Searching for New Physics with Light (and Quantum technology)

Roni Harnik,
Fermilab Theoretical Physics Div.
SQMS Center

UIUC ICASU kickoff

Fermilab SQMS ***DOE QuatISED***

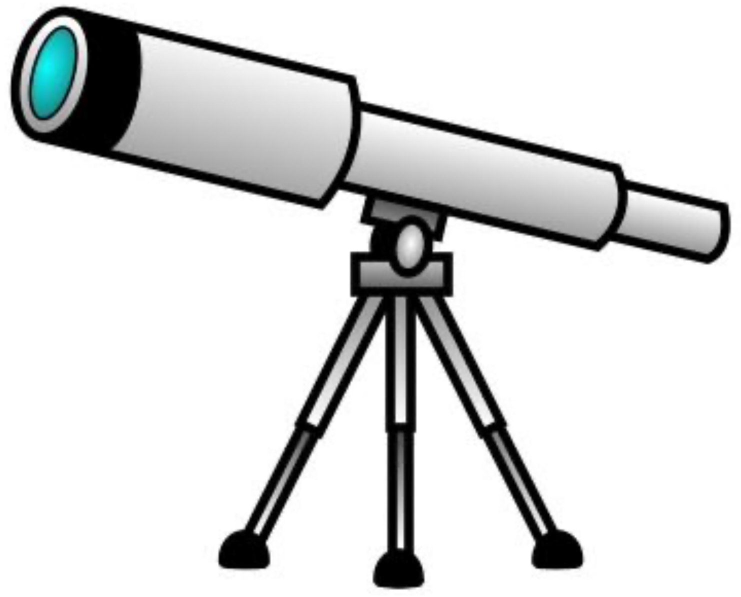
PARTICLE PHYSICS

We are Curious!!!

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

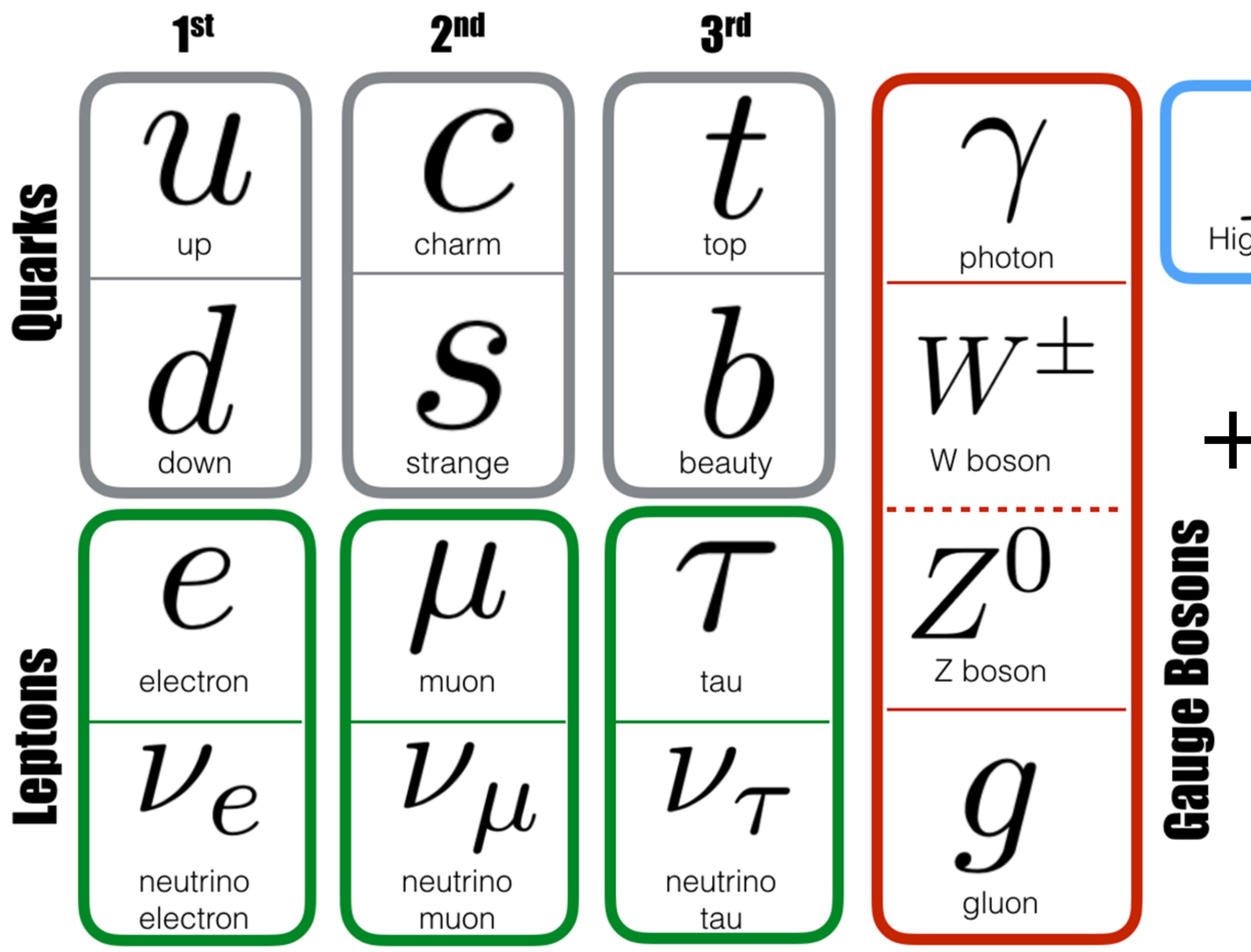
Accelarators, colliders, detectors, neutrino experiments, cosmic rays…

What does the Universe contain?
What is its history?

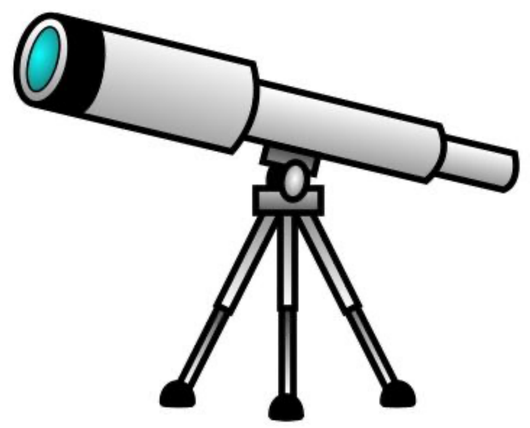


Telescopes, observatories, CMB, x-ray, gamma-ray, radio, direct detection experiments…

The Standard Model
(of particle physics)



+ Gravity



The Standard Model
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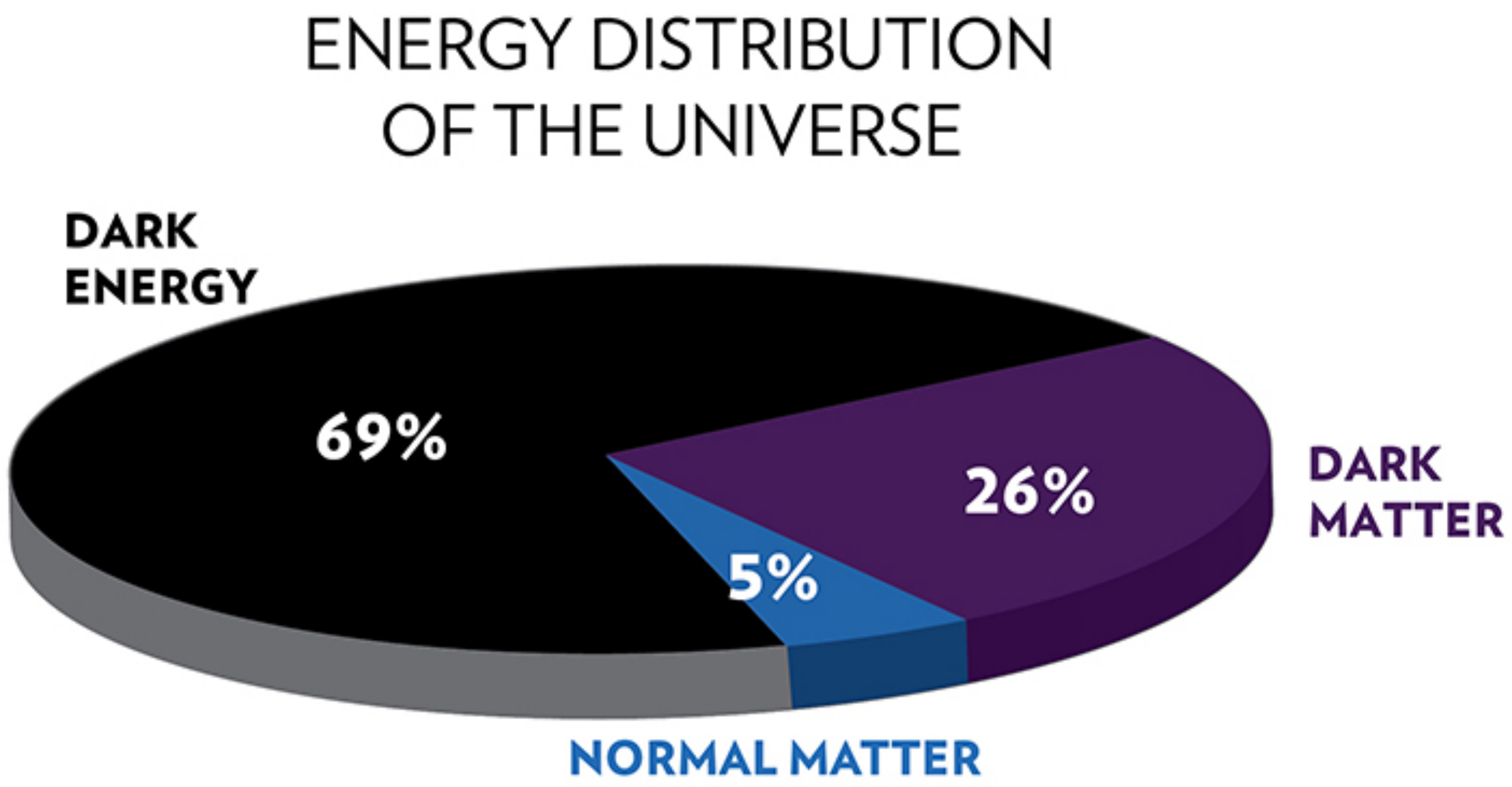

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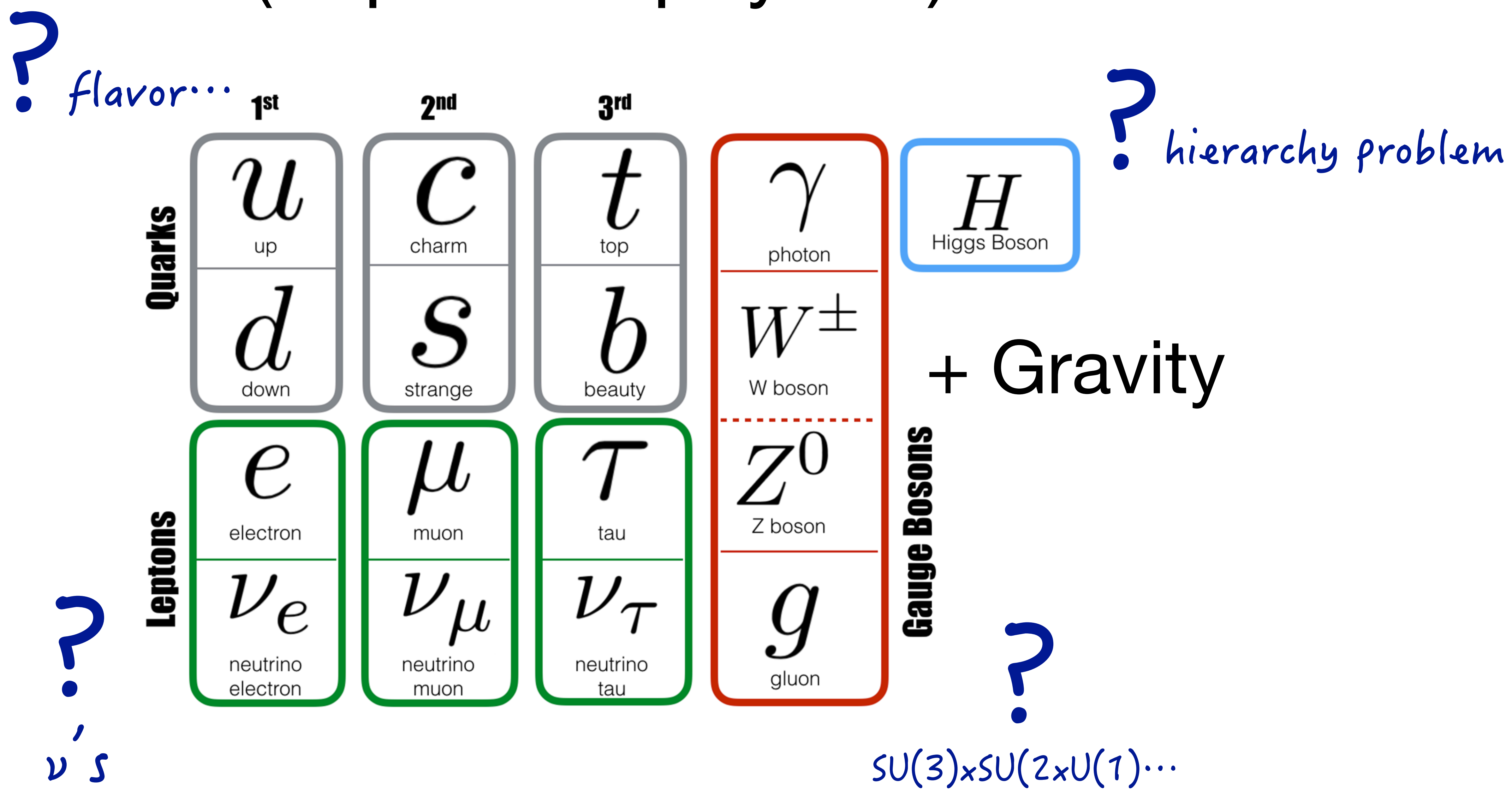

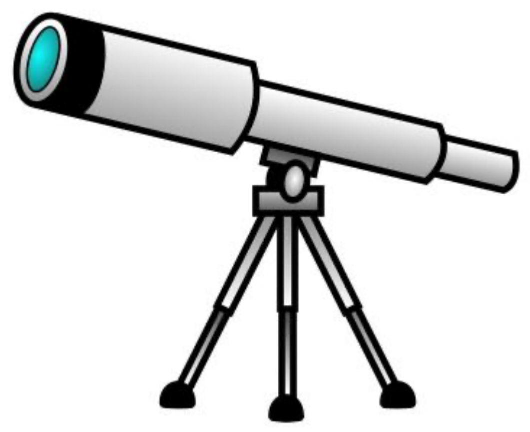

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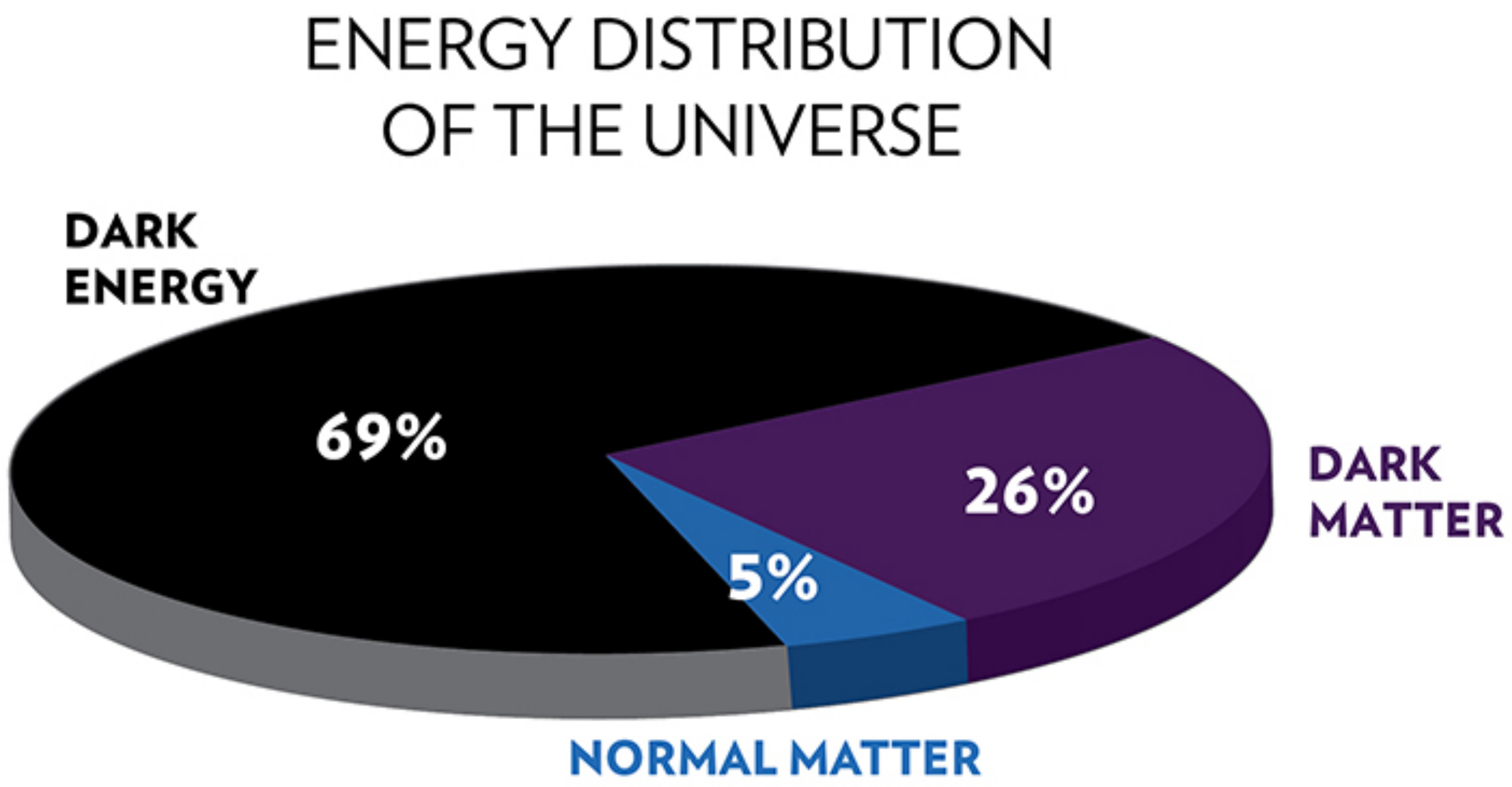

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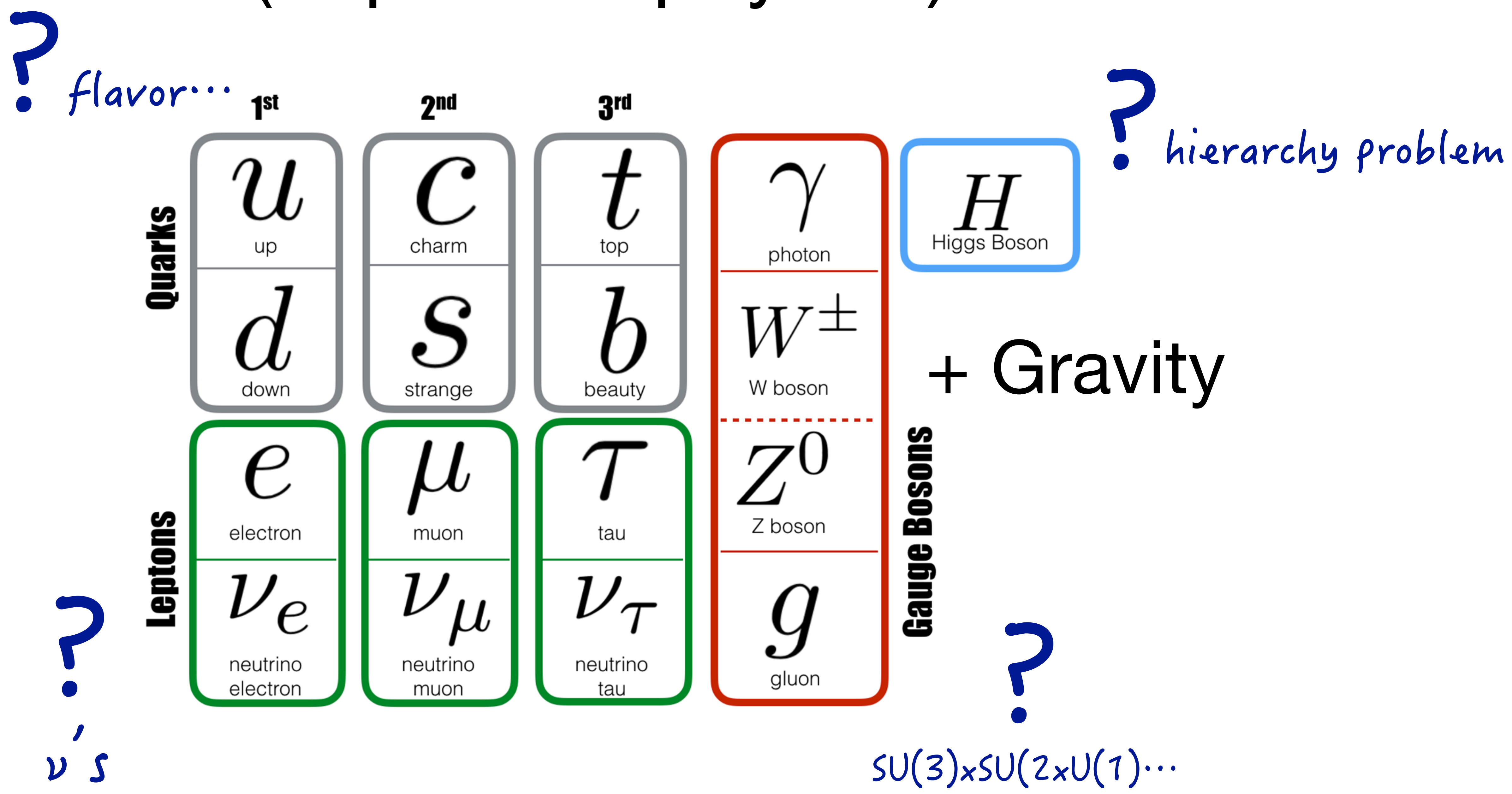

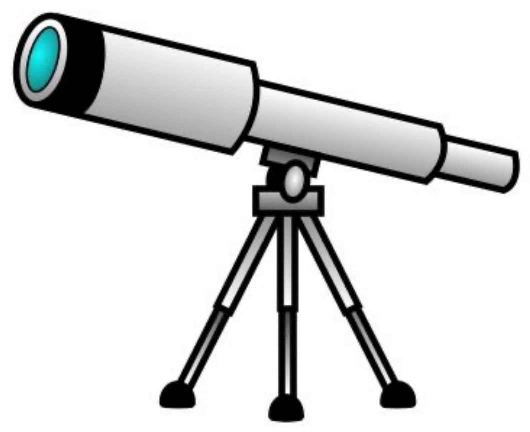

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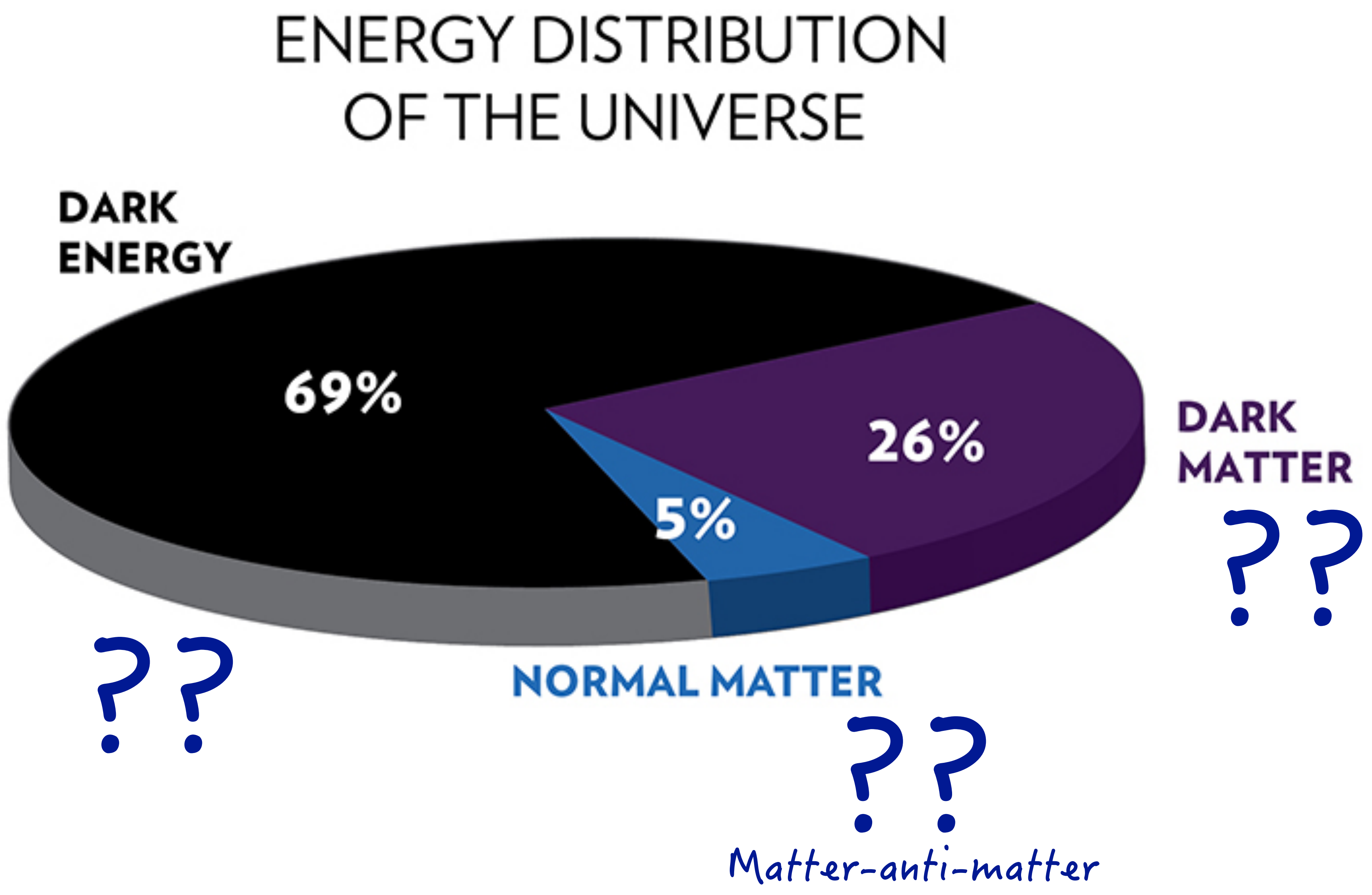
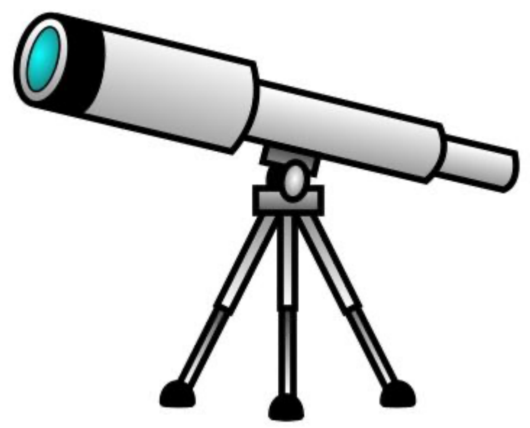
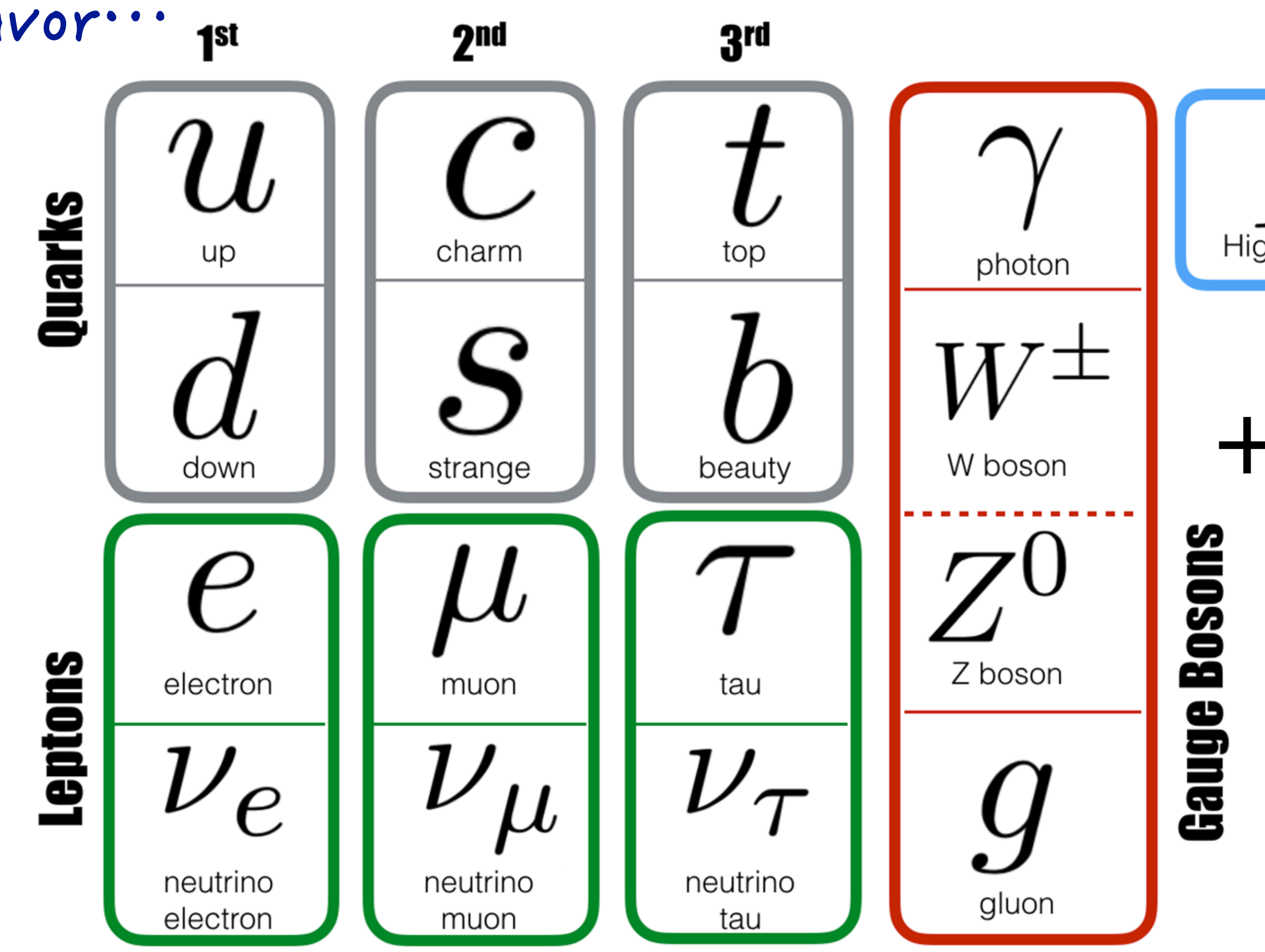




The Standard Model (of particle physics)

The Standard Model (of cosmology)

? flavor…



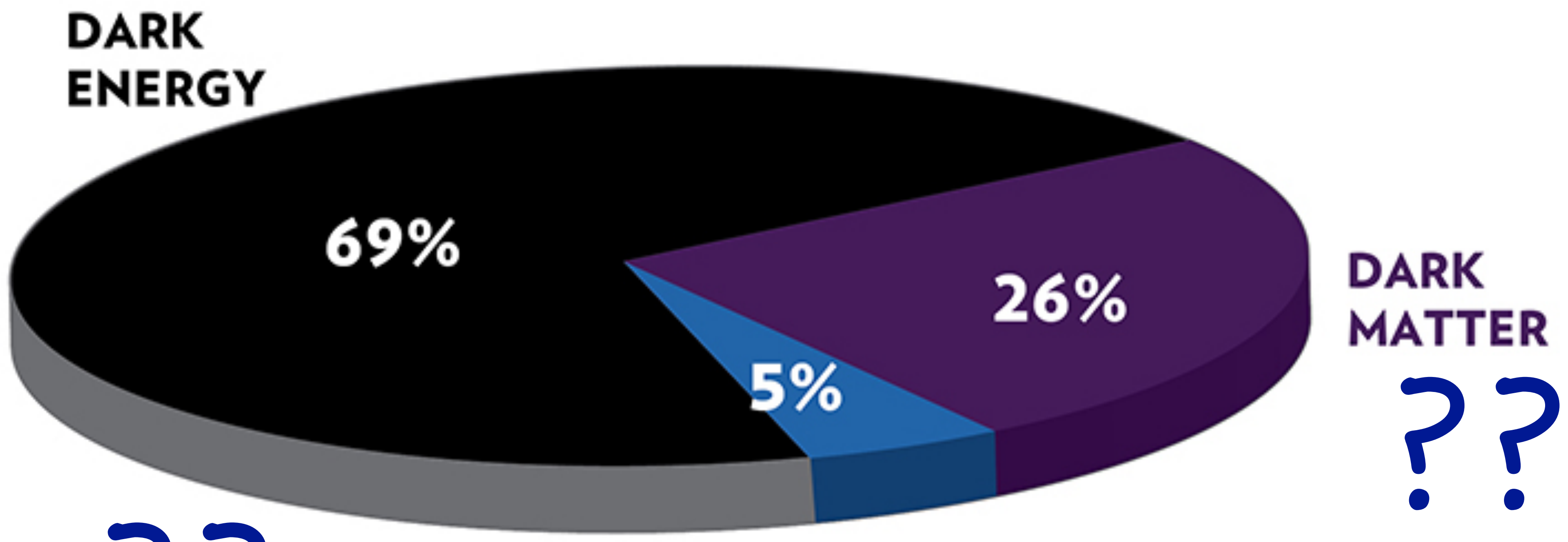
? hierarchy problem

+ Gravity

? ν's

? SU(3)xSU(2xU(1)…

ENERGY DISTRIBUTION OF THE UNIVERSE



??

??

??

Matter-anti-matter

Is there anything else? Could that be the dark matter?

Can we learn more about cosmic history?

Overview - a non technical :

- HEP experimentalists and theorists are pursuing new approaches to address some of these question w/ technology being developed for HEP and for QIS (SQMS center).

- New light particles that interact with photons: **Dark Photons, Axions**
- Advertising cavities (SQMS)
- Ultra-high Q cavities and New physics searches:
  - Light shining through wall
  - Dark matter searches
  - Light-by-light search
- (Not new) light particles interacting with photons: Gravitational waves.
- GW searches with cavities. (and an advertisement for MAGIS-100 if there is time).

Much of the development in QIS technology involves manipulation of light, either in classical or quantum states.

A good place to look for beyond standard mode is

New Particles Interacting w/ Light

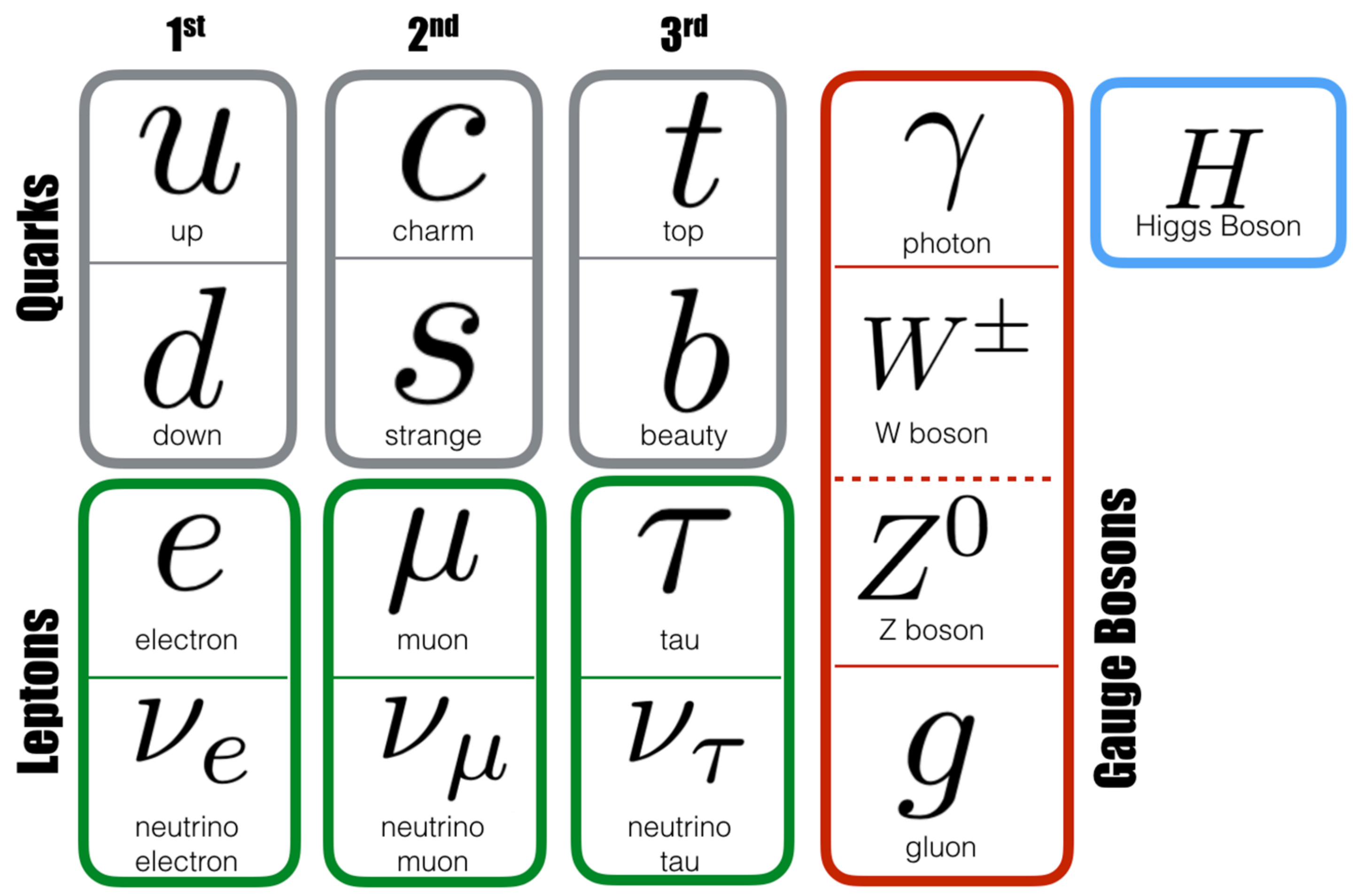
The main actors:

Dark Photons

Axions

(both are good dark matter candidates, but are not assumed to be DM in most of this talk)

Dark Photons - a Linear Extension



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

- Why would such a particle exist? . . .
  Historically "copies" of particles did show up by surprise. (the muon: "who ordered that?!")

- Even by surprise, a dark photon would teach us profound lessons. New force of nature. Grand Unification, etc.

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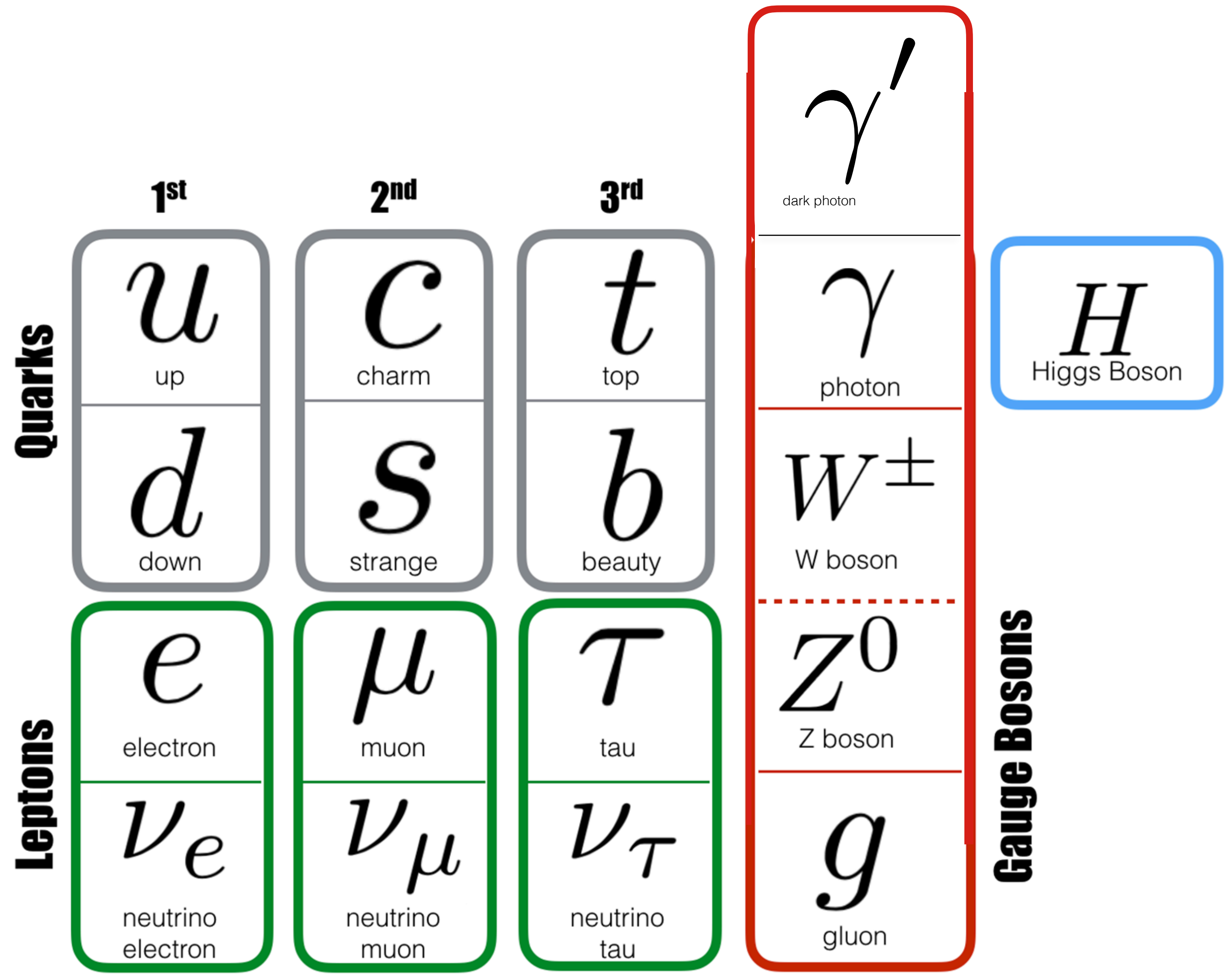

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Dark Photons - a Linear Extension

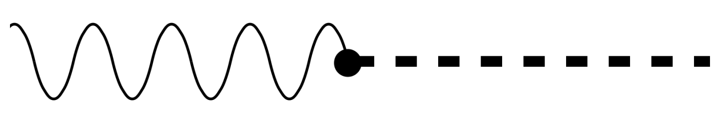
- Normal matter is not charged under the new photon. How will it interact?

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 is a **linear** extension of QED with an effective Hamiltonian:

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

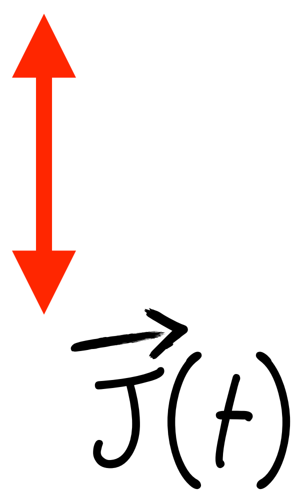


(and dark photon also has a mass)

Graham et al, Phys.Rev.D 90 (2014)

$|photon\rangle + \varepsilon\, |dark\ photon\rangle$

- Photons are emitted by an EM current J, e.g oscillation dipole:



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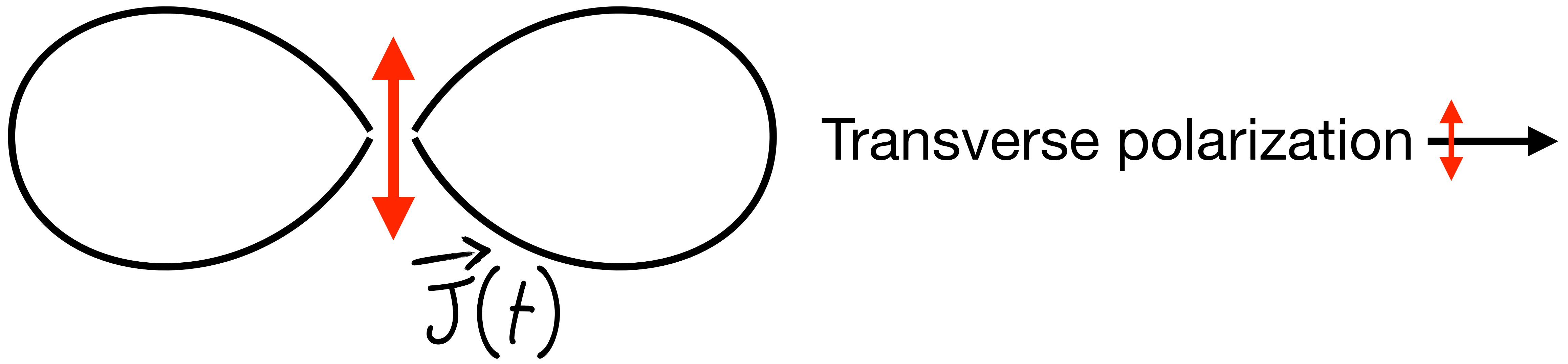

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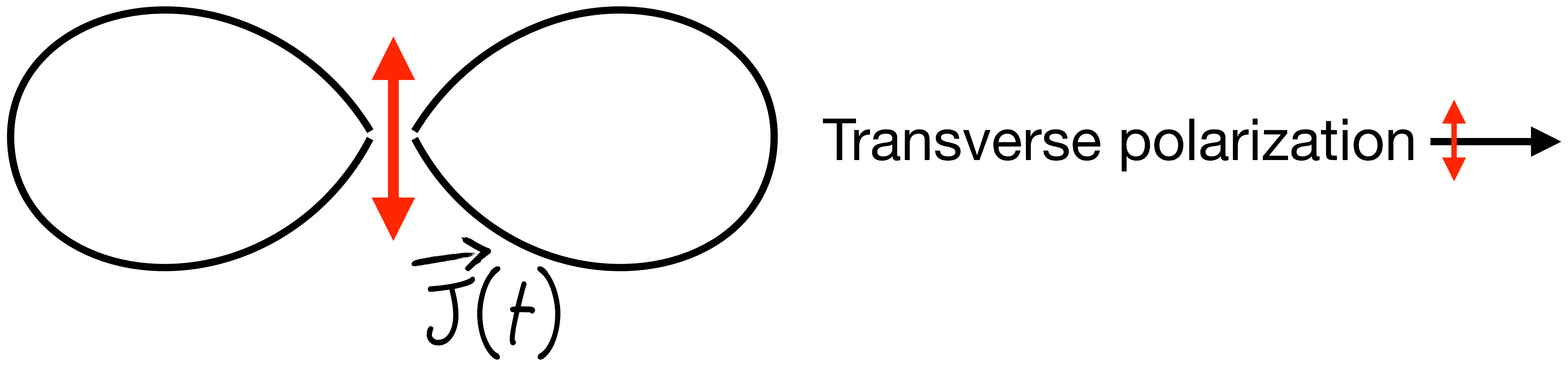

Dark flux $\propto \varepsilon^2$

But now, the emitted state is* $|photon\rangle + \varepsilon\, |dark\ photon\rangle$!

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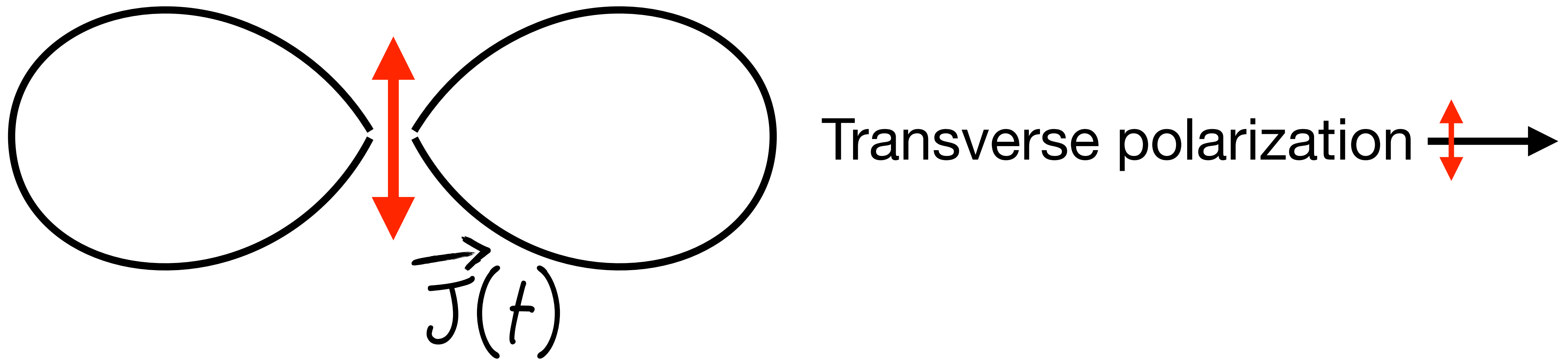

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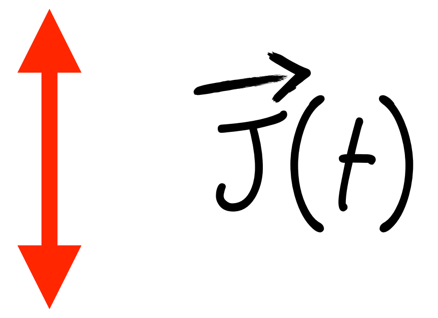
Reminiscent of Rabi (also neutrino) oscillations. Emitted state is a superposition of massless and massive state (mass difference ↔ detuning).

* in fact, ε here also depends on dark photon mass.

Graham et al, Phys.Rev.D 90 (2014)

$|photon\rangle + \varepsilon\,|dark\ photon\rangle$

- Recall a crucial difference b/w photons and dark counterpart – a mass.
- The dark photon has a 3rd polarization!



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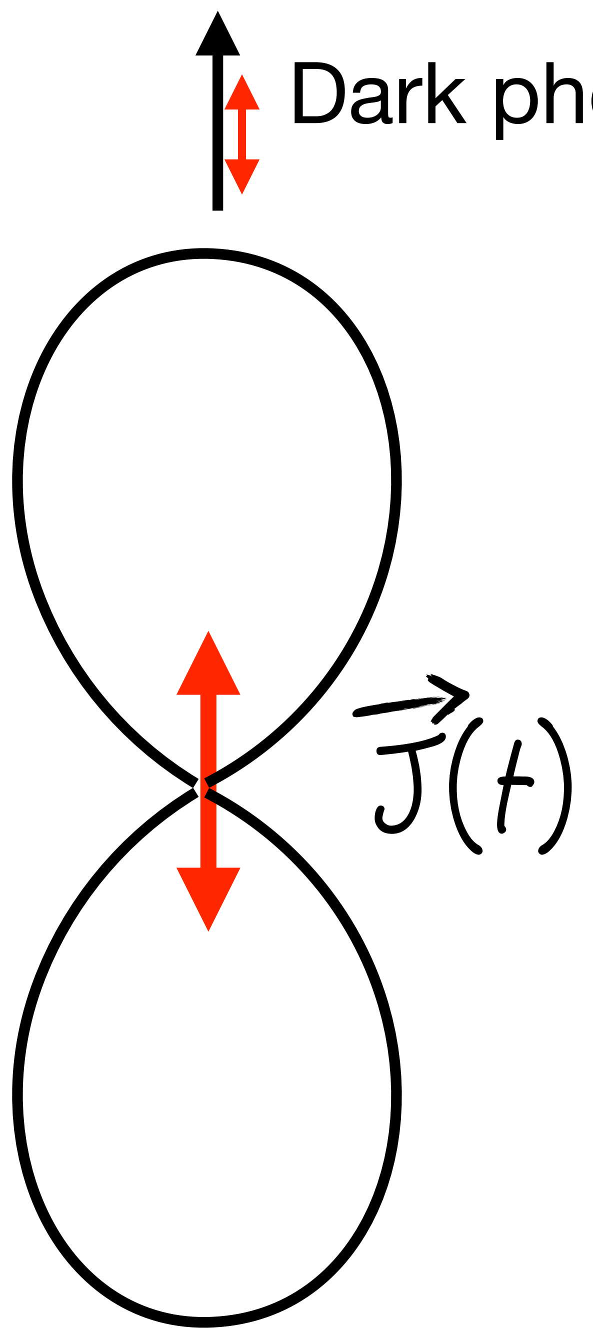
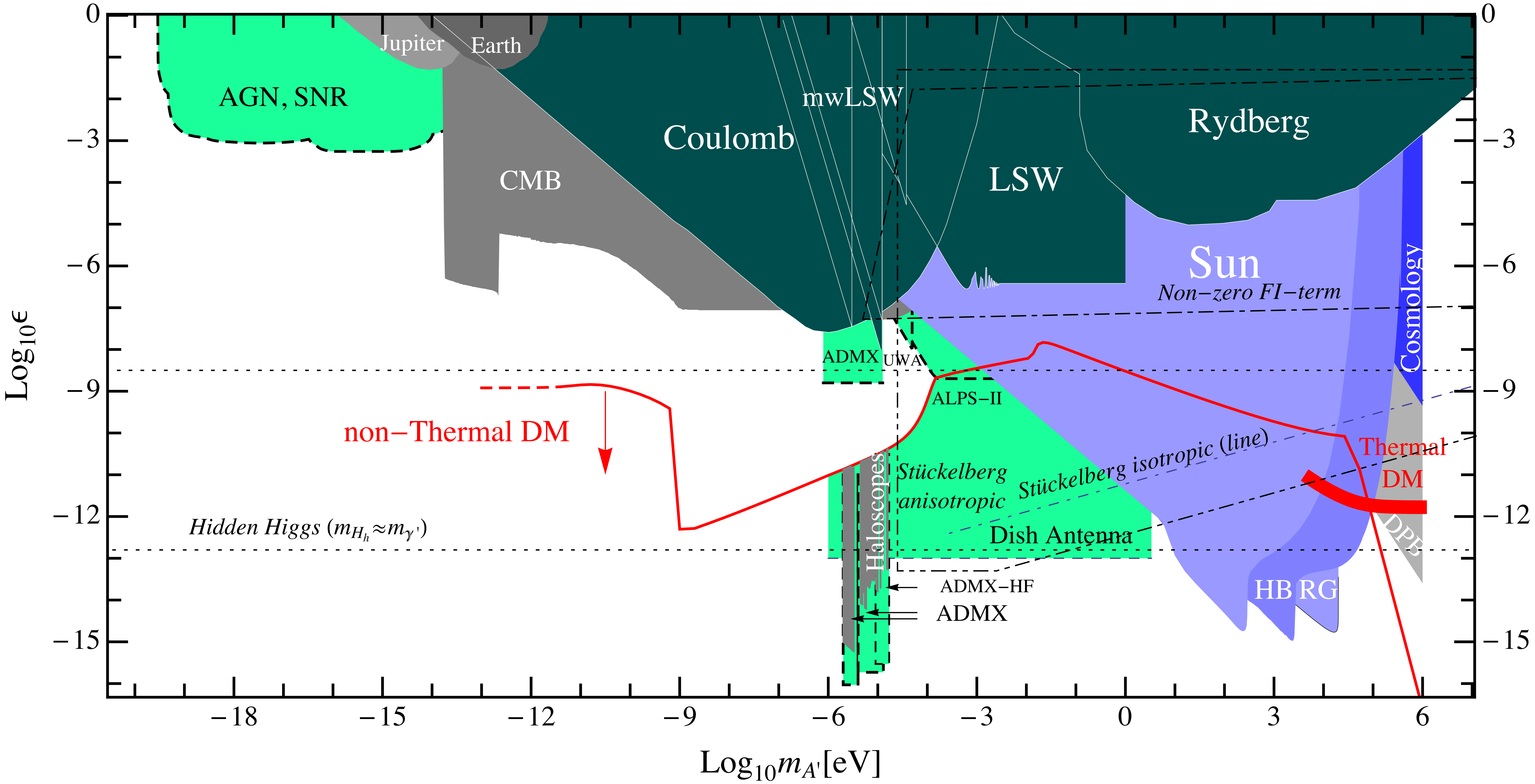


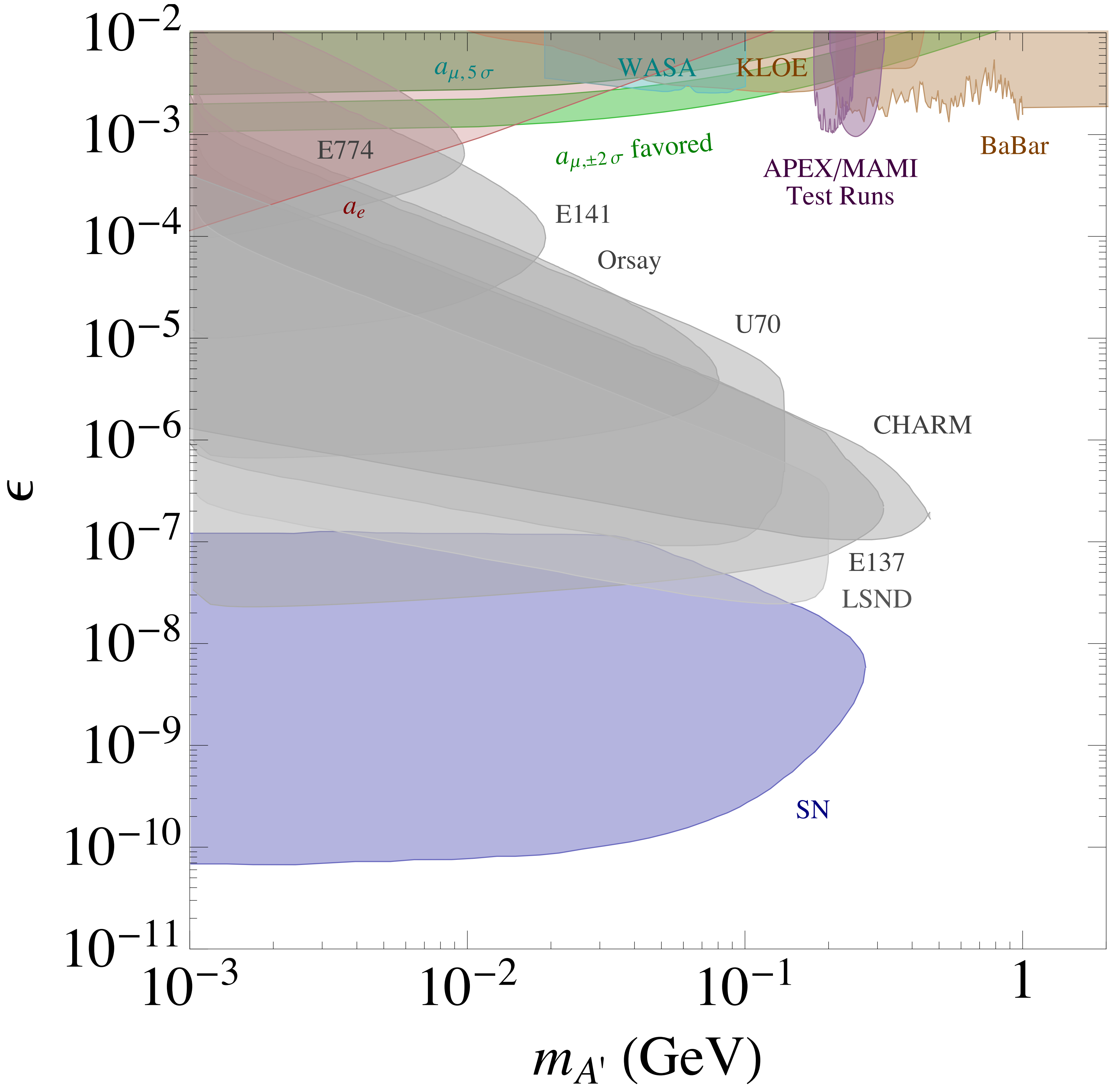
No oscillation, just emission of a feebly coupled state. In fact this flux is greater! *

* in fact, ε here also depends on dark photon mass.

Dark Photon

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





Pecci and Quinn (77)

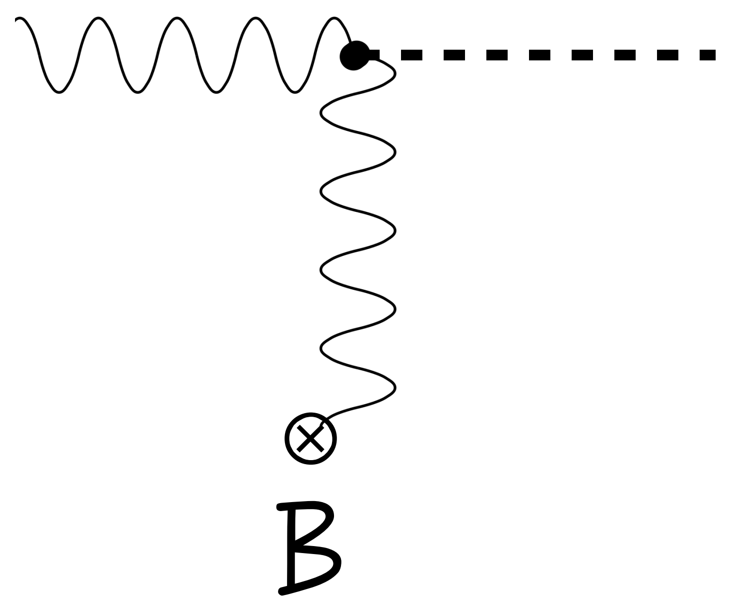
Axions - a Nonlinear Extension

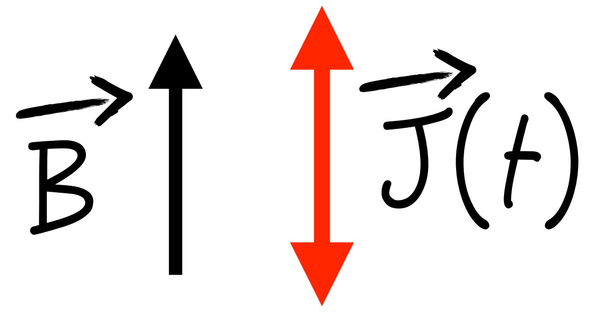
- Invented to address a theoretical puzzle of the strong force: "Strong CP problem" (why dont (gluonic) E and B fields mix?)
- A **nonlinear** extension of QED, with a new invisible field:

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

(1/f is a dimensionful coupling)

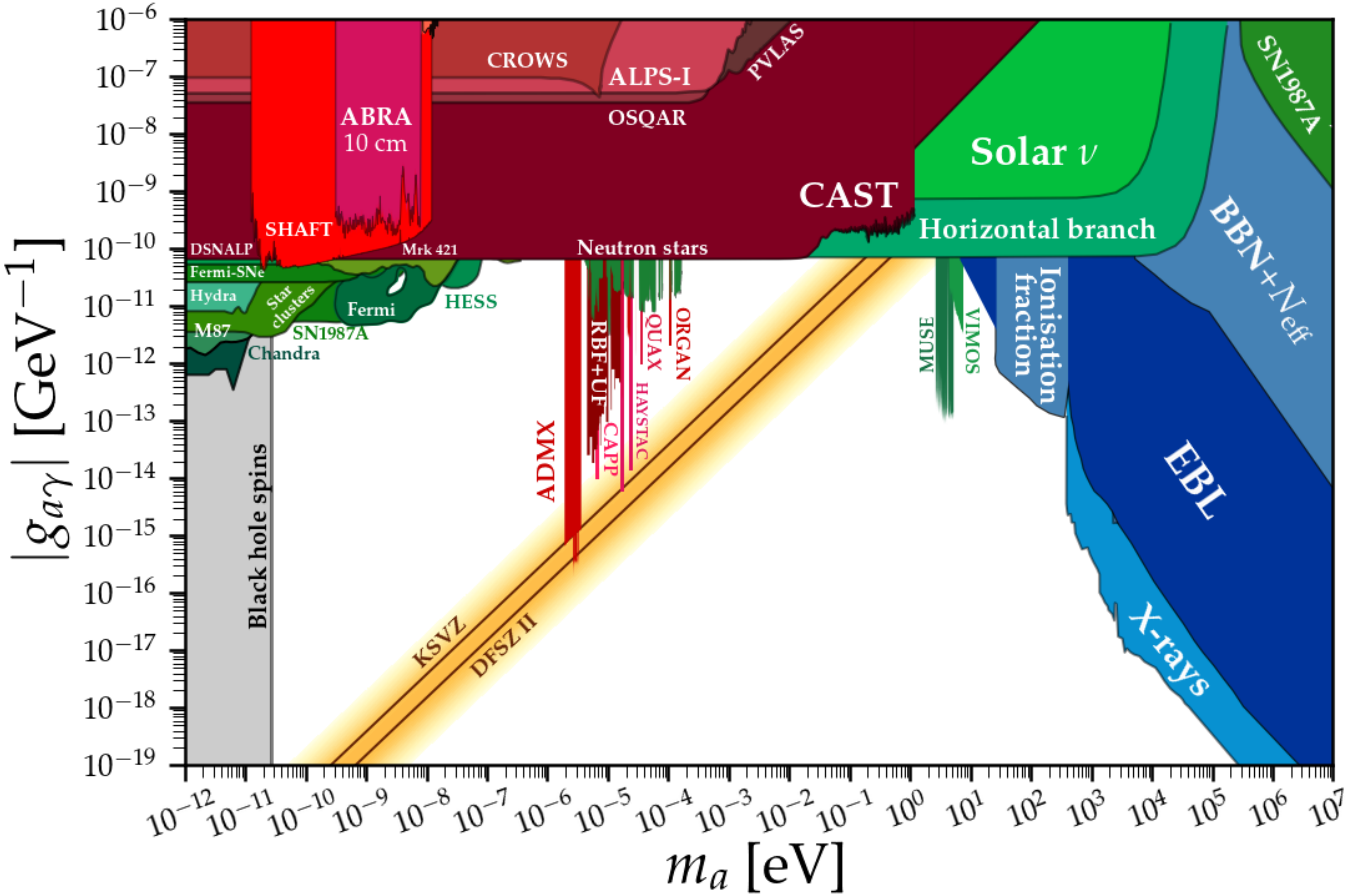
- Axion phenomenology w/ background field is similar to dark photon. Mixing:





Photons polarized along a B field can mix with axions.

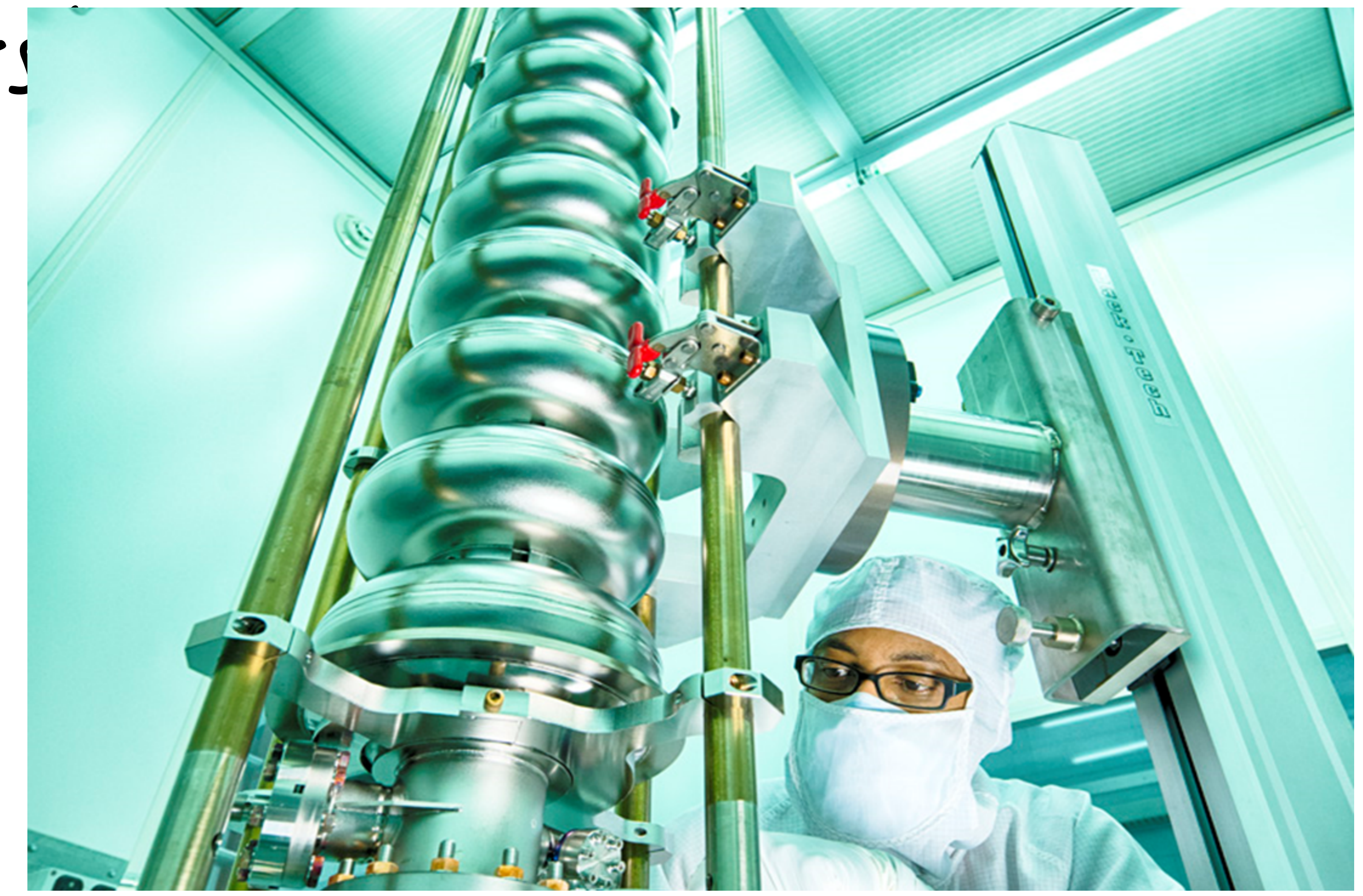
Axions and ALPs



Some technology -superconducting cavities

Superconducting Technology *(and Fermilab)*

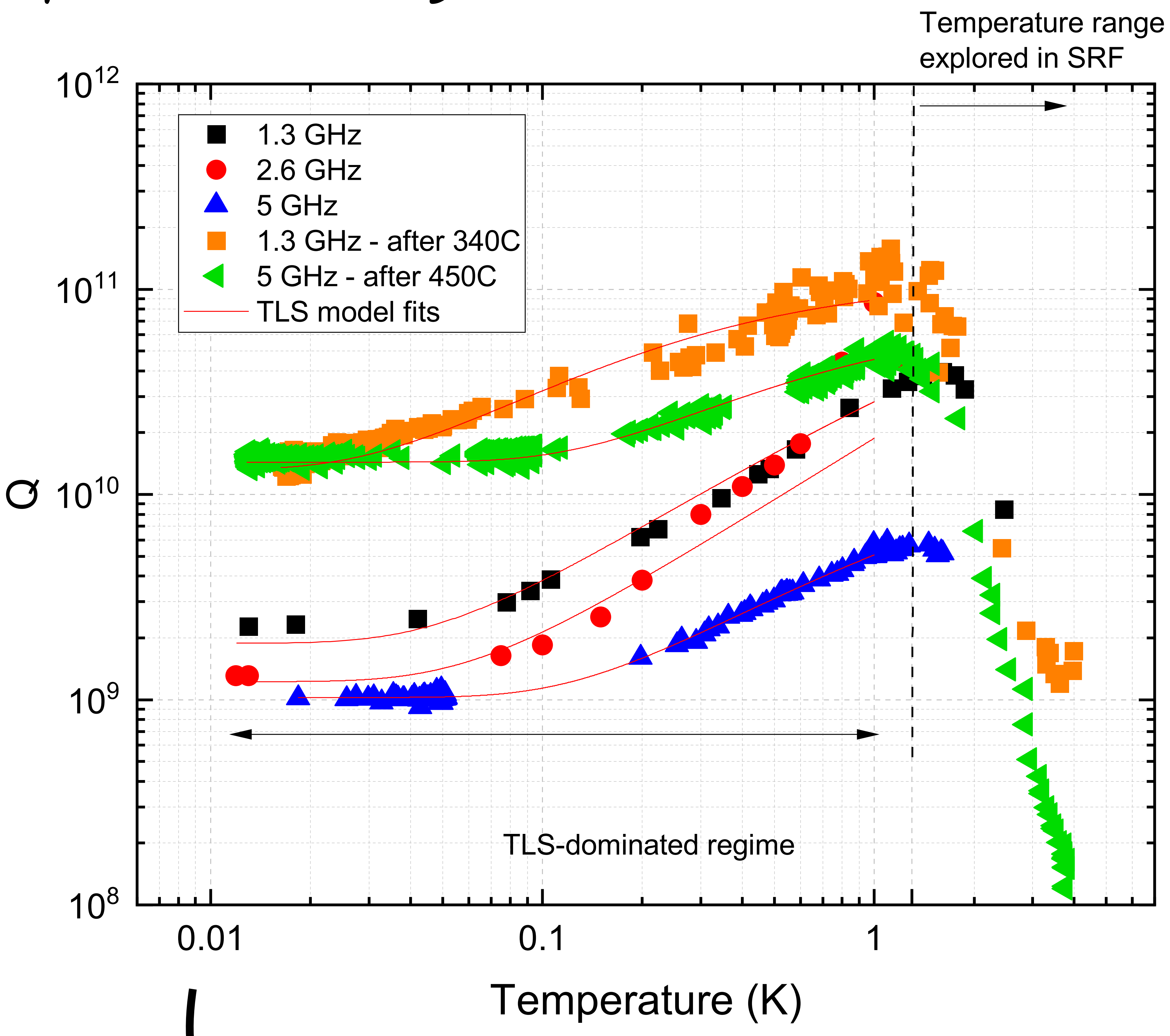
- SC technology is one of the most promising paths toward quantum computing with demonstrated results.
  - SC qubits (frequencies of ~GHz) have achieved coherence times of ~ millisecond ($Q \sim 10^6$).
  - Even higher Q systems were developed for accelerators



SRF cavities developed at Fermilab have achieved $Q \sim 10^{9\text{-}10}$.

Superconducting Technology *(and Fermilab)*

- Also in the quantum regime:



Romanenko et al.
Phys.Rev.Applied 13 (2020)

~2 sec coherence times!

Can we use this as qubits? qudits?

Less than one thermal photon in cavity.

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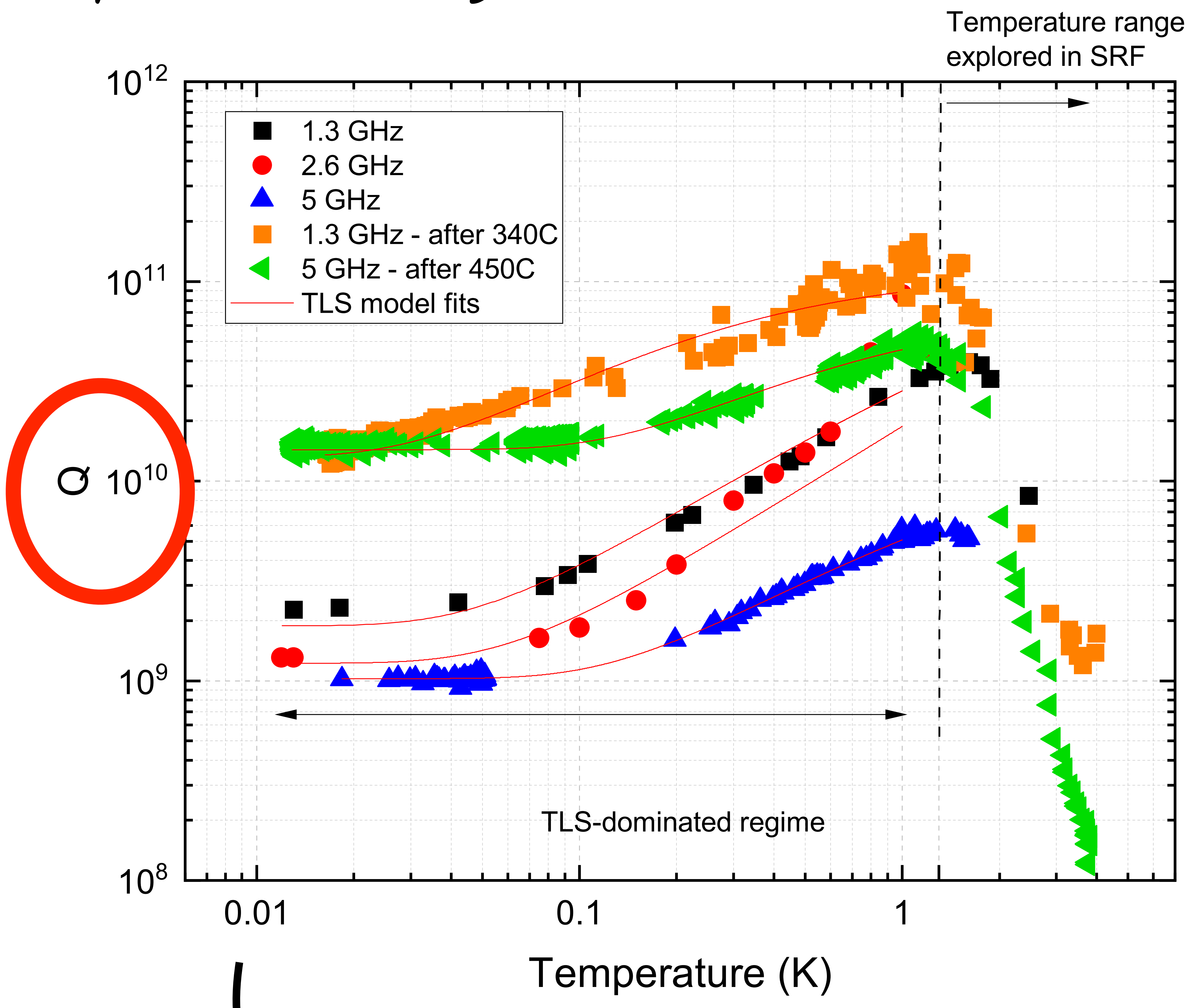

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Romanenko et al.
Phys.Rev.Applied 13 (2020)

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Director: Anna Grassellino

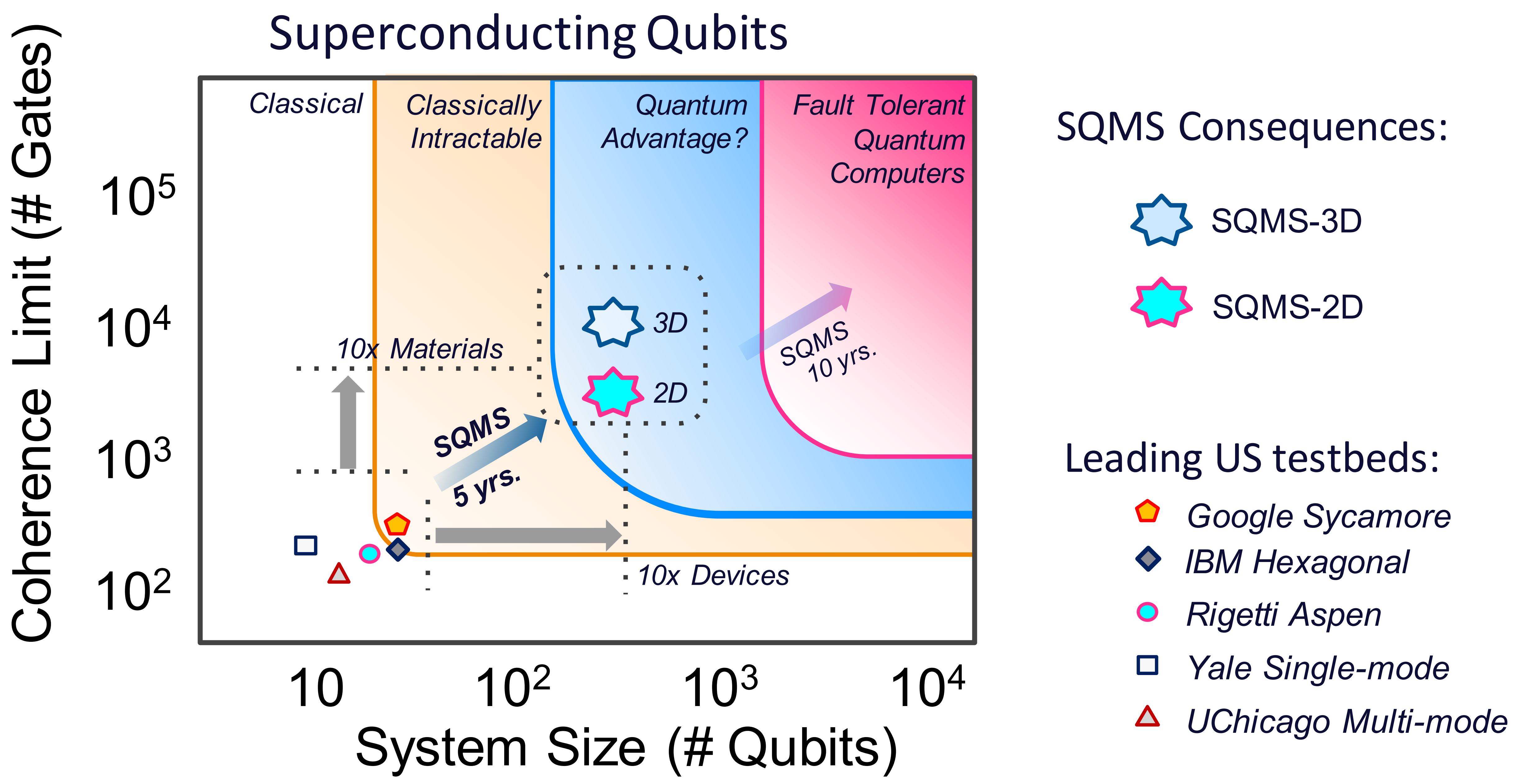
SQMS - *Superconducting Quantum Materials and Systems*

- Fermilab's **SQMS** Center, funded by DOE's National Quantum Initiative, is leveraging this cutting edge SC research to quantum.

- Many institutions, **including** UIUC (Yoni Kahn).

  - SC and material science know-how to improve "regular" qubits.

  - Use SRF cavities modes store quantum information, "3D architecture"

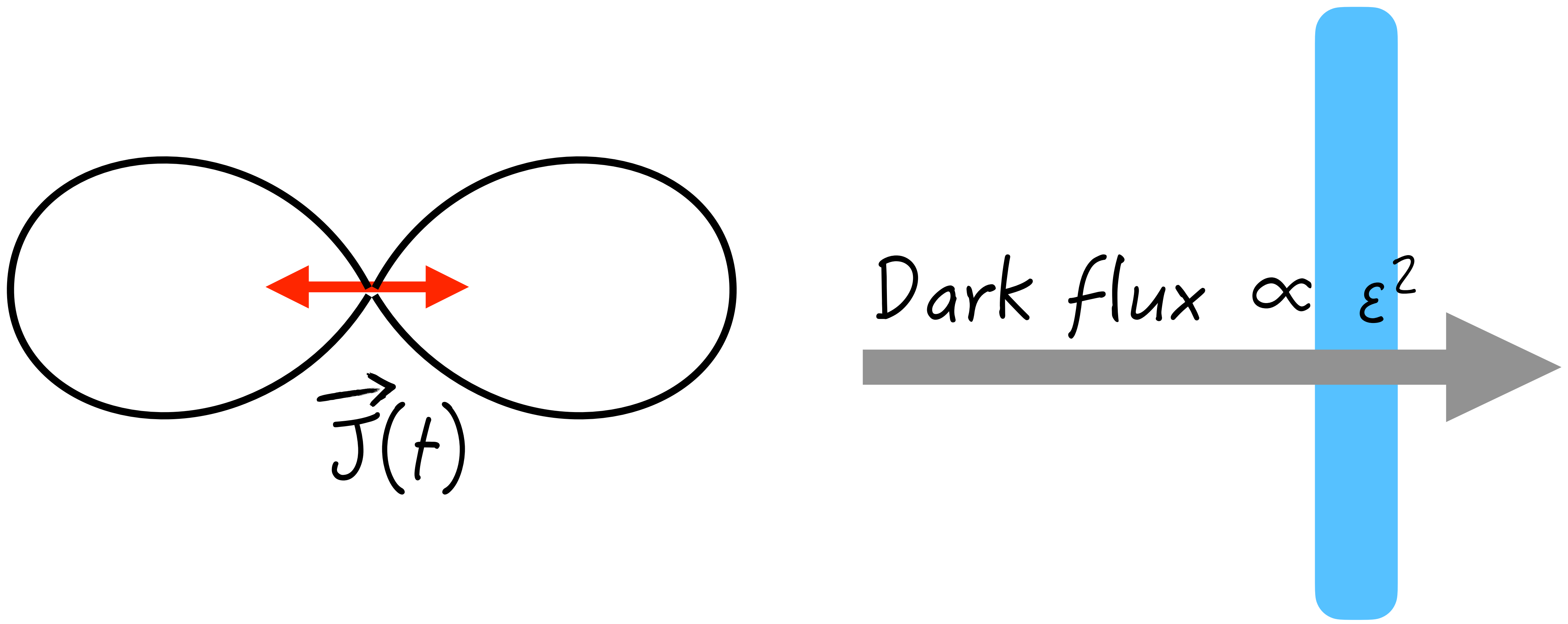


Back to Dark photons, etc…

How can quantum sensing and technology help the search?

Lab Based Dark Photon Search

- Recall our radiating dipole:



Can we sense this dark flux?

We know the frequency…
(and the phase)!

"Light shining through wall (LSW)":

Jaekel et al (2006)

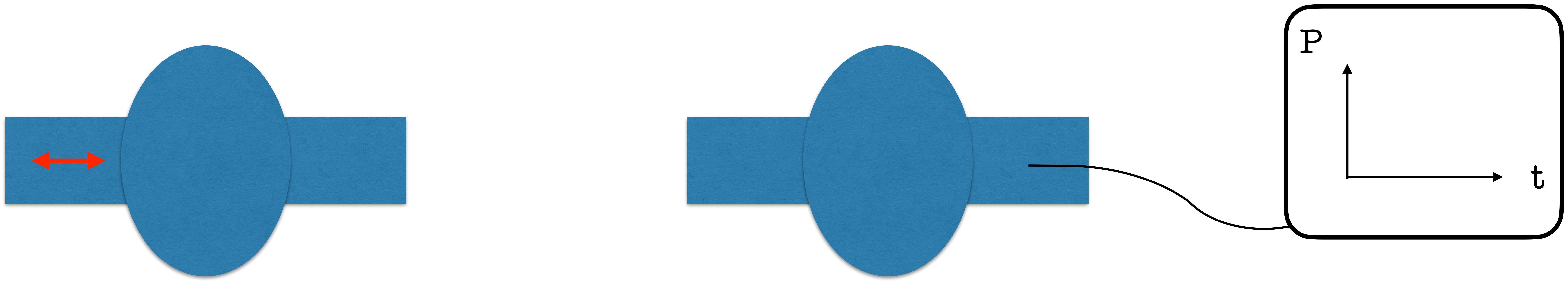
Examples -

Optical: ALPS, ALPSII, OSQAR

RF: CROWS

Light Shining Through Wall (w/ RF cavities)

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



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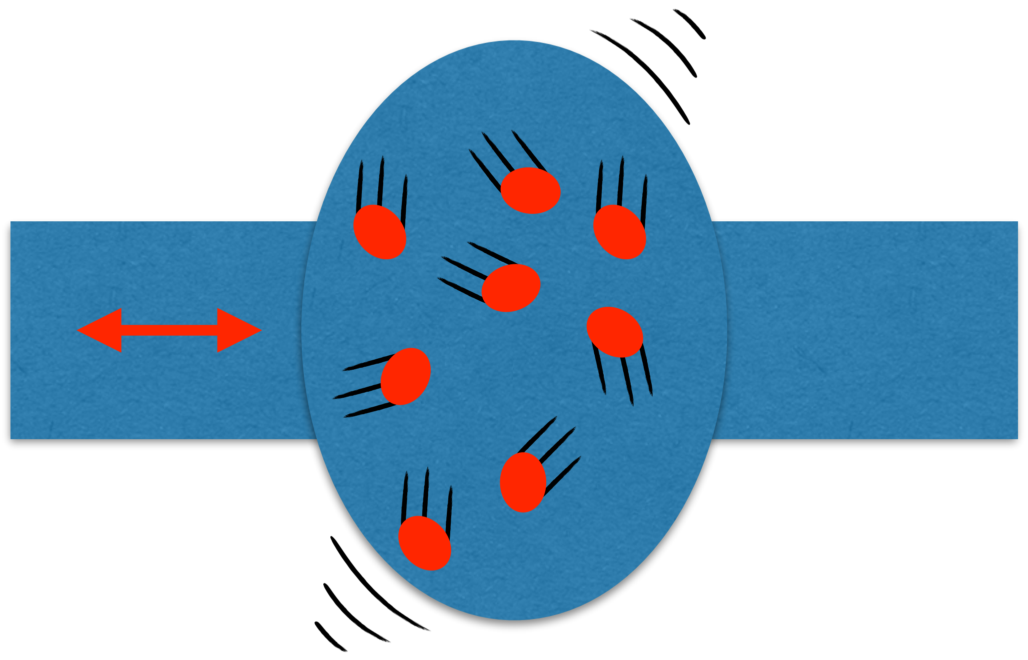
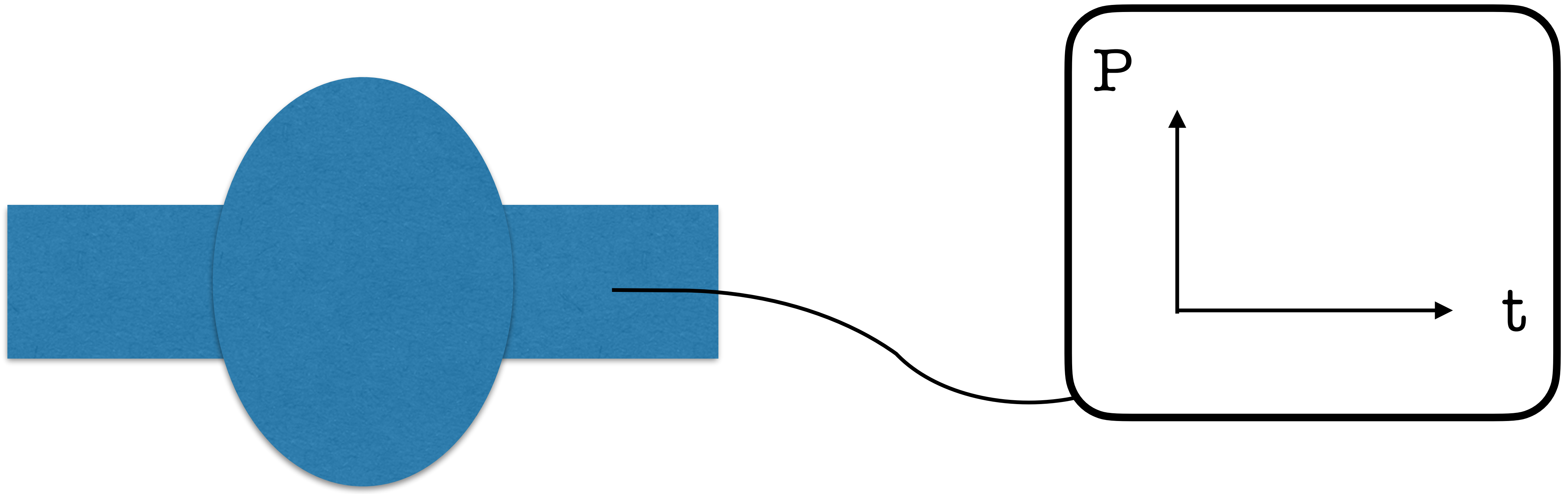


High Q → we can store more photons



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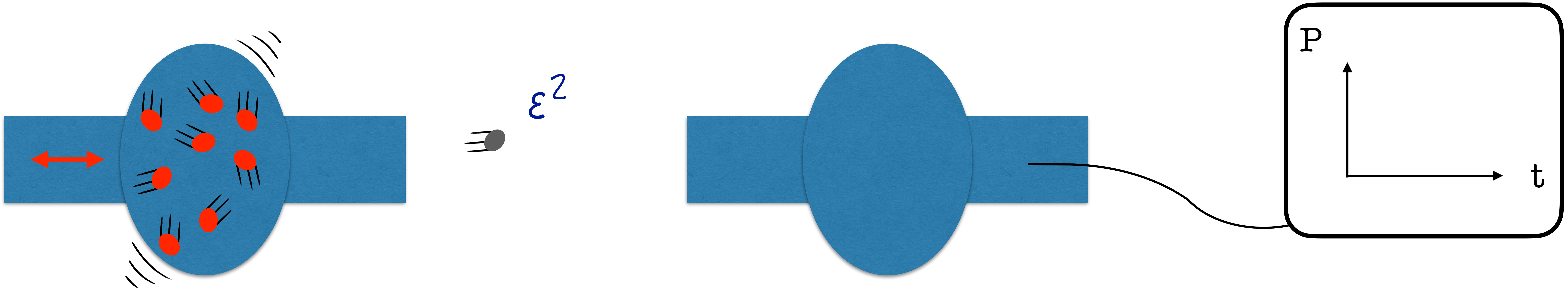

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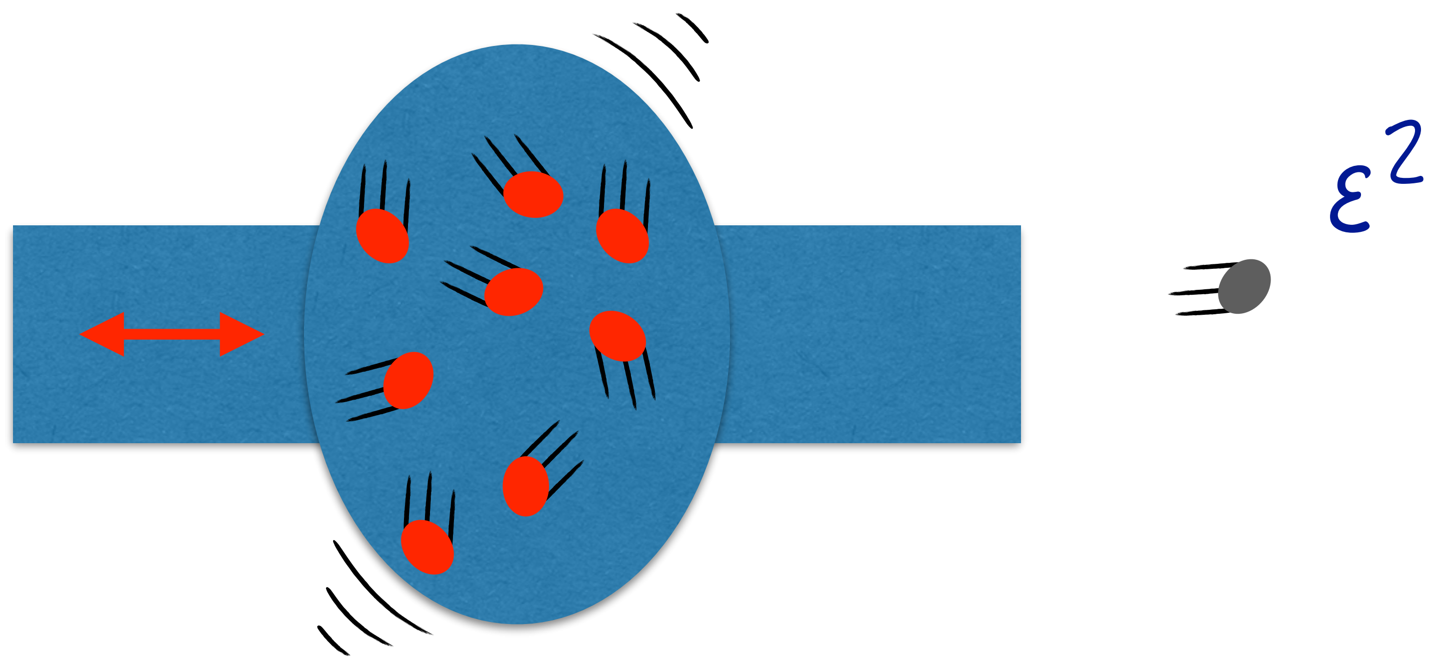

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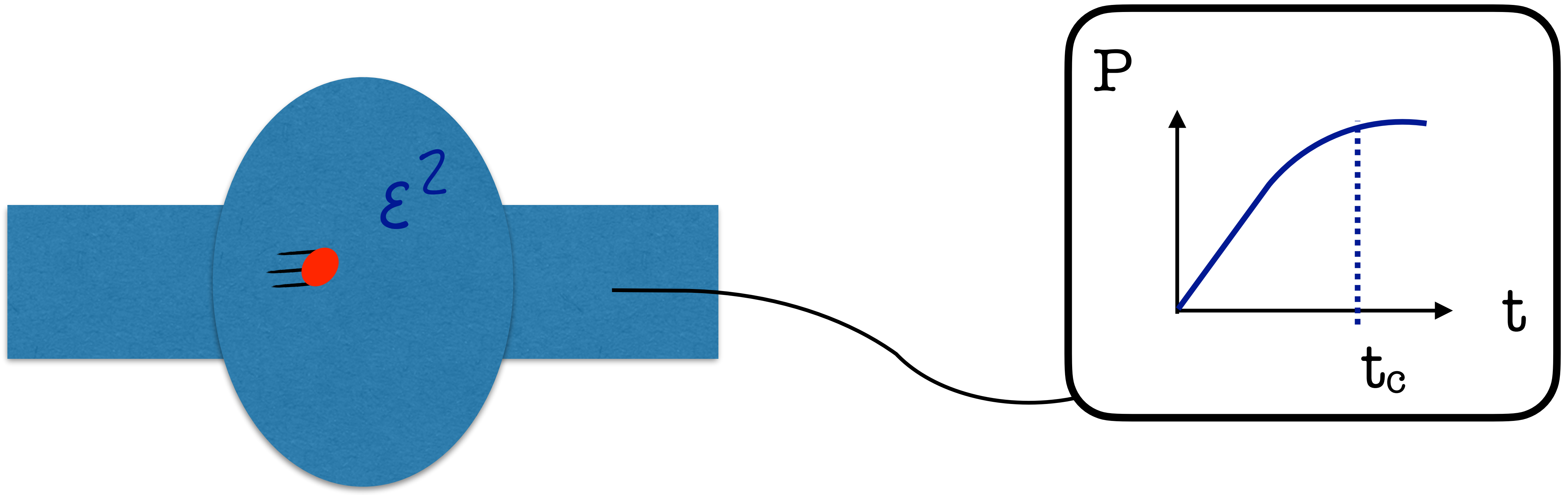

High Q → cavity can ring up for a longer time,

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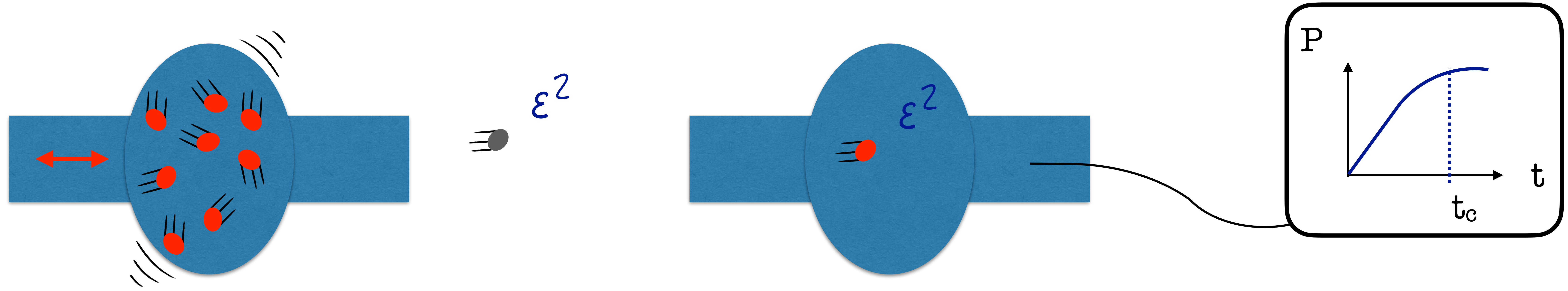


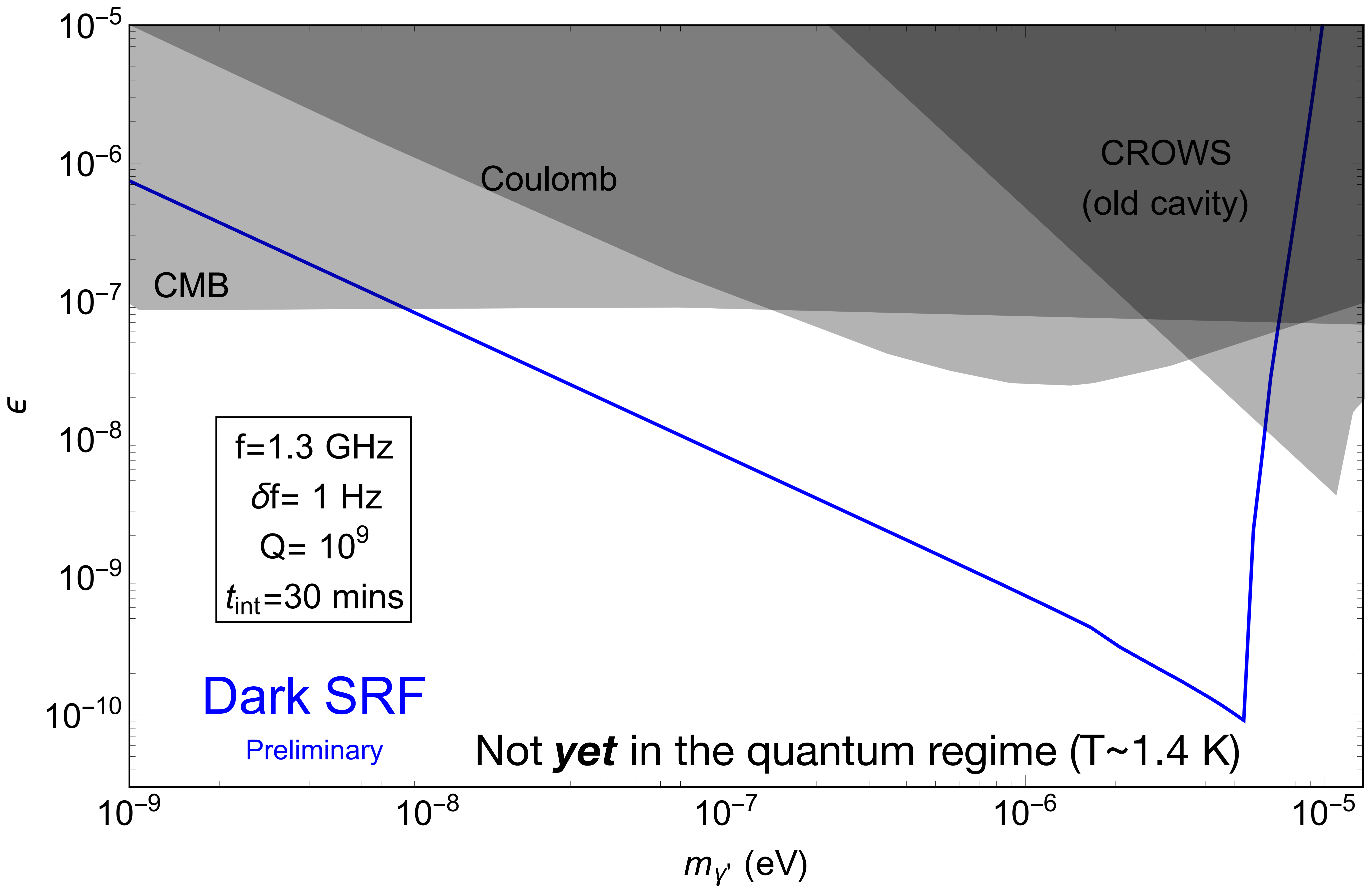
High Q → we can store more photons

High Q → cavity can ring up for a longer time,

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

Dark SRF

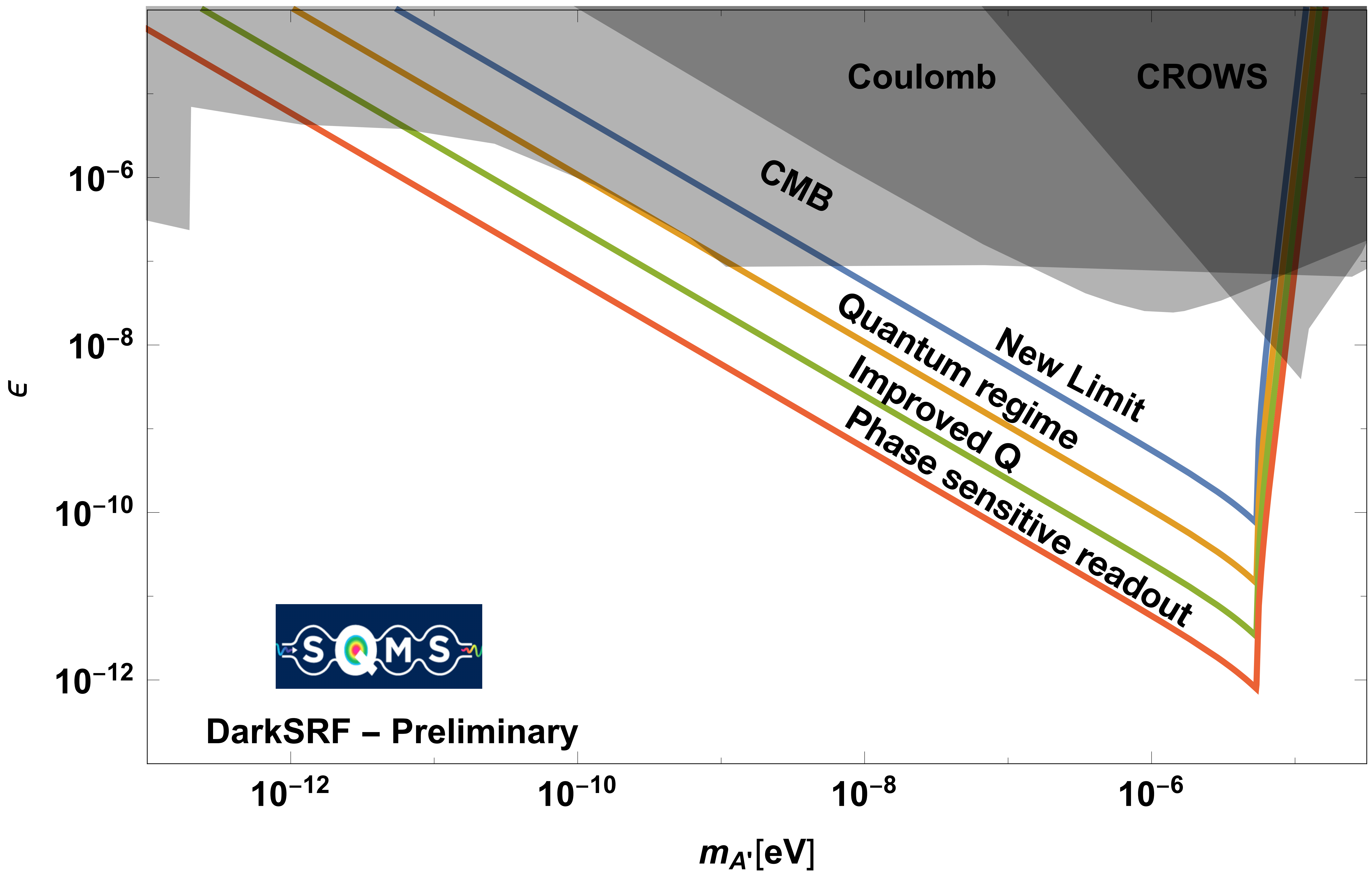
- Proof of concept executed (w/ ingredients in the Fermilab pantry):



Plot by Zhen Liu (UMN)

Dark SRF

- Exciting future plans to exploit quantum sensing:

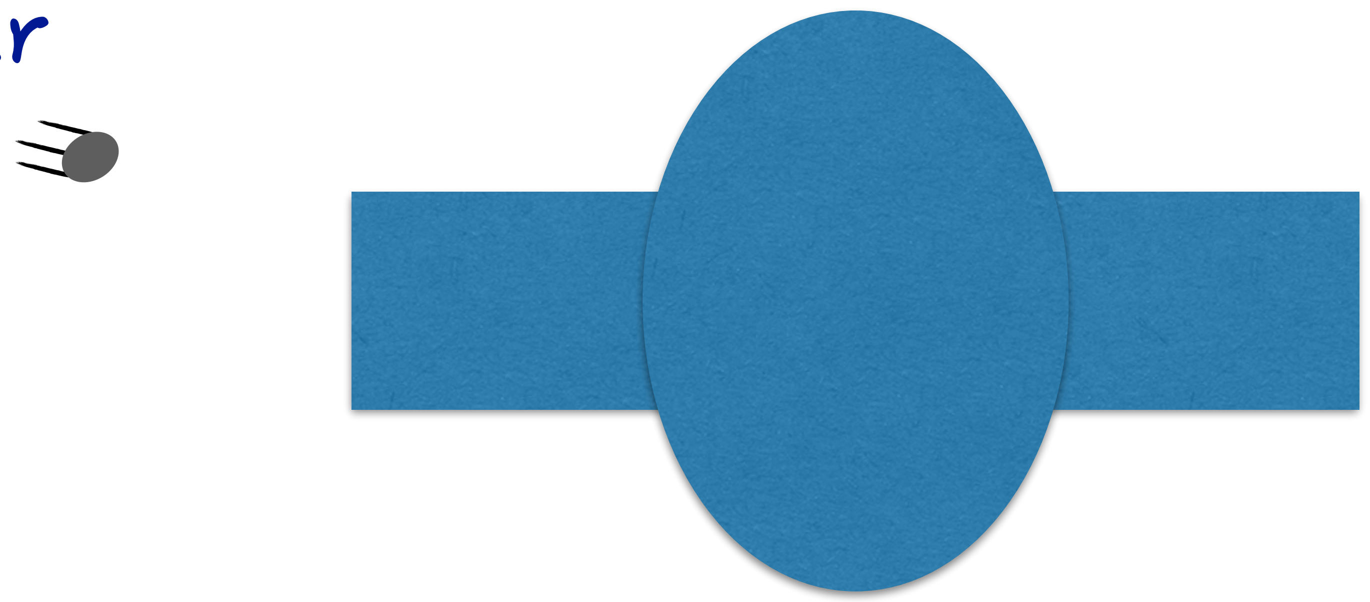


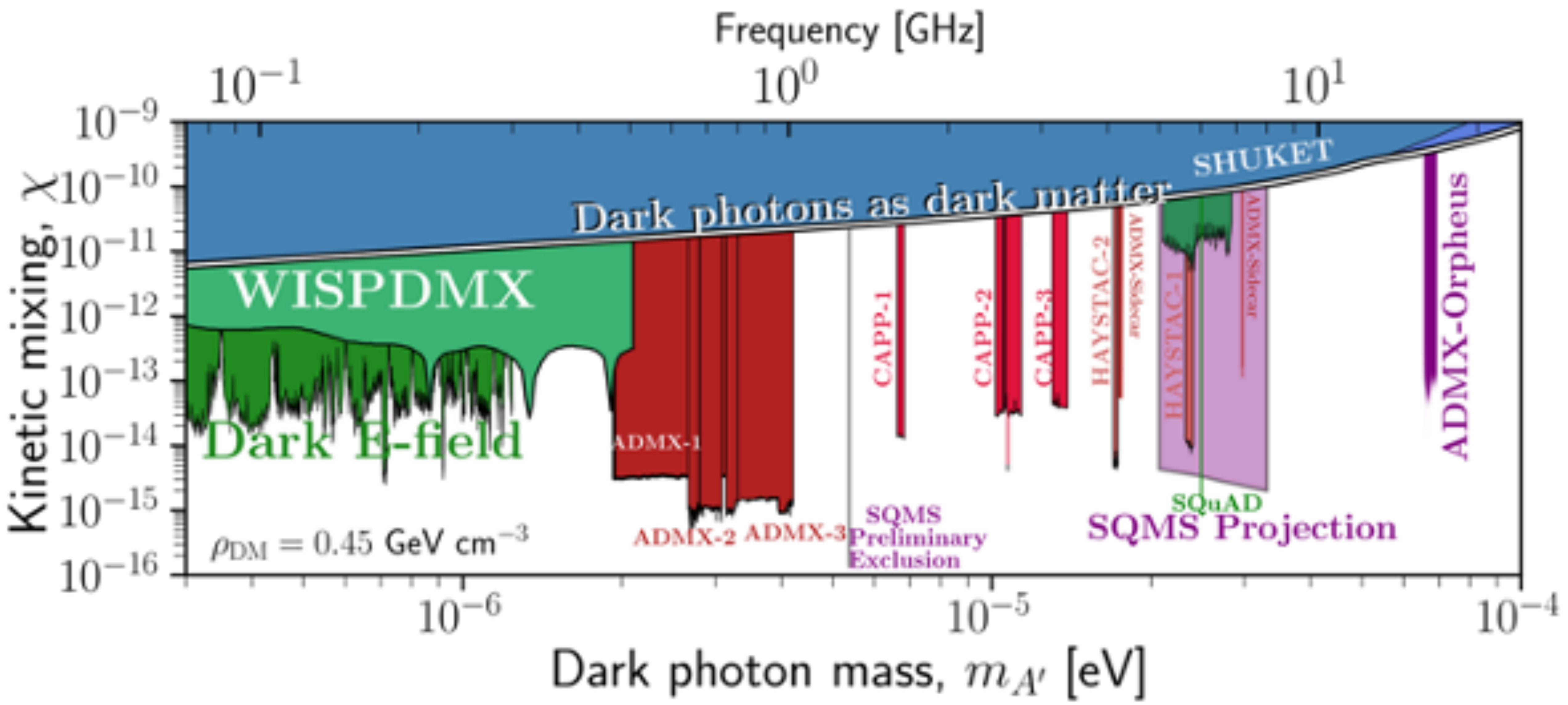
Preliminary DR setup, T~10 mK

Dark Photon Dark Matter

- We are also testing hypothesis that a dark photon is the dark matter:

Dark matter





The dark matter is non relativistic
→ photon frequency is DM mass.

Need to scan cavity frequency

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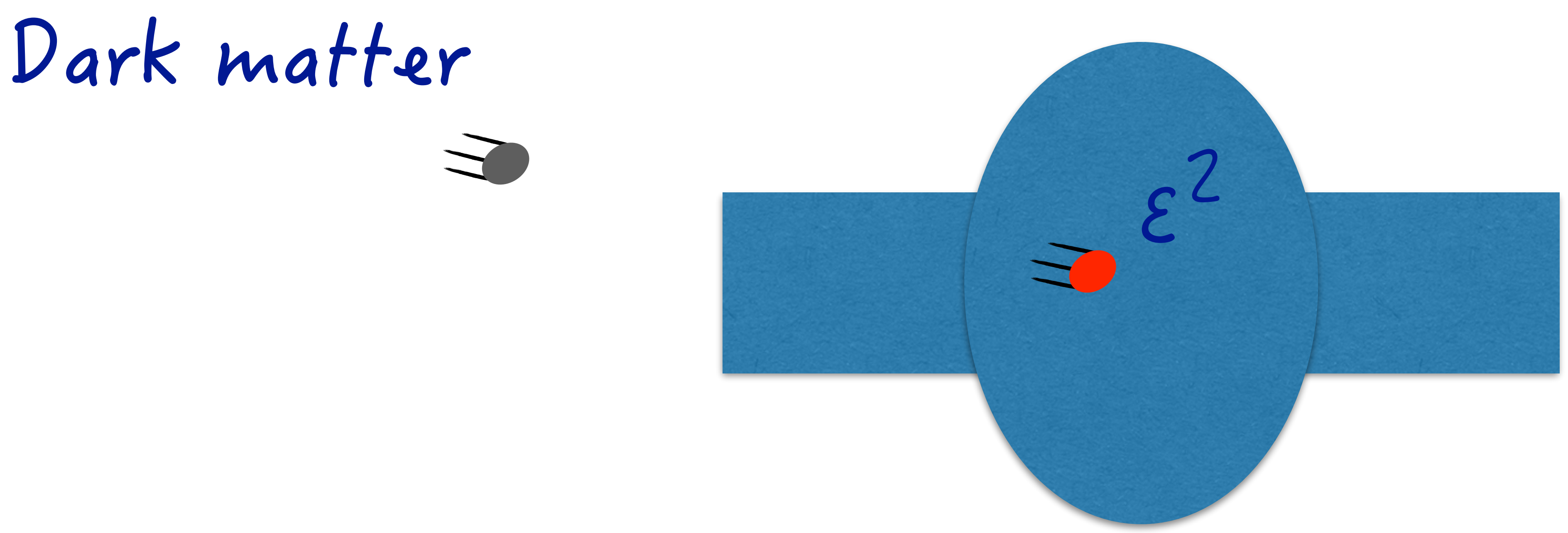

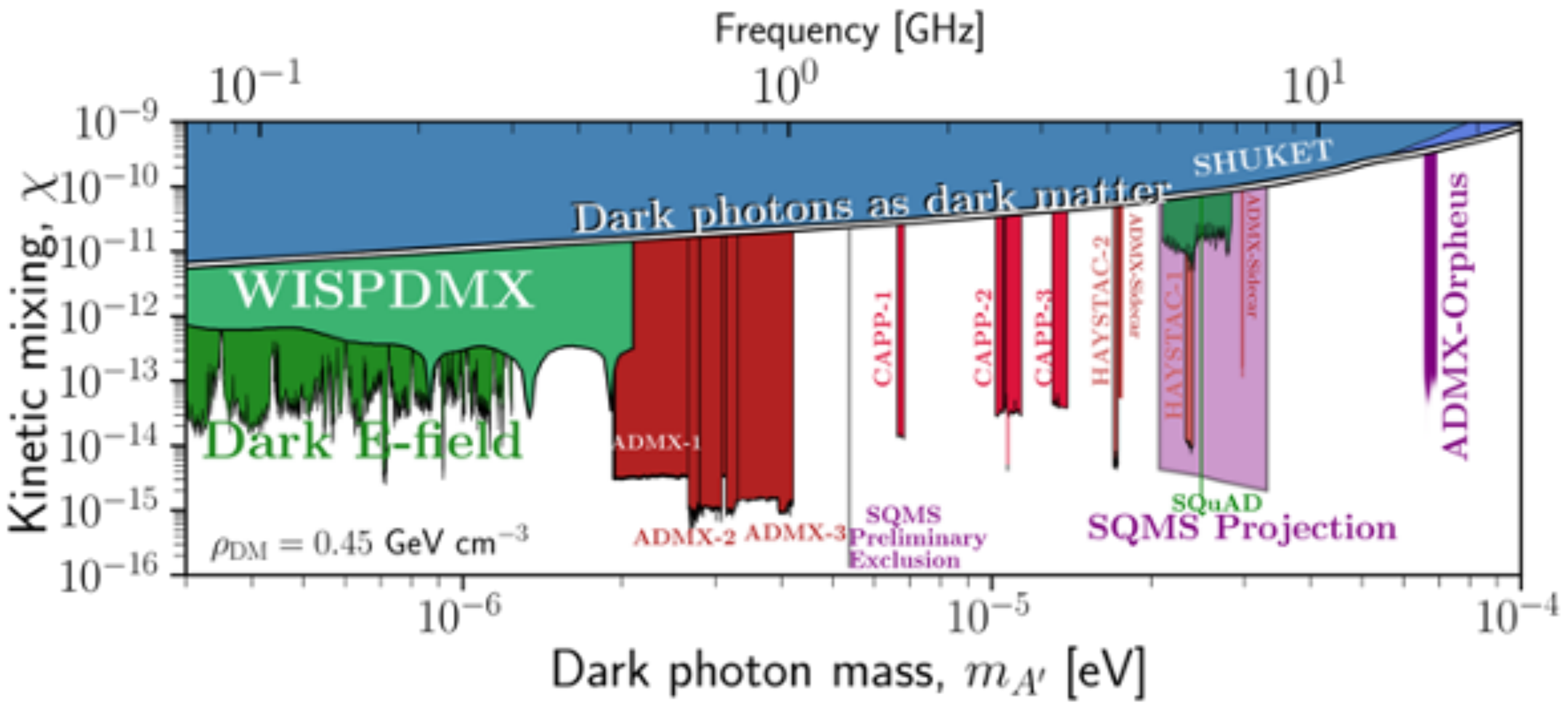

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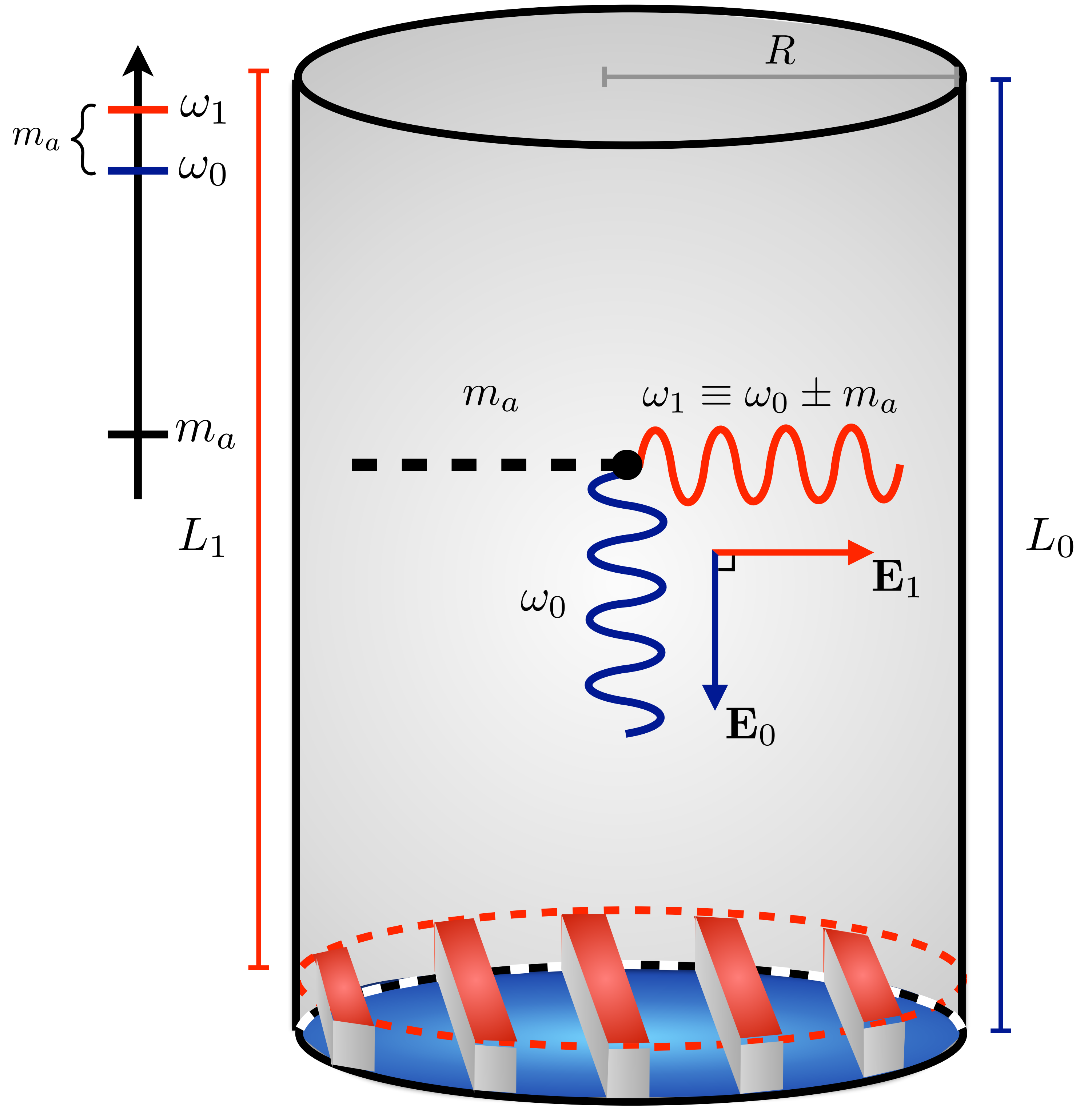
Axion searches

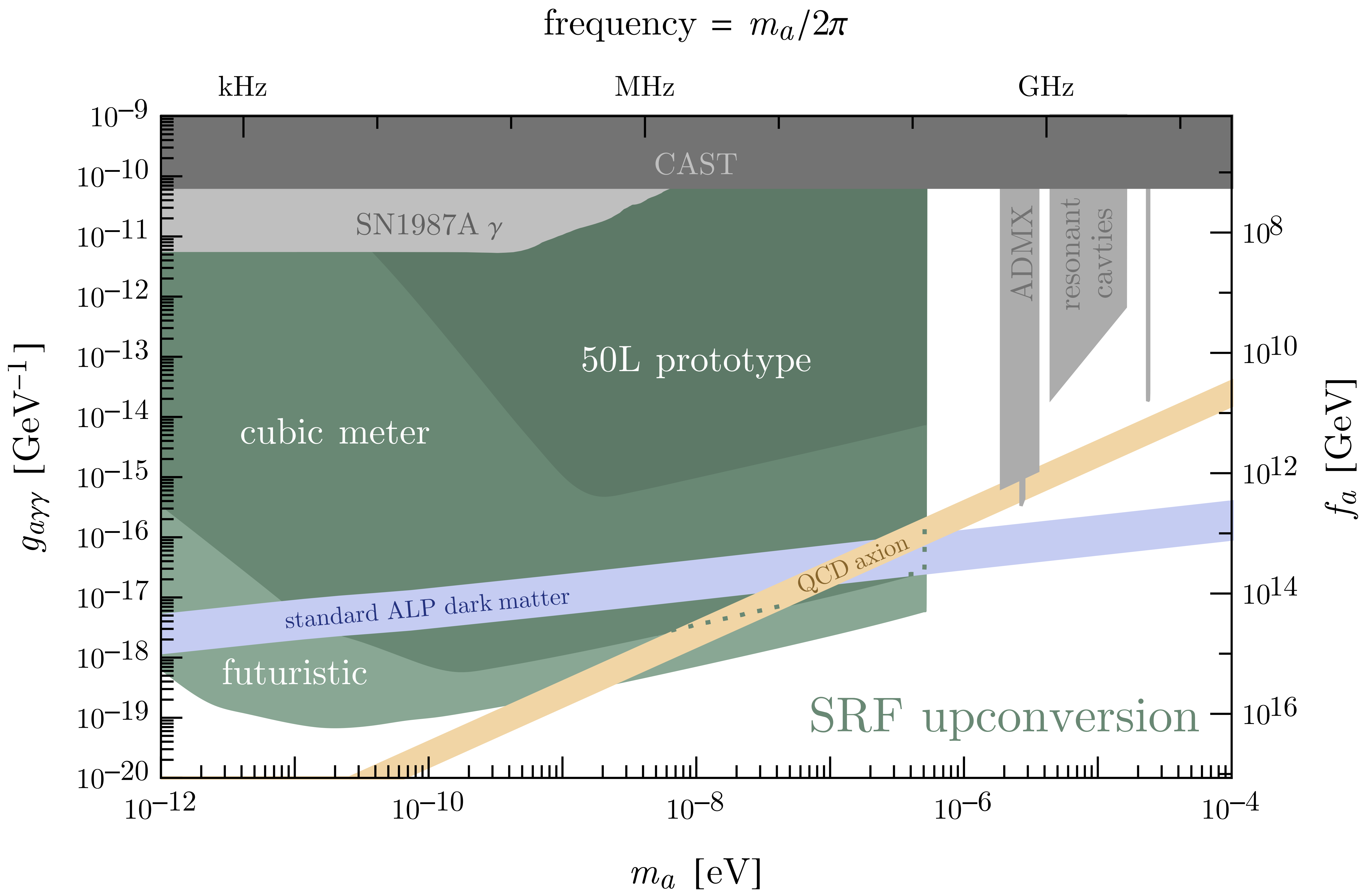
Conceptually similar, but a background field is needed

(recall axion is a nonlinear extension)

Axion Searches

Axion DM search - axion upconvert a pump field.





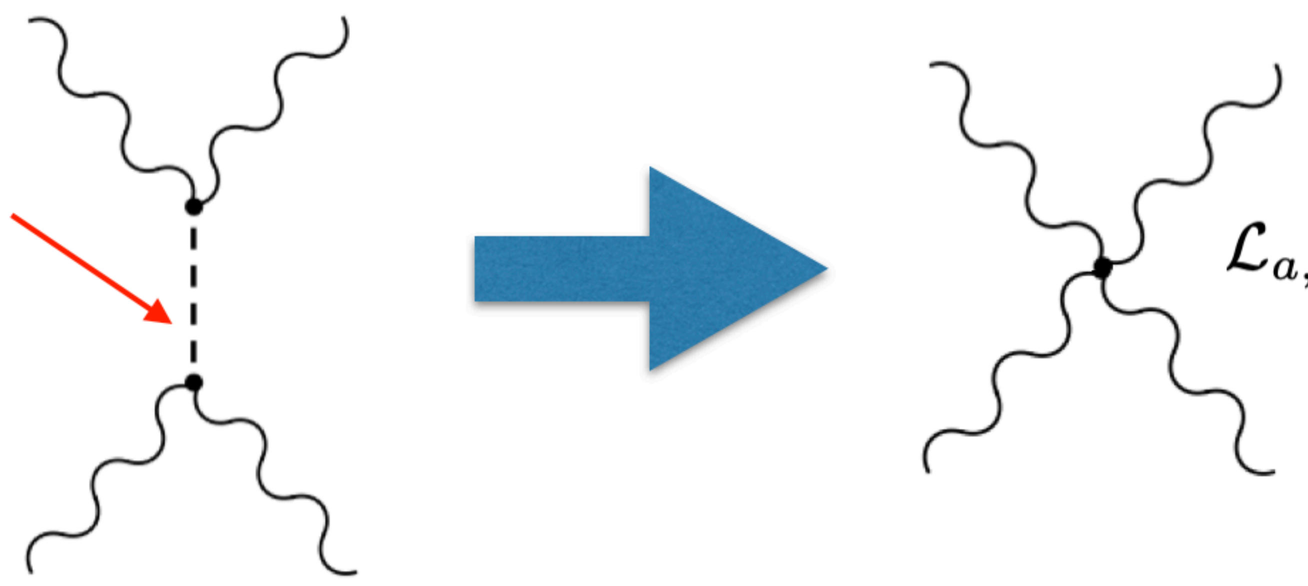
Berlin et al (2019)

Bogorad, Hook, Kahn UIUC , Soreq (2019)

Axion Induced Light-by-Light (and Euler-Heisenberg).

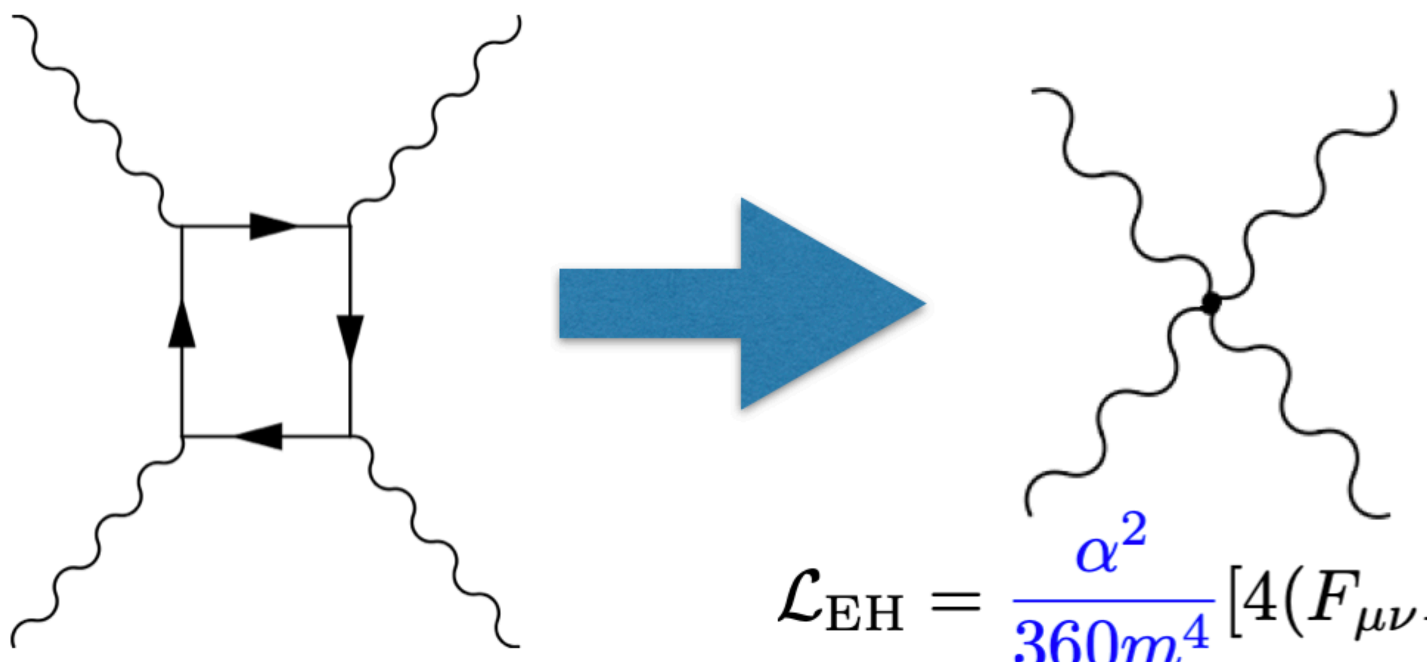
- Our most devious scheme (Kahn and collaborators): searching for a nonlinear effect in as ingle cavity

$\frac{1}{\omega^2 - m_a^2} \approx \frac{1}{m_a^2}$



$\mathcal{L}_{a,\text{eff}} = \frac{g_{a\gamma\gamma}^2}{32 m_a^2}(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2$

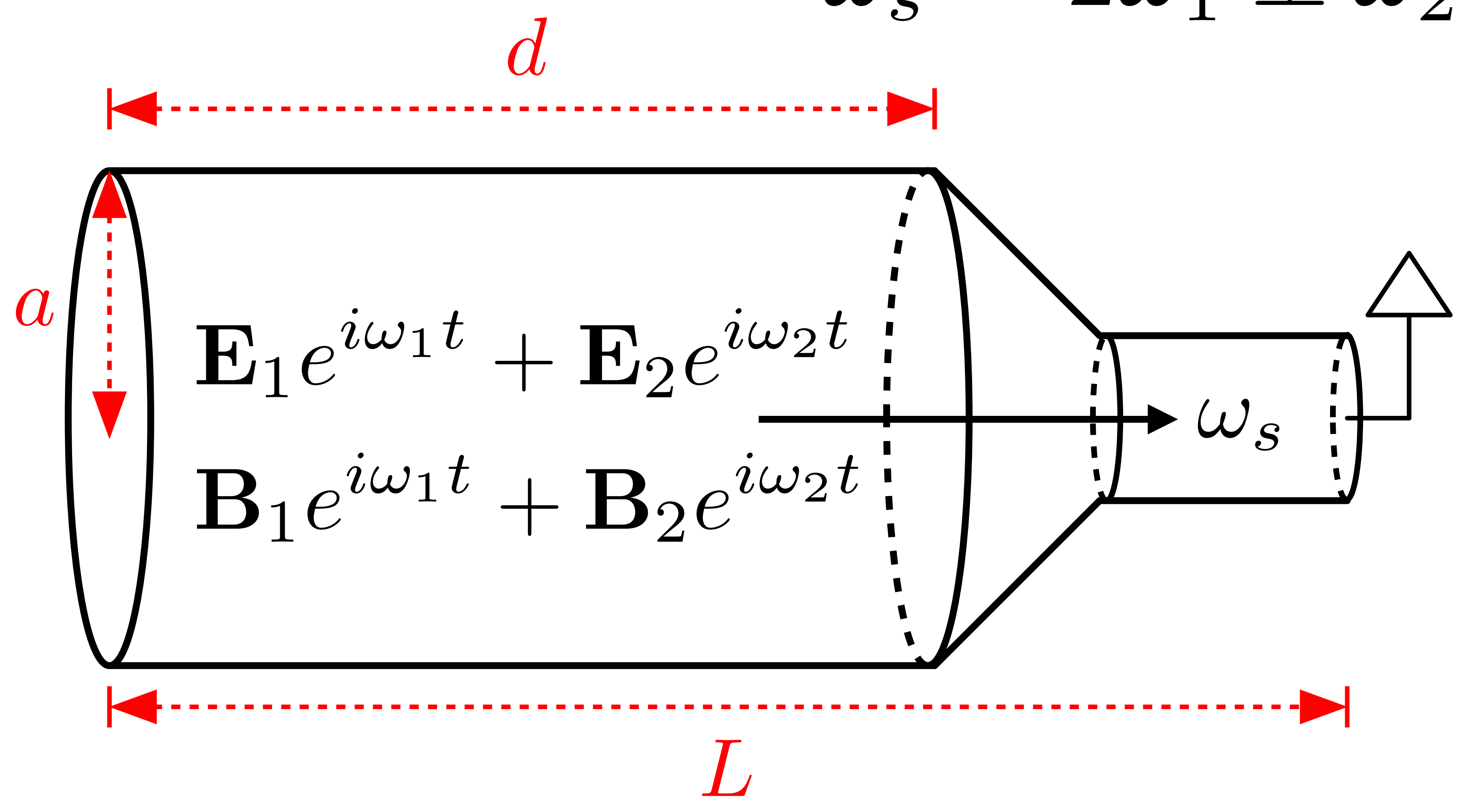
$\omega \ll m_e$



$\mathcal{L}_{\text{EH}} = \frac{\alpha^2}{360 m_e^4}[4(F_{\mu\nu}F^{\mu\nu})^2 + 7(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2]$

Light-by-light scattering among cavity modes

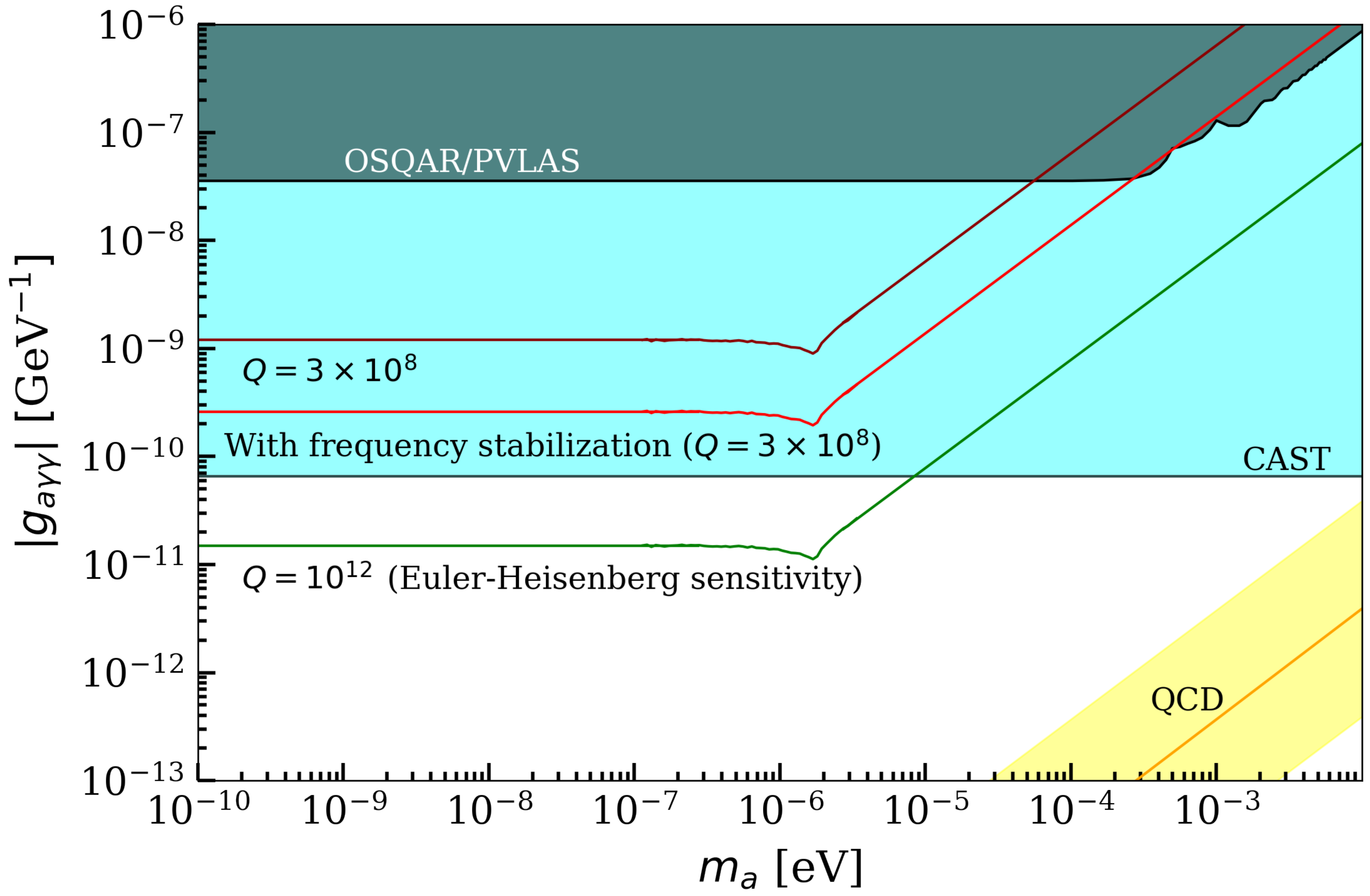
$\omega_s = 2\omega_1 \pm \omega_2$



Bogorad, Hook, Kahn$_{\text{UIUC}}$, Soreq (2019)

Axion Induced Light-by-Light (and Euler-Heisenberg).

Exciting reach:



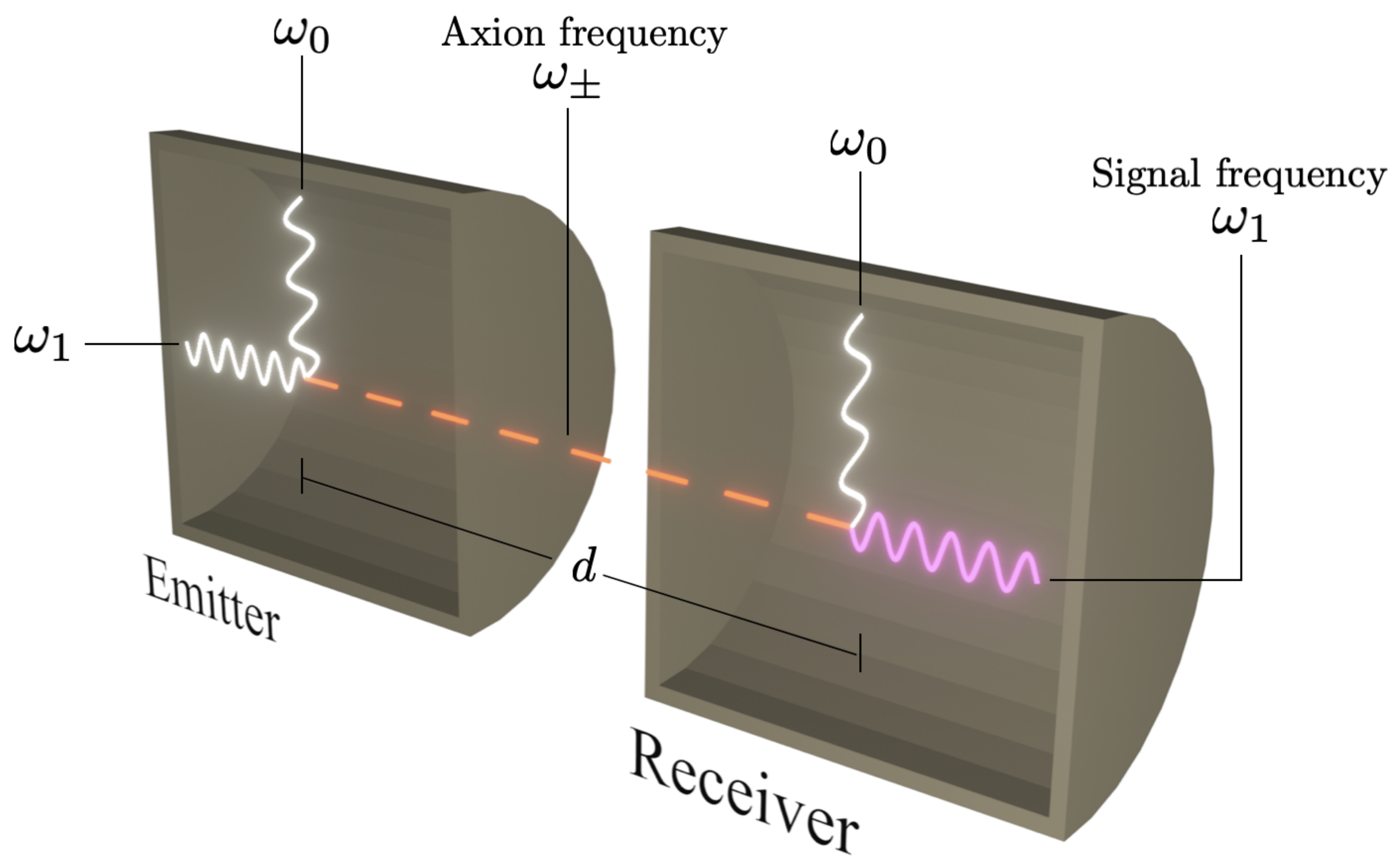
- Also may be the most challenging search! We are studying other sources of nonlinearity, both theoretically and experimentally.

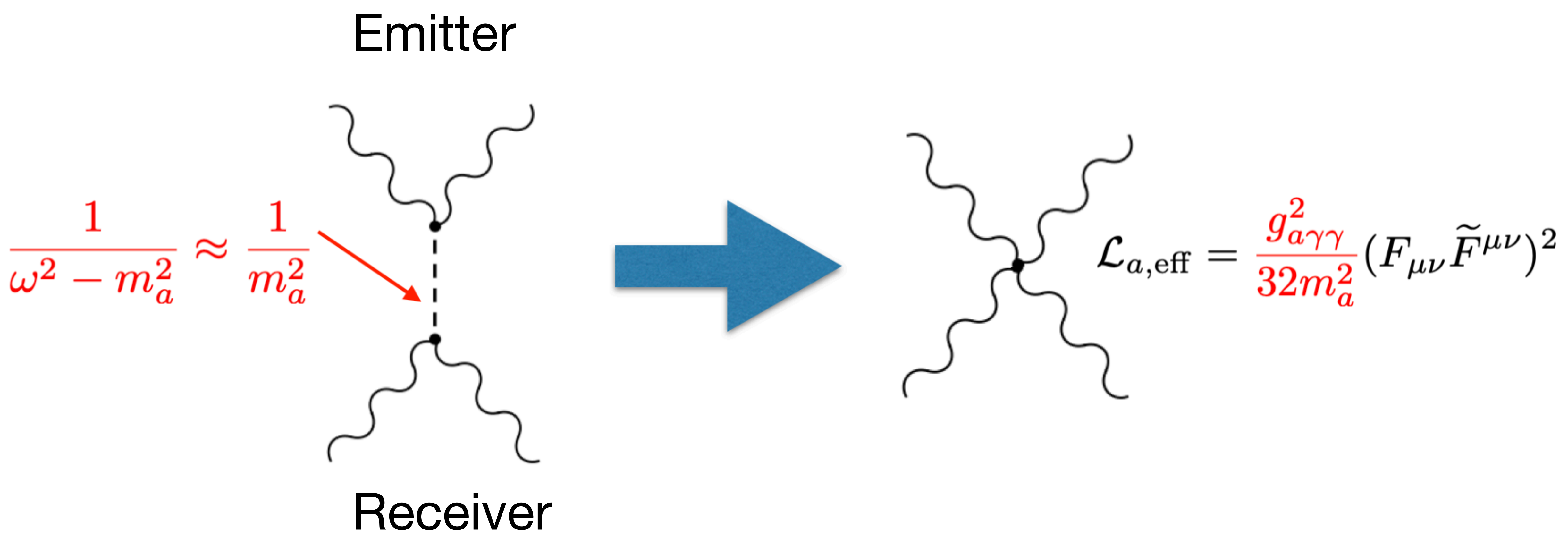
Axion Searches

Gao[UIUC], RH (2021)

If cavity nonlinearities prove to be too big - plan B:

LSW with pump fields excited in both cavities.





Gravitational wave searches

How are GWs related to axions?

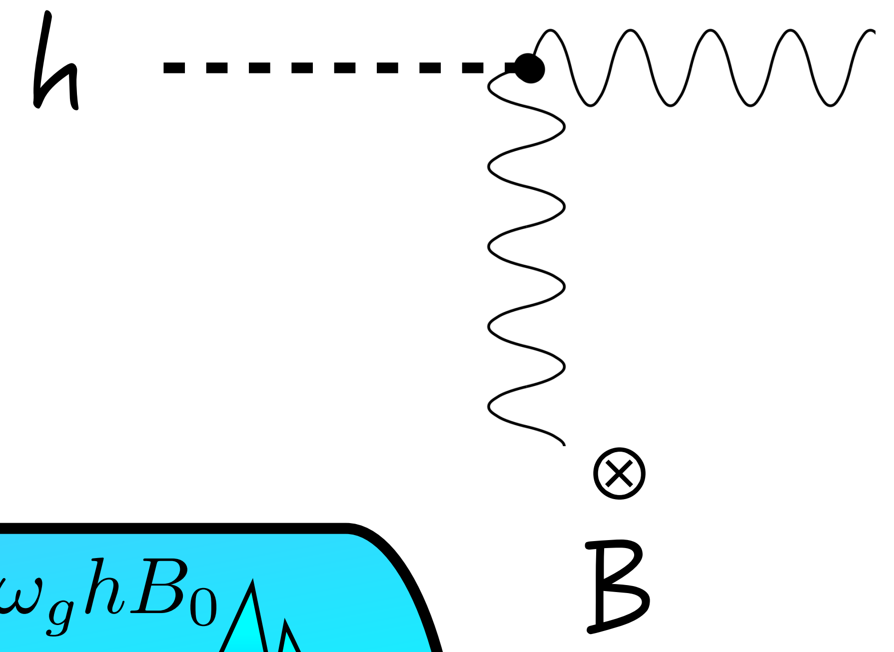
Berlin et al [incliding Khan$_{\text{UIUC}}$, Schutte-Engel$_{\text{UIUC}}$] (2022)

Gravity waves - also a Nonlinear Extension

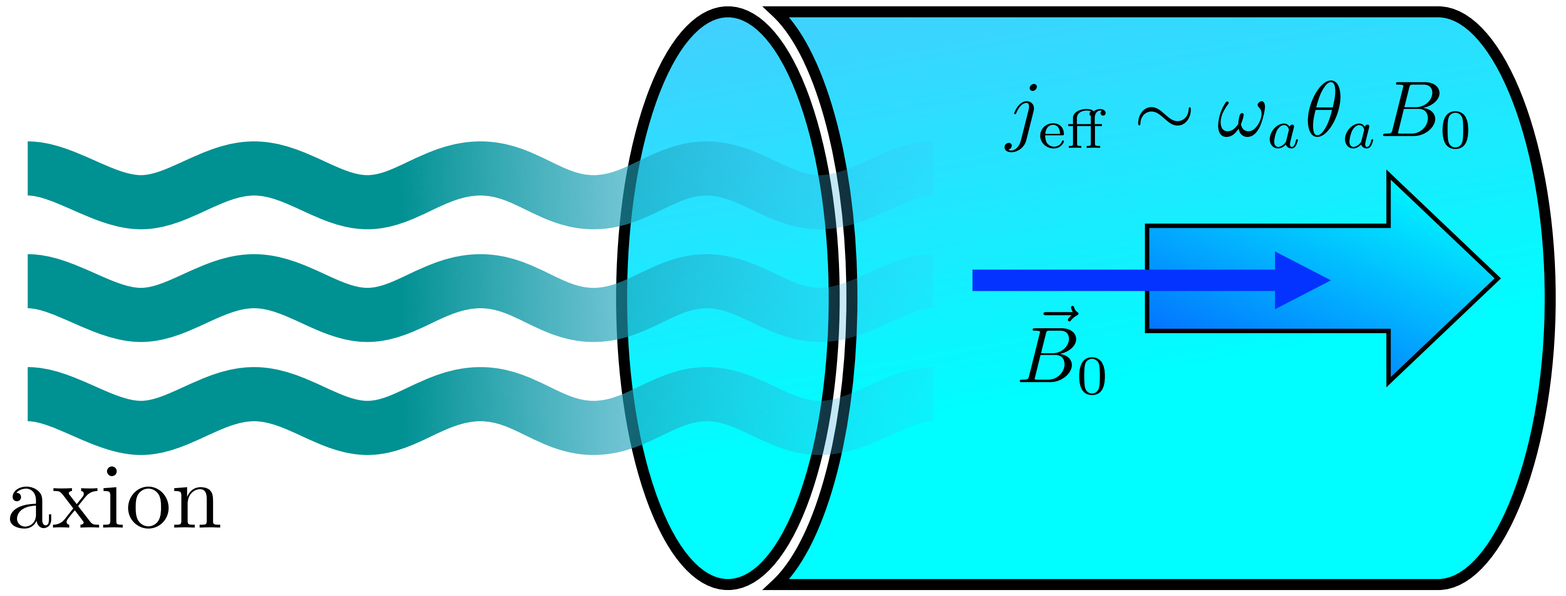
- GW's were only recently discovered.
  Extending the frequency window for GW detection is highly motivated

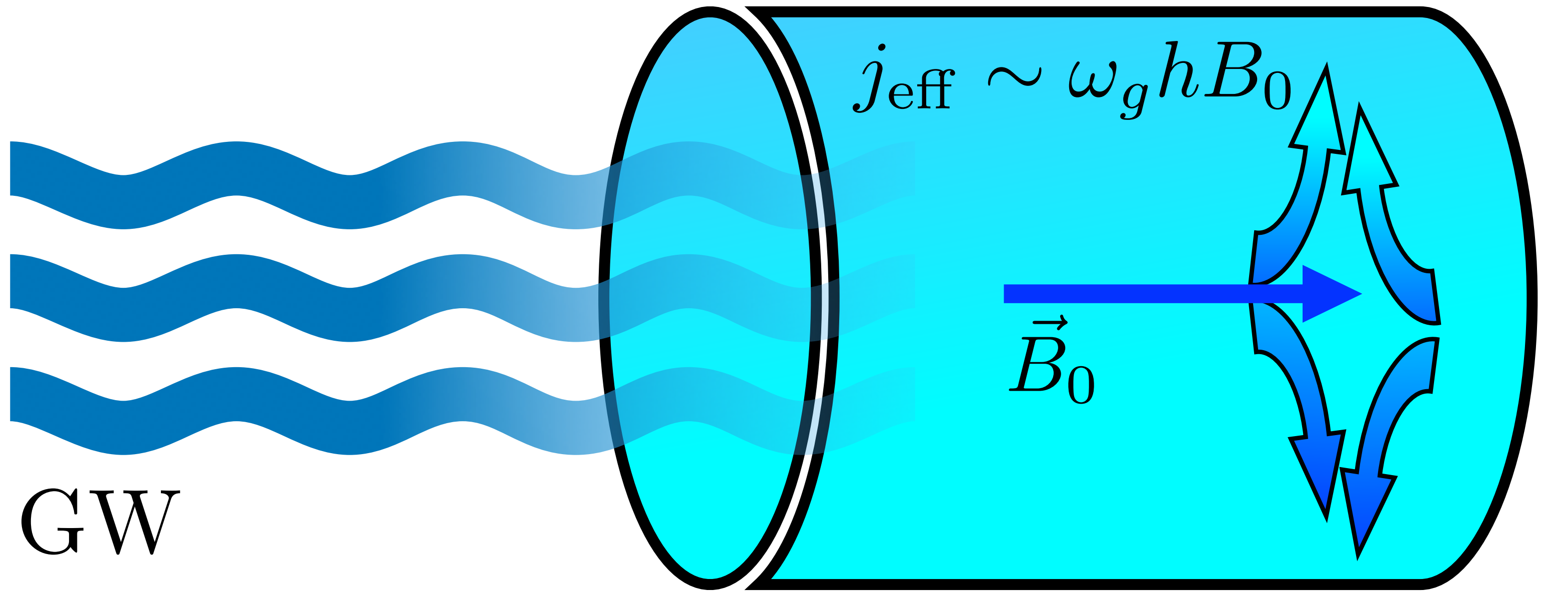
- Gravity is also a nonlinear extension of QED: $\mathcal{L} \supset -\sqrt{g}\; g_{\mu\sigma}\, g_{\nu\rho}\, F^{\mu\nu} F^{\sigma\rho}$

  and GW's are fluctuations in the metric. $g = \eta + h$



- Axion DM searches ↔ GW searches

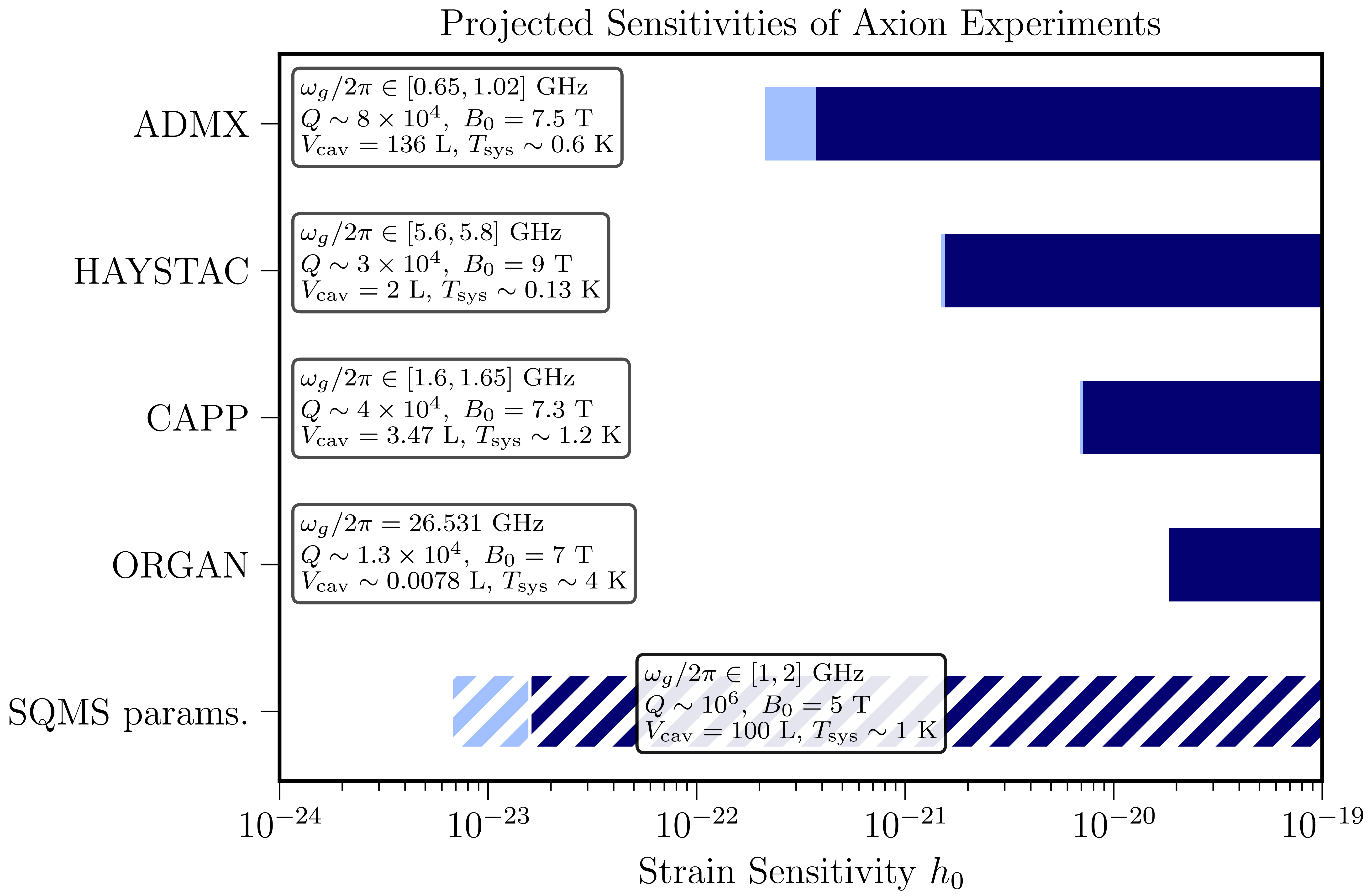




Note: correctly calculating the signal strength, is best done in the proper detector frame. Understanding frame effects and (incorrect) existing literature was alot of fun.

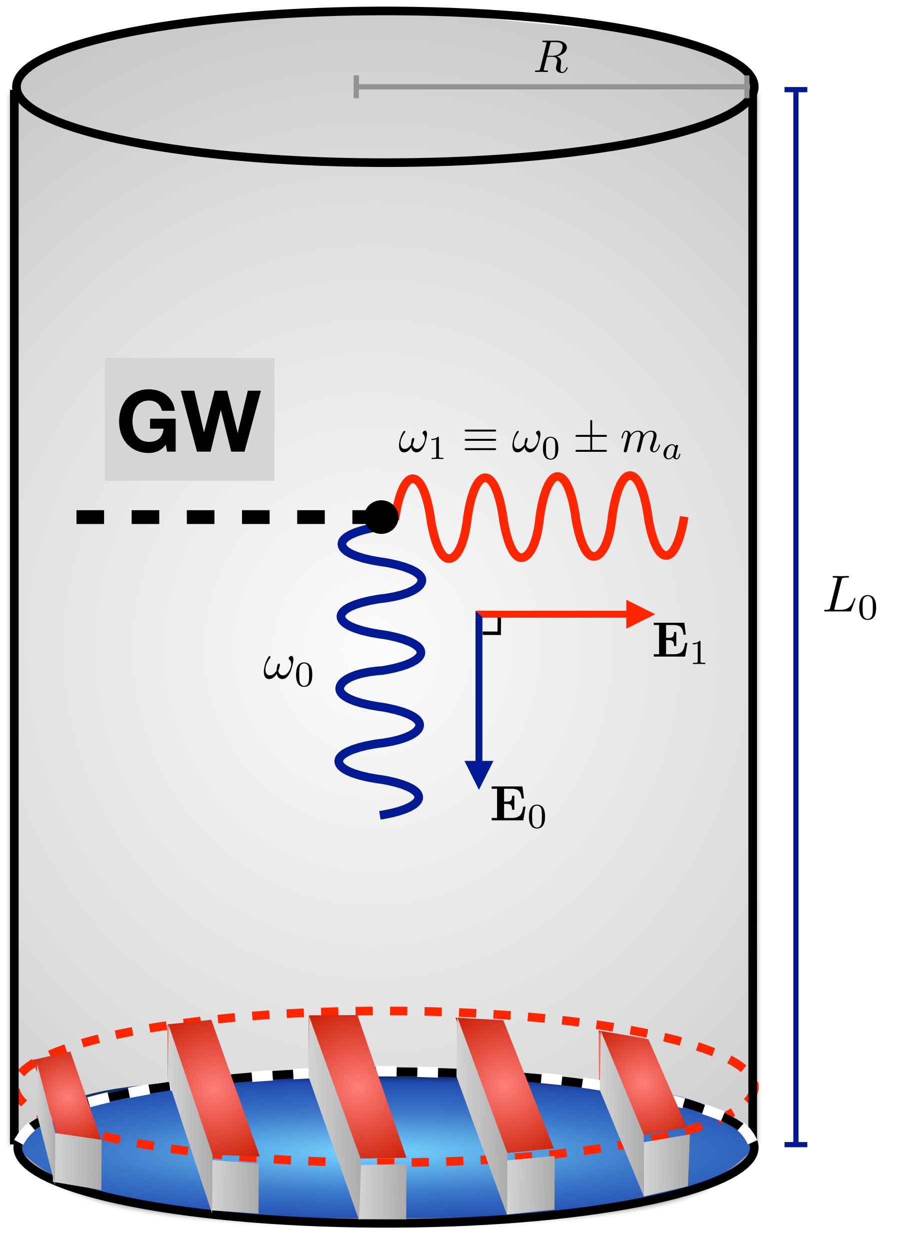
GHz Gravitational waves:

- SQMS has potential to set new limits for GHz GW's (sources anyone…?)



Work in progress:

Up-scattering experiment going to MHz frequencies!



Gravitational Waves with Matter Wave Interferometers

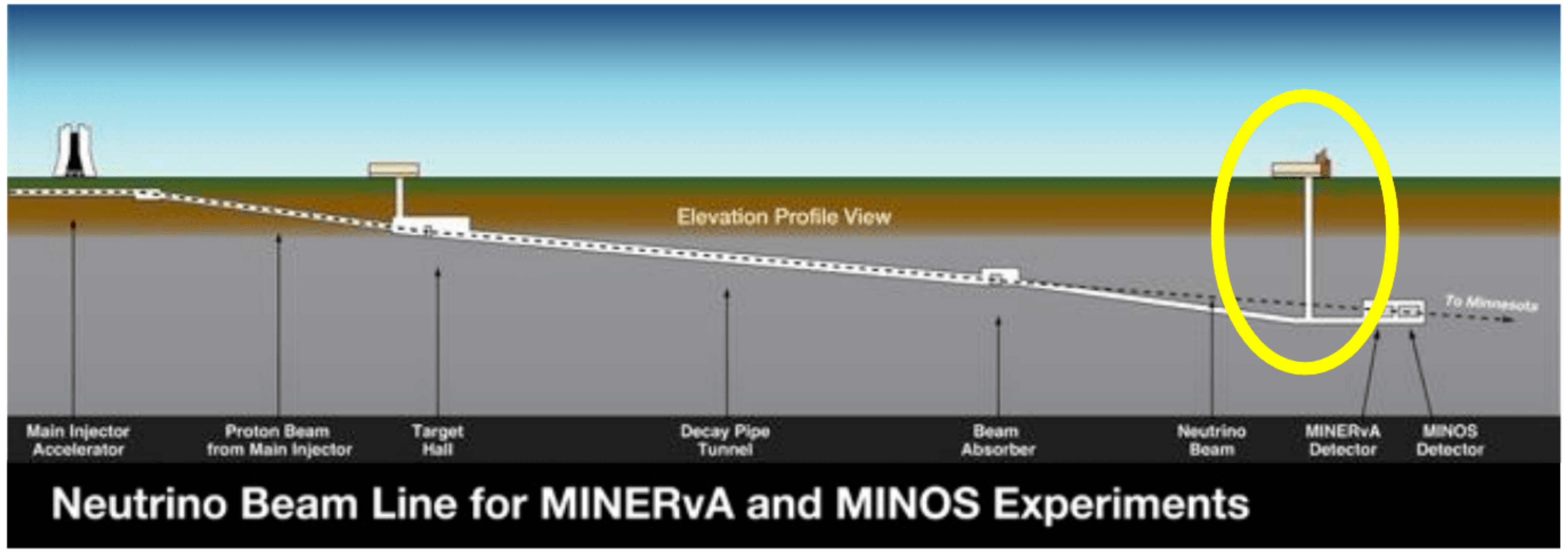
https://arxiv.org/abs/2104.02835

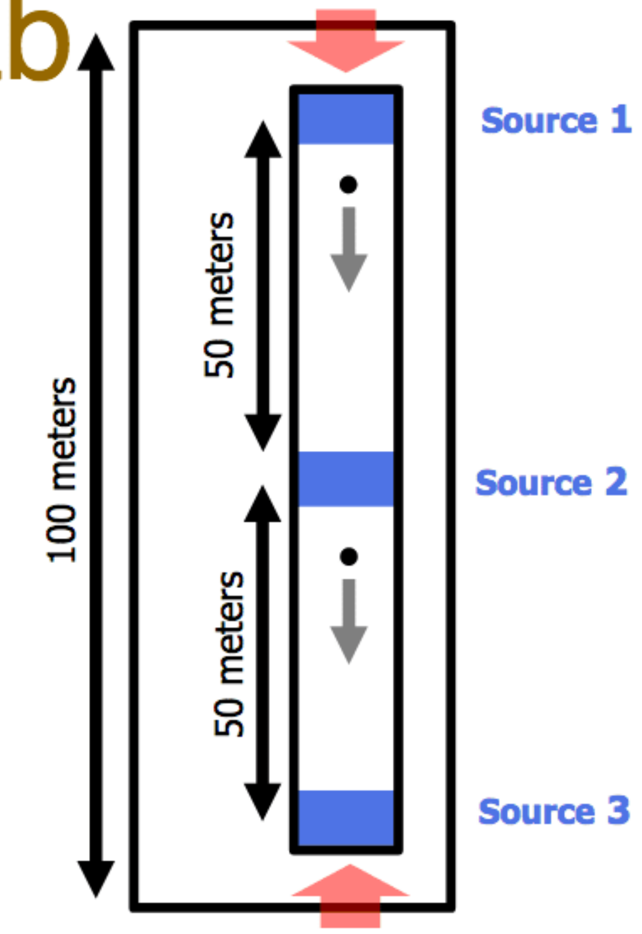
MAGIS-100: Gravitational waves with Atom Interferometry

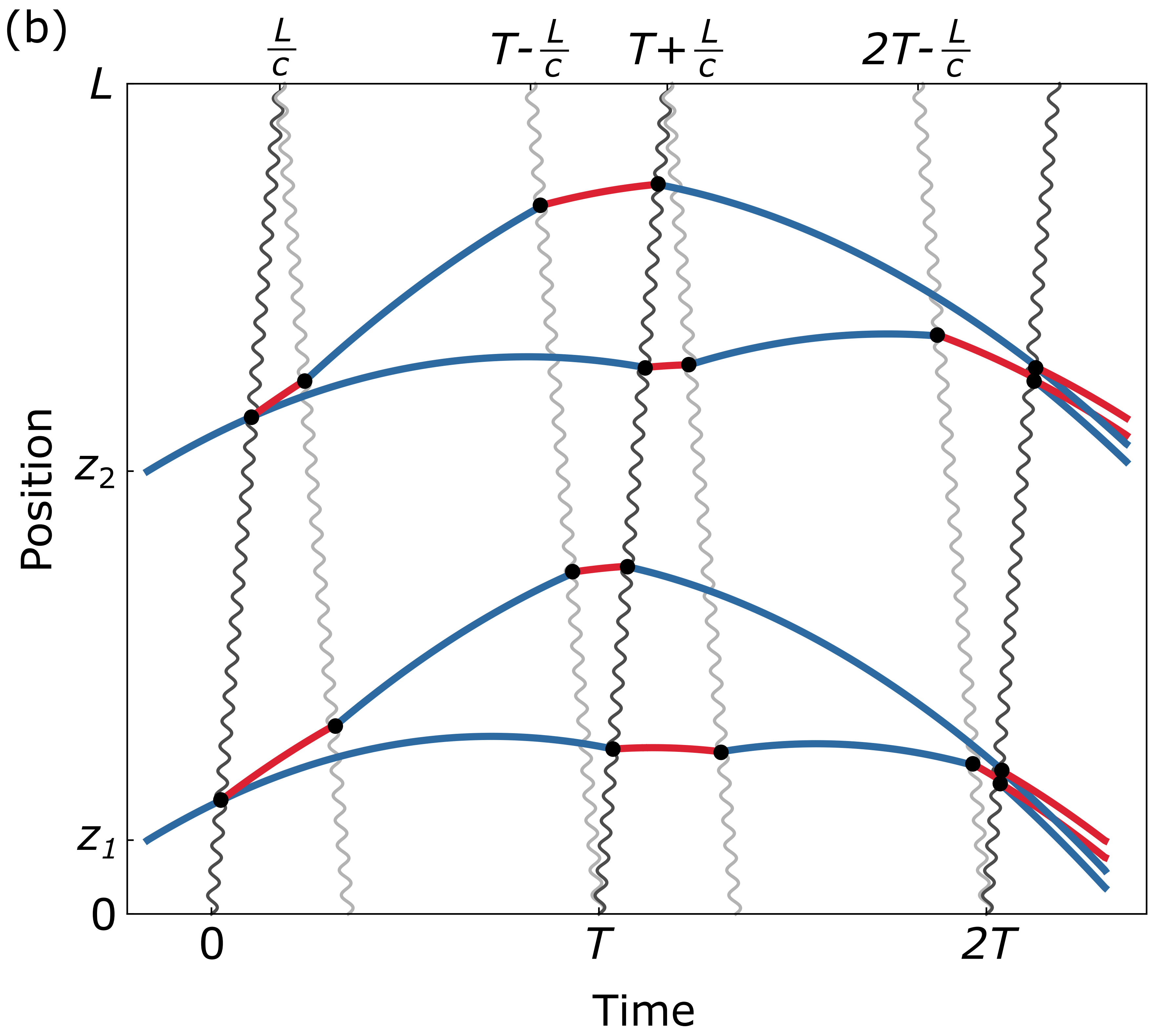
- A collaboration of Fermilab with Stanford, Northwestern and other (Spokesperson: Jason Hogan of Stanford)
- A 100 meter Strontium gravity gradiometer for GW's and **dark matter searches.**

Related talks by C. Williams, S. Luthcke.

MAGIS-100 detector at Fermilab

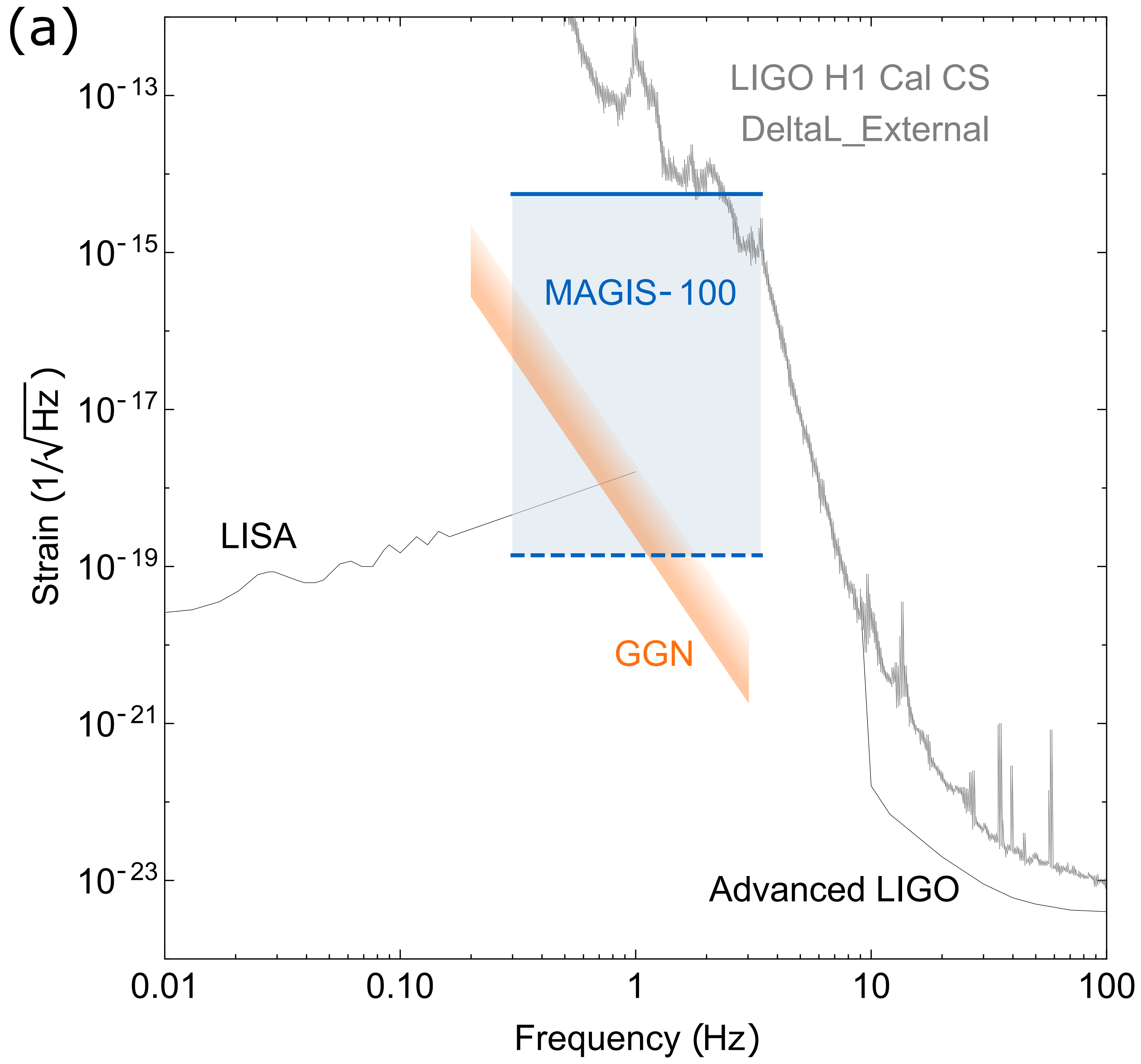


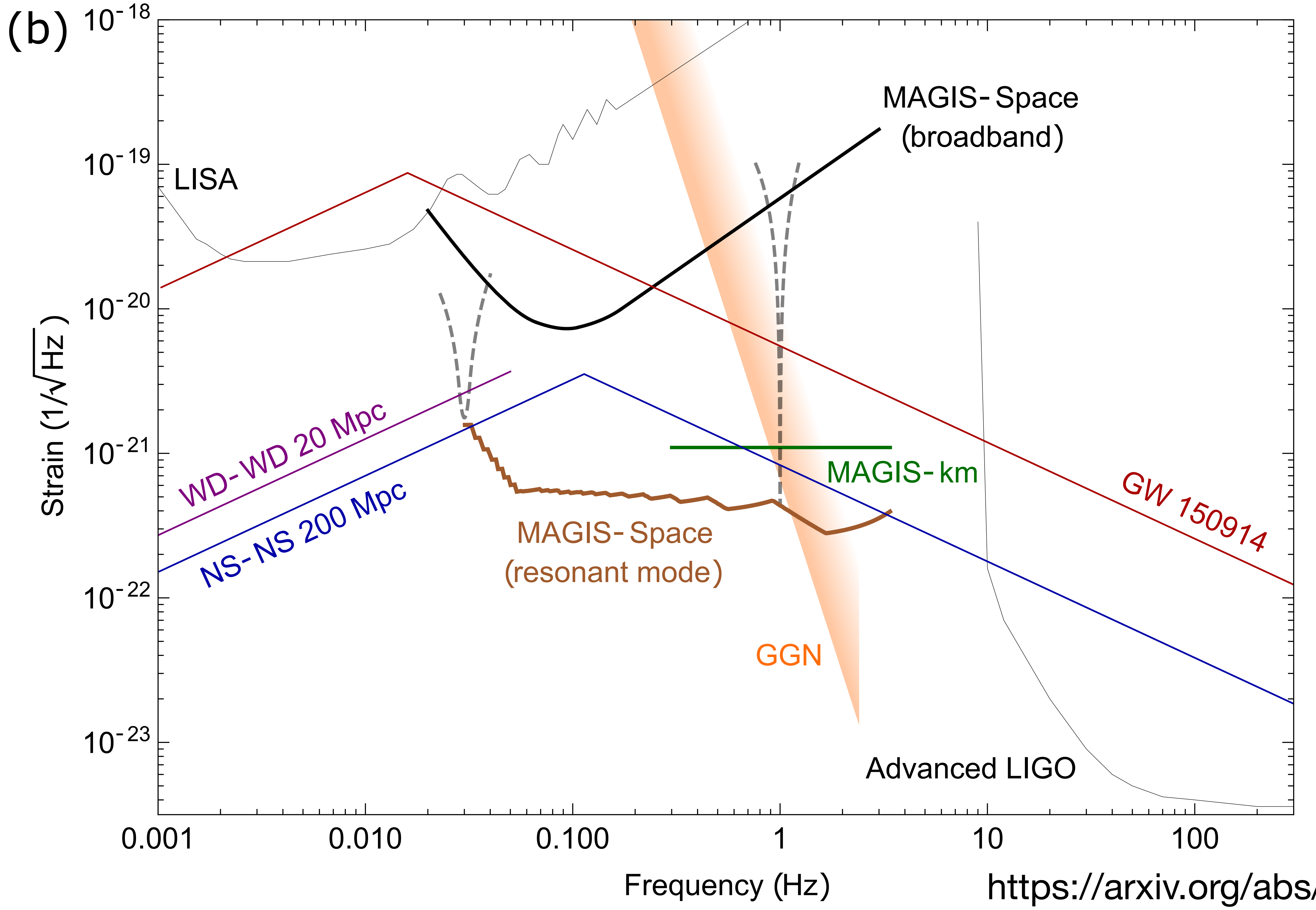




MAGIS-100: Gravitational waves with Atom Interferometry

- 100 meters is a pathfinder toward a km scale gradiometer, as well as a space-based mission.

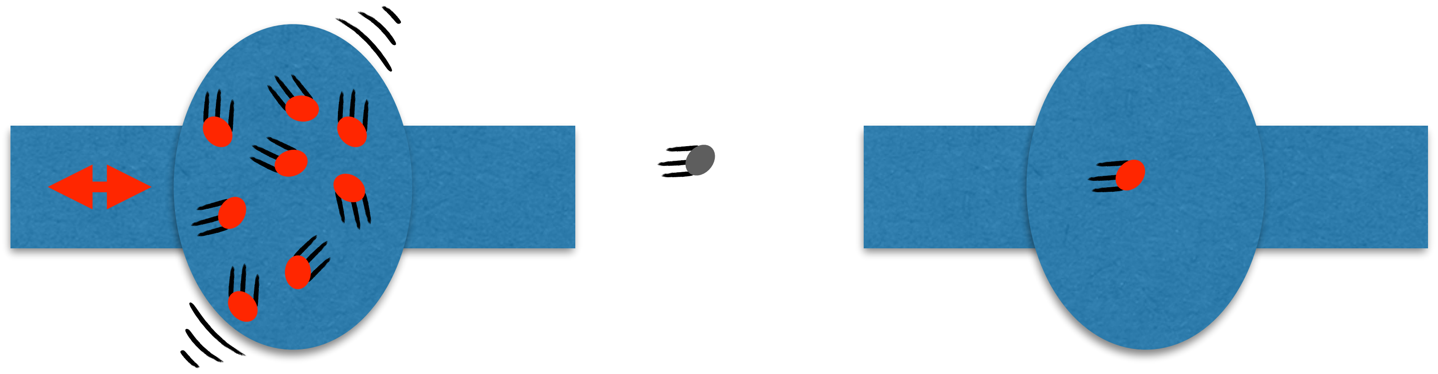




https://arxiv.org/abs/2104.02835
https://arxiv.org/abs/1711.02225
https://arxiv.org/abs/1908.00802

Conclusions

- New light particles that interact with photons are well motivated.
  - Axions and axion-like particles.
  - Dark photons
- Gravitational waves also couple to photons.
- New tools for enhanced coherence, control, and sensing of can be used in the quest for new physics!



Fermilab SQMS **DOE QuatISED**

Deleted scenes

Dark photon and Axion searches with Quantum Optics

A new direction at the HEP-optics interface, in its infancy.

Theory paper:

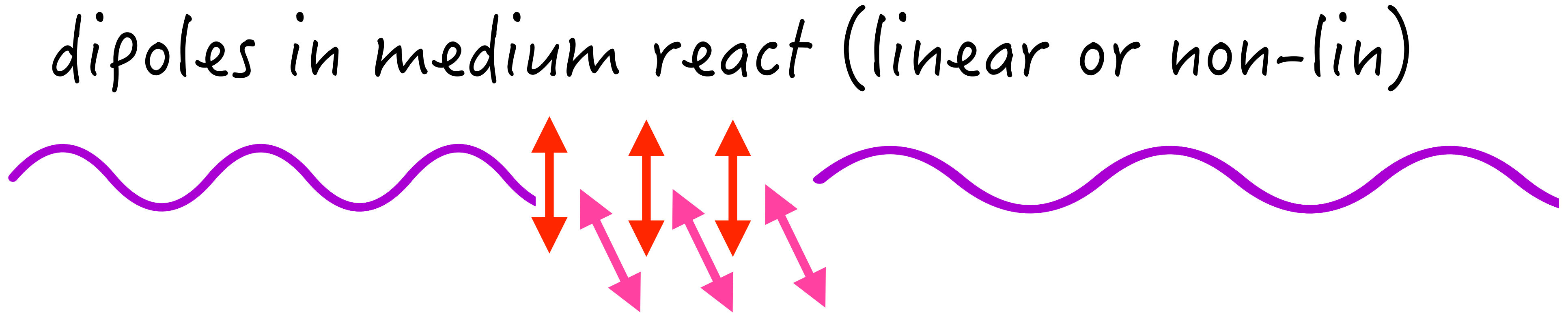
J. Estrada, RH, D. Rodriguez, M Senger - arXiv:2012.04707, Accepted to PRX Quantum

arXiv:2012.04707, Accepted to PRX Quantum

Nonlinear Optics with Dark States

- Any oscillating dipole can emit dark states, including those responsible for optical phenomena

A Cartoon of optics: incoming light

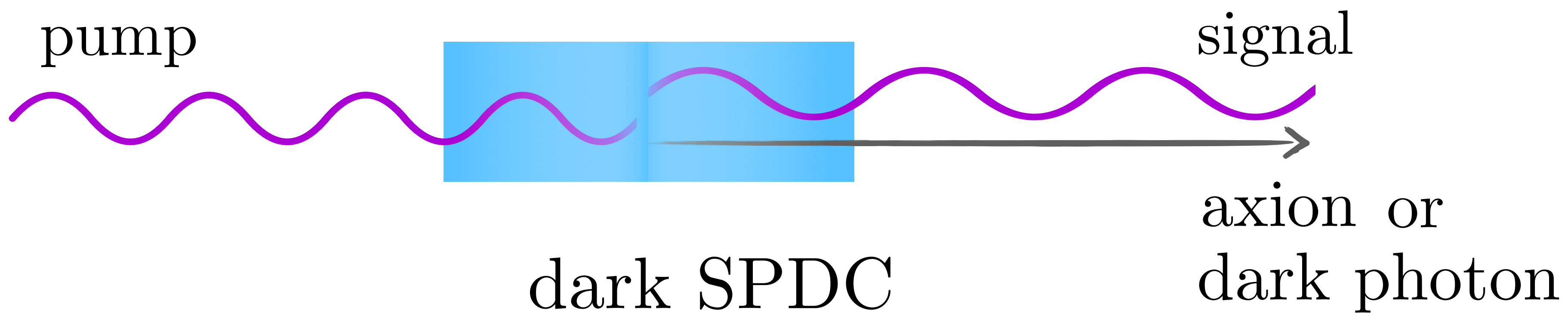


induces emission

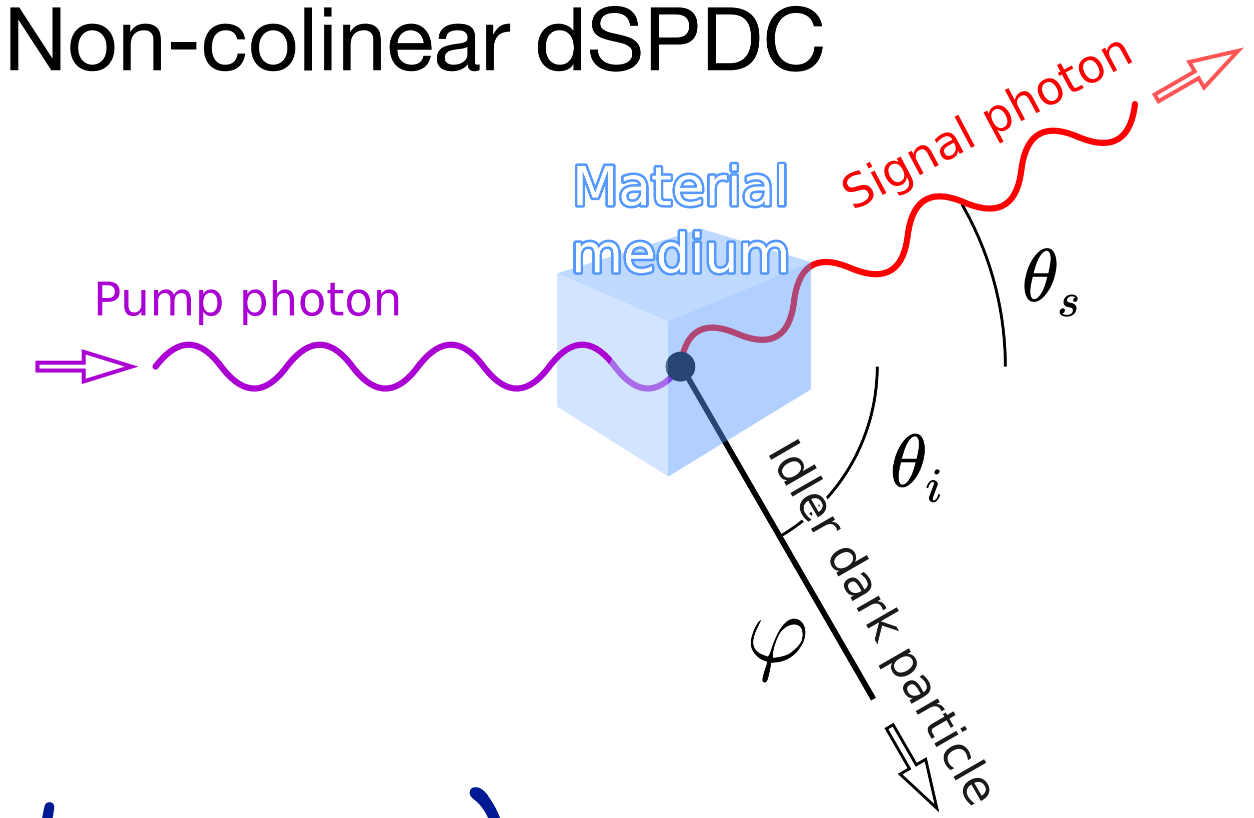
- With nonlinear optics, the existence of one photon can be inferred (or heralded) by the presence of the other, even if it is invisible!

- Dark SPDC:

colinear dSPDC



Non-colinear dSPDC

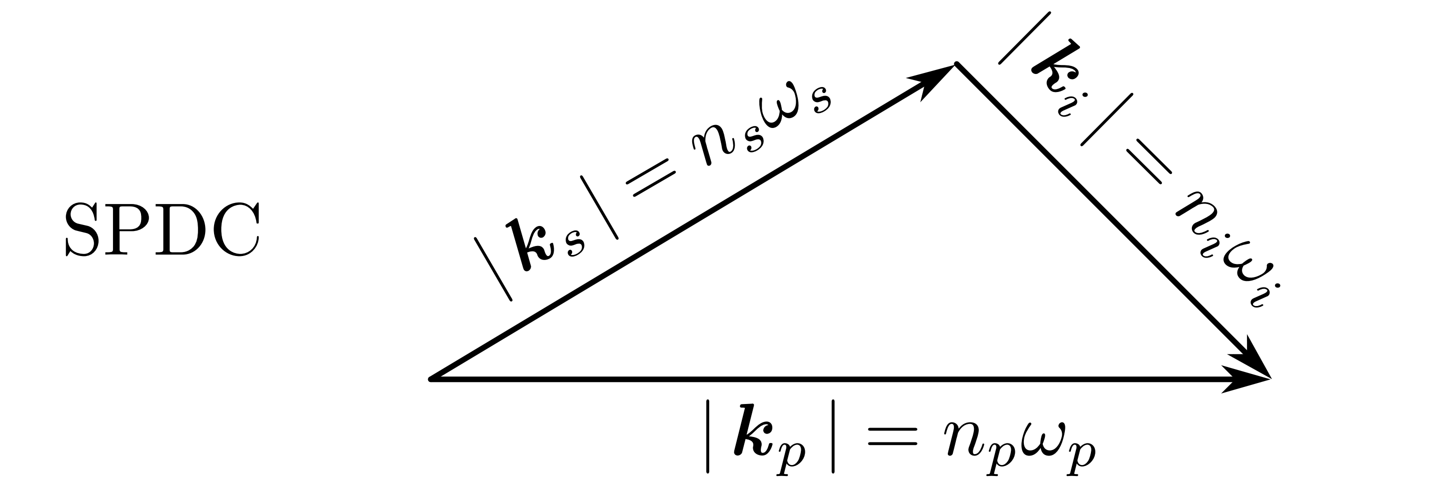


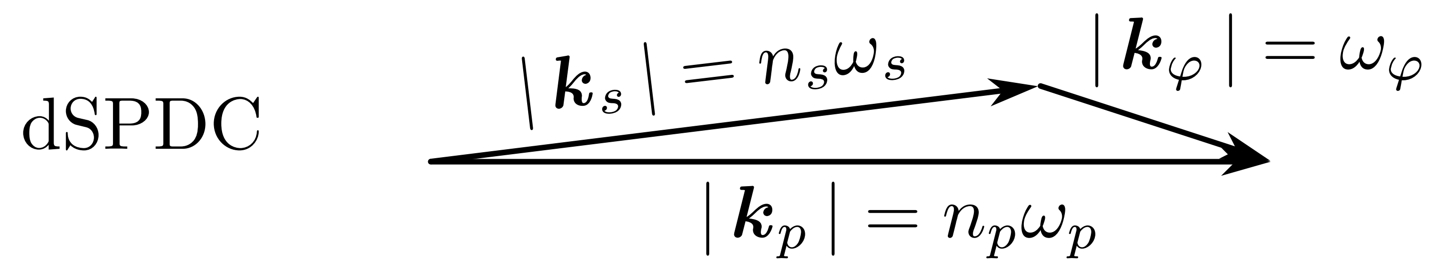
Note: the axion or dark photon have index of refraction of 1 (and a mass).
dSPDC has significantly different phase matching conditions.

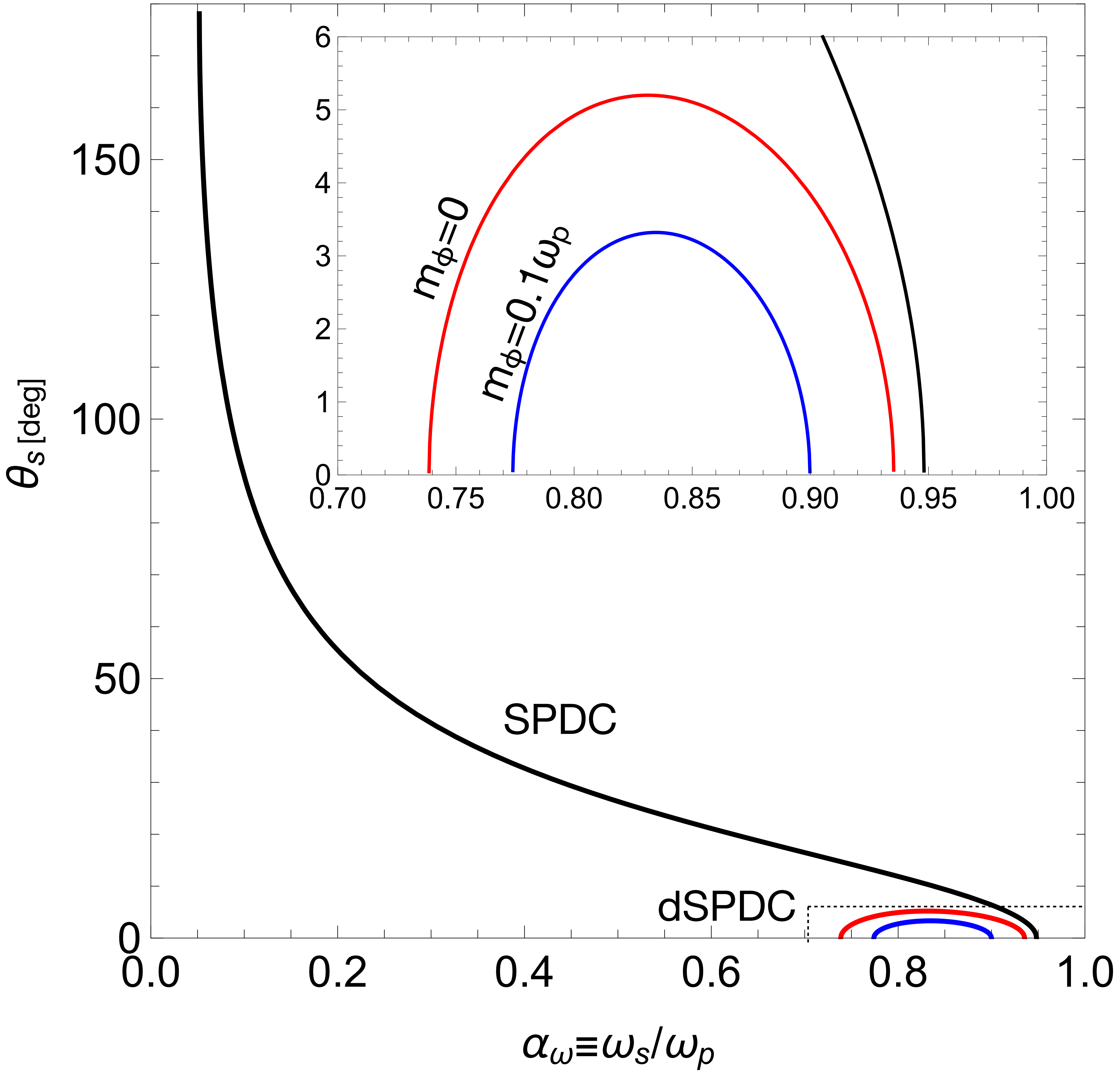
arXiv:2012.04707, Accepted to PRX Quantum

Phase Matching in dSPDC

- Two observables: signal frequency and angle ω_s and θ_s







* Phase matching requires: $n_s > n_p$
e.g. via birefringence (no PP)

* Axion and dark photon searches have different requirements.

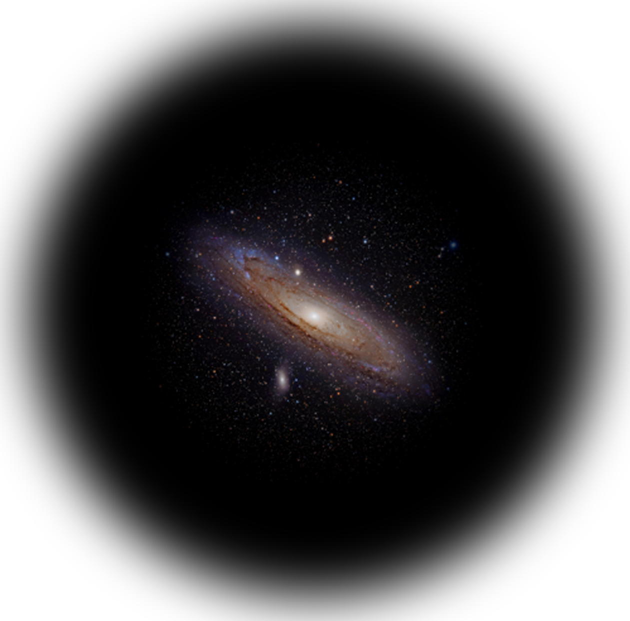
* Experimental realization under exploration

Two Hypotheses: New Particle search vs Dark Matter search

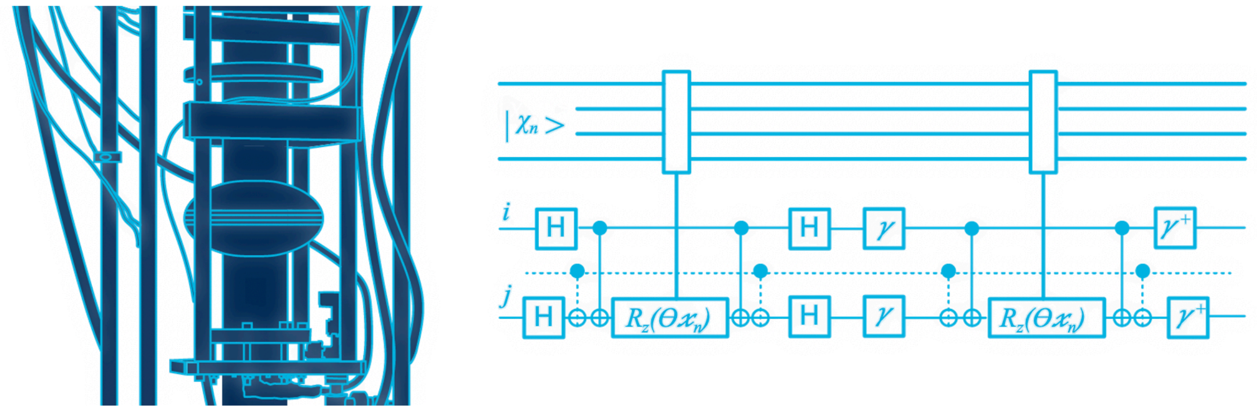
- Axion-like particles, dark photons, B-L, are each well motivated as mediators of long range interactions that can be searched for.

$\supset$ dark photons? axions?

- Axion-like particles, dark photons, B-L, are each dark matter candidates with nice production mechanisms.
- In the Wave-like DM category. Oscillating at $\omega = m_{DM}$.



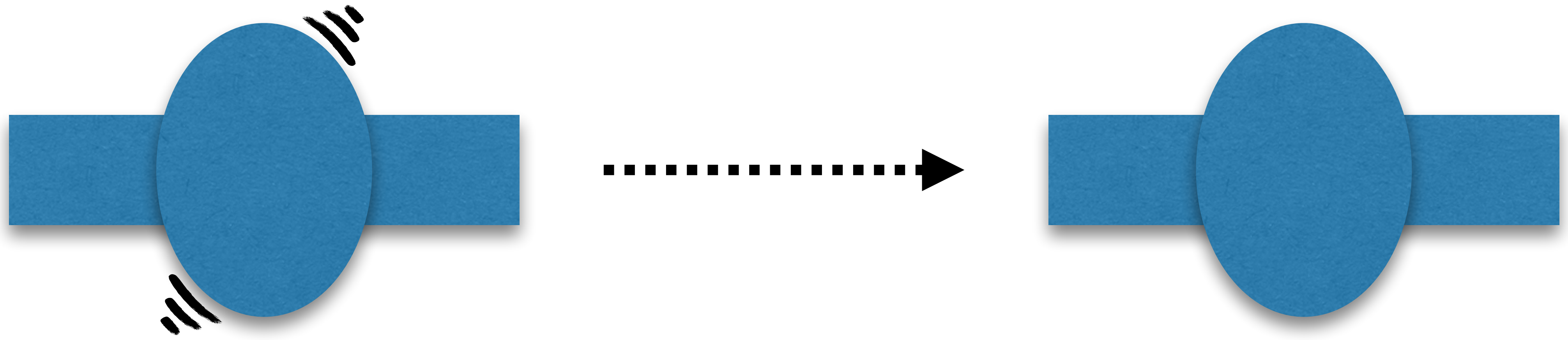
$\supset$ dark photons? axions?



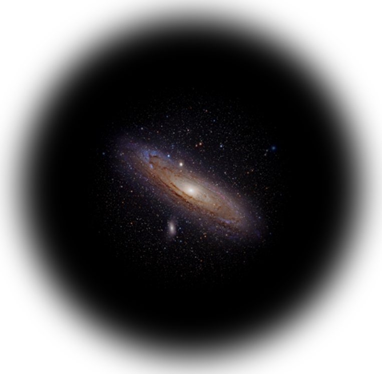
Complementarity: New Particle search vs Dark Matter search

Light Shining through wall:

Emitter Receiver

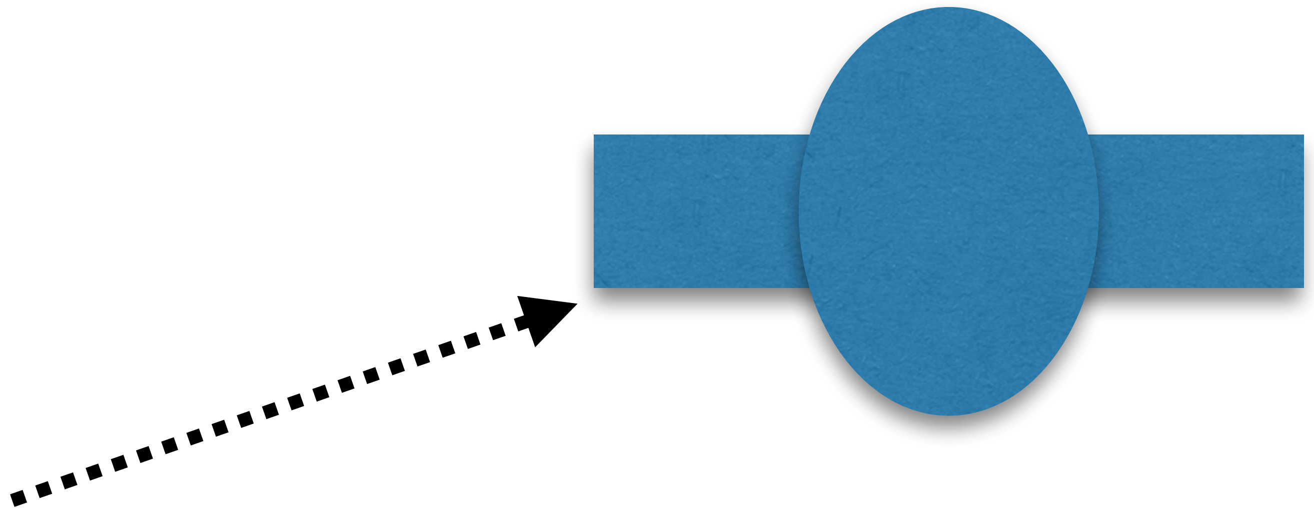


We produce our own dark stuff.



A dark matter search:

Receiver

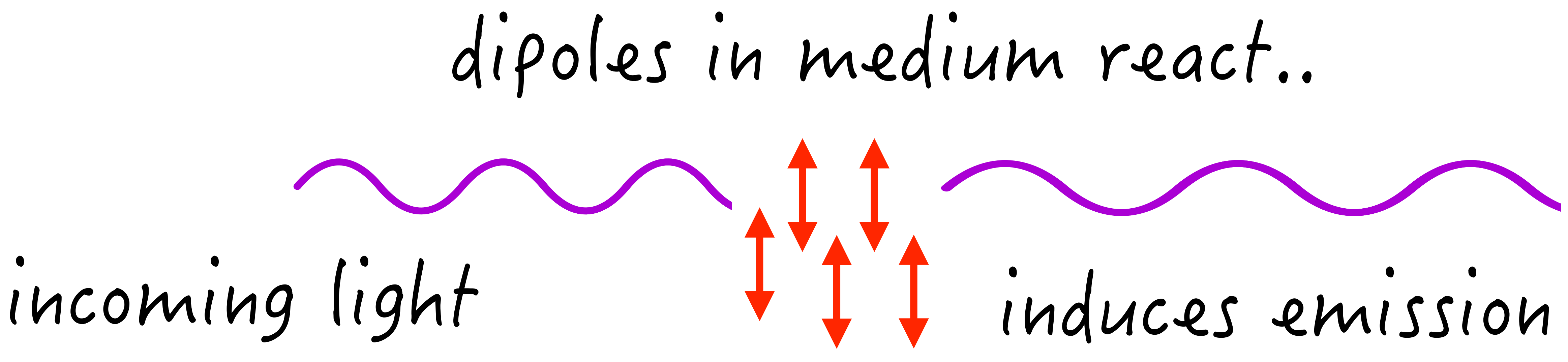


the DM filled Universe is the emitter

Complementary hypotheses.
We want to test both!

Optics and Nonlinear Optics

- Optical phenomena → back-reaction of a medium to an electric field:



Interference in the forward direction
→ index of refraction!

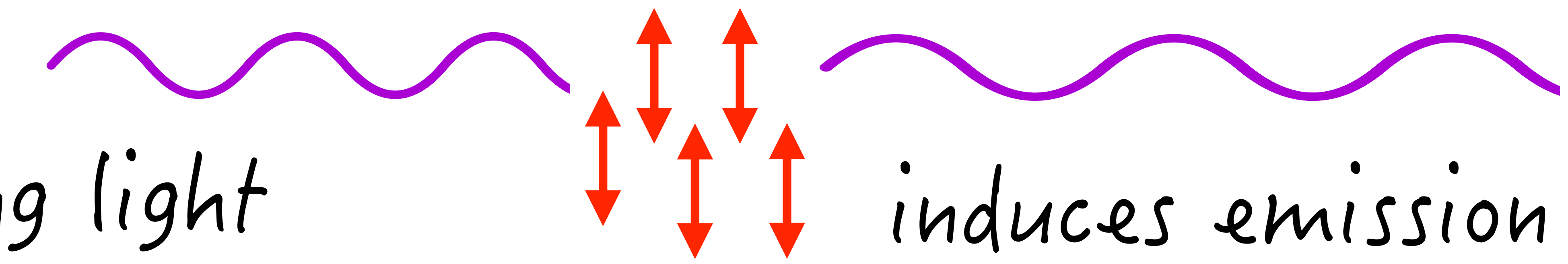
$$\vec{P} = \chi \vec{E}$$

Optics and Nonlinear Optics

- Optical phenomena → back-reaction of a medium to an electric field:

dipoles in medium react..

incoming light



induces emission

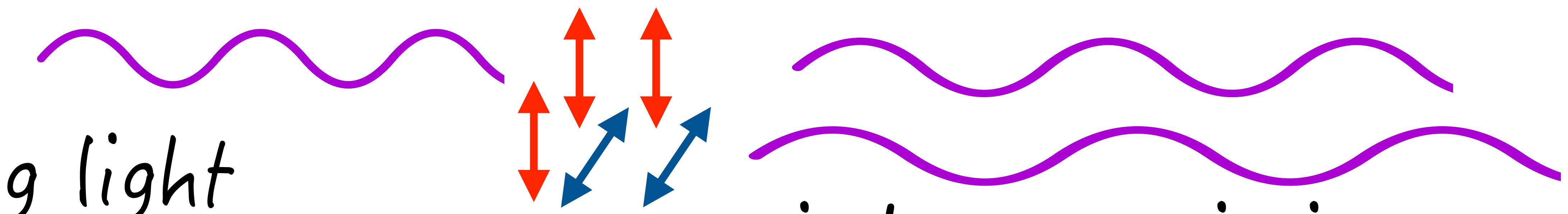
Interference in the forward direction
→ index of refraction!

$$\vec{P} = \chi \vec{E}$$

- Nonlinear optics expands this to higher order:

dipoles react in more than one way..

incoming light



induces emission of more photons.

$$P = \chi E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \cdots$$

(vector nature of P and E implicit. $\chi^{(2)}$ and $\chi^{(3)}$ are tensors)

Axions and ALPs