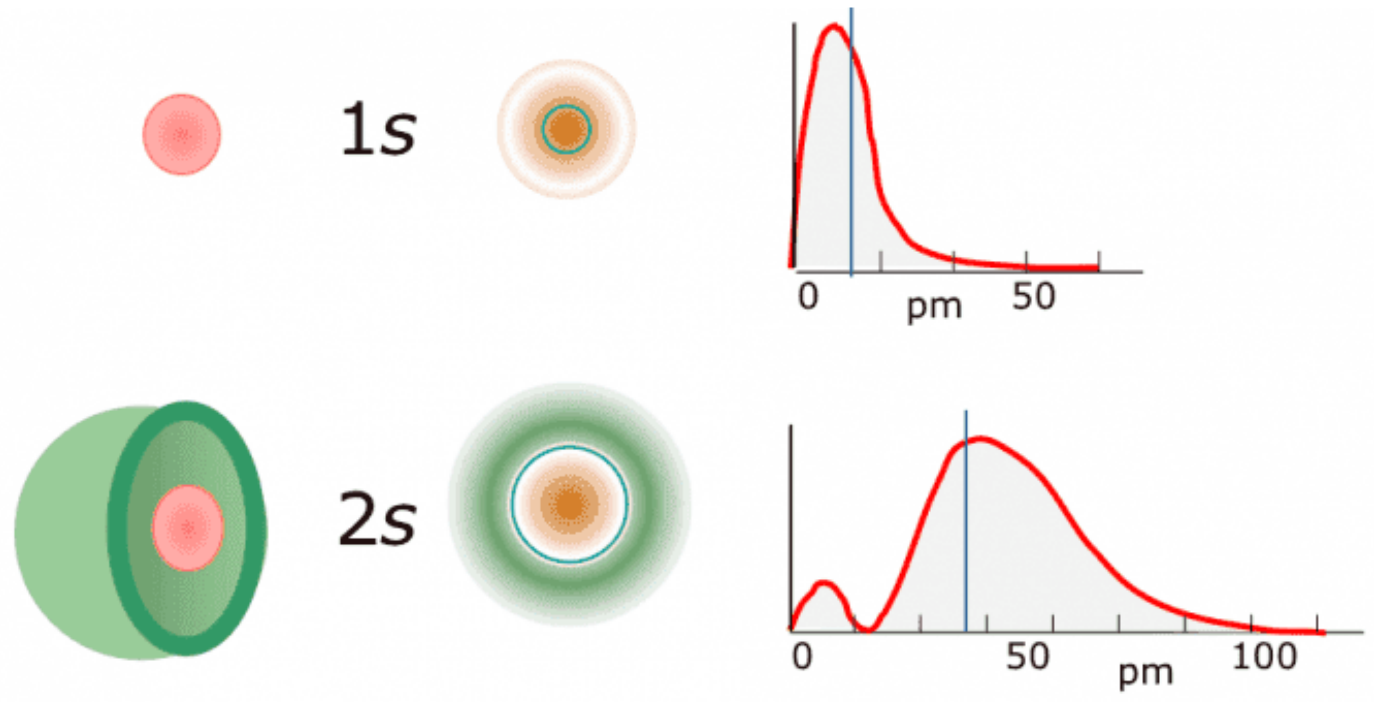


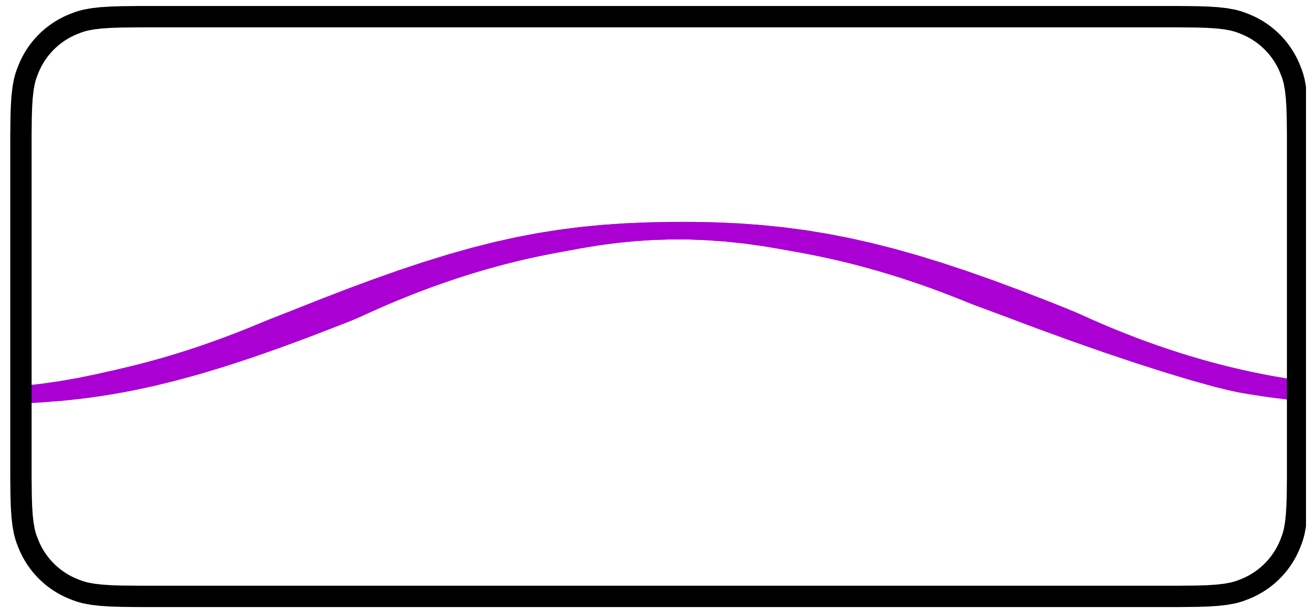
Quantum Fields in Small Devices

- 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.



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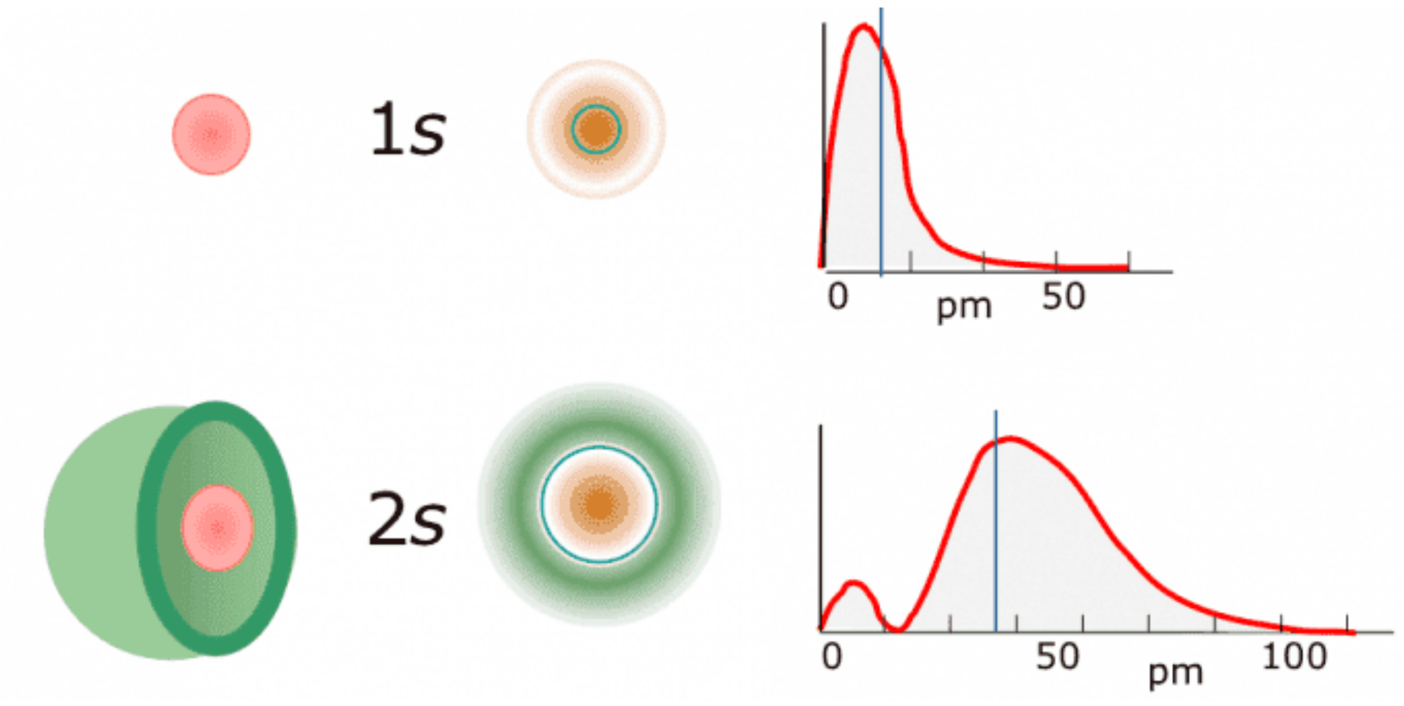
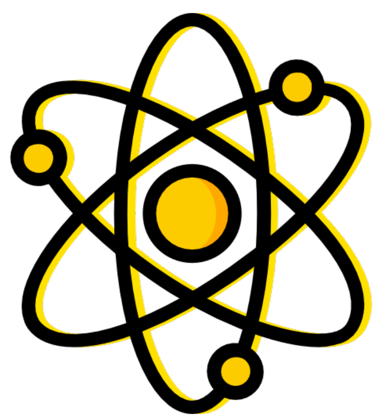


Quantum Fields in Small Devices

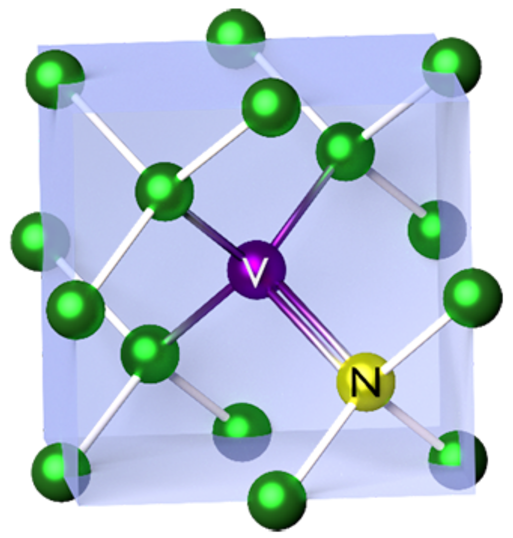
- Consider the low energy EFT of the discretum. Often in terms of a, $a^{\dagger}$

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

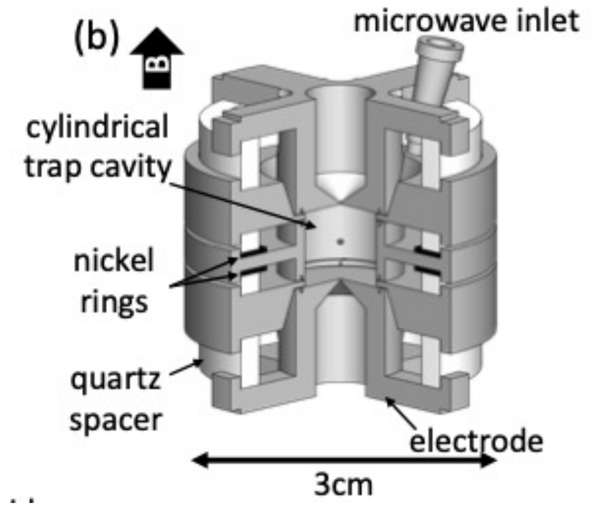
- In these EFTs, modes separate from the continuum, Quantum Mechanics shines:



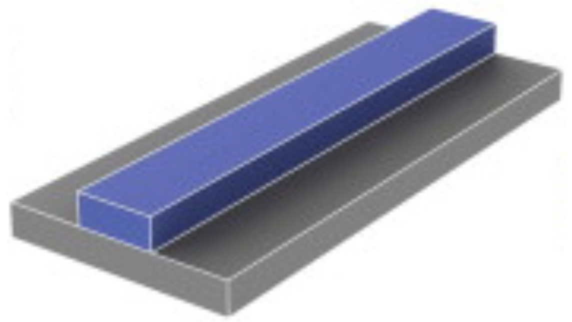
Atoms



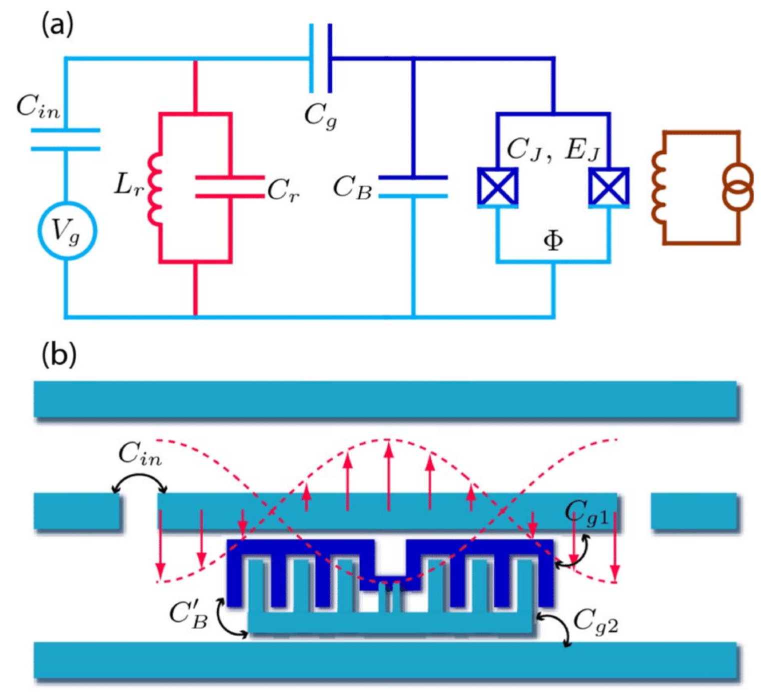
Defects



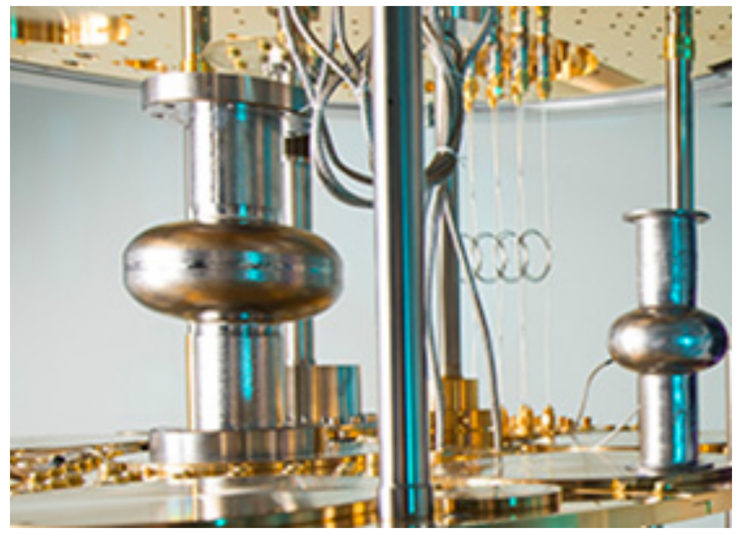
Artificial Atoms (particle in trap)



Optical waveguide

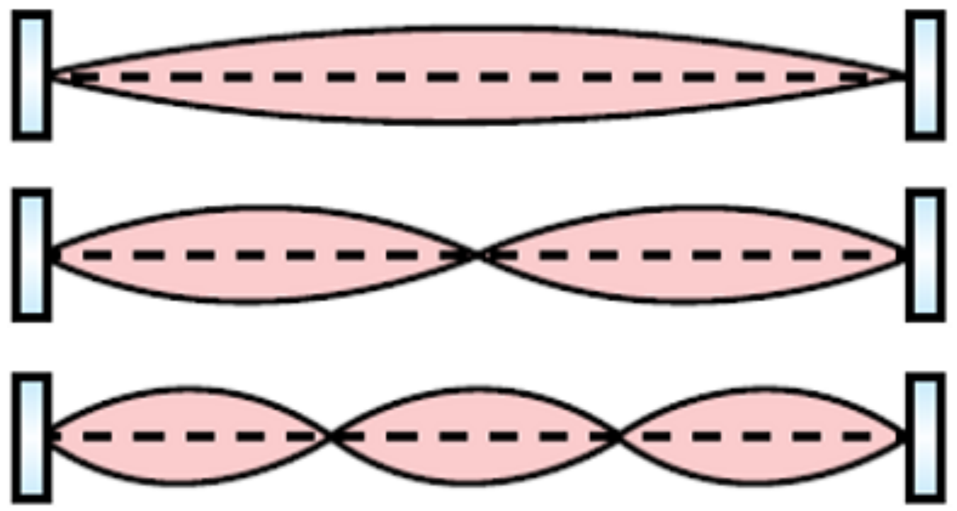


Superconducting circuits



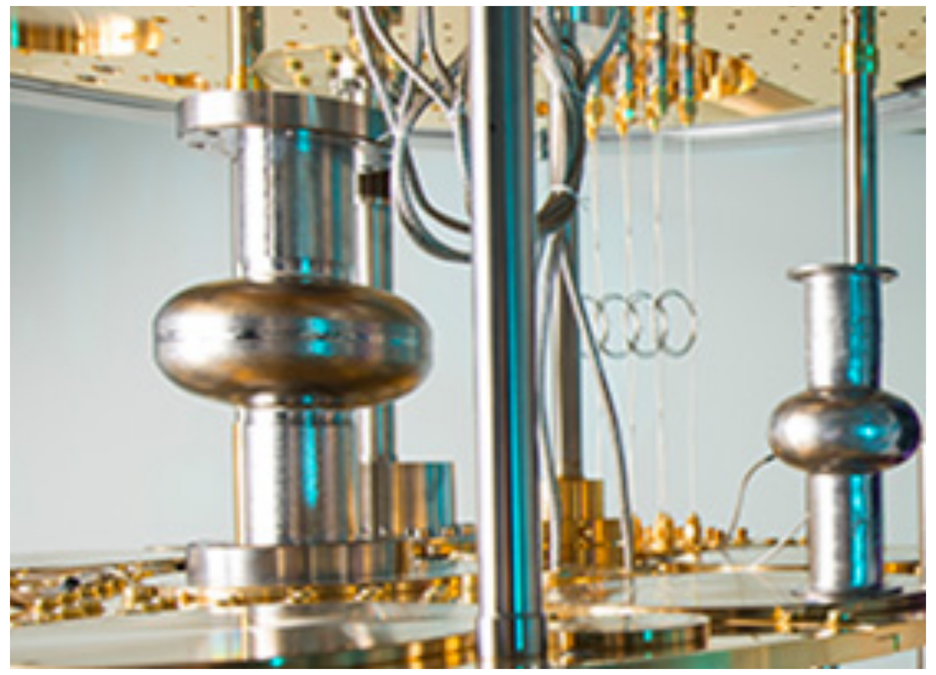
Electromagnetic Cavities

Cavities & Circuits

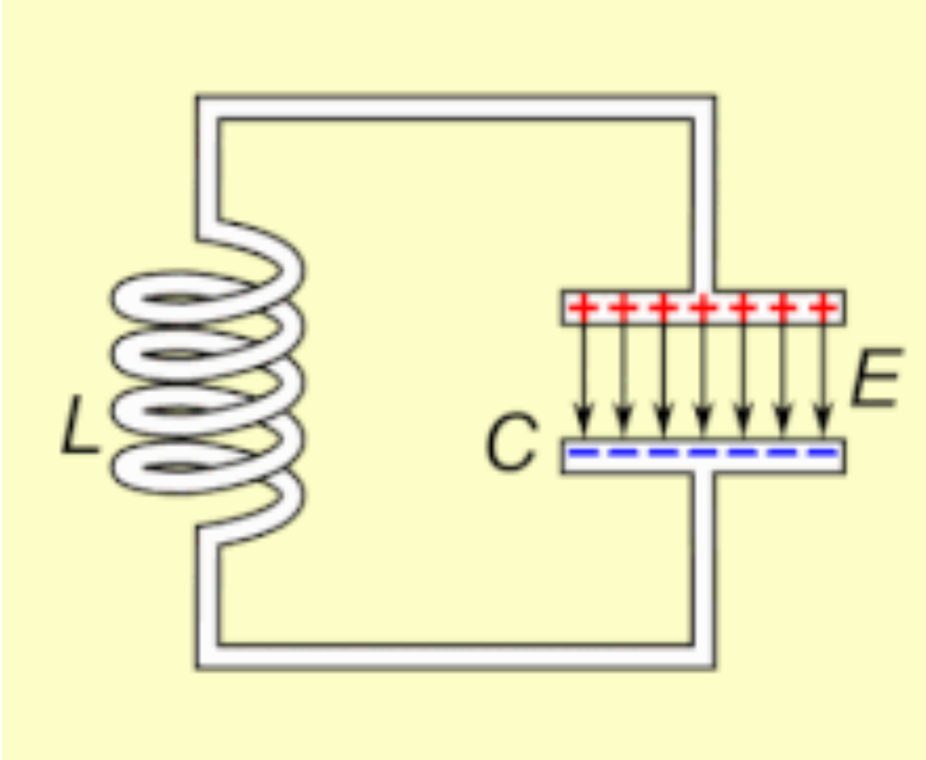


- Cavities: Light in a box. A discretum of states.
- Separation from the continuum is parametrized by Q.

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



- LC Circuits: periodic current/quantized flux.
- Control frequency with L & C.



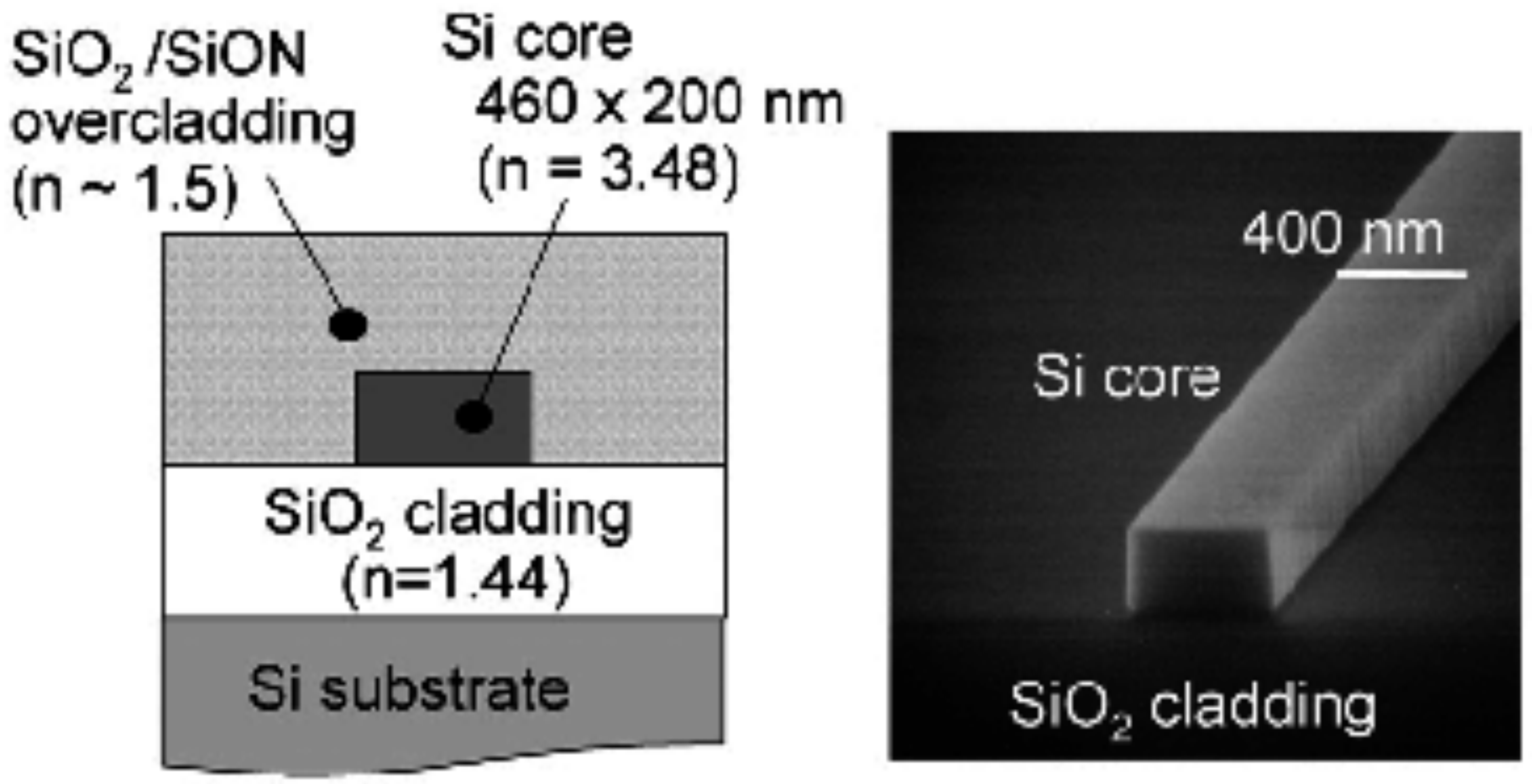
Both are harmonic. Equally spaced levels.

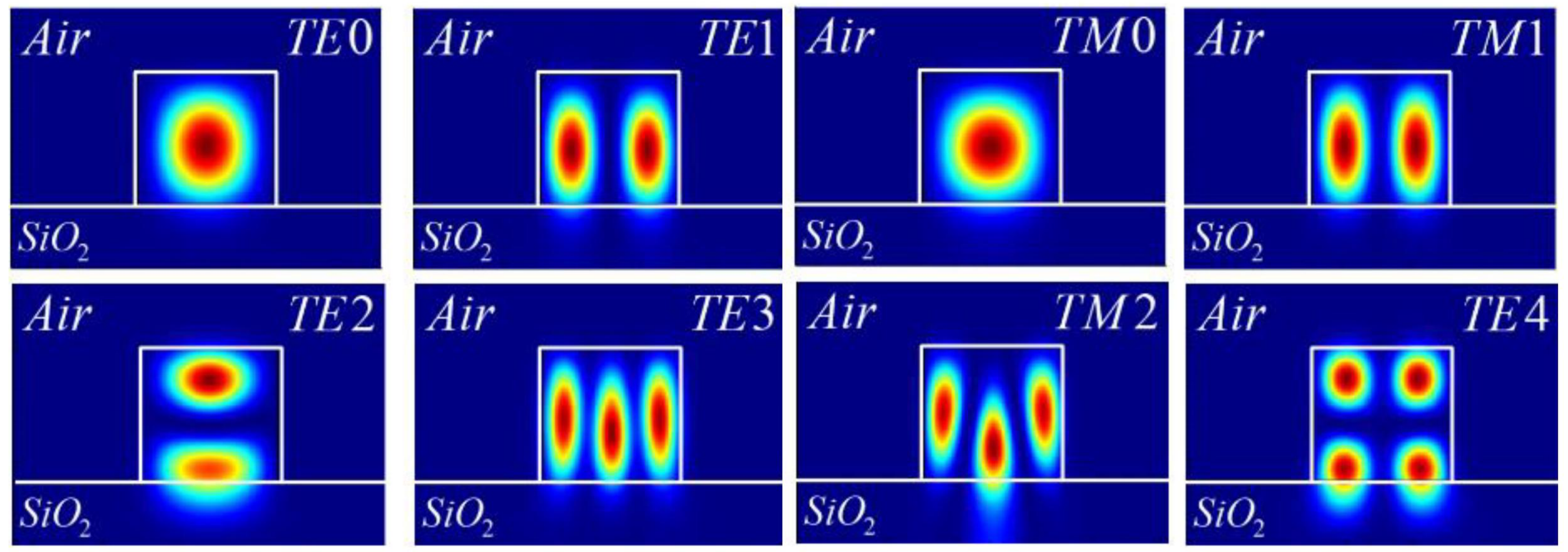
$$H_{mode} = \hbar\omega(a^\dagger a + 1/2)$$

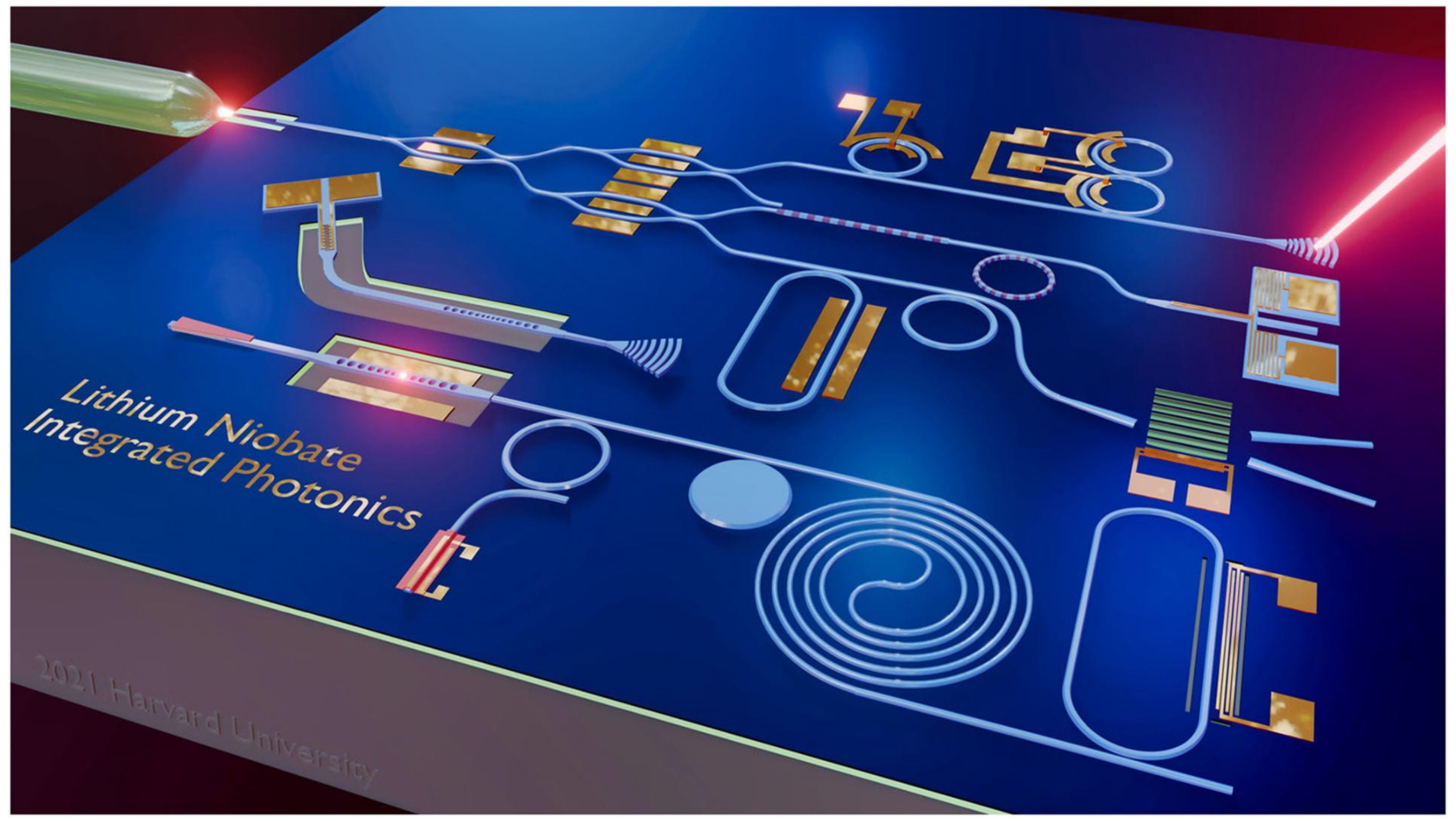
Optical Devices

- 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!)

Linear Optics: $H = E^2 + B^2 = \sum \hbar\omega(a^\dagger a + \frac{1}{2})$







"Integrated photonics"

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

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[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):

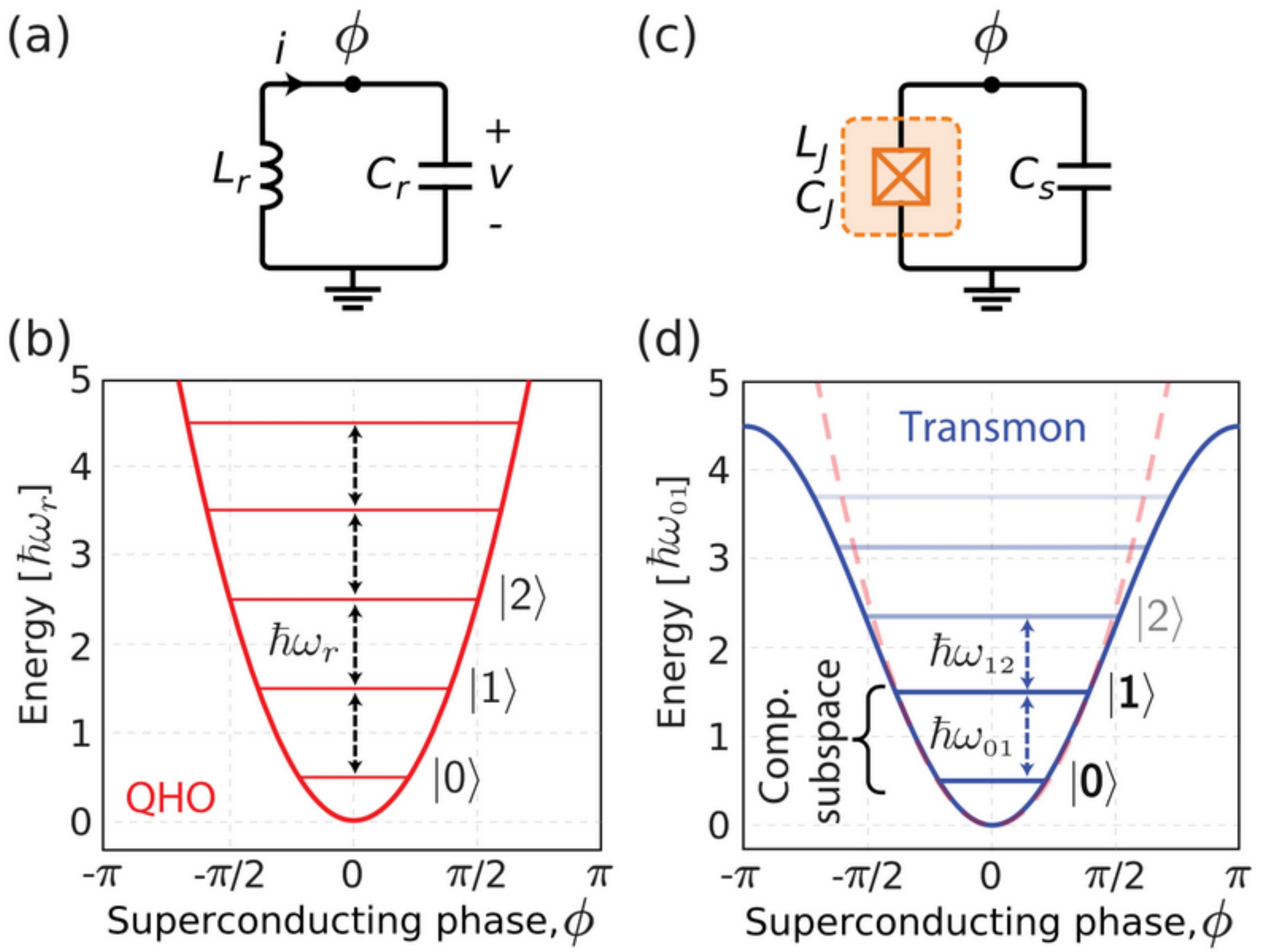
$$E_{\text{atom}} \sim e/4\pi a_0^2 \qquad \chi^{(2)} \sim \frac{\sqrt{4\pi}}{\alpha^{5/2} m_e^2} \qquad \chi^{(3)} \sim \frac{4\pi}{\alpha^5 m_e^4}$$

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

Nonlinear Devices

- Like any EFT, in a quantum device there is a UV cutoff.
- We can add higher dim operators, e.g. making L a function of $a^\dagger a$.

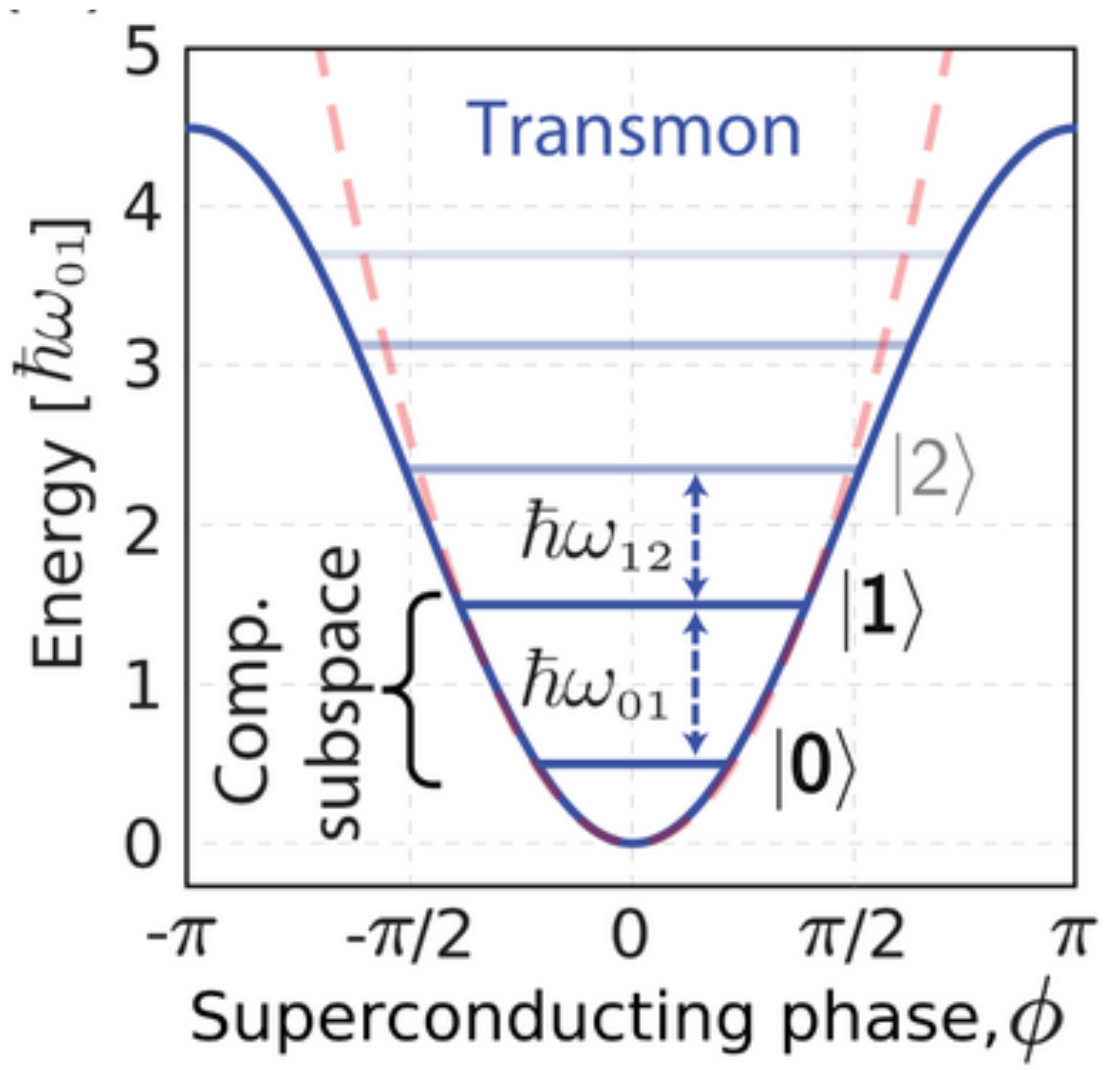
$$H = \hbar\omega(a^\dagger a + 1/2) + \kappa(a^\dagger a)^2$$



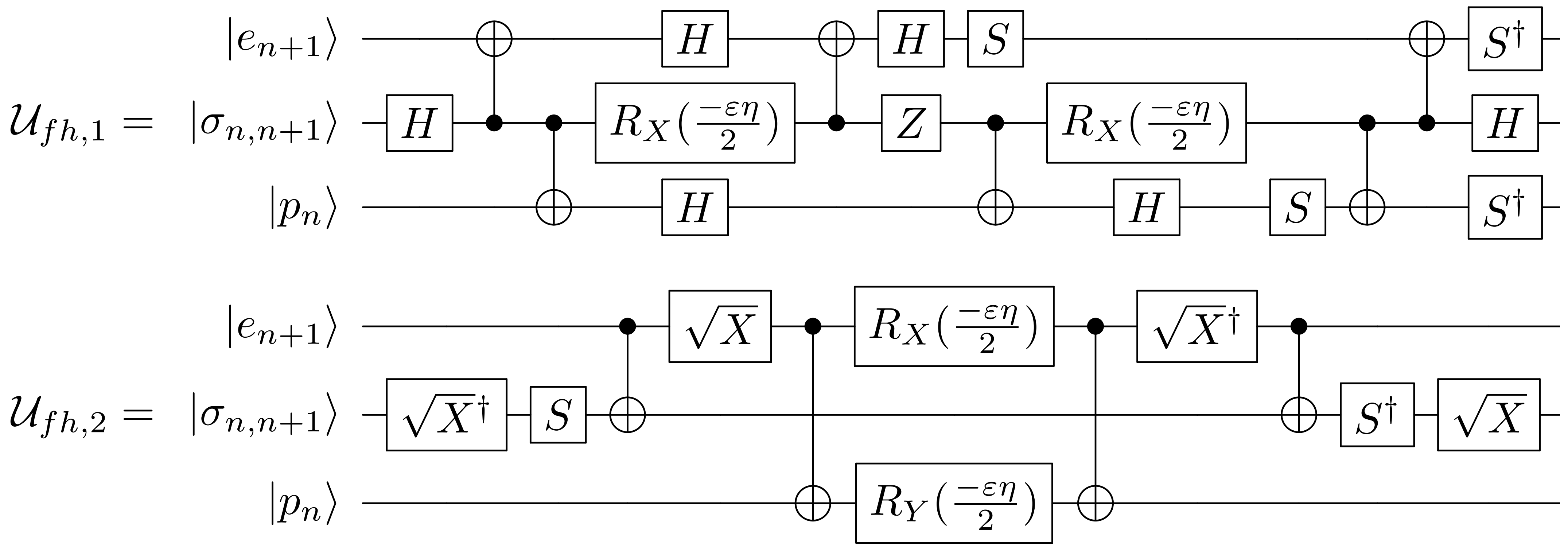
- Level spacing is nonuniform.
- This allows for control of individual levels of a given mode!

Quantum Control

- Within the device EFT, we can control the quantum state.
- Occupation number can stop information



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



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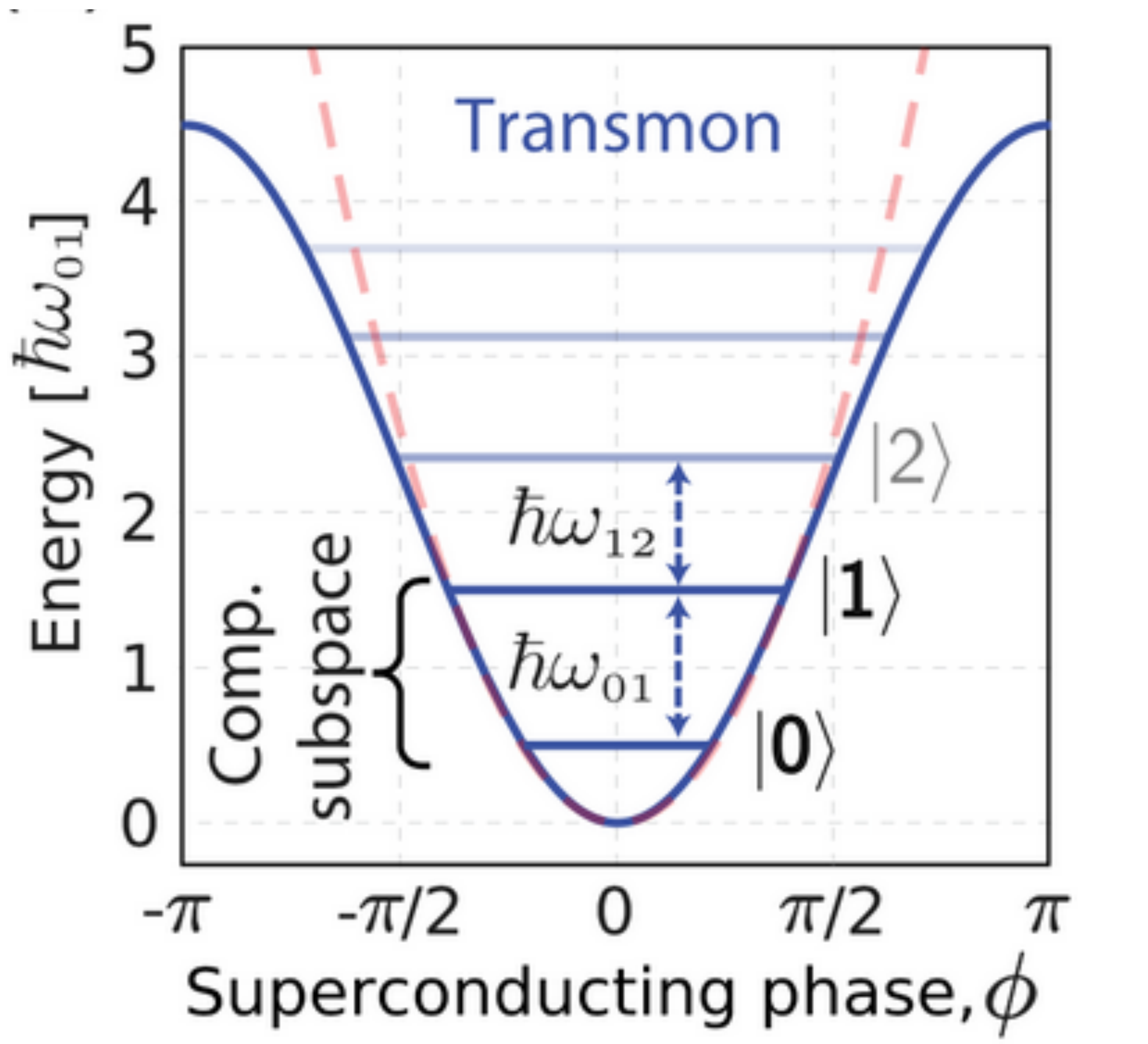

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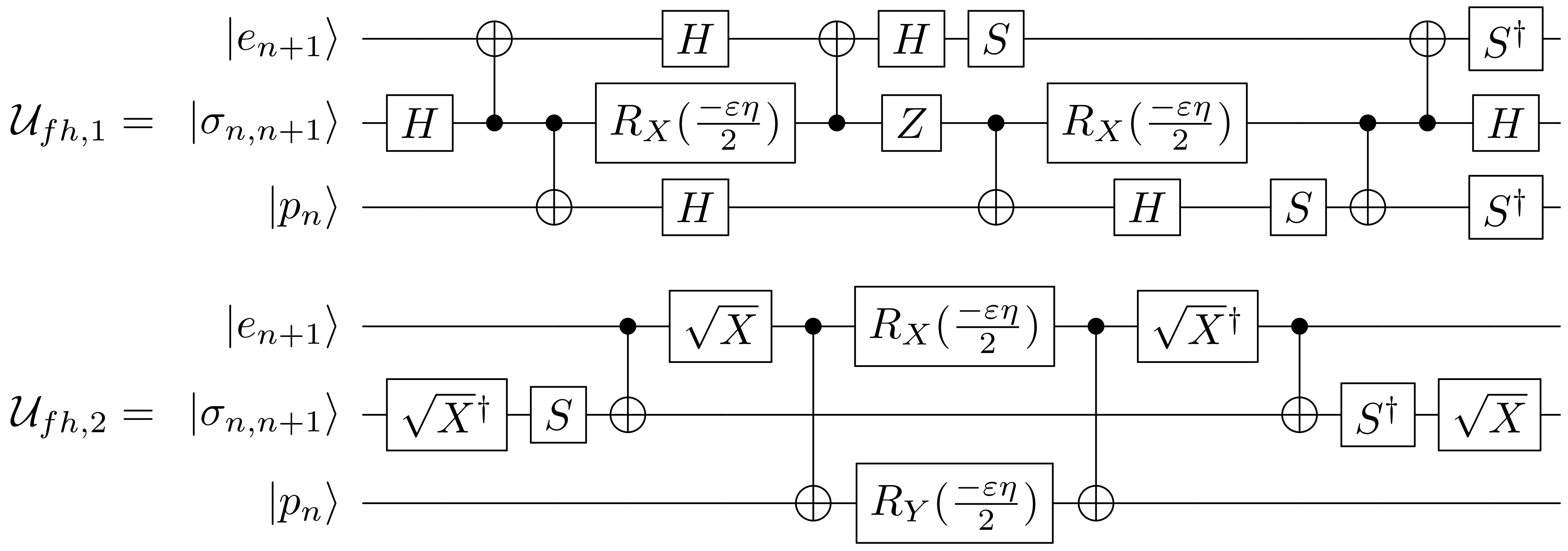

Or Qudit: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle \cdots$

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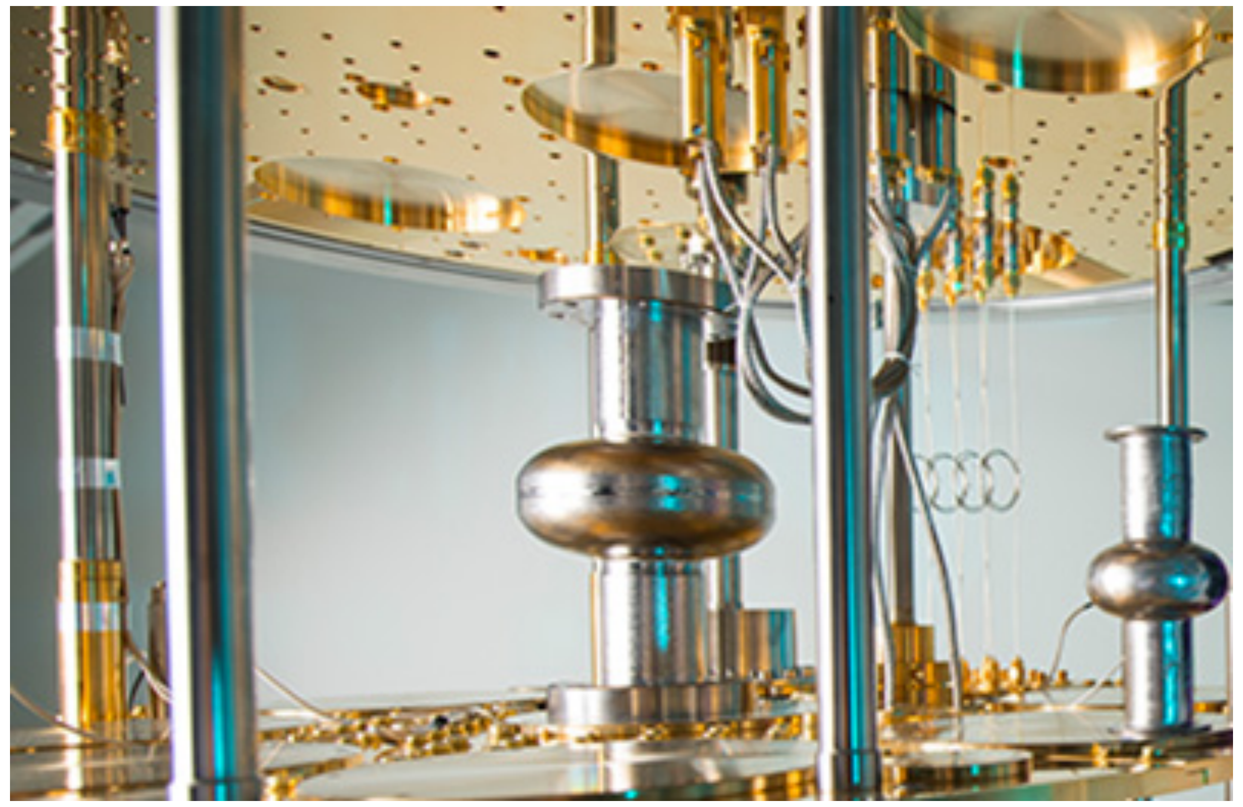
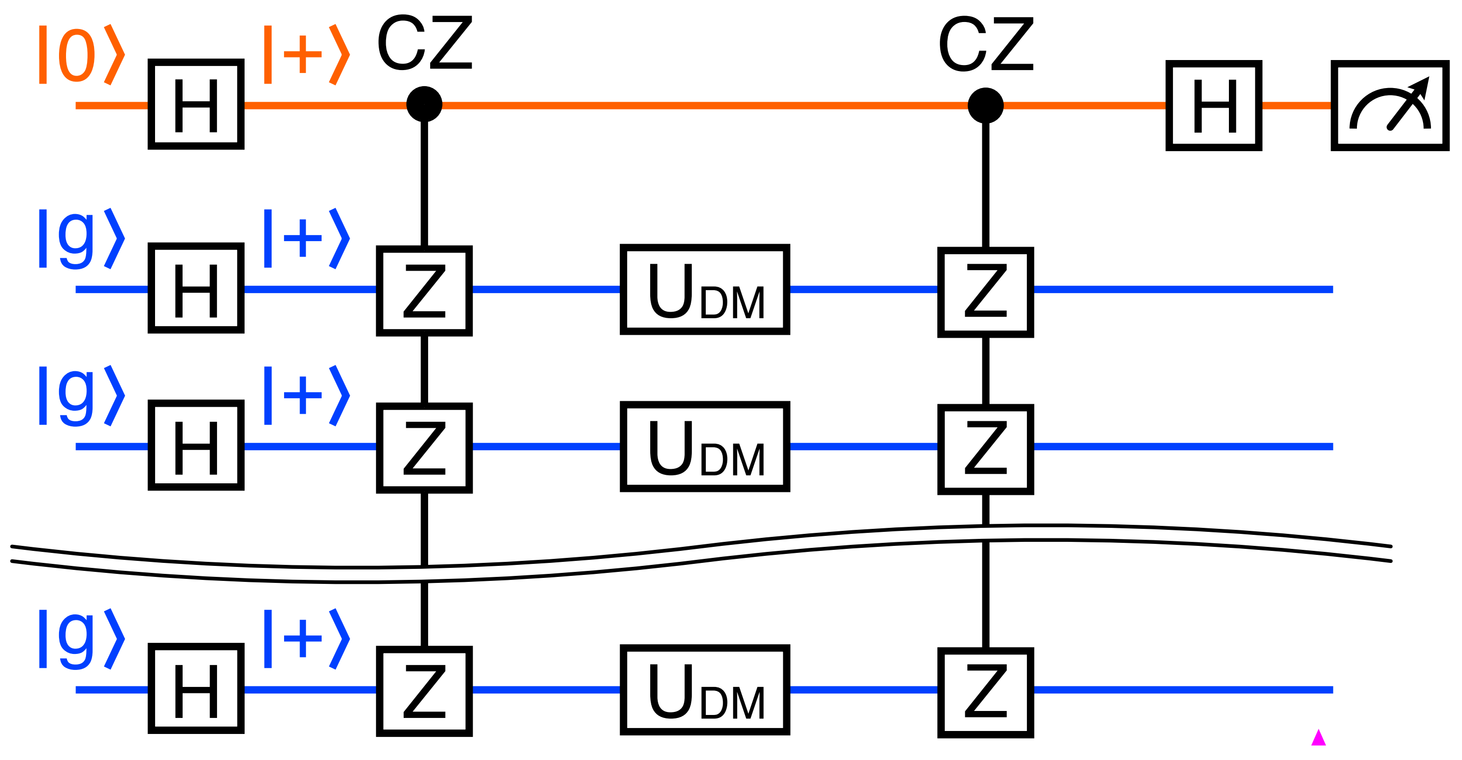
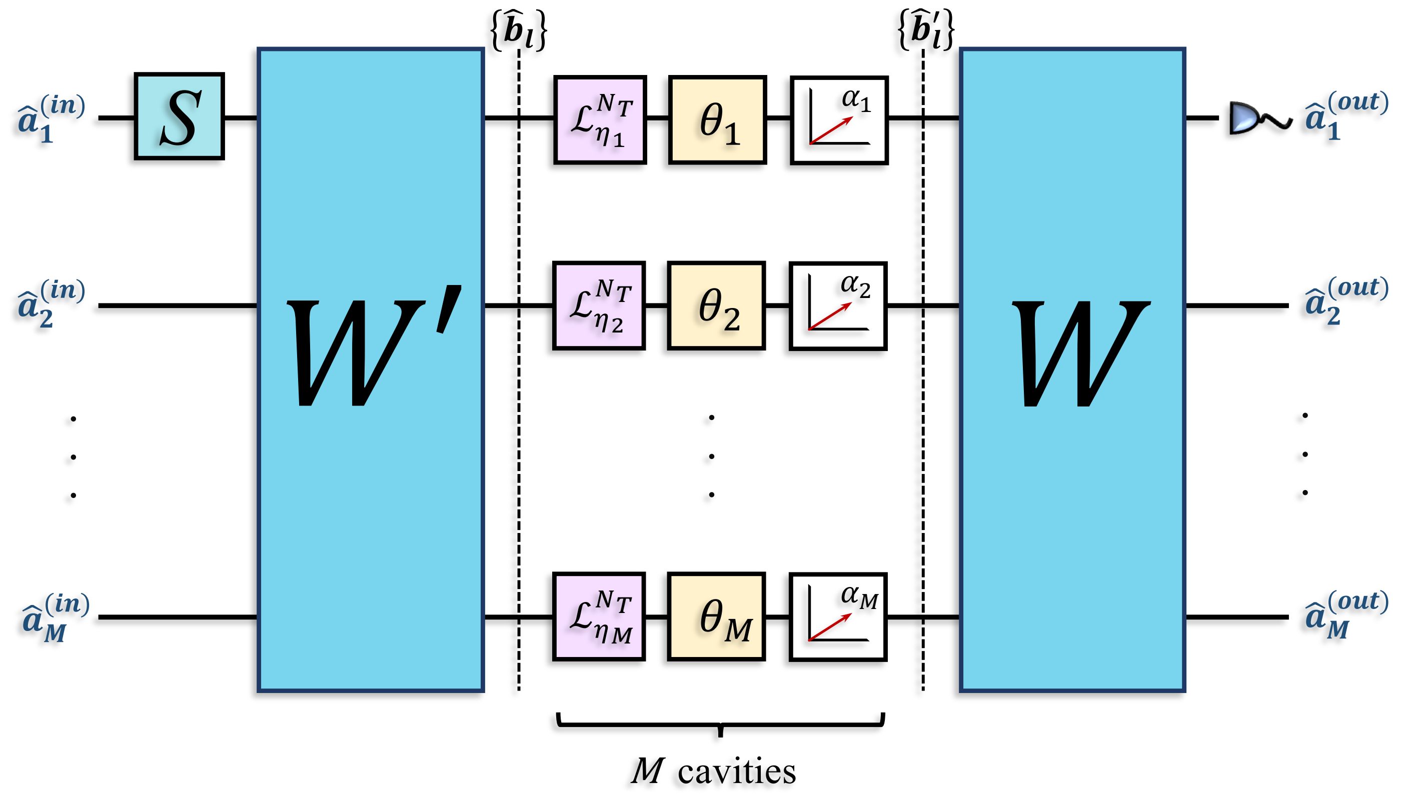


Quantum Sensing

- 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 (TES, Nanowires: SC to normal)
  - Time evolution of ultra sensitive (entangled?) states

Chen et al, 2311.10413
Ito et al 2311.11632

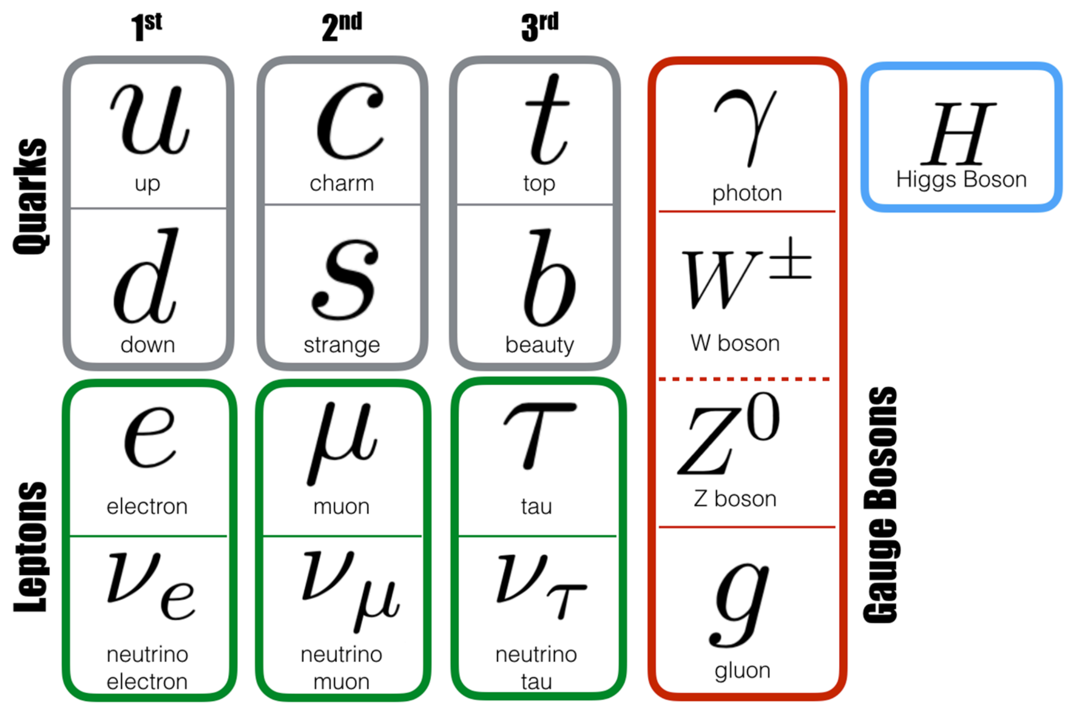




Distributed squeezing:
Talk by Brady,
Brady et al, *PRX Quantum* 3 (2022) 3, 030333

BSM - for Quantum Mechanics

New Physics ⟶ New Fields



+ Something new.

Ok. For concreteness,

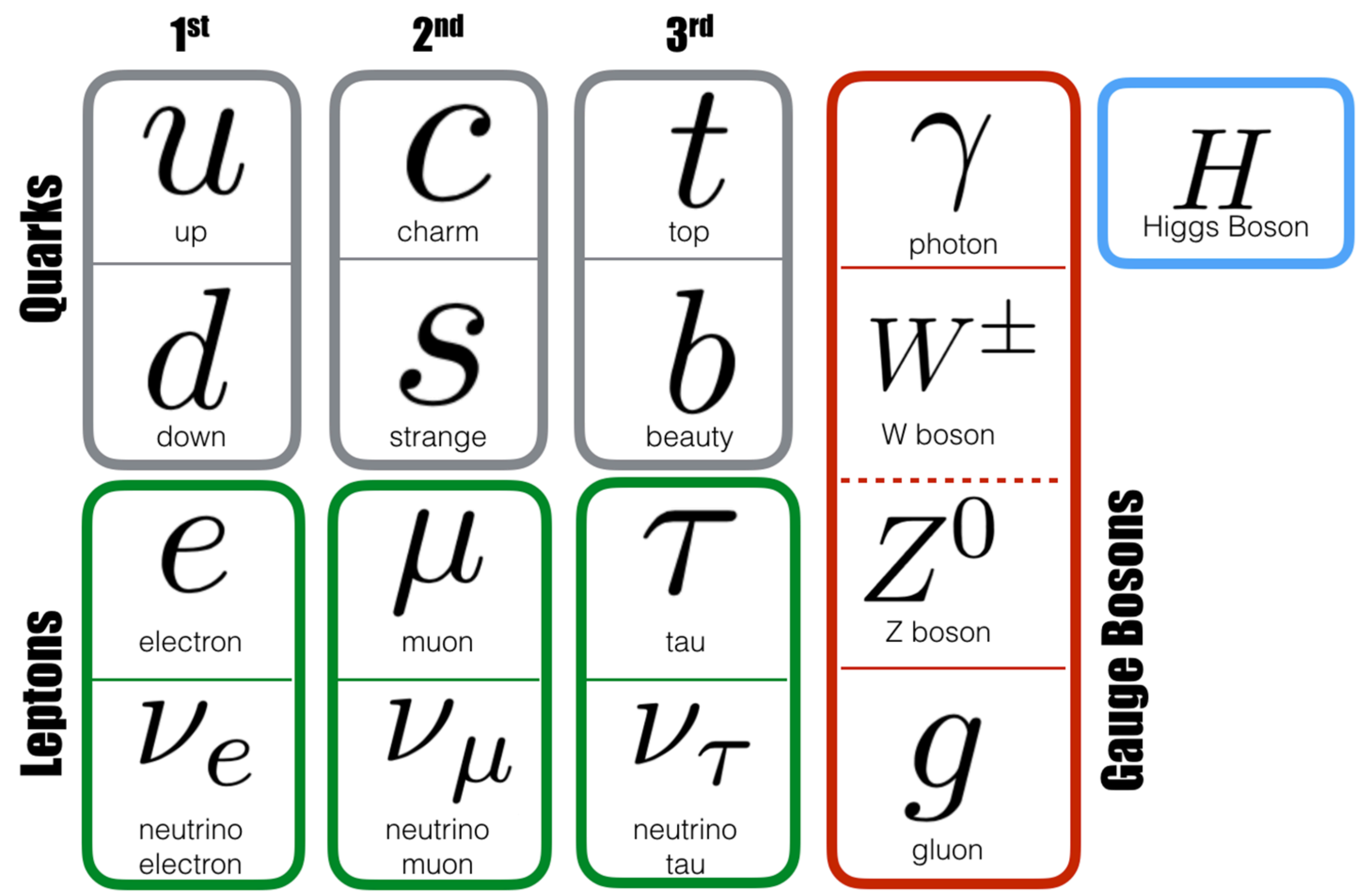
(and because QIS is often about controlling light)

lets assume the new field couples to photons.

Linear or nonlinear?

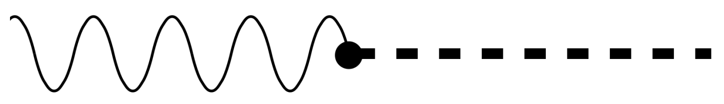
Dark Photons - a Linear Extension

- 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.)

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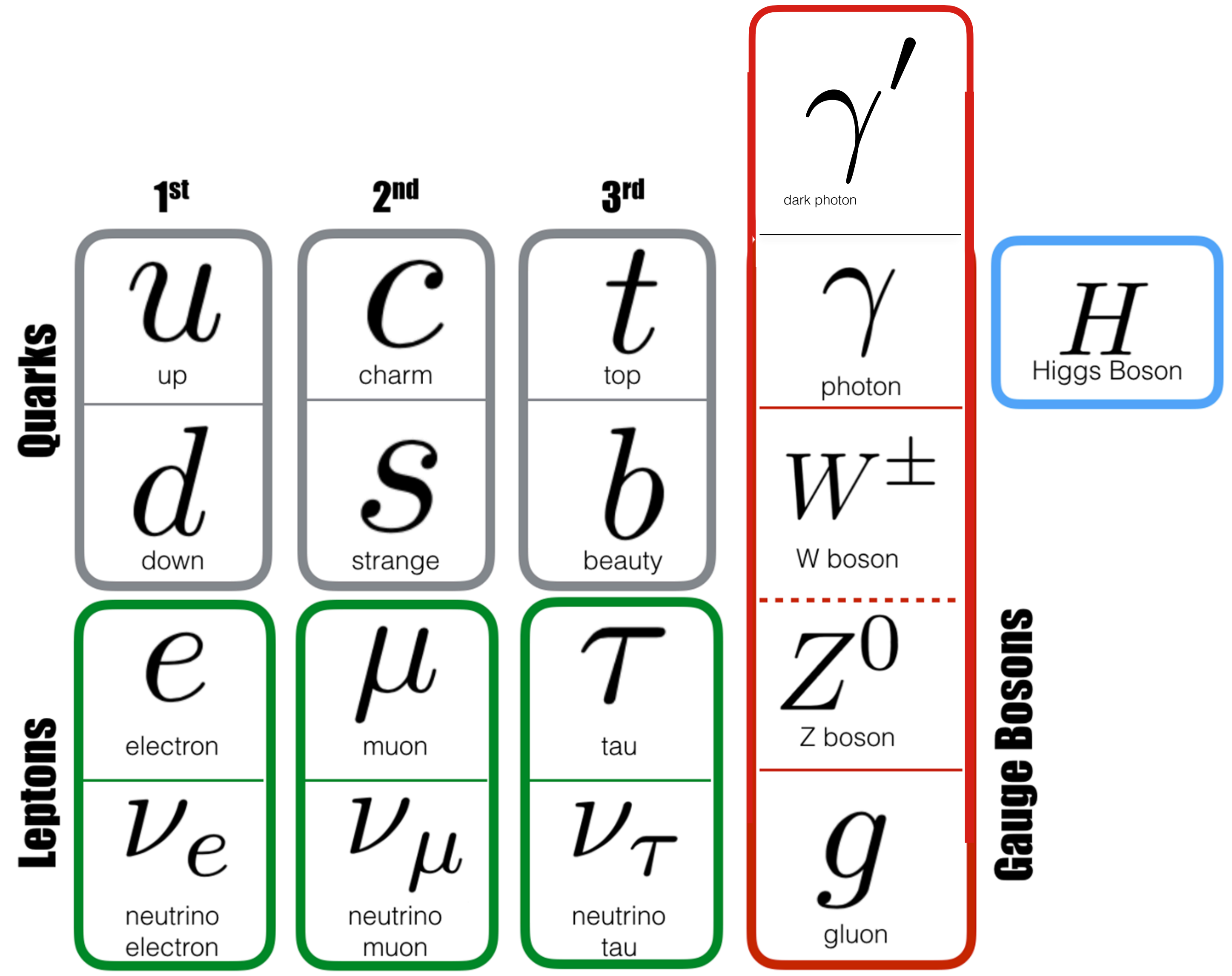

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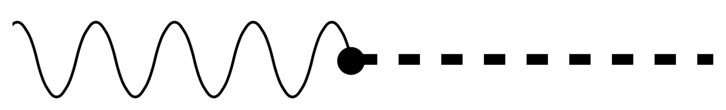

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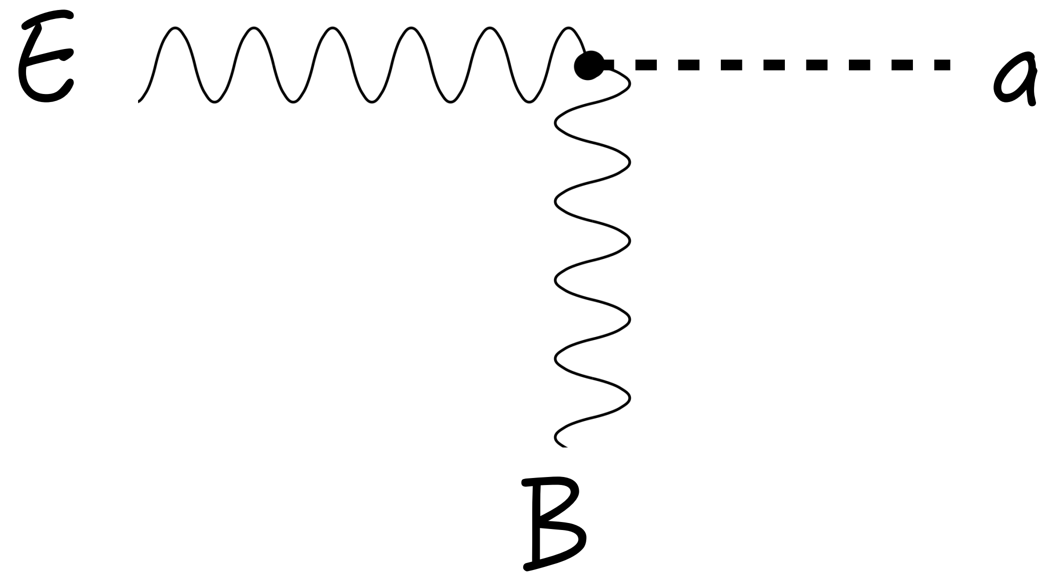
Pecci and Quinn (77)

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.)

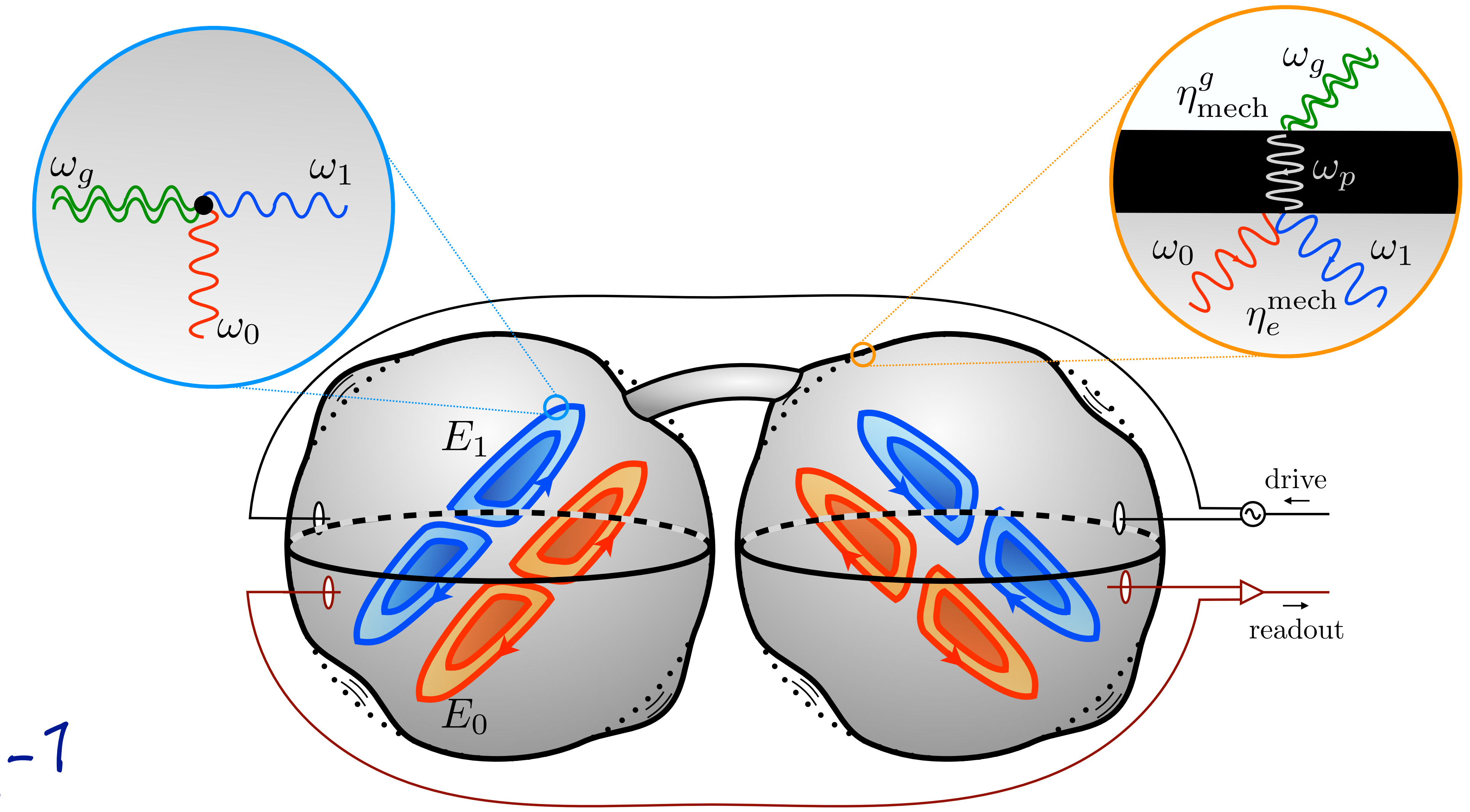
Gravity Waves - A nonlinear extension

- 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.

Examples

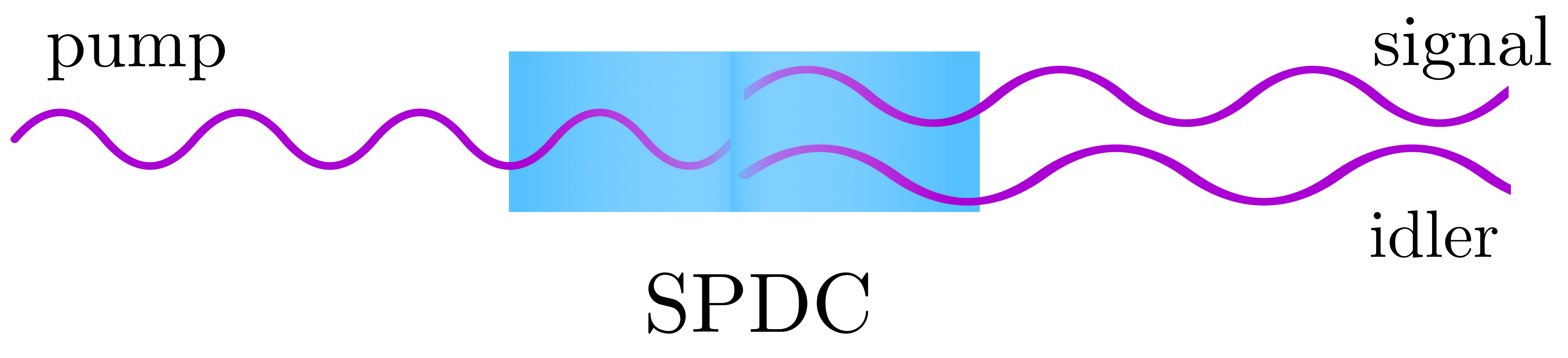
Cavity based Searches @ SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Optics based searches @ our imagination so far

Estrada et al. *PRX Quantum* 2 (2021) 3, 030340
RH in prepration. See also tlk by Gao.

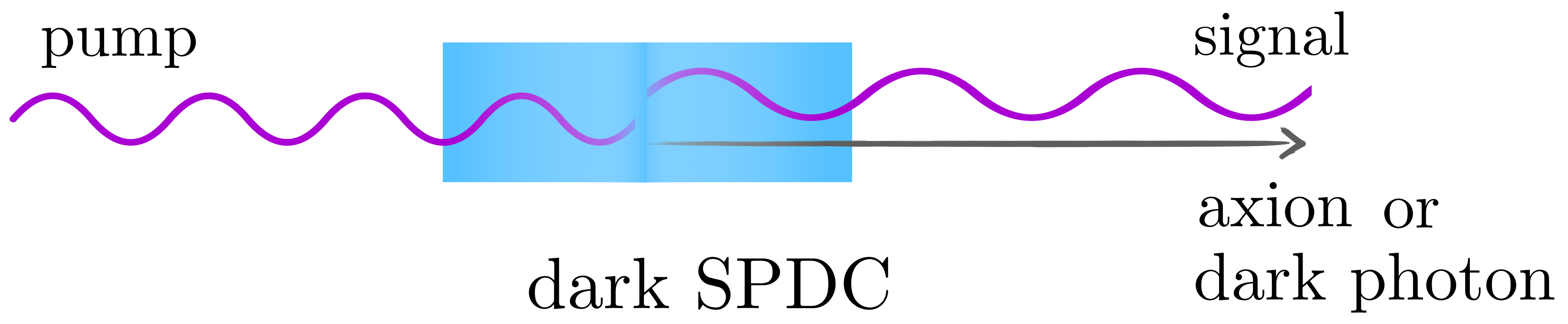
Nonlinear Optics with Dark States

- SPDC: a workhorse in quantum optics.
- Pump -> signal + idler (a "decay")
- Presence of idler is inferred. Might as well be invisible!

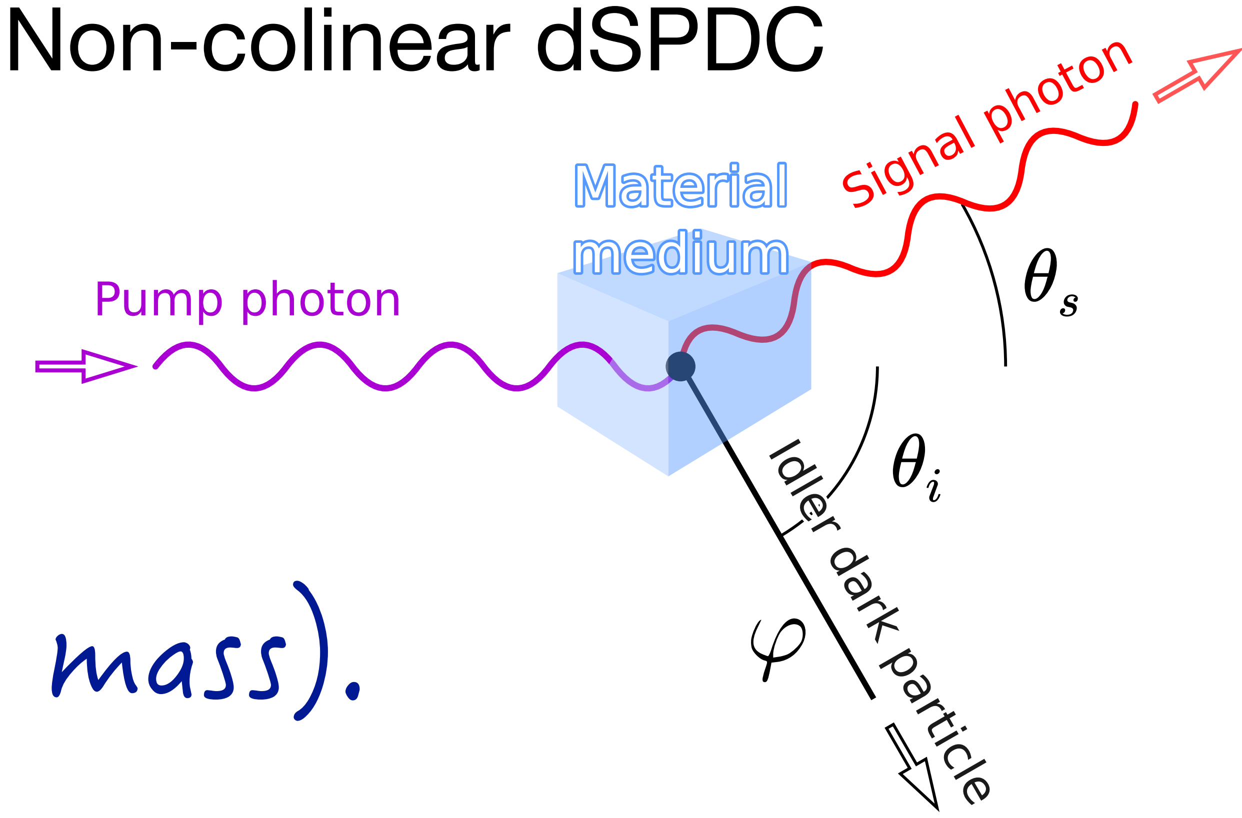


- Dark SPDC: Pump -> signal + axion or dark photon. Rate $\propto \varepsilon^2$ (vs ε^4 for LSW)

colinear dSPDC



Non-colinear dSPDC

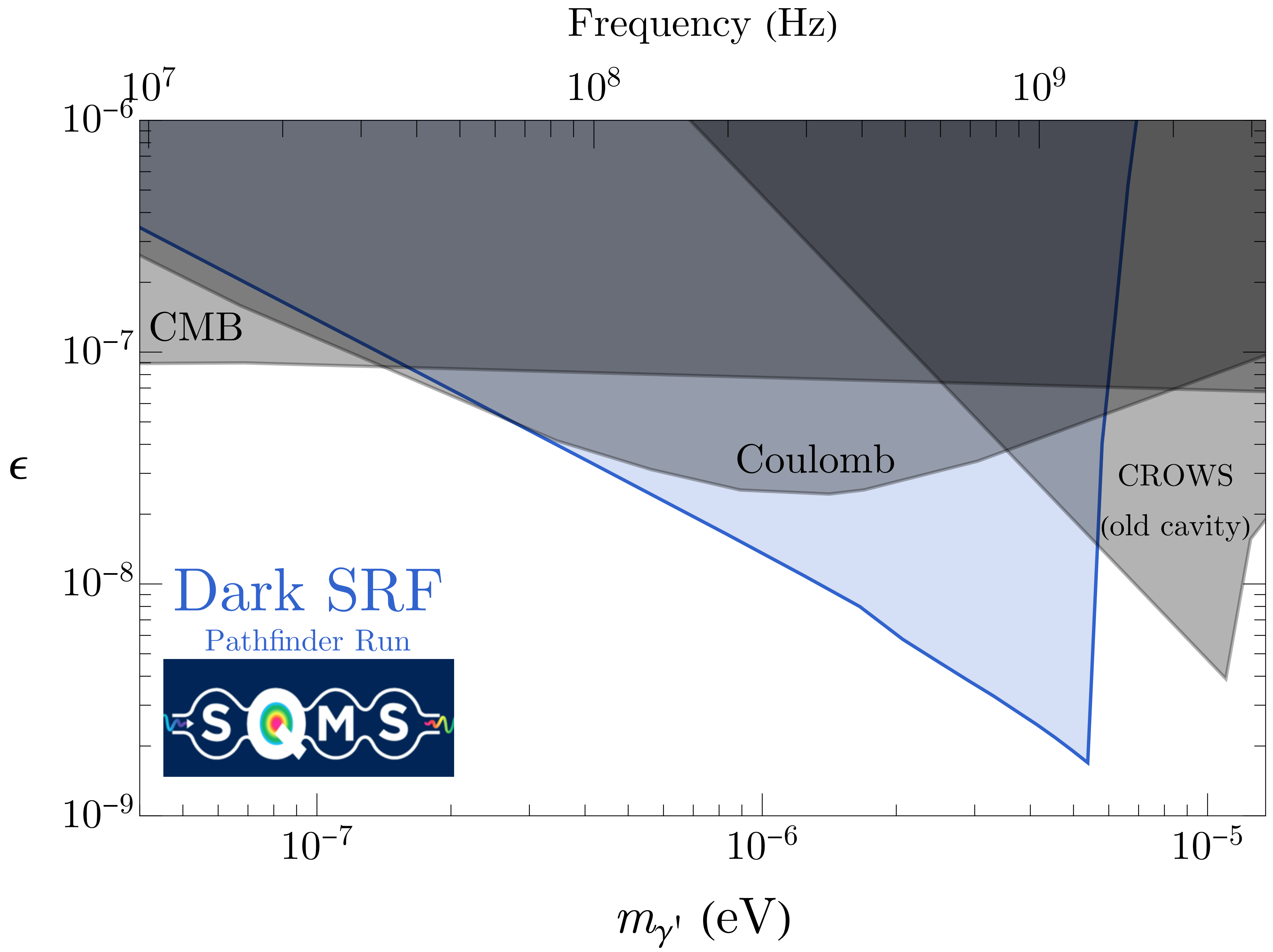


Note: the axion or dark photon have index of refraction of 1 (and a mass).
dSPDC has significantly different phase matching conditions.

Dark SRF: cavity-based search for the Dark Photon

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. Phase sensitive readout.

Will increase the search reach.

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

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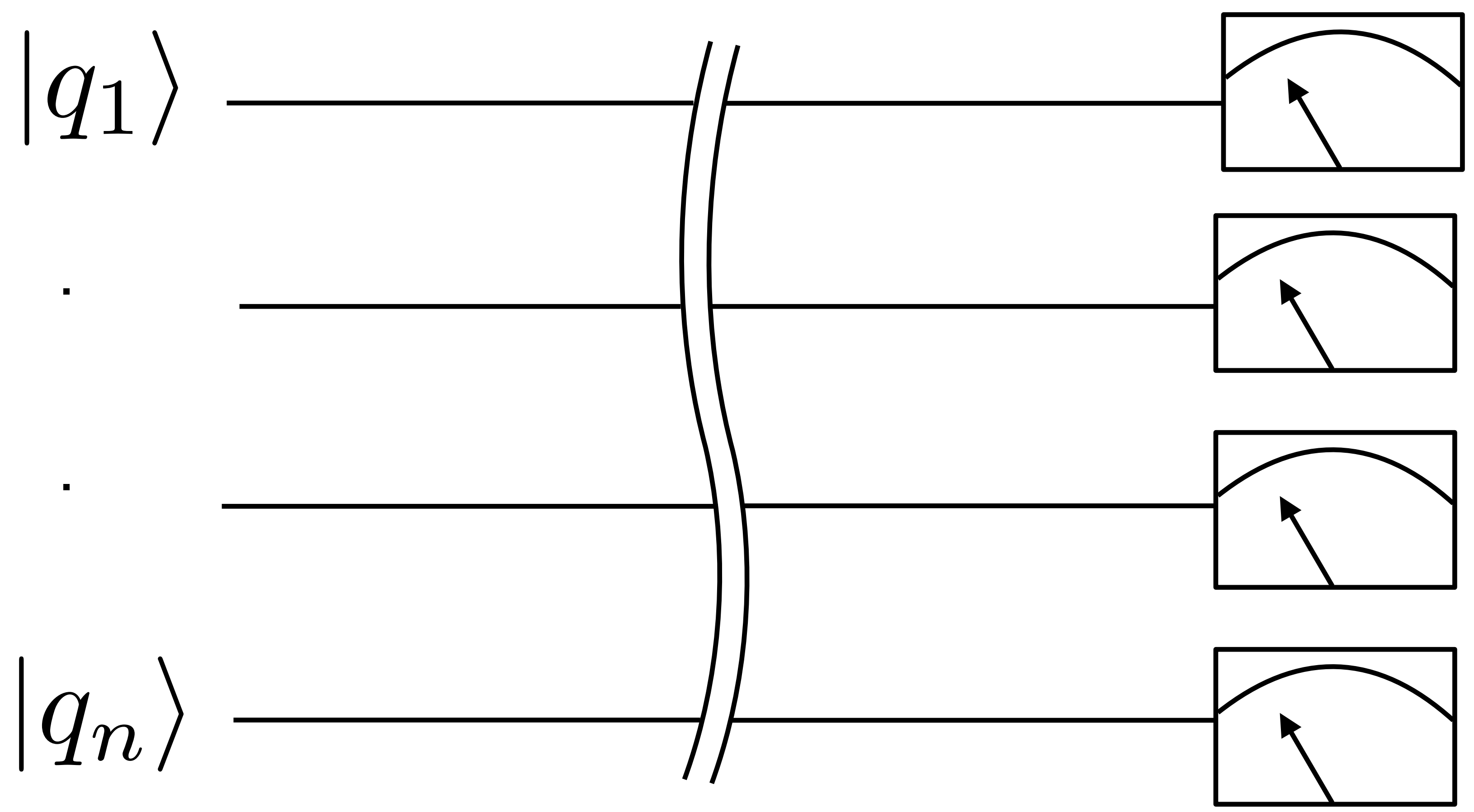
Quantum Advantage

- 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

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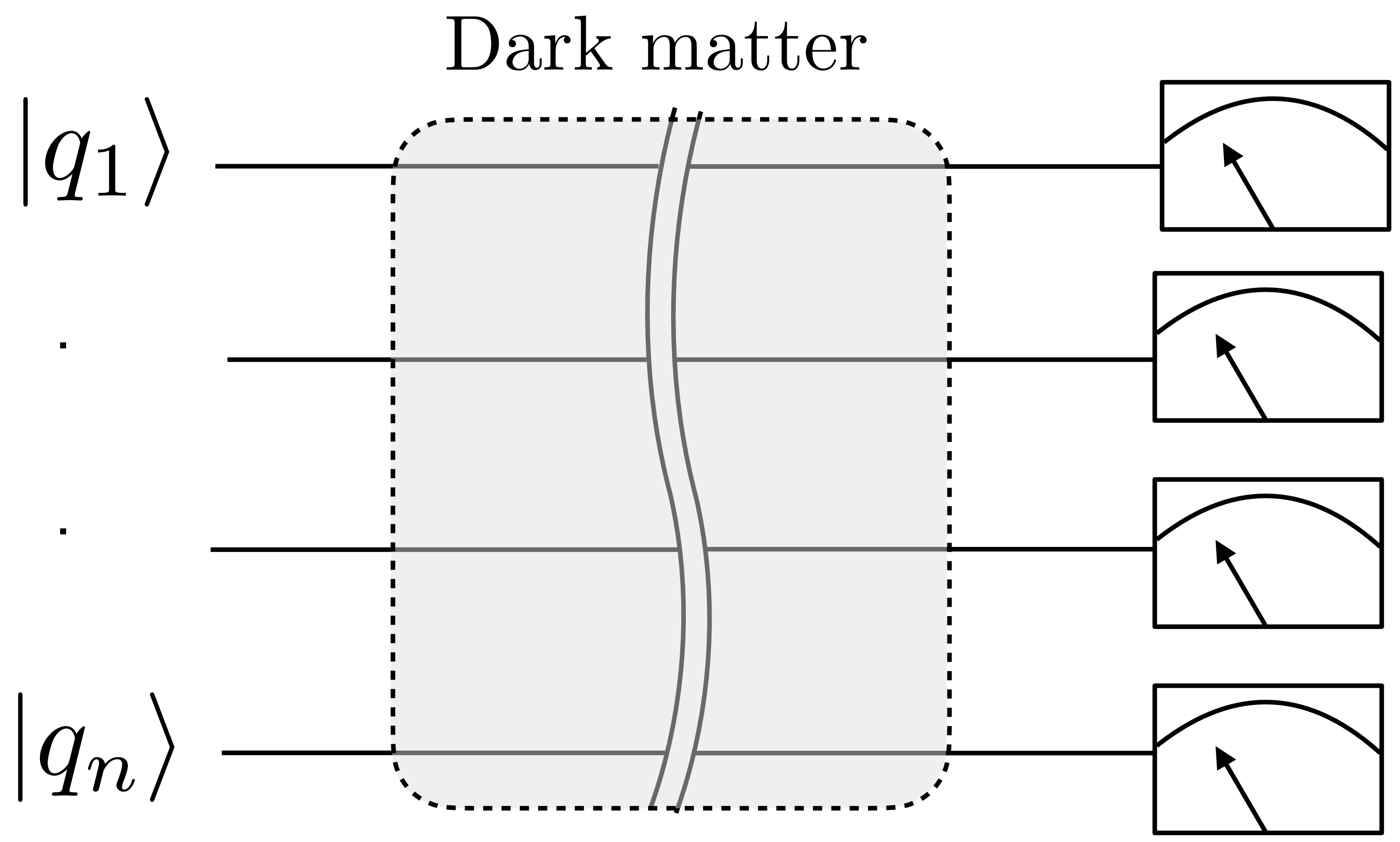

Rate scales as n.

Chen et al, 2311.10413
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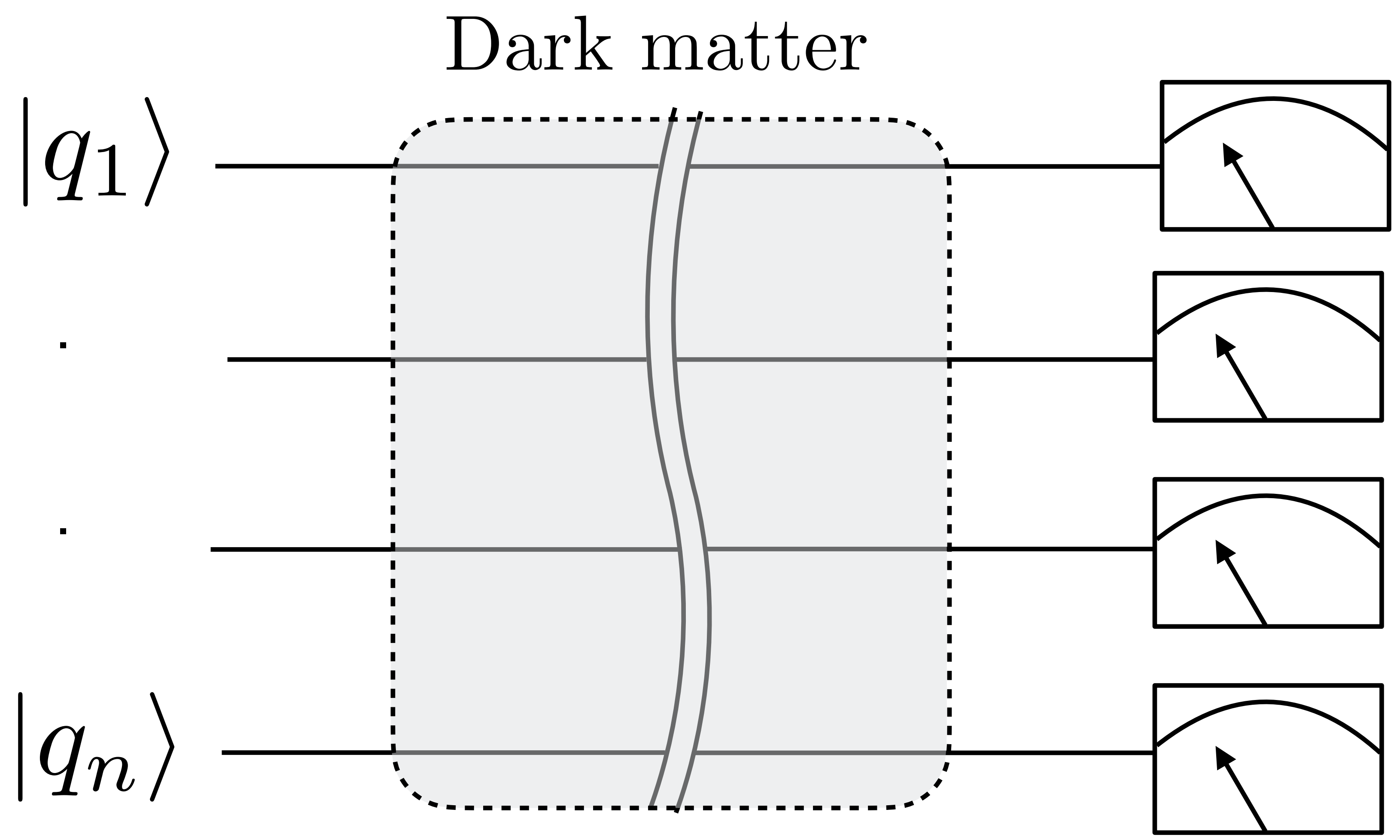

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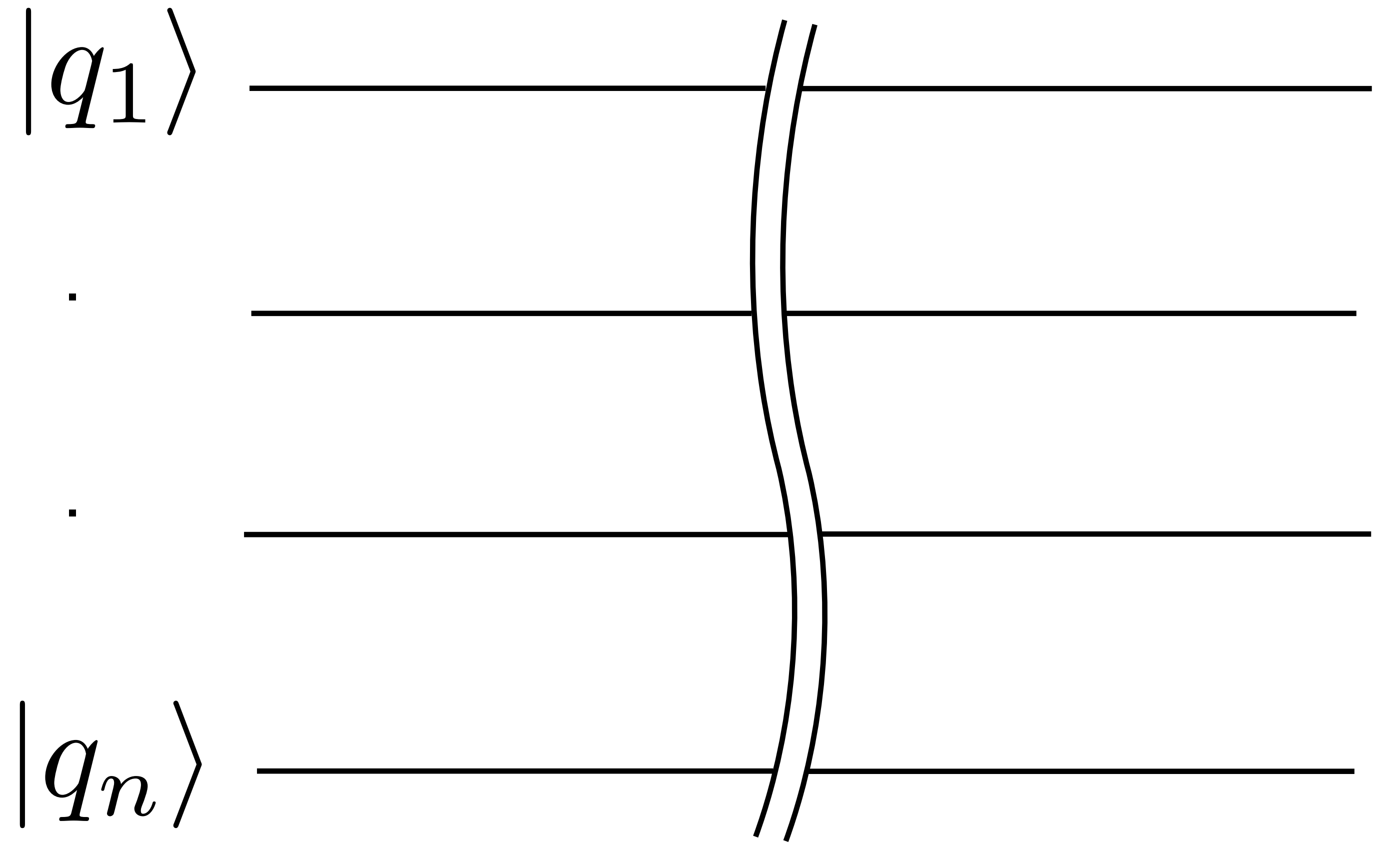

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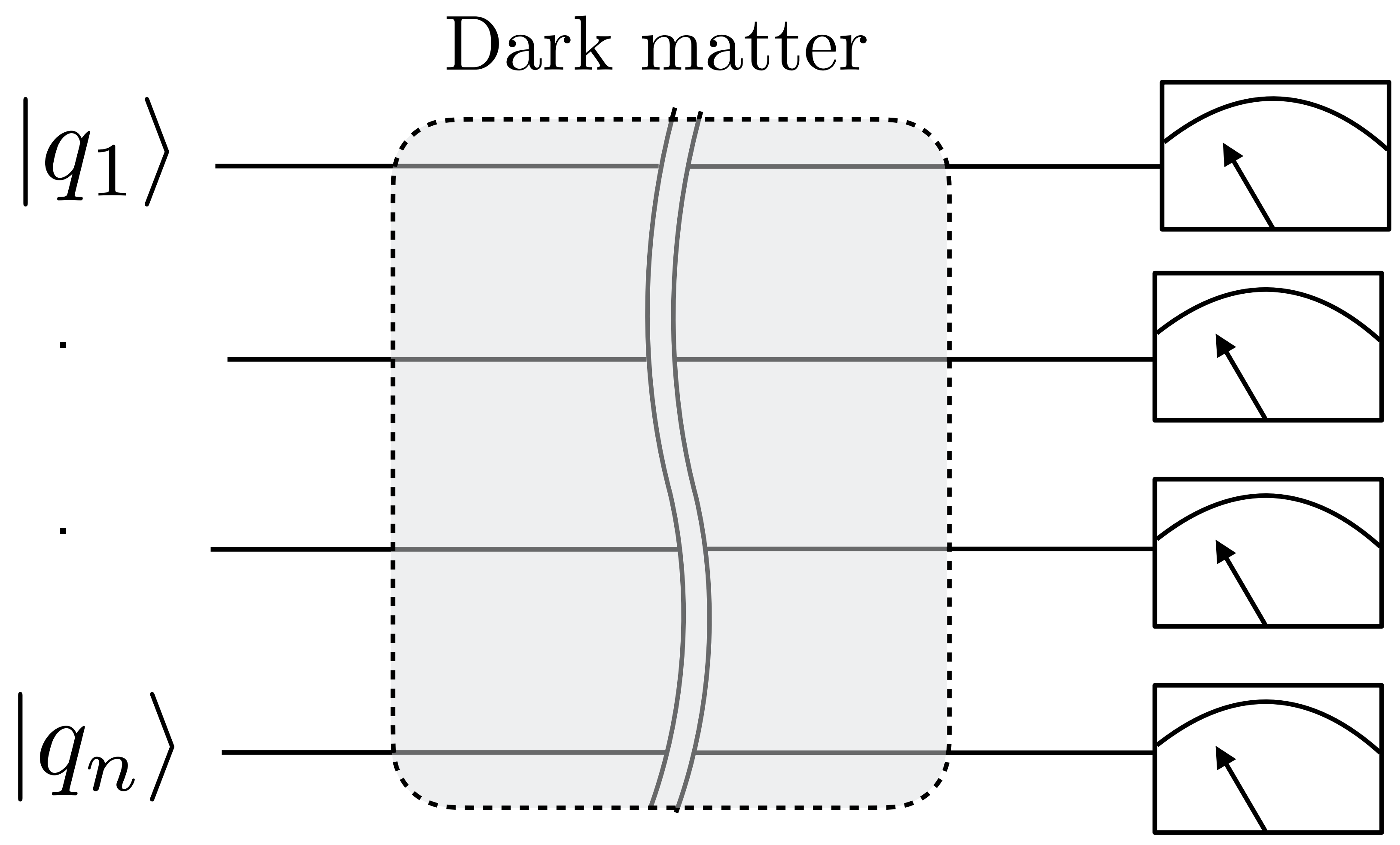

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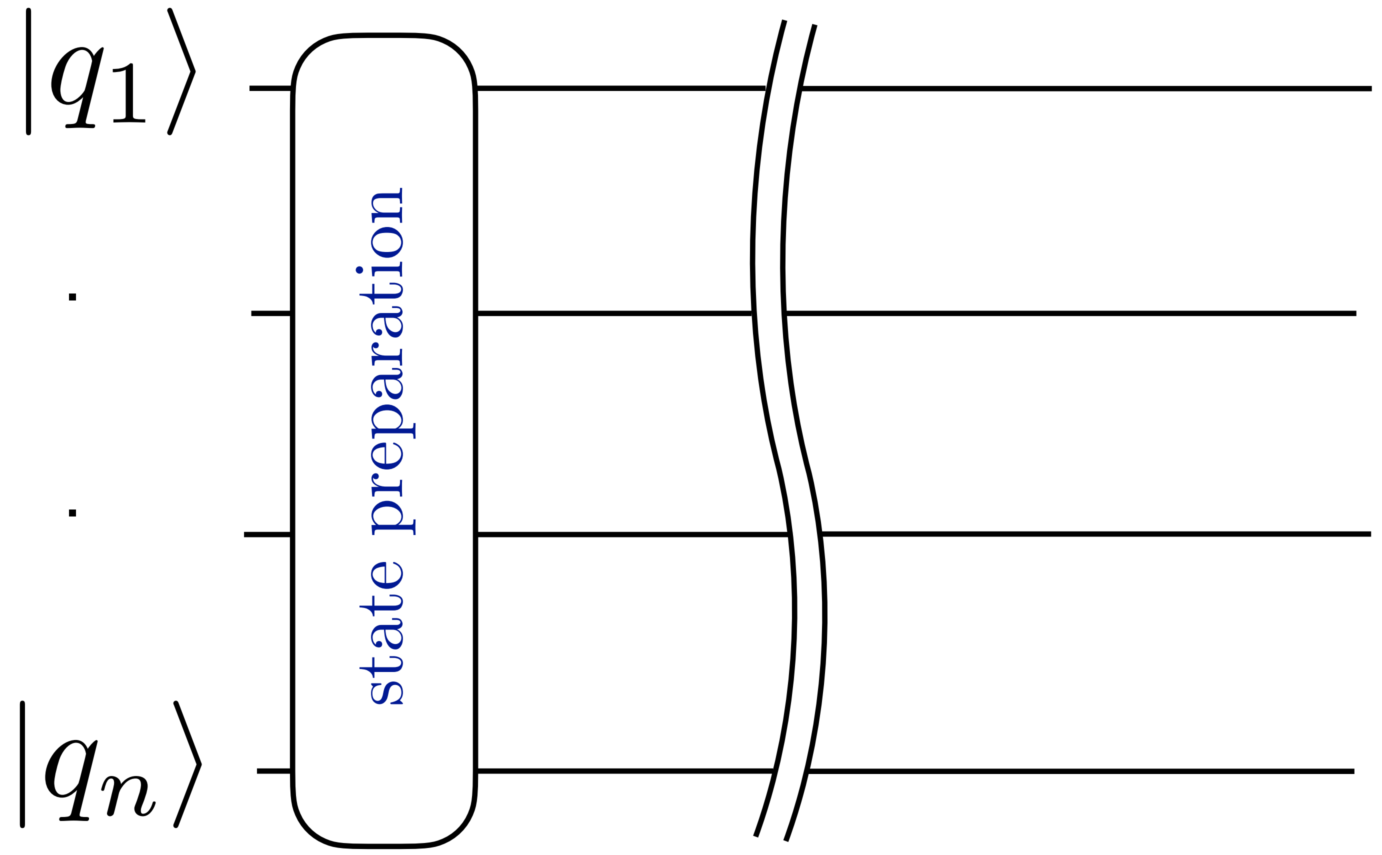

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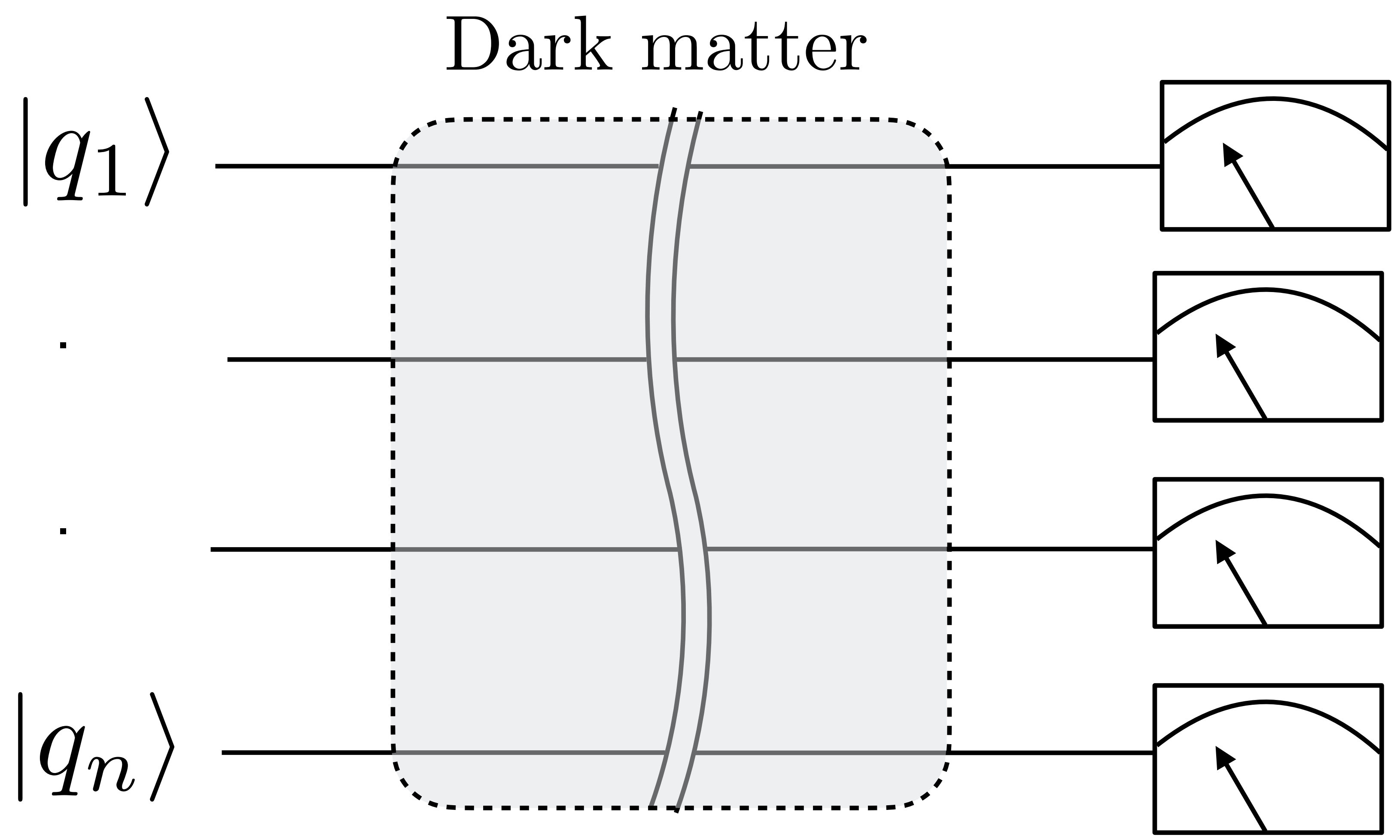

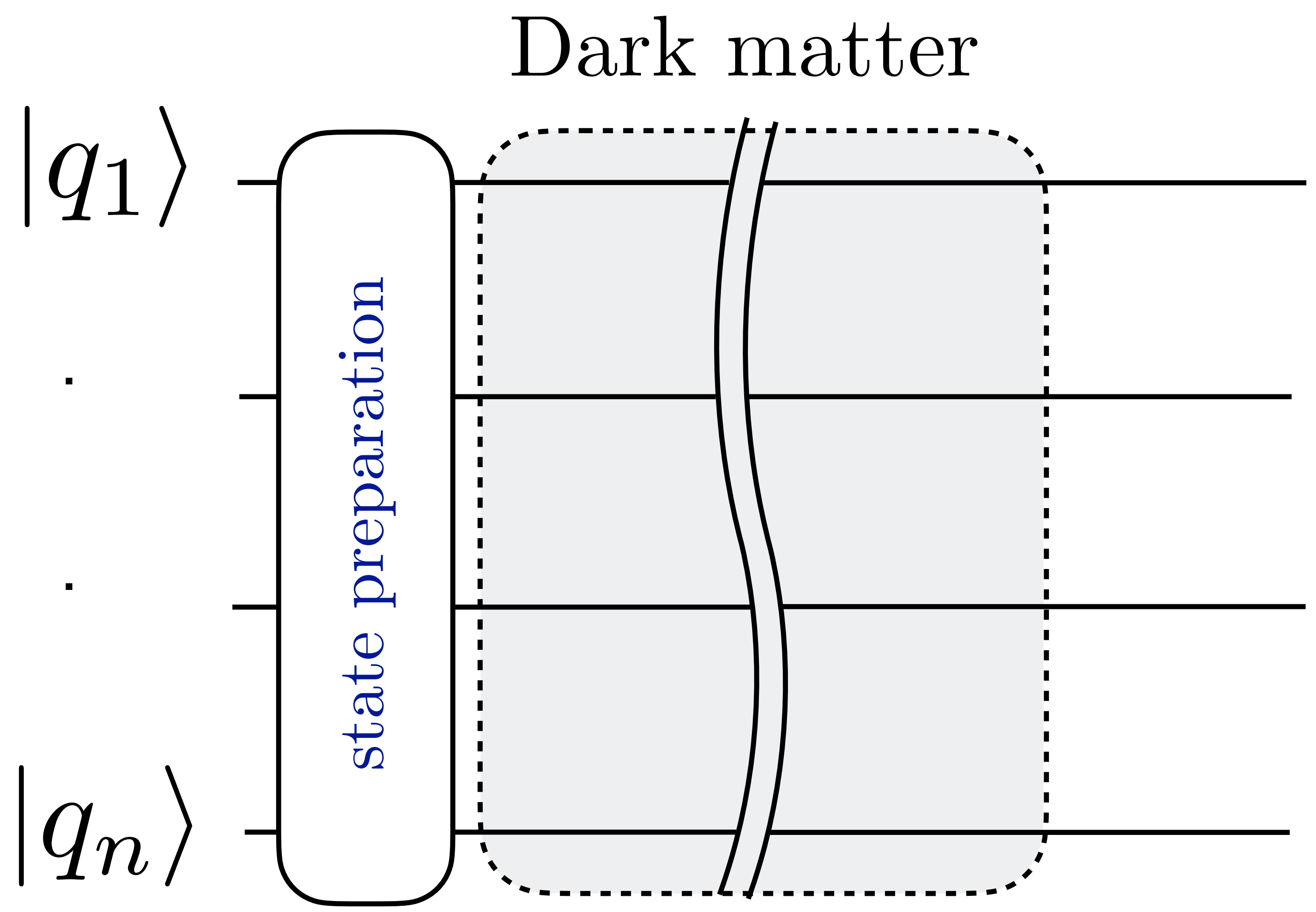

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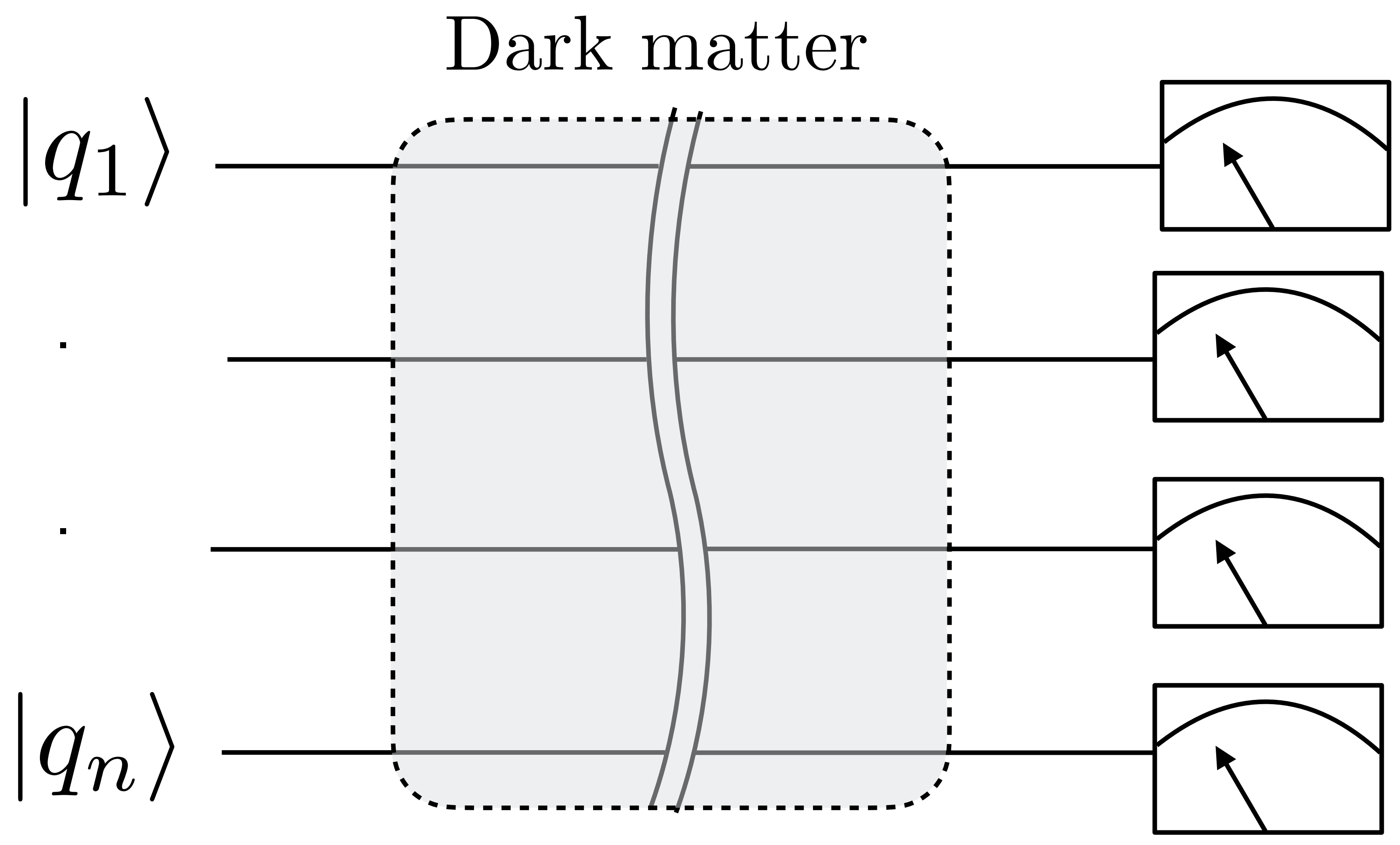

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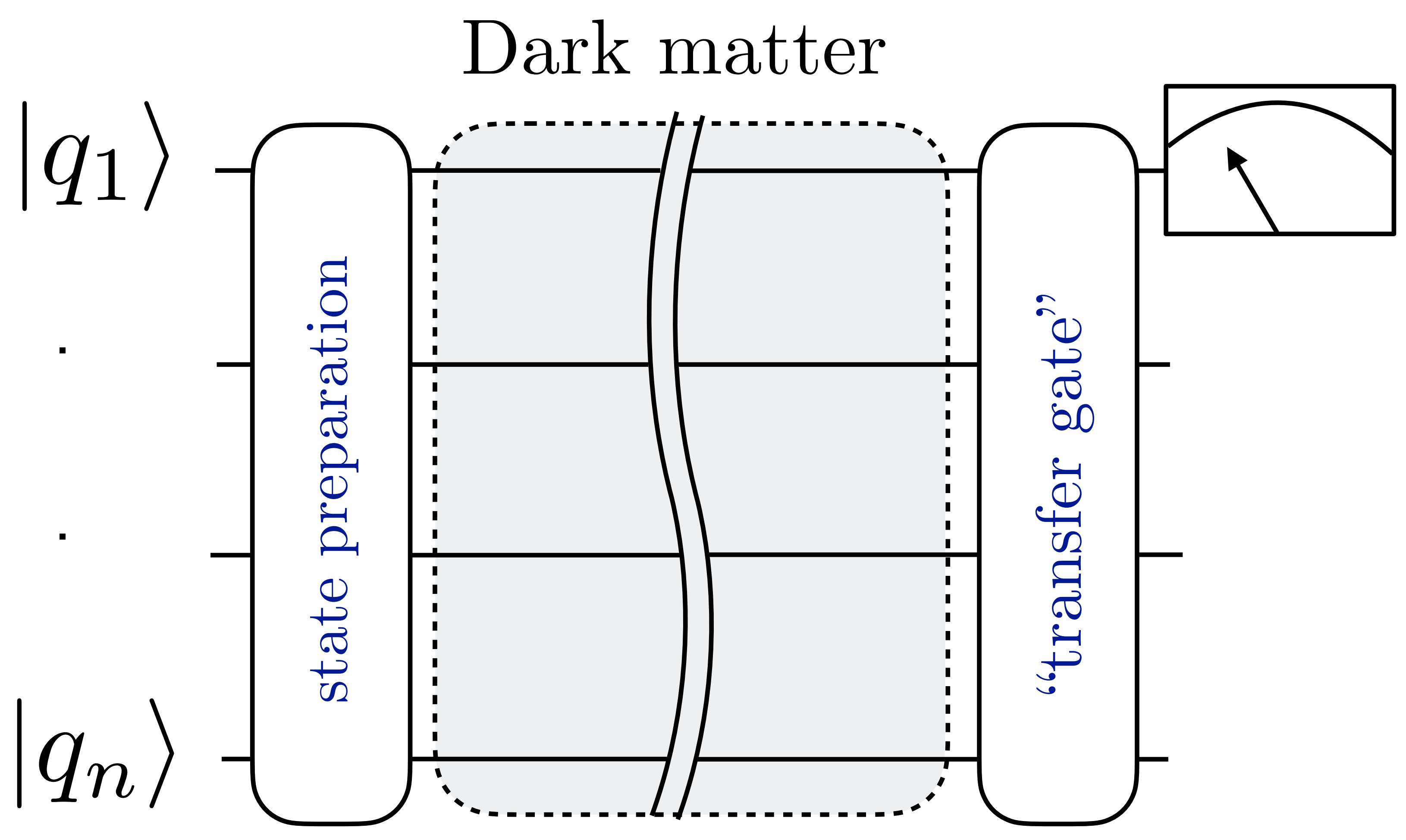

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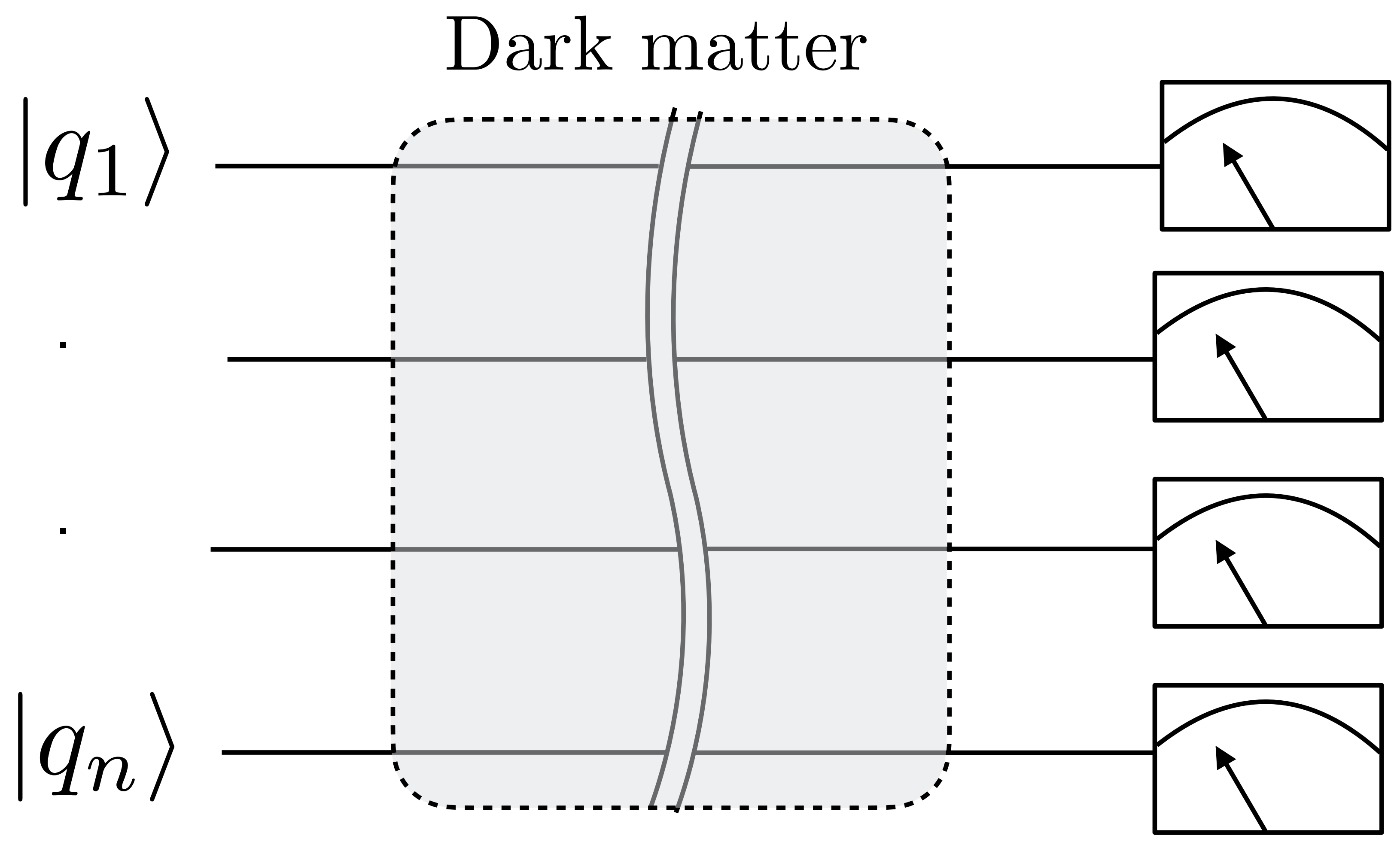
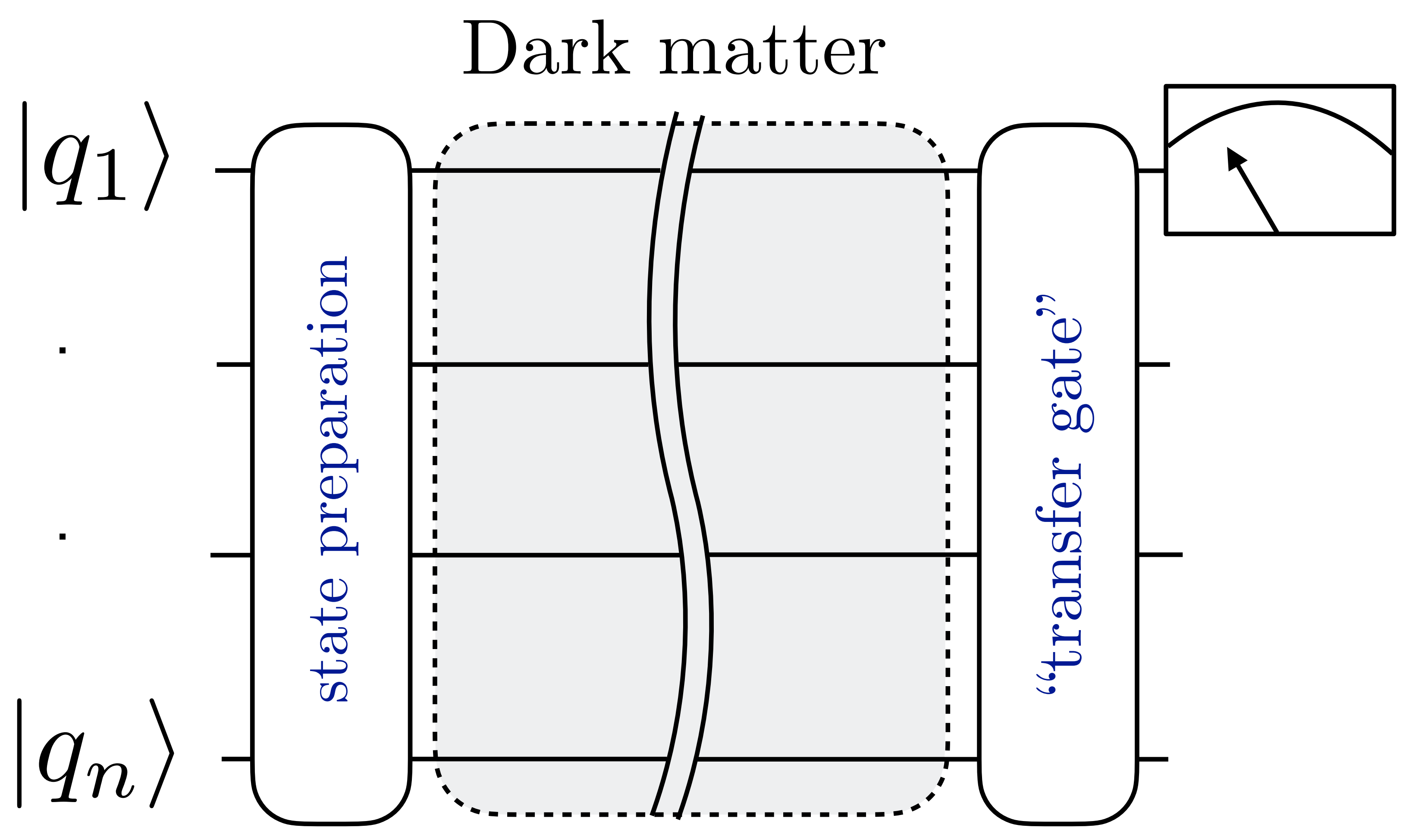


Rate scales as n.



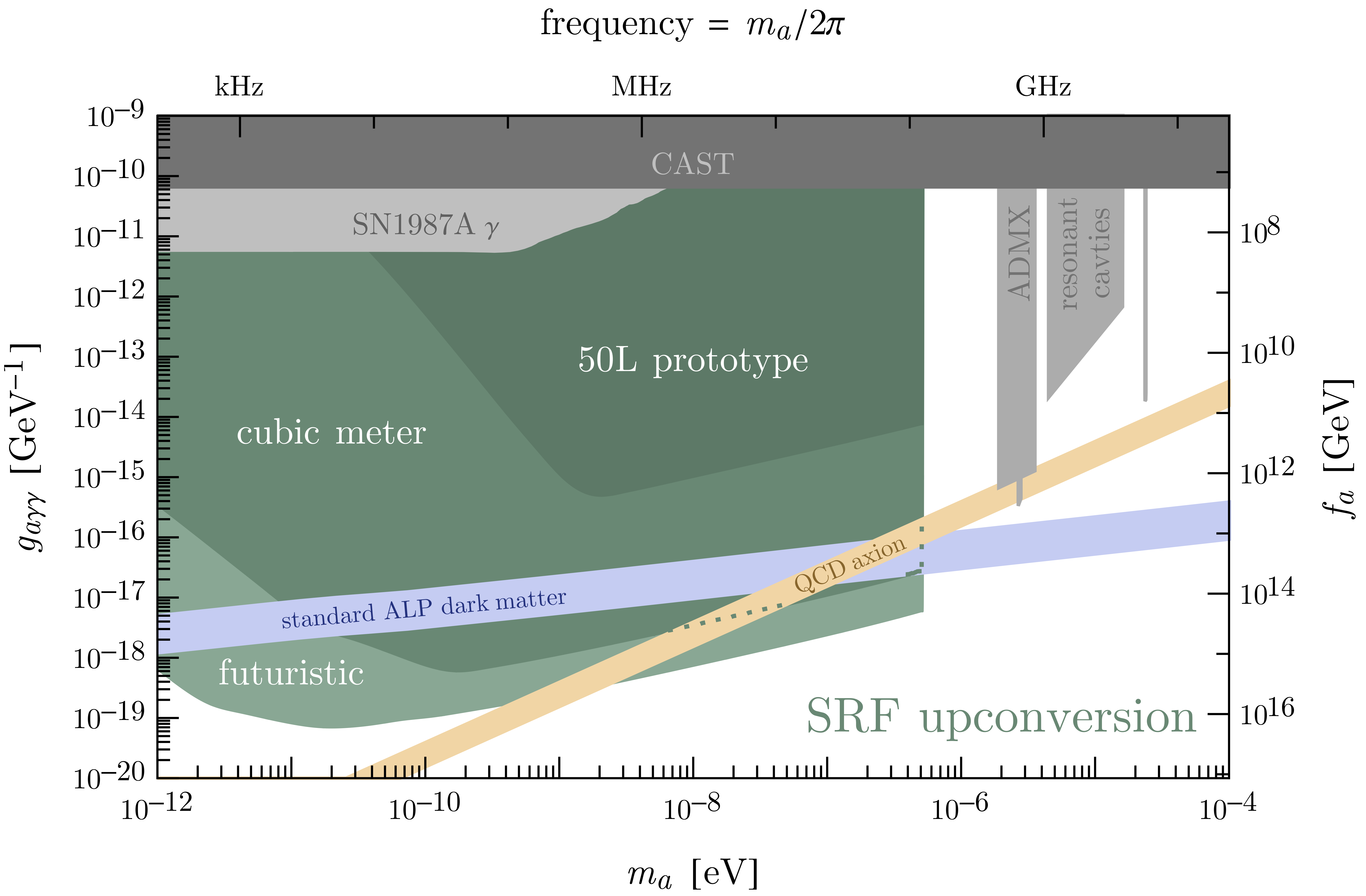
Which qubit interacted?
Amplitude scales as n.
Rate scales as n^2 !!

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

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

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)

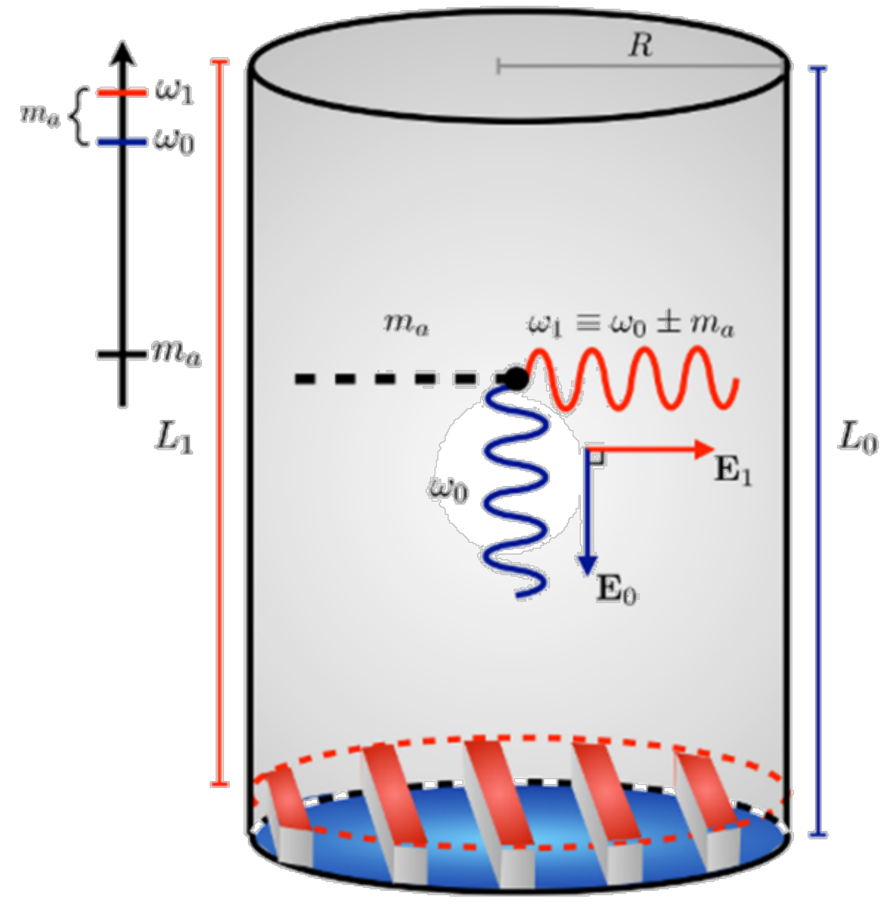


Snowmass name:

SRF-m³

Asher's proposal:

SuperRAD



Contacts: Asher Berlin, Bianca Giacone

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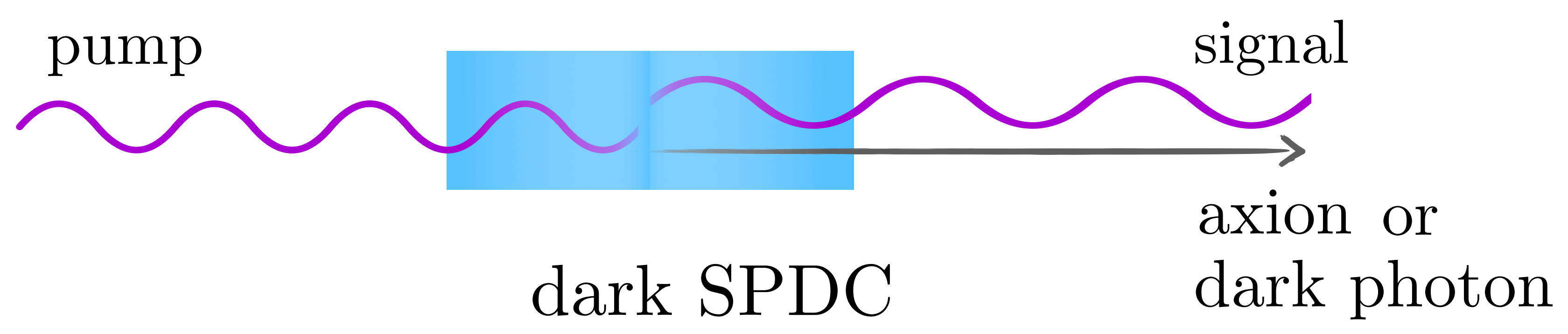
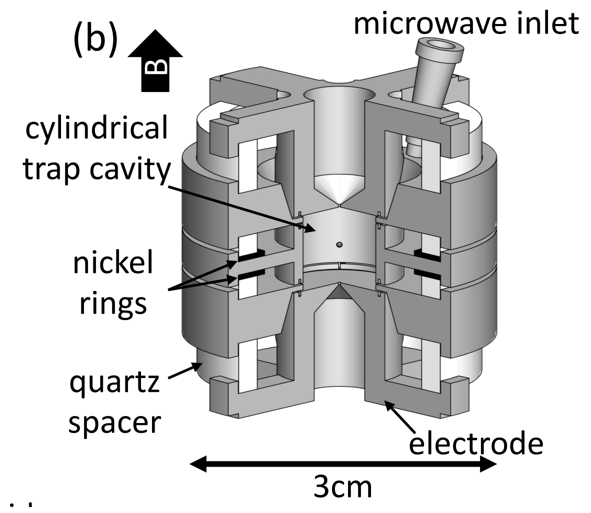
To Summarize

- QIS relies on extending the QFT formalism to devices that impose boundary conditions onto quantum fields.
- The low energy EFT of devices. For me, its is particle physics on small scales.
- BSM extensions of optics are simple well motivated targets, both linear (Dark photons) and nonlinear (Axions, GWs).
- New opportunities to exploit quantum for fundamental physics!

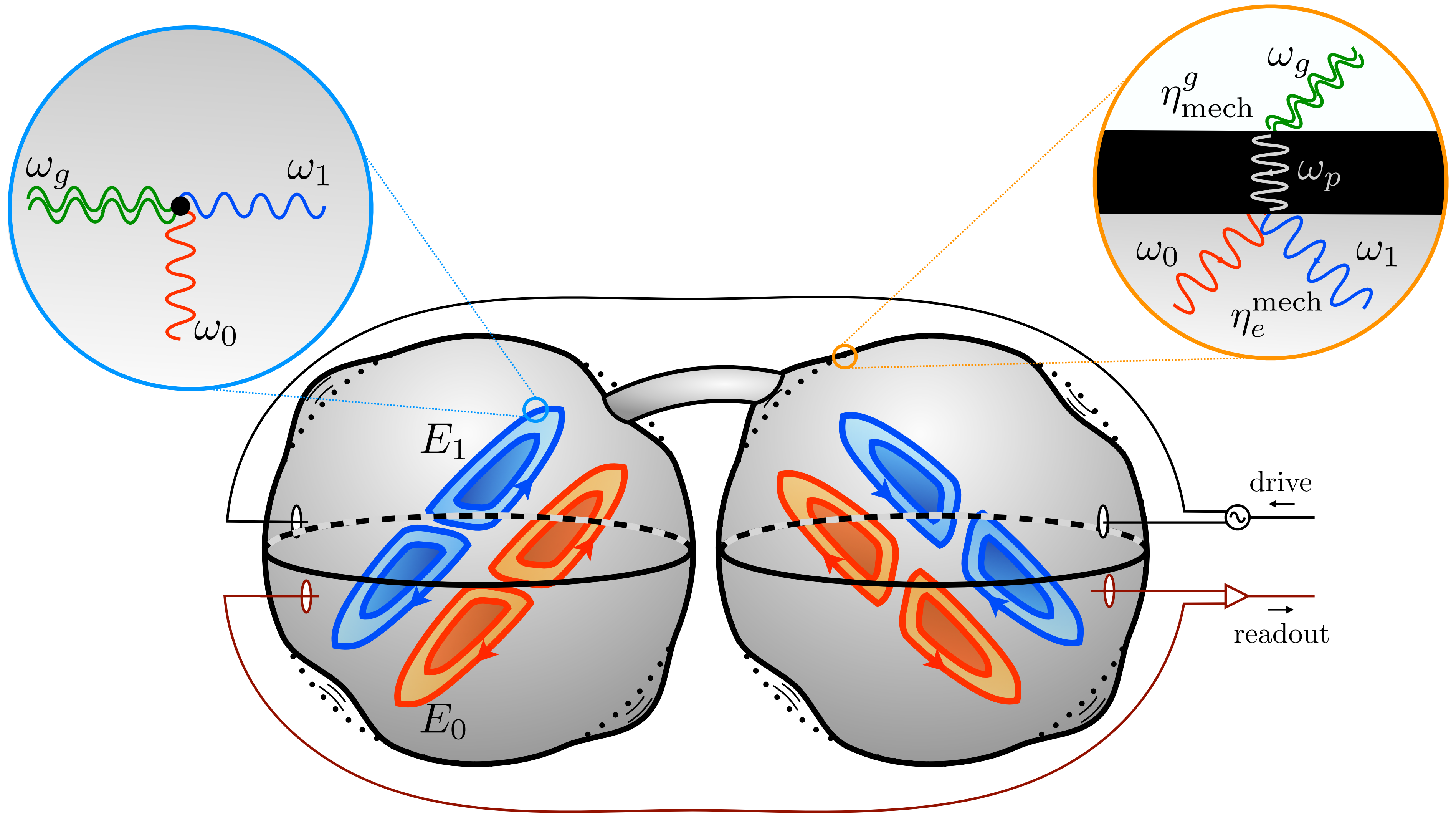




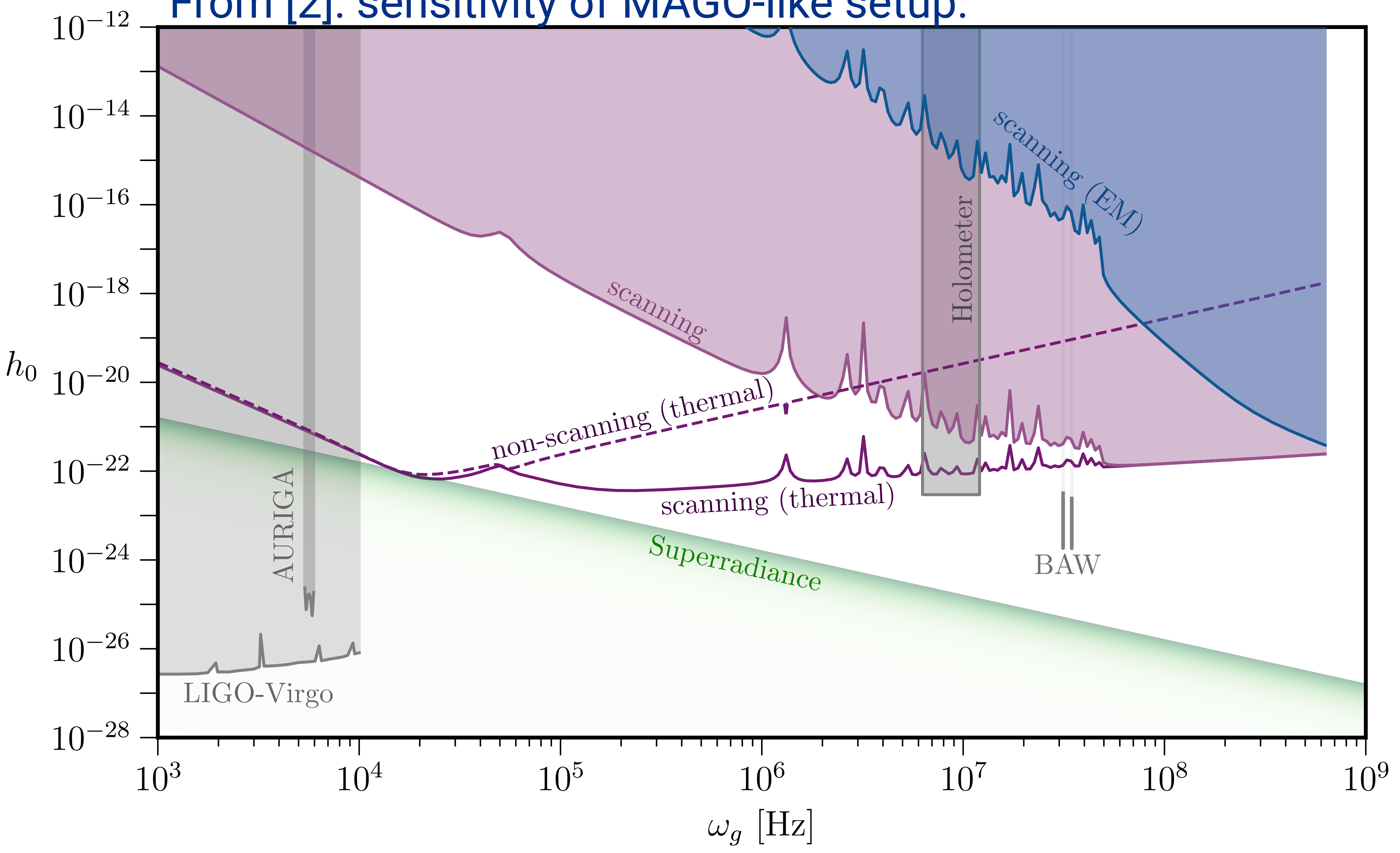
Deleted Scenes

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.

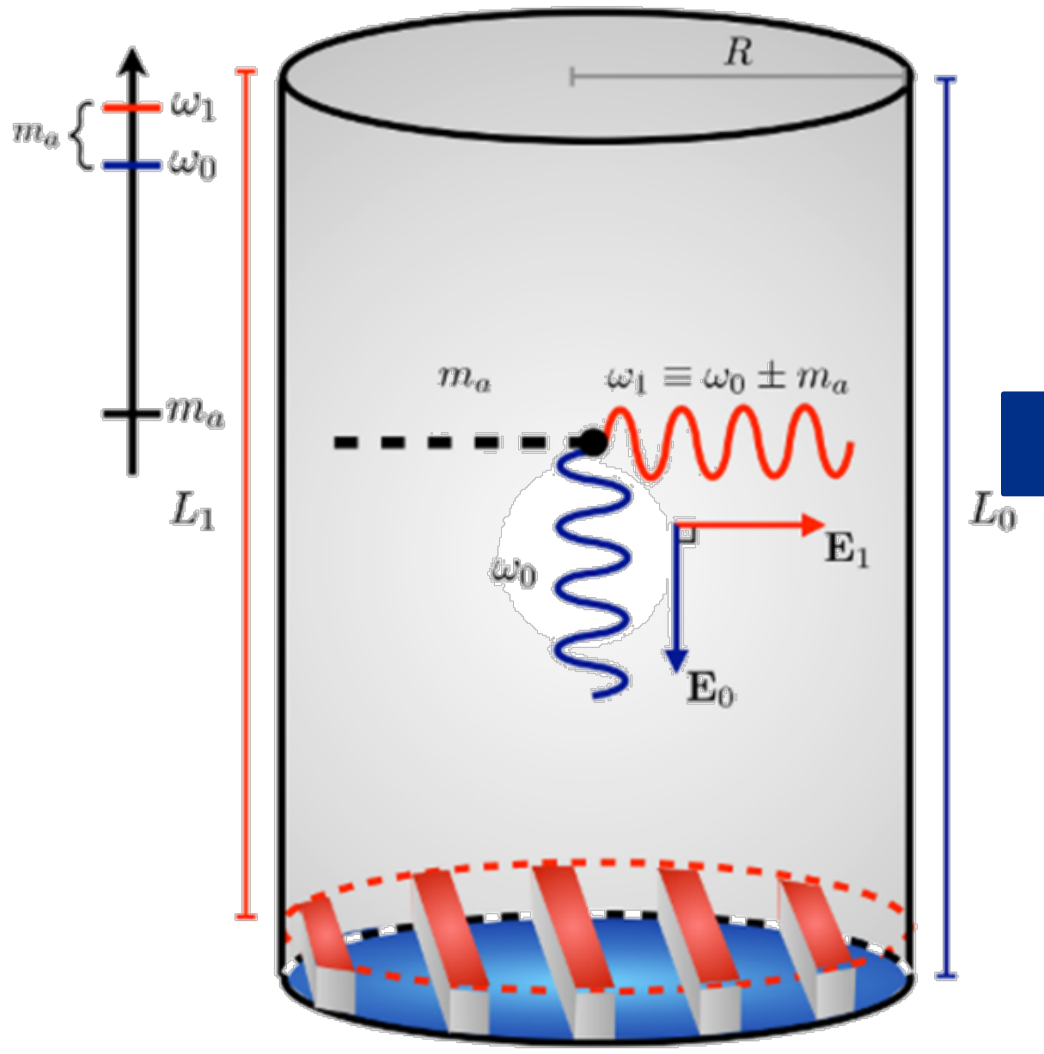


MAGO (INFN)

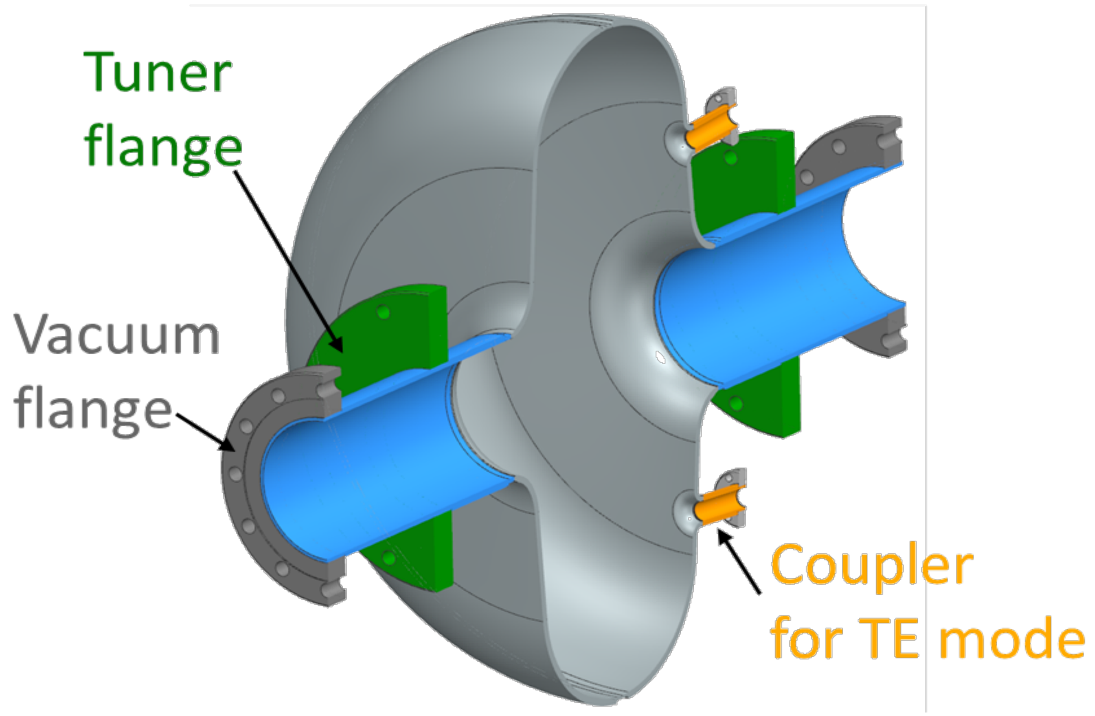
[1] *Phys.Rev.D* 105 (2022) 11, 116011
[2] *Phys.Rev.D* 108 (2023) 8, 084058

Multimode searches

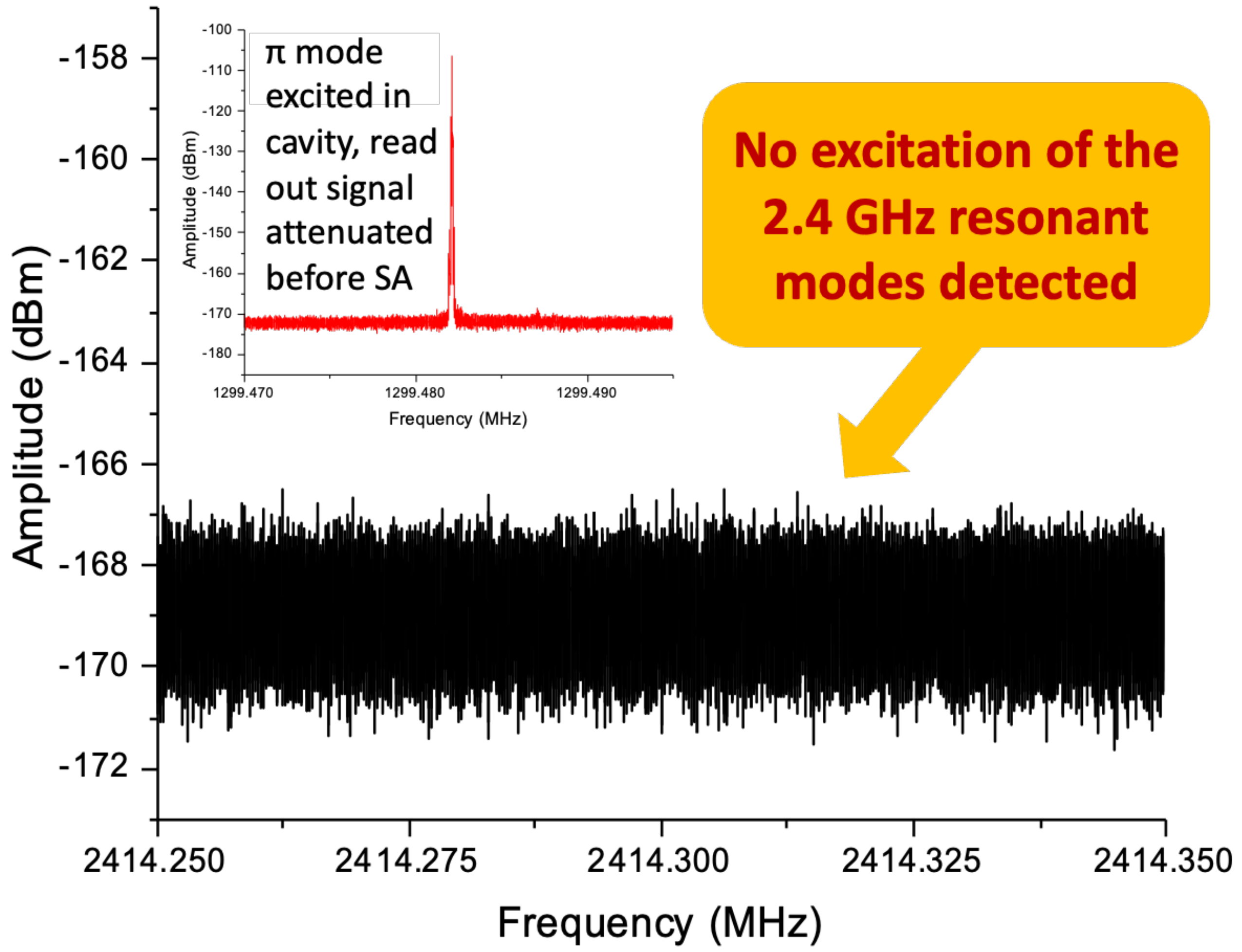
Bogorad, et al., PRL, DOI:10.1103/PhysRevLett.123.021801
Berlin, et al., JHEP, DOI:10.1007/JHEP07 (2020) 088
Gao & Harnik, JHEP, DOI:10.1007/JHEP07 (2021) 053
Berlin, et al., arXiv:2203.12714, Snowmass WP (2022)
Sauls, PTEP, DOI:10.1093/ptep/ptac034 (2022)
Giaccone, et al., arXiv:2207.11346 (2022)



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

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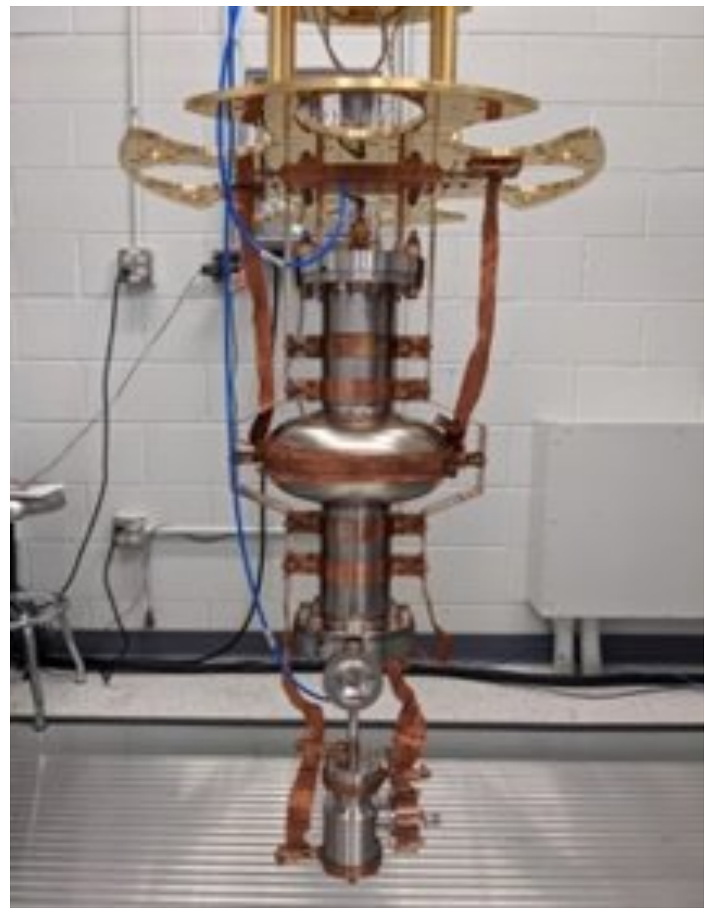
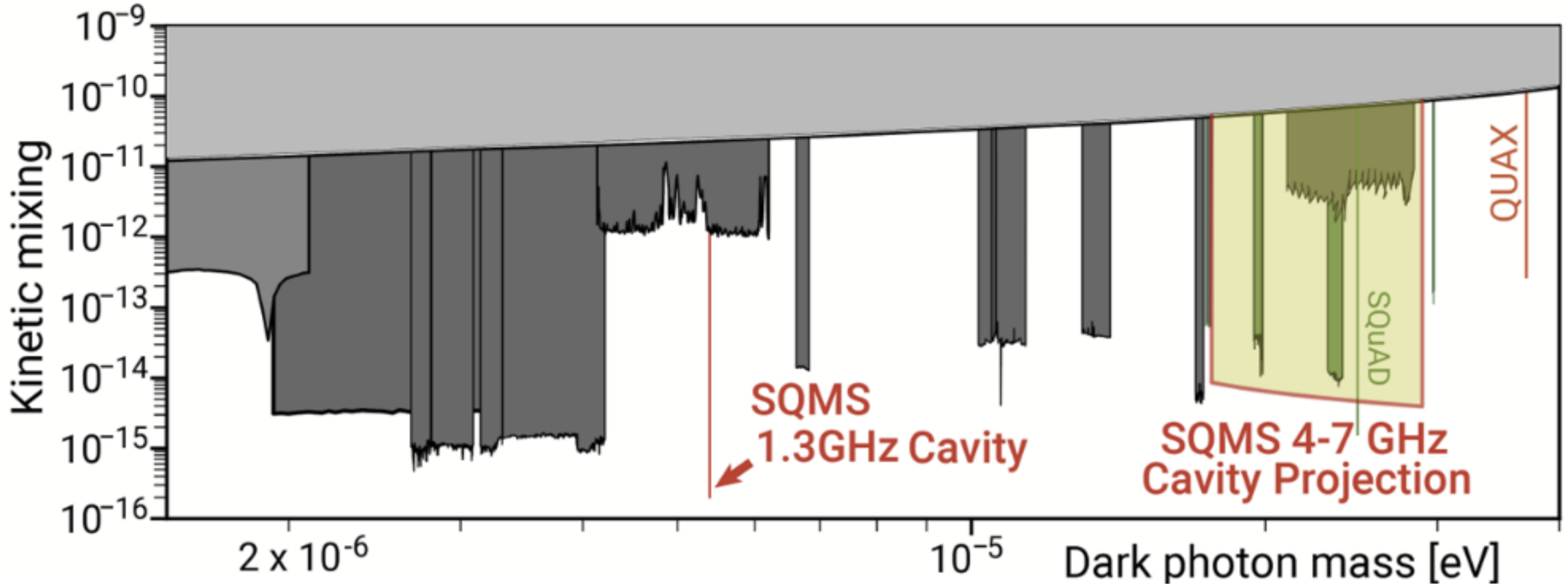
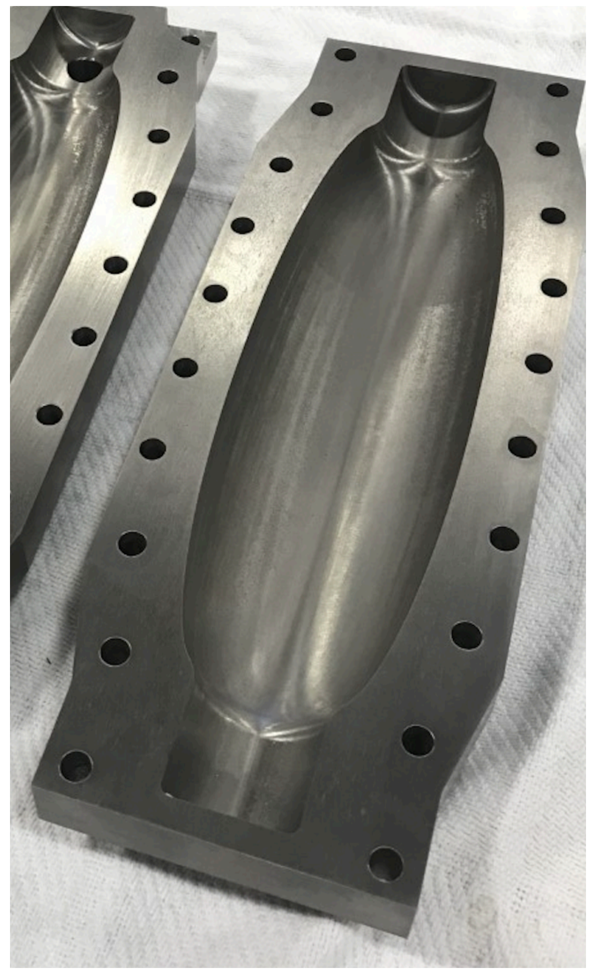
Ultrahigh Q for Dark Matter

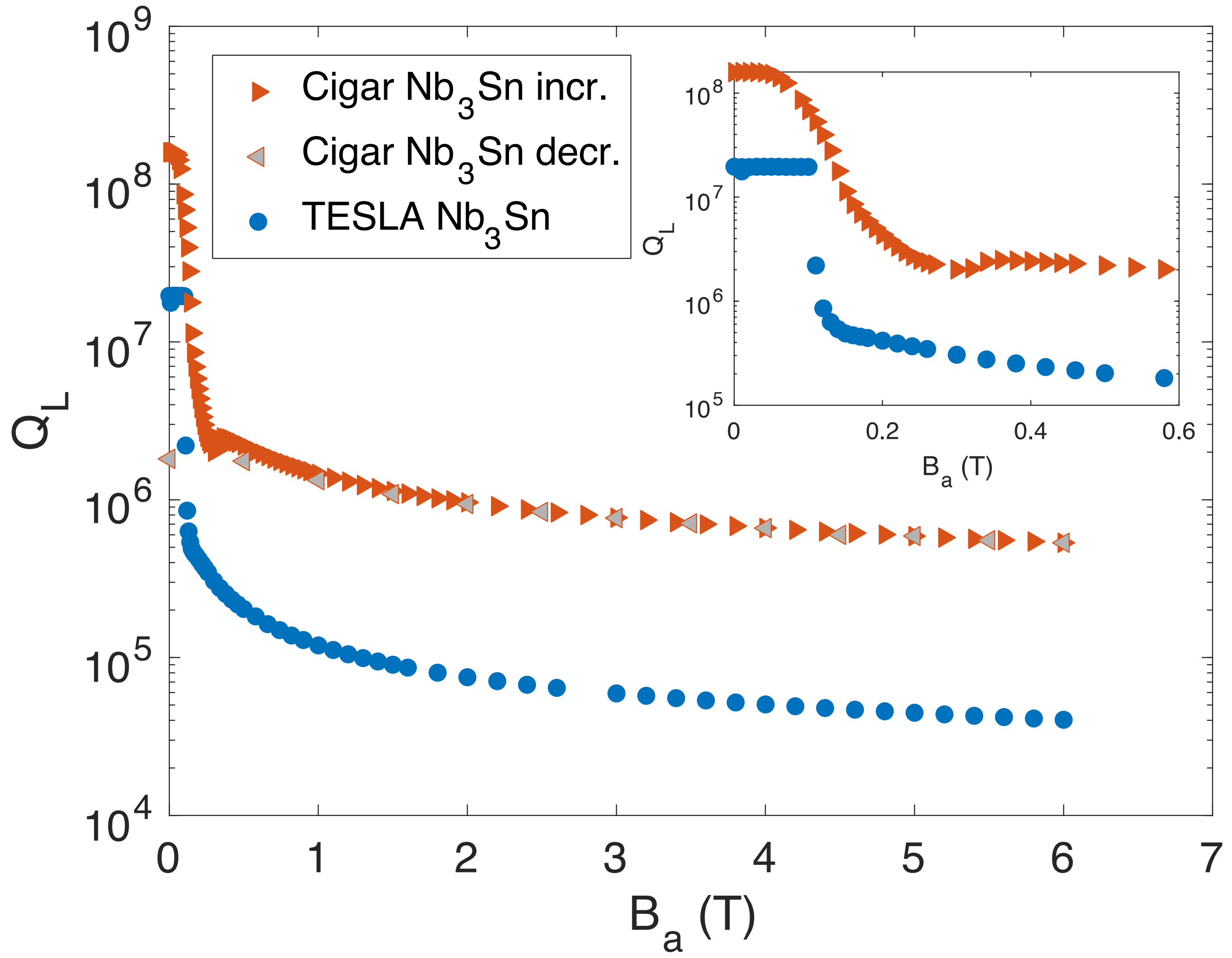




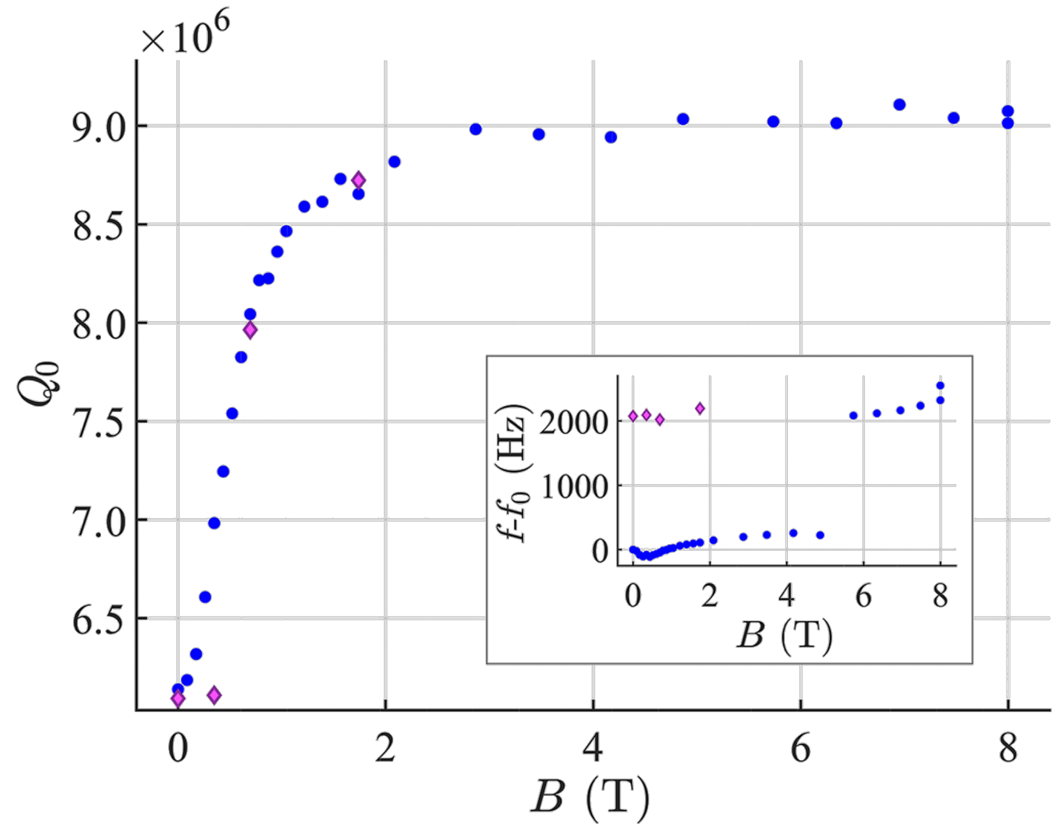
Cervantes et al., arxiv:2208.03183, in review in Phys. Rev. Lett.

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





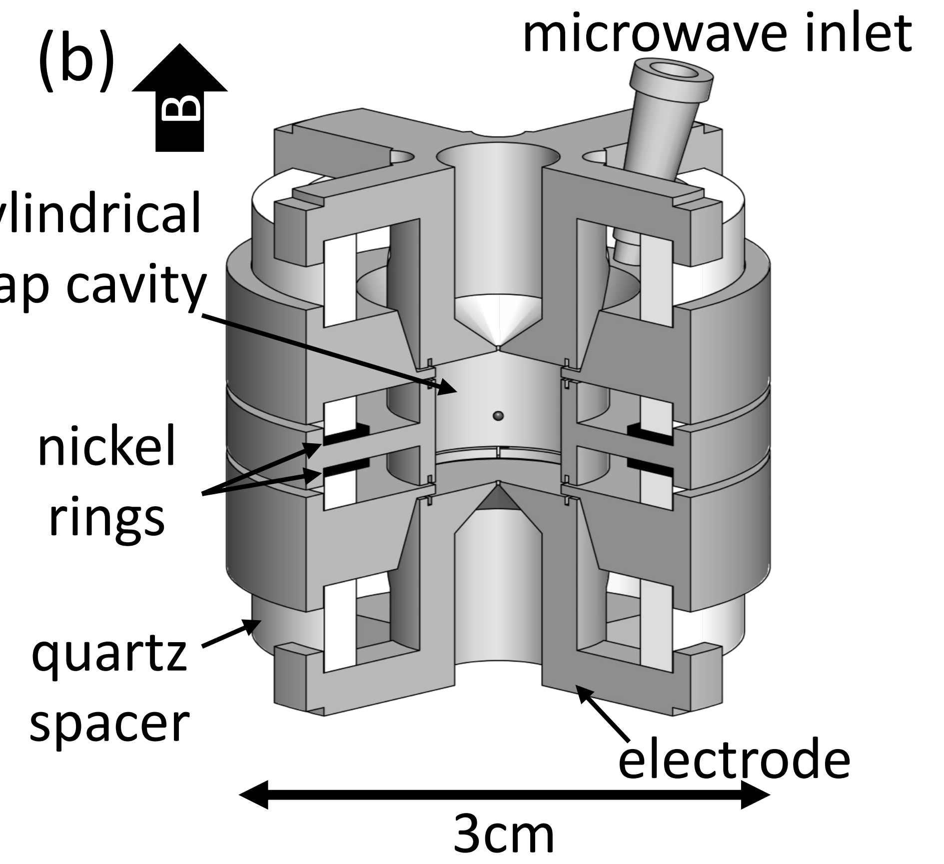
Superconducting Nb_3Sn cavity (FNAL): Posen et al., arxiv:22014.10733, in review in Phys Rev Applied



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

With B-Field: $Q \geq 10^{5\text{-}7}$

Single Particle Qubit



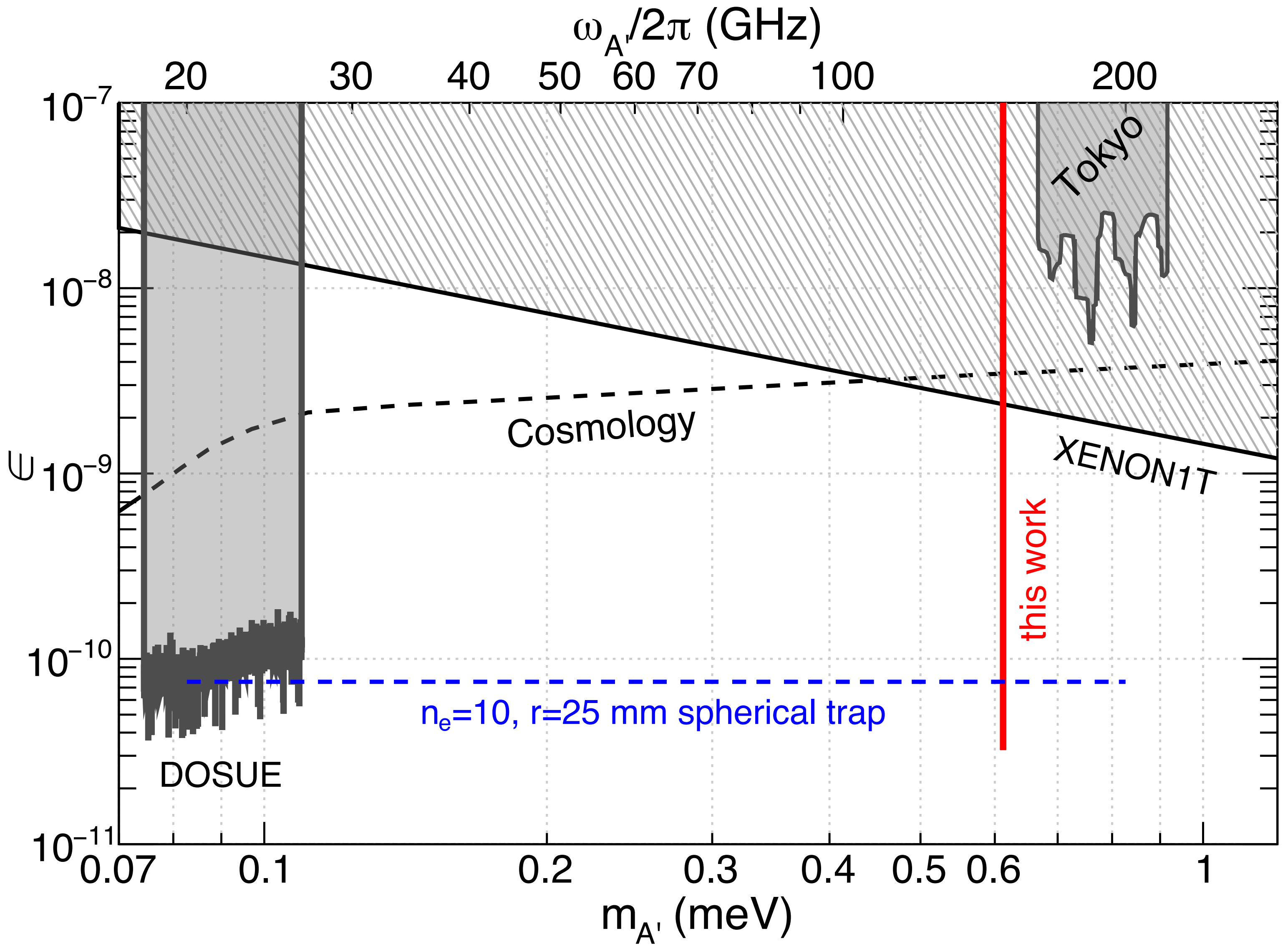
- The most precise theory-experiment comparison in physics:

  Electron magnetic moment (g-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)*](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.130.071801)
Editors choice!

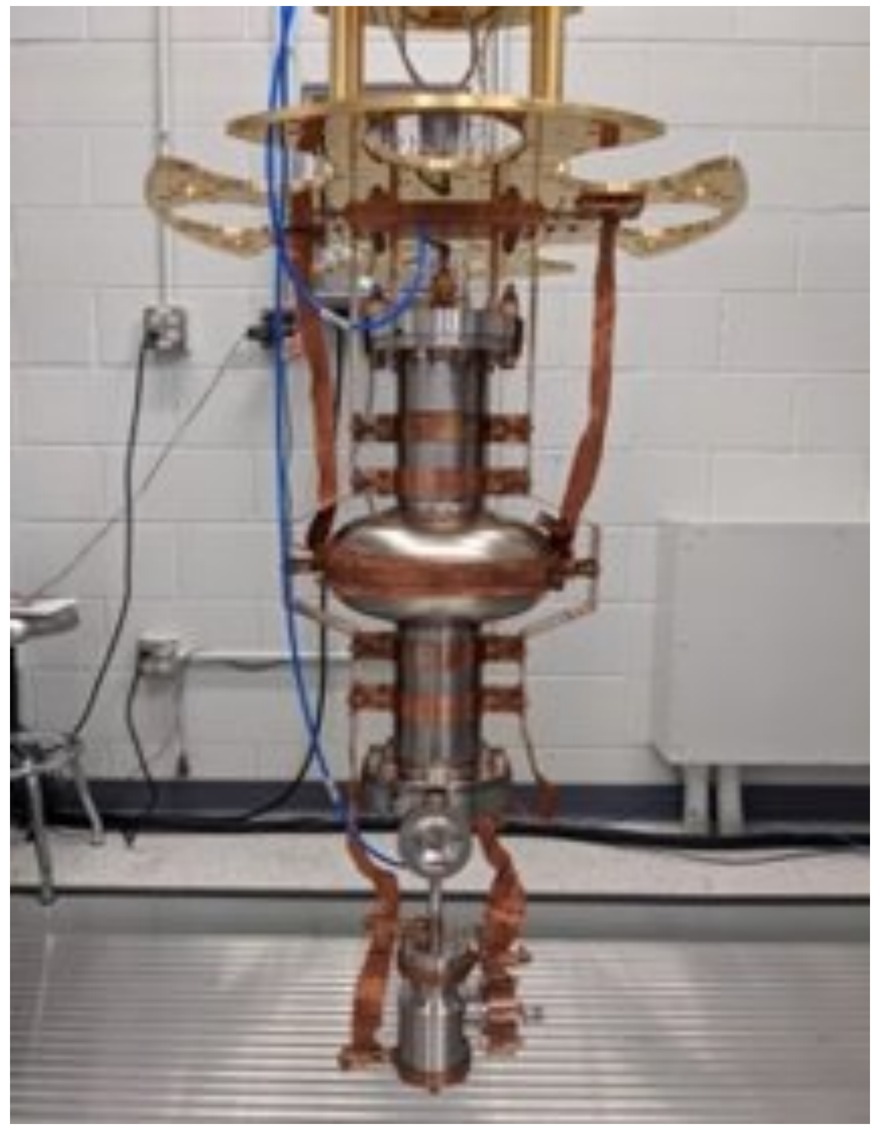
- SQMS joined the effort, contributed to understanding loss sources.

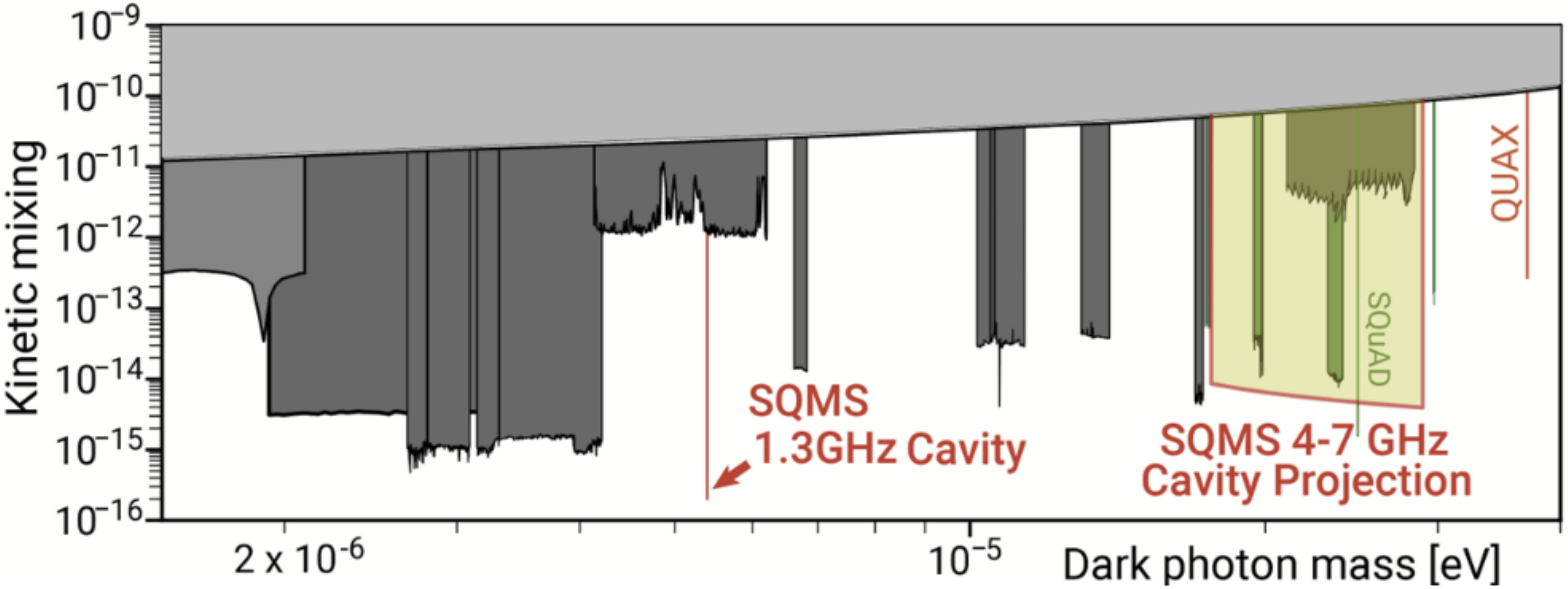


- **SQMS bonus:** We also found that a single-electron qubit is a sensitive DM search in a challenging frequency range!
- Theory + proof-of-concept!

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

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.

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