Fundamental Physics Questions for Quantum Technology (and vice versa)

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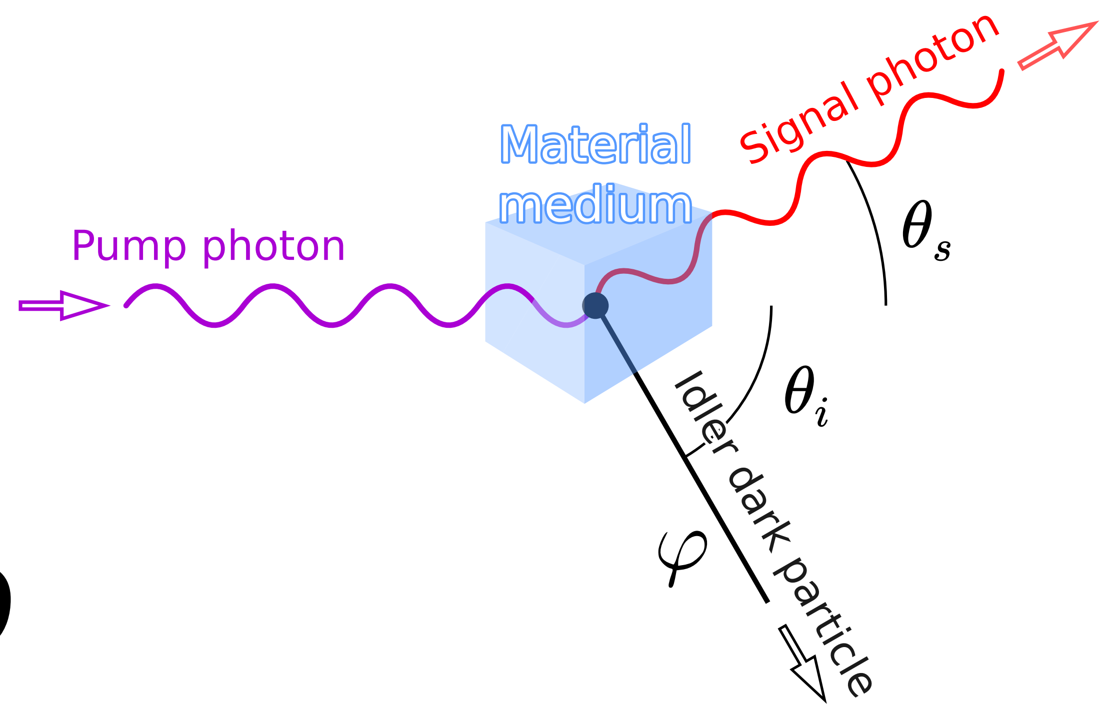
SQMS



Fermilab SQMS ***DOE QuatISED***

In the past week we learnt about amazing quantum technology, present and future achievements.

We learnt this at Fermilab, the US particle physics lab.

What's the connection, QIS to HEP?

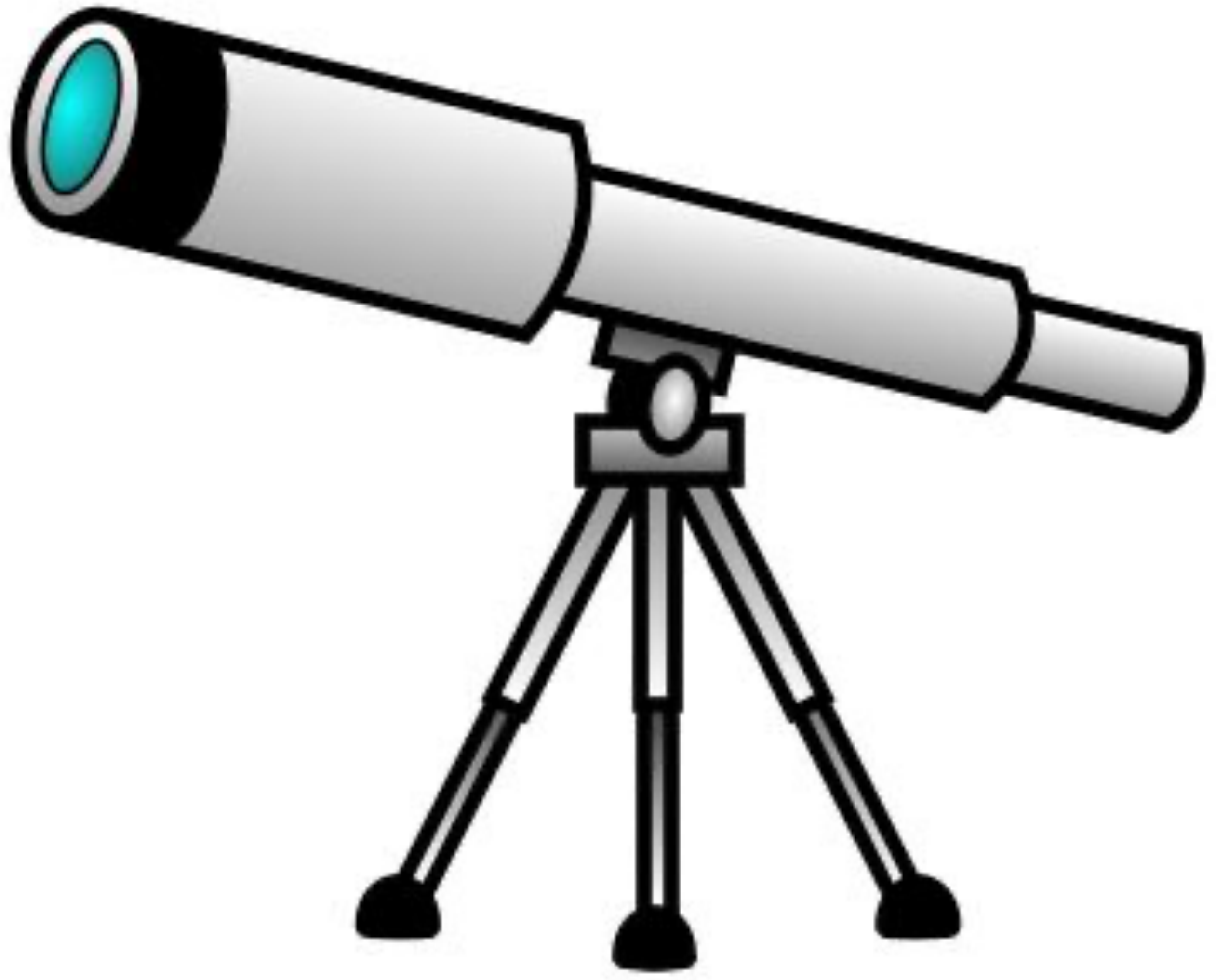
Why are we excited? How can HEP use Quantum?

What drives HEP? What's the language that we use?

We are Curious!!!

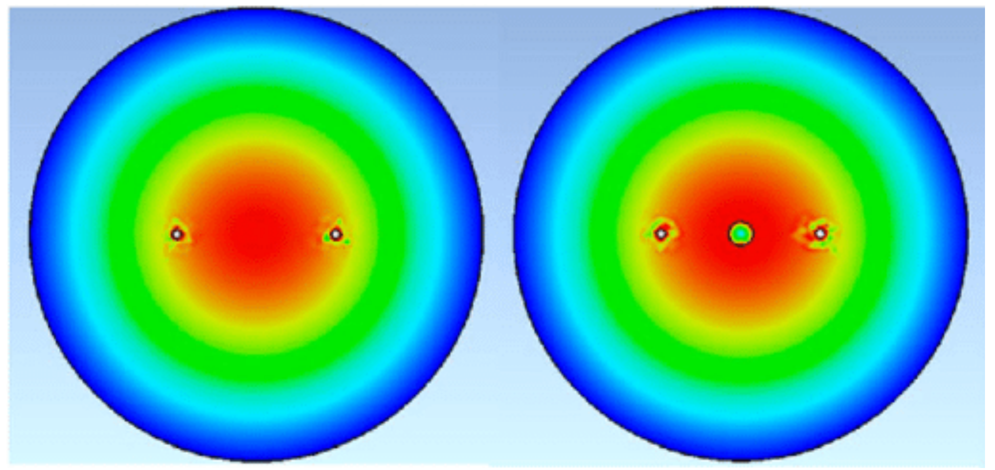
What are the basic degrees of freedom?
What rules do they follow?

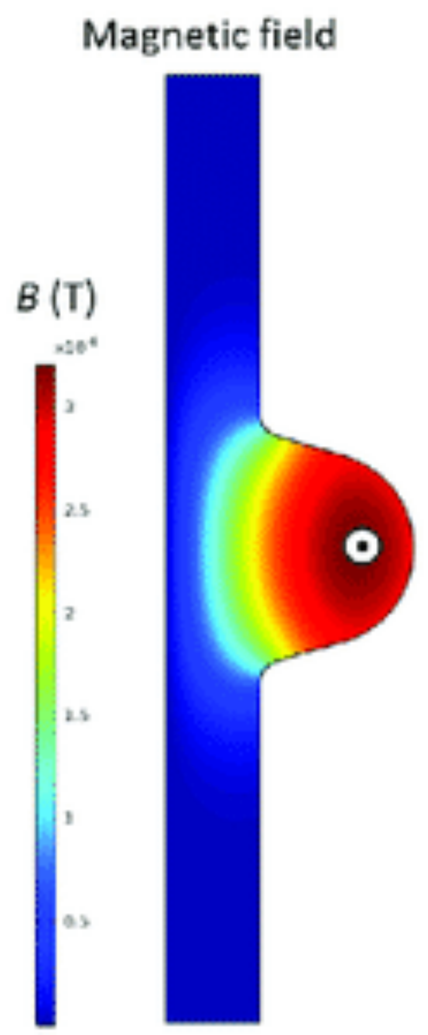
What does the Universe contain?
What is its history?



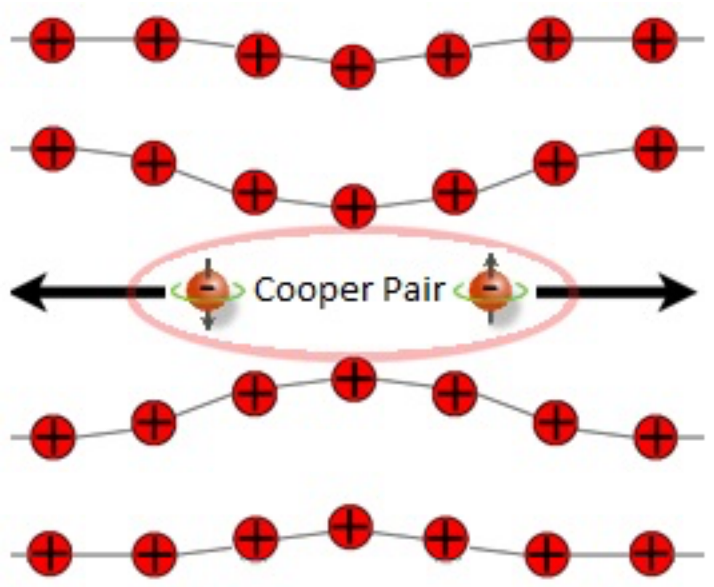
Particles that Star in a QIS school

- Photons (and electromagnetic fileds):

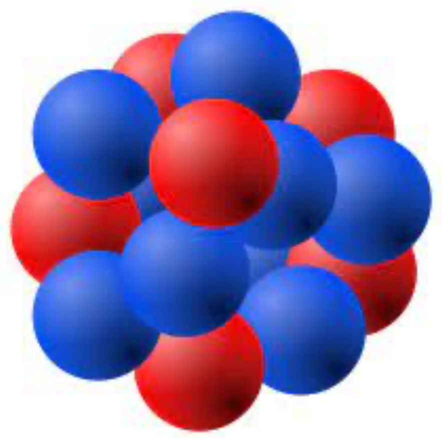




- Electrons: carry charge, combine to Cooper pairs, EM properties of matter.



- Nuclei: supposing actors in QIS, but enable everything!

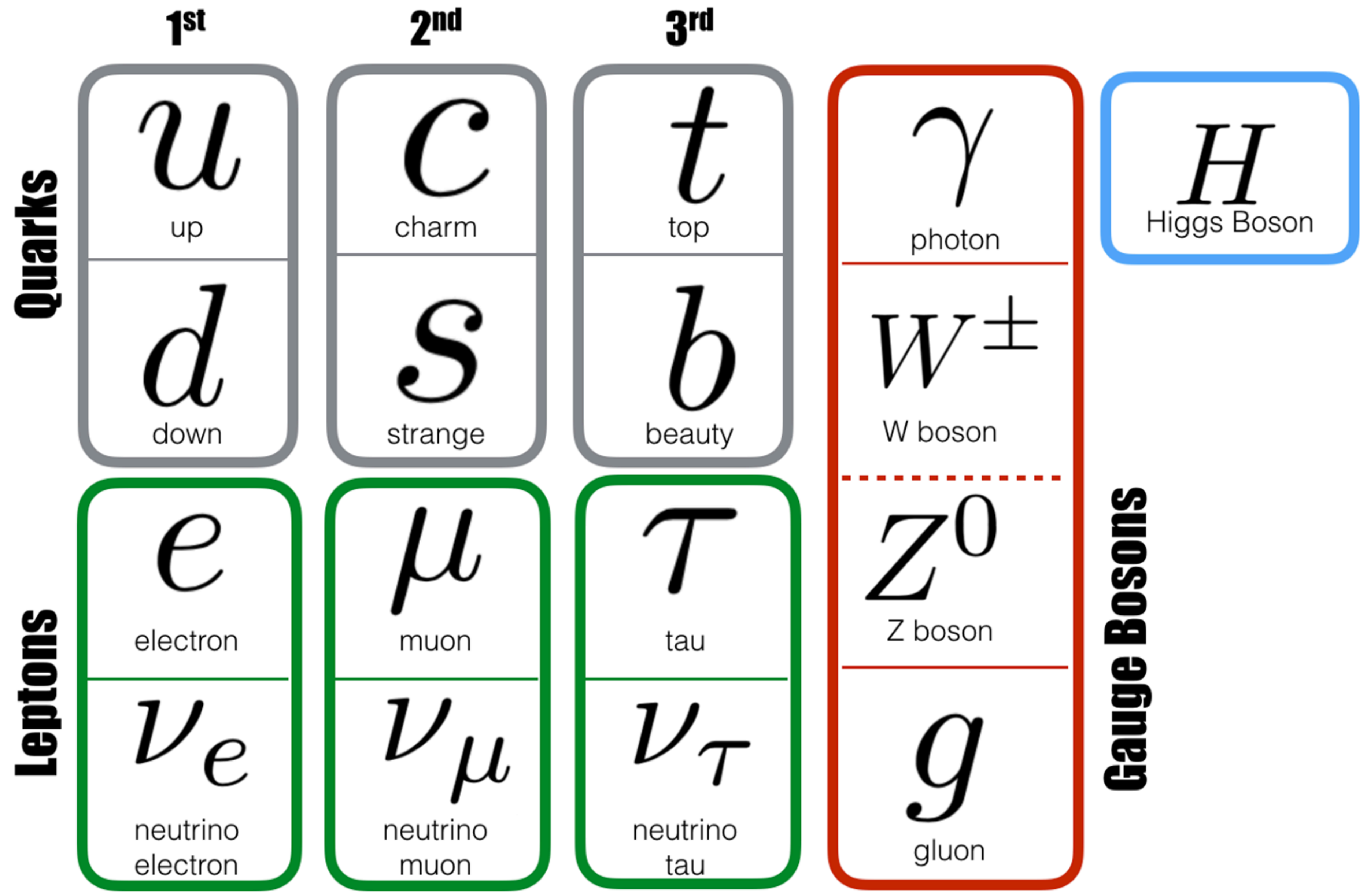


Si, Nb, Cu, He, ….

The Standard Model of Particle Physics

Decades of experiments have taught us of an interesting menu of particles and interactions:

Accelarators, colliders, detectors, neutrino experiments, cosmic rays…



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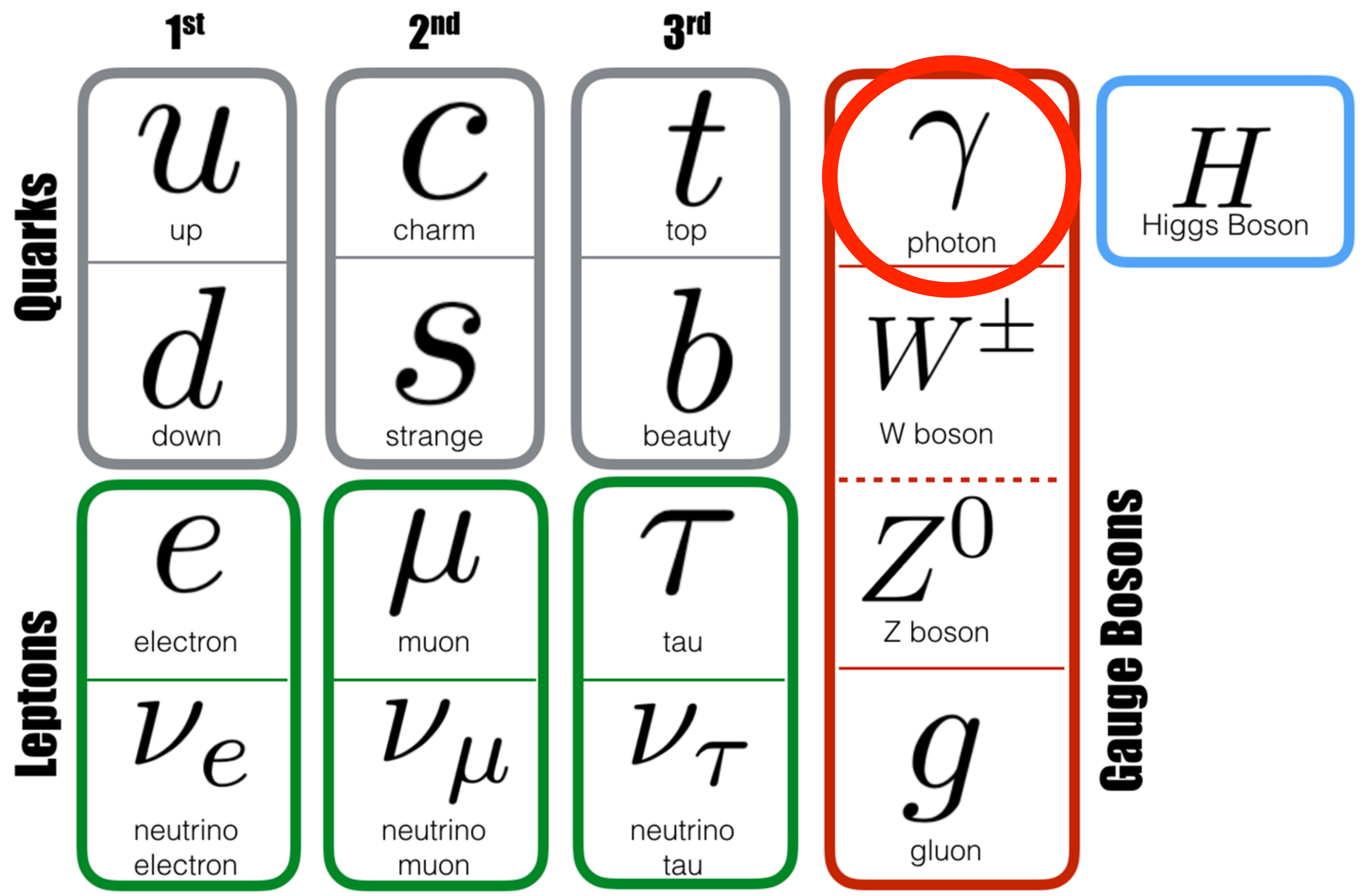

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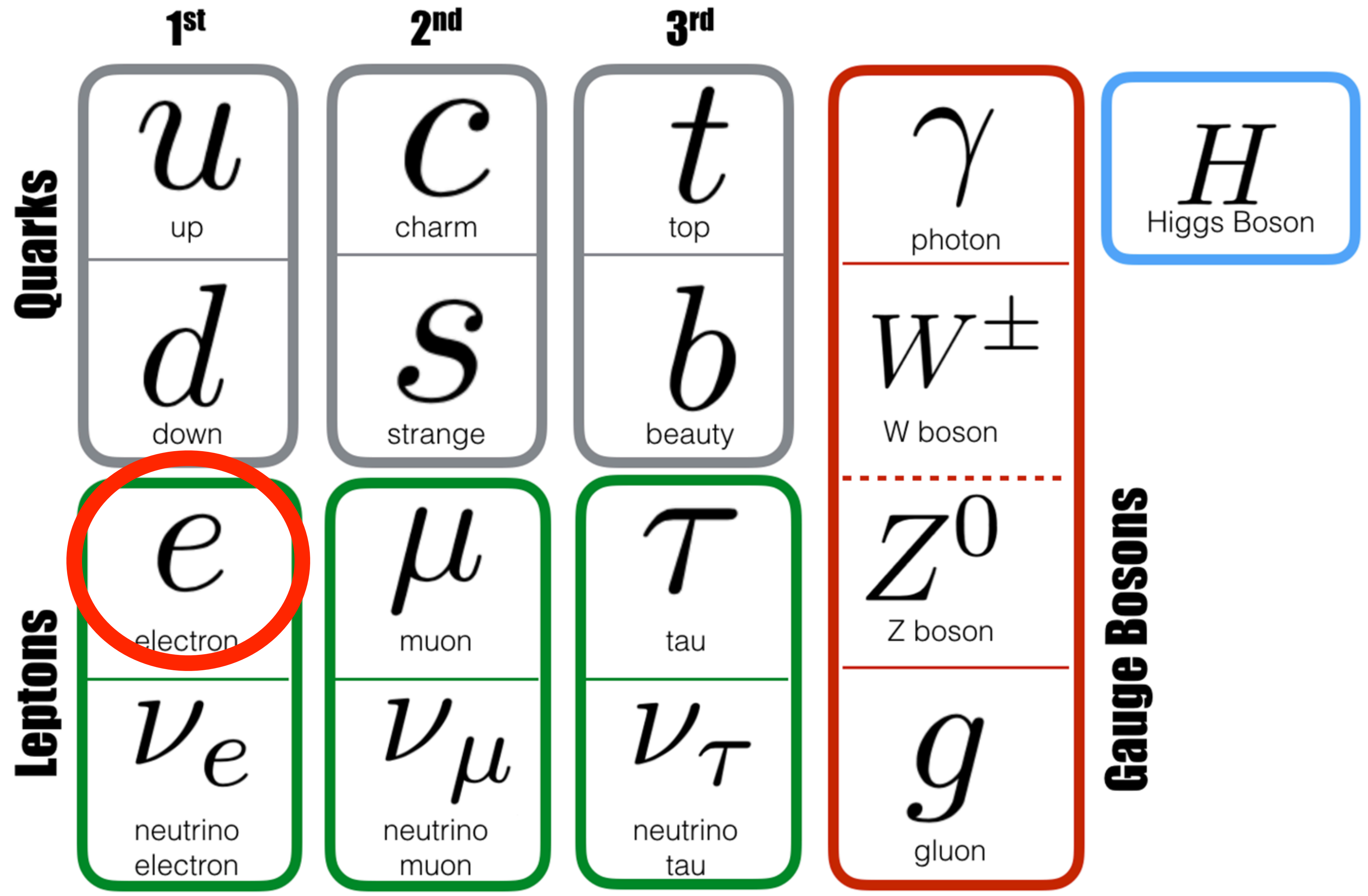

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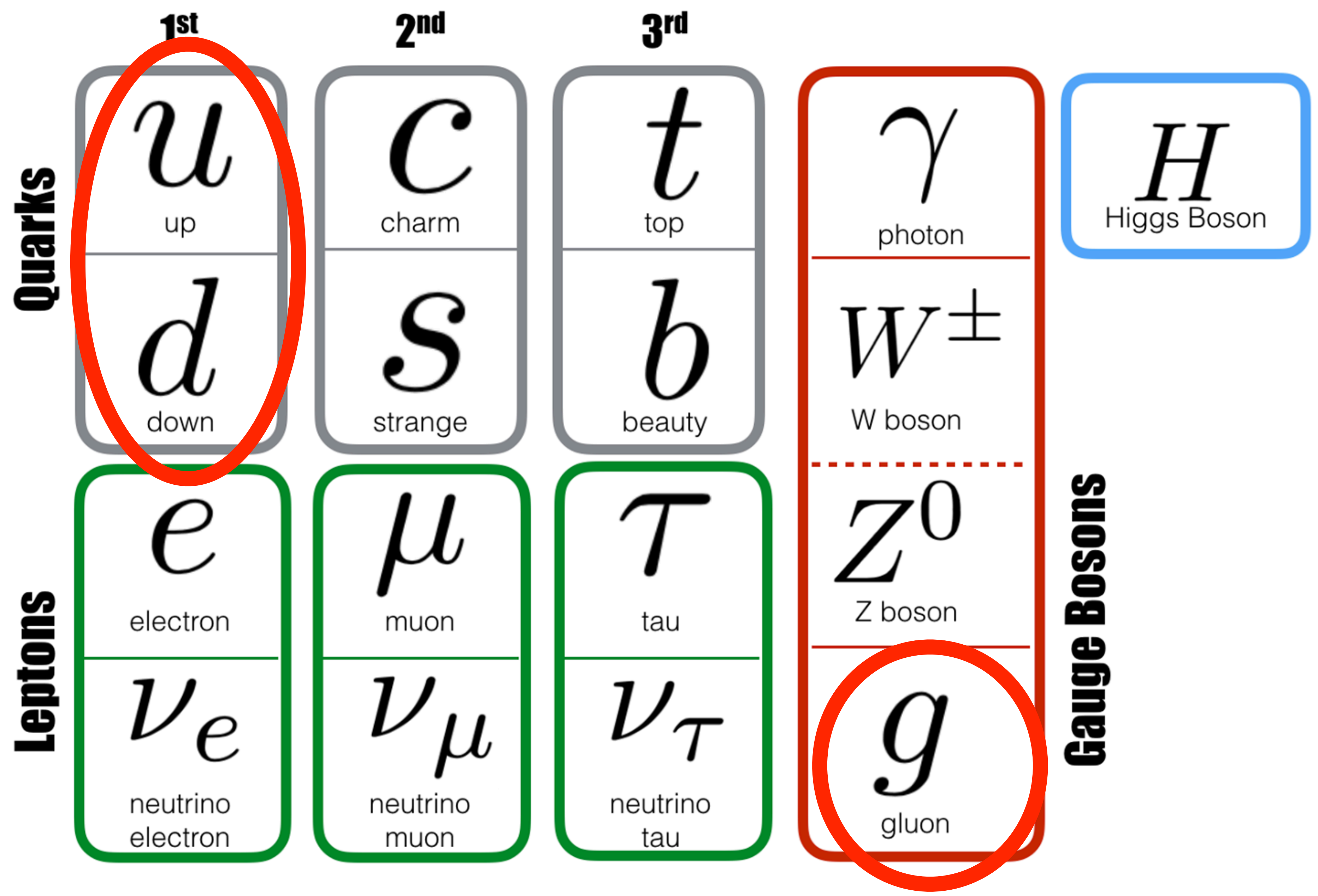

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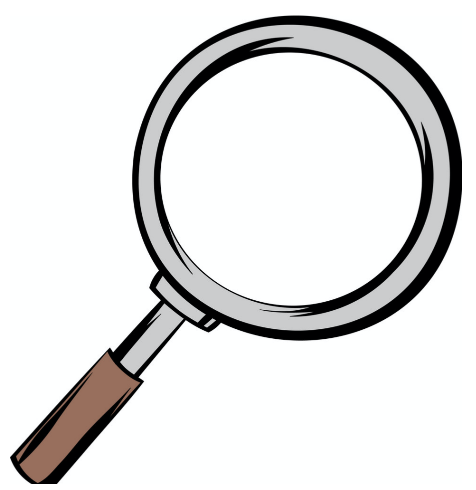

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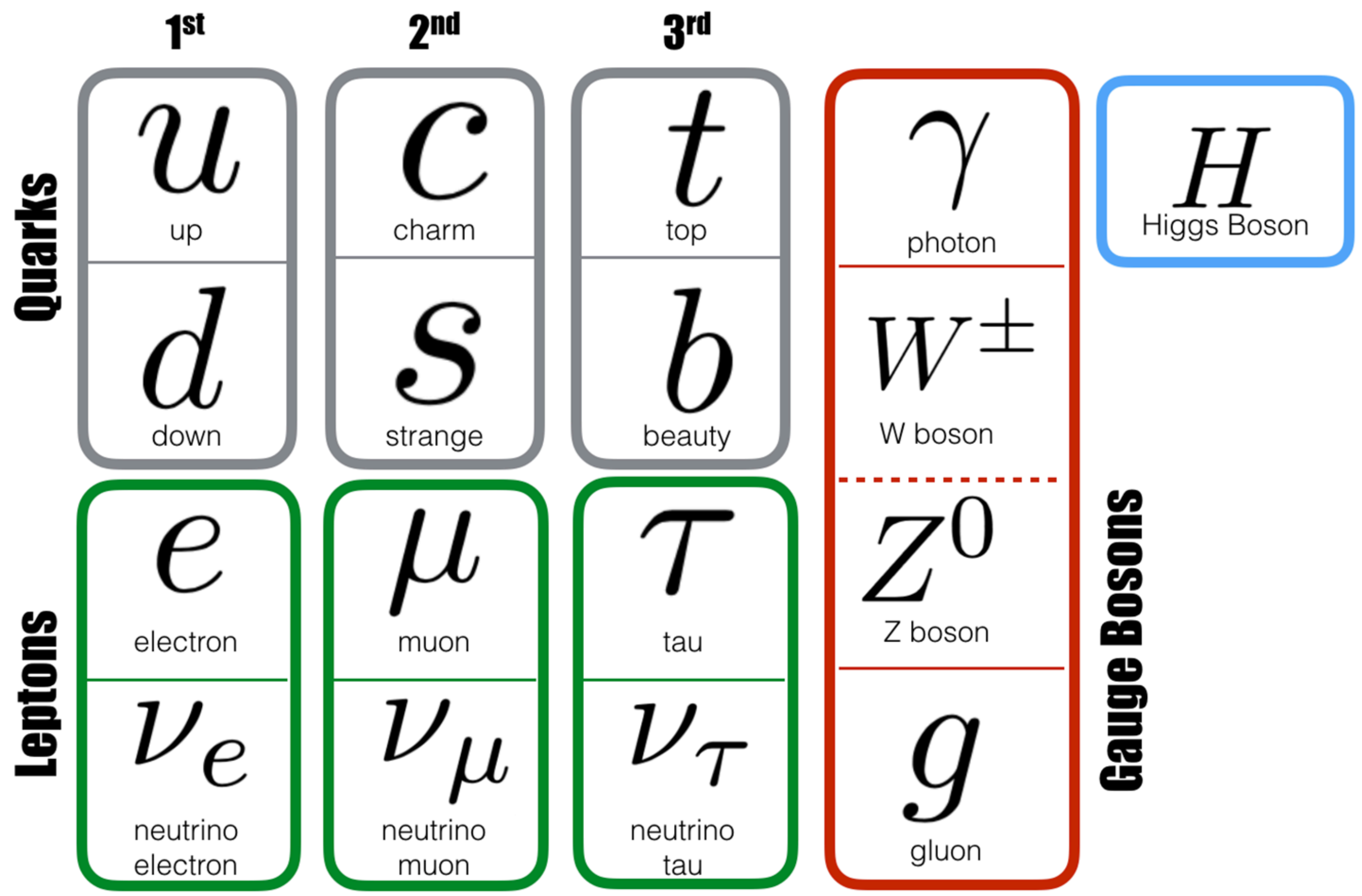

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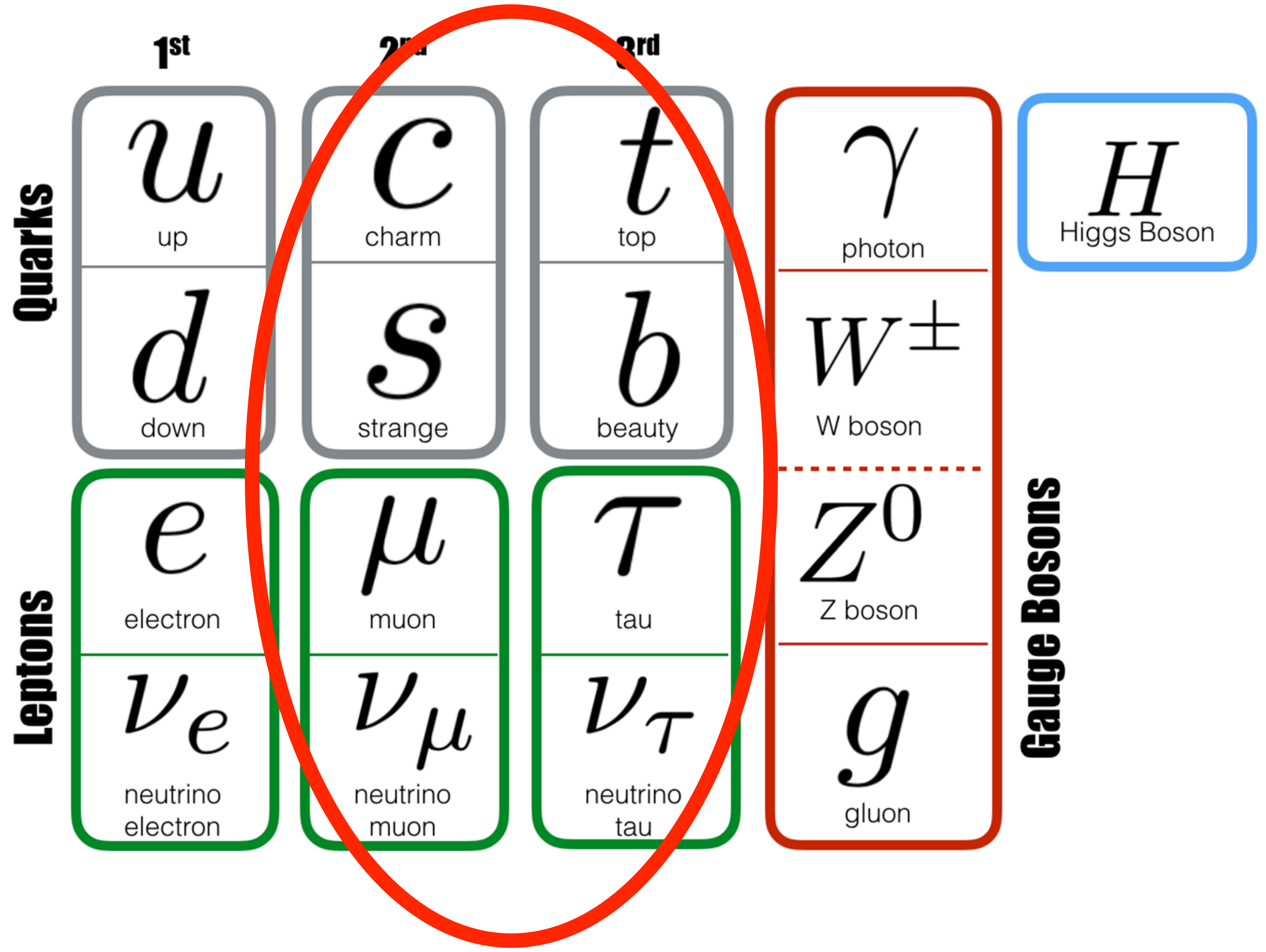

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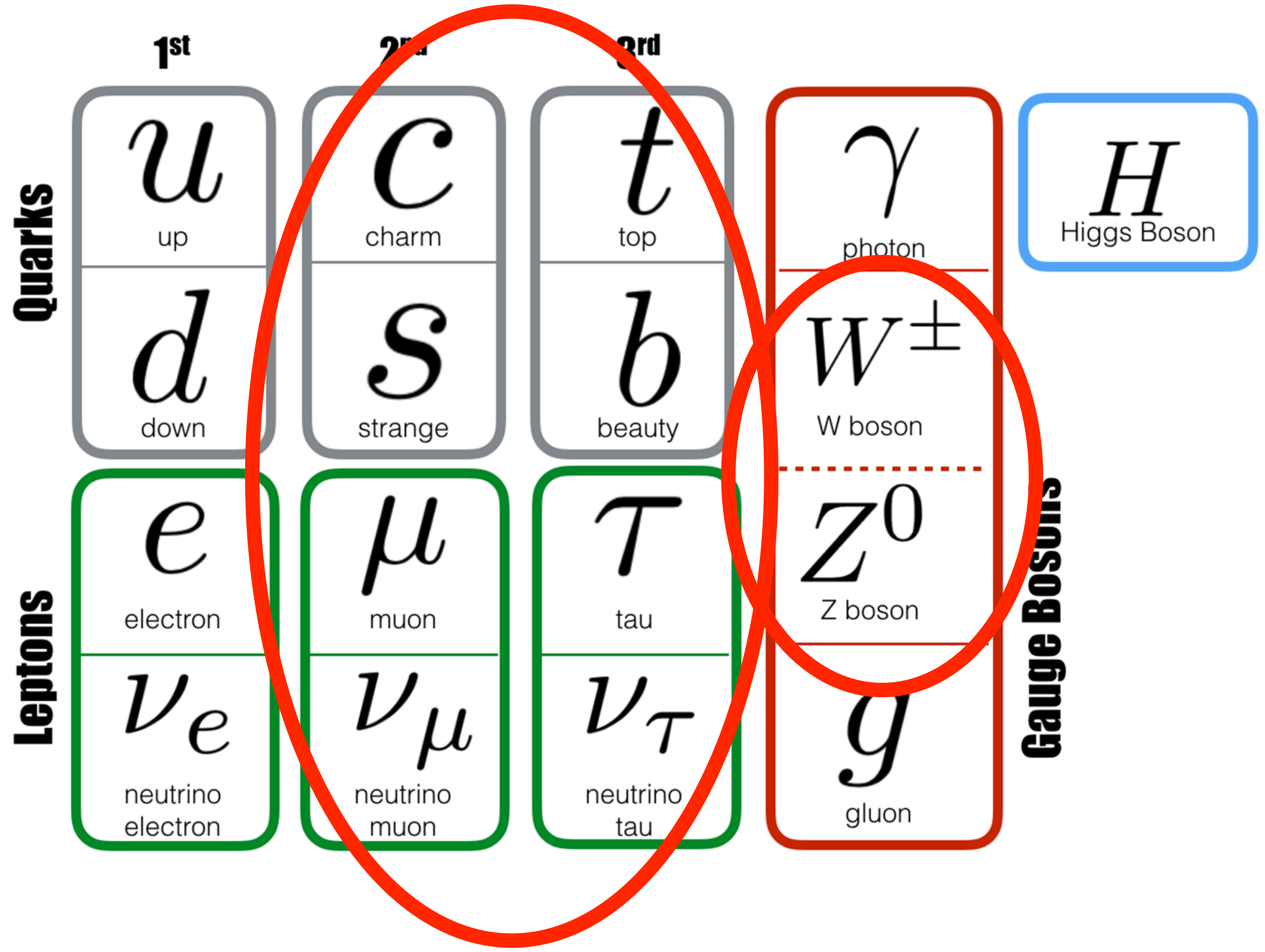

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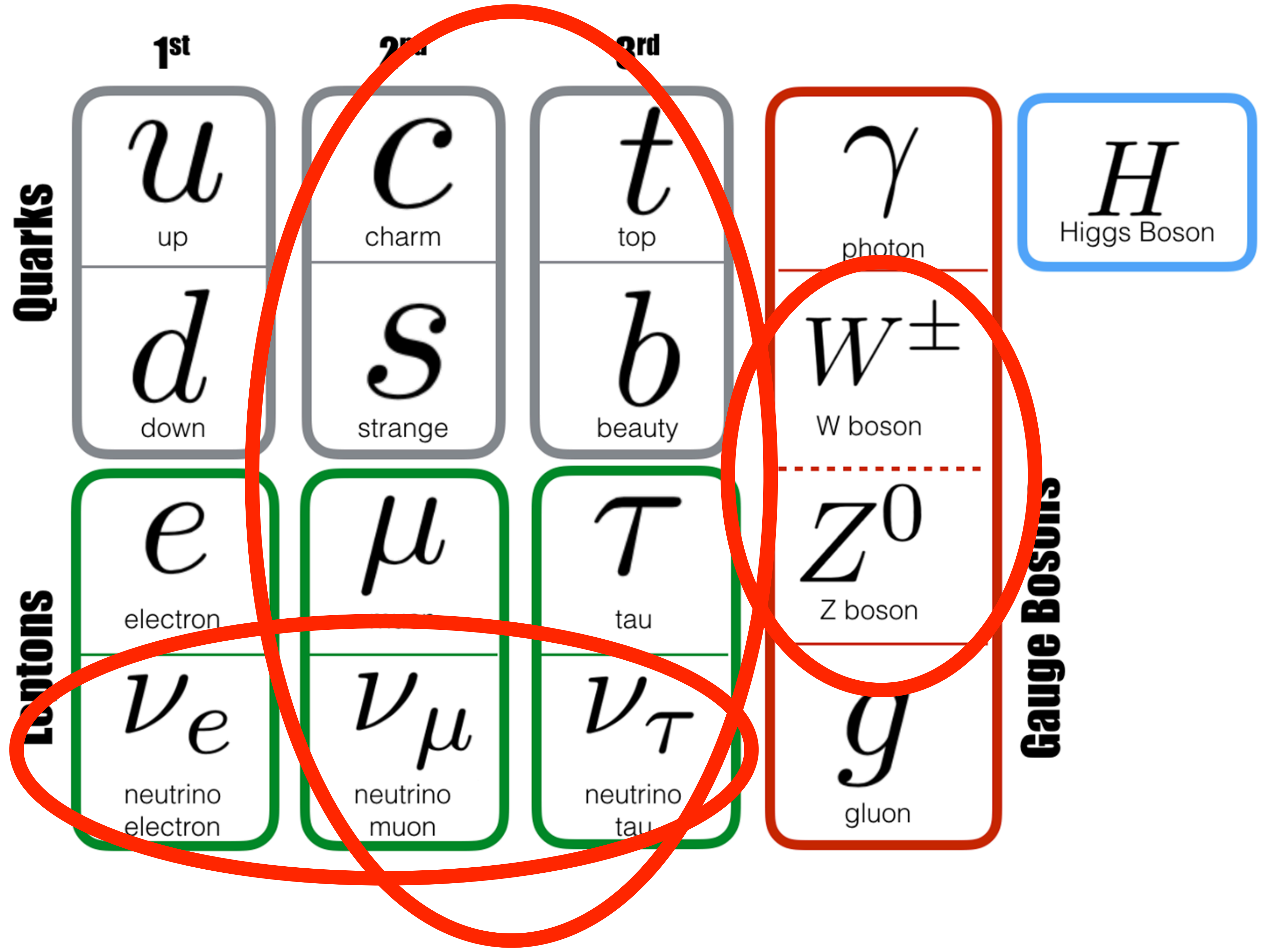

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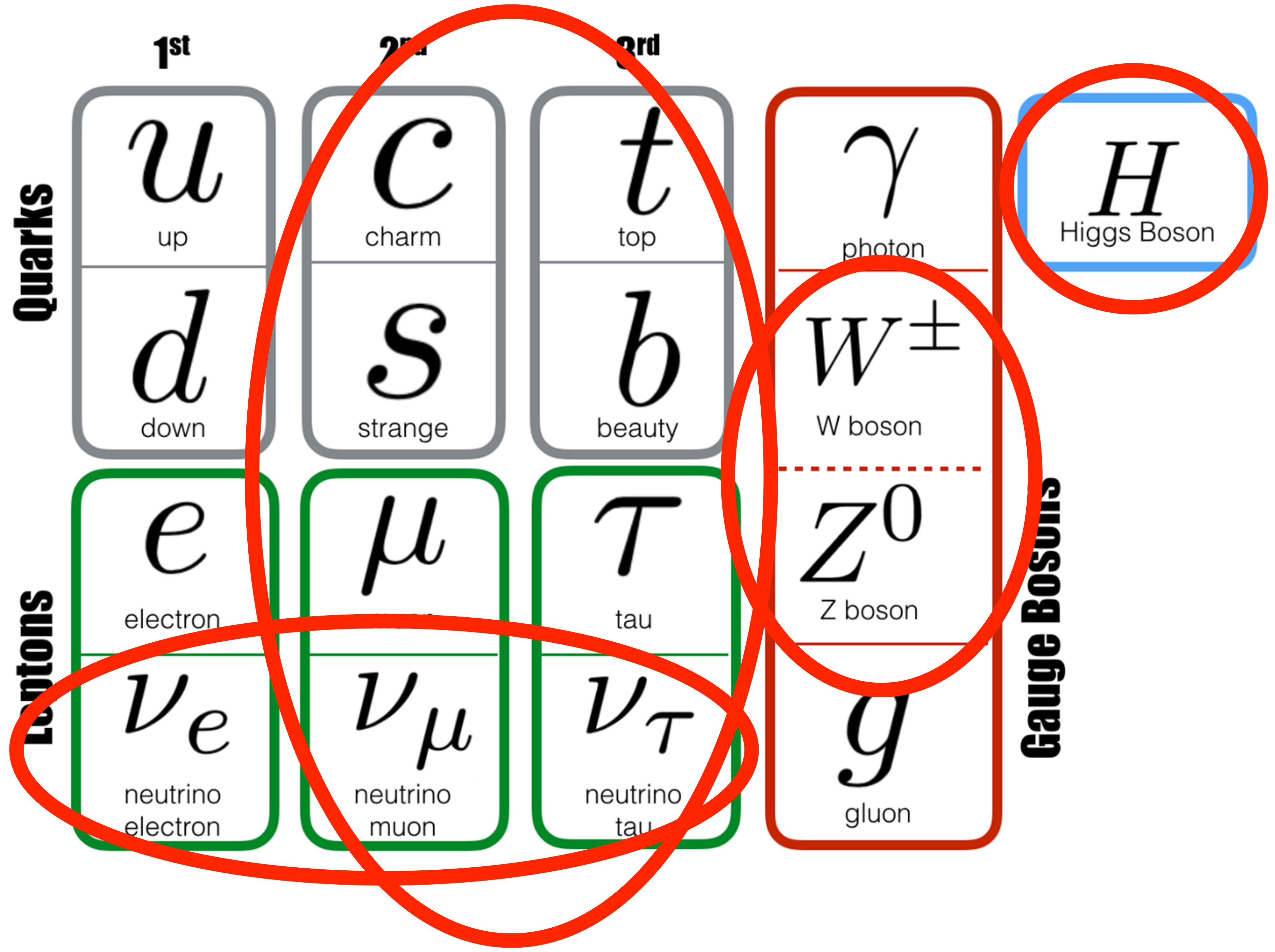
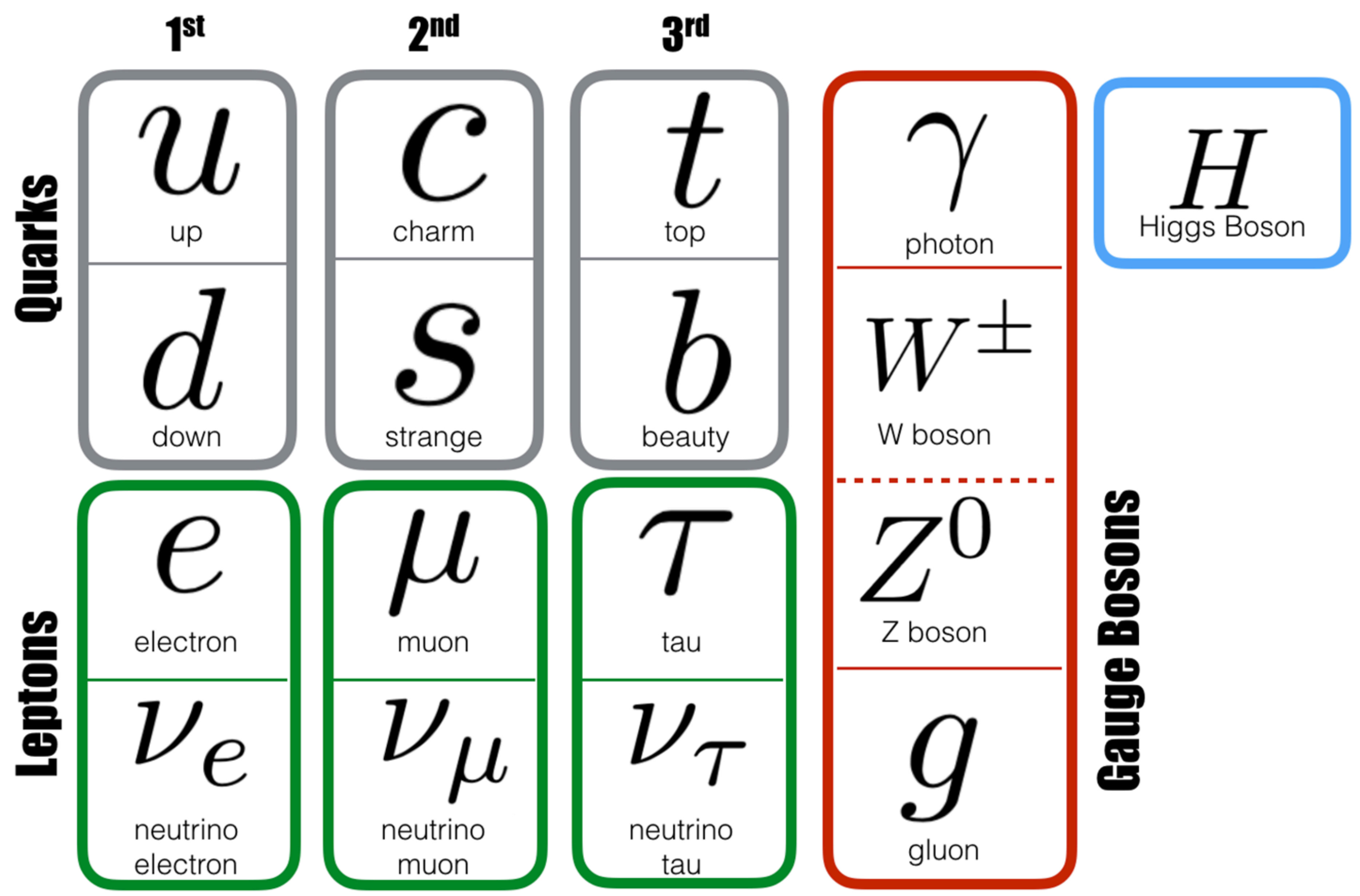


The Standard Model

Open Questions:



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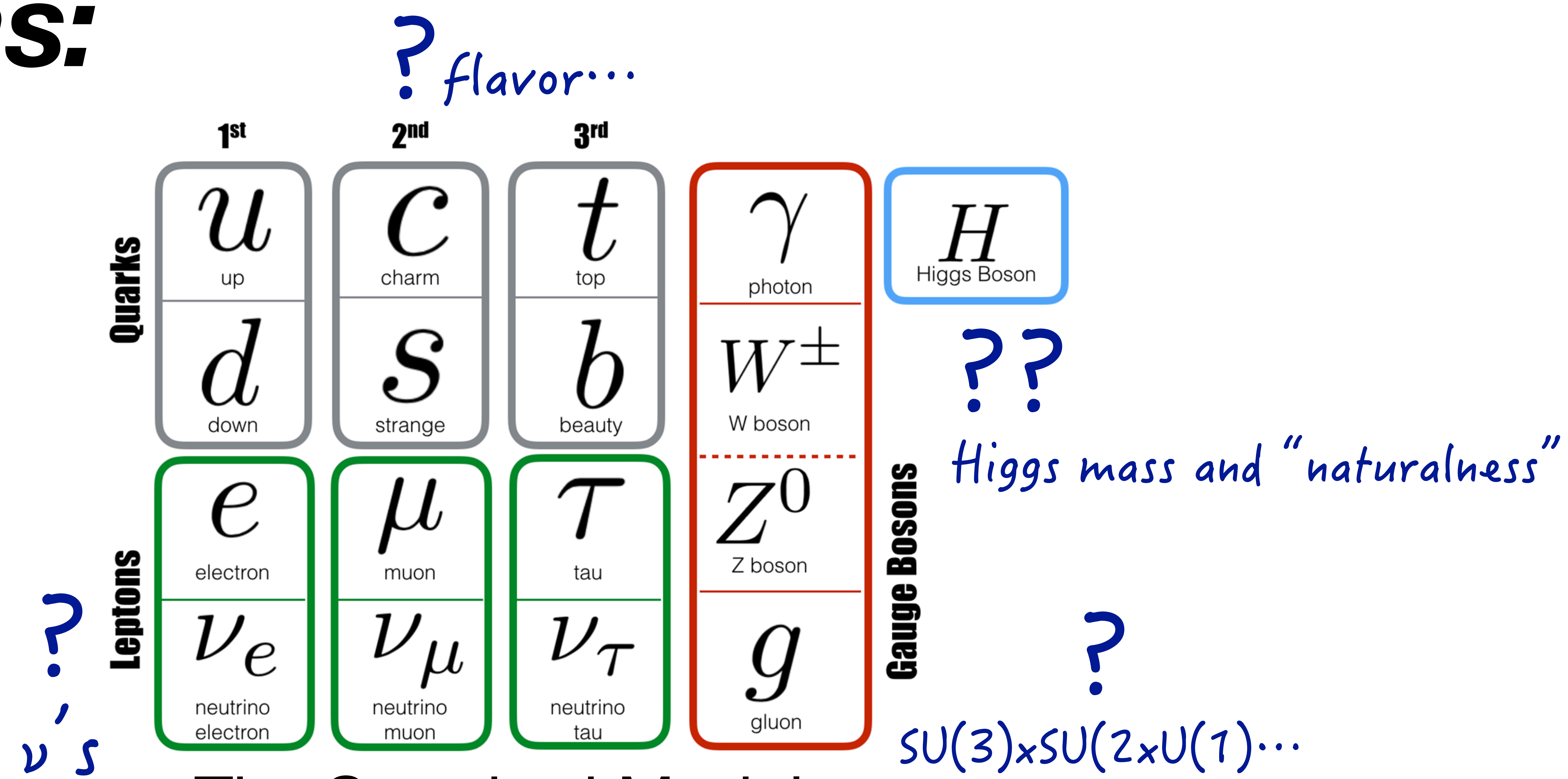

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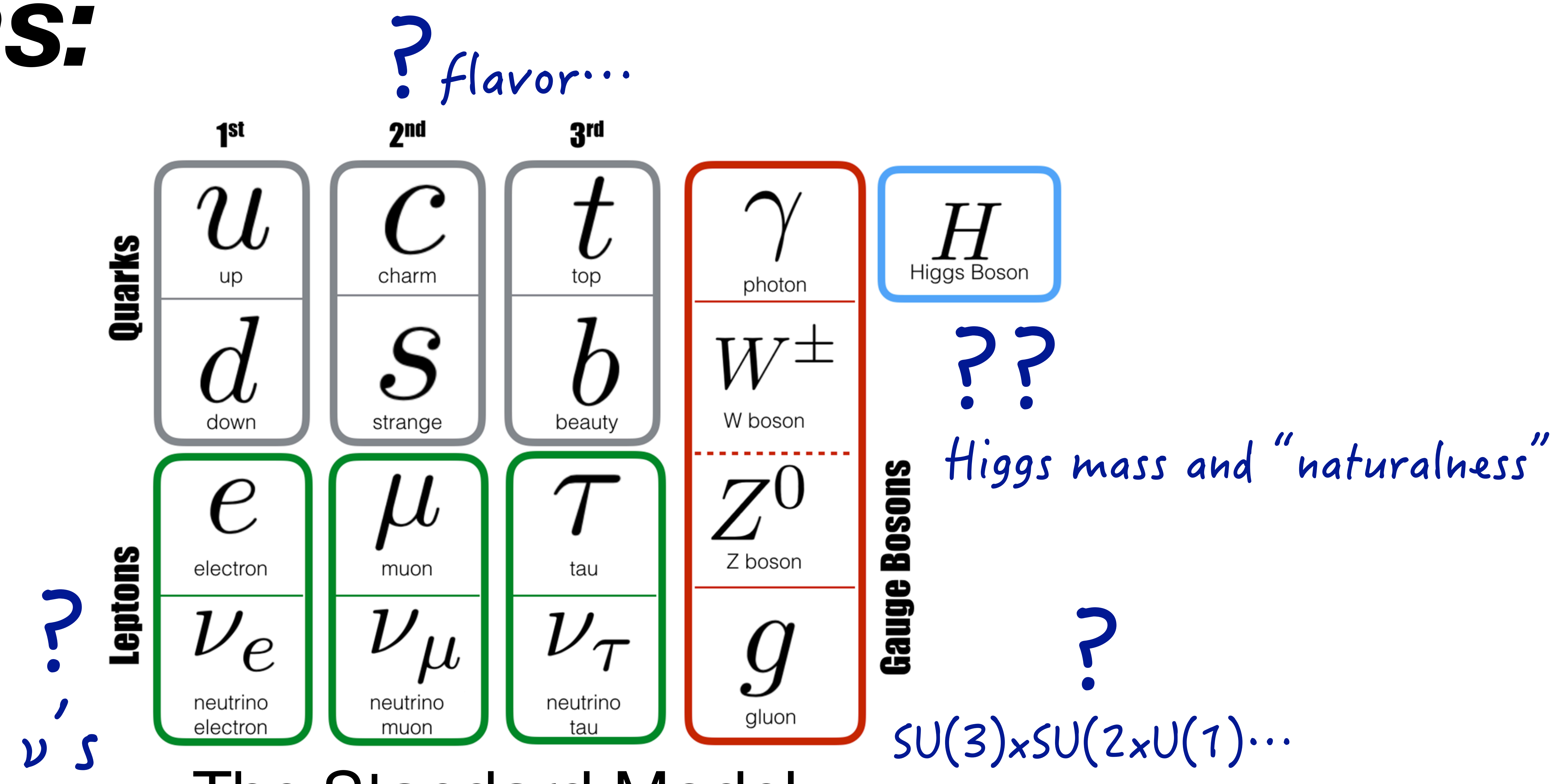
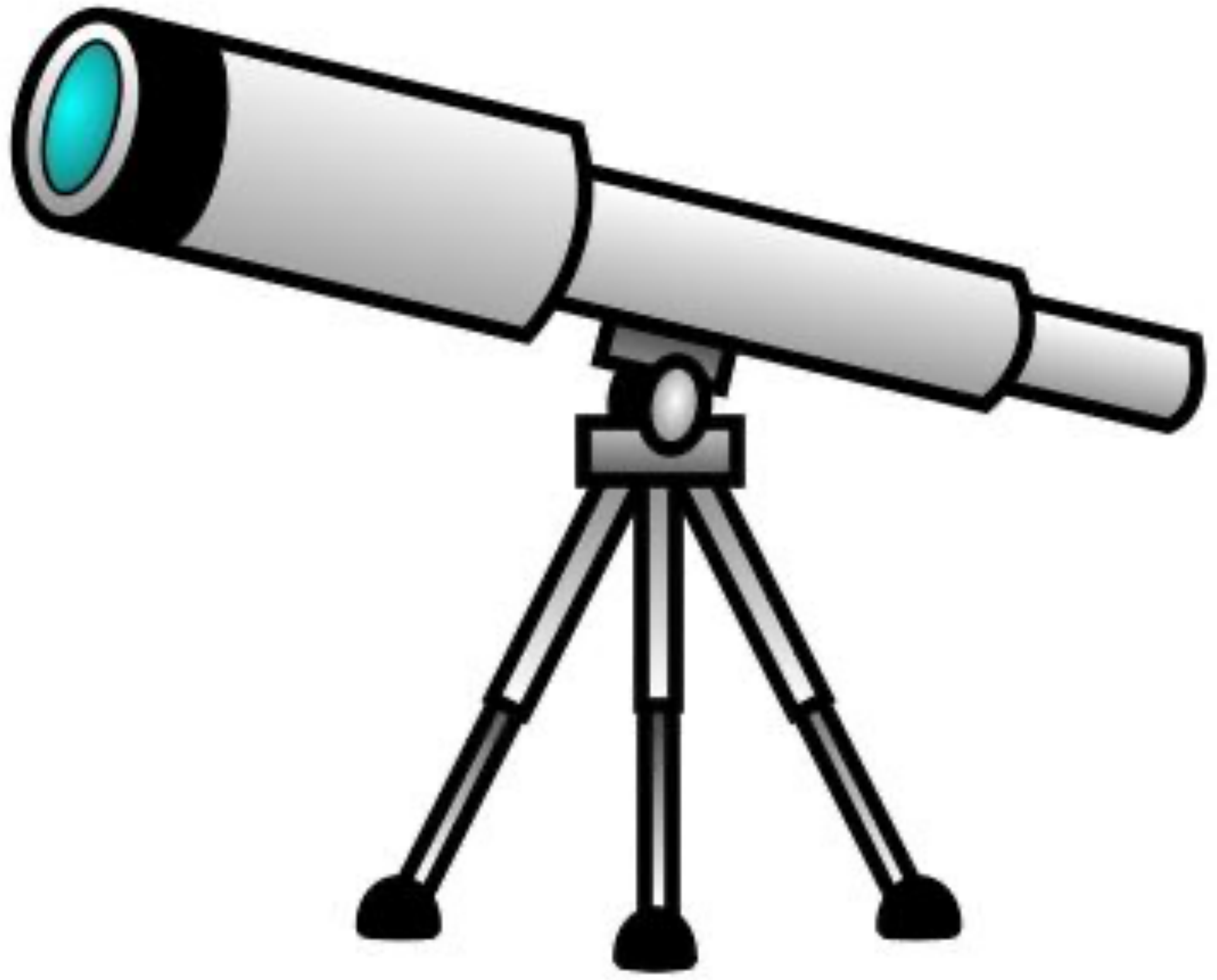


The Standard Model

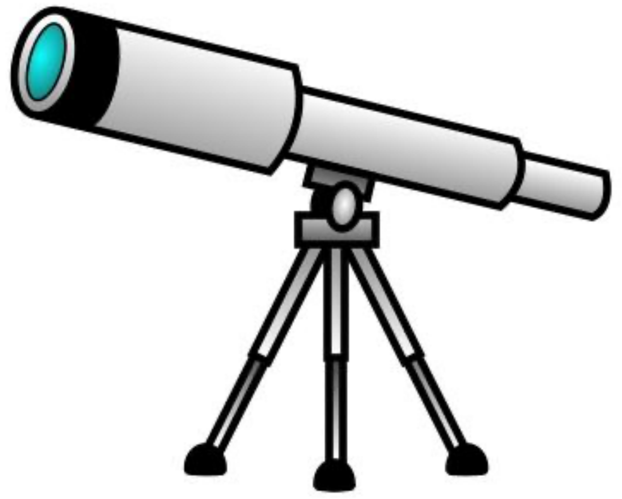
+ is there anything else?

What does the Universe contain?
What is its history?

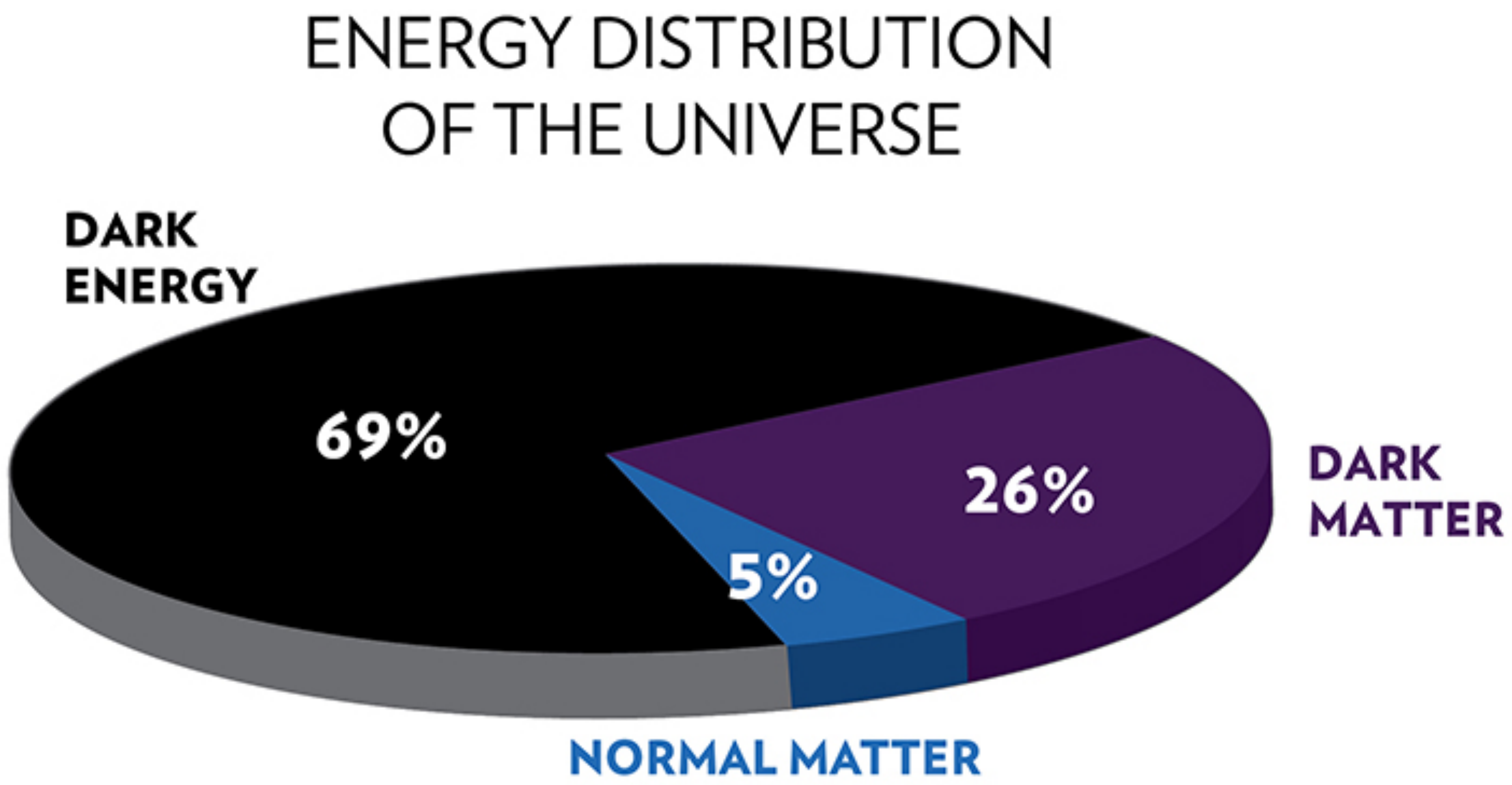


The Standard Model of Cosmology

Decades of observation has taught us that on large scale we are in a homogeneous, isotropic, expanding Universe.



Telescopes, observatories, CMB, satellites, DM direct detection experiments…



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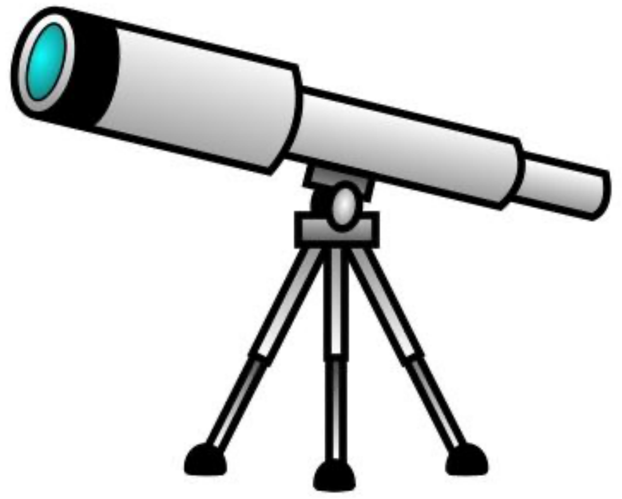

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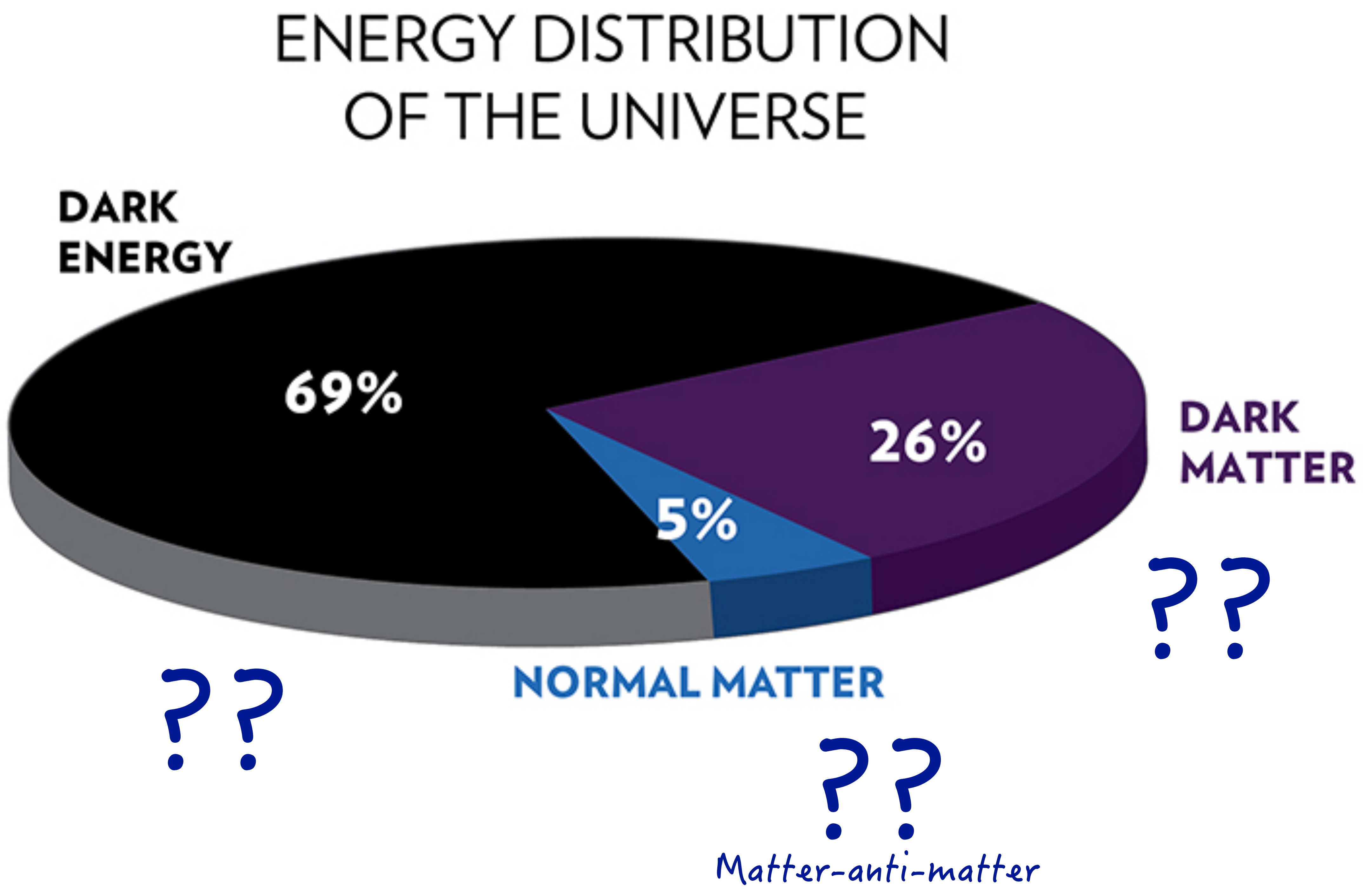
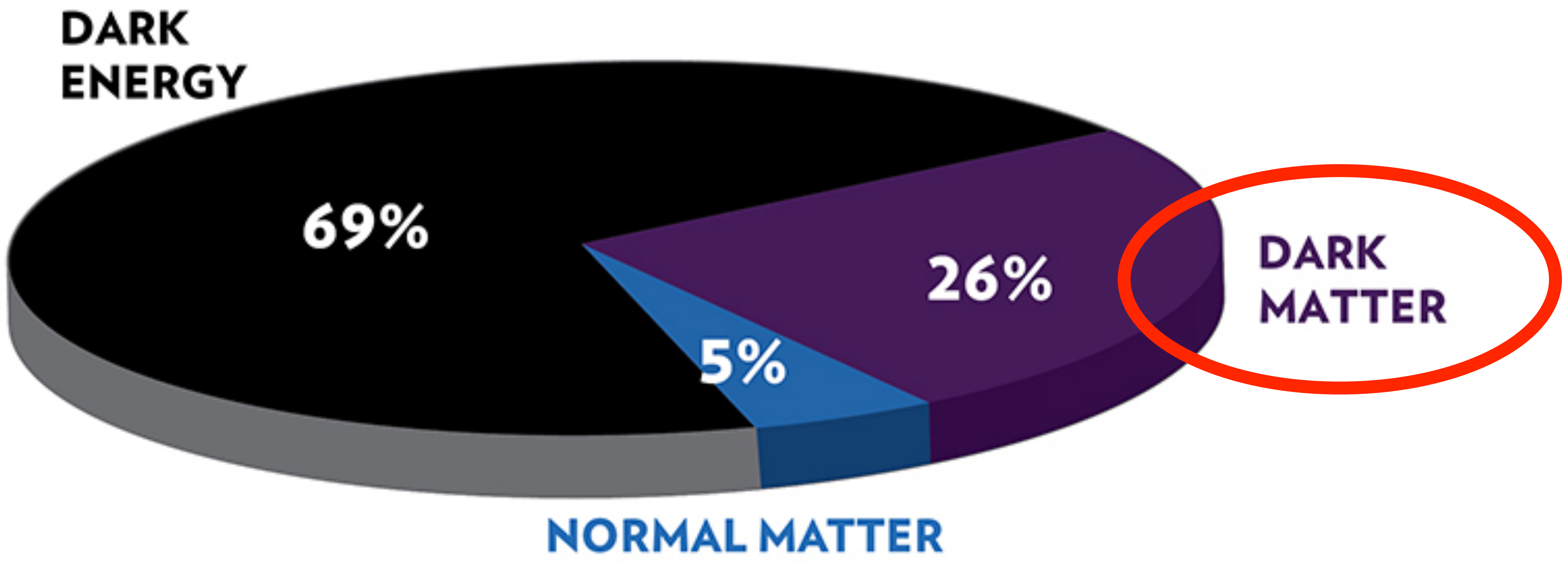


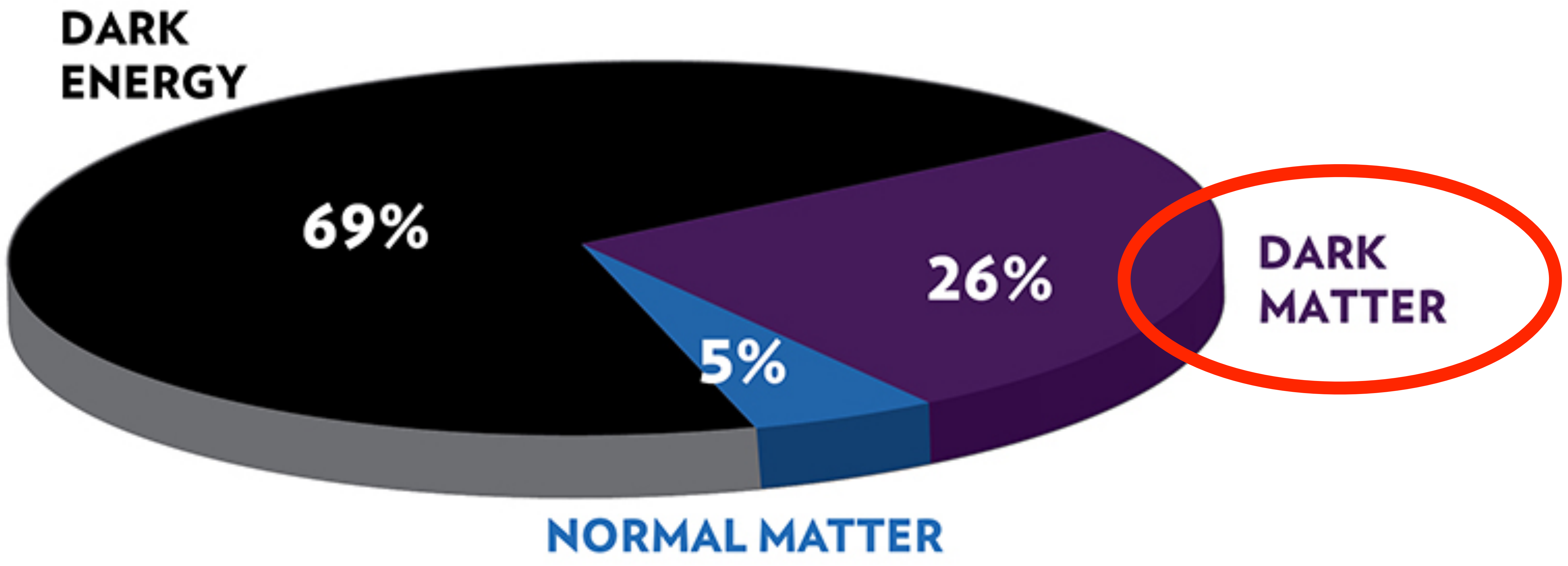
Dark Matter

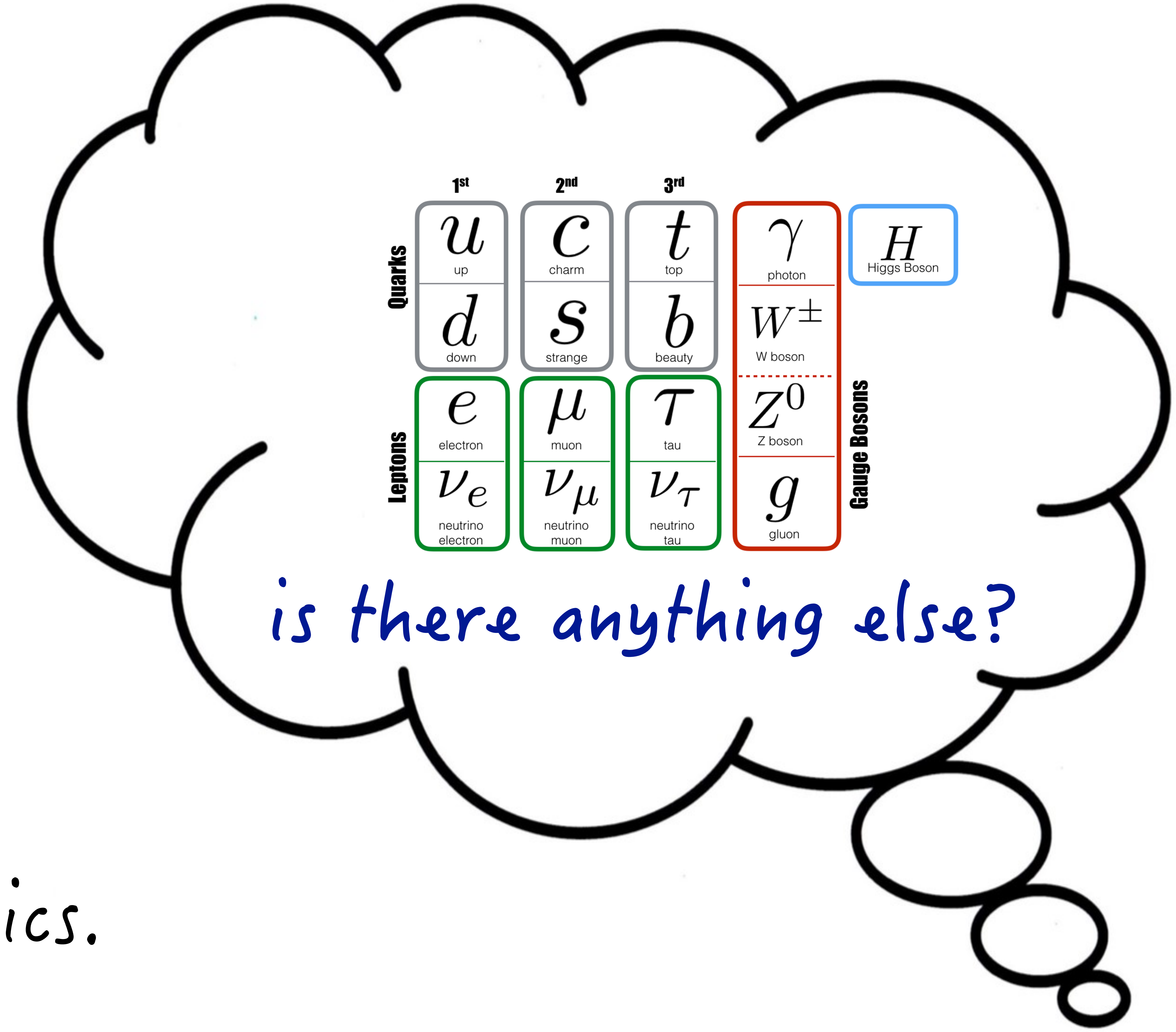


Lets talk more about dark matter:

* Likely has direct connections to particle physics.
* An interesting target for Quantum Sensing.

Dark Matter





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* Likely has direct connections to particle physics.
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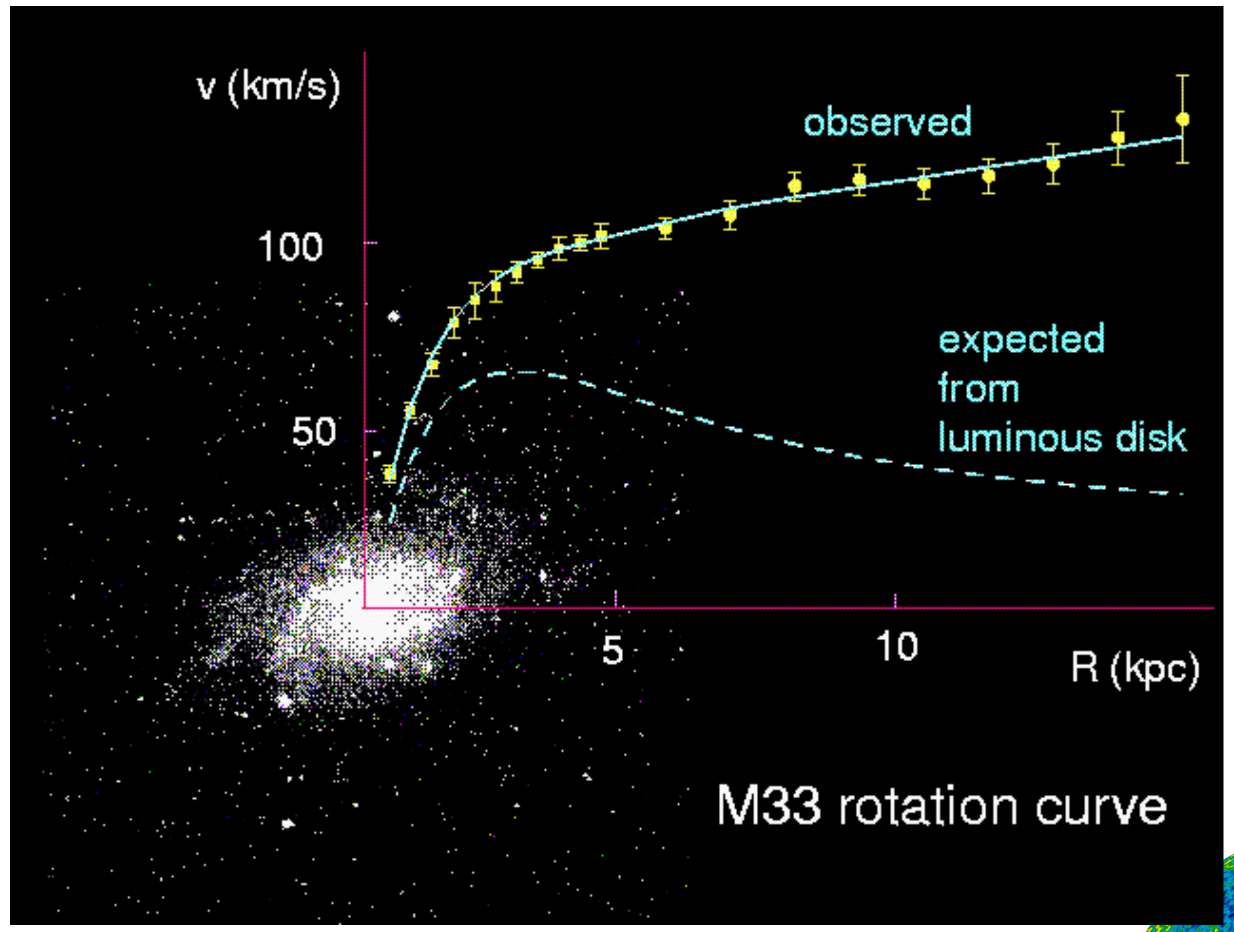
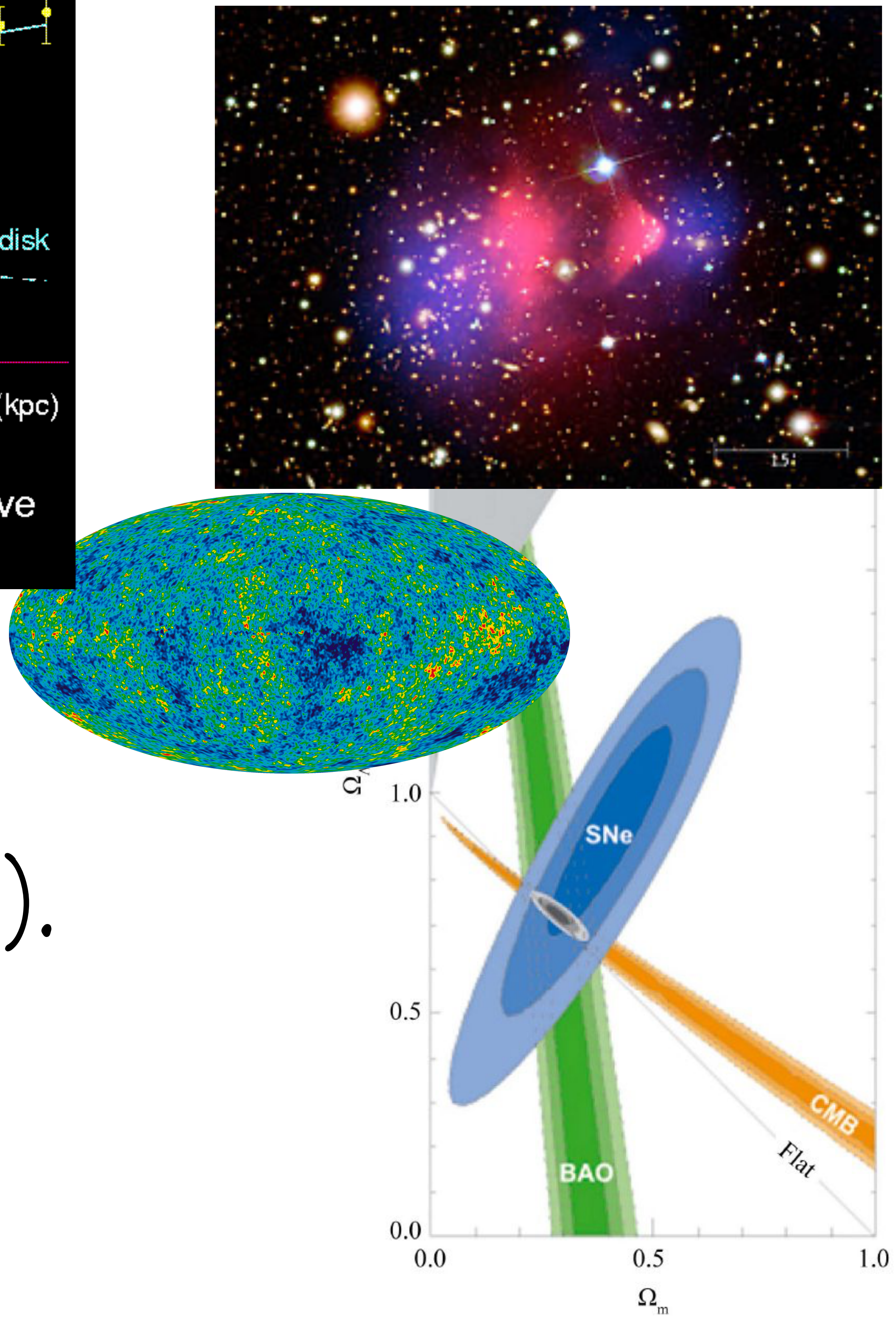
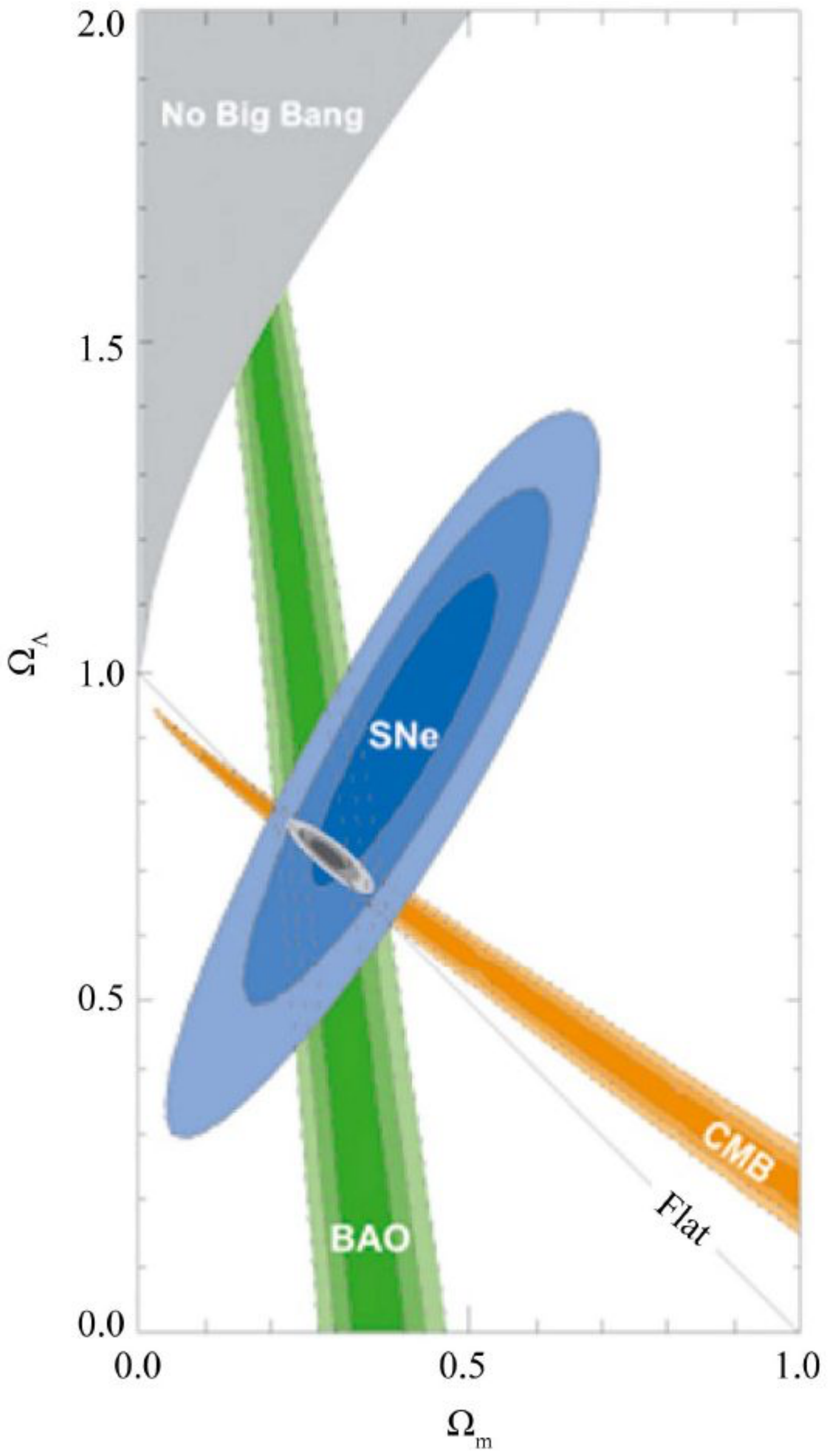
Evidence for Dark Matter

- DM is an observational fact, tested in many ways (all via gravitational interaction).
  - Galaxy rotation curves
  - Velocity dispersion in elliptical galaxies
  - Galactic velocity in clusters
  - CMB measurements
  - Lensing surveys
  - Large scale structure surveys
  - Dark energy (SN)+ visible matter + flatness of Universe (CMB).
  - Some rare galaxies have almost no DM (!)

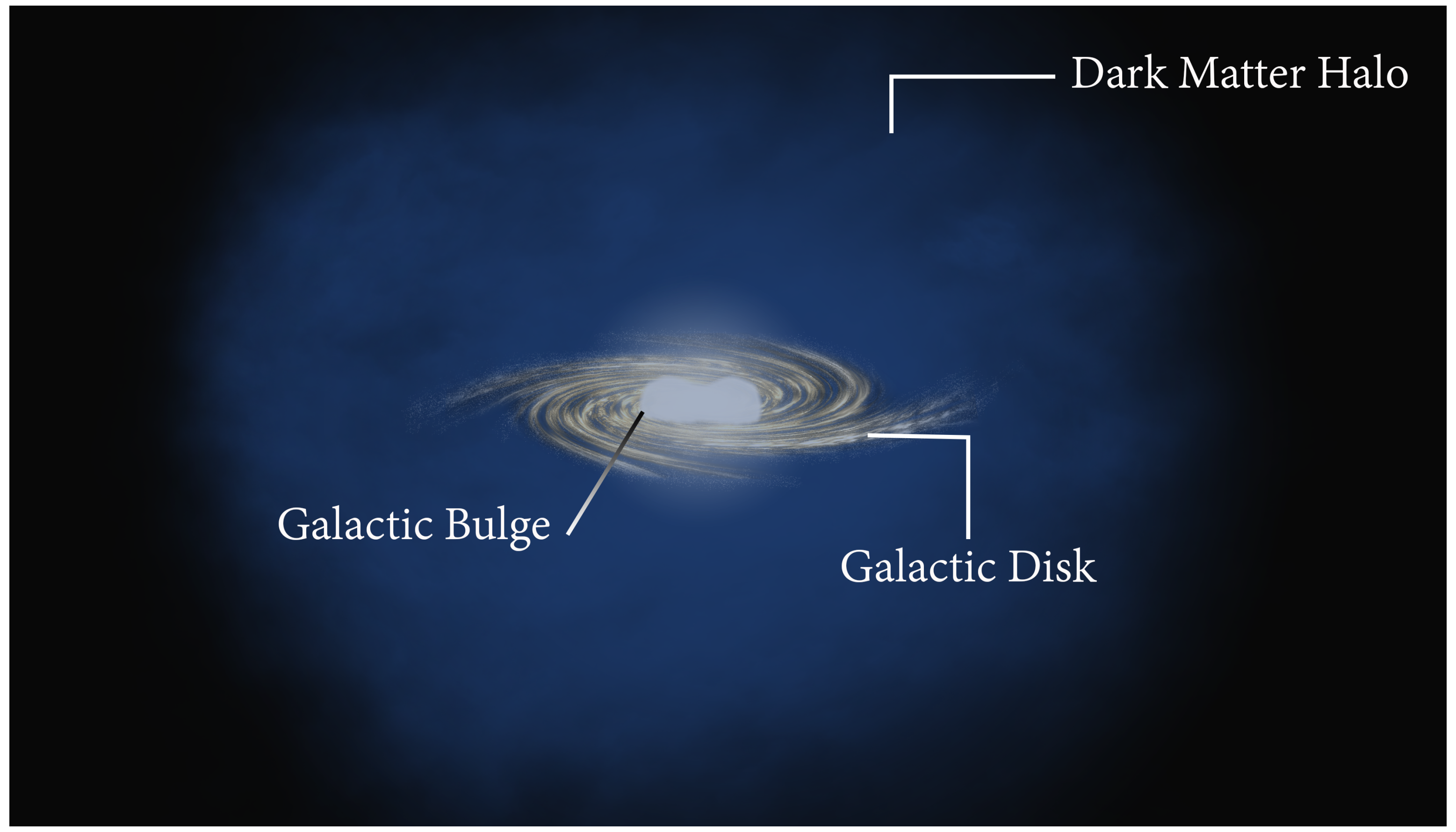





2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
Ω_Λ
Ω_m
No Big Bang
SNe
CMB
Flat
BAO


1.5'

Dark matter Properties



- Dark matter is about x5 normal matter.
- Our galaxy ~ 10^{11} solar masses and 10 kpc radius.
- Locally, density ~ 0.4 GeV/cm^3. (A proton ~ 1 GeV)
- In a ~ spherical halo (because dark matter cannot loose energy).
- Dark matter is slow (must be below the galactic escape velocity)
- Virial velocity in our galaxy ~ 220 km/sec (or 10^{-3} c)

(DM kinetic energy spread is ~10^{-6} of its mass)

There is dark matter in the room!

What is it?

Theorists have **many** ideas!!!

Wimps, Neutralino LSP (Bino or Wino or Higgsino), gravitino, sneutrino, Axions, Dark Photons, lightest T-paritly odd particle, Asymmetric DM, Atomic DM, Inelastic DM, Resonant dark matter, Exothermic DM, Somerfeld enhanced DM, B-L DM, Wimpzillas, Axion stars, Self-destructing DM, Xenon-phobic DM, minimal DM, inert Higgs DM, Singlet scalar DM, Kaluza-Klein DM, Sterile neutrino DM, Luminous dark matter, Heilogenesis, XO-genesis, Black Holes….

For us, it makes sense to focus on something simple

New Particles Interacting w/ Light

The main actors:

Dark Photons

(A linear theory)

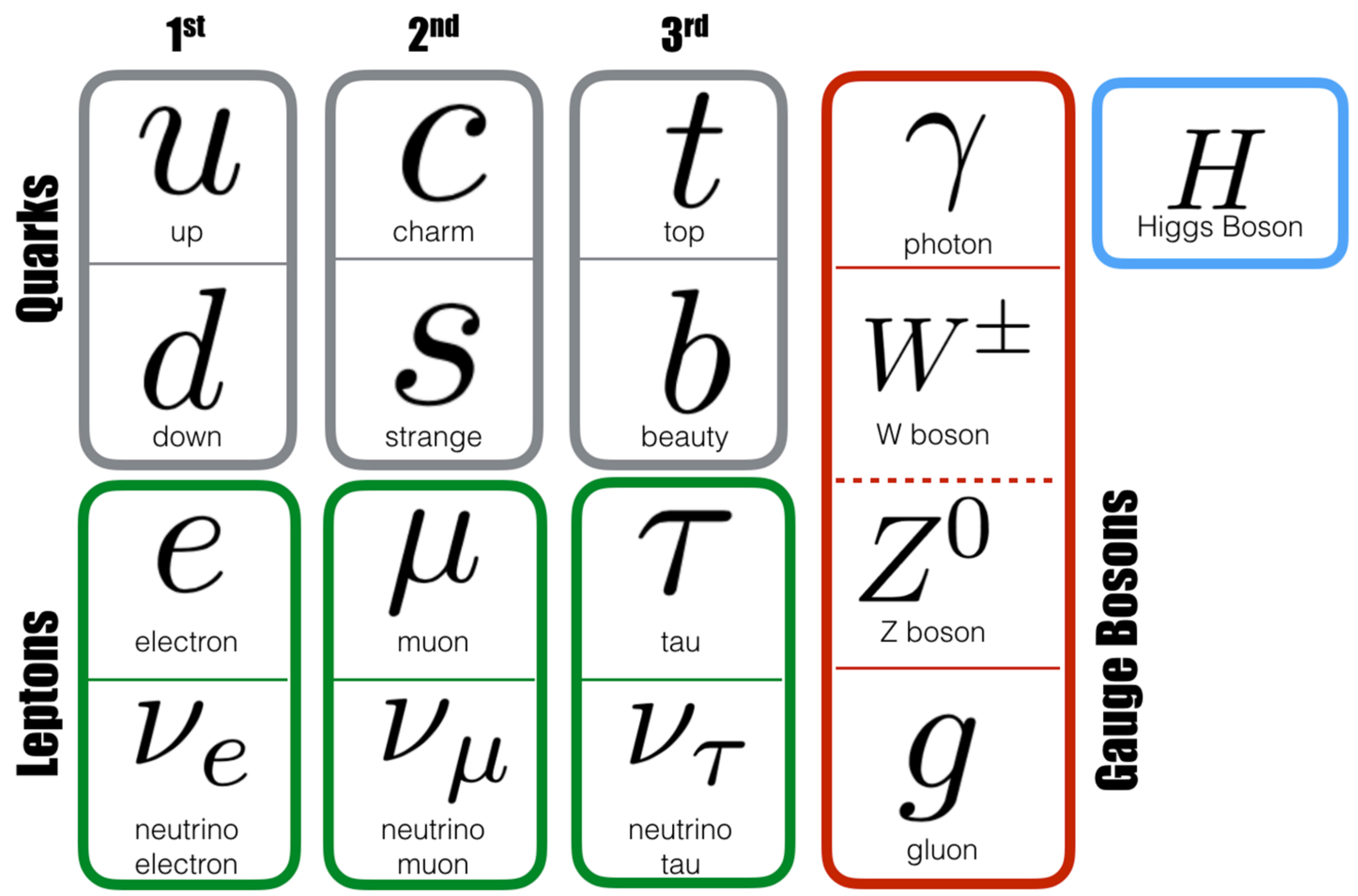
Axions

(A nonlinear theory)

Both are interesting DM candidates. But they may exist without being DM!
Both hypotheses are interesting to test

Dark Photons

- Add another photon to the rule book: (and lets give it a mass)



- Why would I add a new photon? Without good reason?

Why not?

Its simple, and it happened before. (remember the muon, who order that!?)

Dark Photons

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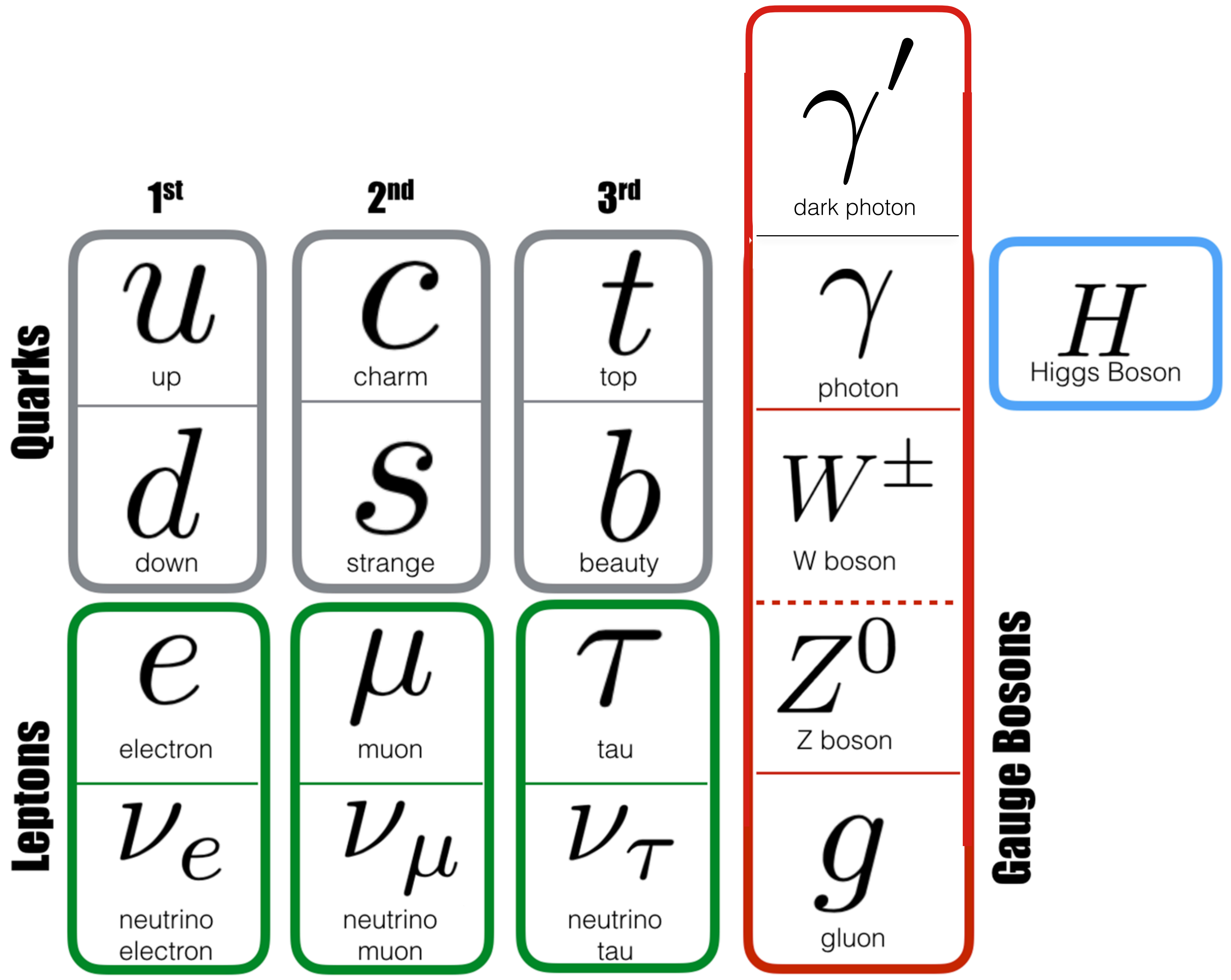

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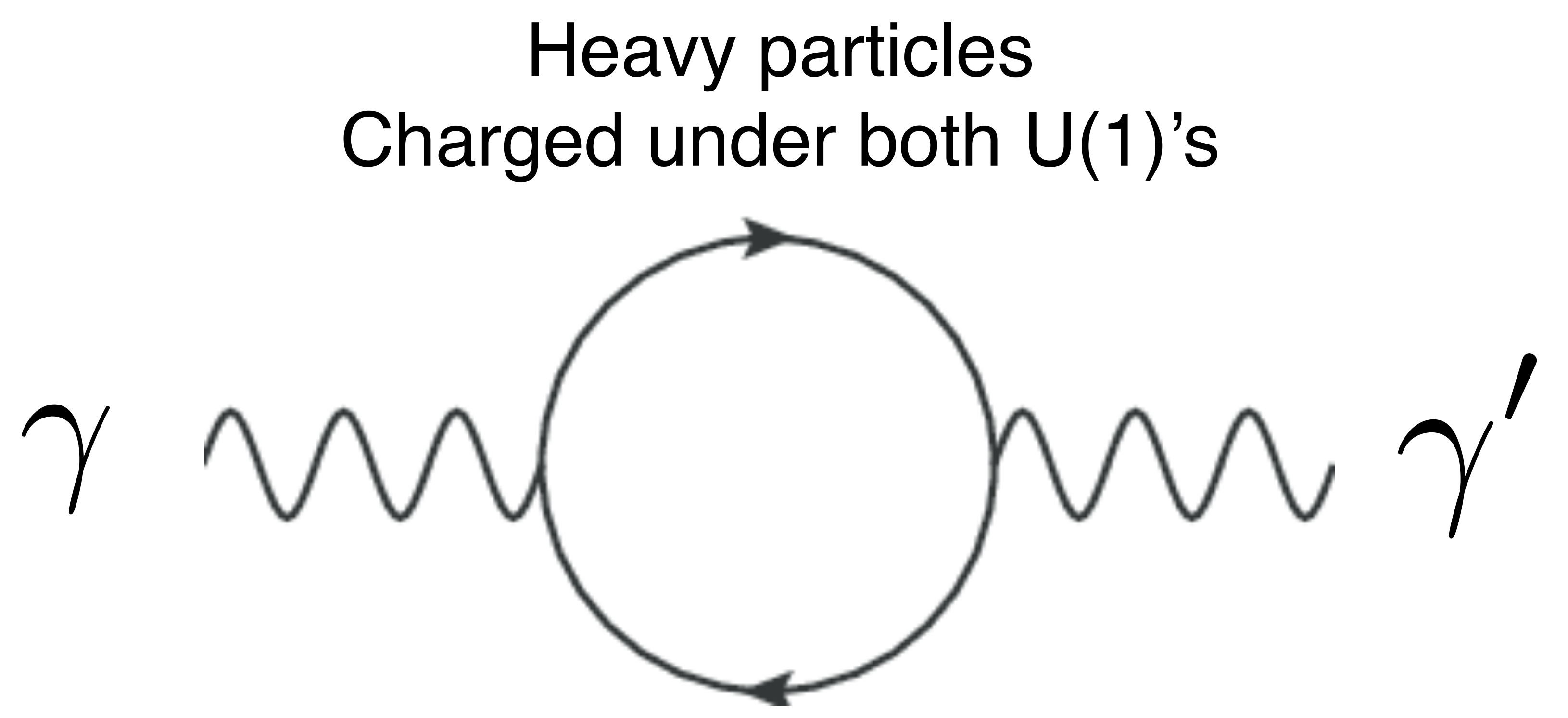
Dark Photon

- Even without "ordering", a Dark Photon would teach us **profound** lessons:
  - There is another gauge interaction. $SU(3) \times SU(2) \times U(1)^2$.
  - Our thinking about Grand Unification would change.
  - What is the abundance of dark photons? Can it be dark matter?
  - The interaction with SM is likely generated by new heavy particles.



Dark Photons - a Linear Extension

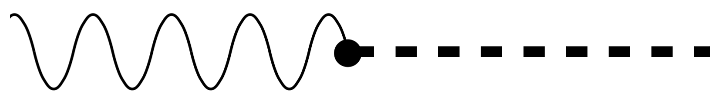
- Normal matter is not charged under the new photon. How will it interact?

In quantum mechanics: two states which have the same quantum numbers can be in a superposition, "mix".

$$|\psi\rangle = |\text{photon}\rangle + \varepsilon\,|\text{dark photon}\rangle$$

- The dark Photon effective Hamiltonian:

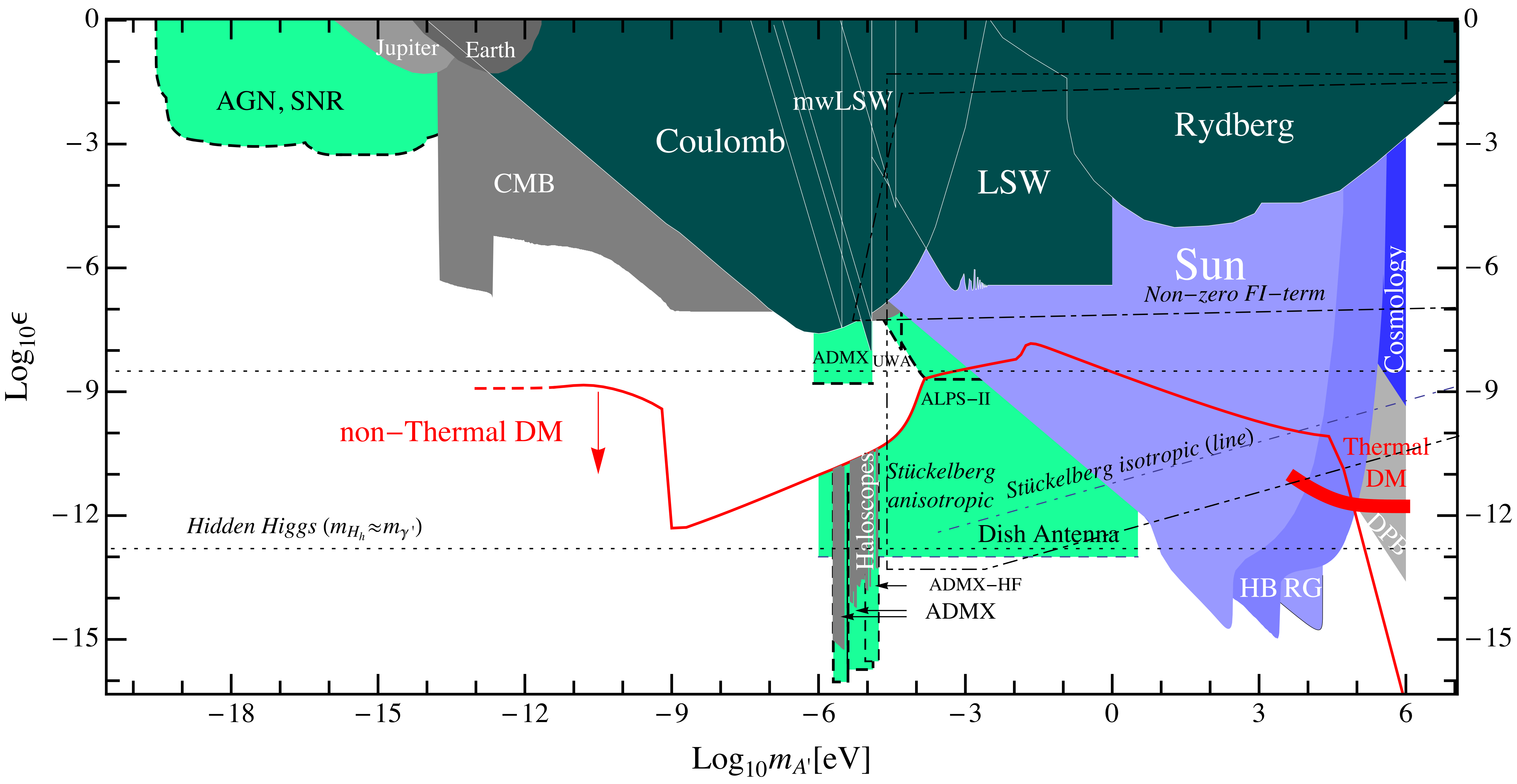
$$\mathcal{H} \supset \mathcal{H}_{QED} + \varepsilon\,\vec{E}\cdot\vec{E}' + \vec{B}\cdot\vec{B}'$$

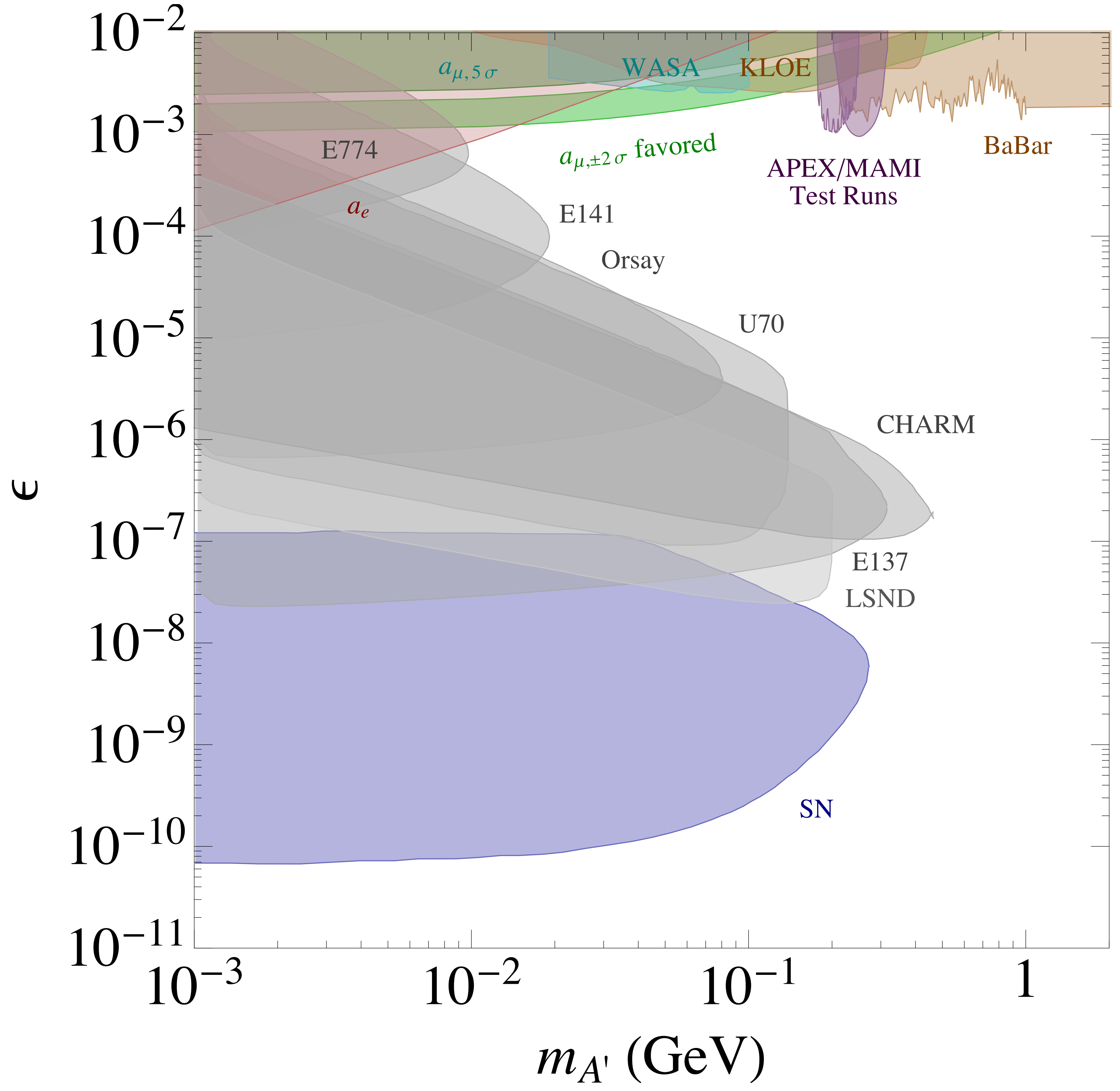


(and dark photon also has a mass, and a longitudinal polarization!)

Dark Photon

- Many constraints on the dark photon! (a review: Essig et al 1311.0029)





Dark Photon - Photon Interaction

$\mathcal{H}_{A'} \supset \varepsilon\, \vec{E}\cdot\vec{E}'$ is similar to $\mathcal{H}_{dipole'} = \vec{E}'\cdot\vec{d}'$!

- An oscillating dipole emits photons ⟶ oscillating EM field emits dark photons!
- A dark photon can convert to a photon and vice versa.

$\vec{J}(t)$

* there is a slight cheat on this slide. I'll come clean later.

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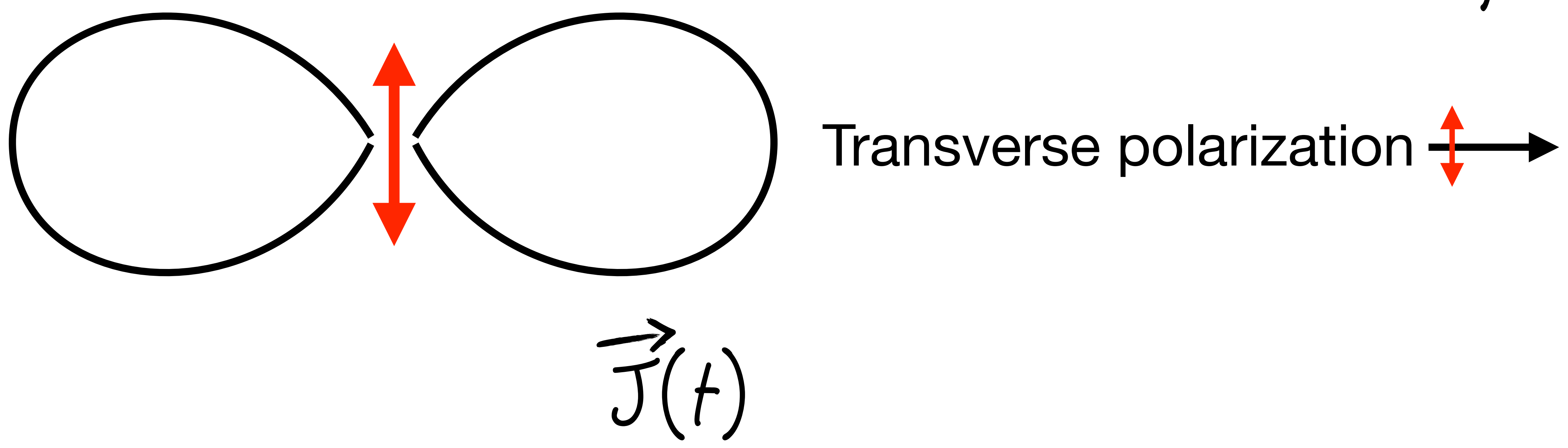
Dark flux $\propto \varepsilon^2$



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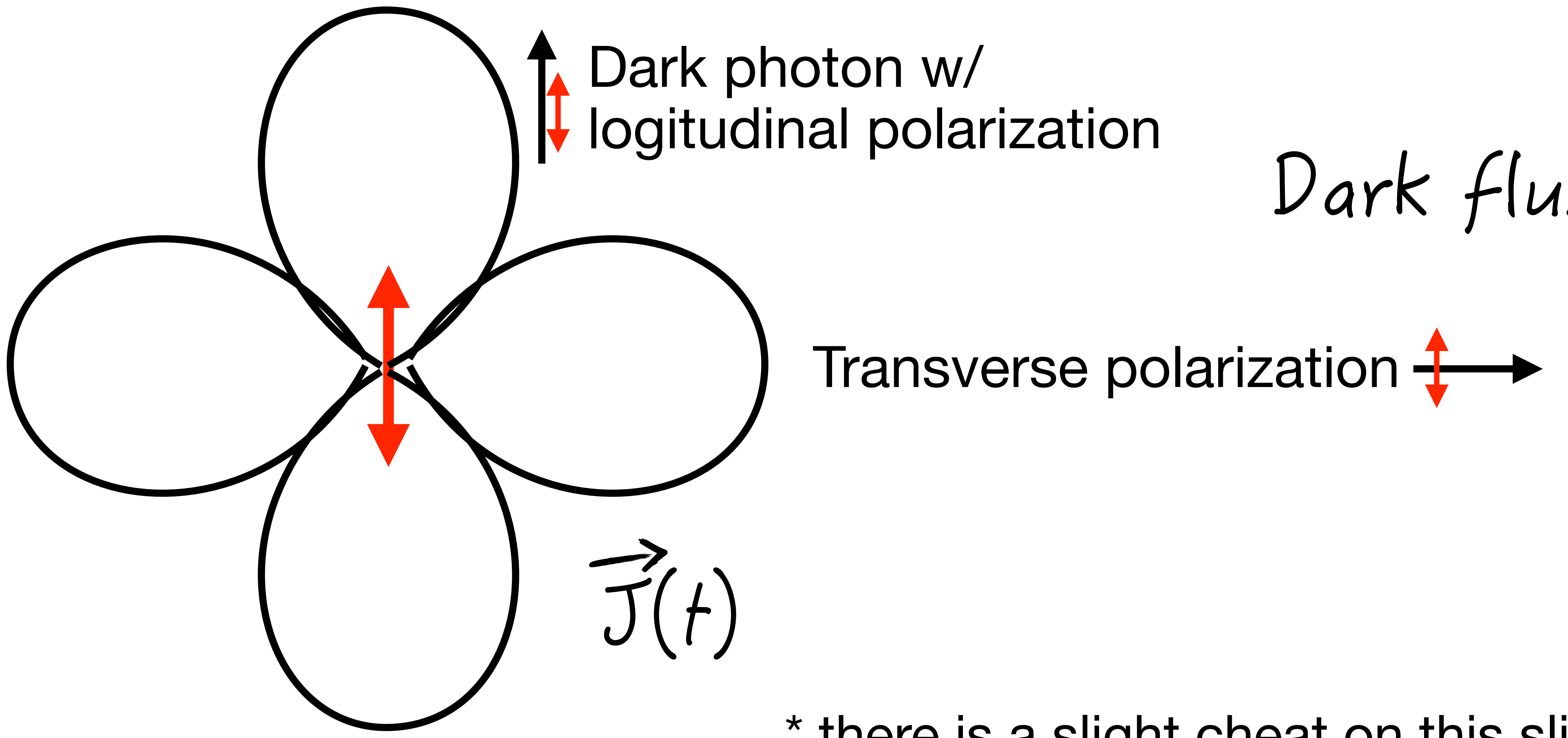

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- An oscillating dipole emits photons ⟶ oscillating dark field emits photons!
- A dark photon can convert to a photon and vice versa.
- In particle physics language, a background dark photon field is an effective EM current.

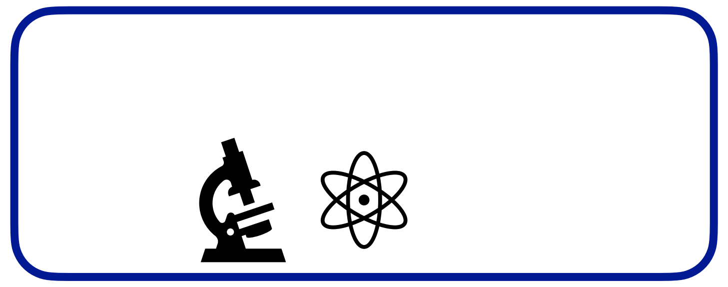
$$\vec{J}_{eff} = \varepsilon \, m_{A'}^2 \vec{A}'$$

Dark Photon Dark Matter

- Great! We learnt about a new particle, and how it interacts with photons. Can we make it dark matter?

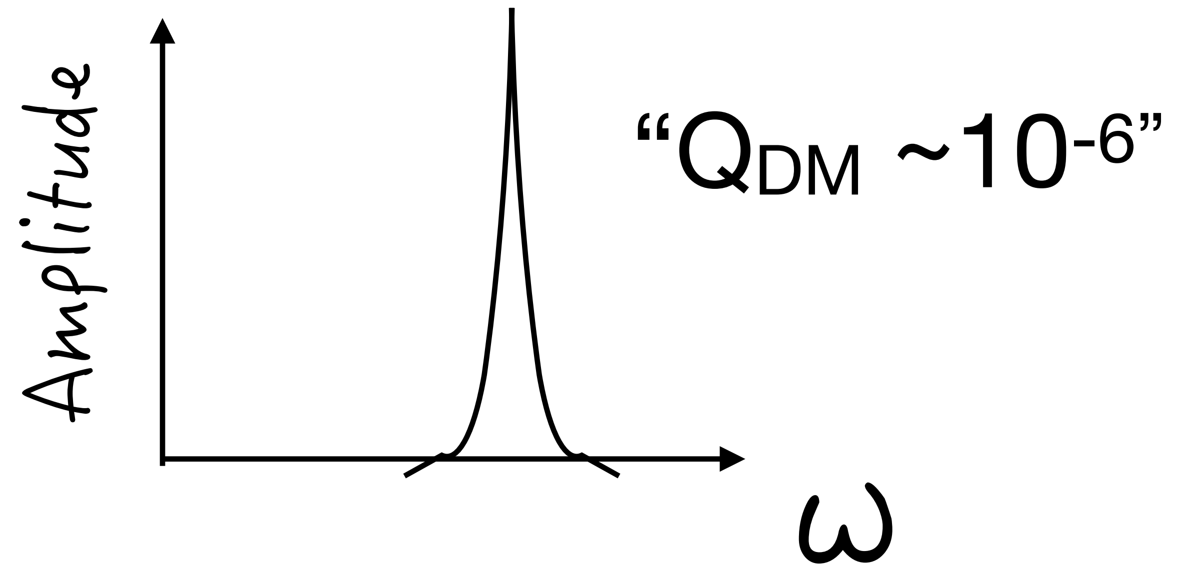
- Yes!!!

- We will assume the dark photon is very light - hence will need to have a very high occupation number. **Better described as a wave** (and not a bunch of particles)!



- The frequency of the wave is the energy of a DM particle

$$\omega_{DM} = m_{DM} + (\text{corrections of order } mv^2 \sim 10^{-6})$$



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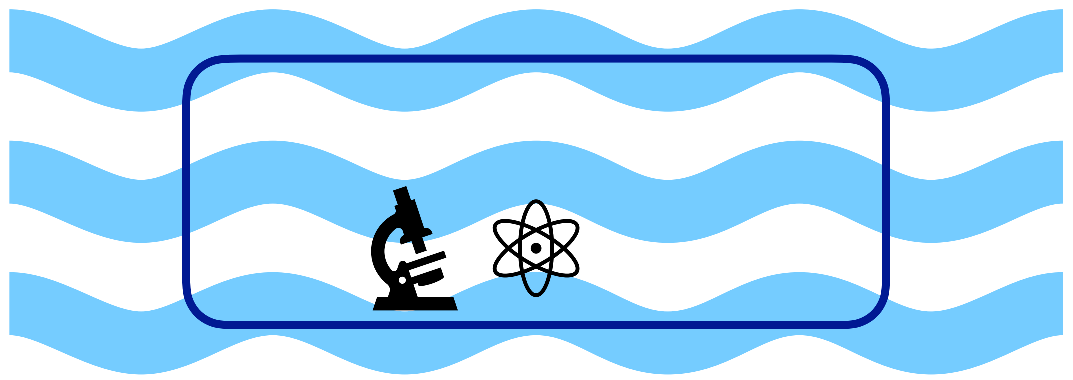

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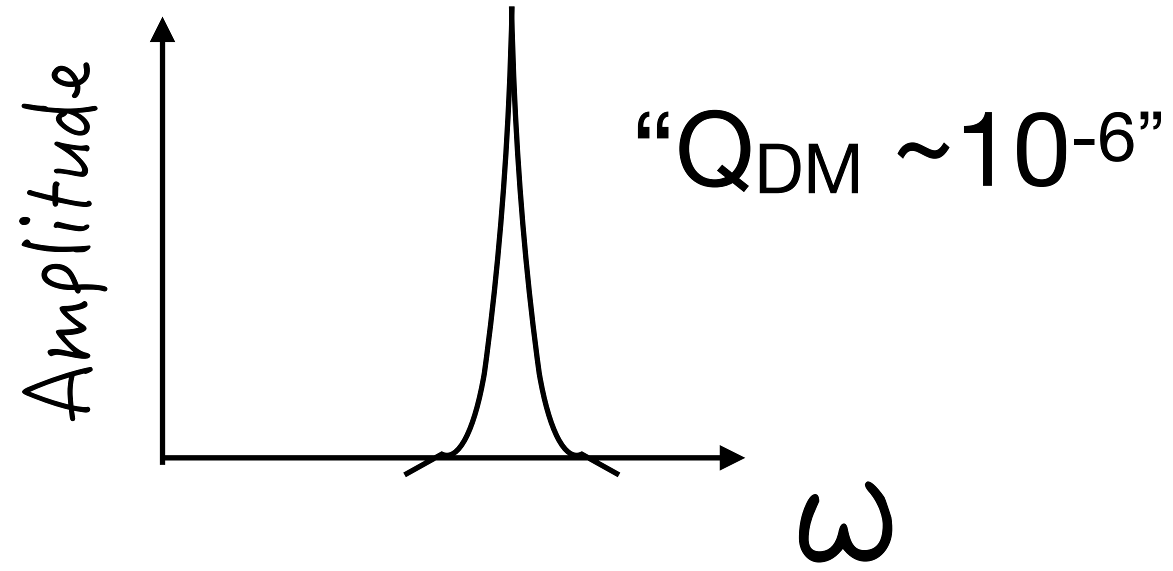
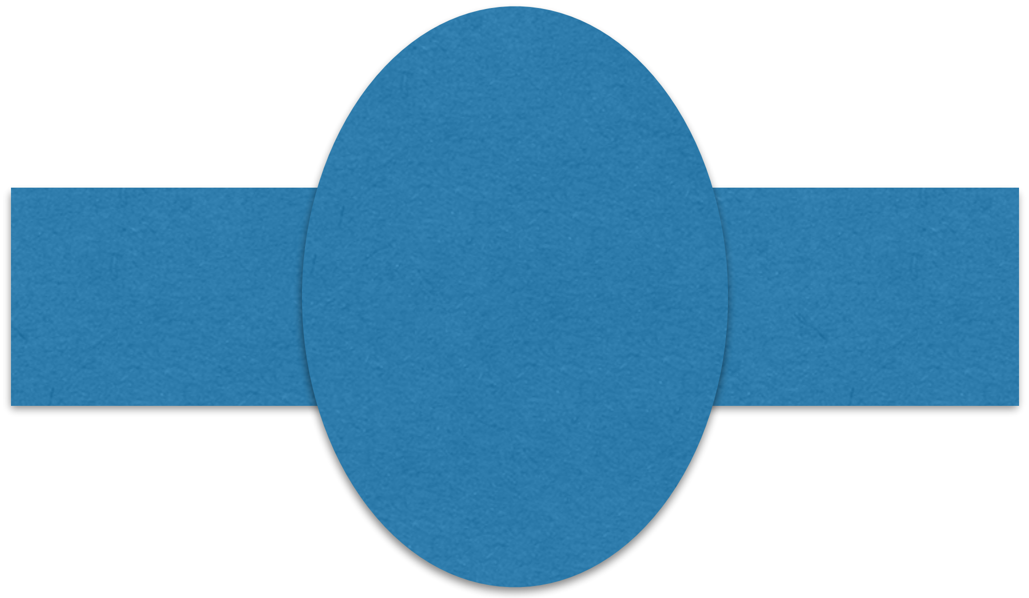


Dark Photon Dark Matter

- A background DPDM wave is a background effective current!
- Consider a high quality cavity:



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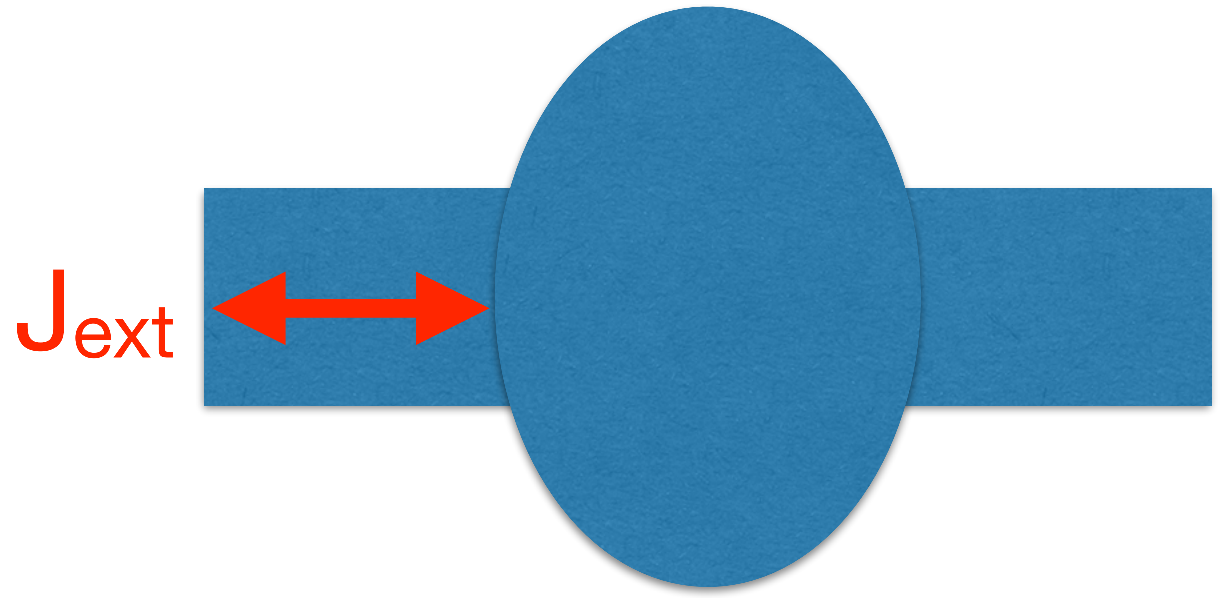

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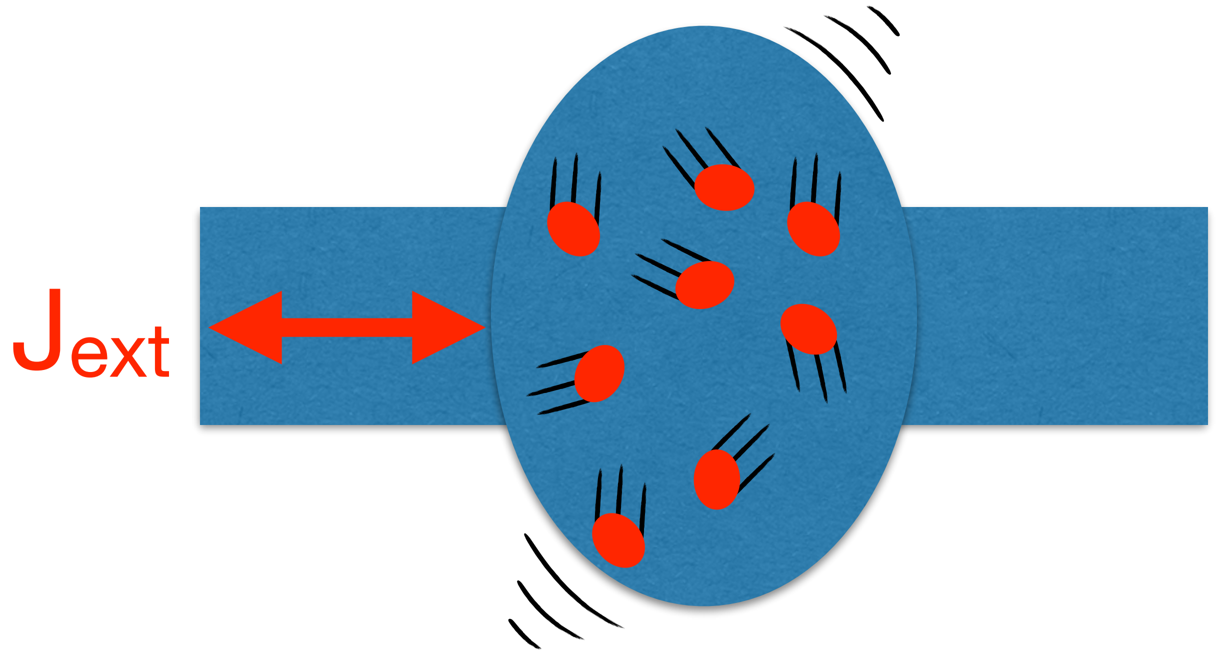

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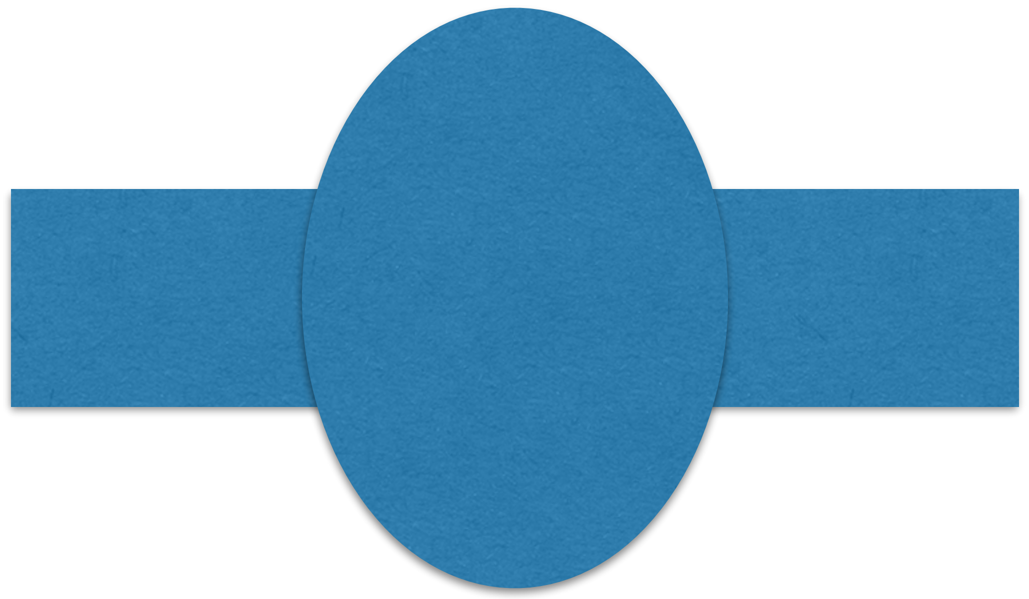

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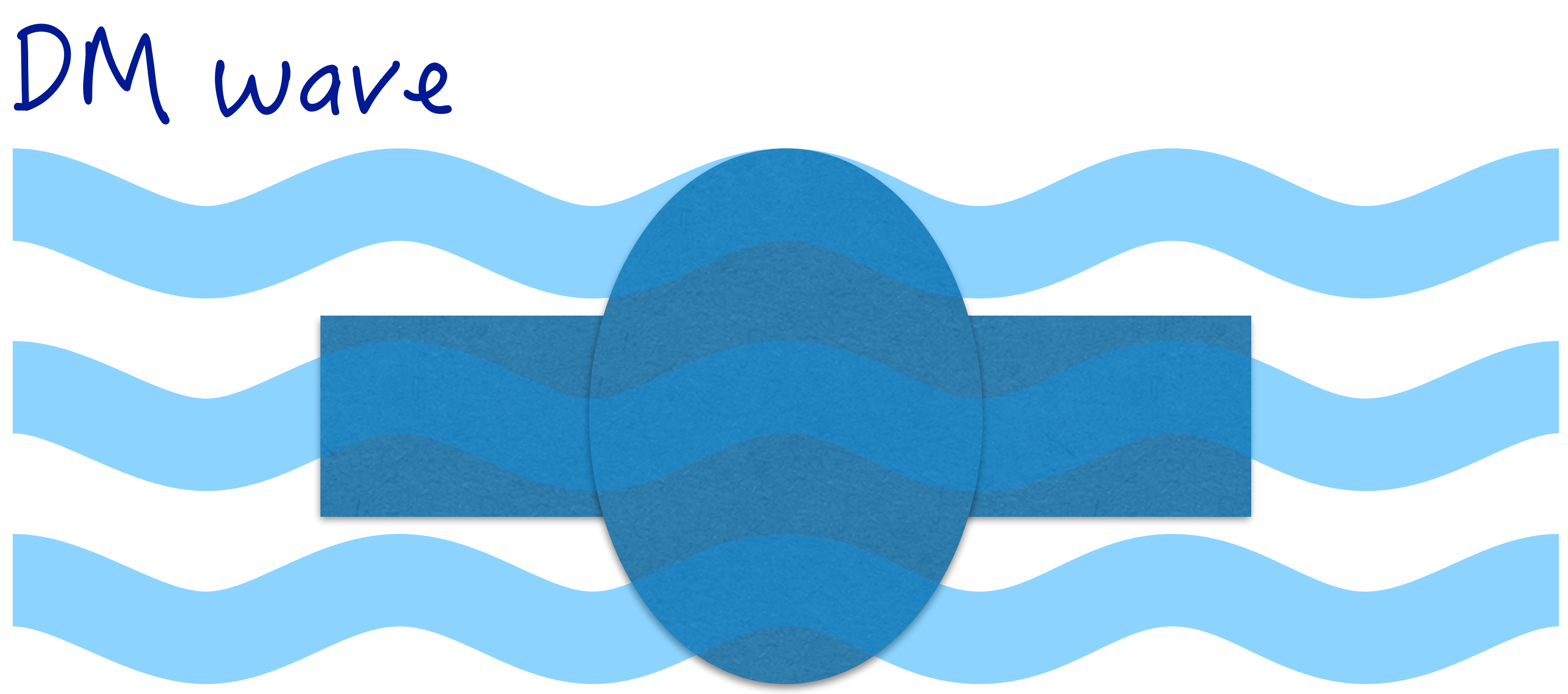

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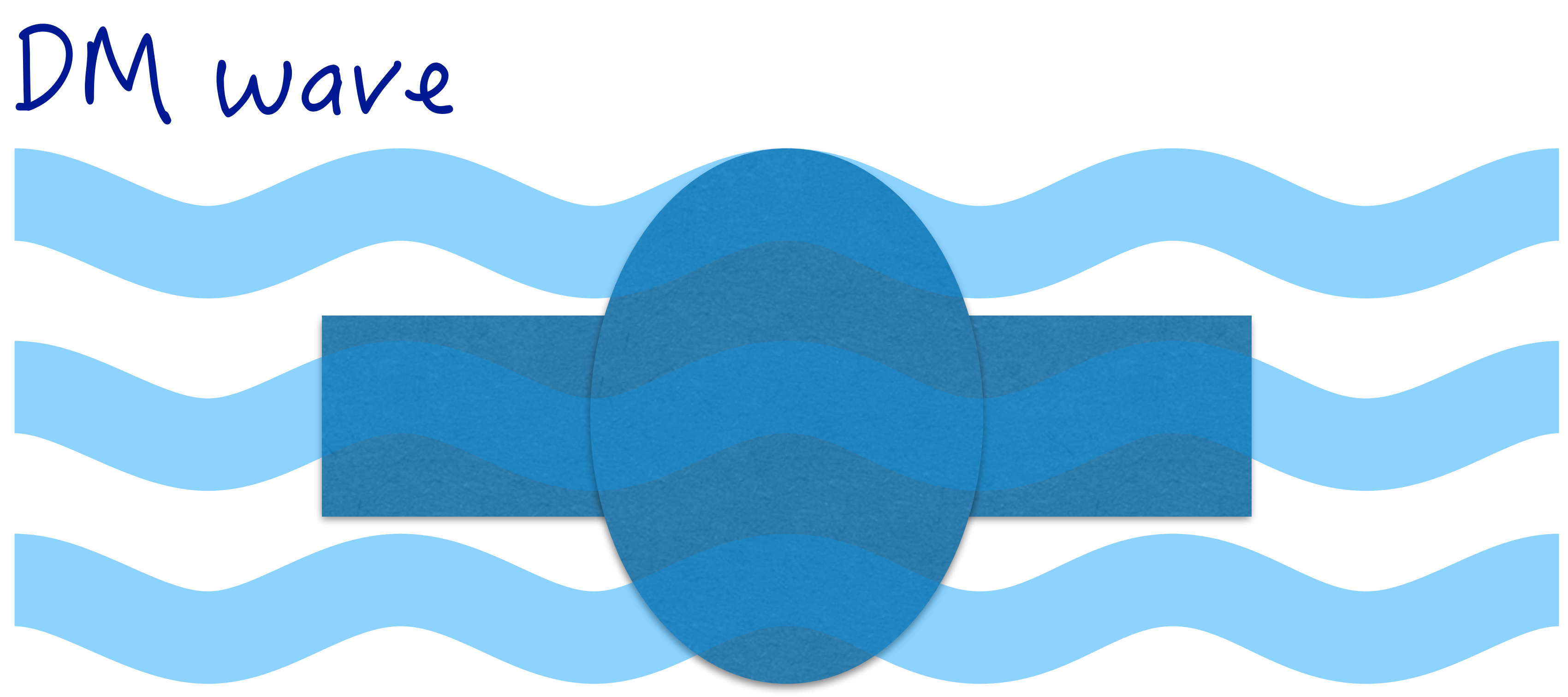

$$\vec{J}_{eff} = \varepsilon \, m_{A'}^2 \vec{A}'$$

An effective current inside the cavity!

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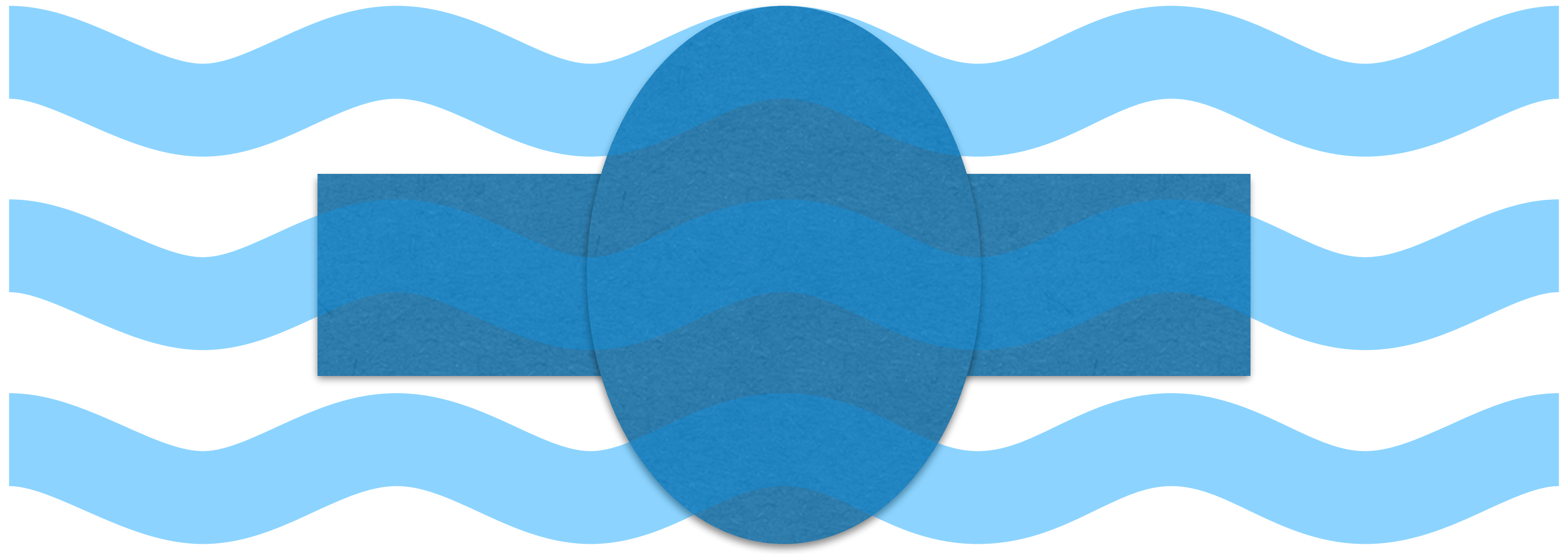
DM wave



$$\vec{J}_{eff} = \varepsilon\, m_{A'}^2\, \vec{A}'$$

An effective current inside the cavity!

DM signals: a low powered injection of photons into EM devices at a **fixed frequency**, and an unknown phase. *(Enter Quantum sensing. Kent and Aaron's talks)*.

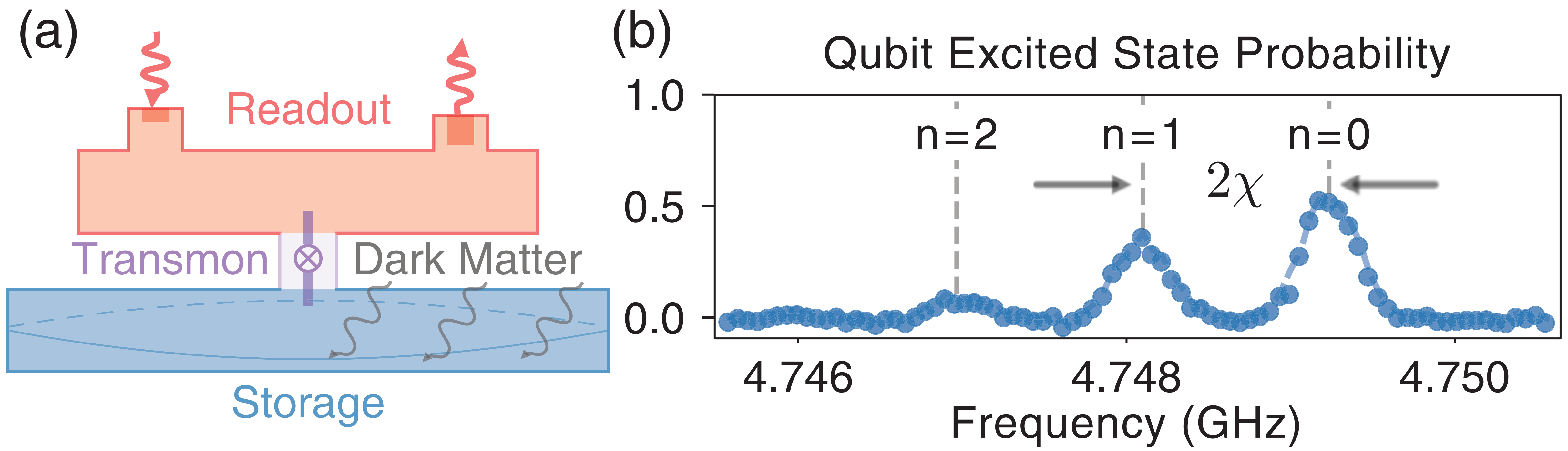
Searching for Dark Matter w/ a Qubit

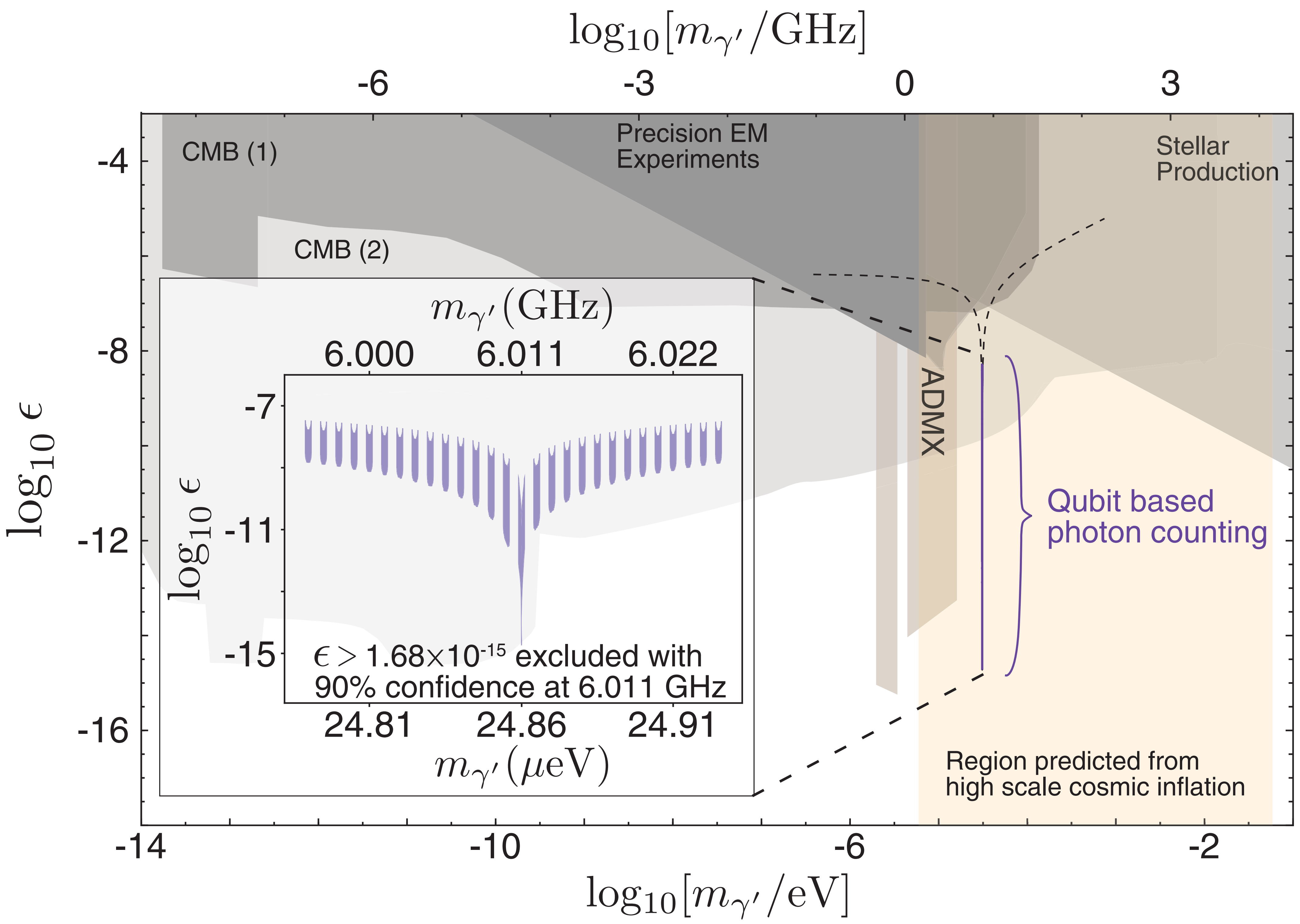
- A proof of concept:

PHYSICAL REVIEW LETTERS **126,** 141302 (2021)

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit,[1,2,3,*] Srivatsan Chakram,[1,2,4] Kevin He,[1,2] Ankur Agrawal,[1,2,3] Ravi K. Naik,[5]
David I. Schuster,[1,2,6] and Aaron Chou[7]

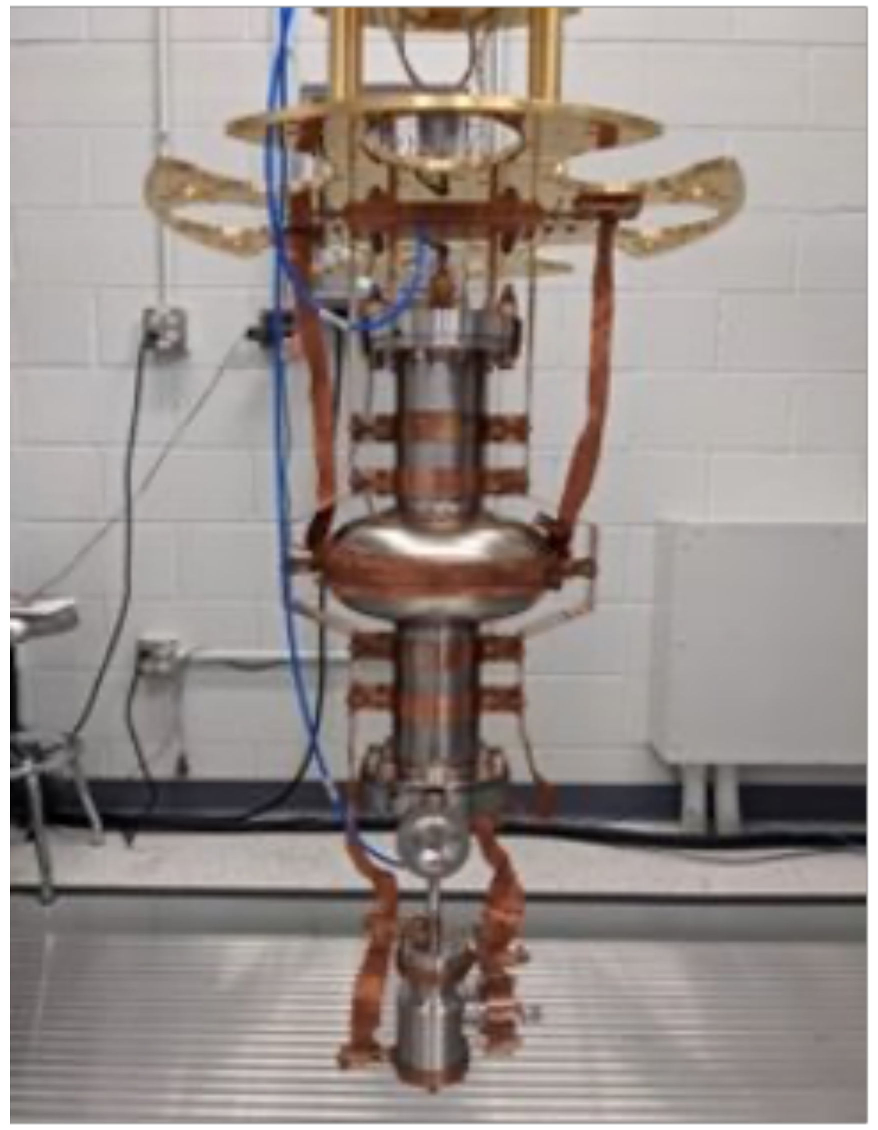


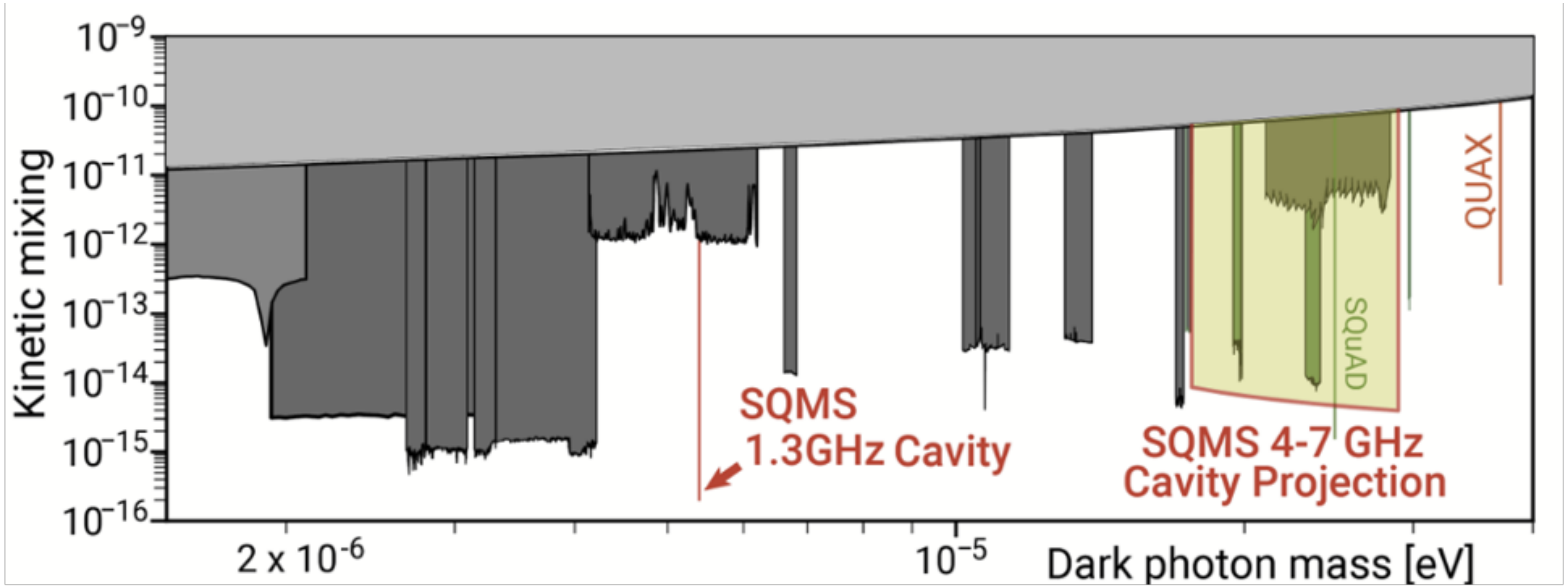


Proof of concept for sensing below with Photon counting and QND.

Dark Photon DM at SQMS

- Meantime: The Ultra high-Q cavities y'all have been playing with allow to search in a very narrow band (reducing noise :-).



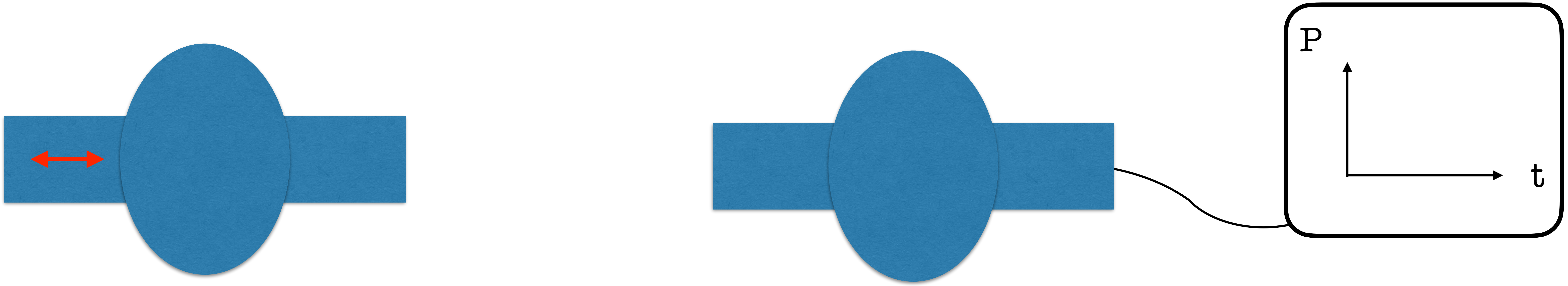


Cervantes et al., arxiv:2208.03183, in review in Phys. Rev. Lett.

Photon counting vs homodyne

Light Shining Through Wall (w/ RF cavities)

- Consider two cavities with with **exactly** same frequency



Light Shining Through Wall (w/ RF cavities)

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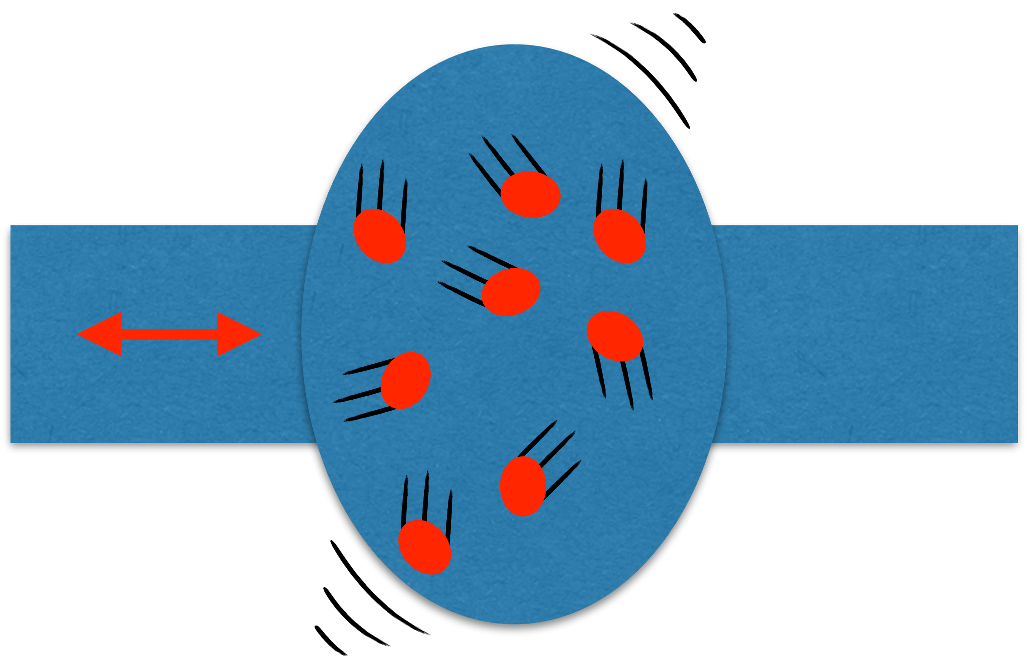

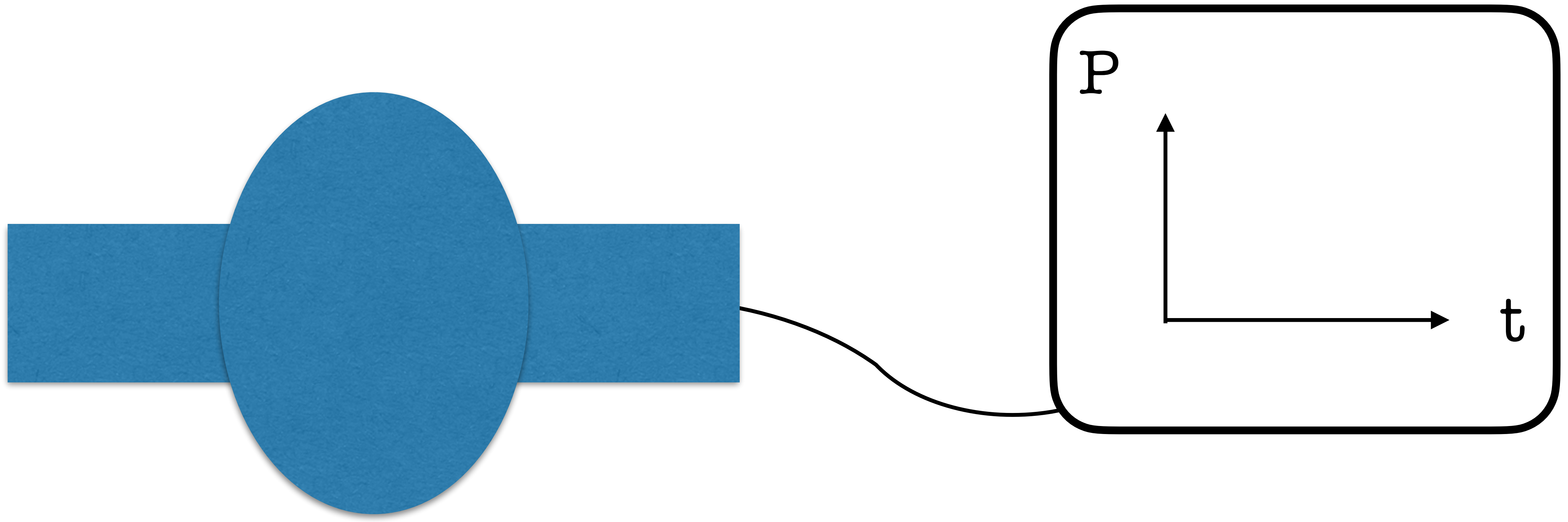

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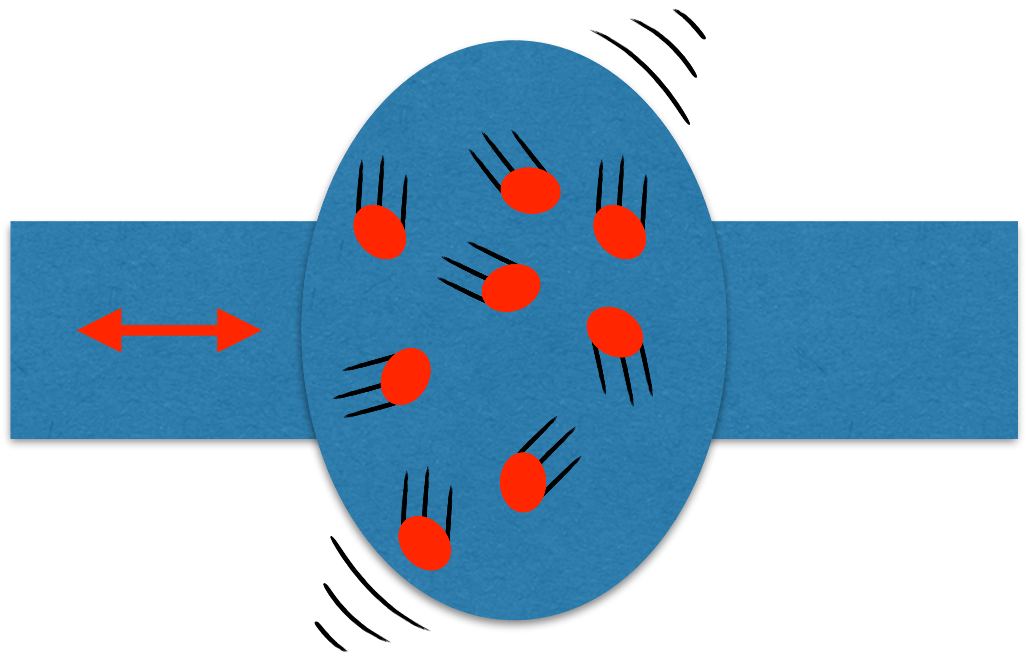

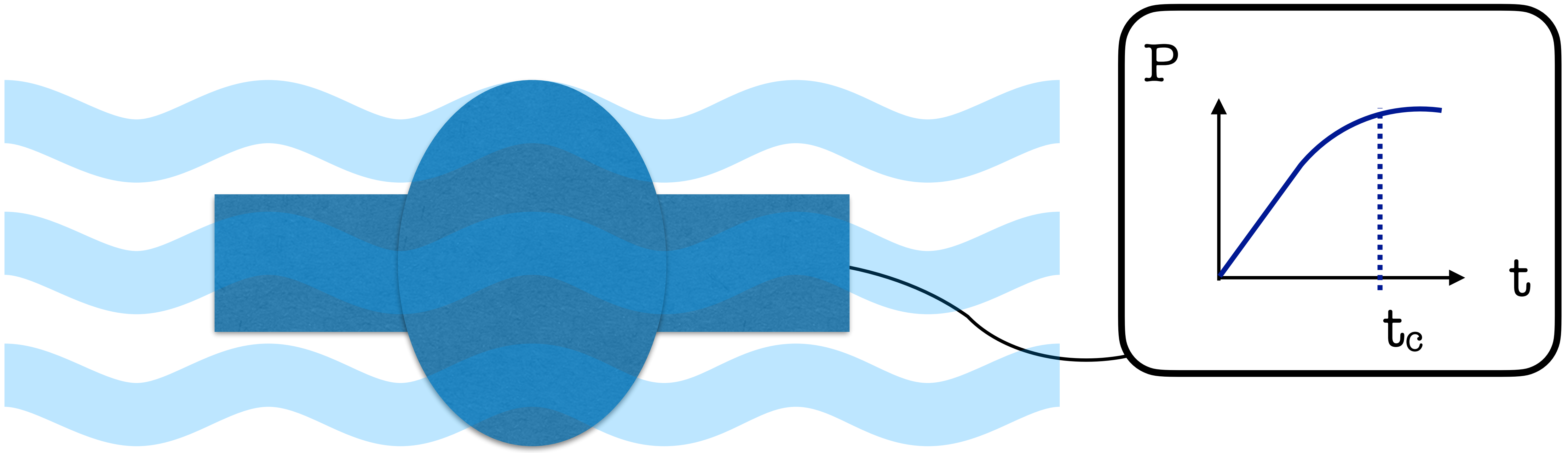

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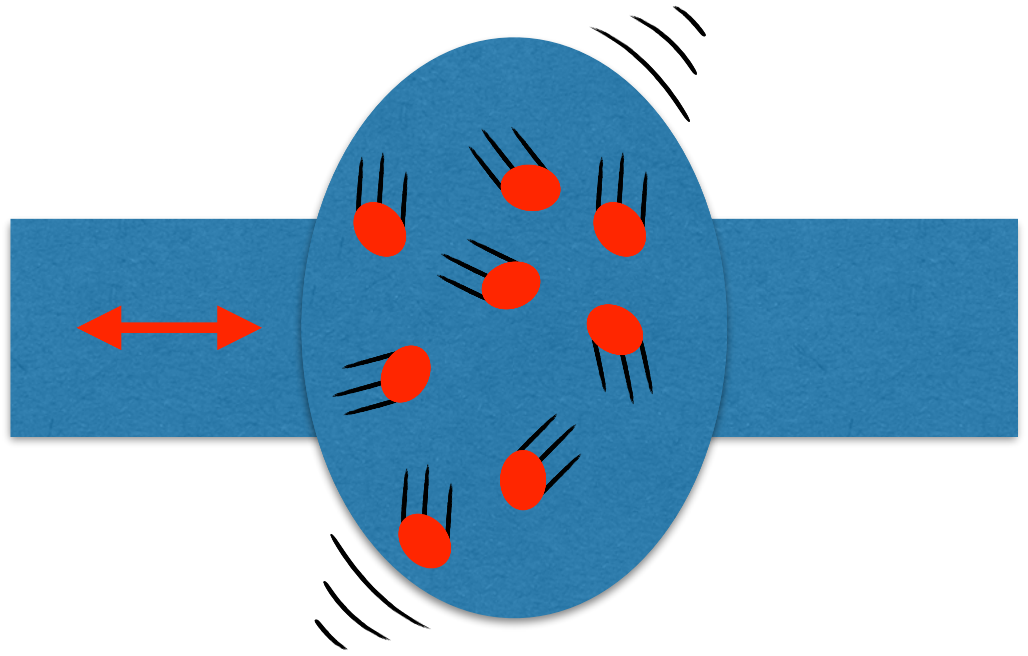

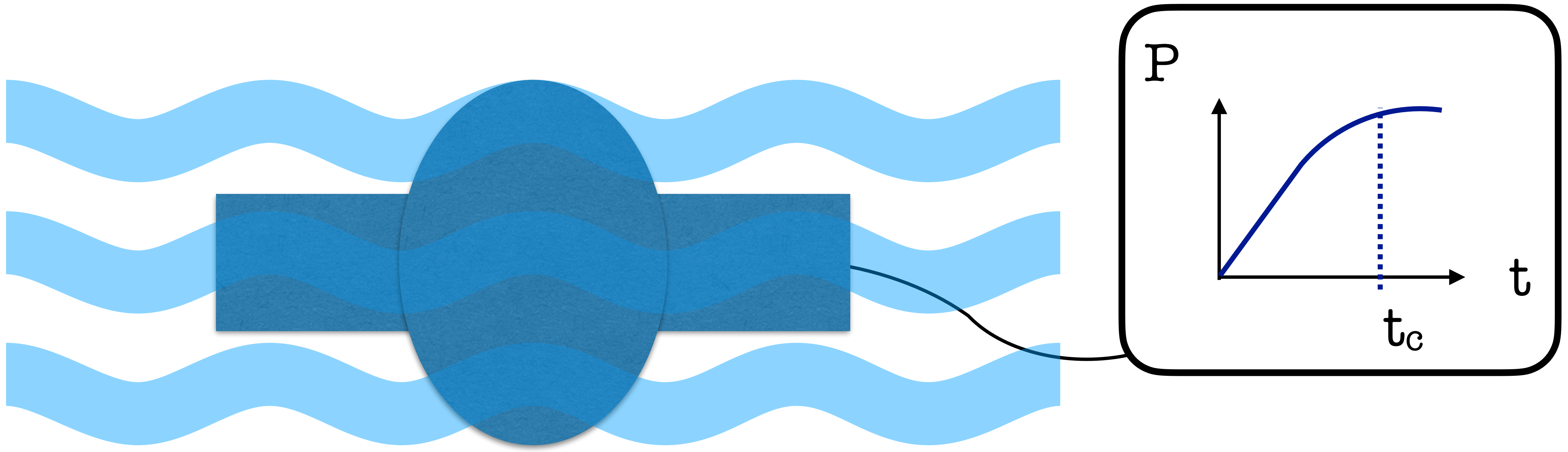

Light Shining Through Wall (w/ RF cavities)

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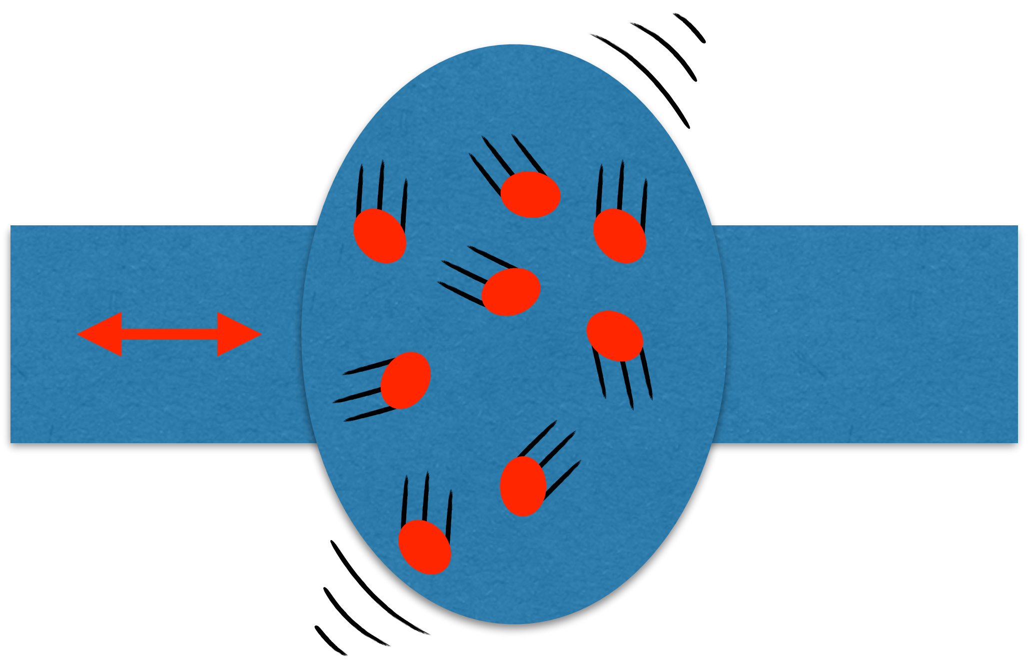
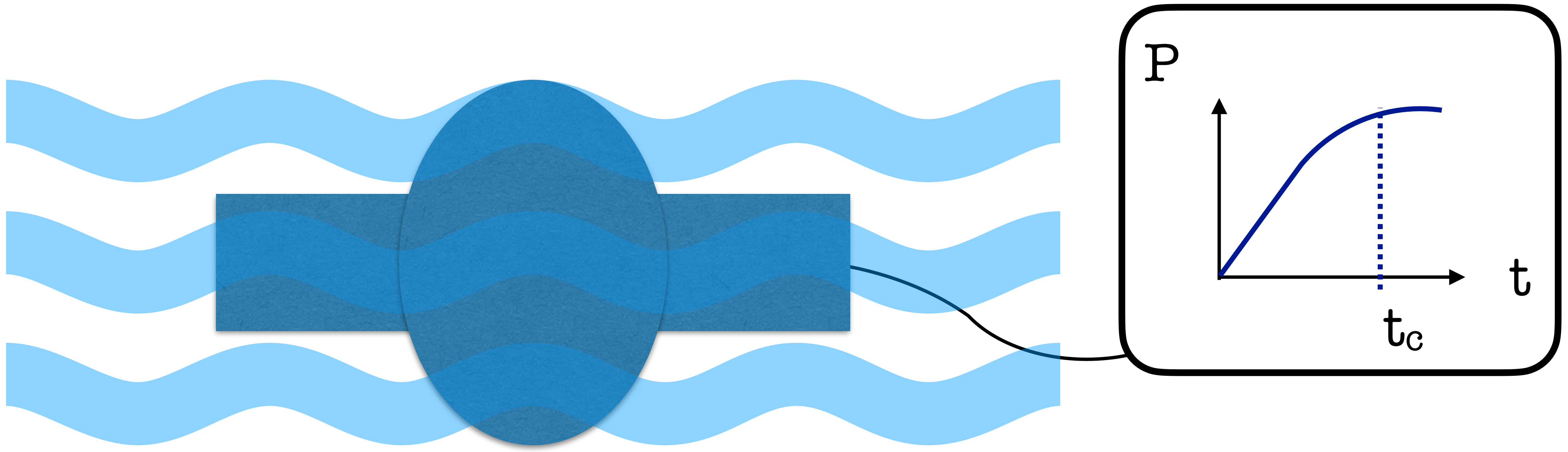


High Q → we can store more photons. Coherent field.



High Q → cavity can ring up for a longer time

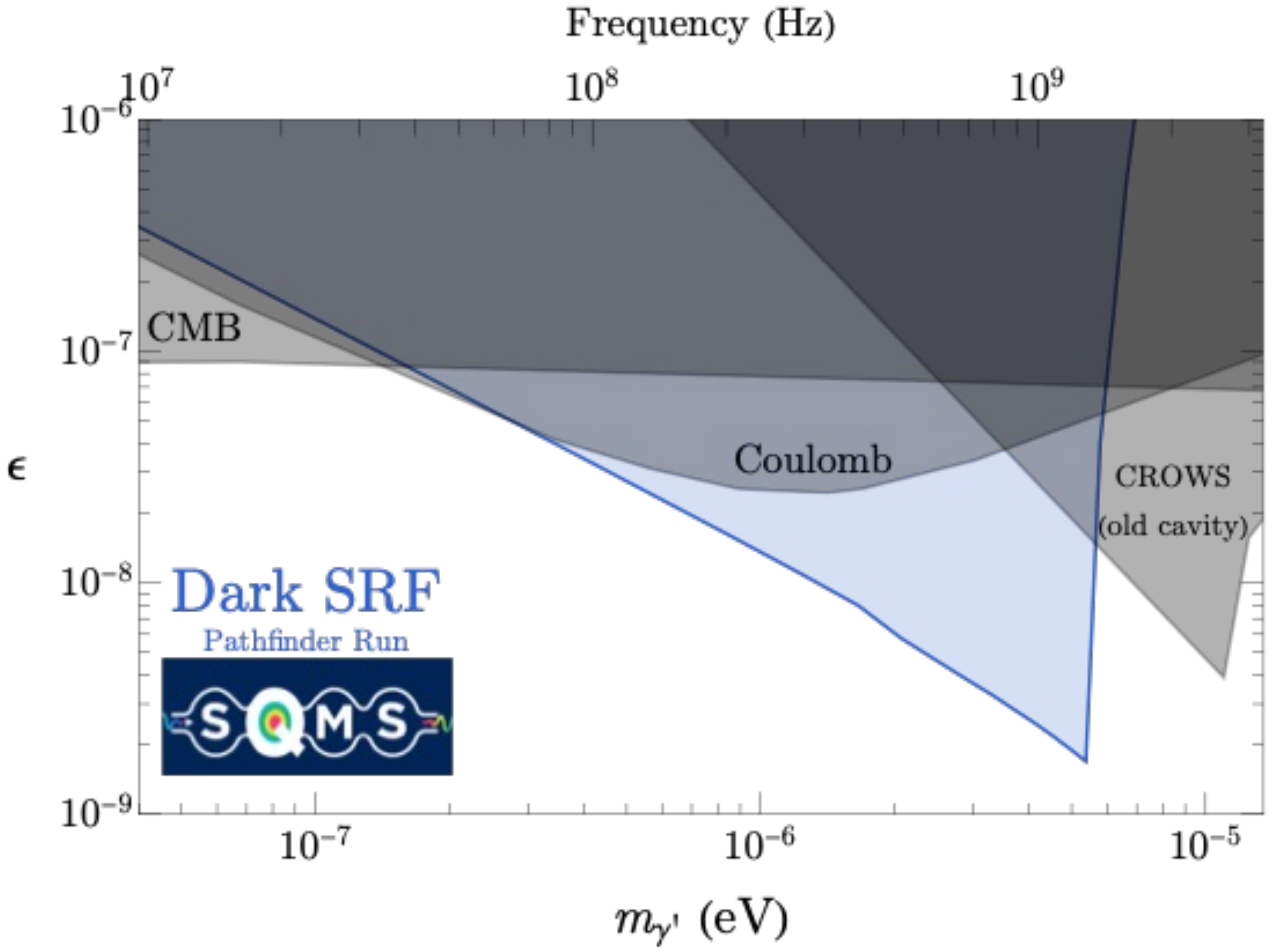
$$P_{\rm rec} \sim G^2\, \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 Q_{\rm rec} Q_{\rm em} P_{\rm em}$$

* Coming clean: scaling with mass depends on the polarization.

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.

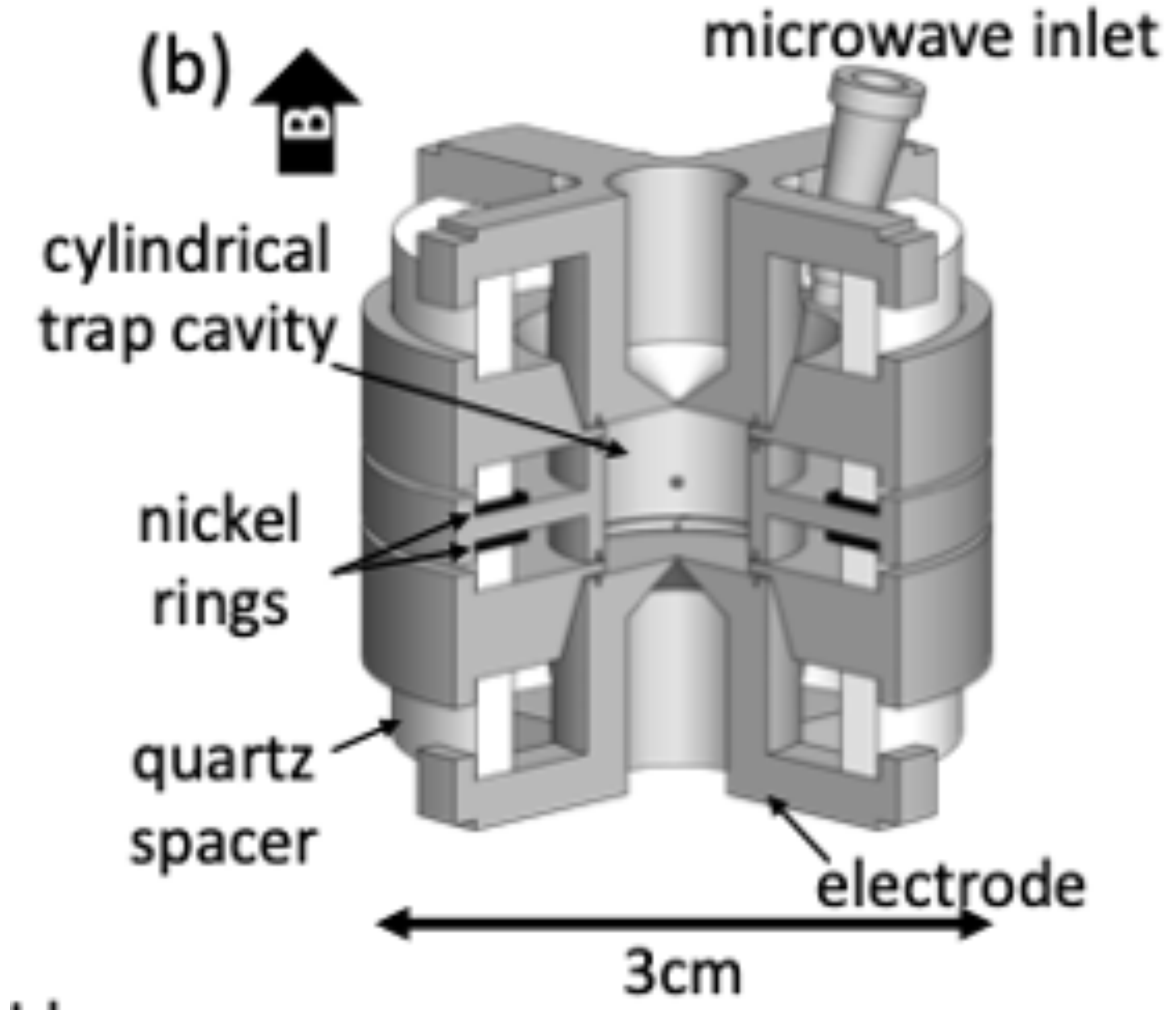
Romanenko et al., arXiv:2301.11512 (2023), Published in PRL

Single Particle Qubit

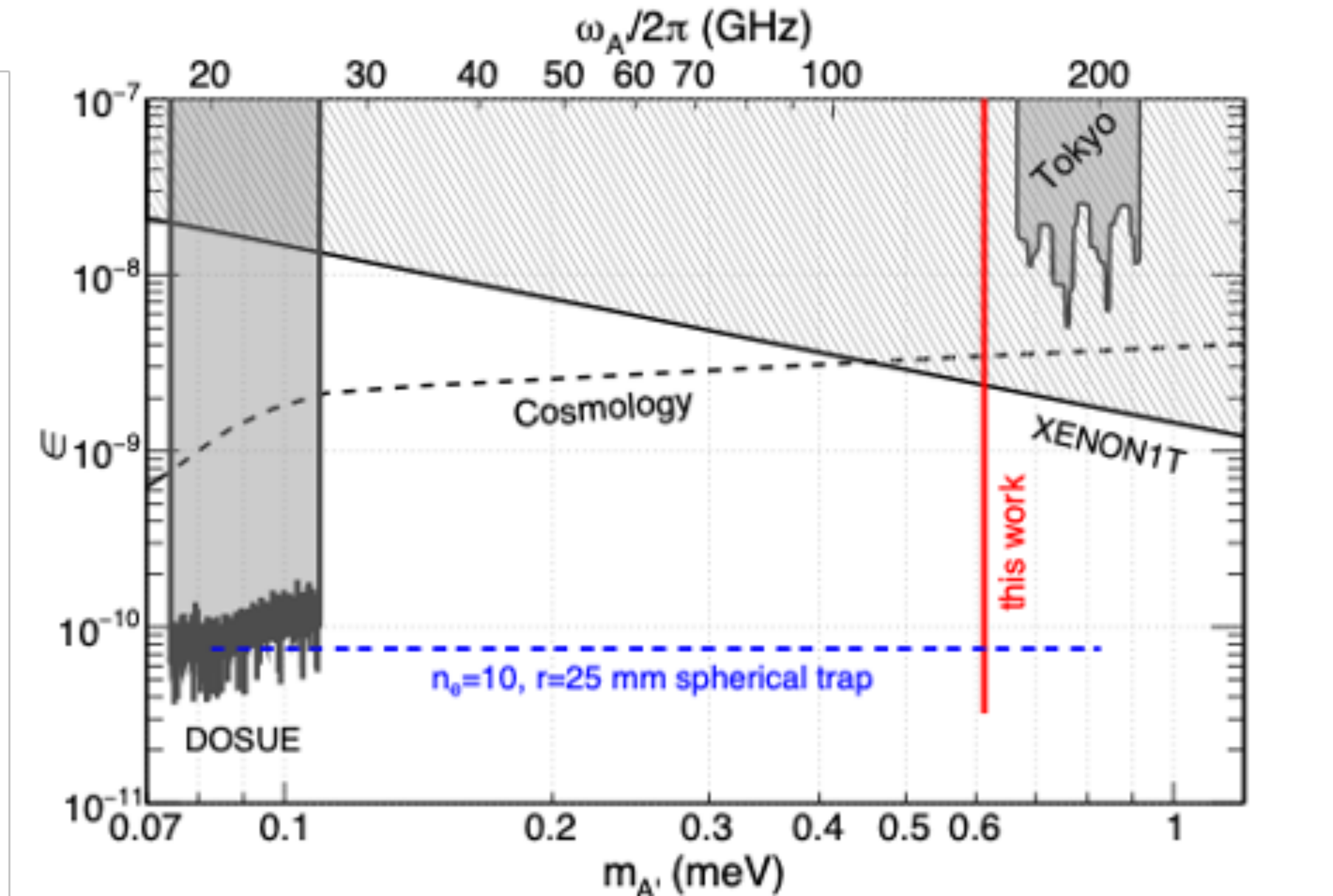
- At Northwestern, the quantum state of a single electron in a Penning trap is monitored with a QND measurement.
- The most precise test of the SM of particle physics!!!

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

Phys. Rev. Lett. 130, 071801 (2023)



- This is a quantum-number counting experiment.
- Also sensitive to Dark Photon DM at 150 GHz!



Phys.Rev.Lett. 129 (2022) 26, 261801

SQMS

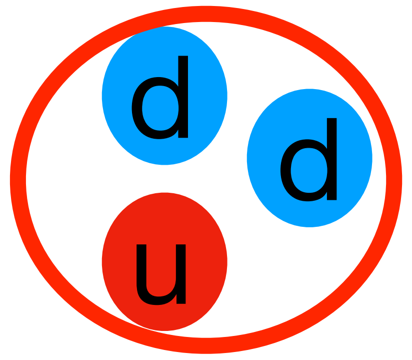
Axions

A nonlinear extension of QED

Pecci and Quinn (77)

Axions - and Strong CP

- Invented to address a theoretical puzzle of the strong force: "Strong CP problem"
- The Electric dipole moment of particles violate parity and charge conjugation. Both are symmetries that are violated at the subatomic level.
- The neutron's EDM is observationally consistent with 0, 10^{-10} smaller than the (neutron size) x (fundamental charge unit)



- The neutron is a collection of quarks. Somehow the strong force dynamics respects CP.

Why don't (gluon) E-fields and B-fields mix?

Pecci and Quinn (77)

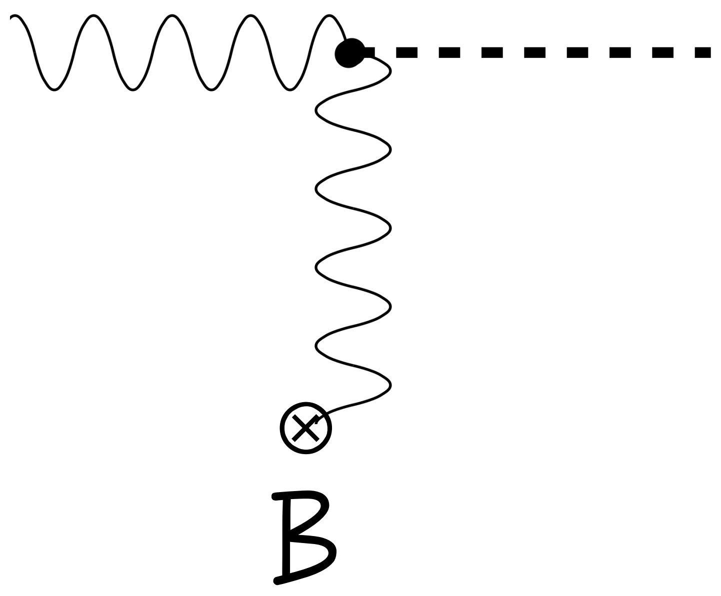
Axions - A nonlinear extension of QED

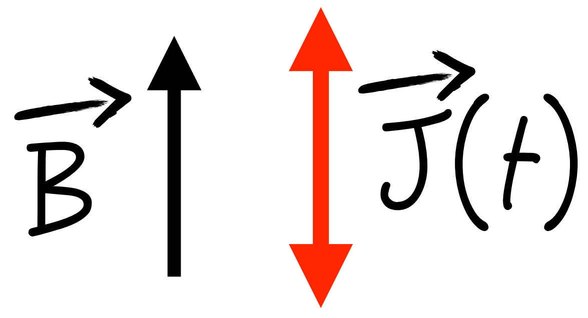
Introduce a field: $\mathcal{L} \supset \frac{a}{f} G^{\mu\nu}\tilde{G}_{\mu\nu} = \frac{a}{f} \vec{E}_G \cdot \vec{B}_G$ $\langle a \rangle \to 0$ dynamically.

- Naturally, one would also expect: $\mathcal{L} \supset \frac{a}{f} F^{\mu\nu}\tilde{F}_{\mu\nu} = \frac{a}{f} \vec{E} \cdot \vec{B}$

- Axion phenomenology w/ background B field is similar to dark photon. Mixing:

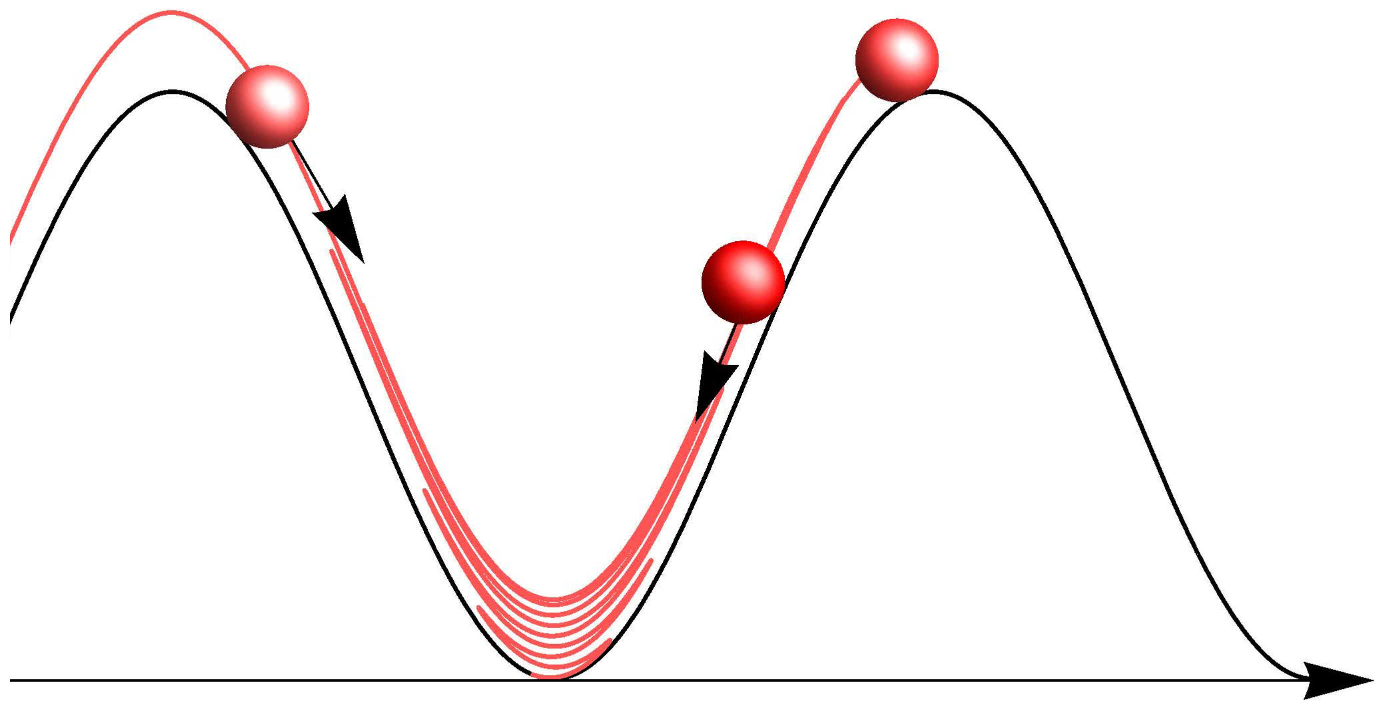
$$\mathcal{L} \supset \frac{a}{f} F^{\mu\nu}\tilde{F}_{\mu\nu} = \frac{a}{f} \vec{E} \cdot \vec{B}$$





Photons polarized along a B field can mix with axions.

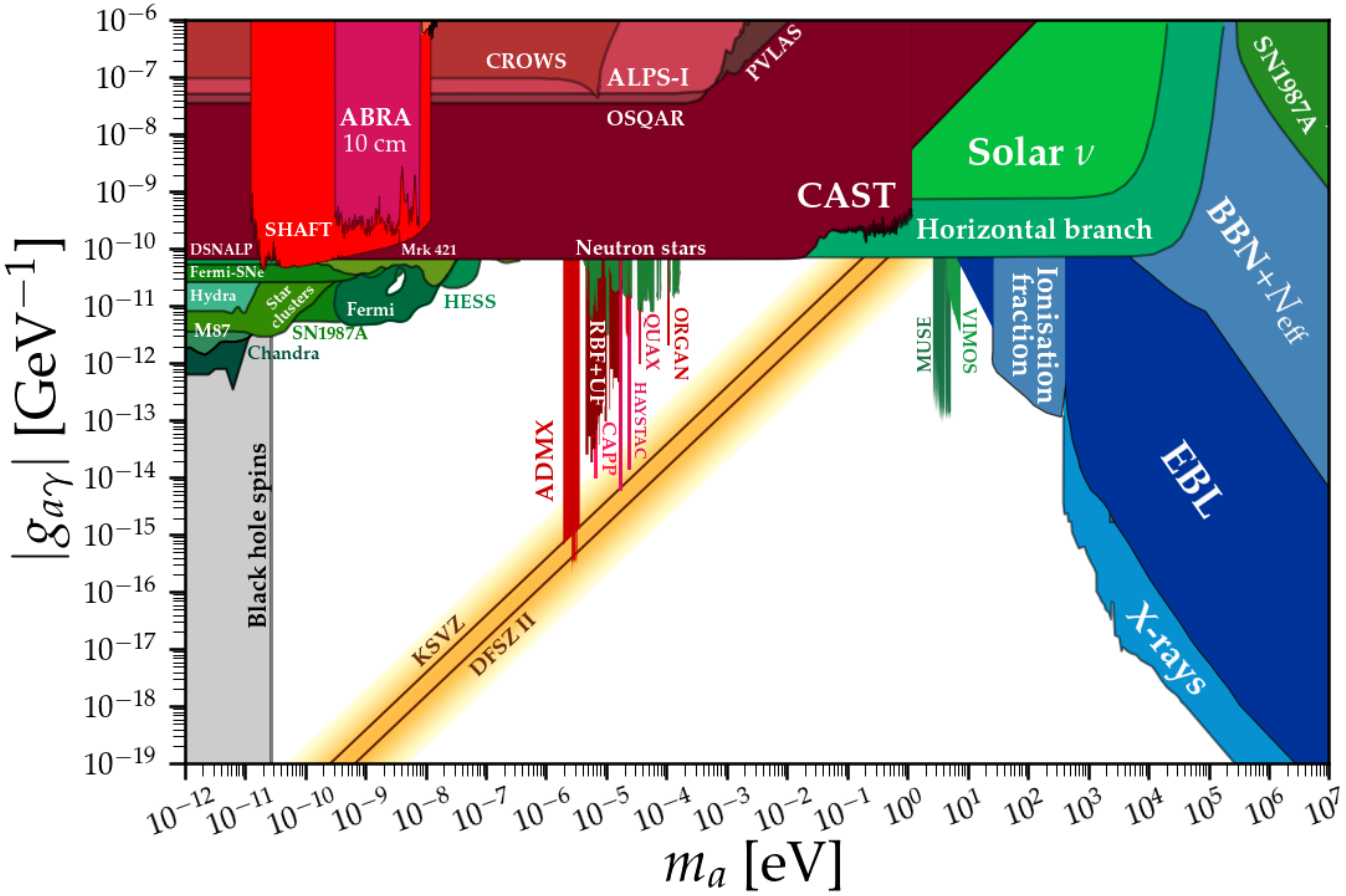
Axion Dark Matter

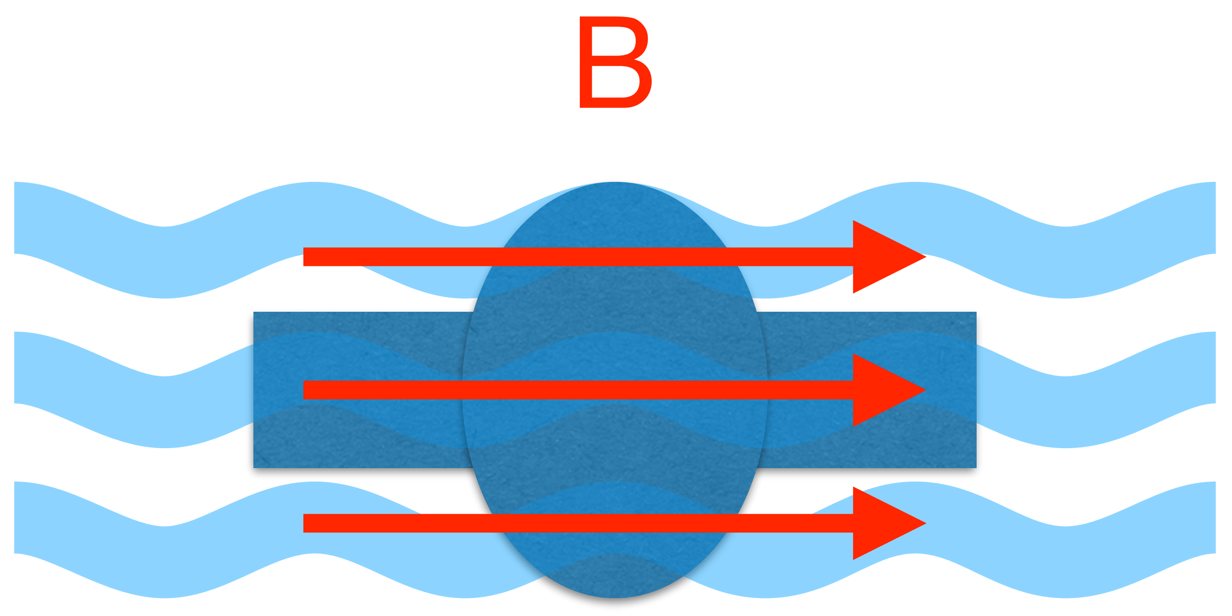


- Like the dark photon:
  coherent waves of the axion fields can be a good dark matter candidate!

- <u>Very attractive theoretically:</u>
  - there are other reasons for the field to exist.
  - It can get excited at some level. Can that be (some of) dark matter?
  - The QCD axion predicts the interaction strength (gives a goal!).

Axions and ALPs





New challenges:

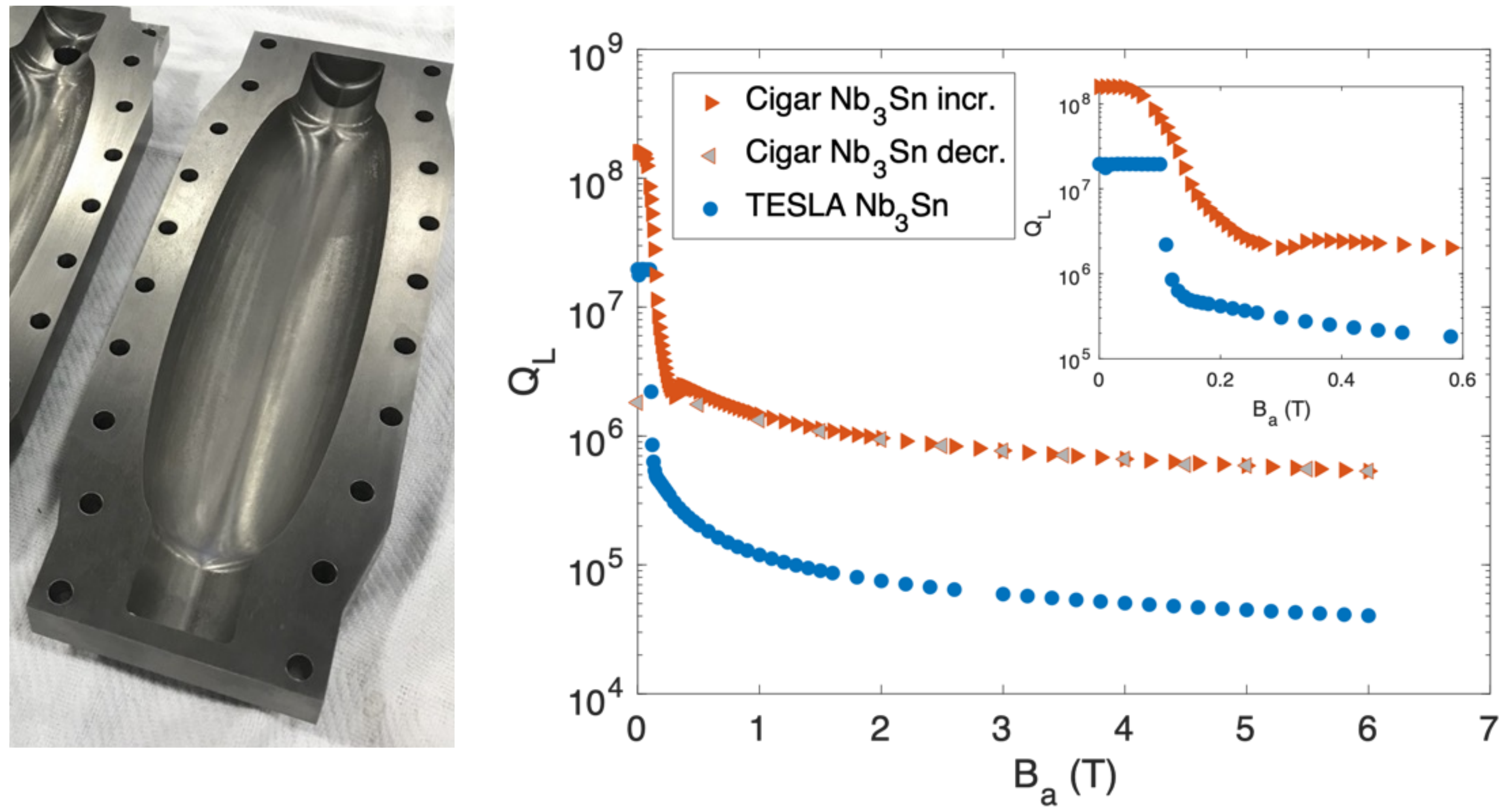
superconducting quantum devices that can operate in (or near) high magnetic fields!

Dark Sector: High Q in Multi-Tesla Fields

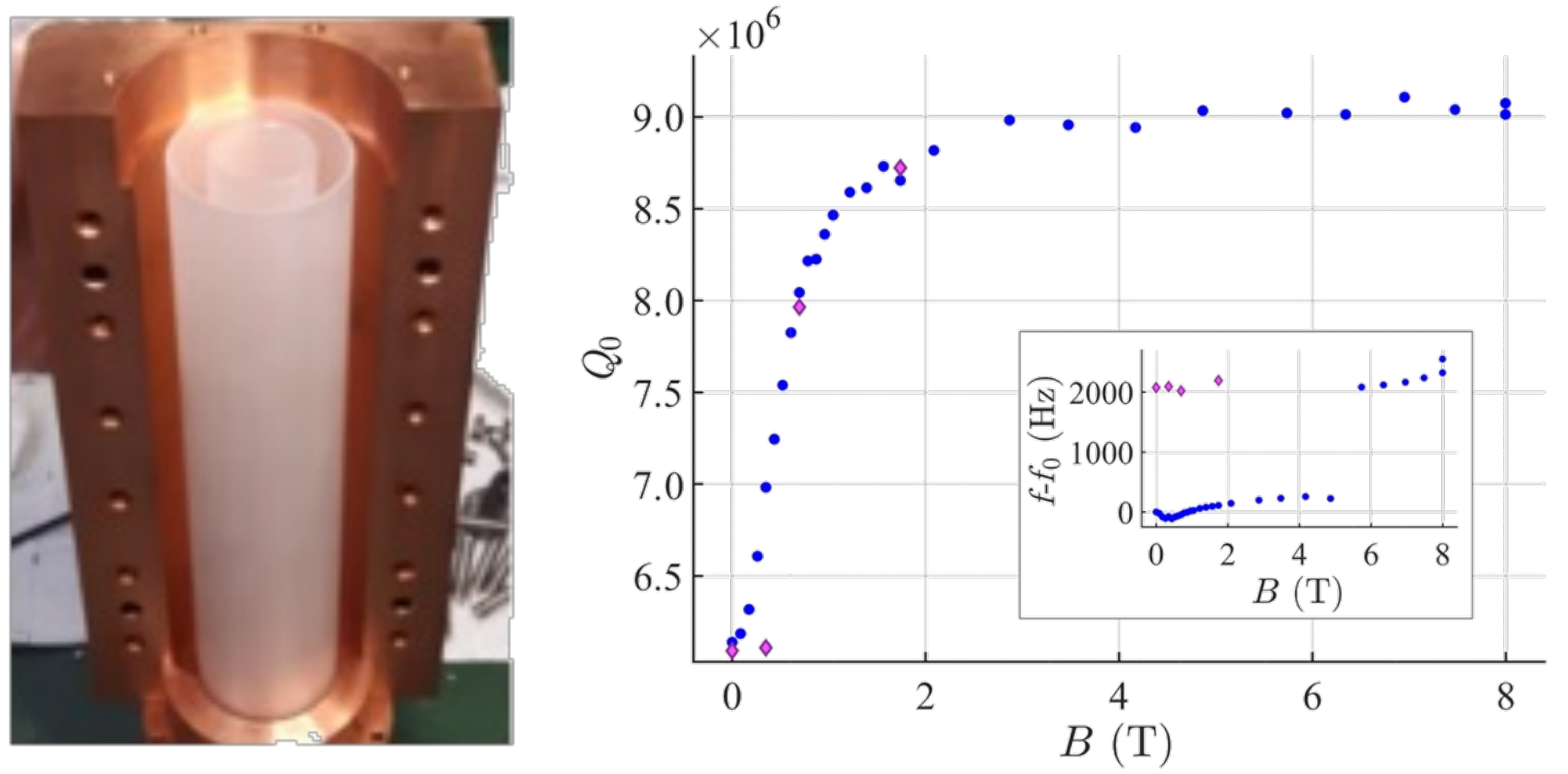
Axion haloscope: search for dark matter with high Q cavity in multi-tesla magnetic fields

Two SQMS designs substantially outperform state of the art copper cavities (and these ideas can be combined!)

Other Challenges: counting photons near a magnetic field. Cavity and qubit frequency tuning. etc.



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

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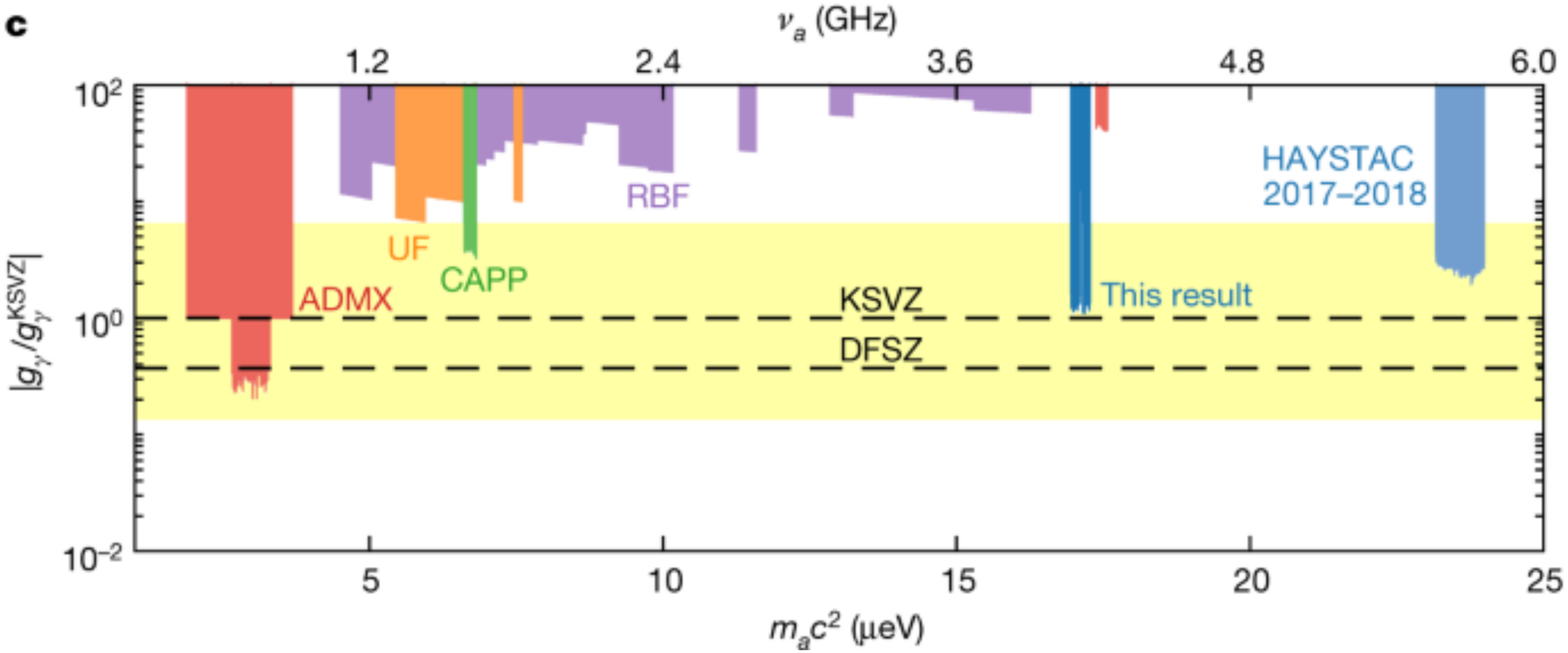
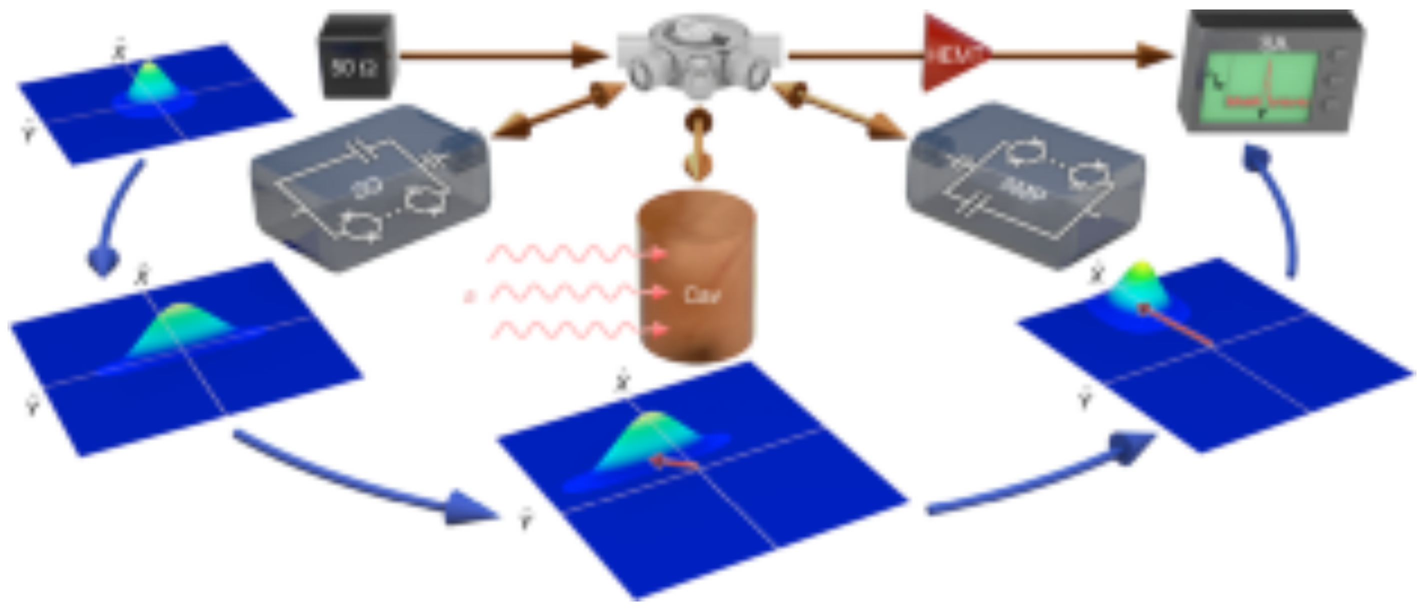
Axions and ALPs



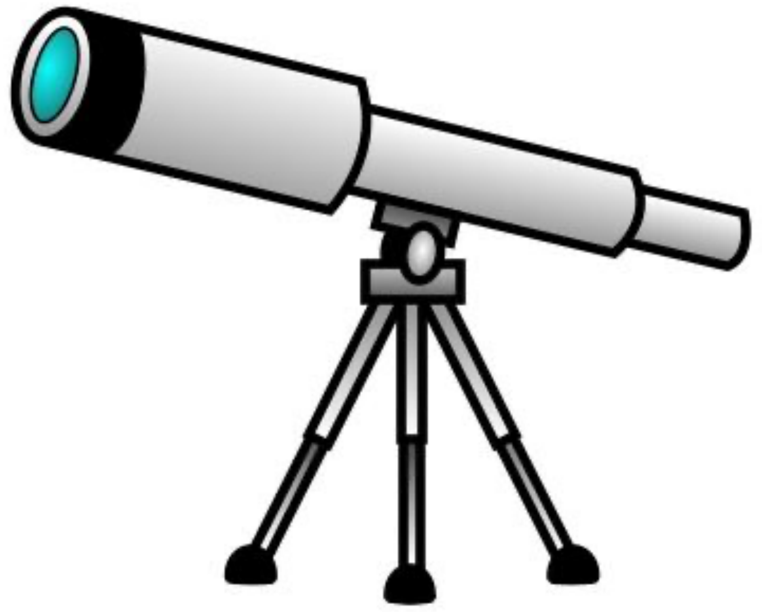


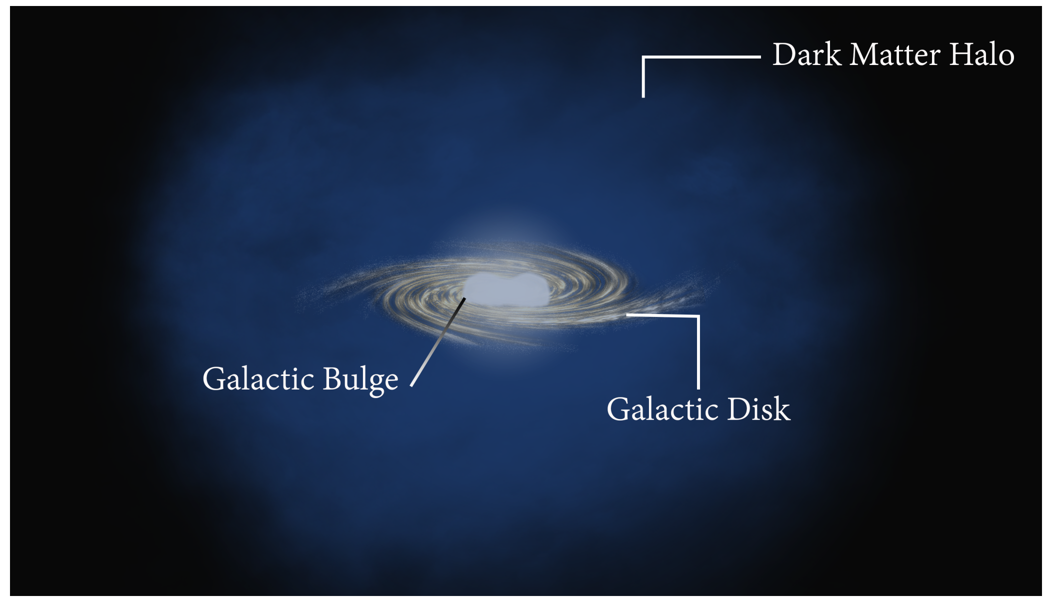
Quantum sensing already playing a role for Axion DM:

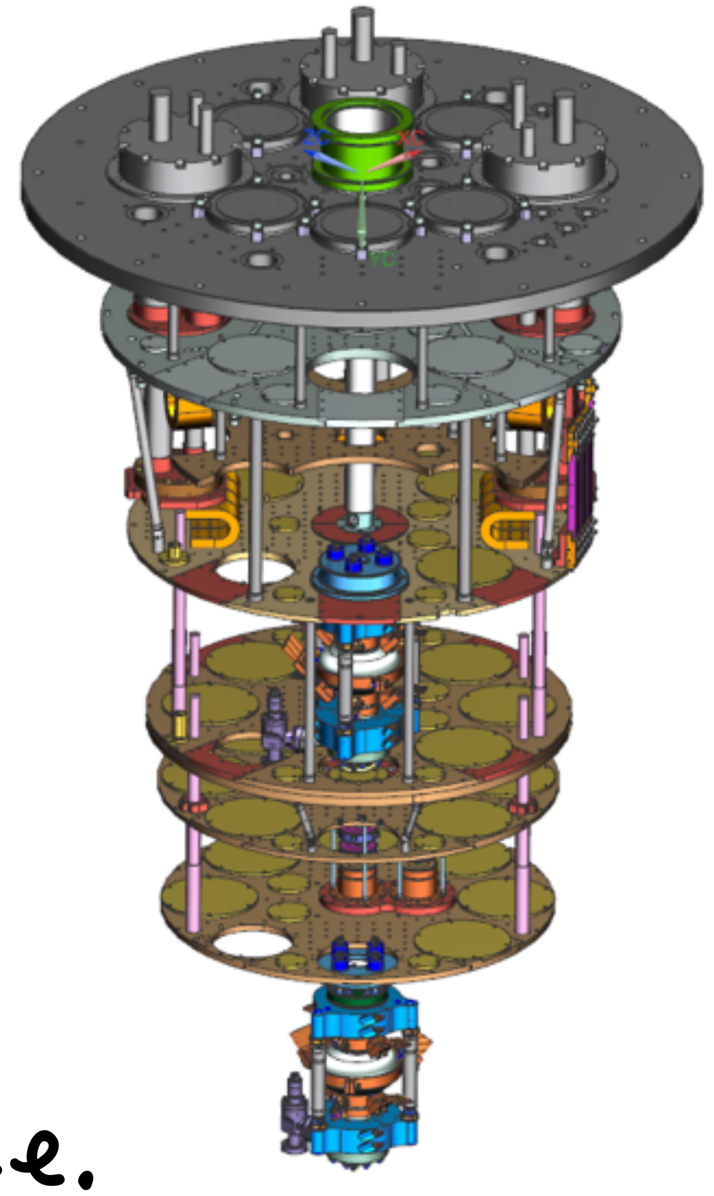
e.g. **HAYSTAC** used squeezed states for factor of 2 in scan speed.

Backes, K.M., Palken, D.A., Kenany, S.A. *et al.*
A quantum enhanced search for dark matter axions. *Nature* **590**, 238–242 (2021)

In Conclusion







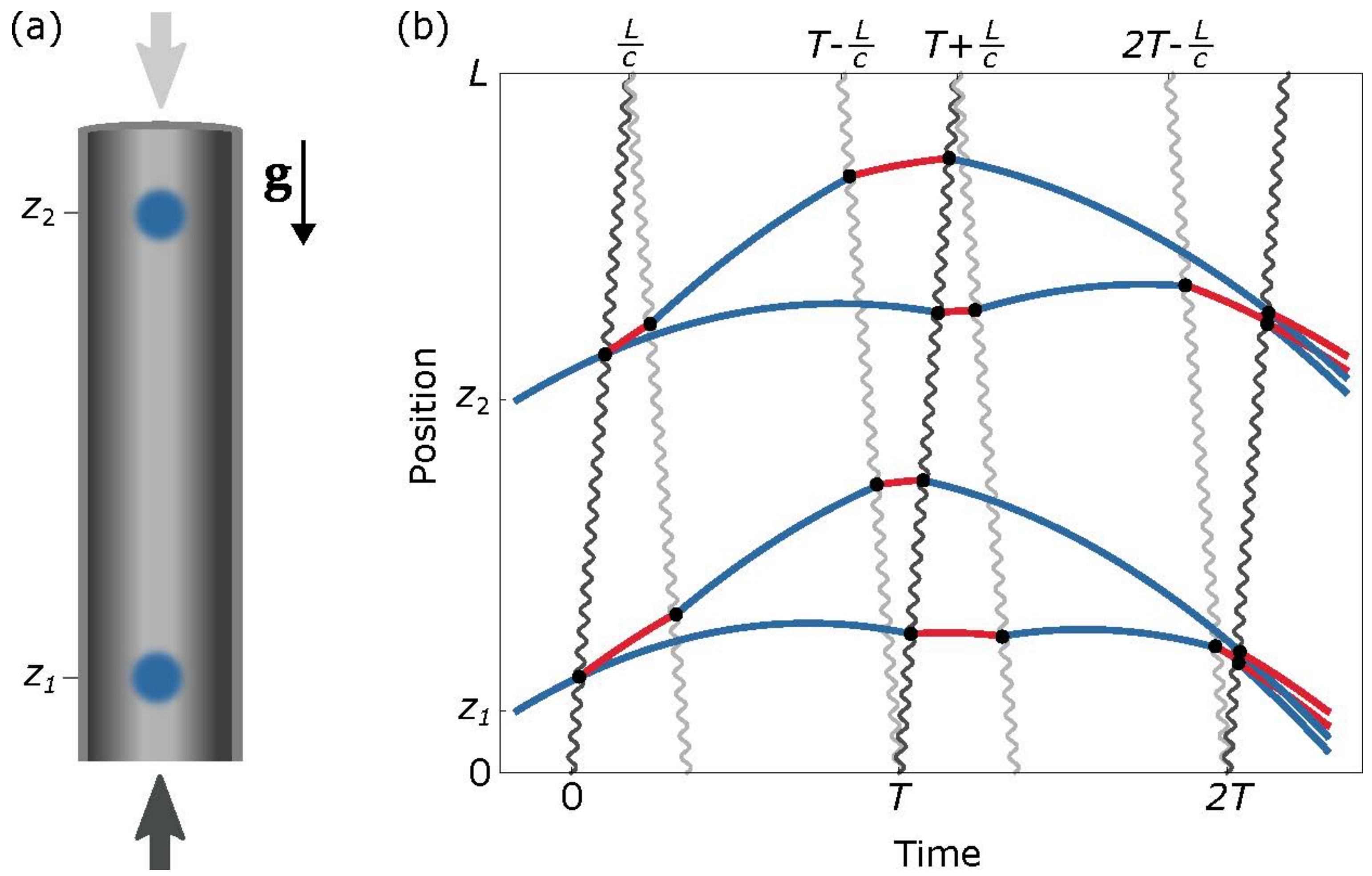
- We are curious about the Universe?
  - What new particles exist?
  - What is dark matter?
  - What can we learn from gravitational waves?
- These ambitious questions require the most sensitive detectors in existence.
- We can let standard quantum limits get in our way! We need QIS!

Deleted scenes

Atom Interferometers

- Superposition allowed for more cool stuff.
- E.g. atomic clocks: am atom in a superposition of quantum states can keep time!

$$|\psi_1\rangle + e^{i\Delta E t/\hbar}|\psi_2\rangle$$



MAGIS 100, under construction, will look for gravity waves!

(The distance between clocks oscillating…)

Gravitational waves

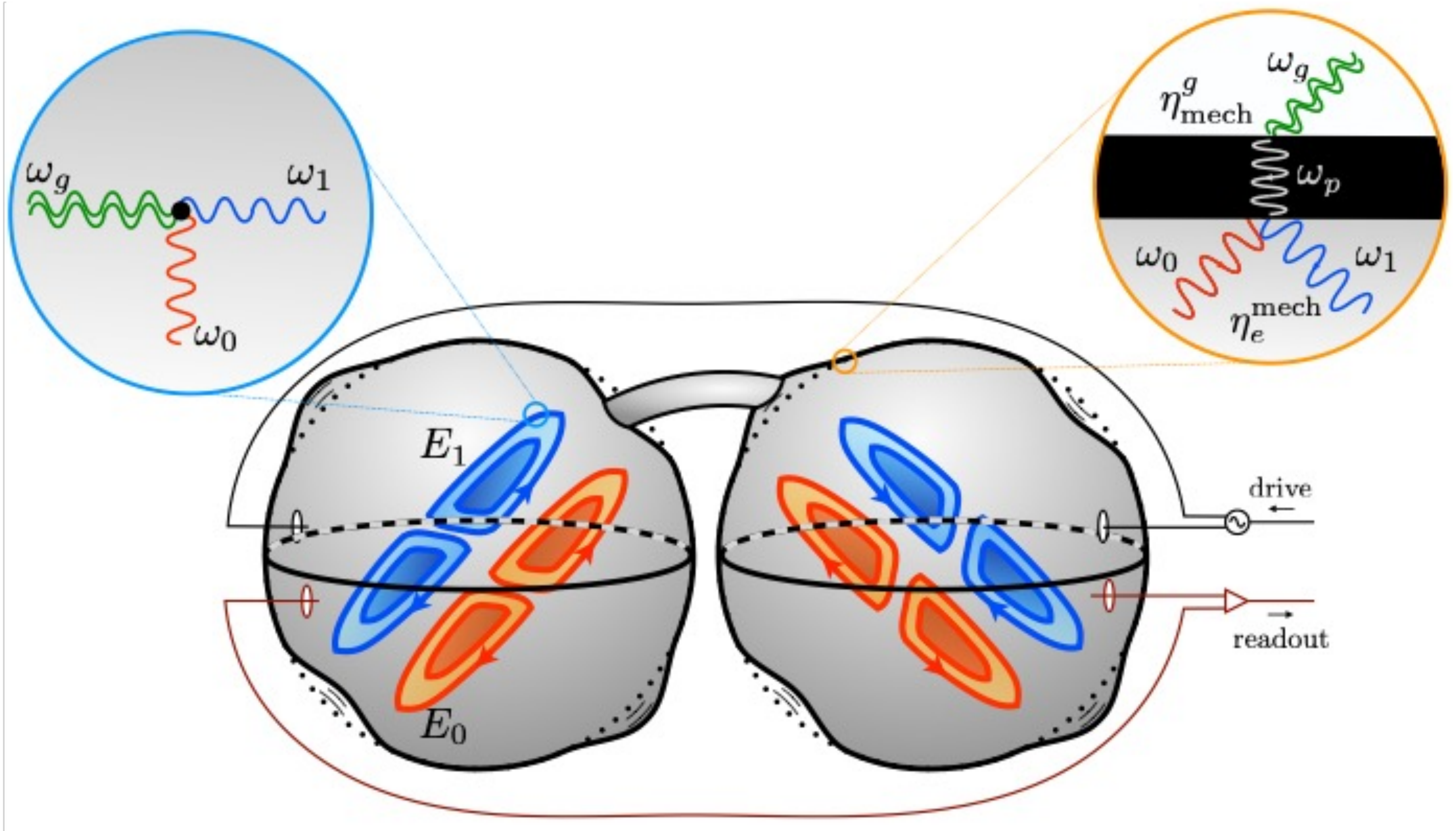
SQMS theorists have laid the formalism for GR-EM cavity interaction.

Two types of signals: EM and mechanical.

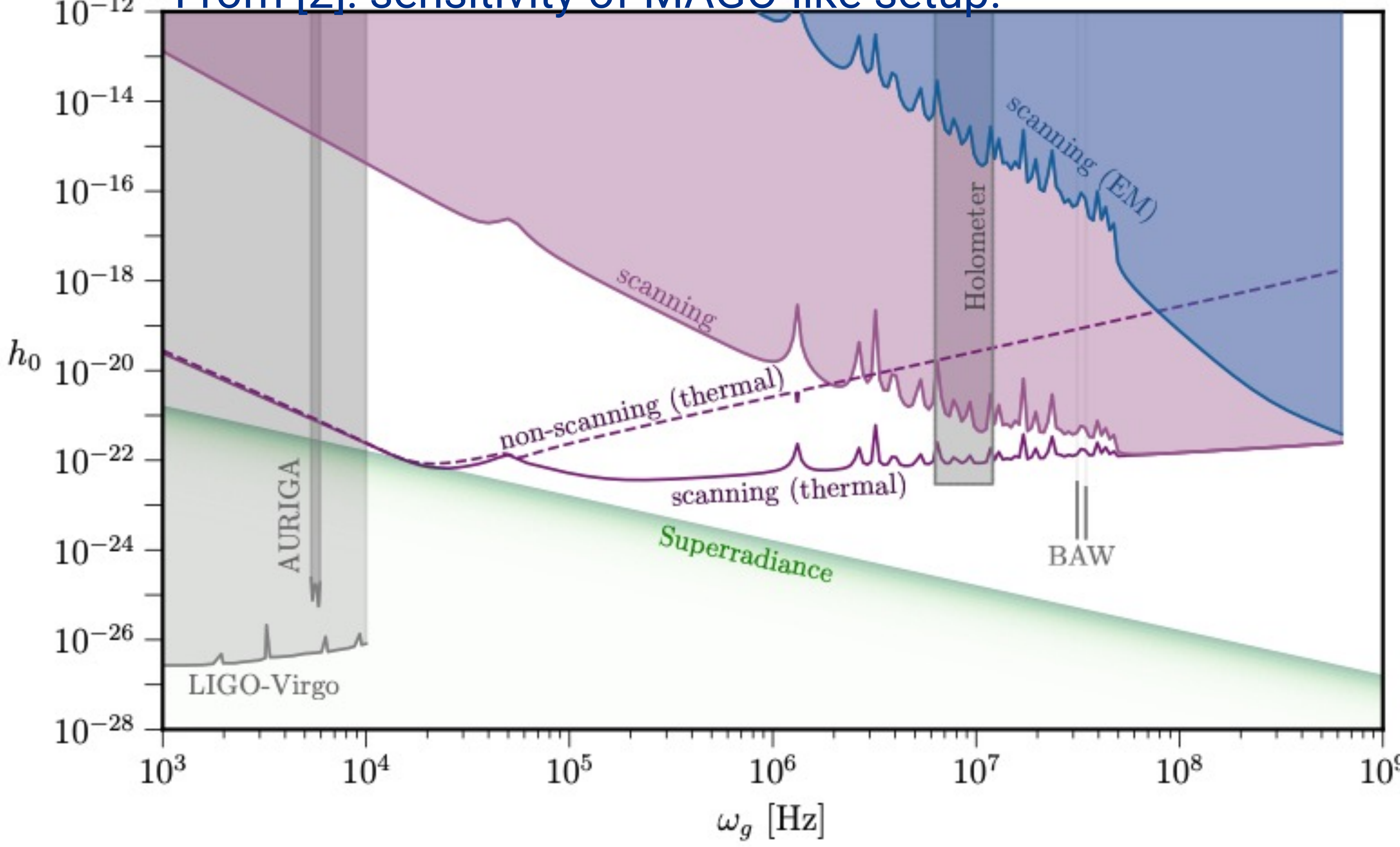
Current axion experiments have sensitivity to GHz Gravity waves [1].

A dedicated cavity experiment, e.g. MAGO, has significant reach at MHz [2].

A new collaboration with INFN and DESY to revive MAGO is being formed.



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



MAGO (INFN)

[1] *Phys.Rev.D* 105 (2022) 11, 116011

[2] Berlin et al, in preparation.

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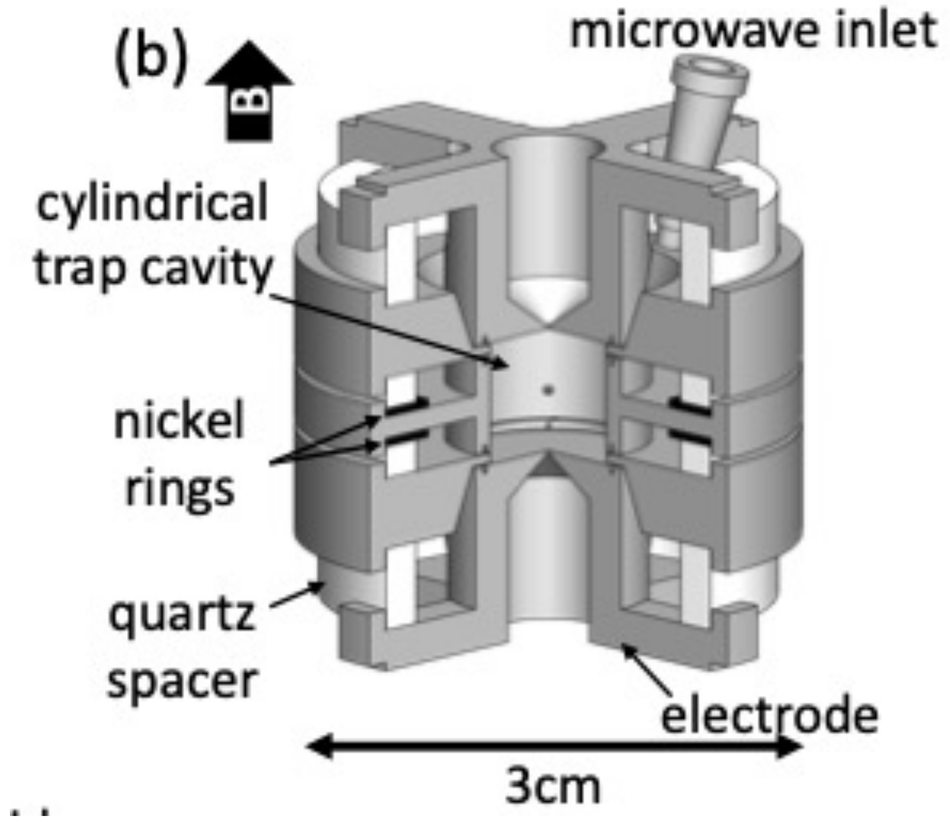
Single Particle Qubit



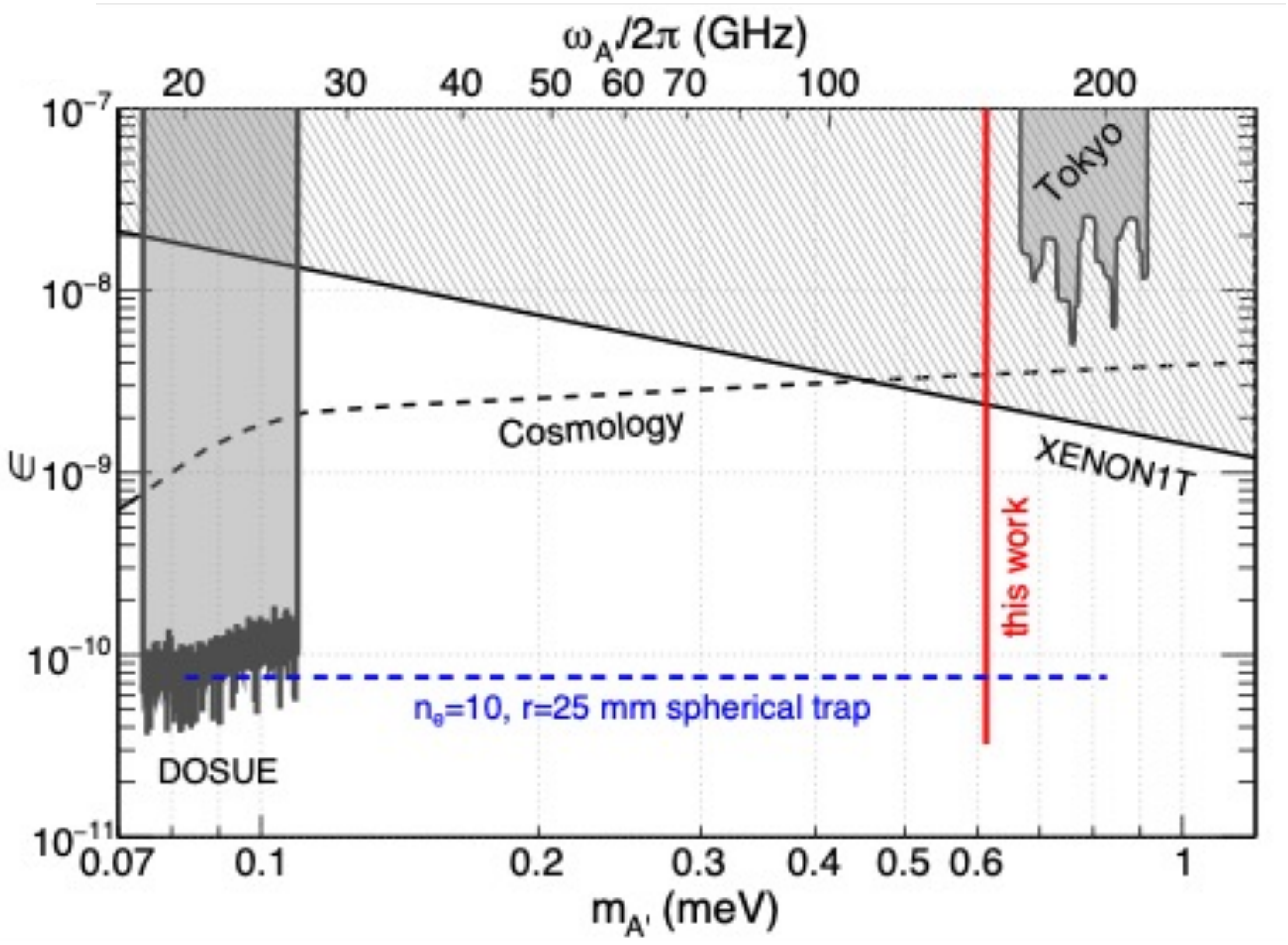
The most precise theory-experiment comparison in physics:

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)
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)

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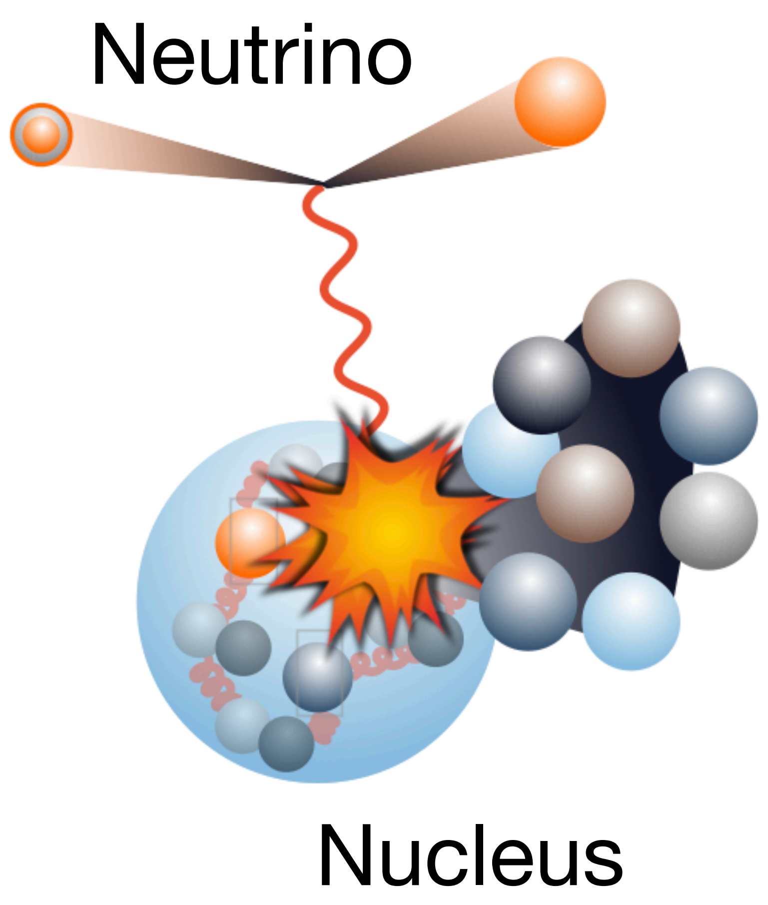
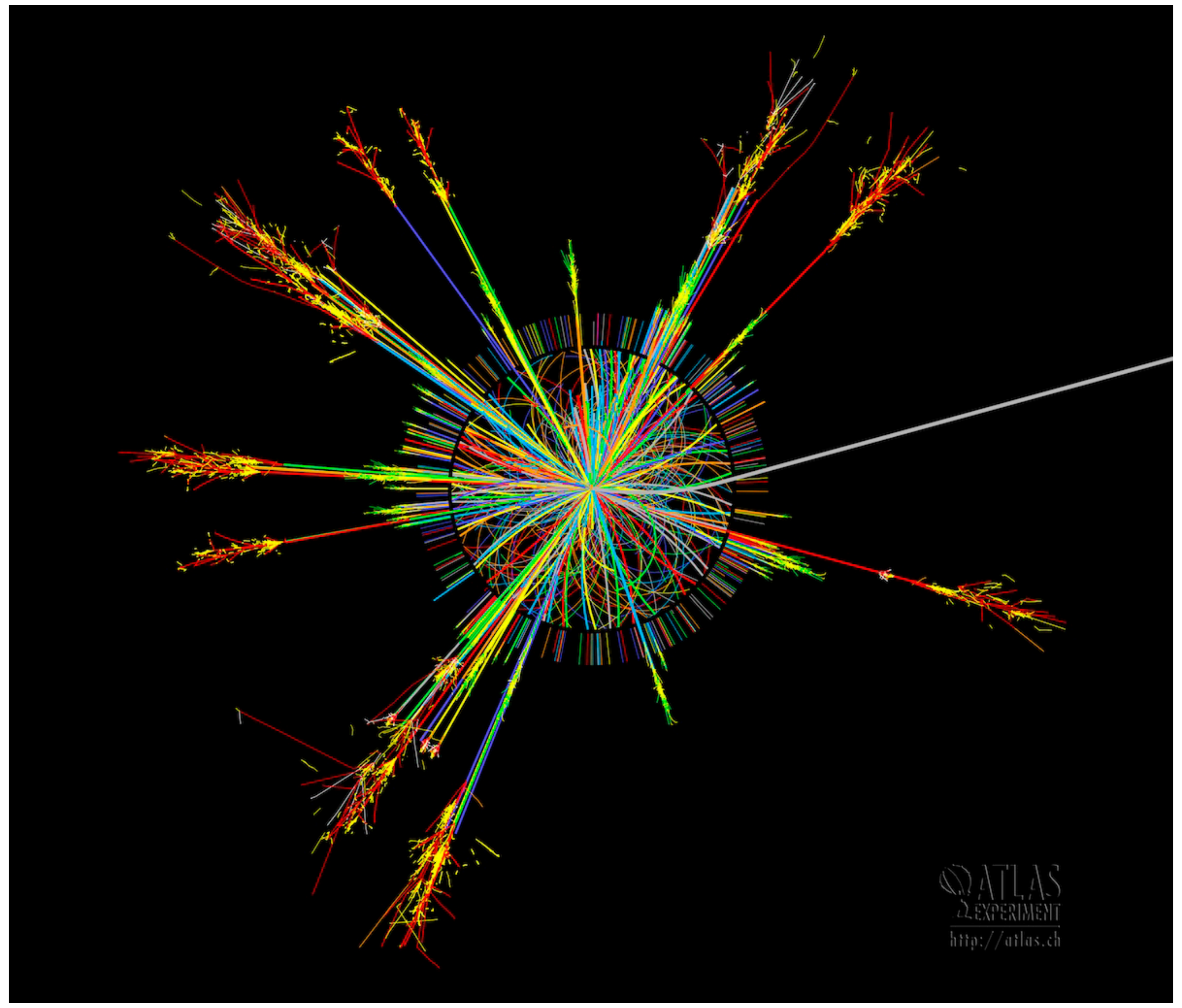
Quantum Simulation

- We would like to simulate particle physics processes.
- Perturbation theory does not always work!





- Feynman: "Nature isn't classical, dammit! and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Quantum Simulation

- But why should we make it quantum mechanical?
- Here is a reason: Simulating a quantum system evolving in time is numerically hard!

A “sign problem”

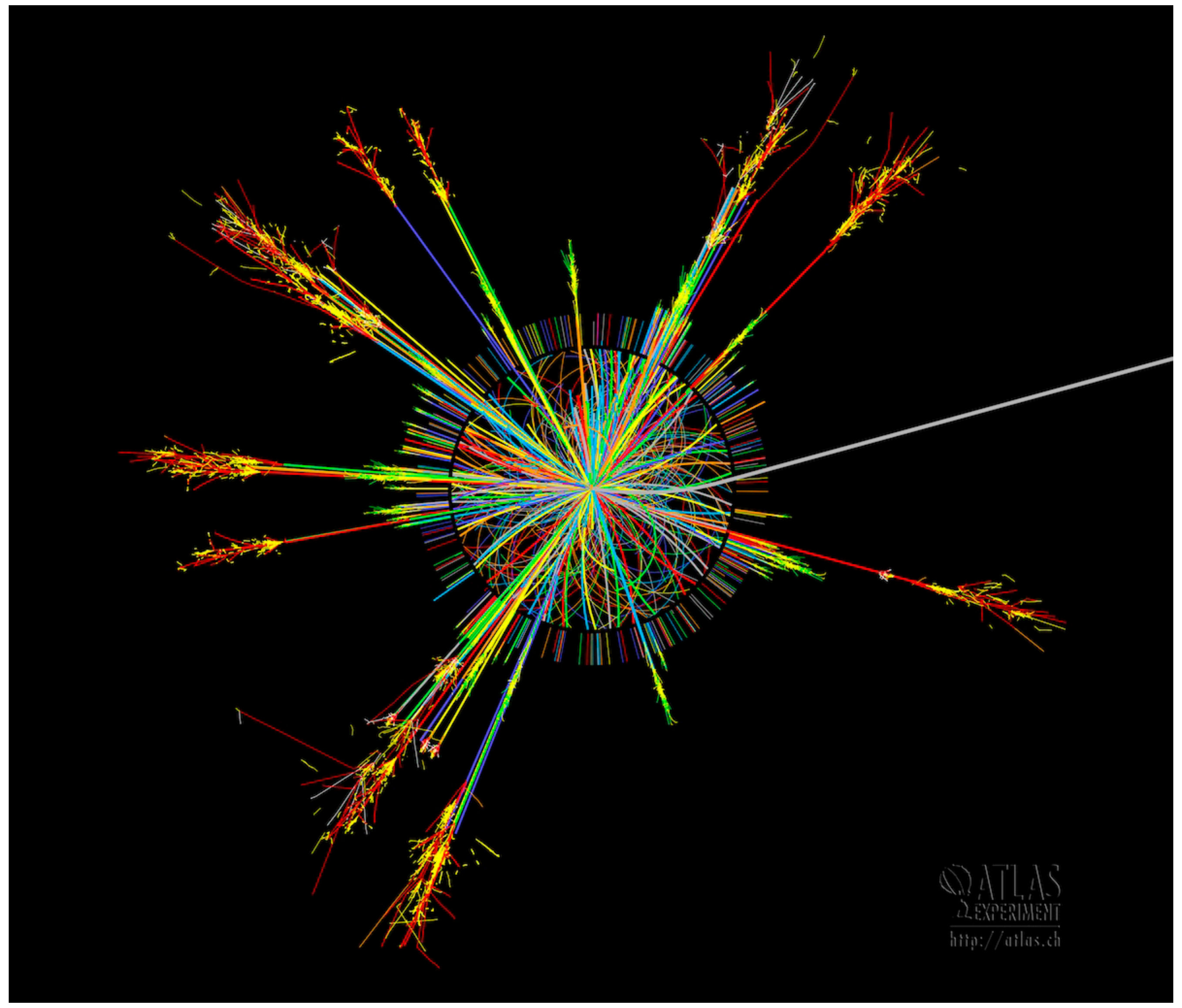
$$\psi(t) = e^{iEt/\hbar}\psi(0)$$

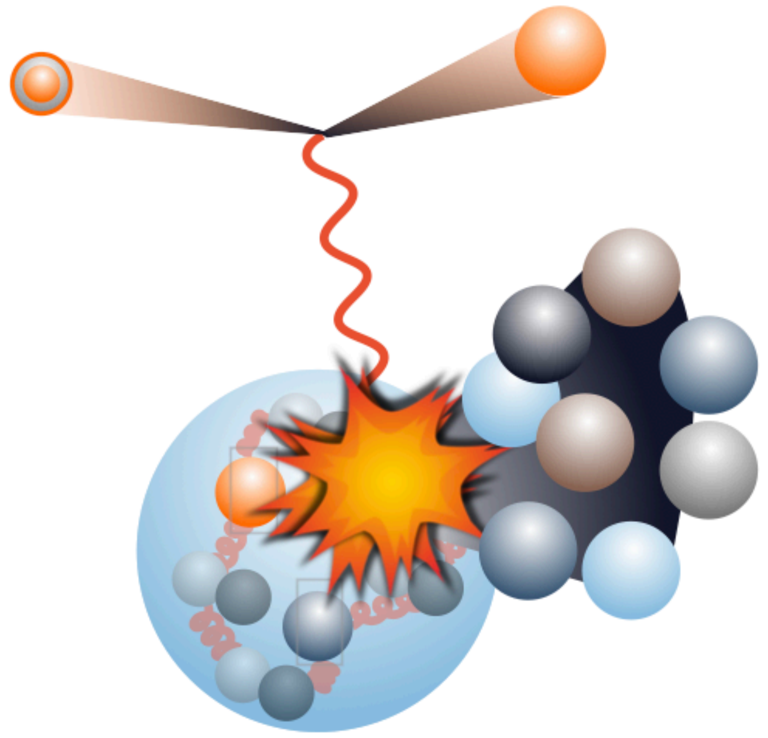
Rapid oscillation!

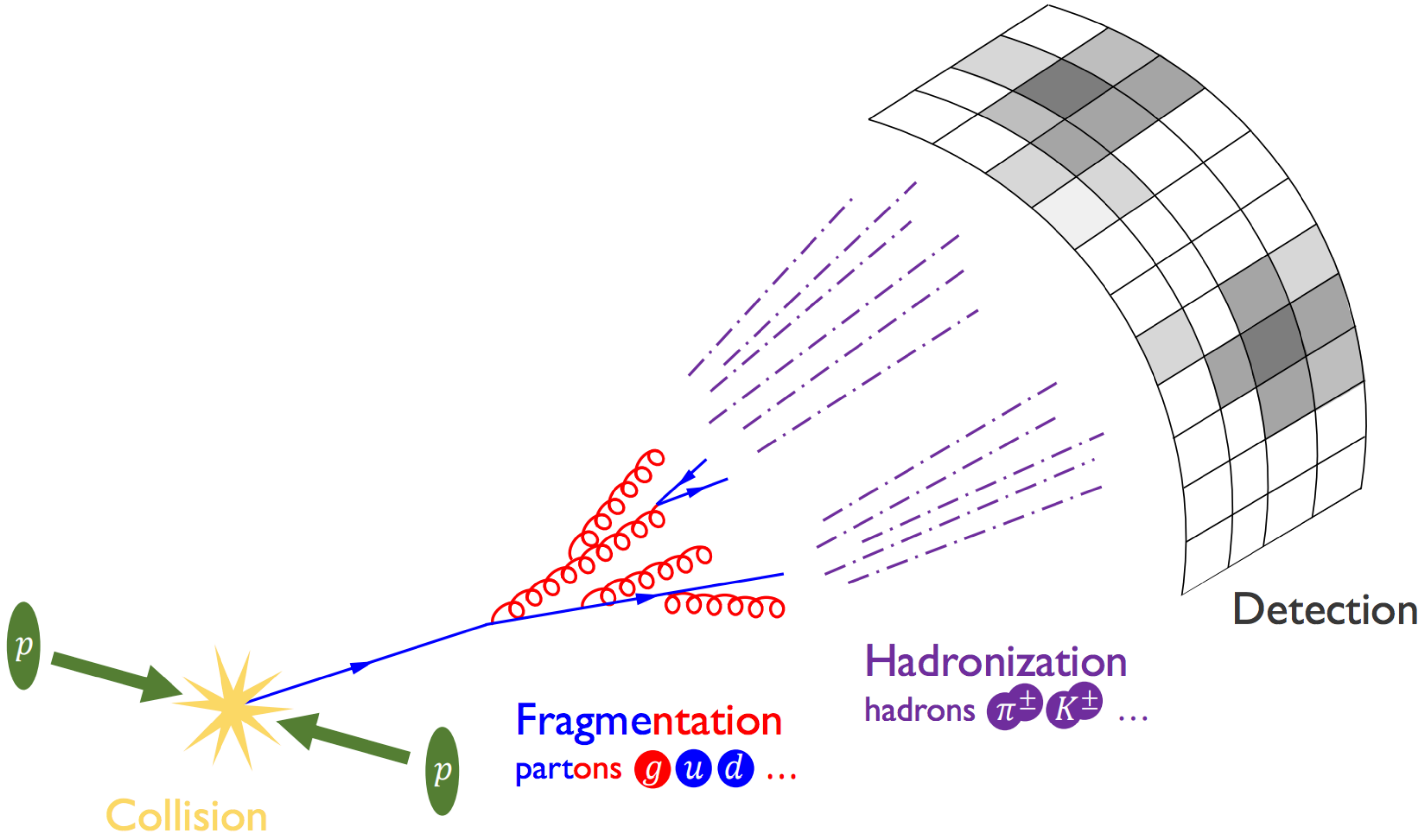
A quantum system will keep track of this inherently

Quantum Simulation

- What would we simulate?
- For example, some day, Hadronization
- Neutrino interacting with a nucleus.
- Processes in the early Universe







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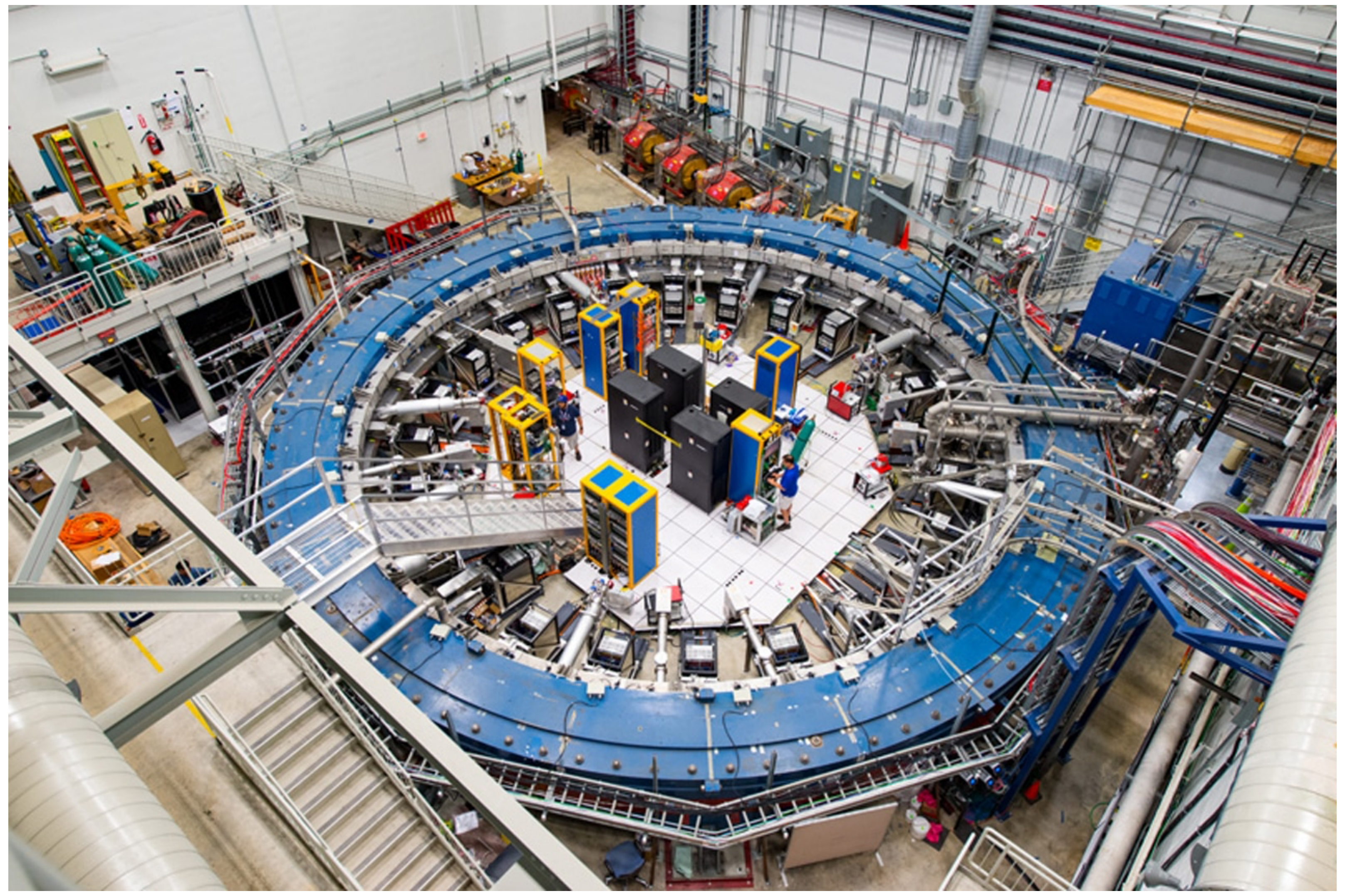
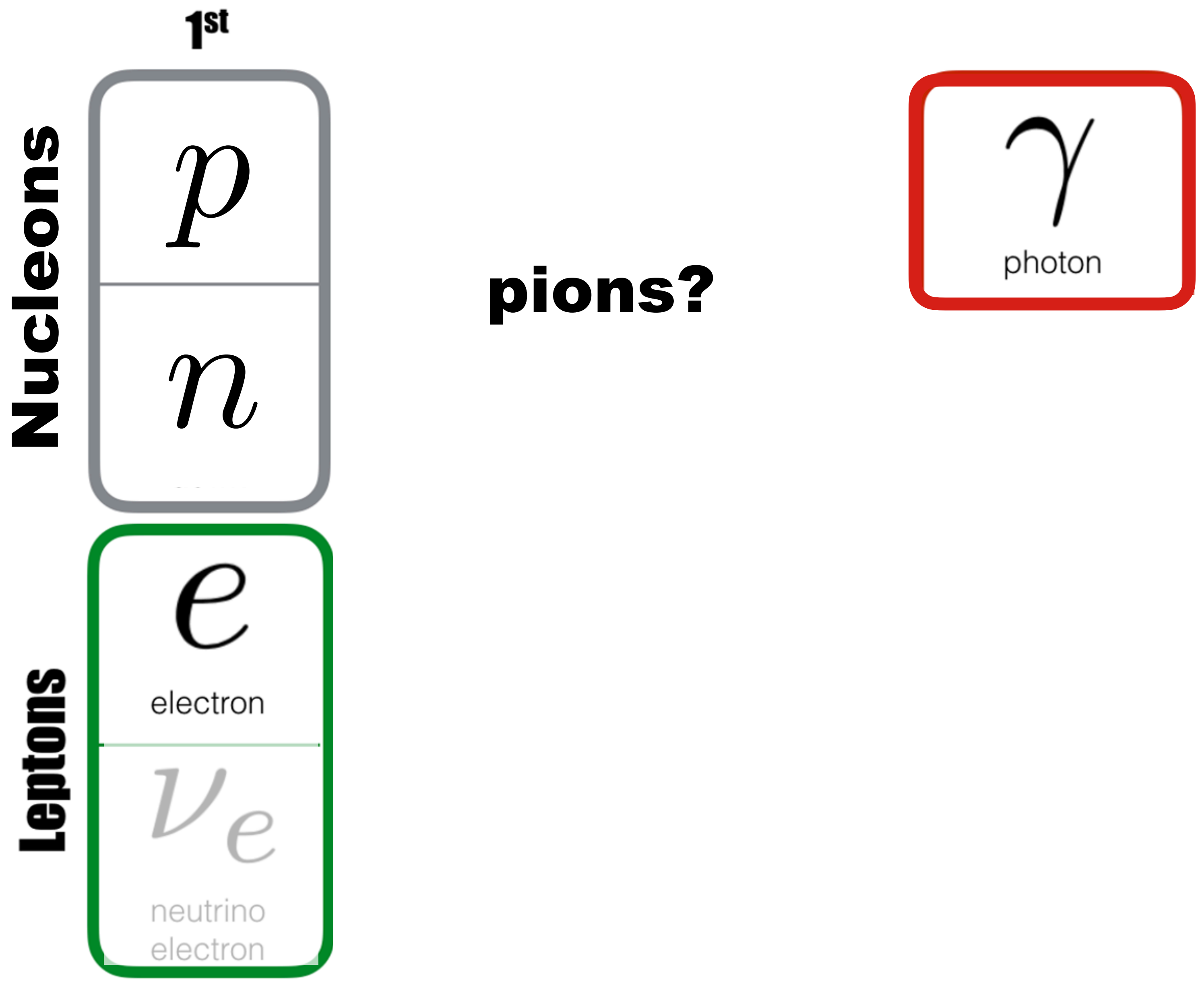
The Muon

- Yes, that muon!
- Recall the mid-30's: The SM of the time is





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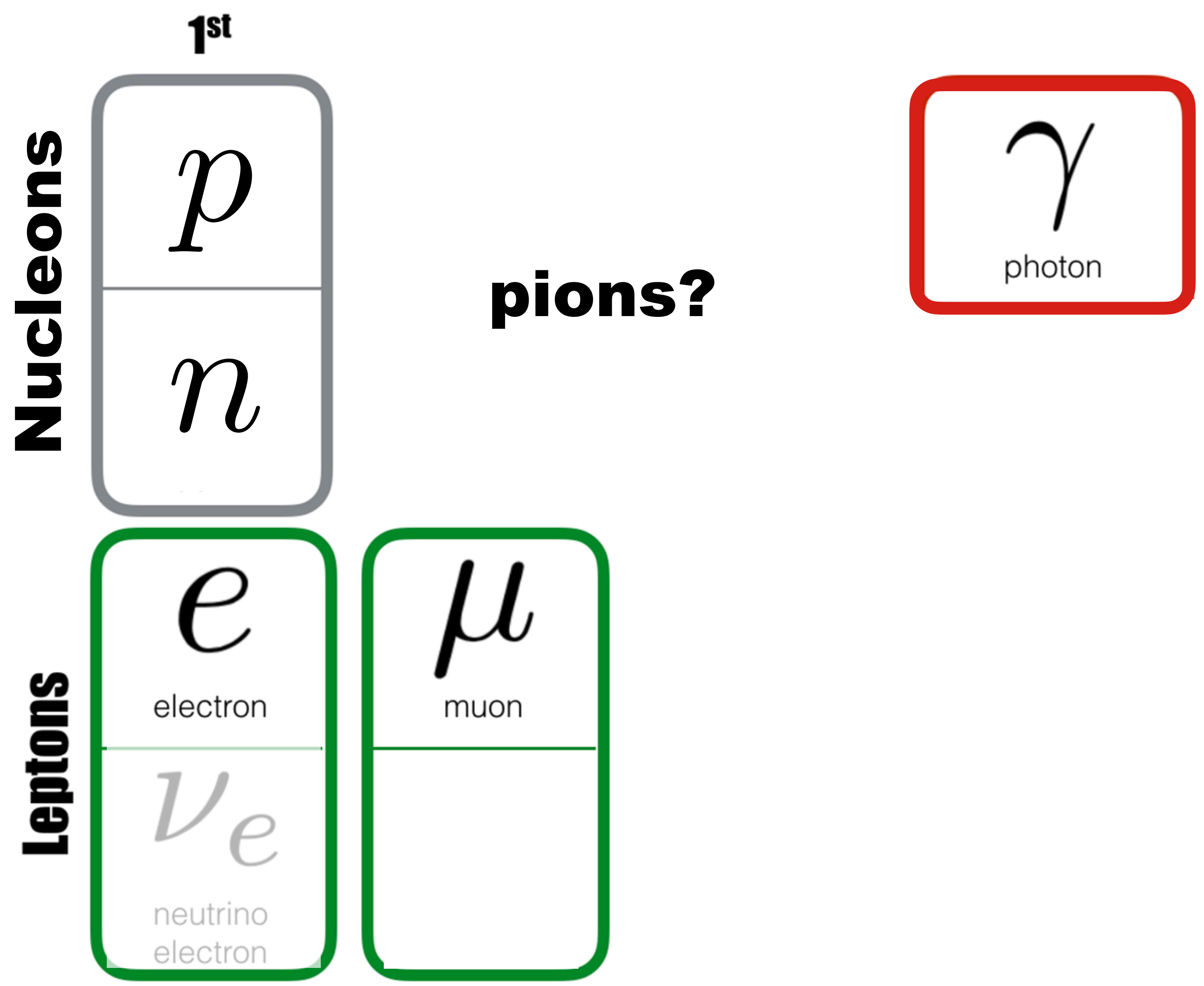
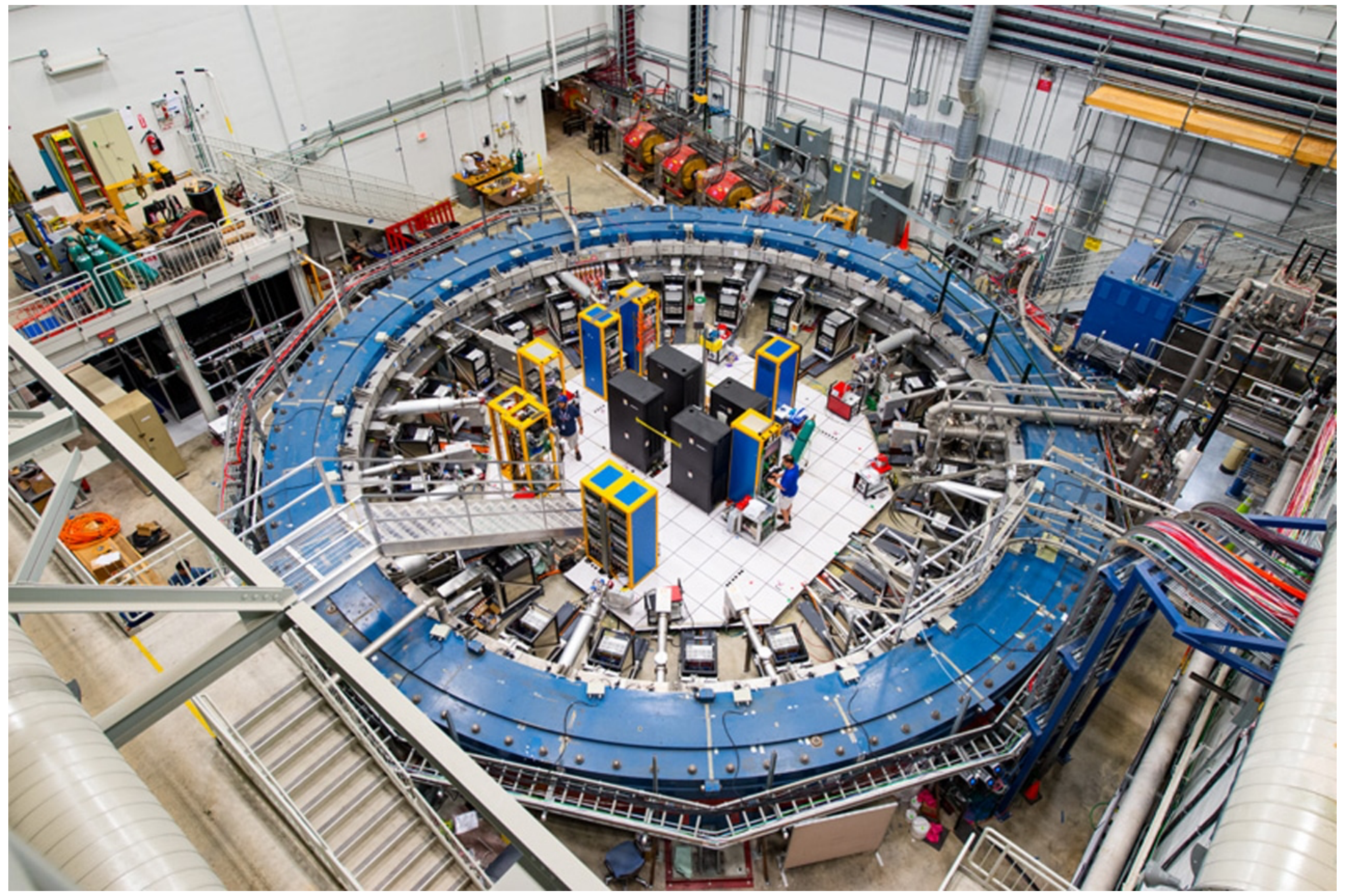




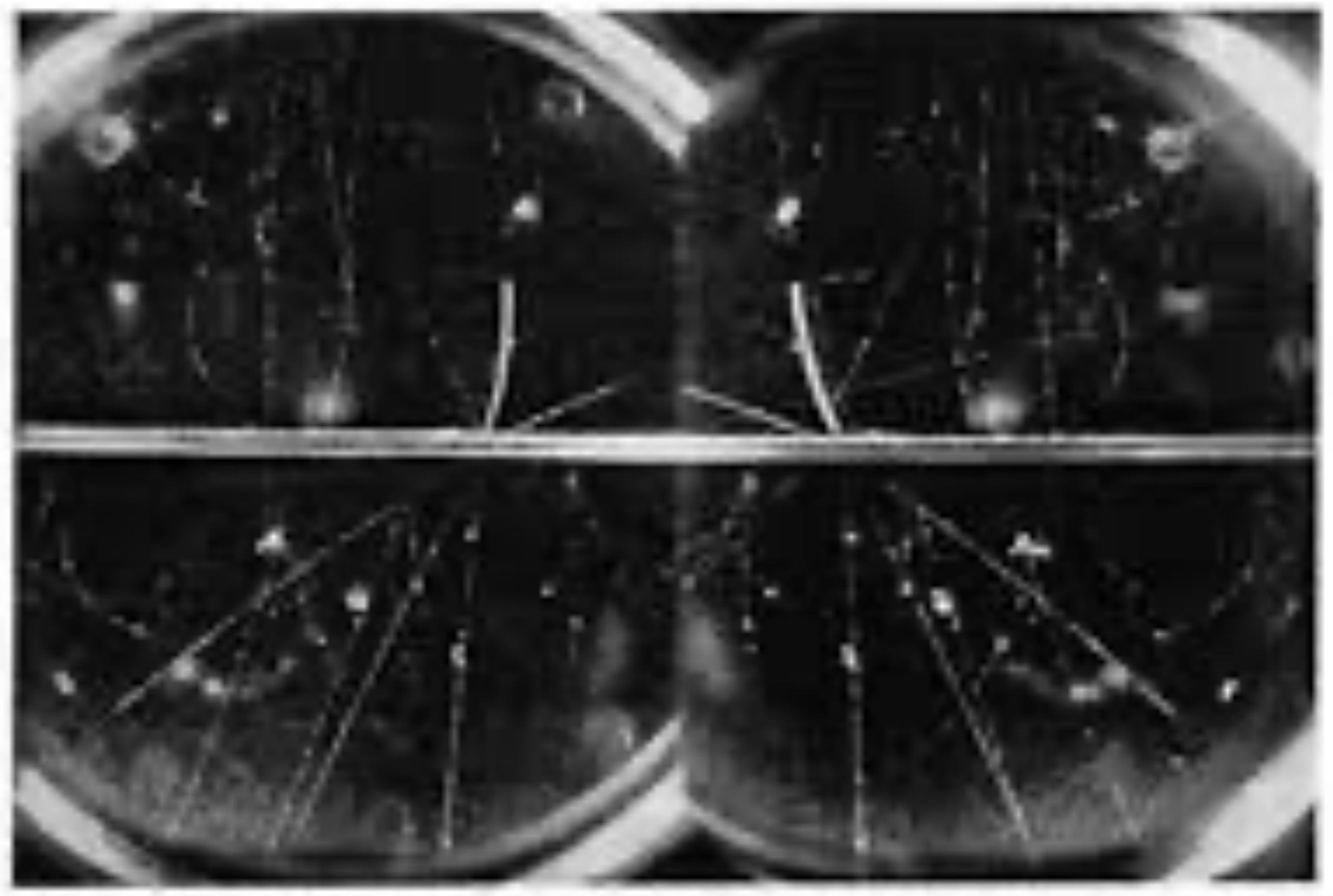
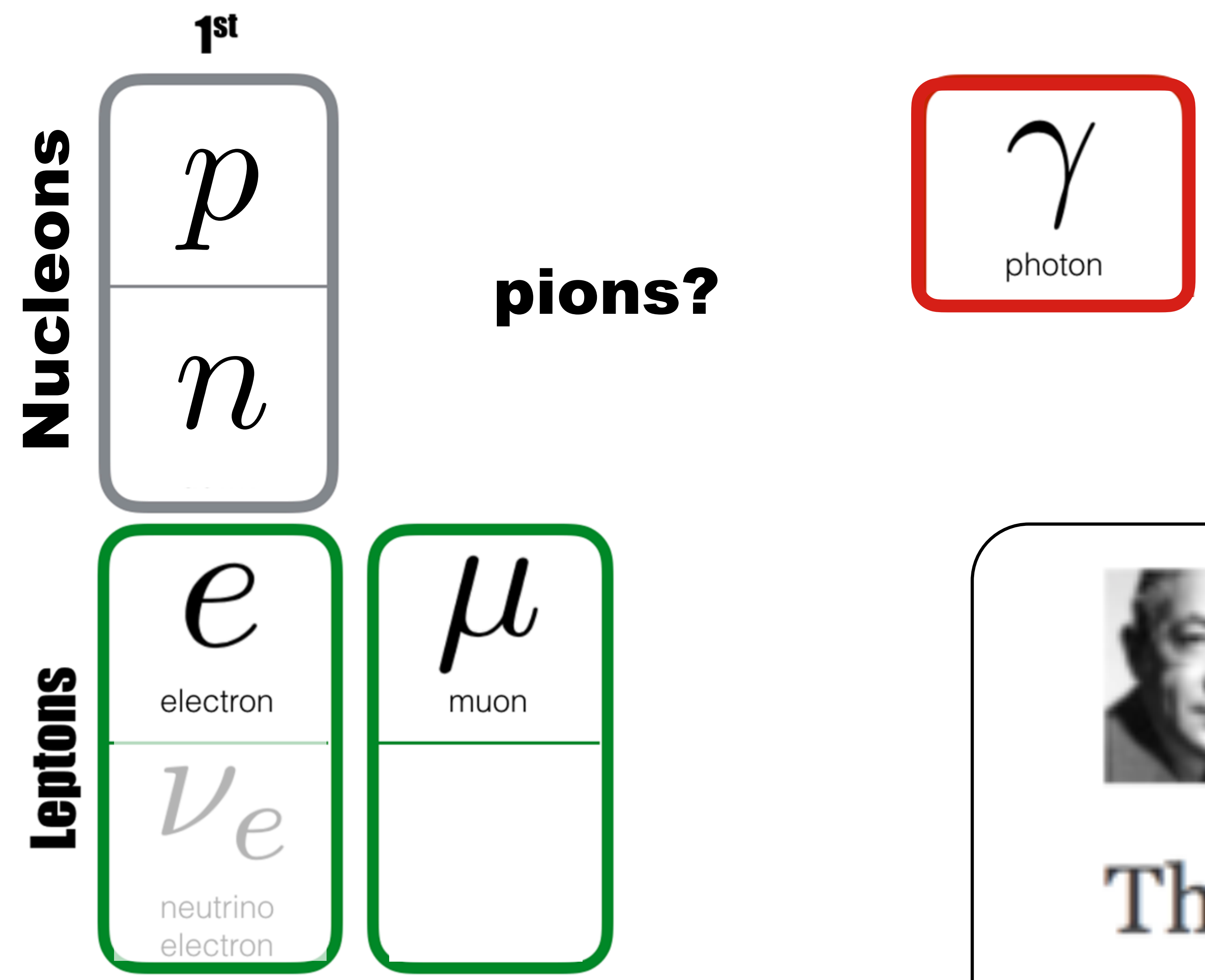
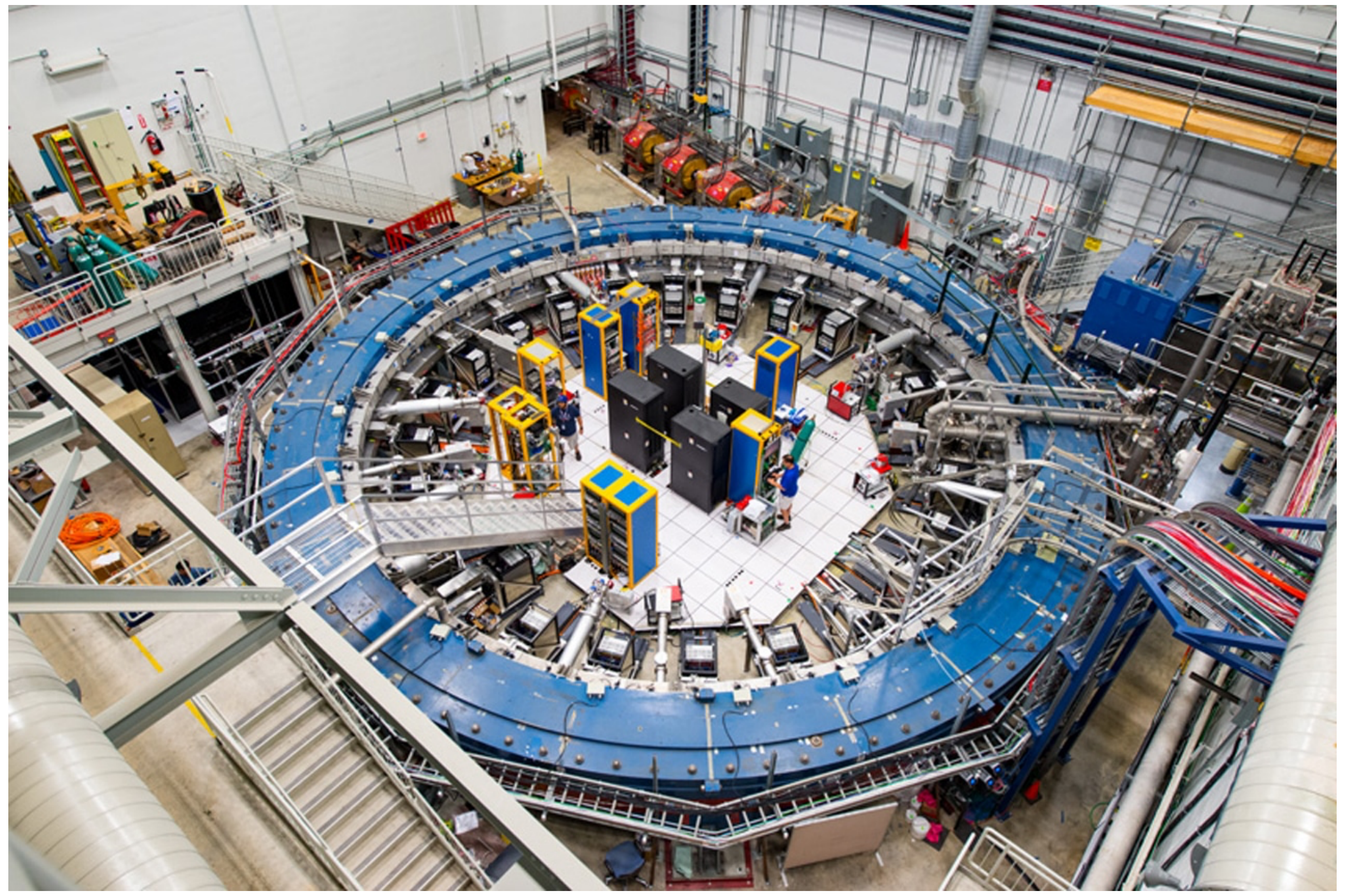


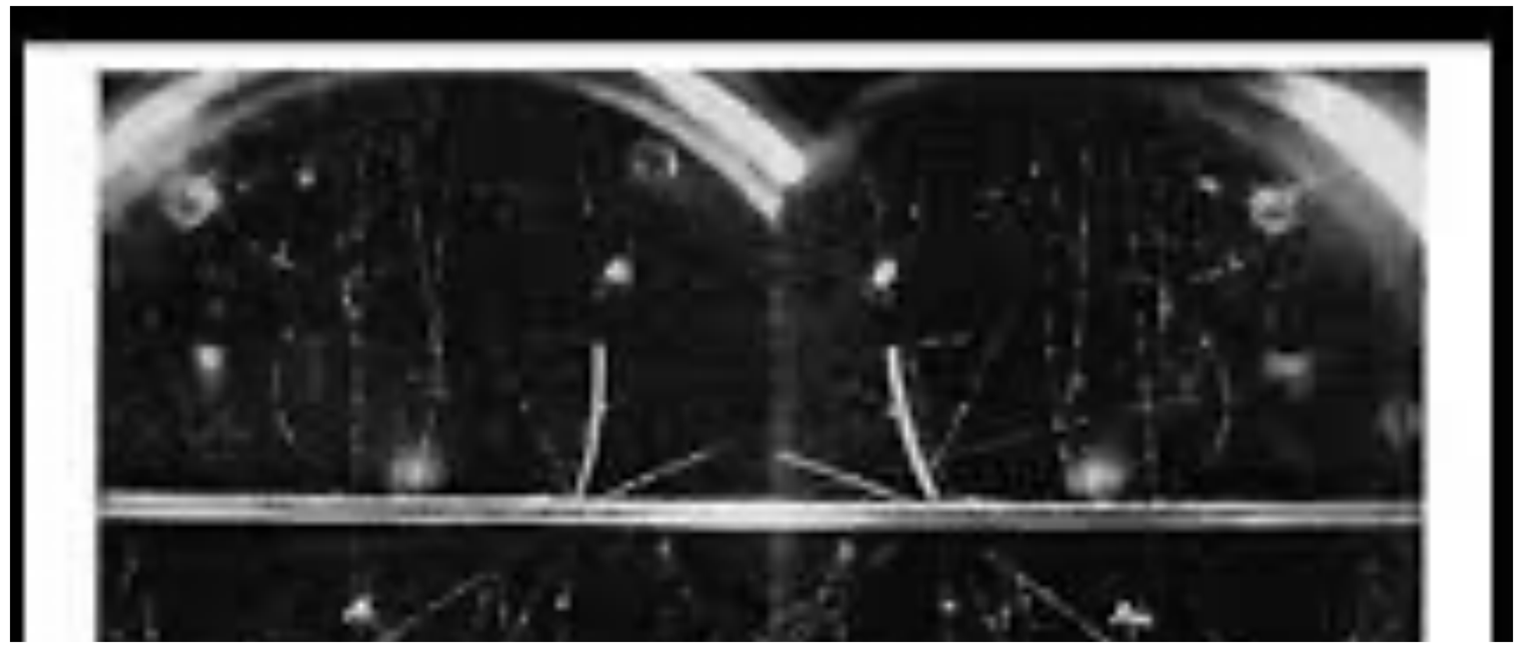
FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple

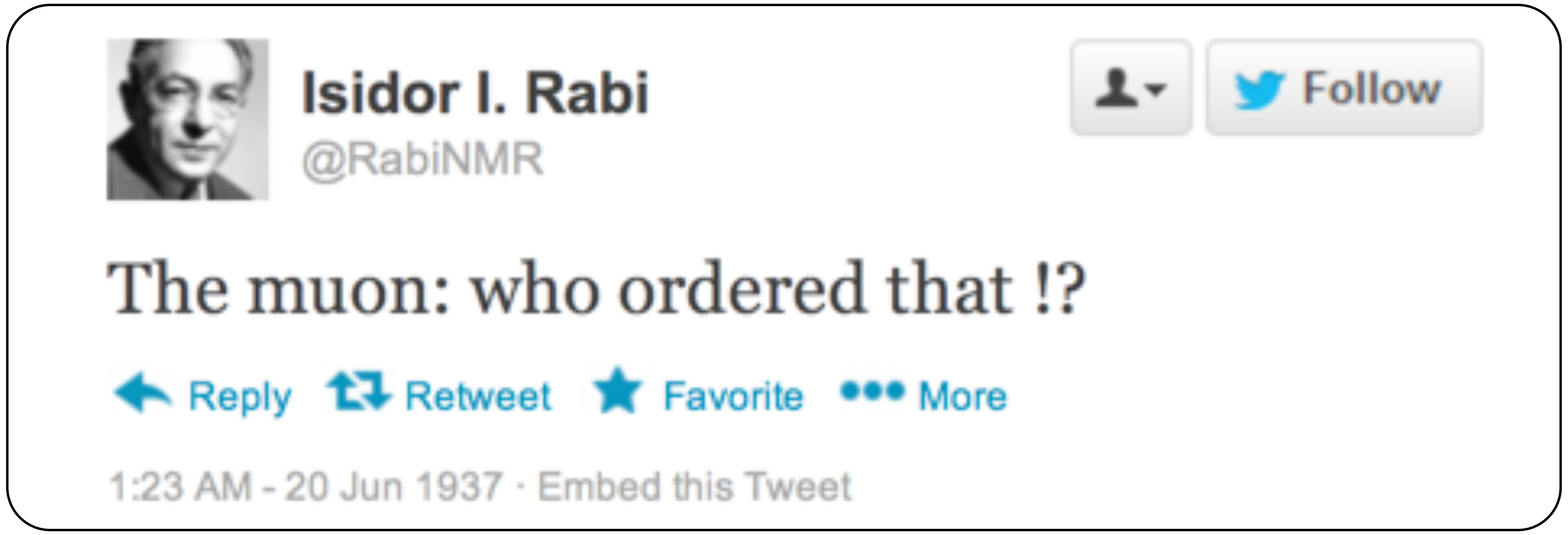
The Muon

- Yes, that muon!
- Recall the mid-30's: The SM of the time is









So you don't always get what you ordered . . .)

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.

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

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

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

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

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