# Theory Meets Experiments 2025:

## Direct Detection across Dark Matter mass ranges

## Wave Dark Matter Experiments

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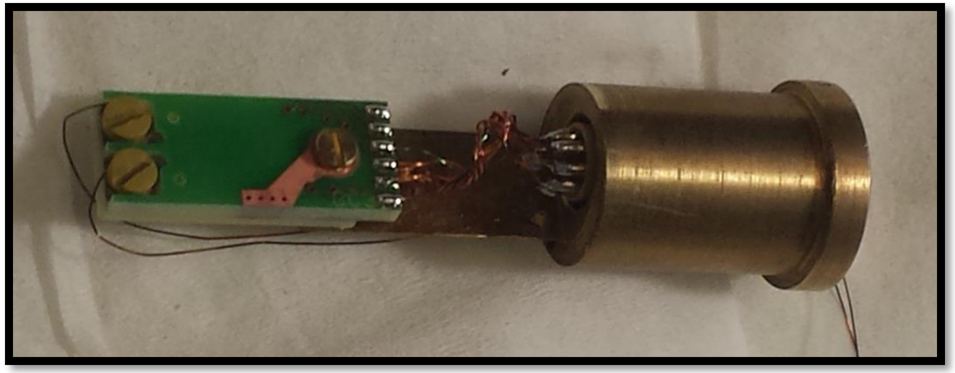
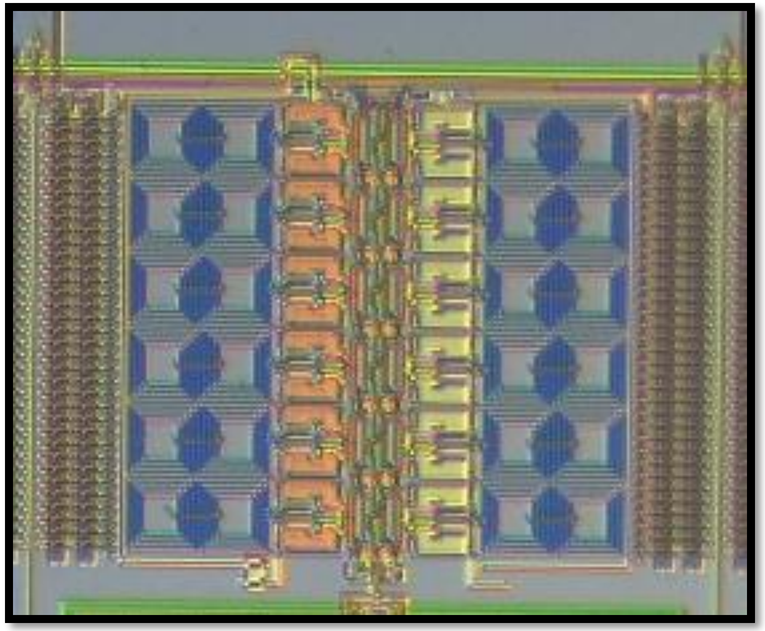
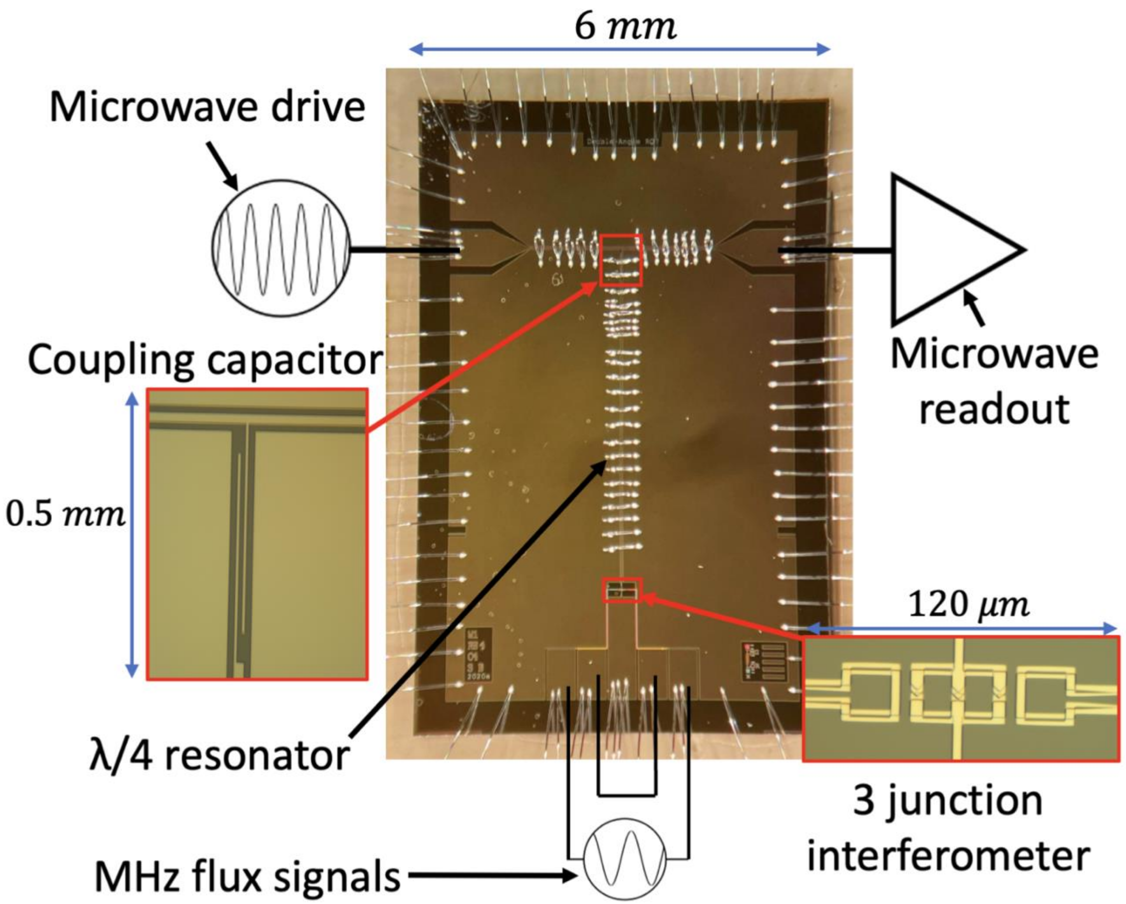
# Some SQUID + RQU photos



Magnicon 2-stage SQUID
(ABRACADABRA-10cm)



NIST SQUID array
(DMRadio-50L initial configuration)



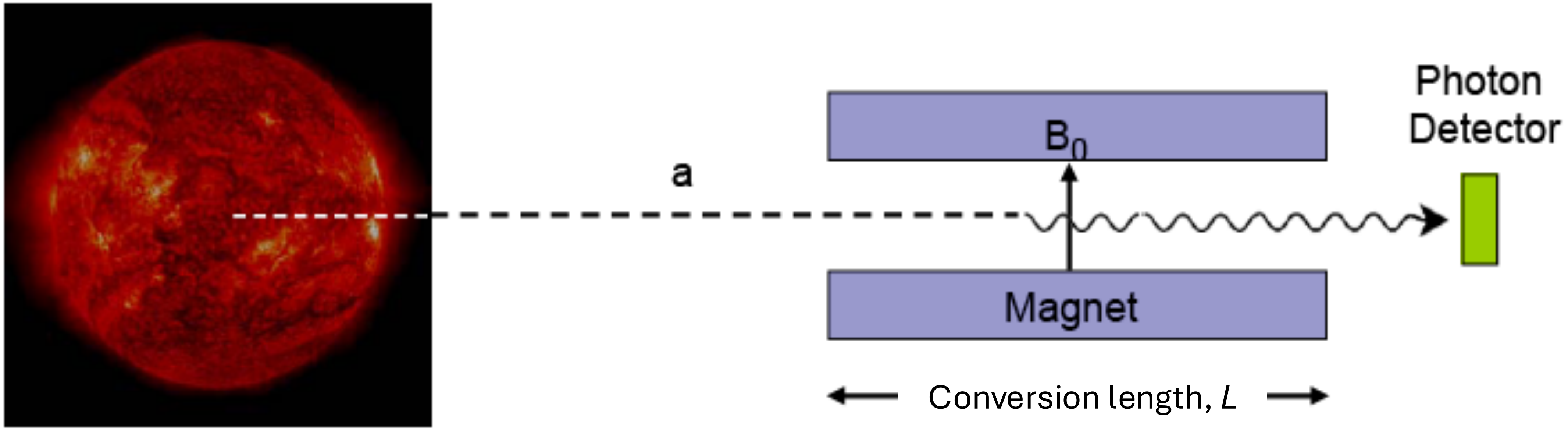
# Lecture 4: high-mass axion dark matter detection

- Moved from Monday: non-dark matter direct axion searches
- High-mass wave DM detection
  - Reflectors
  - Dielectric stacks
- “Low threshold” sensors
- Pair-breaking superconducting sensors
- Qubit sensors

# Non-dark matter axion detection

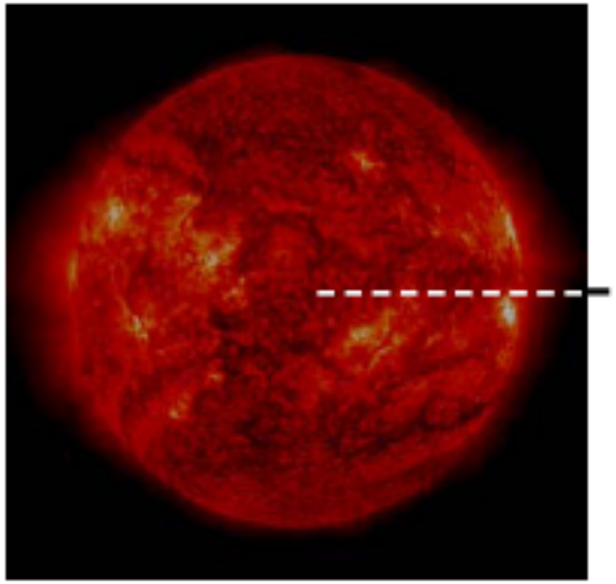
# Sources of axions: the sun

"Helioscopes": massive magnet + x-ray telescope pointing at the sun



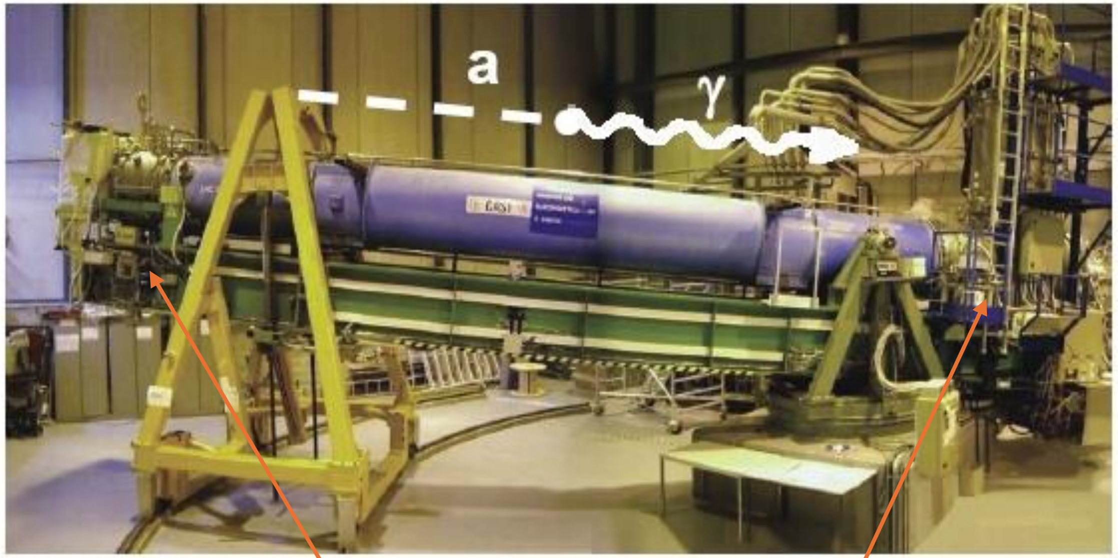
# Sources of axions: the sun

“Helioscopes”



a

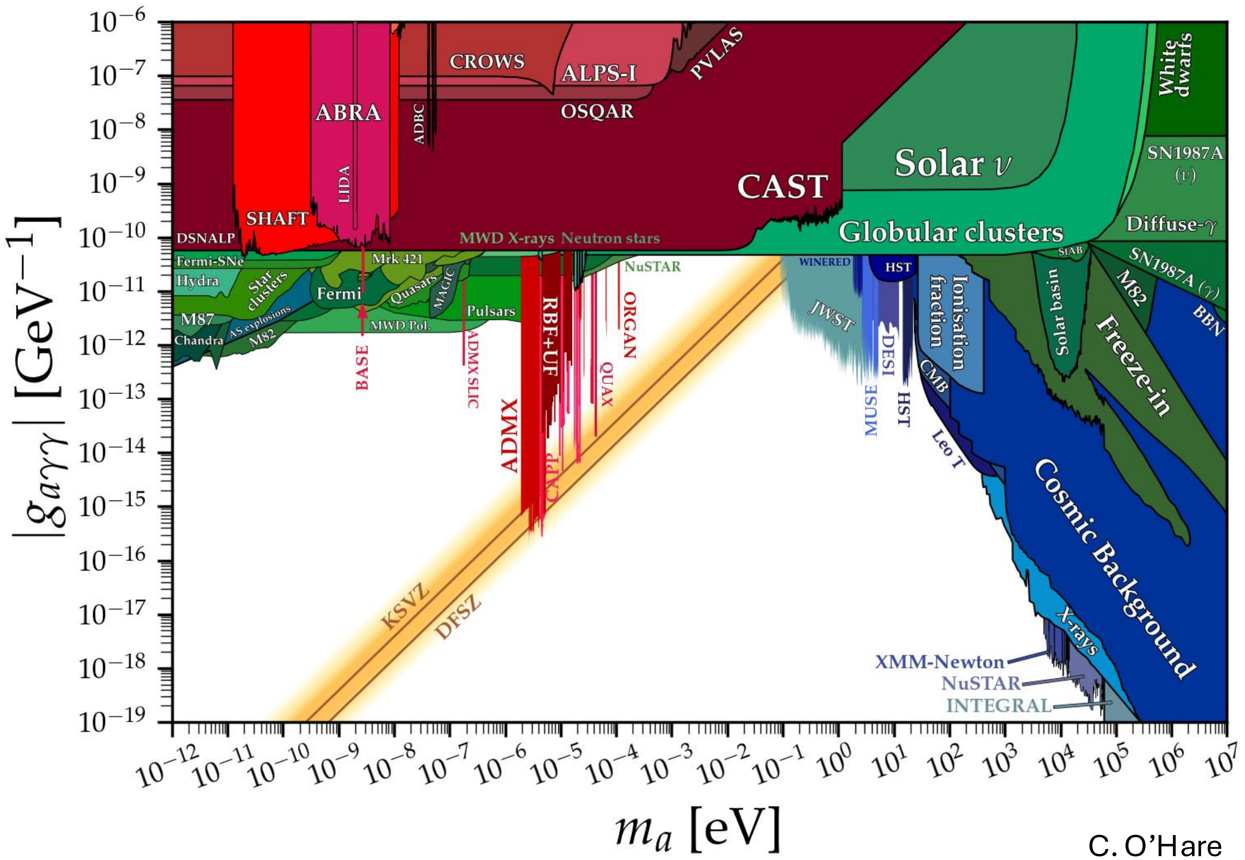
**CAST experiment** – uses a recycled LHC dipole magnet on a movable stand for pointing at the sun!




detectors at both ends:
sunrise + sunset

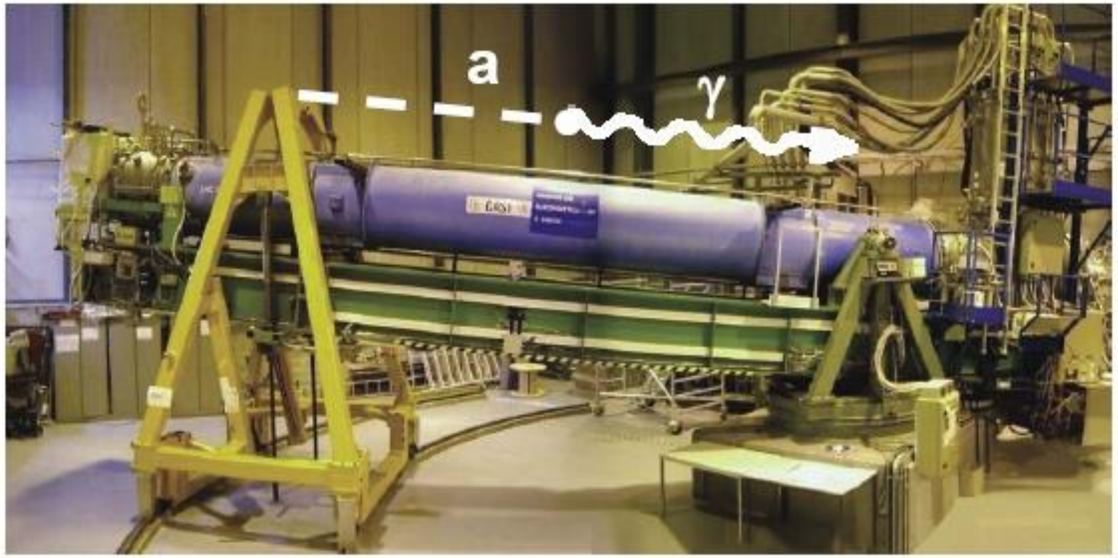
# Sources of axions: the sun

“Helioscopes”



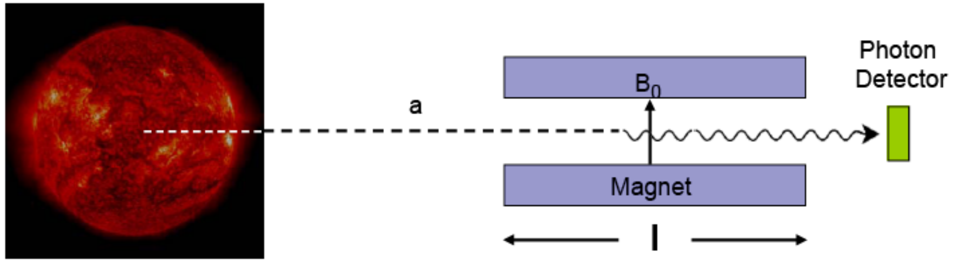

C. O’Hare

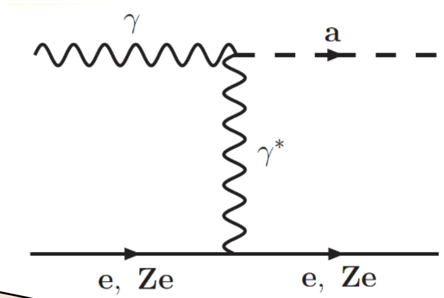
**CAST experiment** – uses a recycled LHC dipole magnet on a movable stand for pointing at the sun!



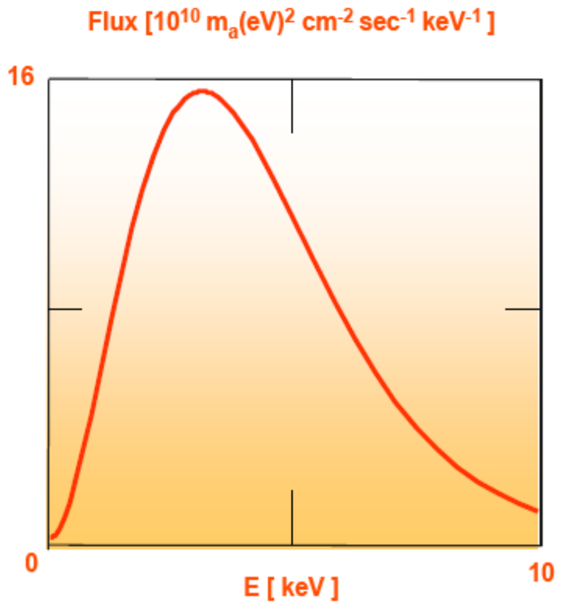
# How the sun generates axions (1)

Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagnetic fields in the plasma



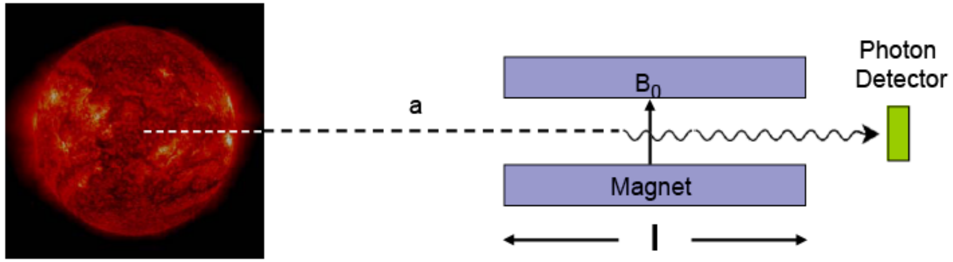




Primakoff effect!



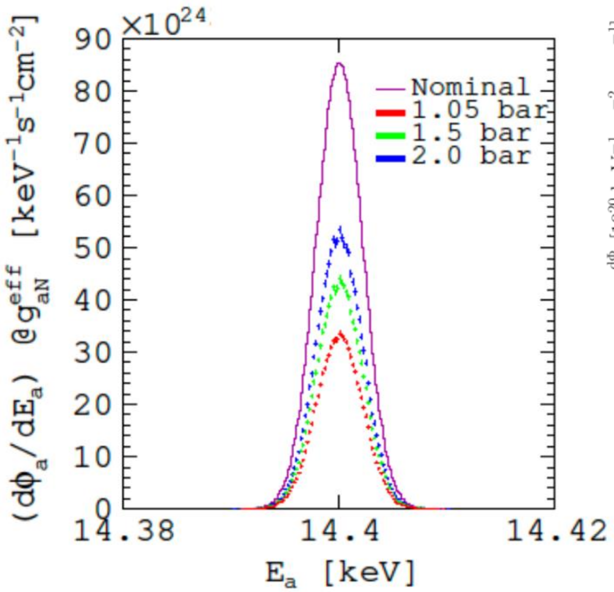
# How the sun generates axions (2)

Can also generate axions through axion-electron and axion-nucleon couplings

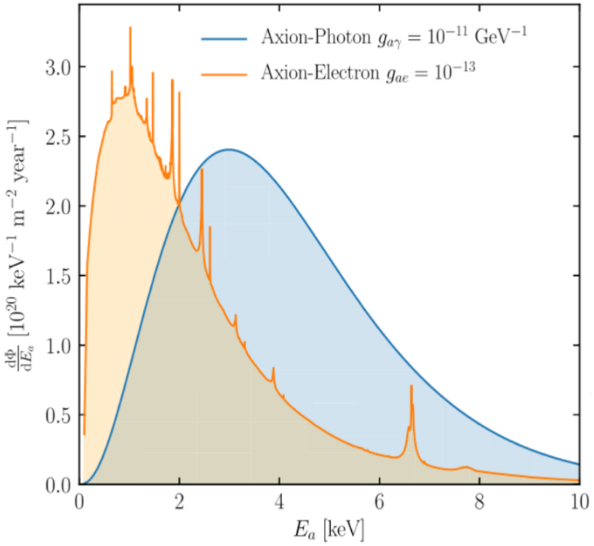



many diagrams!

Fe-57 emission

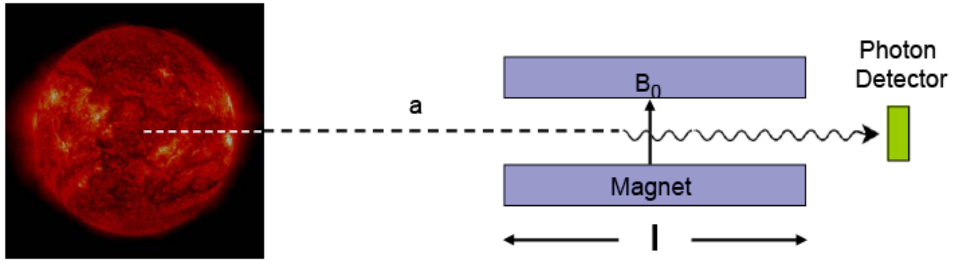


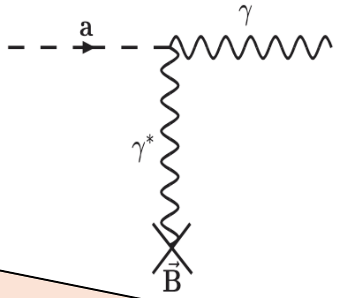

"ABC" a-e coupling



# How the helioscope receives axions

1. Dipole magnet converts axions into x-ray photons



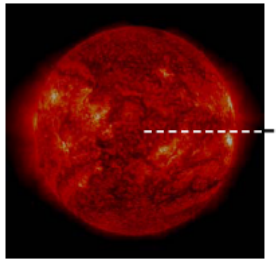



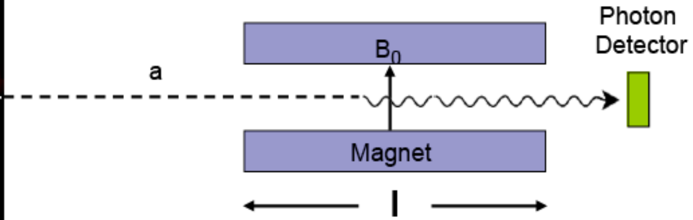

Primakoff effect!

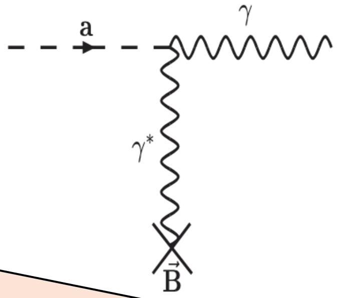
Why a dipole?

# How the helioscope receives axions

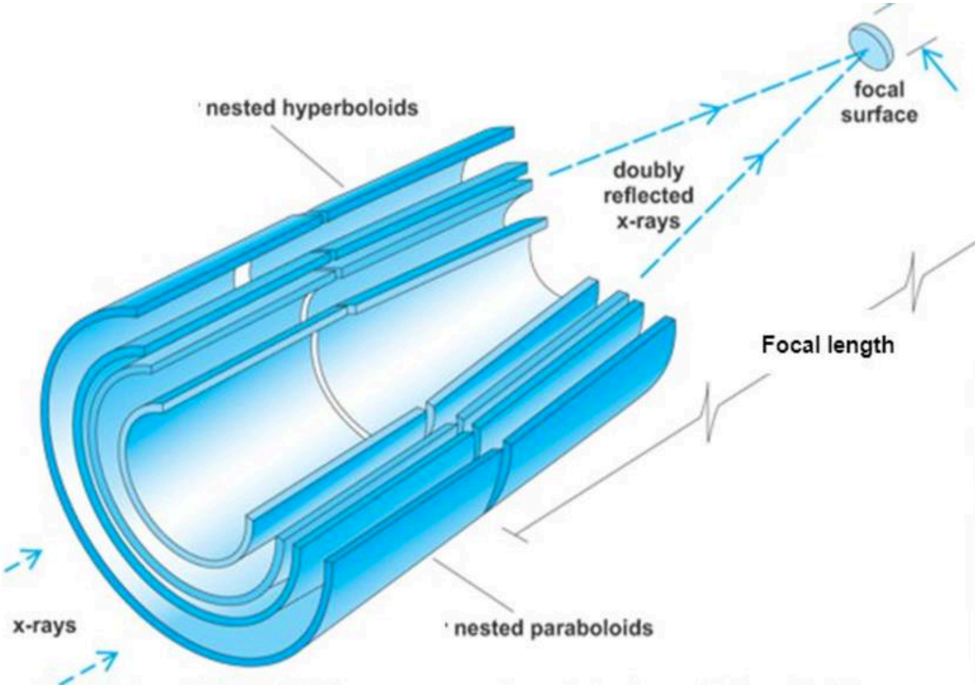
1. Dipole magnet converts axions into x-ray photons
2. X-ray optics focus light onto photon detector






Primakoff effect!



# Sensitivity?

Can think of axion as mixing with the photon in the magnetic field

$$P_{a\to\gamma} = \left(\frac{BLg_{a\gamma\gamma}}{2}\right)^2$$ for $$\frac{qL}{2} < \pi$$ (“coherence condition”)

where $q = k_a - k_\gamma$

Works great for low axion masses but lose coherence as axion gets “less massless”

# Sensitivity?

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("coherence condition")

where $q = k_a - k_\gamma$

regain coherence condition over large L by reducing q: give photon an effective mass

Works great for low axion masses but lo axion gets "less massless"

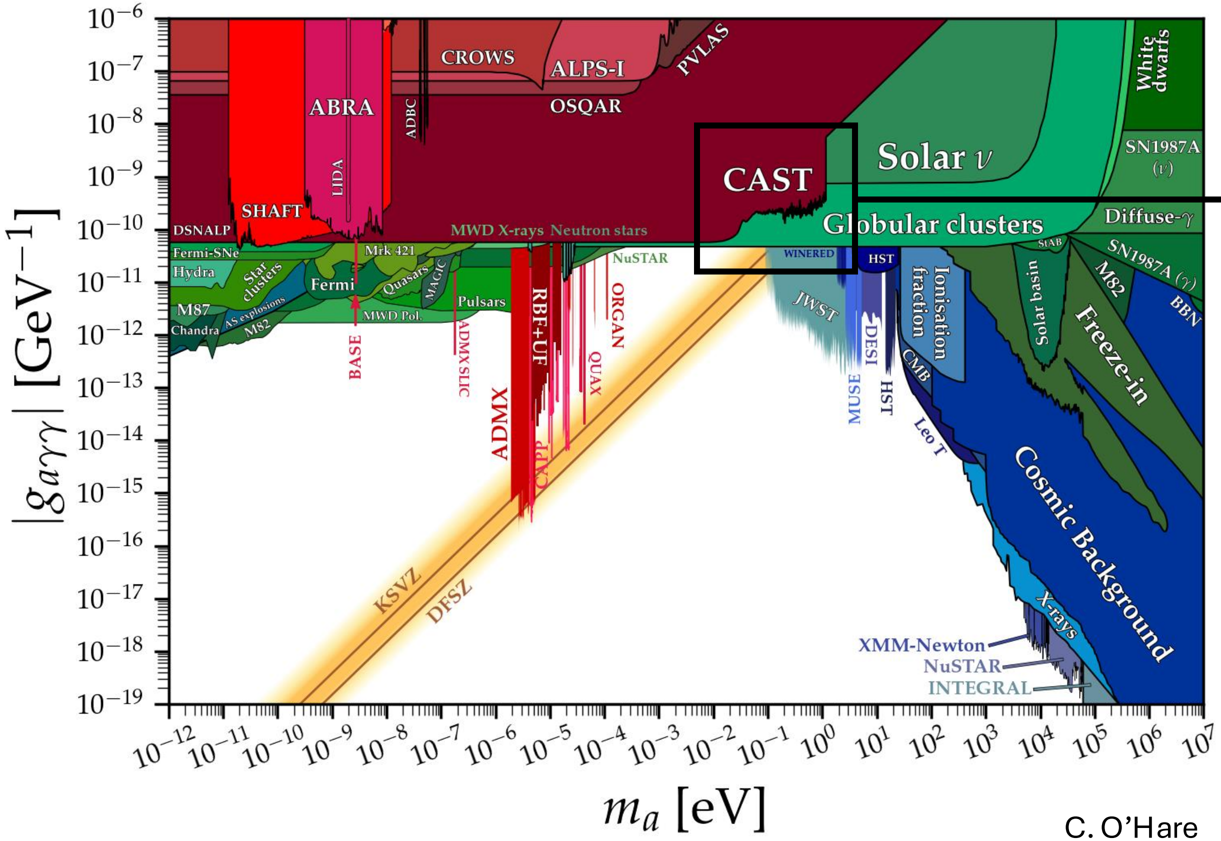
# Can extend mass range upwards a bit

- Buffer gas gives photon an effective mass
- Tune pressure: $\omega_p = (4\pi\alpha N_e / m_e)^{1/2} \equiv m_\gamma$
- Conversion probability including effect of dispersion mismatch and photon absorption in medium ($\Gamma$):

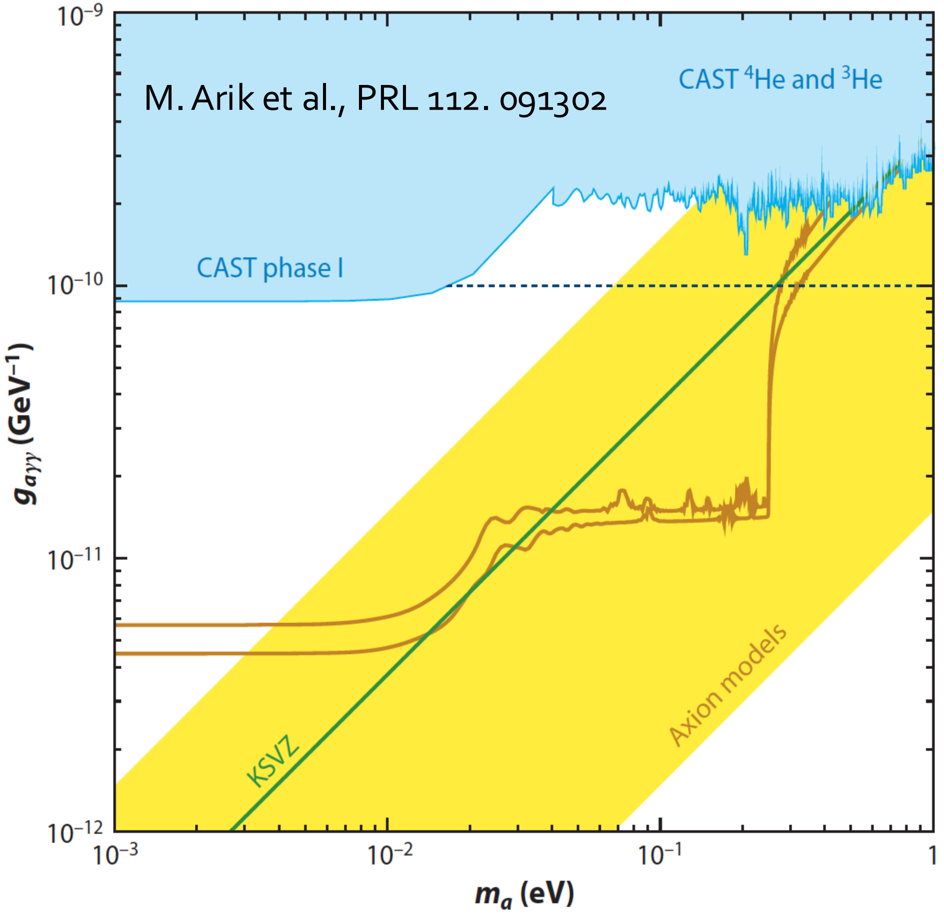
$$P_{a\to\gamma} = \left(\frac{B g_{a\gamma}}{2}\right)^2 \frac{1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)}{q^2 + \Gamma^2/4}$$

Cannot extend mass range up infinitely because increasing the pressure increases photon absorption

# Can extend mass range upwards a bit

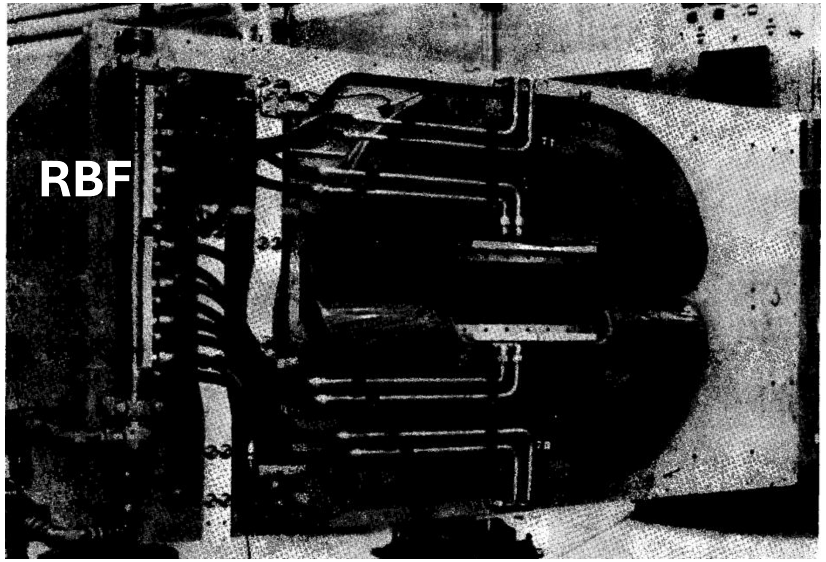



C. O'Hare

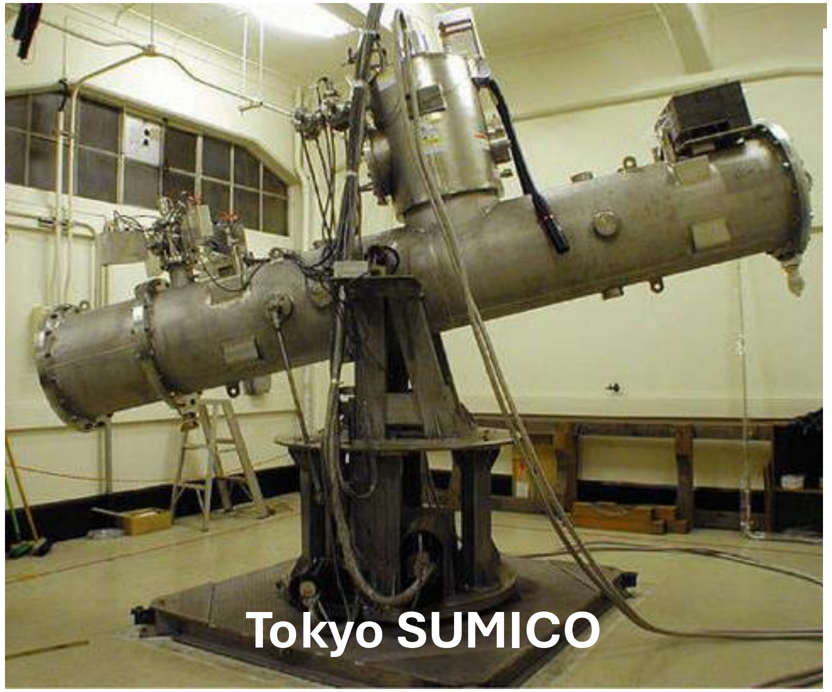


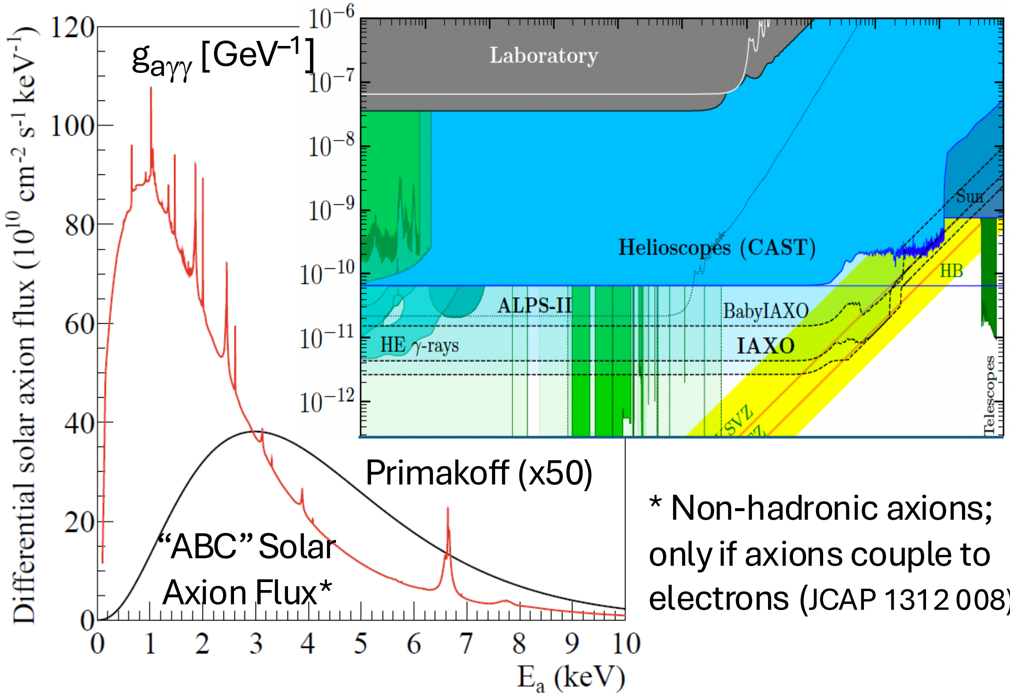

van Bibber, McIntyre, Morris, Raffelt, Phys. Rev. D 39 (1989) 2089

# A history of helioscopes




CERN CAST



* Non-hadronic axions; only if axions couple to electrons (JCAP 1312 008)

*slide c.o. Karl van Bibber*

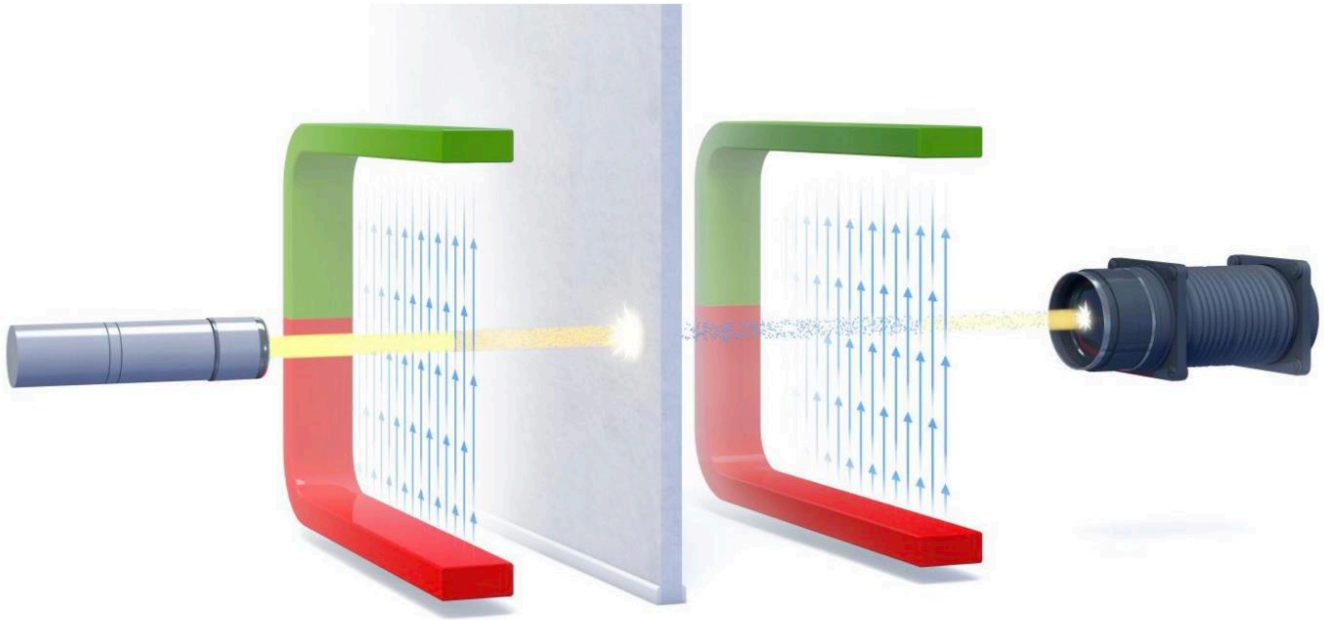
# The future: International Axion Observatory (IAXO)

- Toroidal 8-coil magnet $L$ = 20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Very low background detectors, i.e. CCDs, Micromegas, TES …
- Rotating platform with services

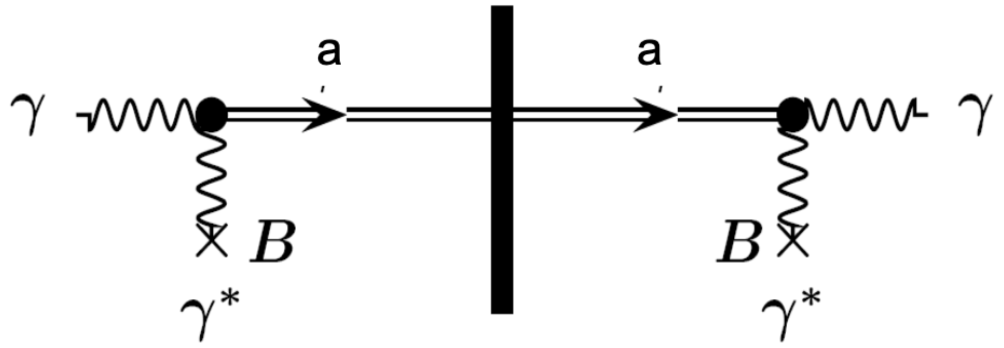

*slide c.o. Karl van Bibber*

# Sources of axions: lab-generated

"Light shining through walls"

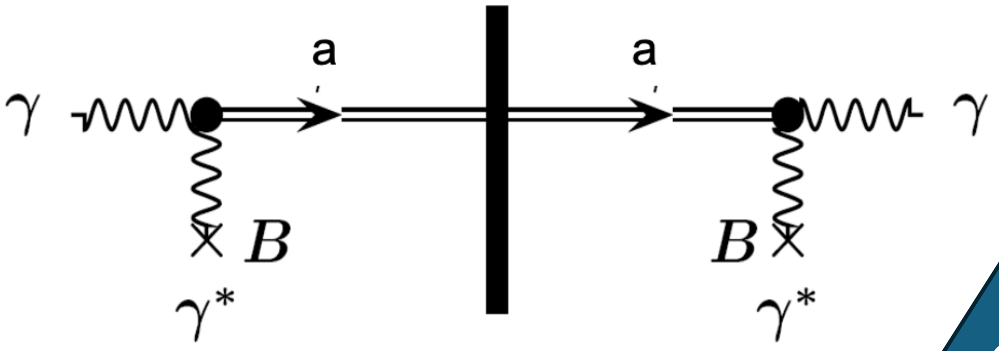


# Sensitivity?




Assume a cw laser of 70 W:
one photon through the wall each 90,000 years.

# Sensitivity?



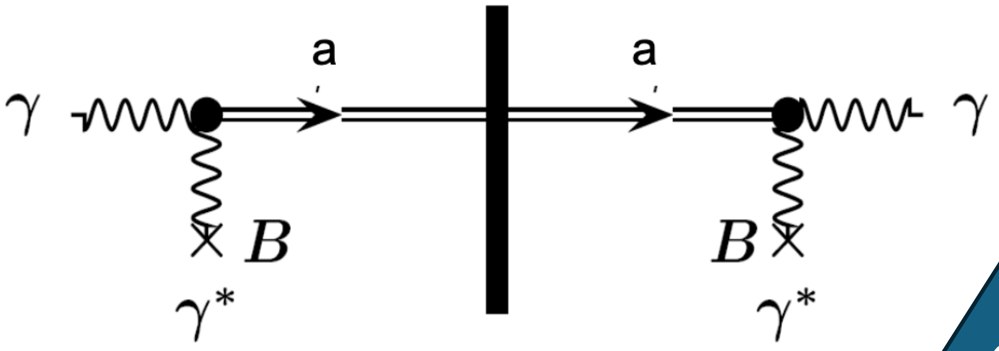

Assume a cw laser of 70 W:
one photon through the wall each 90,000 years.

resonantly enhance!


One photon through the wall each 90,000 years
boosted by 1,000·10,000
equals 0.3 photons per day!

F. Hoogeveen, T. Ziegenhagen, *Nucl. Phys. B* 358 (1991) 3
P. Sikivie, D.B. Tanner, K. van Bibber, *Phys. Rev. Lett.* 98 (2007) 172002
G. Mueller, P. Sikivie, D.B. Tanner, K. van Bibber, *Phys. Rev. D* 80 (2009) 072004

# Sensitivity?




resonantly enhance!

Assume a cw laser of 70 W:
one photon through the wall each 90,000 years.

aka. LIGO + magnets


One photon through the wall each 90,000 years
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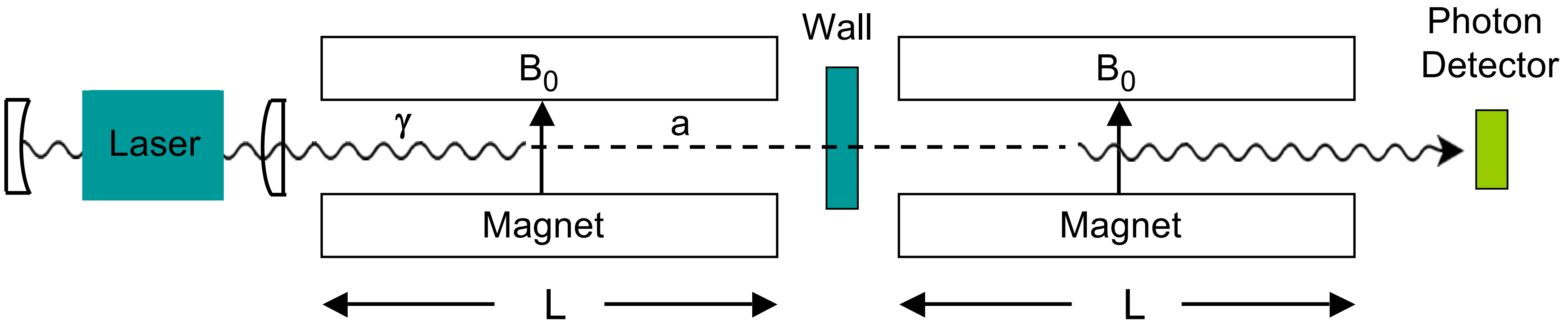
# In practice (no resonant enhancement)

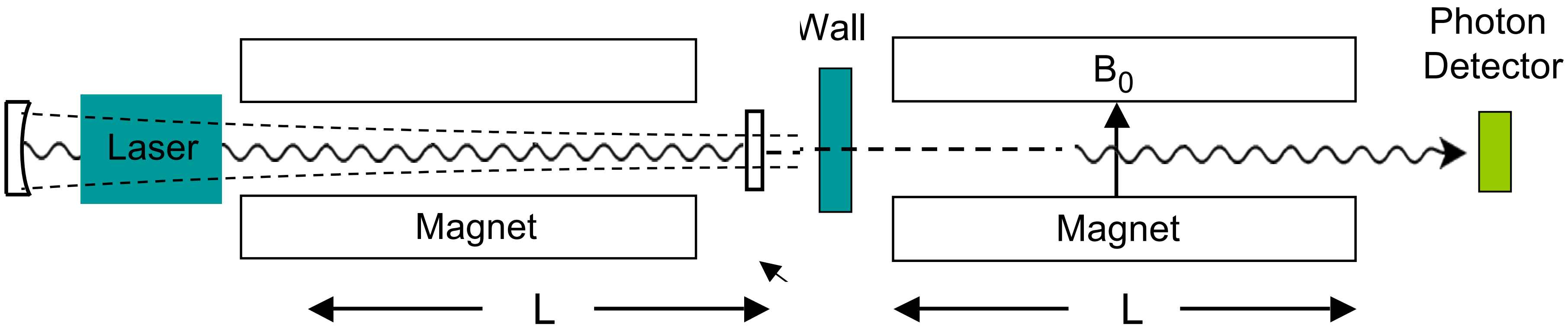



$$P_{\gamma\to\phi\to\gamma}(B,L,q) = \frac{1}{16}(gBL)^4\,F^2(qL)$$

$$F(qL) = \left[\frac{\sin\left(\frac{1}{2}qL\right)}{\frac{1}{2}qL}\right]^2$$

$$q = k_a - k_\gamma$$

# In practice (enhance axion production)

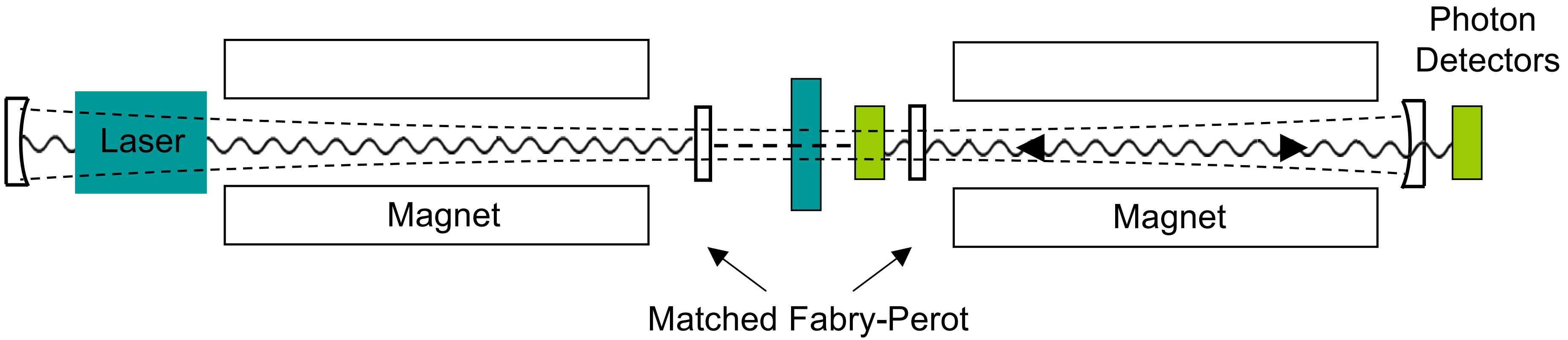



$$P_a = \frac{1}{\eta} p P_0$$

axion power through wall depends on:

- reflectivity of mirrors in production cavity: $R = 1 - \eta$
- probability to convert to axion in production cavity: $p$
- laser power: $P_0$

# In practice (enhance axion production and photon regeneration)



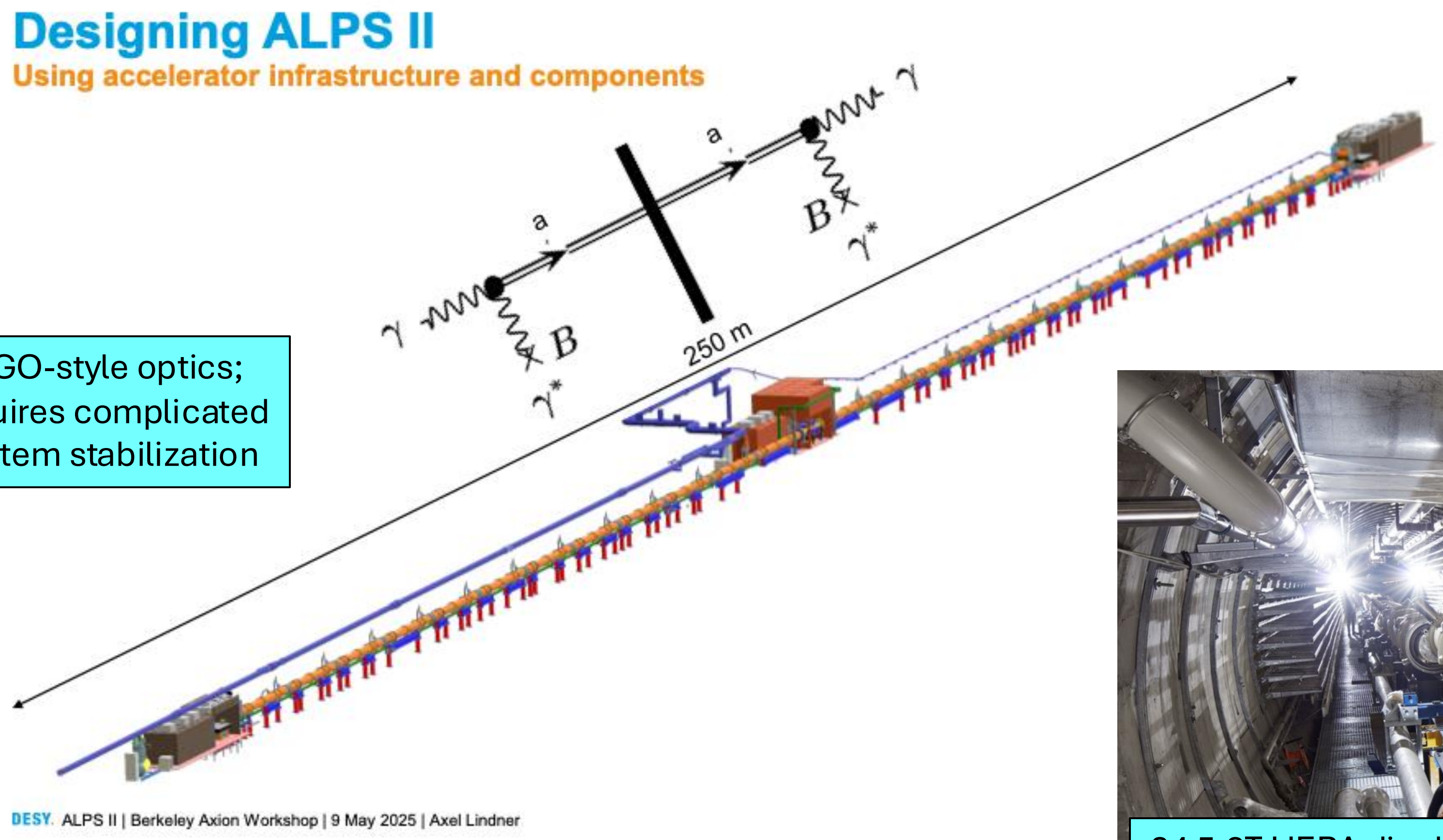

requires coherent "photon recycling" in production cavity and phase locking with matched photon regeneration cavity

$$P^{FP}_{\gamma\to\phi\to\gamma}(B,L,q) \;=\; \mathbf{F}^{2}\,\frac{1}{16}(gBL)^4\,F^2(qL)$$

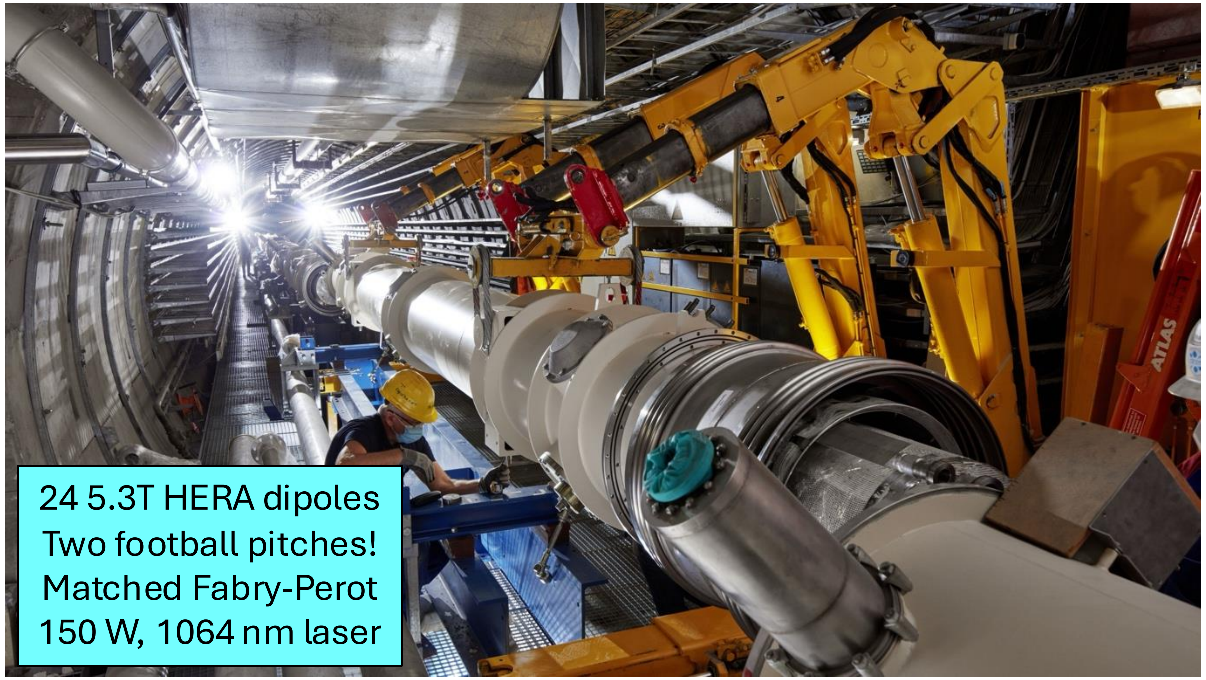
$\mathbf{F} \;=\; \text{Cavity Finesse} \;\leq\; 10^6$

**Finesse:** measure of spacing/spread of resonances

# Big science!



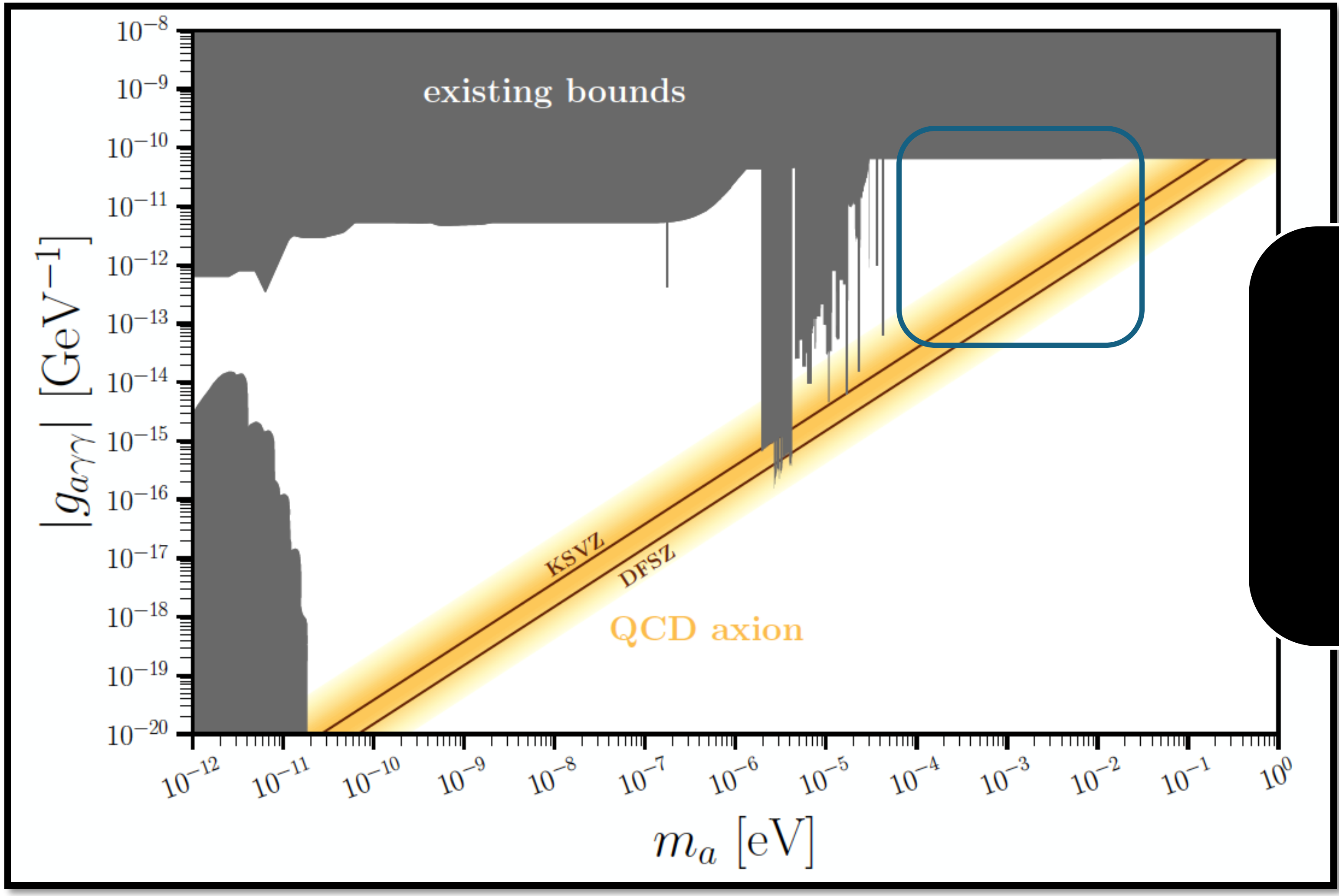

LIGO-style optics; requires complicated system stabilization



24 5.3T HERA dipoles
Two football pitches!
Matched Fabry-Perot
150 W, 1064 nm laser

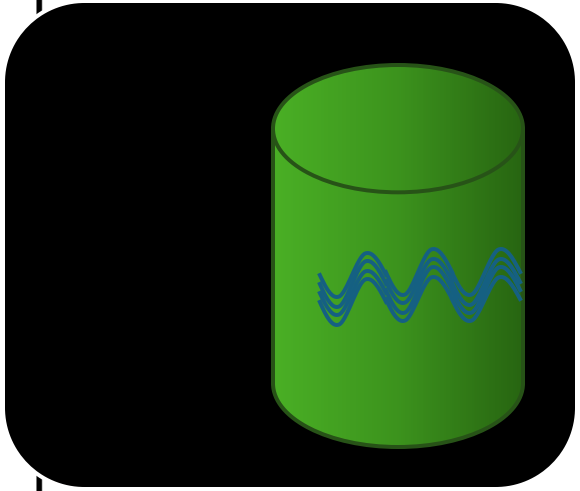
# Dark matter axion detection

# Different wavy regimes: high masses



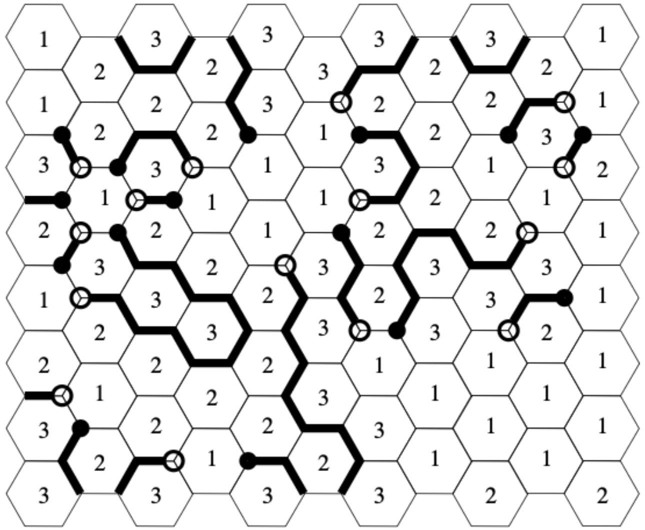

A. Berlin and others

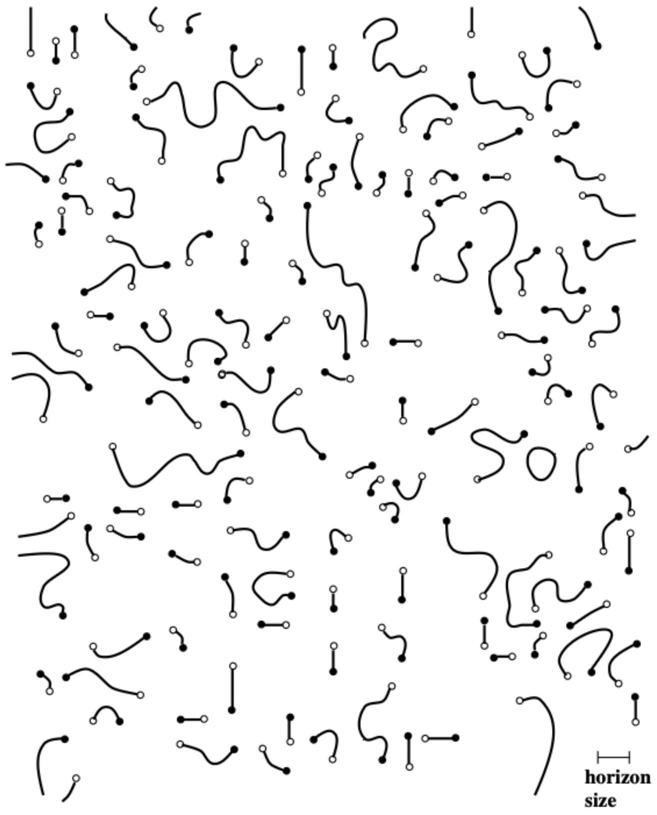
reflectors,
dielectric stacks



# Why look at these masses?

Post-inflationary production, including decay of topological defects





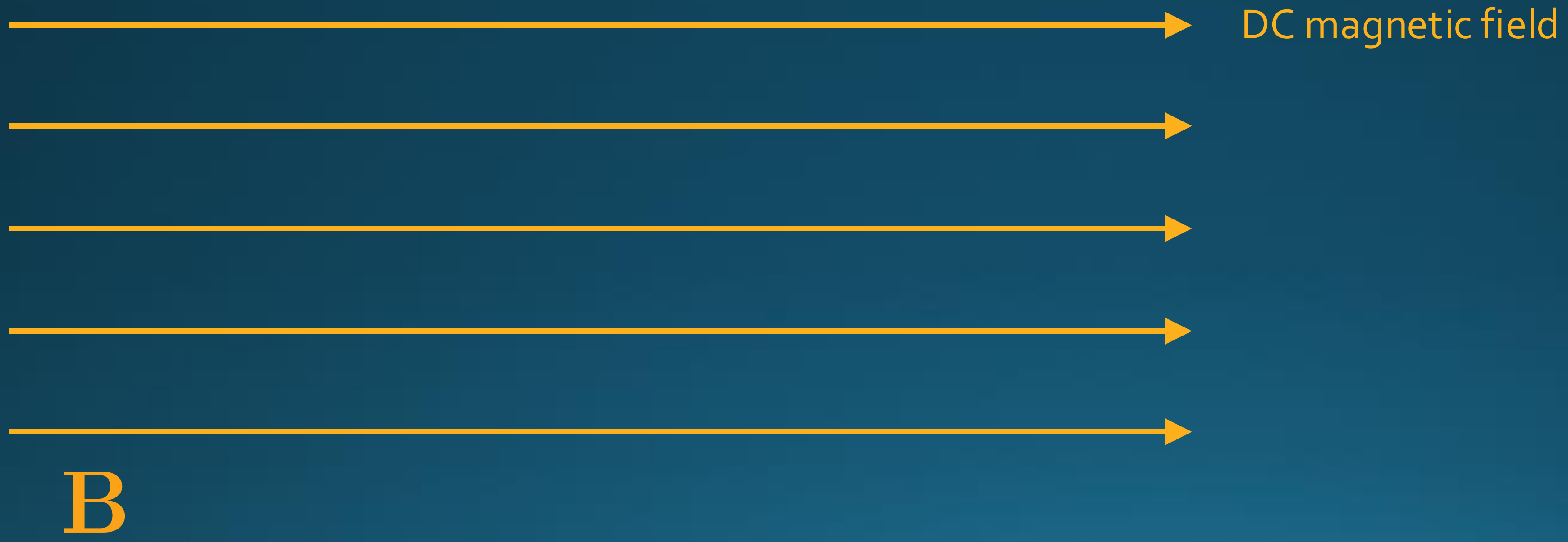

*Chang, Hagmann, Sikivie 1998*

BREAD

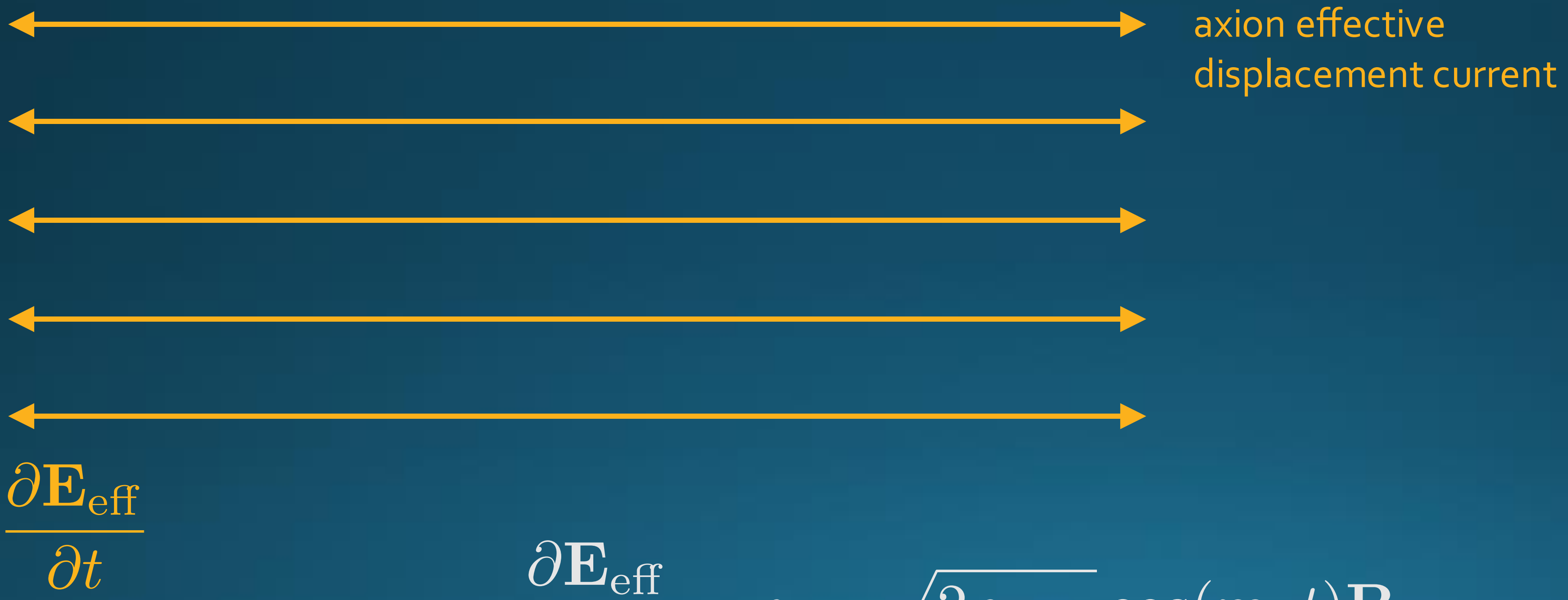
# Broadband Reflector Experiment for Axion Detection

**note:** BREAD is not the first experiment to use a reflector technique to look for wave dark matter.
It is unique in its adaptation to a solenoidal magnet geometry

# BREAD detector concept



# BREAD detector concept

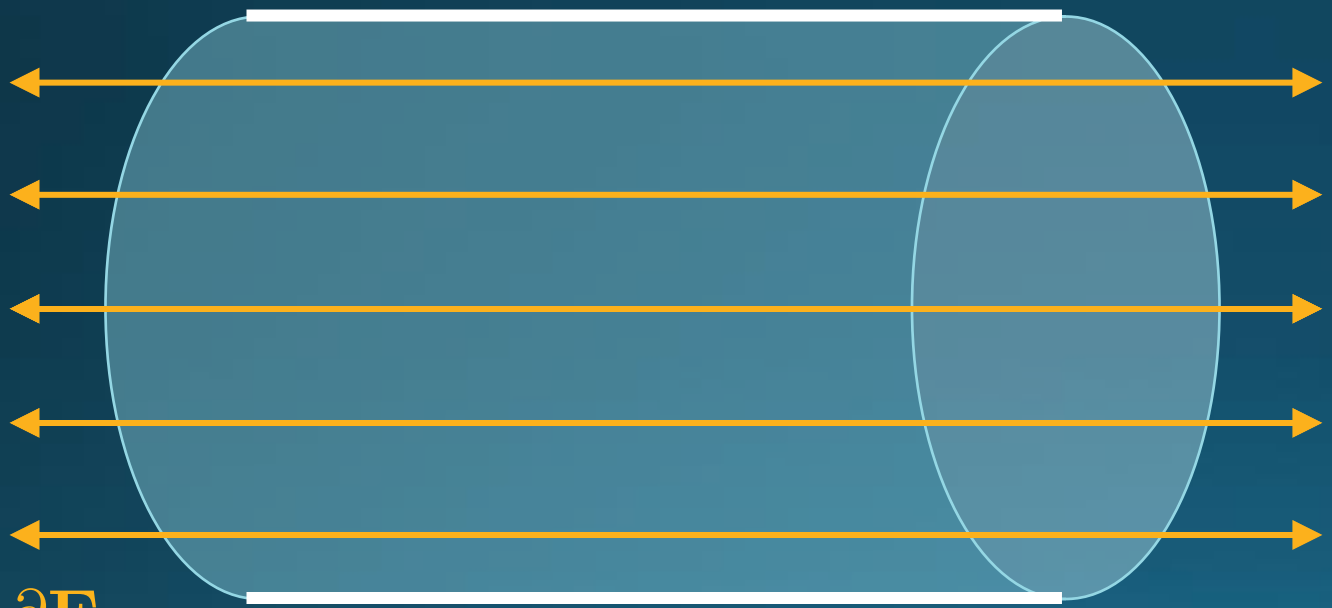



$$\frac{\partial \mathbf{E}_{\text{eff}}}{\partial t} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

# BREAD detector concept

$$\frac{\partial \mathbf{E}_{\text{eff}}}{\partial t}$$

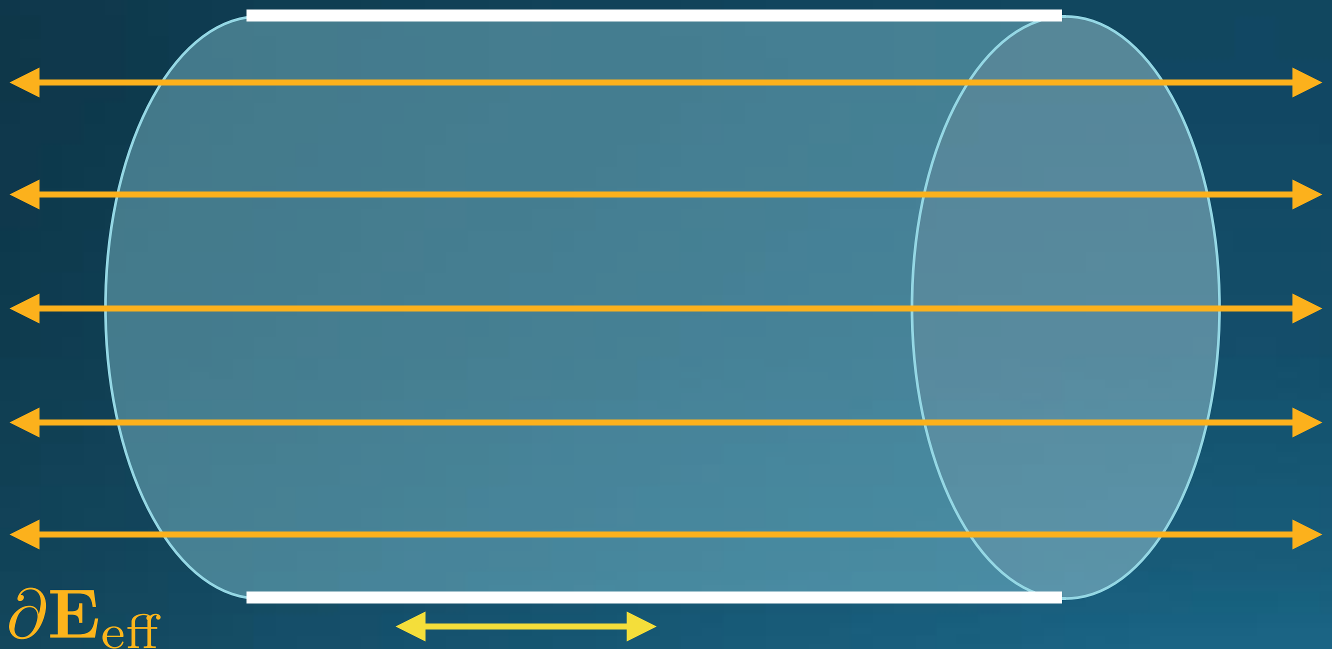
# BREAD detector concept



$$\frac{\partial \mathbf{E}_{\mathrm{eff}}}{\partial t}$$

$$\mathbf{E}_{||} = 0$$

# BREAD detector concept



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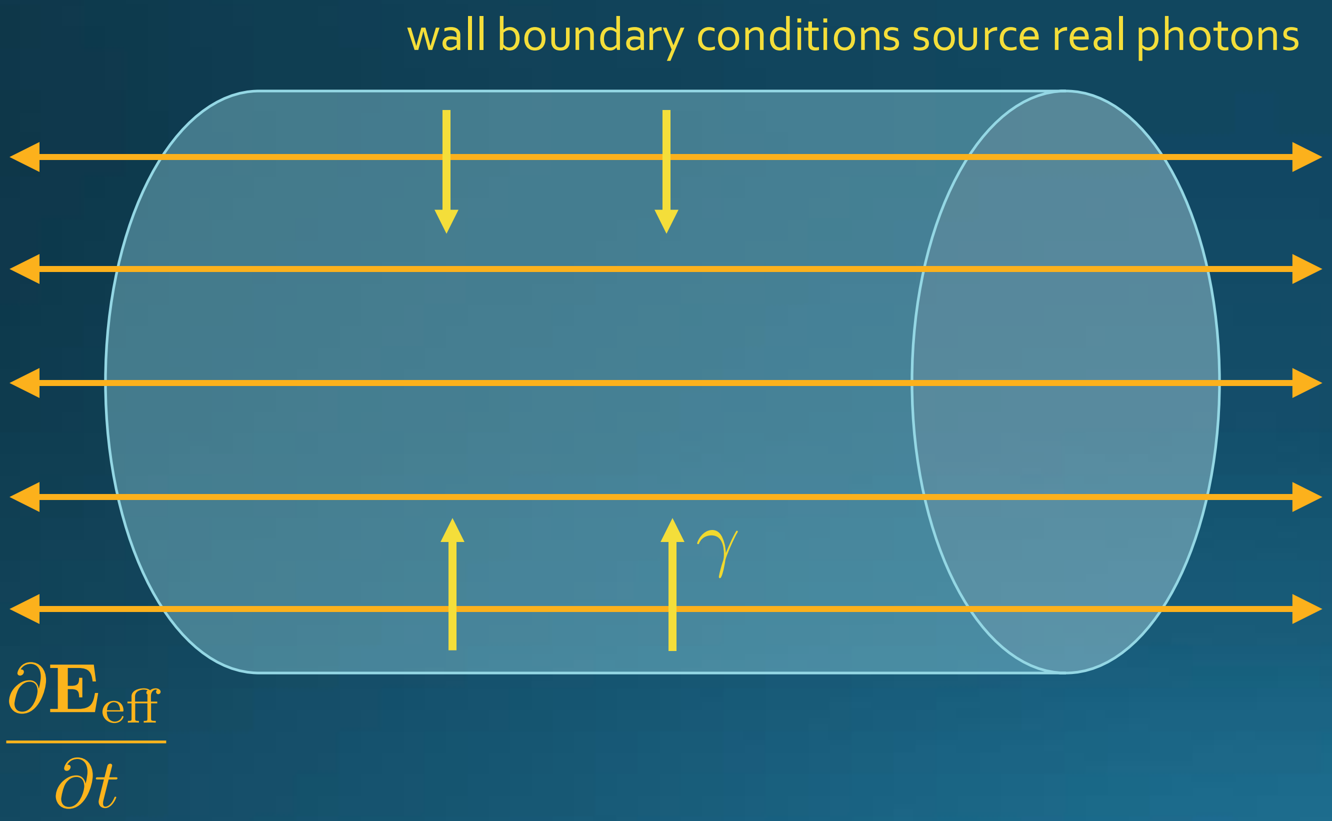

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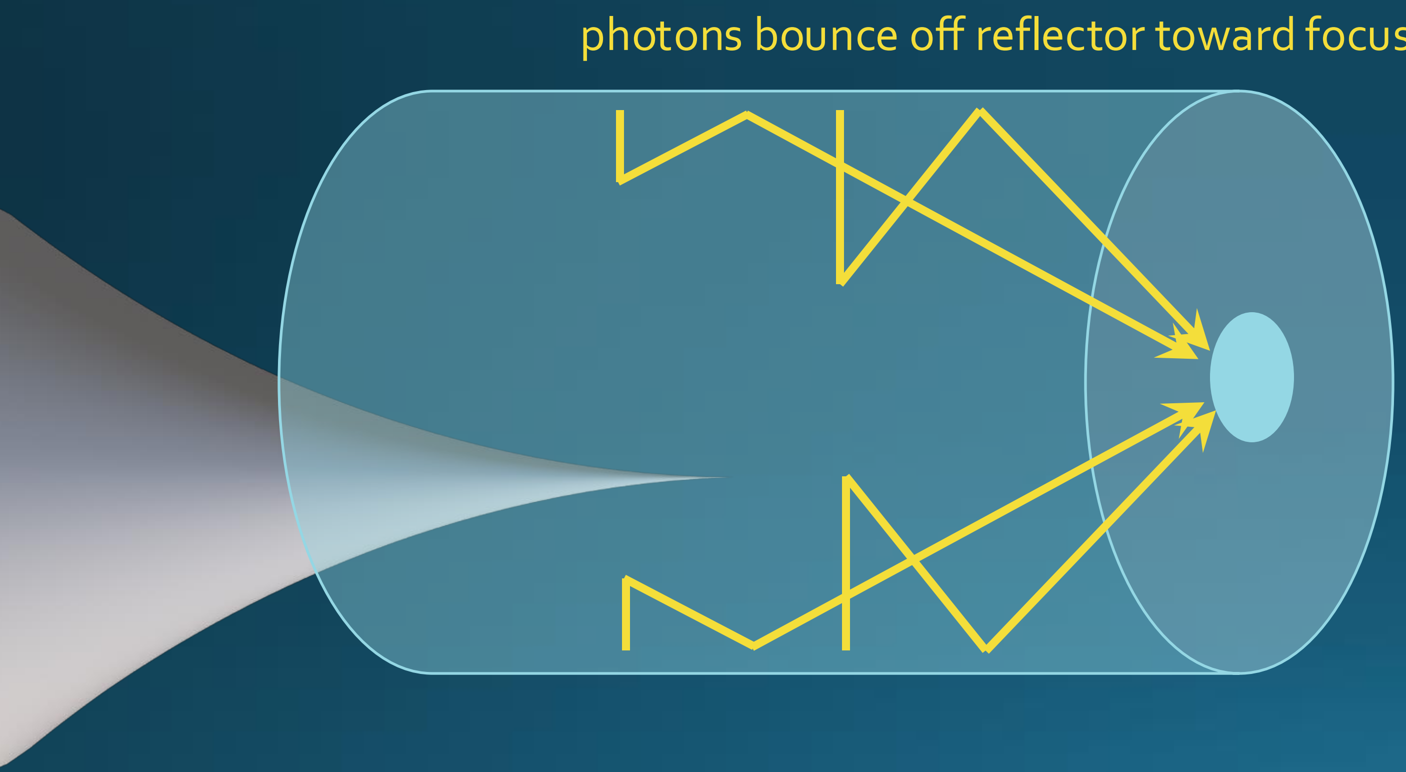

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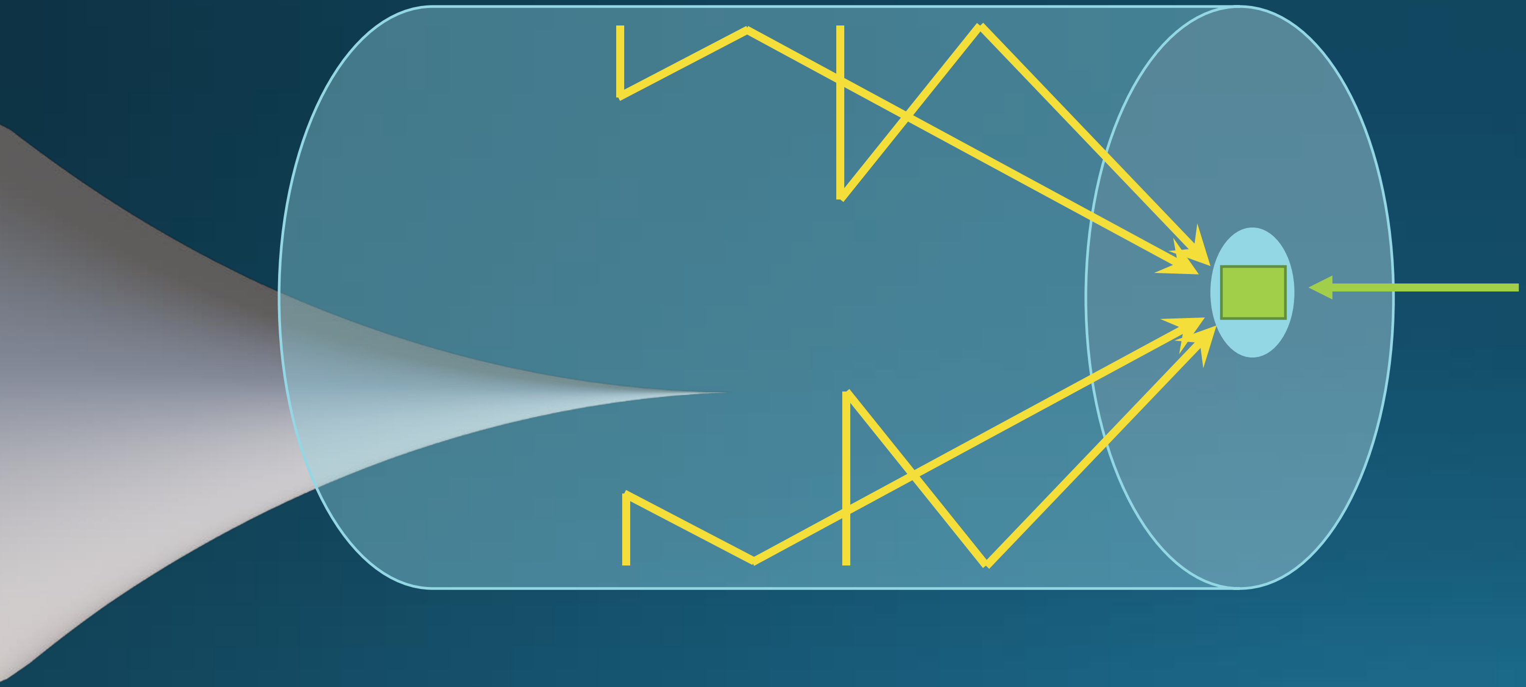
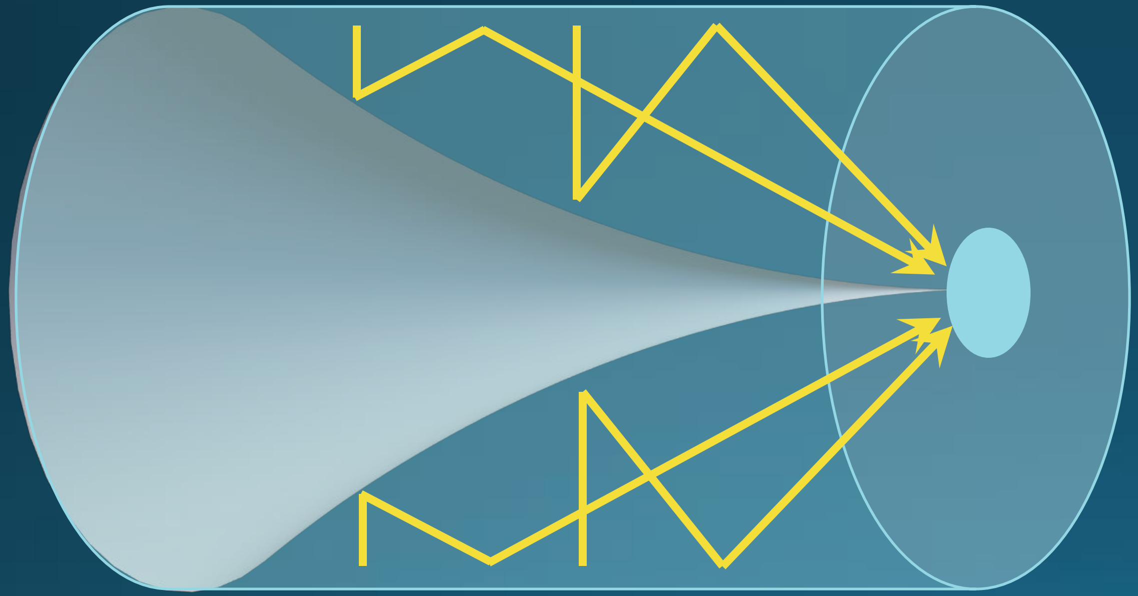


detect photons with quantum sensors

- SNSPD
- KID
- TES
- QCD
- SQUAT

# Measure axion velocities



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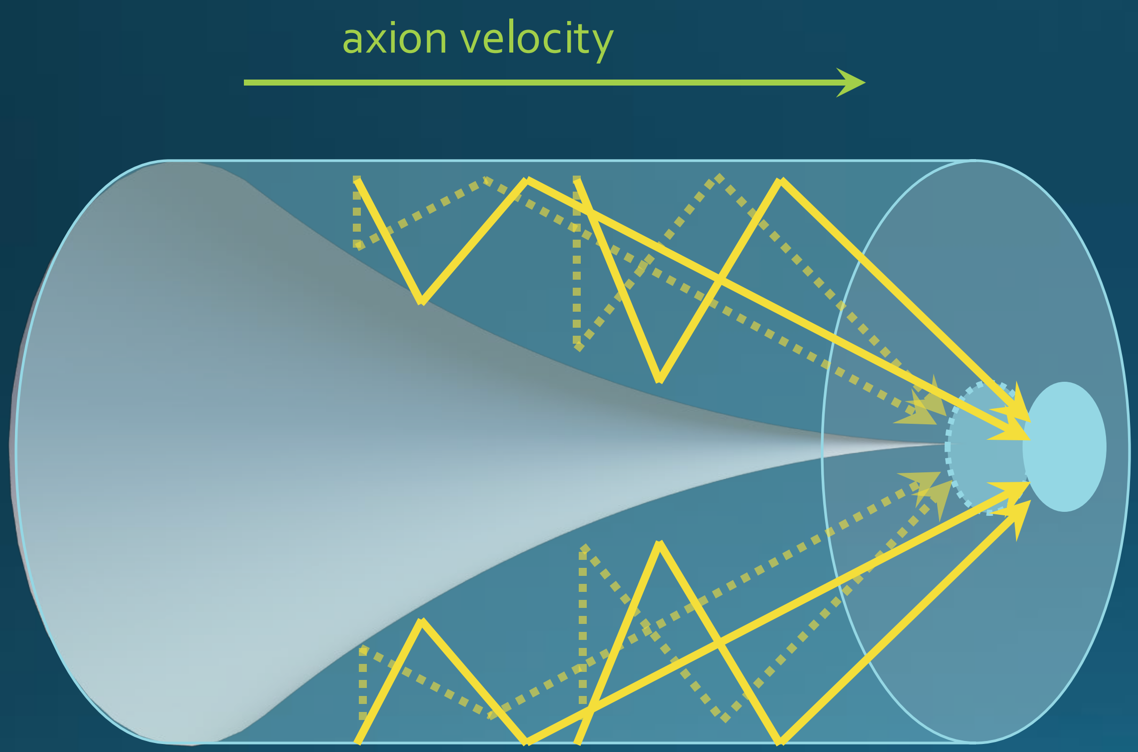

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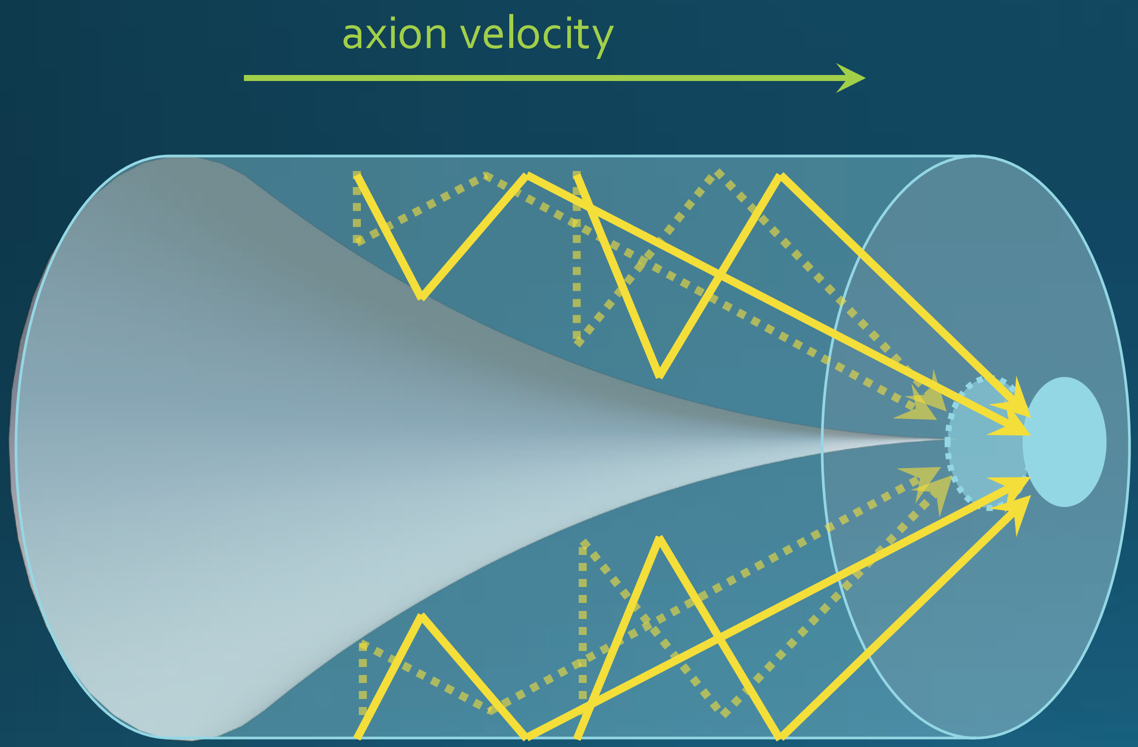


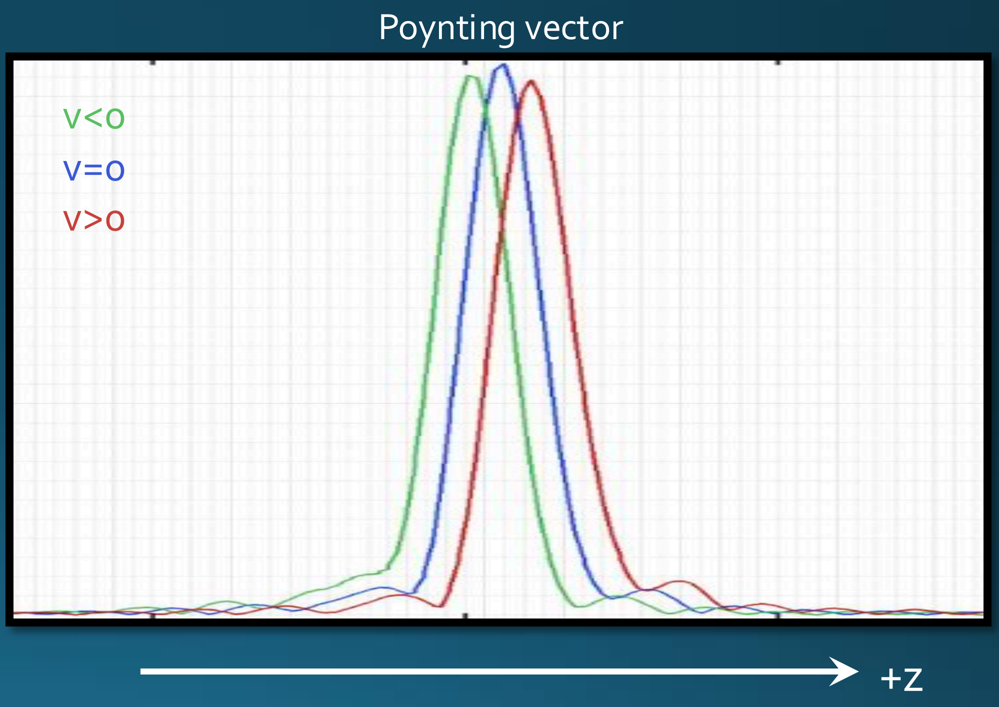

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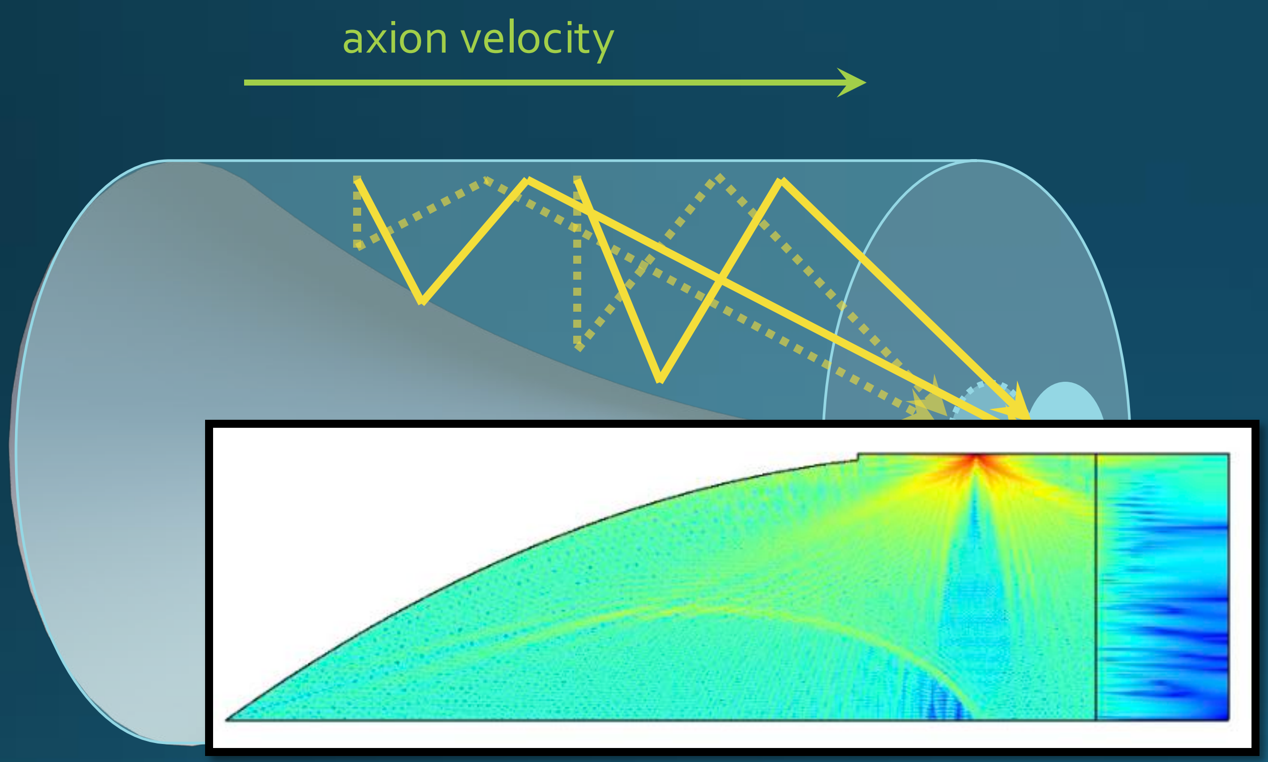
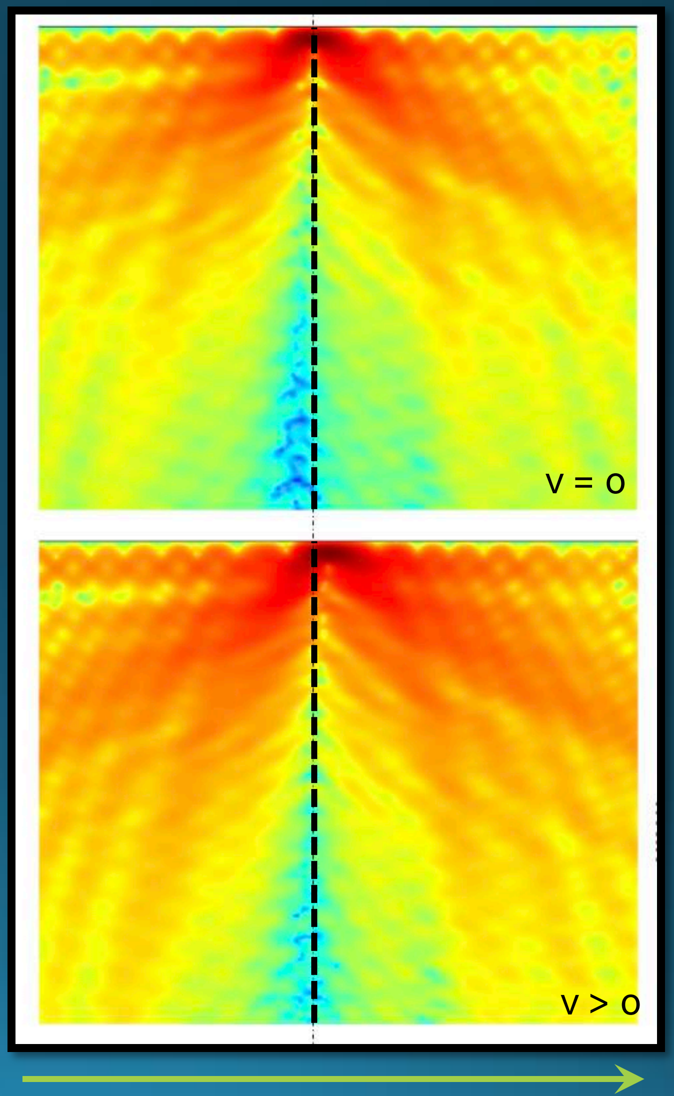
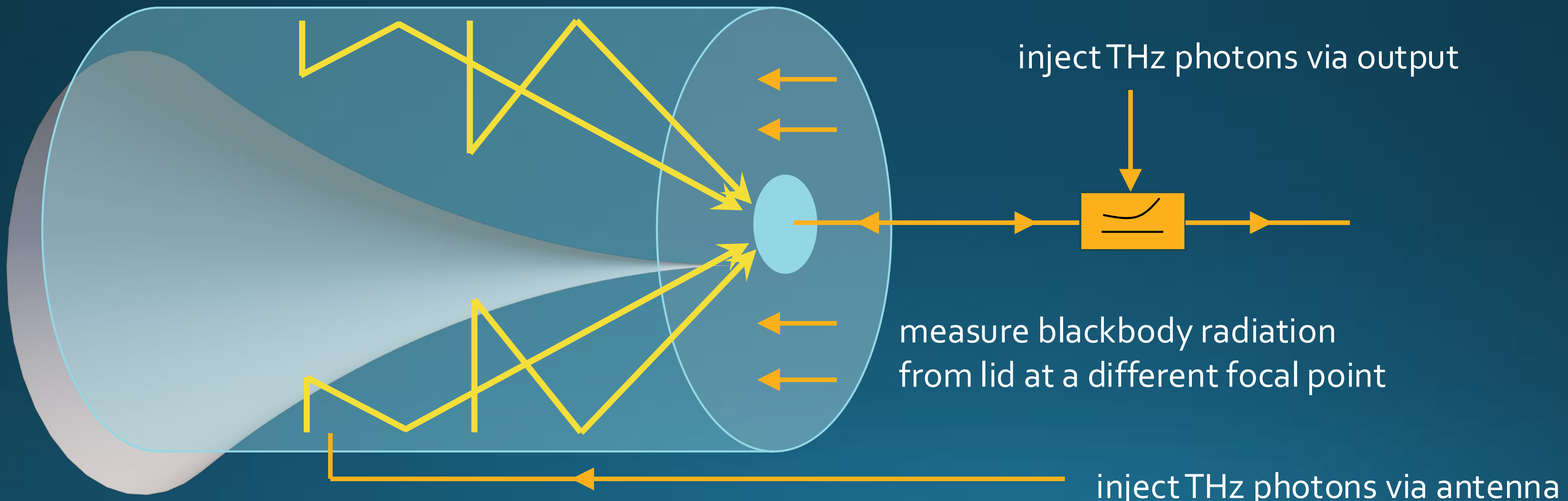



Lionel Whitehead

# How to calibrate



# Reflector sensitivity (Horns et al. 2013)

Different noise scaling for different detection mechanisms (power measurement or photon counting)

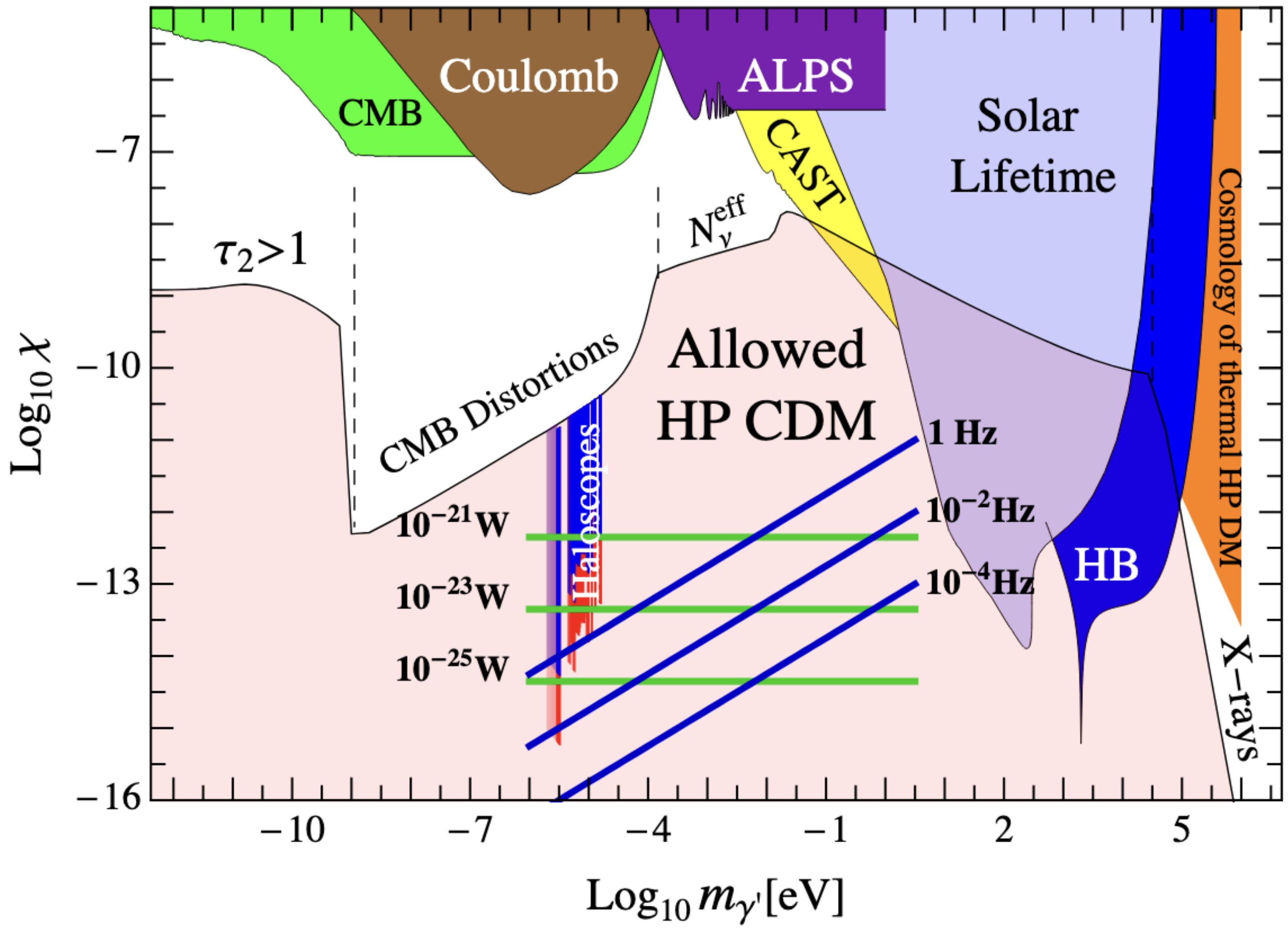
$$g_{\phi\gamma\gamma,\,\text{sens}} = \frac{3.6\times10^{-8}}{\text{GeV}}\left(\frac{5\,\text{T}}{\sqrt{\langle|\mathbf{B}_{||}|^2\rangle}}\right)\left(\frac{P_{\text{det}}}{10^{-23}\,\text{W}}\right)^{\frac{1}{2}}\left(\frac{m_\phi}{\text{eV}}\right)\left(\frac{0.3\,\text{GeV/cm}^3}{\rho_{\text{DM,halo}}}\right)^{\frac{1}{2}}\left(\frac{1\,\text{m}^2}{A_{\text{dish}}}\right)^{\frac{1}{2}}, \tag{3.4}$$

and

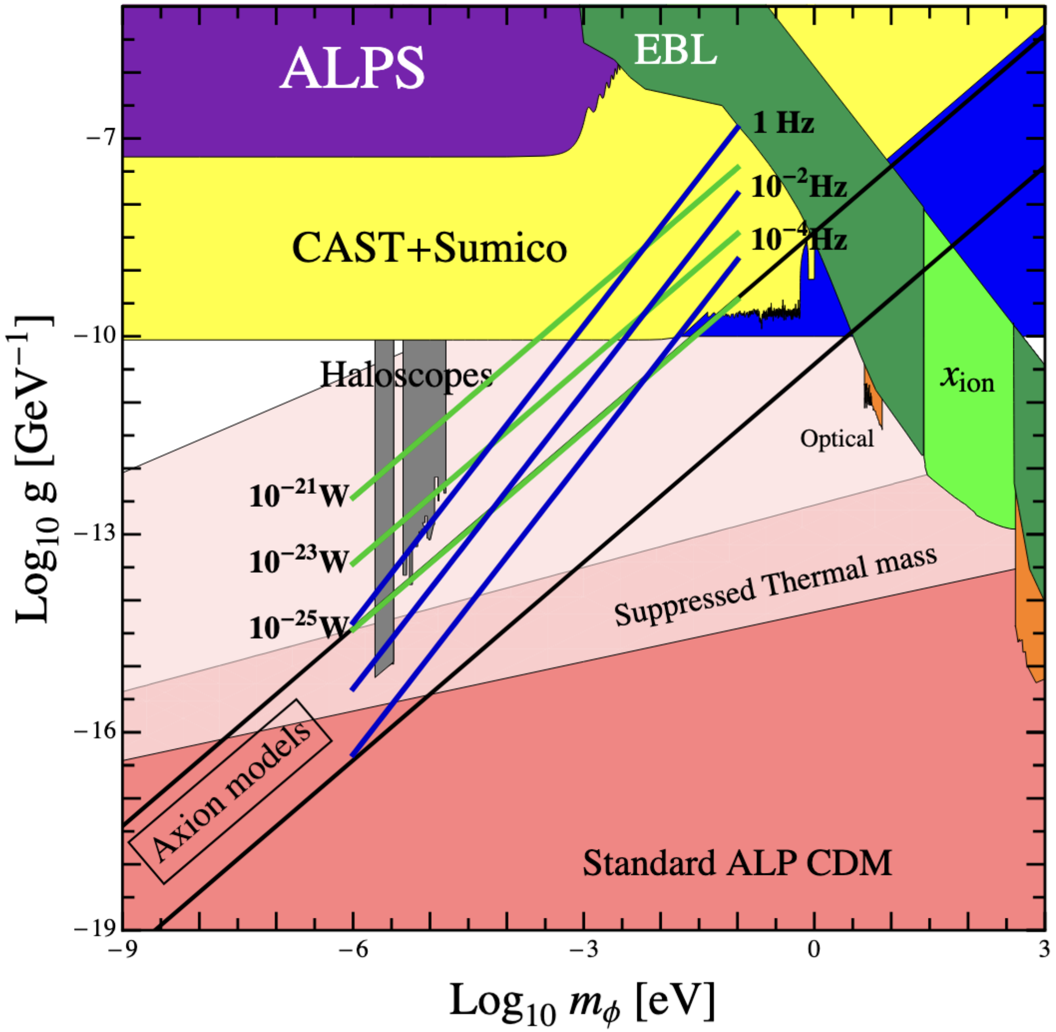
$$g_{\phi\gamma\gamma,\,\text{sens}} = \frac{4.6\times10^{-6}}{\text{GeV}}\left(\frac{5\,\text{T}}{\sqrt{\langle|\mathbf{B}_{||}|^2\rangle}}\right)\left(\frac{R_{\gamma,\text{det}}}{1\,\text{Hz}}\right)^{\frac{1}{2}}\left(\frac{m_\phi}{\text{eV}}\right)^{\frac{3}{2}}\left(\frac{0.3\,\text{GeV/cm}^3}{\rho_{\text{DM,halo}}}\right)^{\frac{1}{2}}\left(\frac{1\,\text{m}^2}{A_{\text{dish}}}\right)^{\frac{1}{2}}, \tag{3.5}$$

# Reach?

**Dark photons**

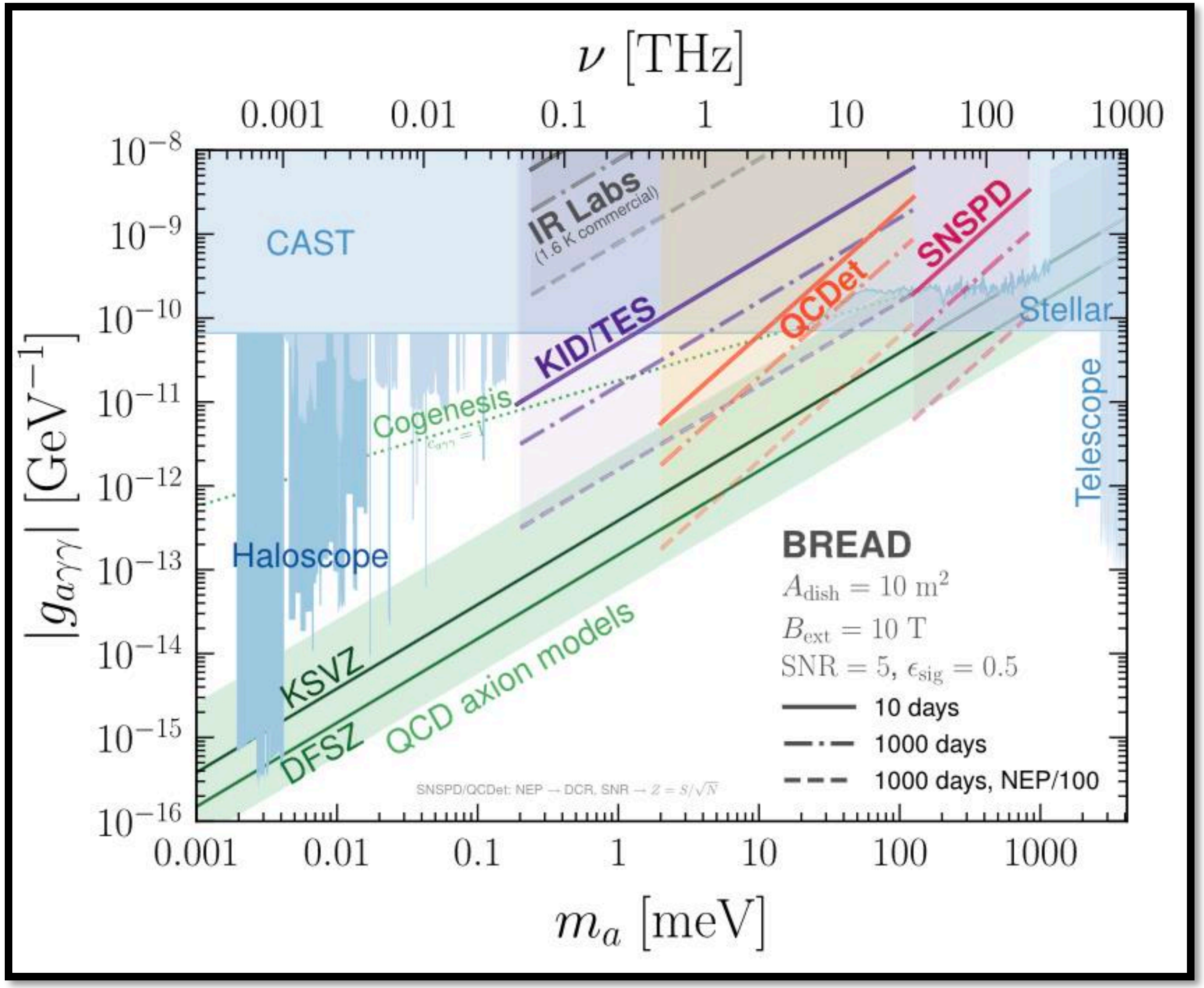



**Axions**




*Horns et al. 2013*

# Reach?

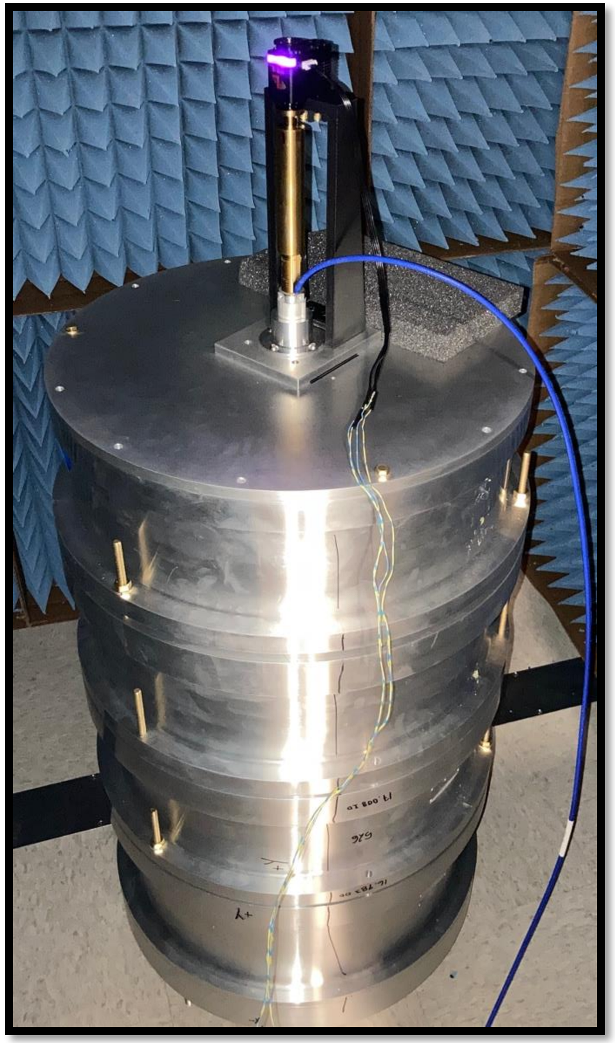


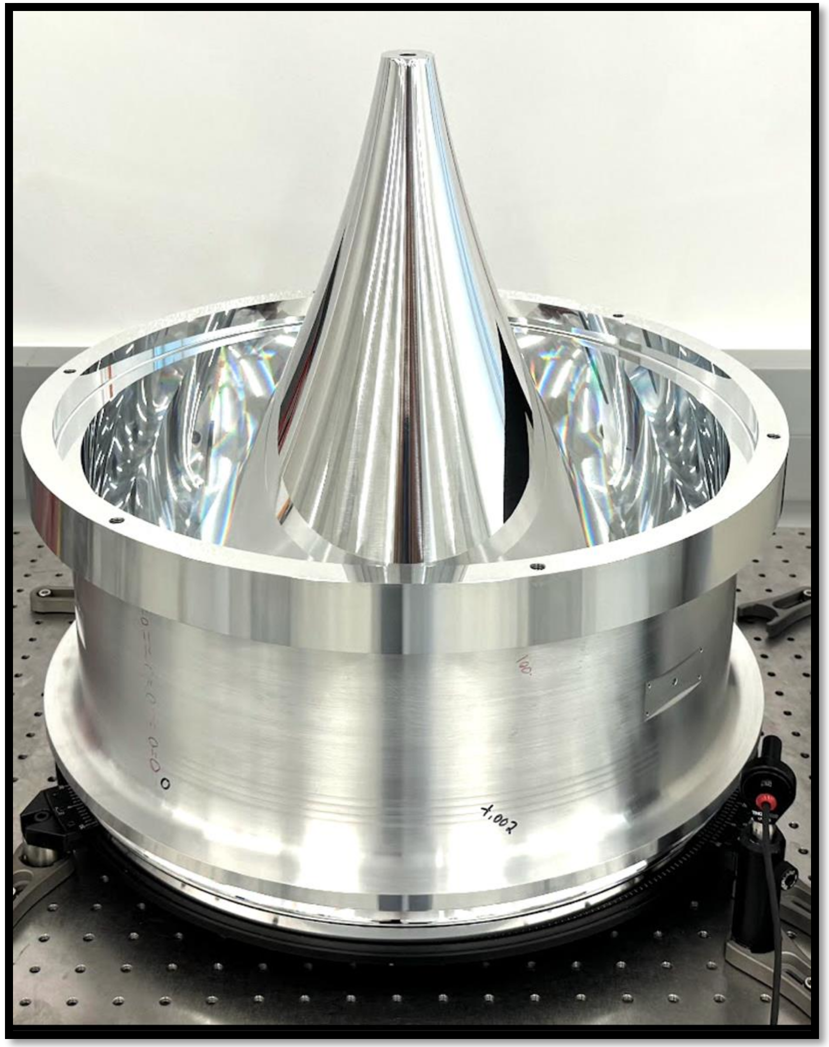

*Liu et al. PRL 2022*

$$\left\{ \begin{matrix} \left(\frac{g_{a\gamma\gamma}}{10^{-11}}\right)^2 \\ \left(\frac{\kappa}{10^{-14}}\right)^2 \end{matrix} \right\} = \left\{ \begin{matrix} \frac{1.9}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\frac{10\ \mathrm{T}}{B_{\mathrm{ext}}}\right)^2 \\ 7.6\,\frac{2/3}{\alpha_{\mathrm{pol}}^2} \end{matrix} \right\} \frac{10\ \mathrm{m}^2}{A_{\mathrm{dish}}}\left(\frac{\mathrm{hour}}{\Delta t}\right)^{1/2}$$

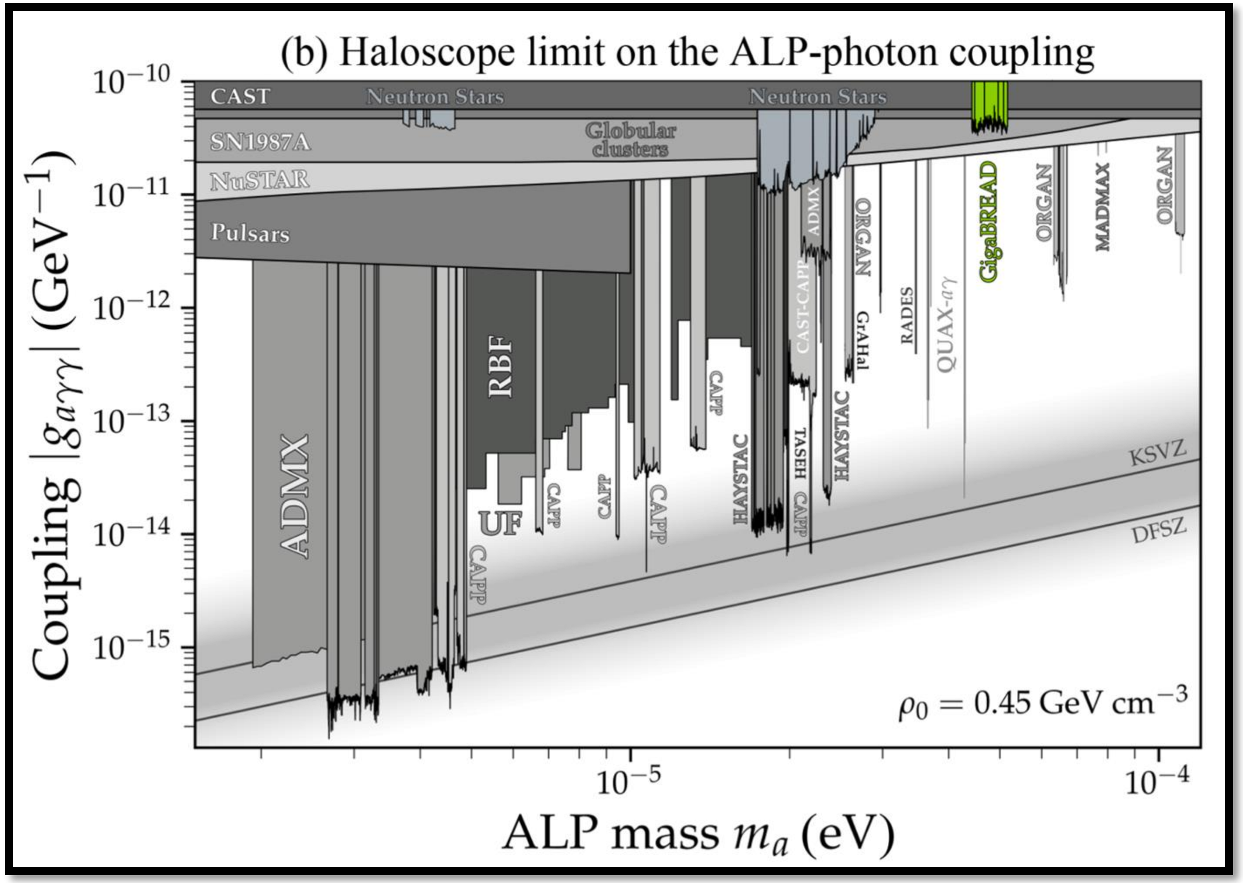
$$\times \frac{\mathrm{SNR}}{5}\frac{0.5}{\epsilon_s}\frac{\mathrm{NEP}}{10^{-21}\ \mathrm{W}/\sqrt{\mathrm{Hz}}}\frac{0.45\ \mathrm{GeV/cm}^3}{\rho_{\mathrm{DM}}}$$

# Photos





# BREAD first axion results




# Dielectric stack detectors

adding resonant enhancement to the reflector concept

MADMAX

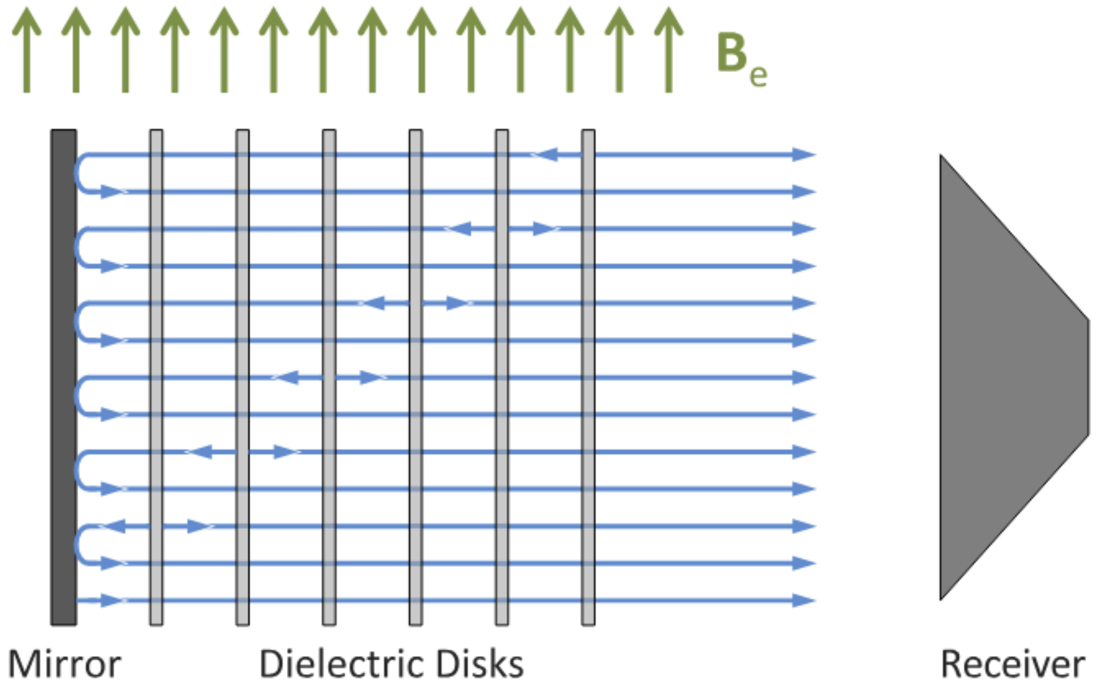
MAgnetized Disk and Mirror Axion eXperiment

**LAMPOST**

Light A’ Multilayer Periodic Optical SNSPD Target

Caldwell et al. 2017

# Detection concept




$$\frac{P}{A} = \beta^2 \frac{P_0}{A}$$

$P_0$ : power from mirror (no additional layers)
A : mirror area

Boost factor:

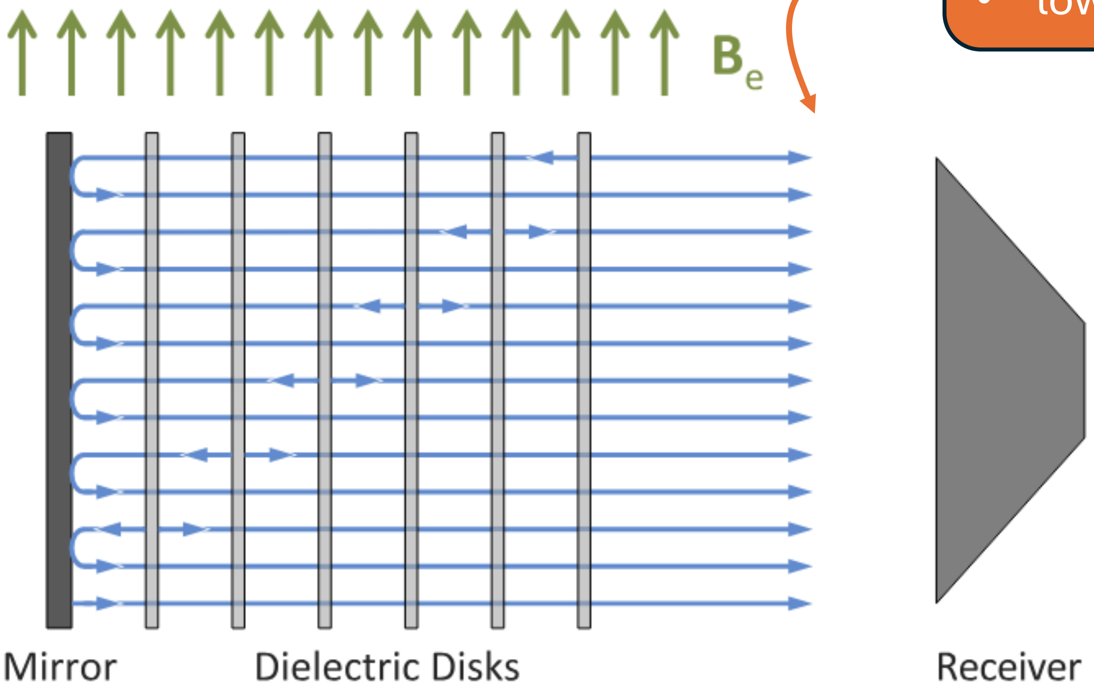
$$\beta(\nu_a) \equiv |E_{\rm out}(\nu_a)/E_0|.$$

*Caldwell et al. 2017*

# Detection concept

compared to cavities:

- increased volume
- lower “Q”

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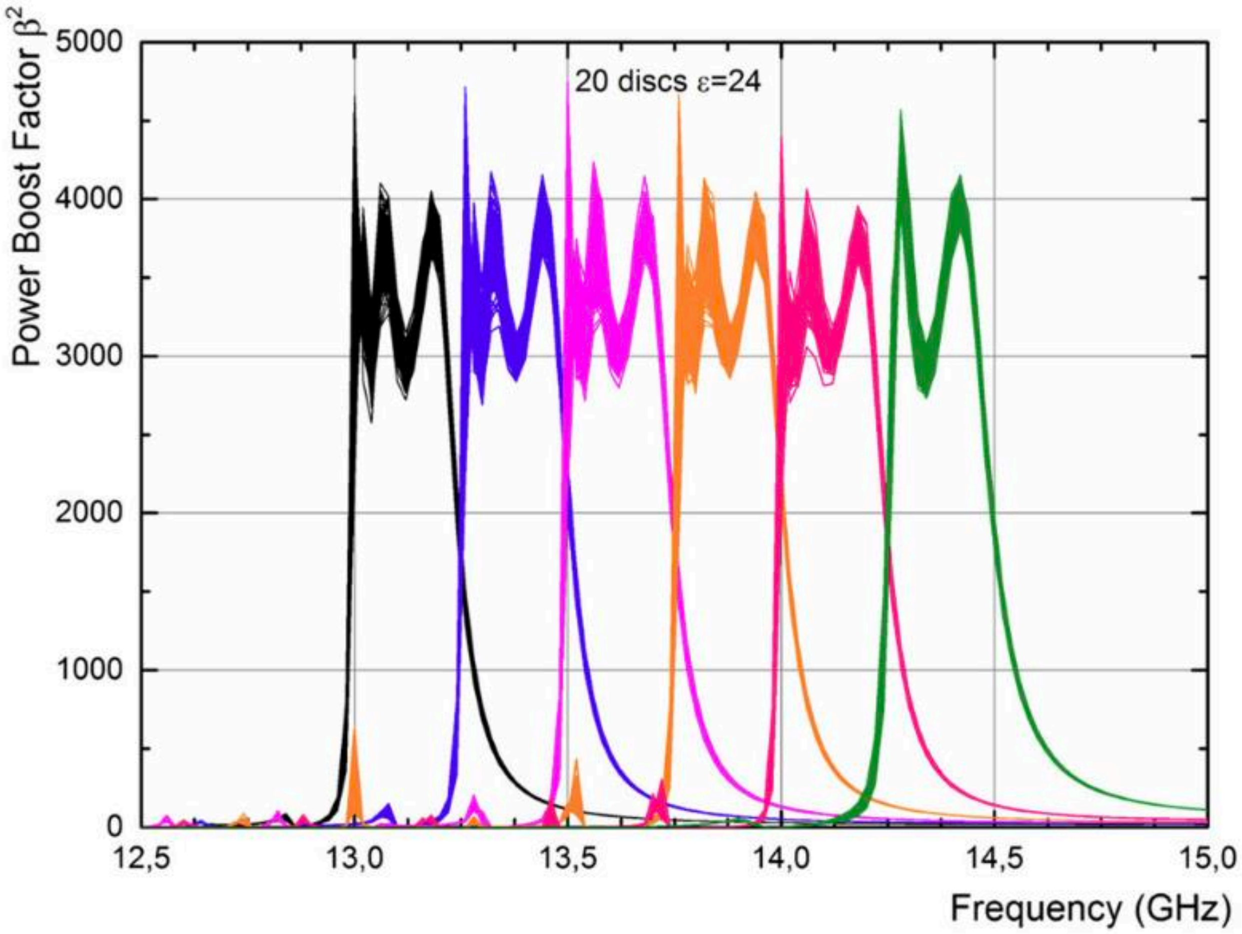
$P_0$ : power from mirror (no additional layers)
A : mirror area

Boost factor:

$$\beta(\nu_a) \equiv |E_{\text{out}}(\nu_a)/E_0|.$$

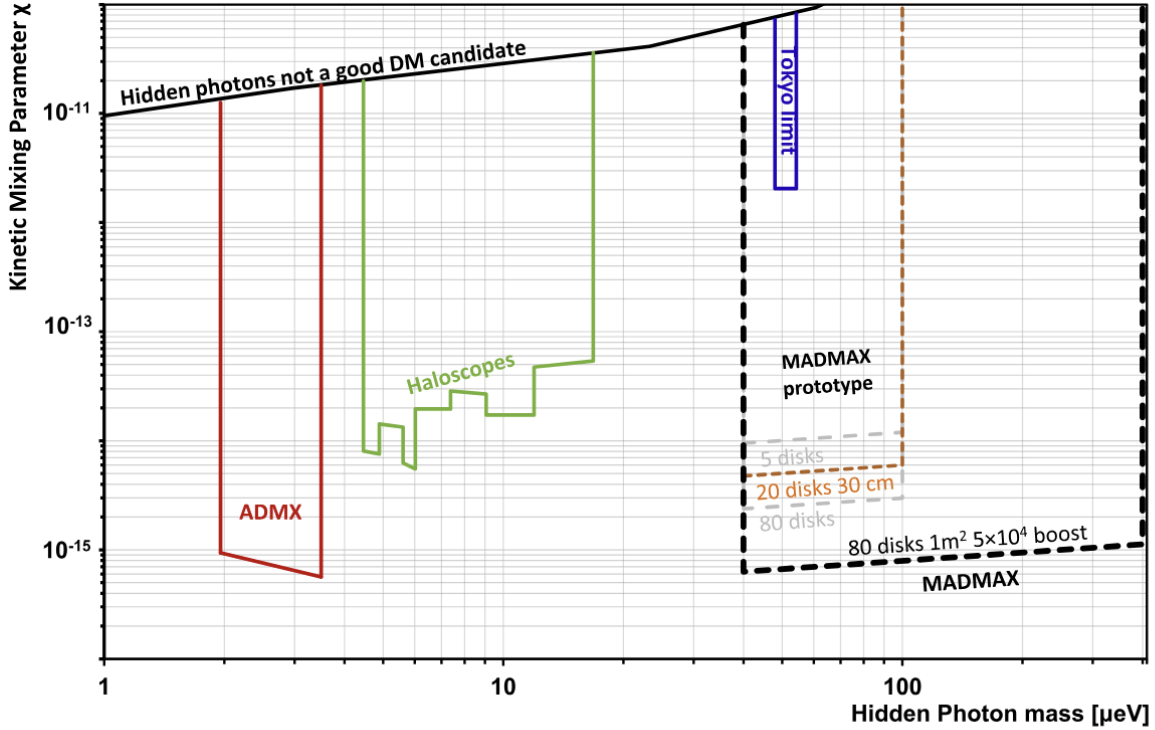
# How much boost can you do?



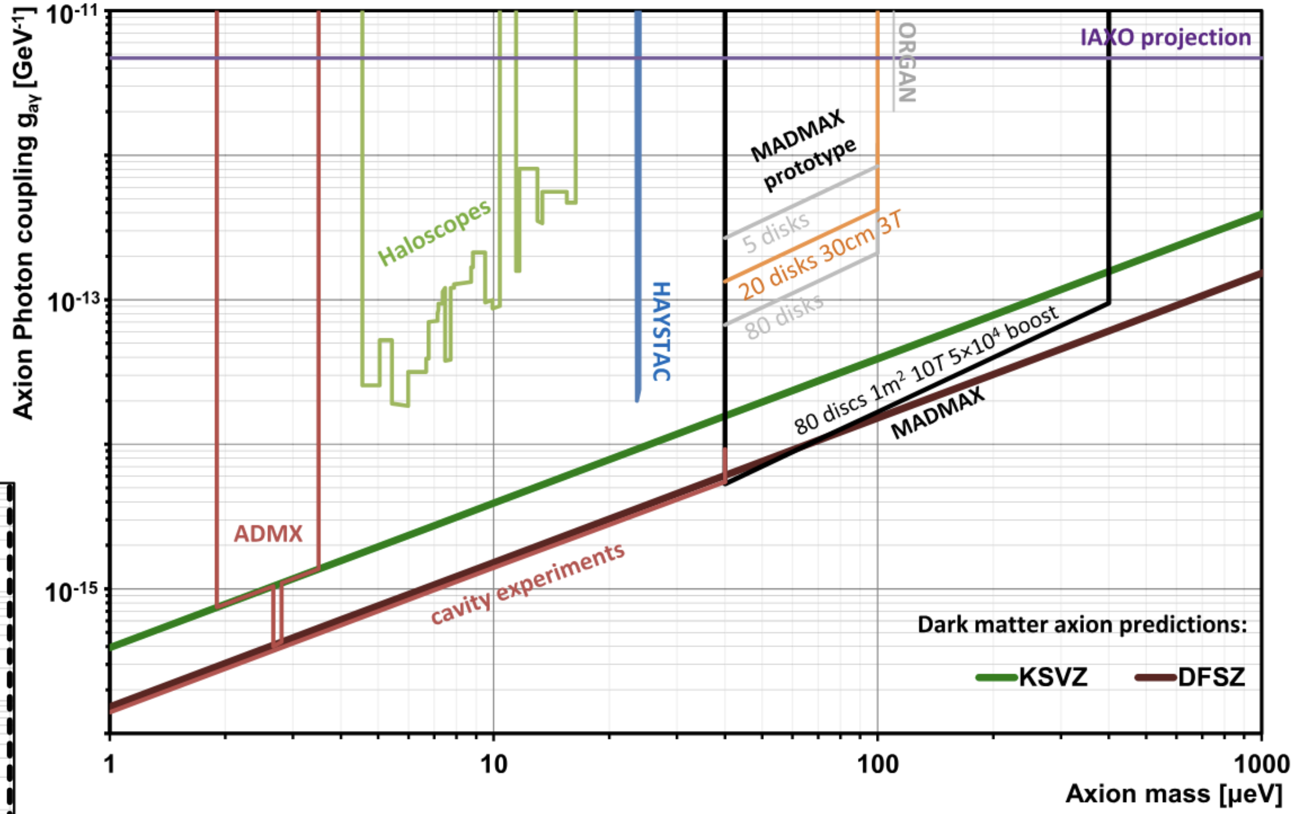

Want:

- High dielectric constant, $\epsilon$
- Low loss, $\tan\delta$
- Mechanically and cryogenically stable and compatible
- Affordable

# Reach?

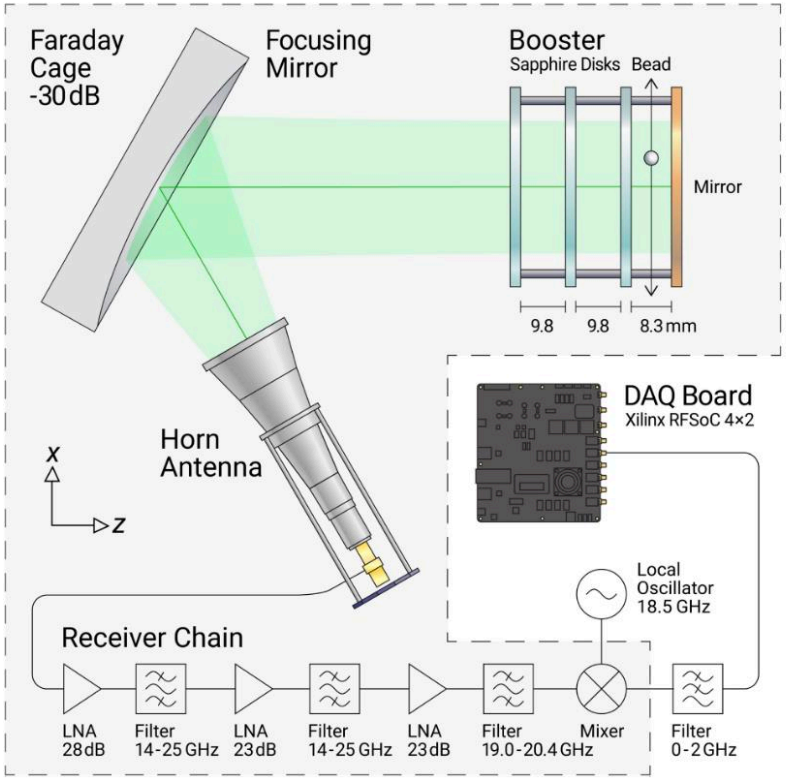


Kinetic Mixing Parameter χ
$10^{-11}$
$10^{-13}$
$10^{-15}$
Hidden photons not a good DM candidate
ADMX
Haloscopes
Tokyo limit
MADMAX prototype
5 disks
20 disks 30 cm
80 disks
80 disks 1m² 5×10⁴ boost
MADMAX
1
10
100
Hidden Photon mass [μeV]

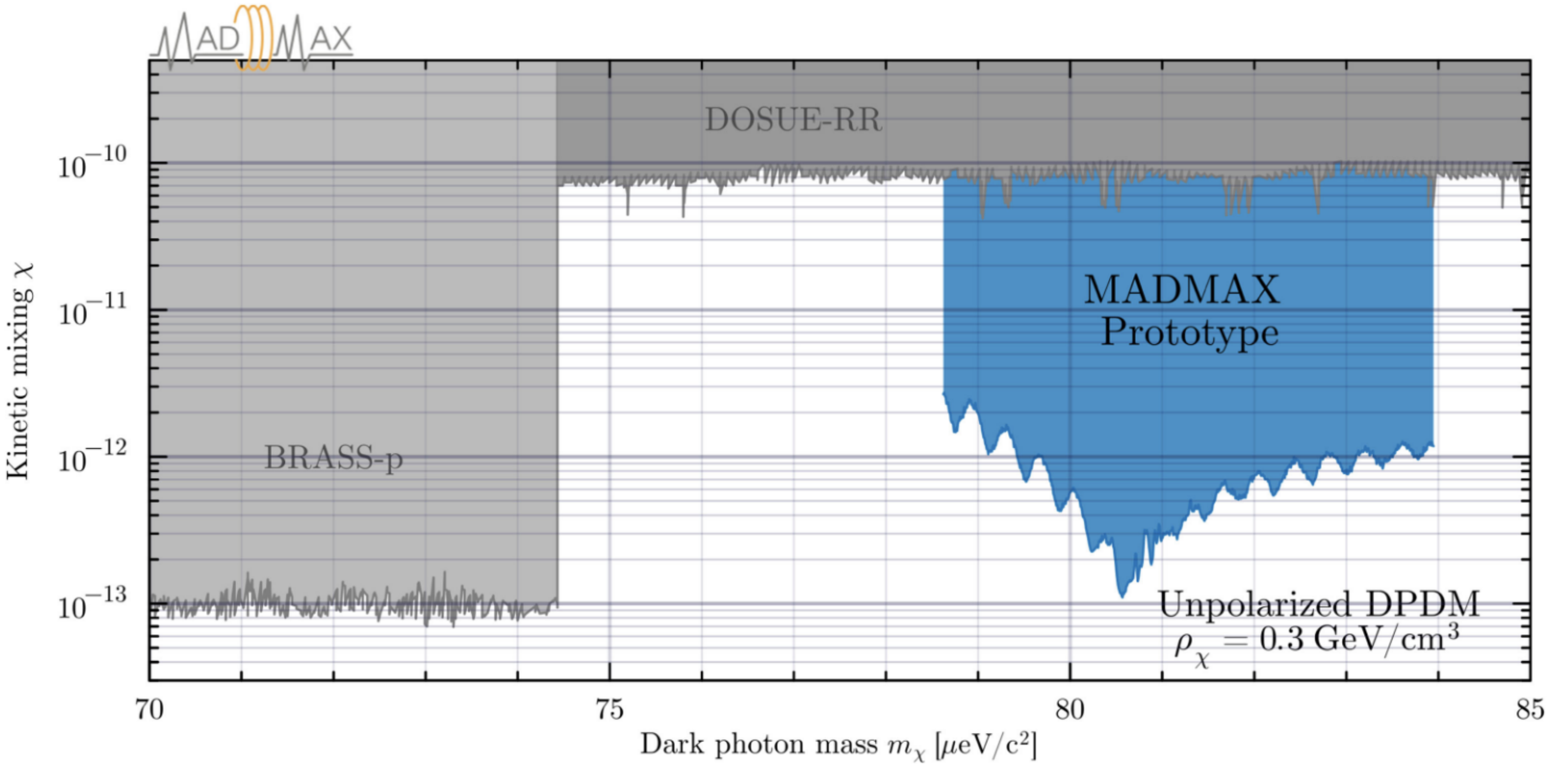



Axion Photon coupling $g_{a\gamma}$ [GeV⁻¹]
$10^{-11}$
$10^{-13}$
$10^{-15}$
IAXO projection
ORGAN
MADMAX prototype
5 disks
20 disks 30cm 3T
80 disks
Haloscopes
HAYSTAC
ADMX
cavity experiments
80 discs 1m² 10T 5×10⁴ boost
MADMAX
Dark matter axion predictions:
KSVZ
DFSZ
1
10
100
1000
Axion mass [μeV]

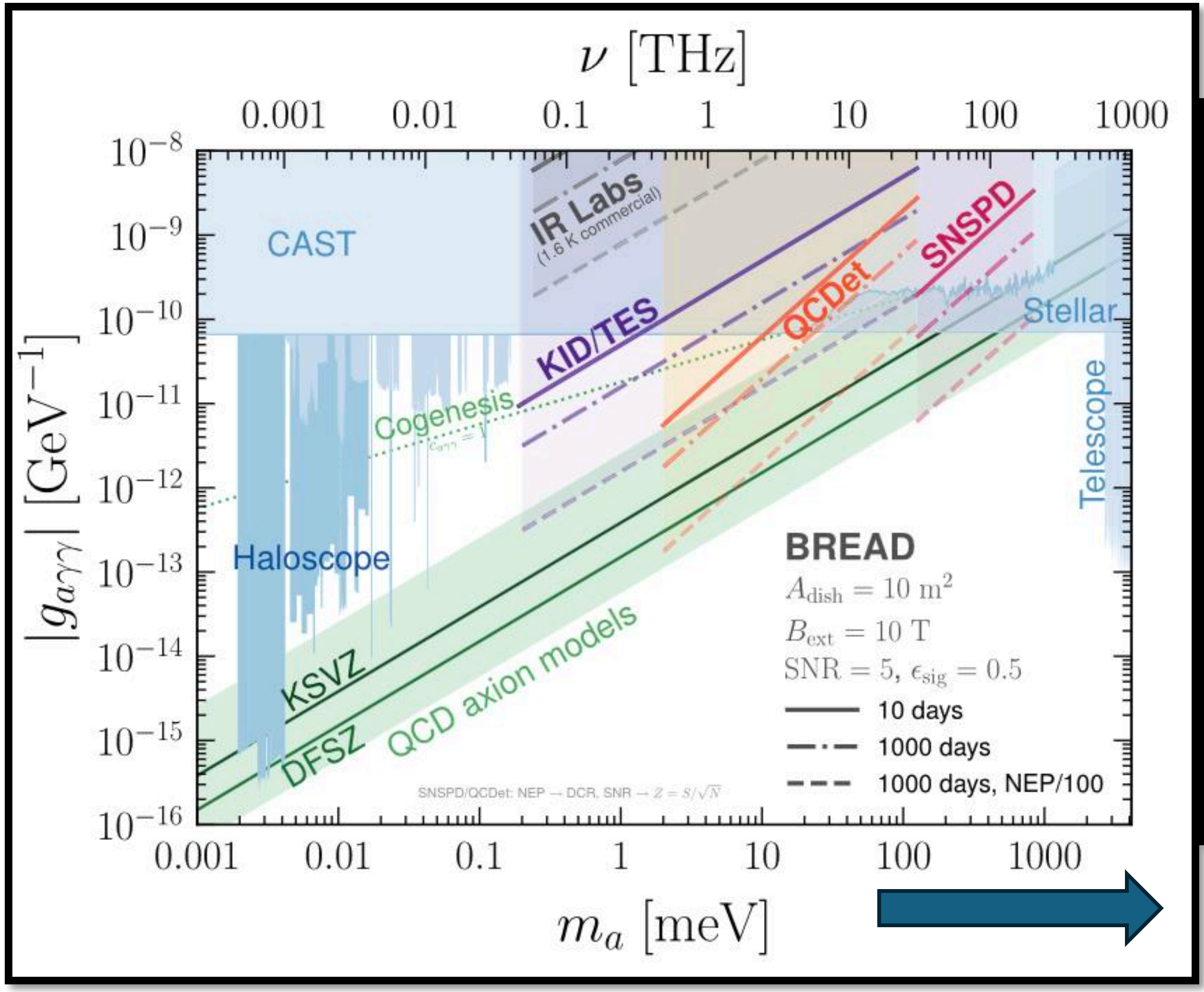
# Recent results



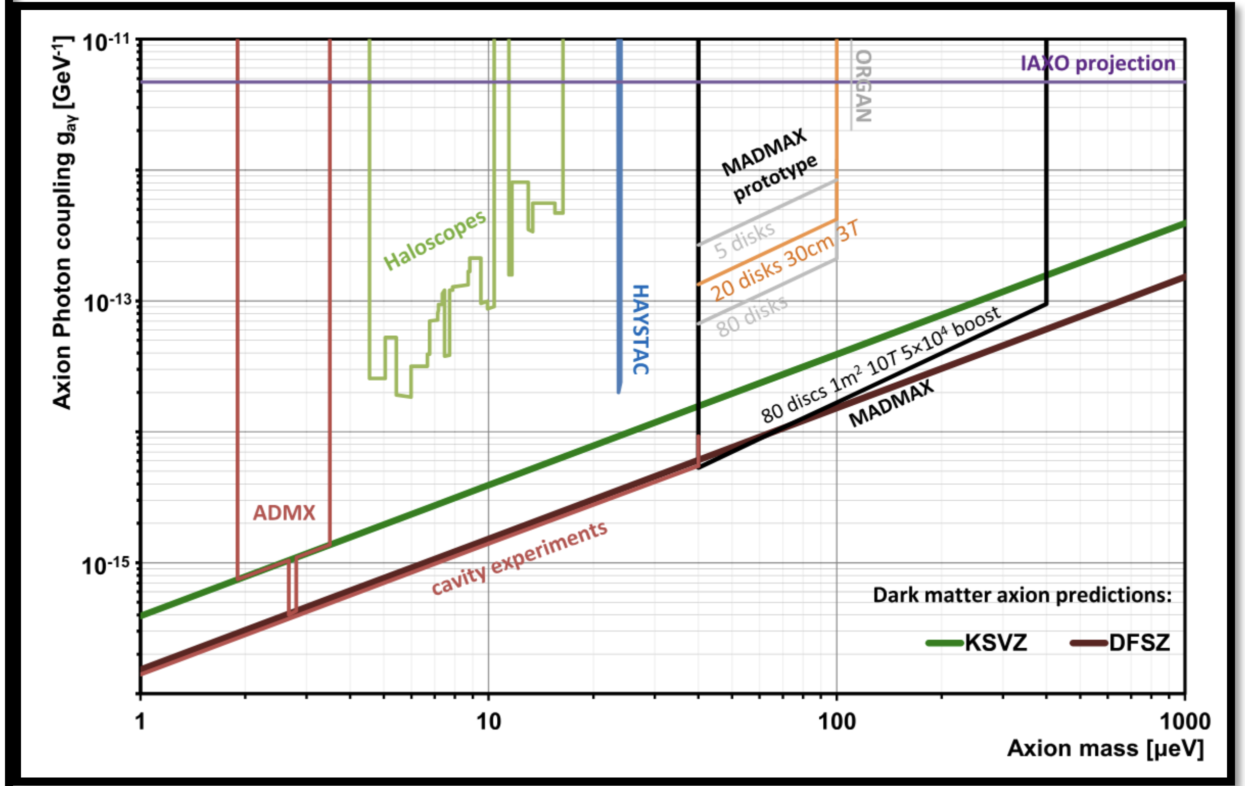

3 sapphire disks



# Familiar energy scales?

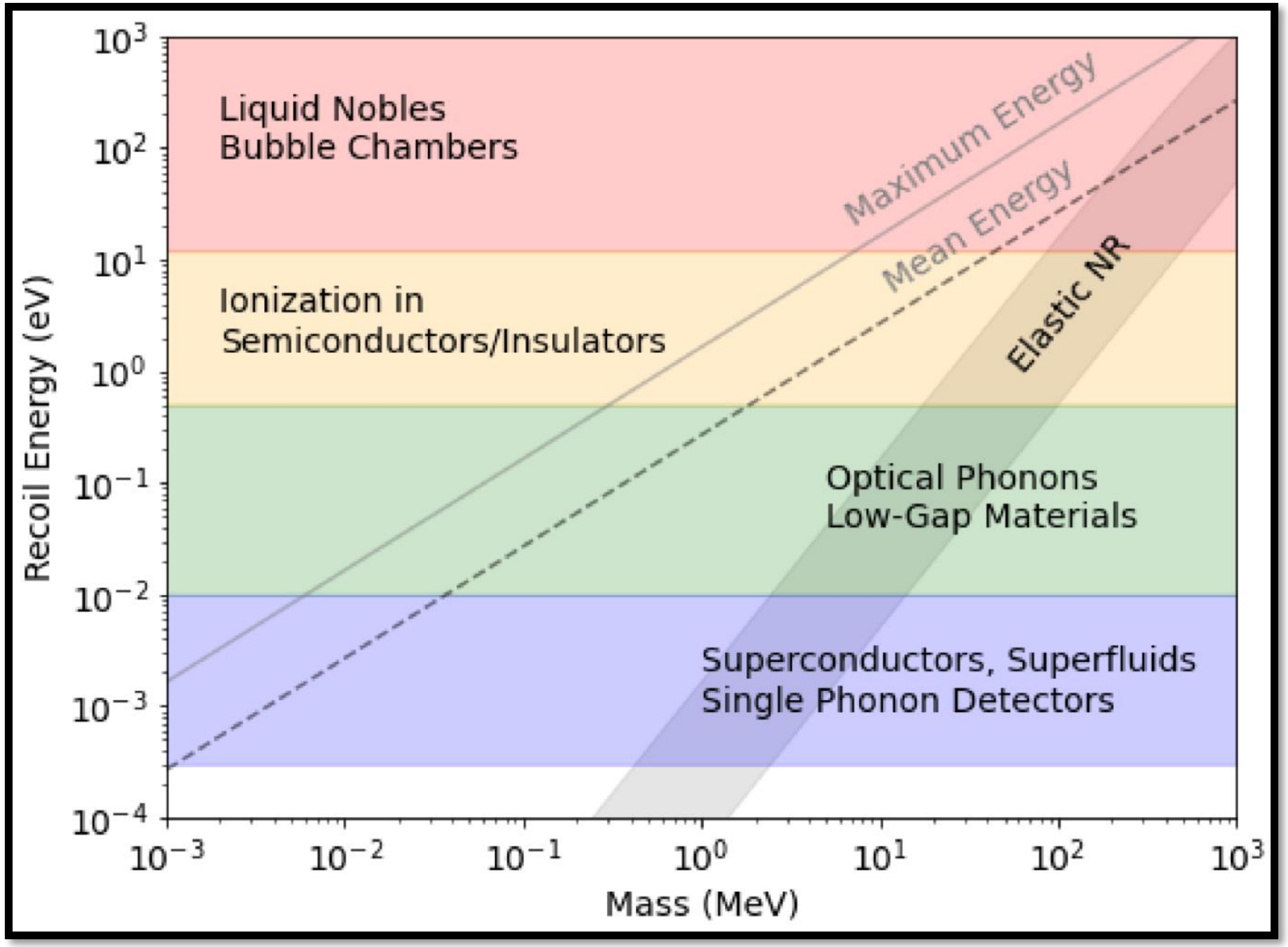



*Liu et al. PRL 2022*



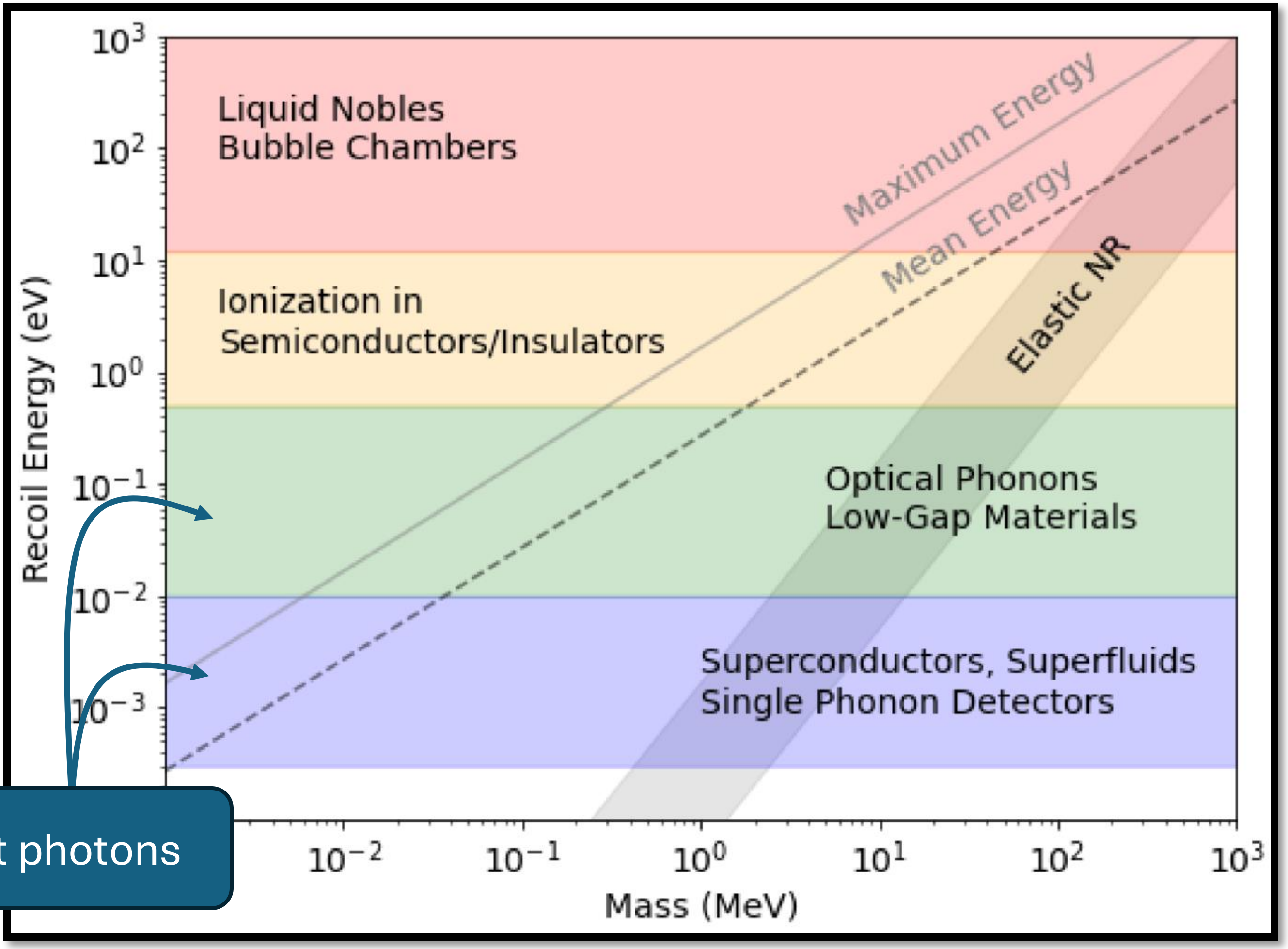

*Horns et al 2013*

# Low-mass particle dark matter scattering




Dark matter scattering
Snowmass (arXiv:2203.08297)

# Low-mass particle dark matter scattering

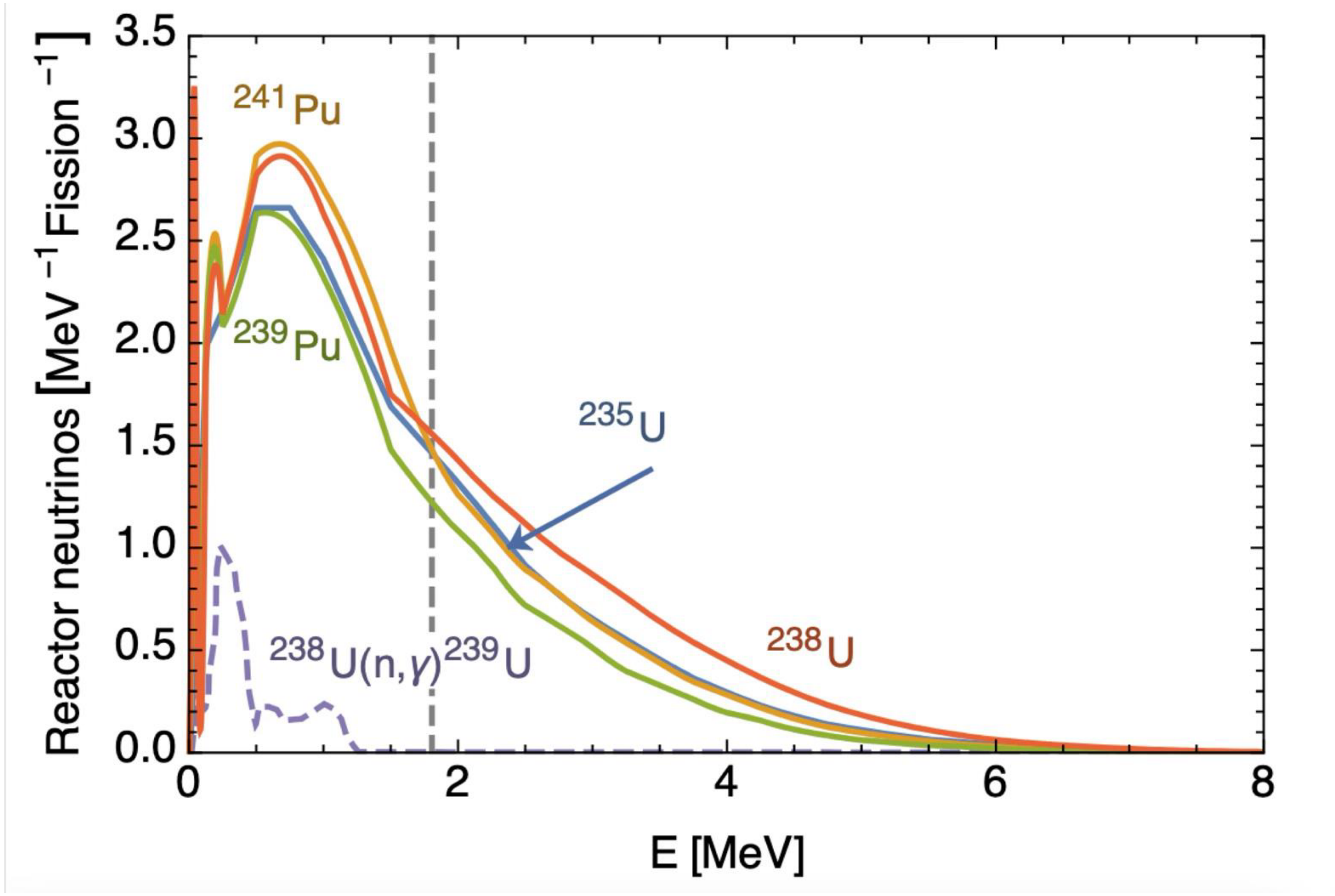


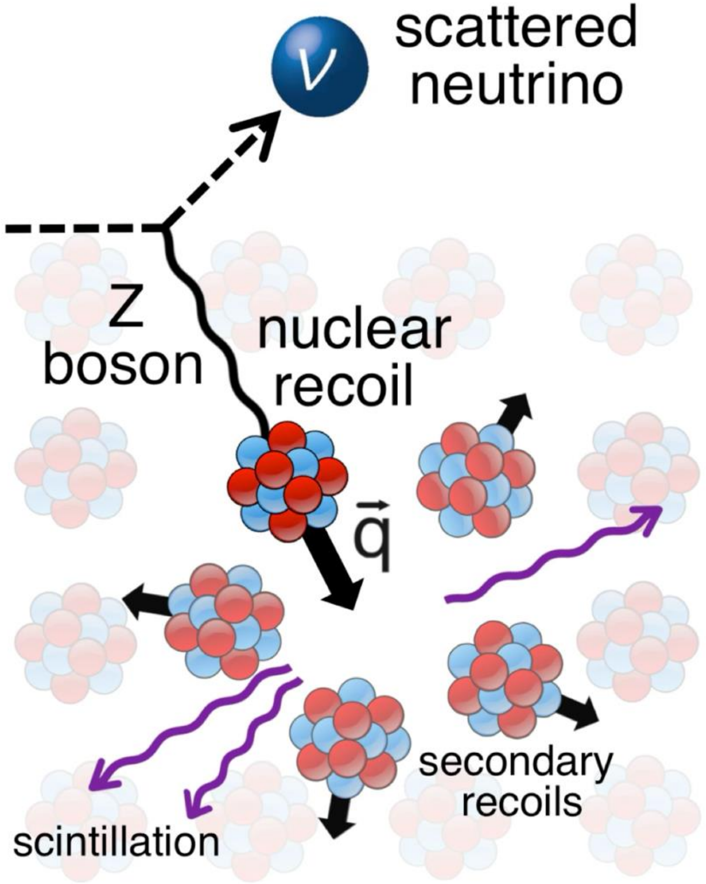

signal is phonons, not photons

Dark matter scattering

Snowmass (arXiv:2203.08297)

# And another reason for low-threshold sensors




**CEvNS**

(coherent elastic neutrino-nucleus scattering)

# meV sensor needs

- Low energy threshold
- Good energy resolution
- High efficiency
- High surface coverage
- Low dark counts
- Compatibility with various substrates

# Low-threshold, pair-breaking superconducting sensors

- Compare semiconductor gap
  - Si (1.14 eV)
  - Ge (0.67 eV)
- to superconducting gap
  - Al (~300 ueV)
  - Hf (~30 ueV)

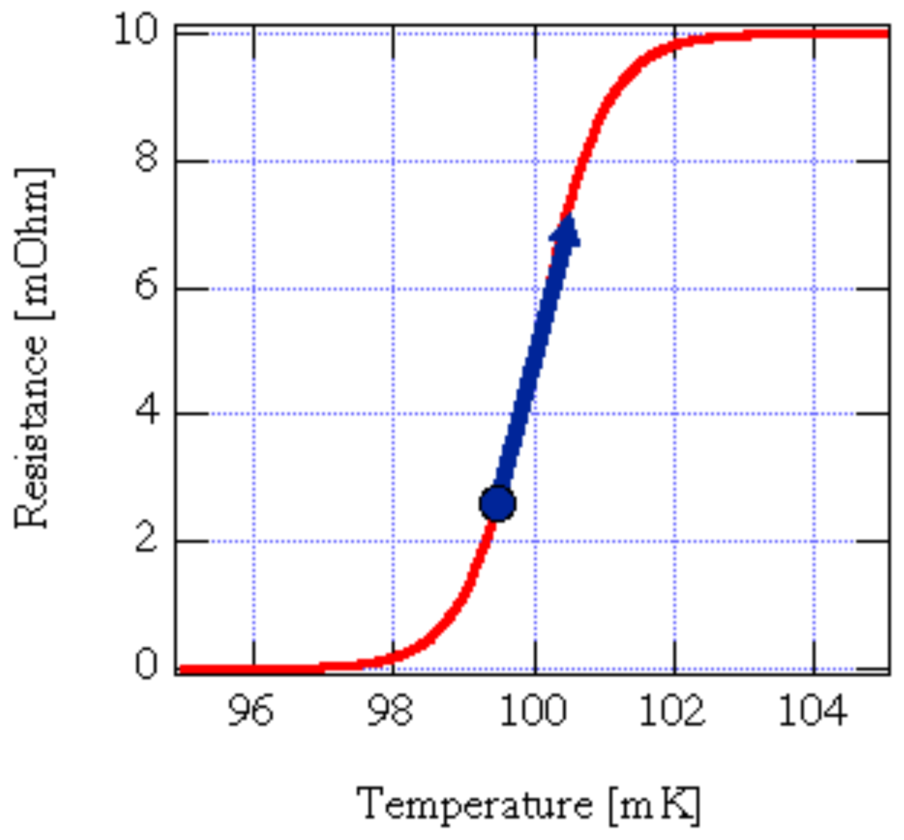
# Low-threshold, pair-breaking superconducting sensors

- Compare semiconductor gap
  - Si (1.14 eV)
  - Ge (0.67 eV)
- to superconducting gap
  - Al (~300 ueV)
  - Hf (~30 ueV)

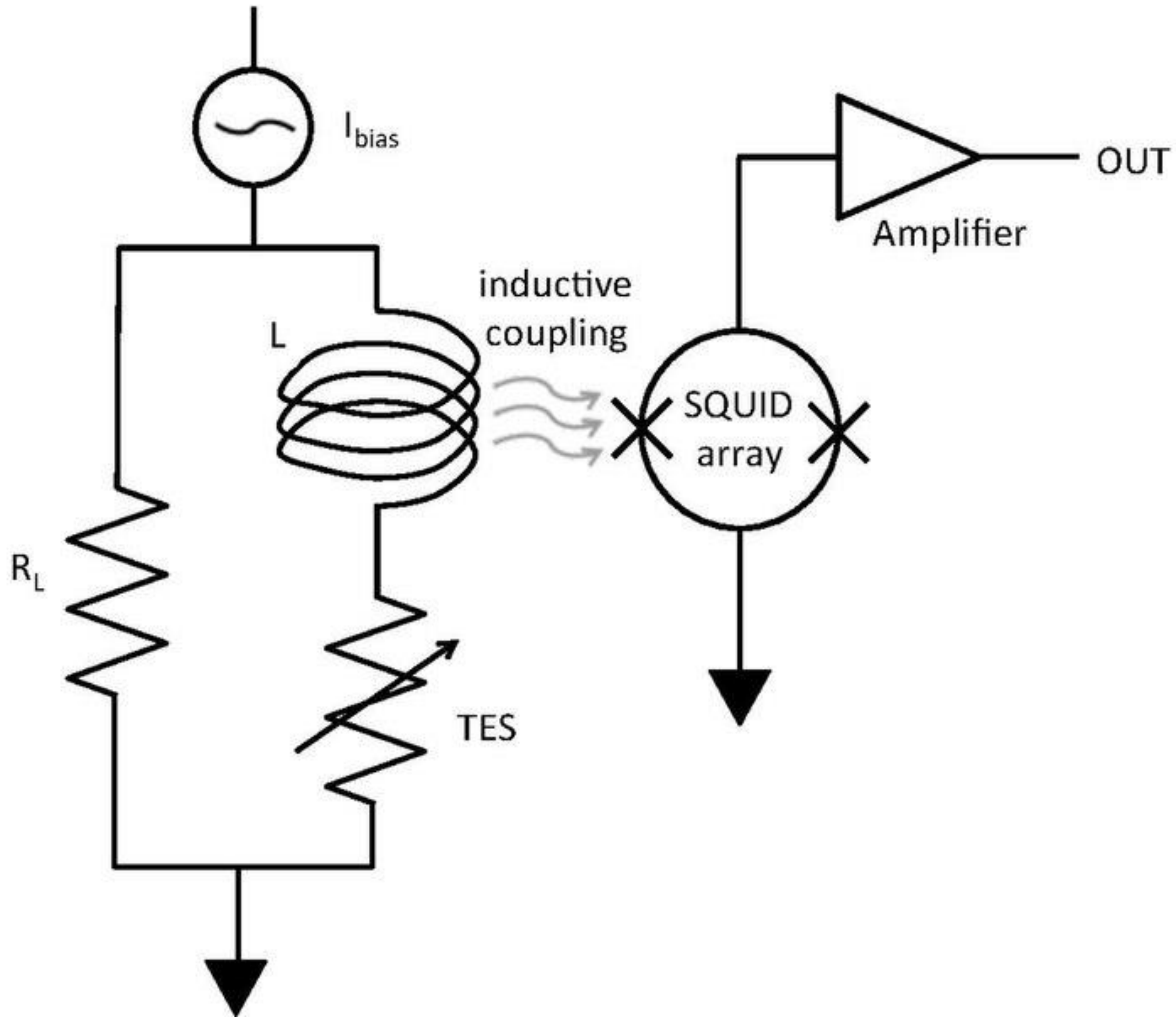
Several methods to exploit this!

# TES (transition edge sensor)

- A highly sensitive bolometer
- Hold a superconductor right at its transition point
- Small amount of heat will create a large change in resistance



# TES operation




- Current bias
- Energy deposition drives TES normal
  - $R_{TES} >> R_L$
- Change in current in TES branch changes flux in coupled SQUID (signal)
- Thermal link removes heat from TES, allowing it to reset (go superconducting)

# More on TESs

- Used in many CMB telescopes
- Lowest demonstrated thresholds in an energy-resolving sensor
- Hard to multiplex
- Resolution improvements limited by critical temperature and making your device smaller (fundamentally a bolometer measuring a heat bath)

$$\Delta E \propto T_c \sqrt{C}$$

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How could we get around the issue of needing to reduce the size?

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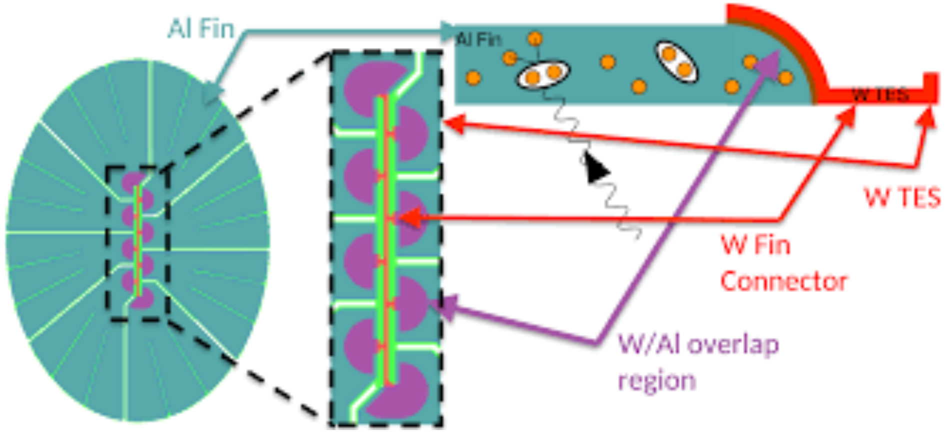
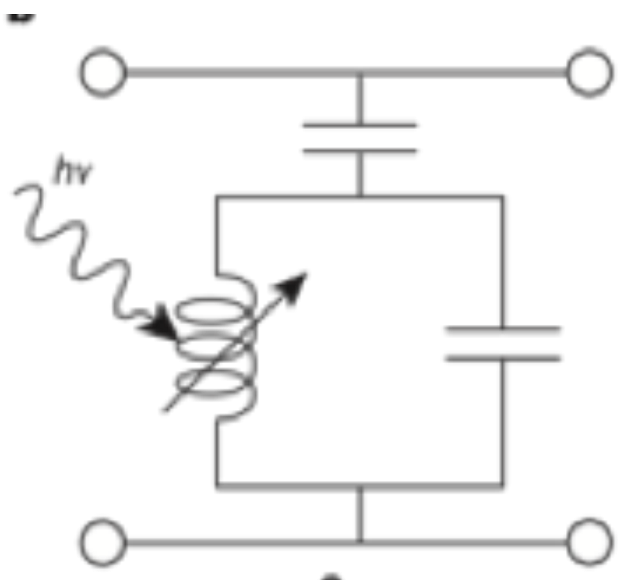
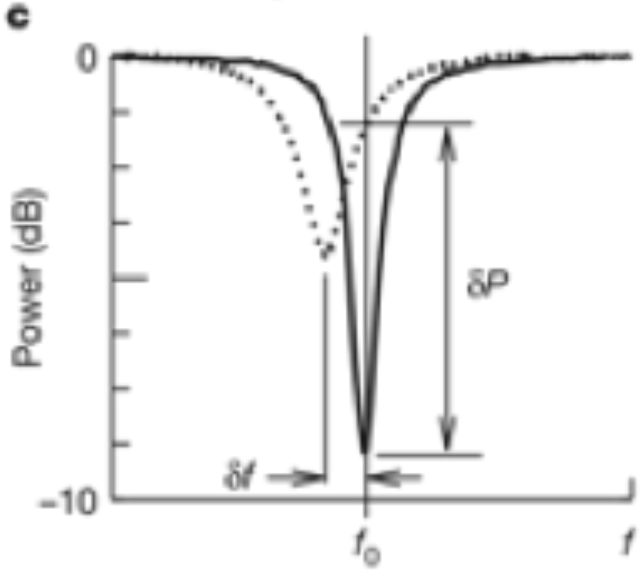



Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensors (QET)

# MKID (microwave kinetic inductance detector)

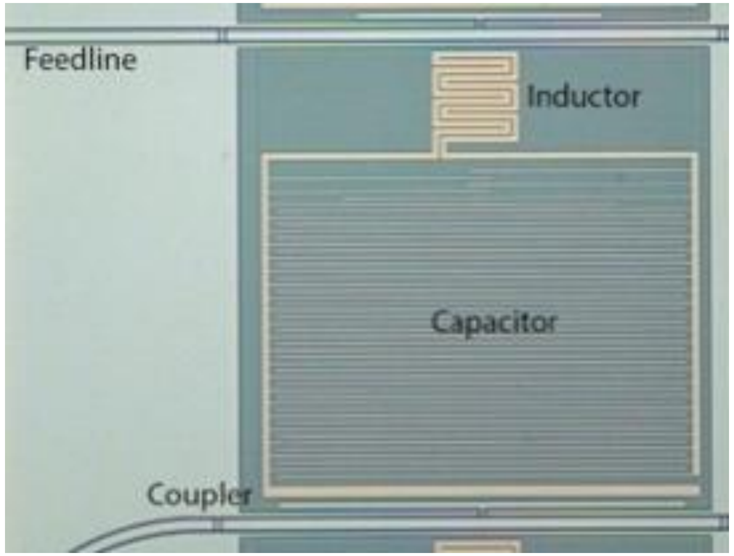
- GHz LC resonator
- Inductor is due to kinetic inductance of charge carriers in narrow line
- Energy deposition changes quasiparticle density in inductor, changing its kinetic inductance
- Change in inductance moves LC resonance frequency and reduces its quality factor

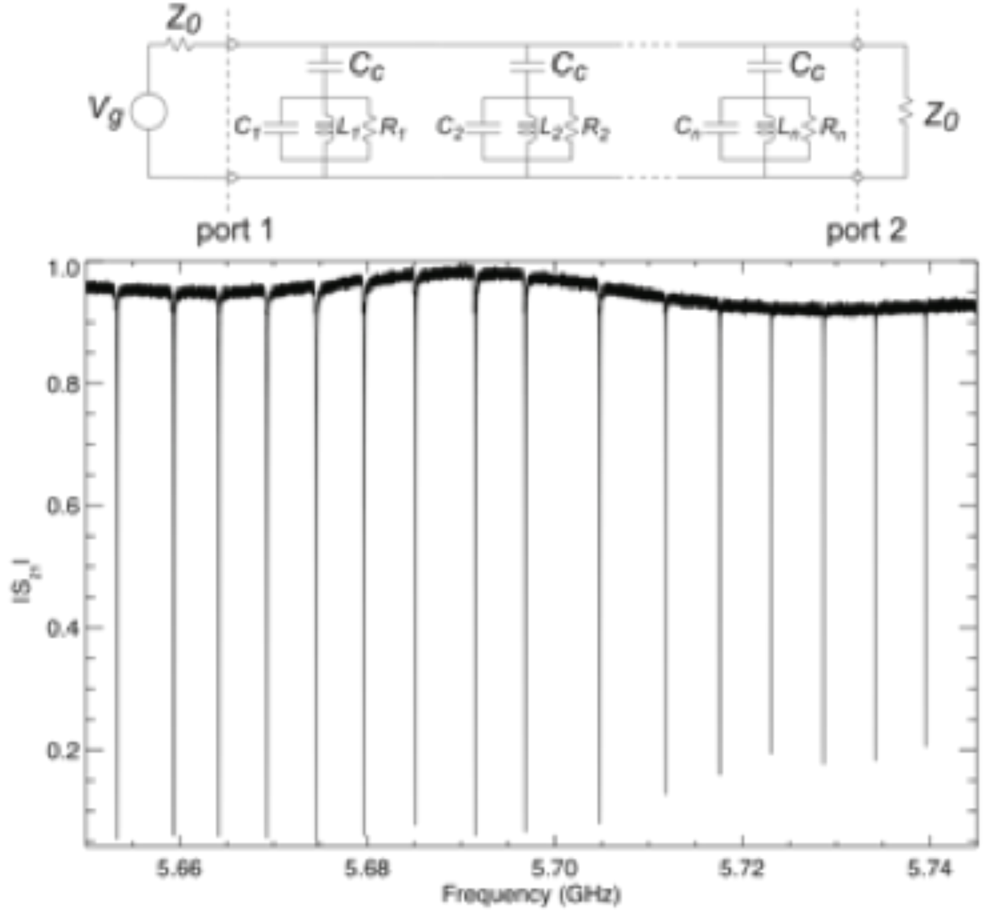


# More on MKIDs

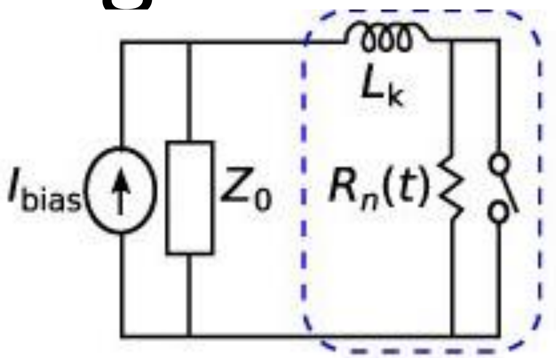
- Easily frequency-multiplexable
- Prone to two-level system noise

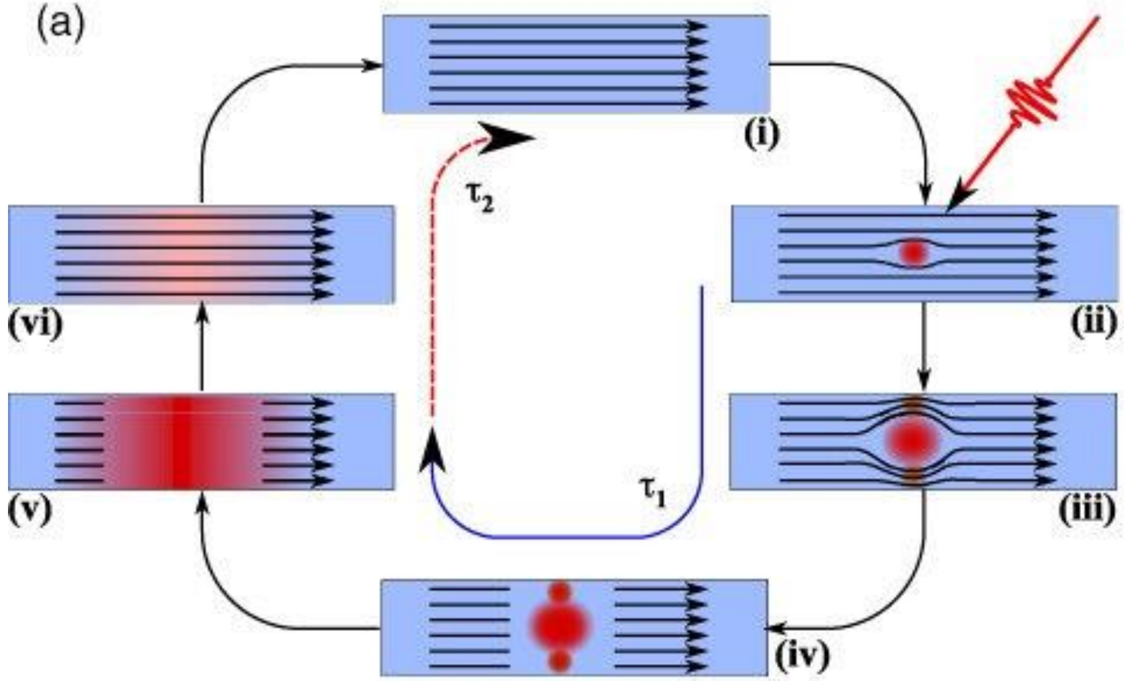


# SNSPD (superconducting nanowire single photon detector)

- Thin superconducting wire, current biased
- Energy deposition creates a normal “hot spot”
- Runaway effect
  - current squeezed into narrower part of wire
  - hot spot grows wider as hot quasiparticles break other Cooper pairs*
  - hot spot spreads to encompass full wire width
- Current flow is interrupted, resetting the heating and returning to superconducting state

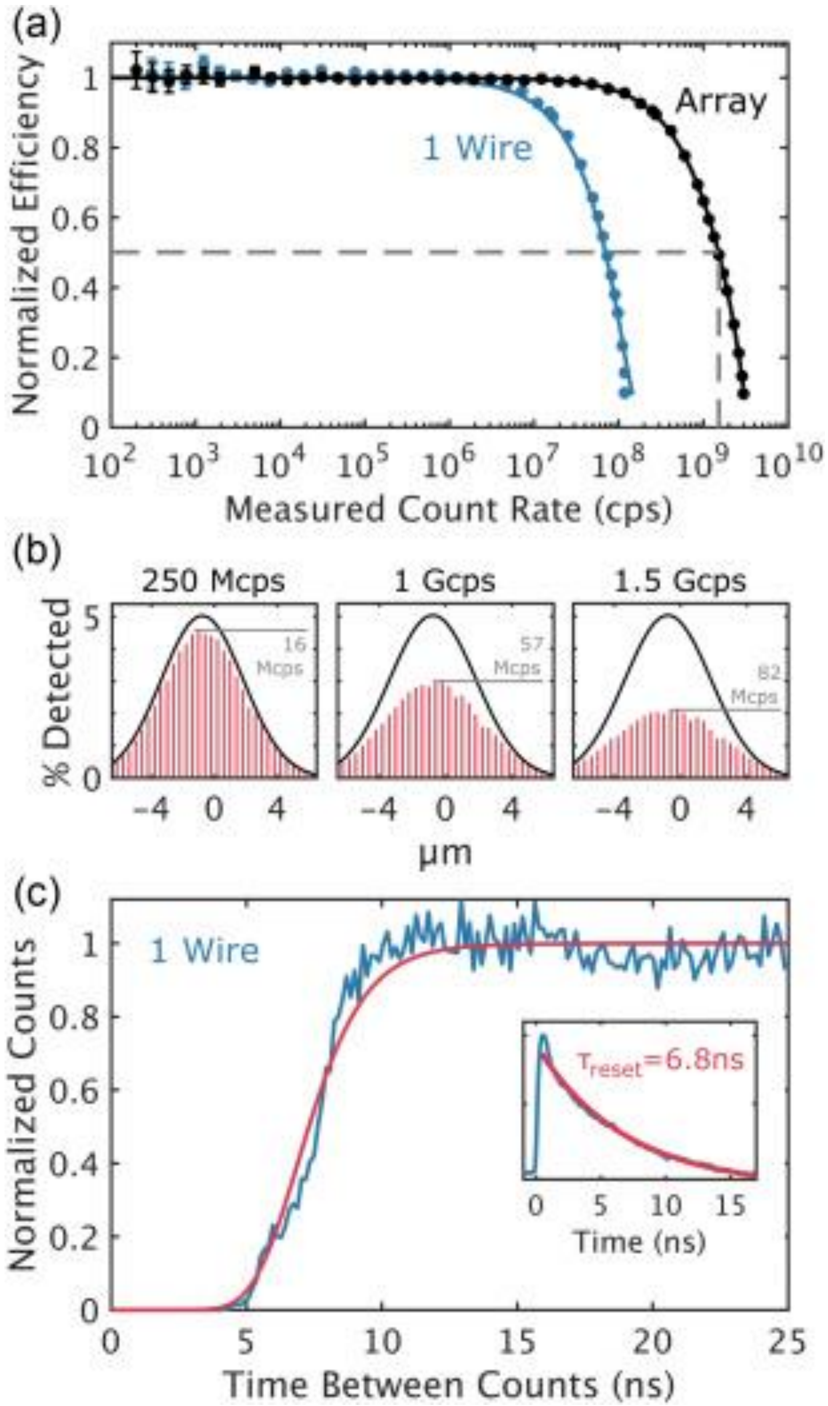



*microphysics of hotspot propagation is under debate

# More on SNSPDs

- Very fast!
  - up to Gcounts/s
  - timing jitter below 50 ps
- No energy resolution
- Limited threshold
  - record: 29 um/10 THz




*Craiciu et al. 2023*

# Qubits

SQUAT – Superconducting Quasiparticle-Amplifying Transmon
QCD – Quantum Capacitance Detector
QPD – Quantum Parity Detector

More on this coming!

- Original device: quantum capacitance detector for counting single 1.5 THz photons
  - lowest threshold achieved in pair-breaking sensor

# Comparison

| Sensor | Photon Energy Threshold ($5\sigma_\gamma$) [meV] | Background Rate [Hz/(eV mm$^2$)] (Energy Range [eV]) | Notes |
|---|---|---|---|
| TES (this work) | 1840 | $3.7 \times 10^{-3}$ (2.3-2.9) | With discrimination |
| TES | 284[b] | | Best demonstrated in our lab |
| TES (leading) | 142[10] | $1.4 \times 10^{-2}$ (0.8-1.5)[36] | Good threshold and backgrounds |
| KID (leading) | 816[10] | 1.41 (1.36-1.48)[34] | Highly multiplexable |
| SNSPD (leading) | 43[39] | $2.7 \times 10^{-5}$ (0.73-5.0)[a][5] | Not energy resolving |
| QCD (leading) | 6.2[20] | $6.2 \times 10^{3}$ (0.006-5.0)[a][20] | Best demonstrated threshold |

[a] No upper limit to energy sensitivity was given in Refs.[5,20]. To normalize the background rate, we arbitrarily choose 5 eV.
[b] Estimated assuming a $\varepsilon_T = 35.1$ % as measured in this work. This device was an improved version of the device we published in Ref.[38].

*Romani et al. 2024*

# Comparison

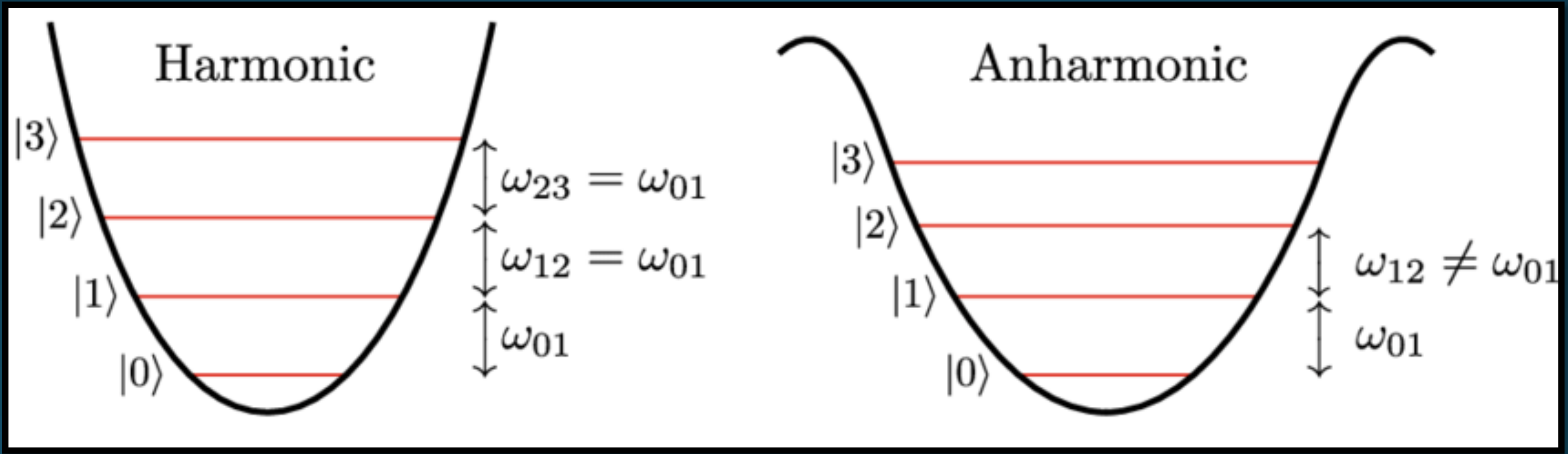
Table 1 Overview of important detector characteristics of the superconducting single-photon detectors introduced in Section 5 and the corresponding requirements for infrared emission experiments as discussed in Section 7.2.1

| Figure of merit | Amorphous SNSPD (WSi, MoSi) | Polycrystalline SNSPD (NbN, NbTiN) | TES | MKID | Requirements for IR emission experiments |
|---|---|---|---|---|---|
| Wavelength range (single-photon sensitivity) | 0.3–10 μm[32,33] | UV – 4 μm[34,35] | <4 μm[36] | <1.55 μm[37] | 2.5–25 μm |
| System detection efficiency | 98% (1550 nm)[38]<br>50%[a] (2–10 μm)[10,33] | 99.5% (1350 nm)[39]<br>98% (1590 nm)[40]<br>70%[b] (2000 nm)[34] | 98% (805 nm)[41]<br>98% (850 nm)[42] | 17%[43] | ≈100% |
| Timing jitter | 10.3 ps (1550 nm)[44]<br>76 ps (1550 nm)[45]<br>150 ps (1550 nm)[46] | 4.3 ps (1500 nm)[47]<br>14.3 ps (2000 nm)[34] | 25 ns (850 nm)[48]<br>4.1 ns (1550 nm)[49] | 1 μs (1550 nm) | 1–100 ps |
| Dark counts (counts $s^{-1}$) | 0.01[32]<br>0.000006[50] | 0.1[51] | 0.06[52]<br>0.0086[53] | — | <0.01–1 |
| Maximum count rate (counts $s^{-1}$) | $10^7$ [45]<br>$1.2 \times 10^9$ (64 pixel array)[54] | $1.5 \times 10^9$ [55] | $10^5$ [53,56] | $2 \times 10^3$ [43] | $10^6$–$10^8$ |
| Number of pixels | 1024[57] | 64[58]<br>590[59] | 36[60] | 2024[43]<br>20 440[61] | — |

*Lau, Vermer, Schwarzer, Wodtke 2023*

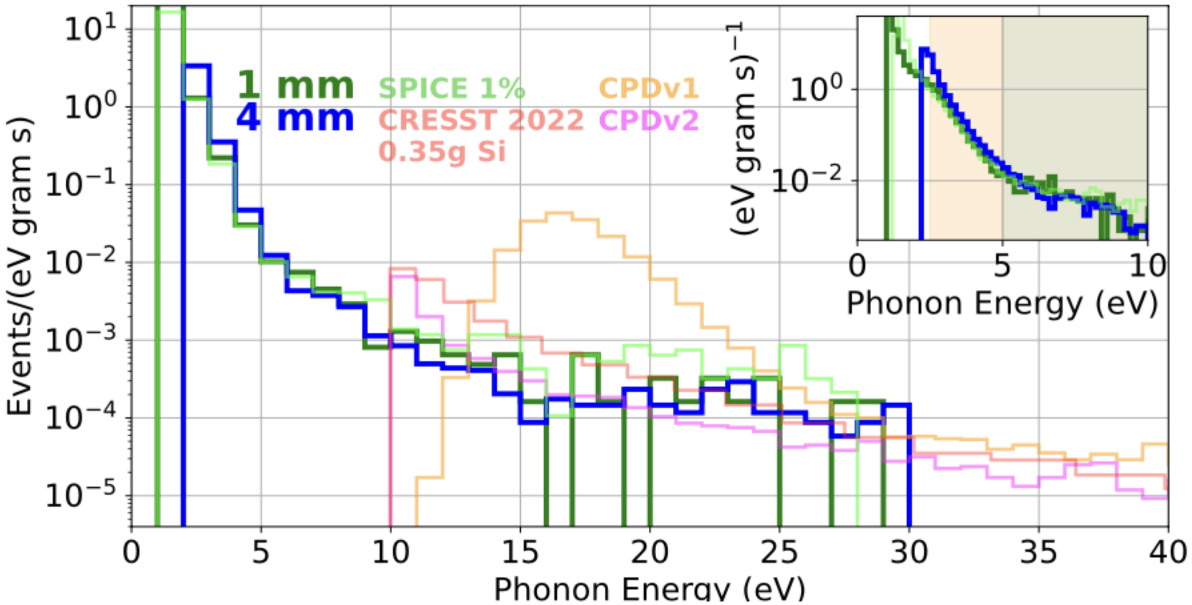
# What is a qubit?

- Two-level system
  - |0> and |1>
- Can achieve in practice with anharmonic oscillator
  - Unequal level spacings



# A problem plaguing low-energy sensors: LEE

- All cryogenic low-threshold sensors see an excess of events at low energies
  - regardless of detector type
- Not dark matter ☺
- Excess seems to decay as a function of time cold



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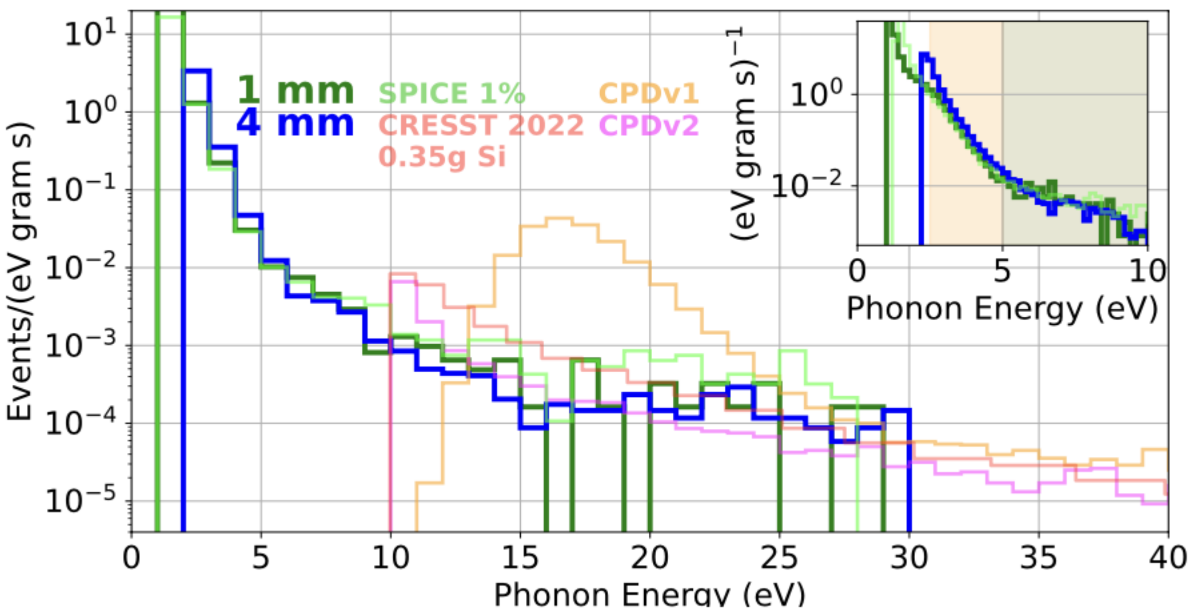


Any ideas what could be causing this?

# A problem plaguing low-energy sensors: LEE

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  - regardless of detector type
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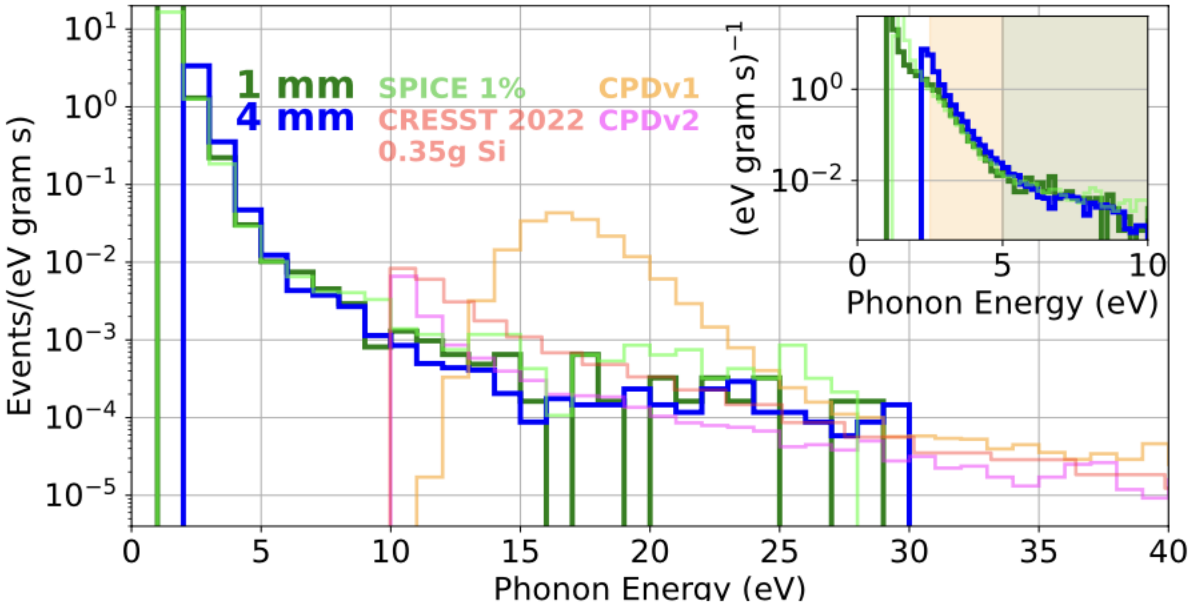
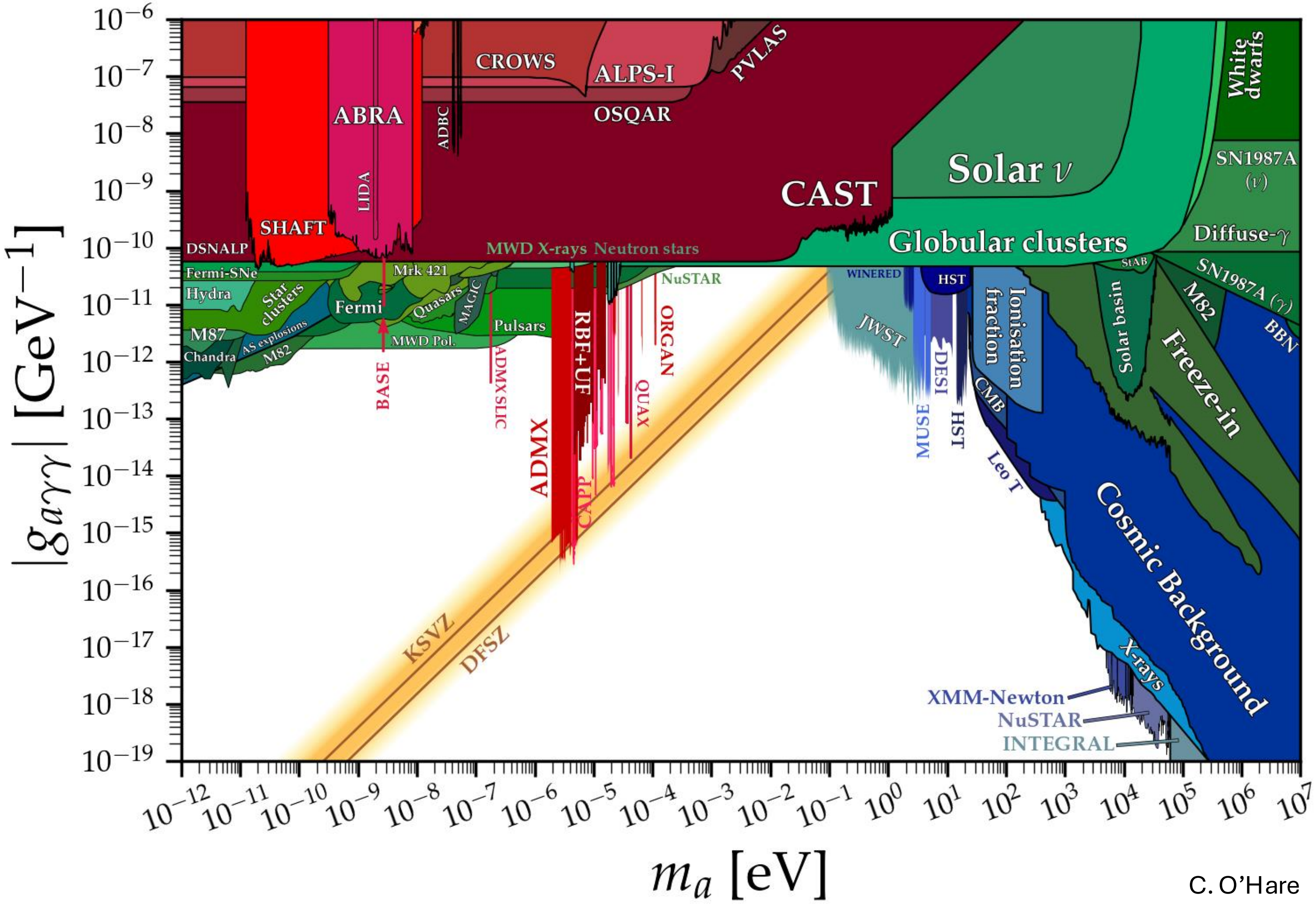
- Excess seems to decay as a function of time cold



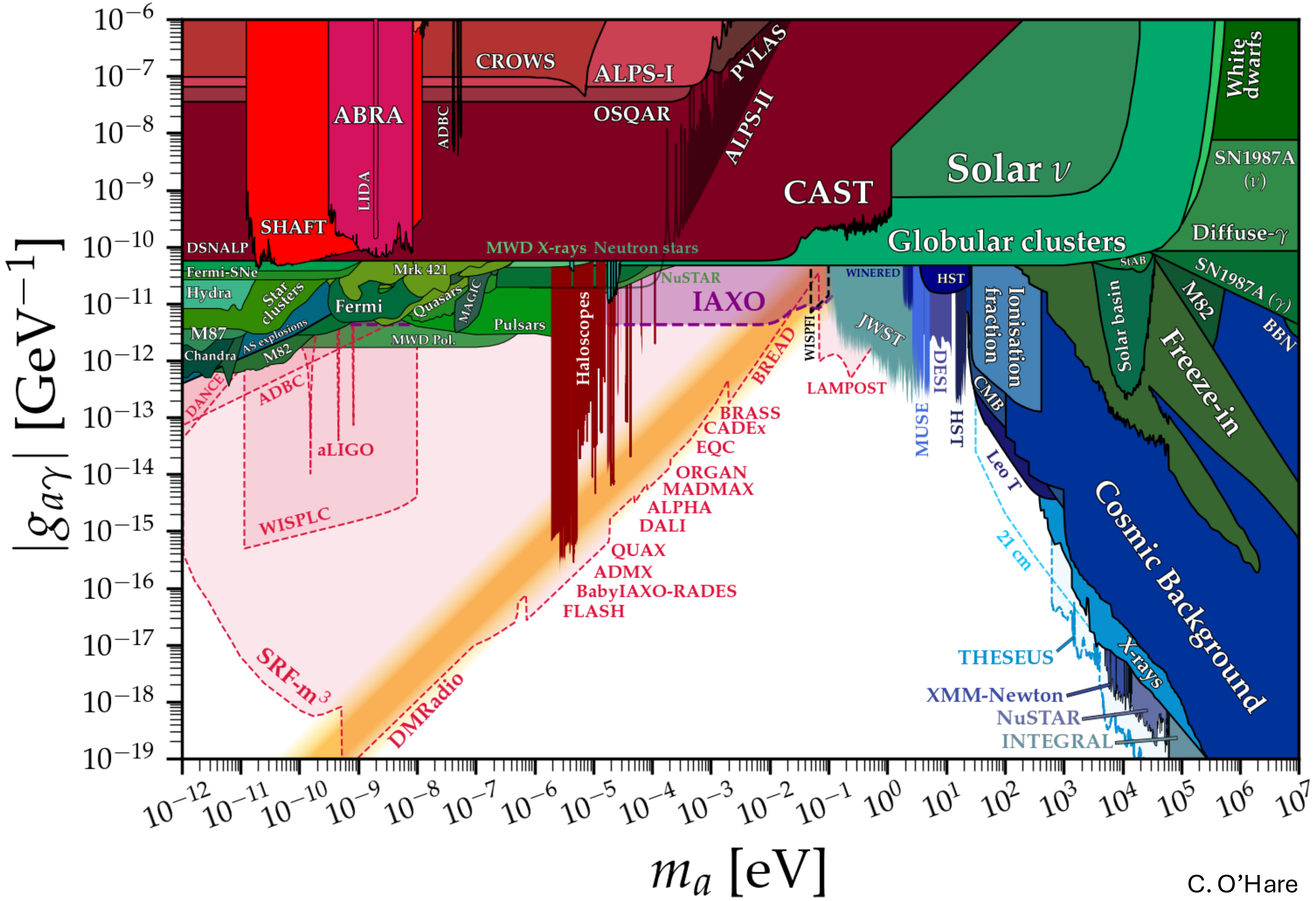

Must be solved if we are going to find high-mass axions or low-mass particle dark matter!

# The current landscape




C. O'Hare

# The future




C. O'Hare