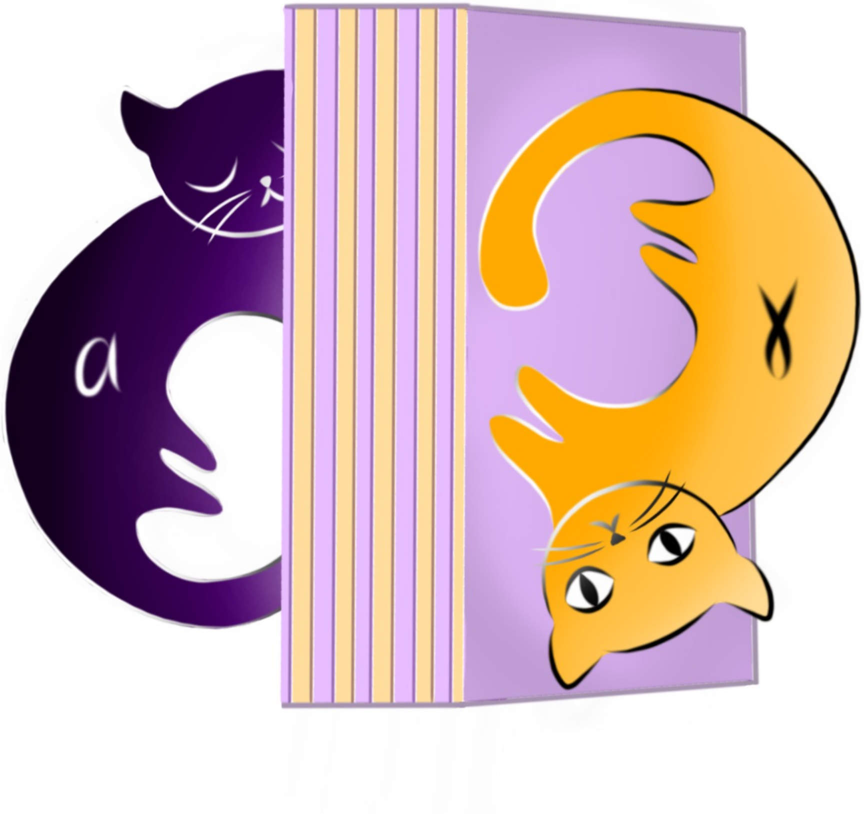
SQWARE-ing the circle

A new strategy to close the meV axion gap

Andrew J. Long
Rice University

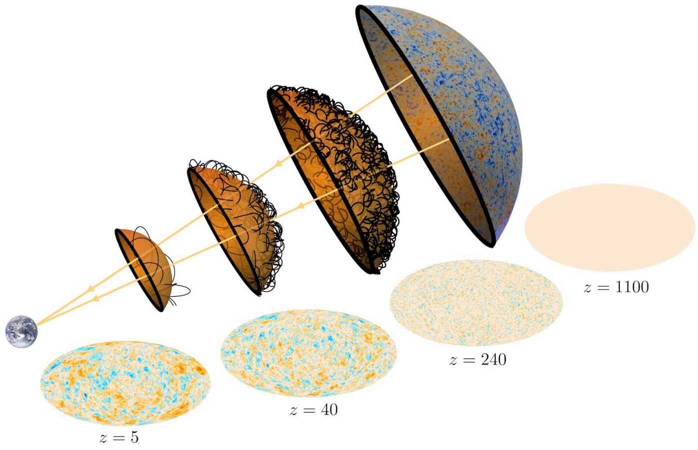
@ Light-Dark World
July 30, 2026

RICE



[https://www.storyberries.com/fairy-tales-goldilocks-and-the-three-bears/]
[illustration: L. Leslie Brooke]

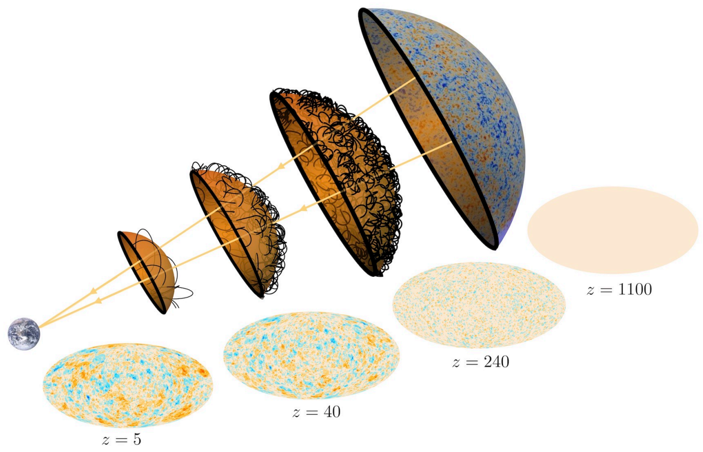
[https://www.storyberries.com/fairy-tales-goldilocks-and-the-three-bears/]
[illustration: L. Leslie Brooke]



this talk is ***too light***

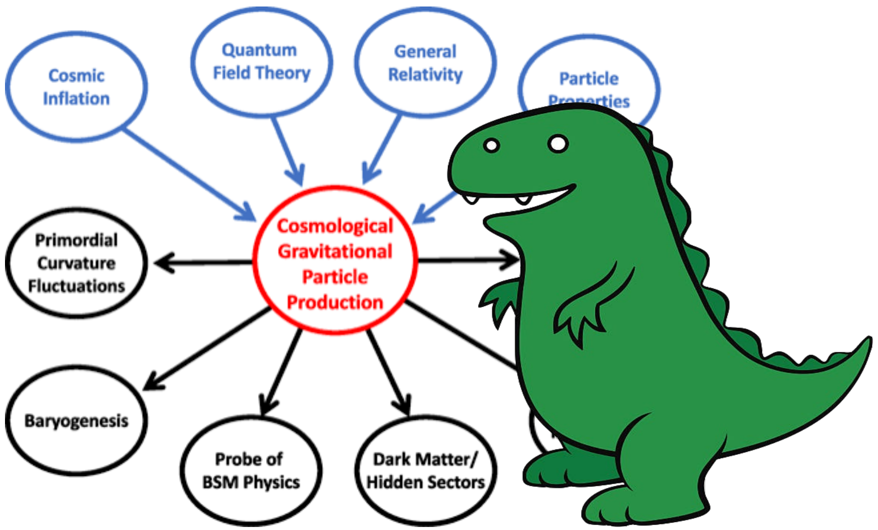
(and not dark enough)

[https://www.storyberries.com/fairy-tales-goldilocks-and-the-three-bears/]
[illustration: L. Leslie Brooke]



this talk is ***too light***

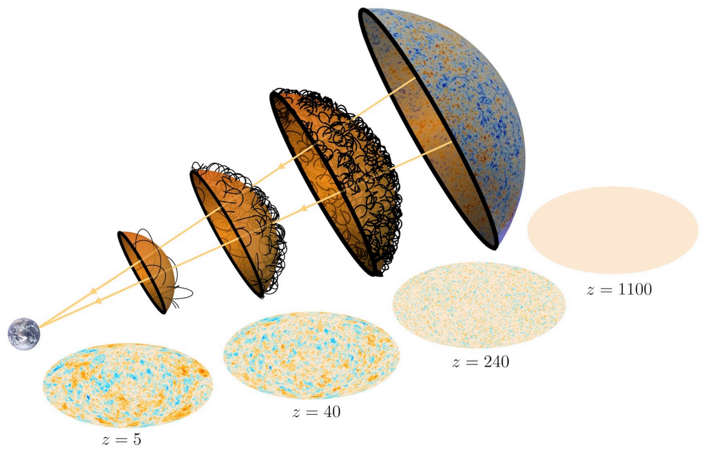
(and not dark enough)



this talk is ***too dark***

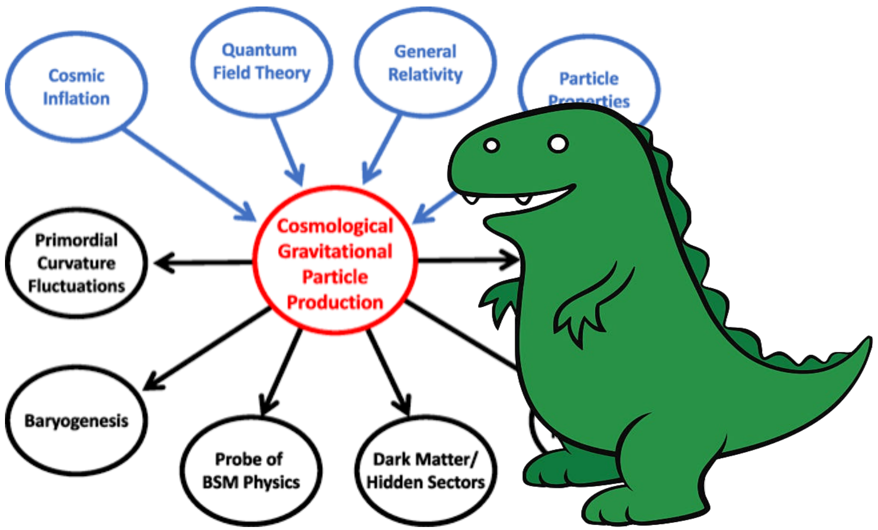
(and way too heavy)

[https://www.storyberries.com/fairy-tales-goldilocks-and-the-three-bears/]
[illustration: L. Leslie Brooke]



this talk is ***too light***

(and not dark enough)



this talk is ***too dark***

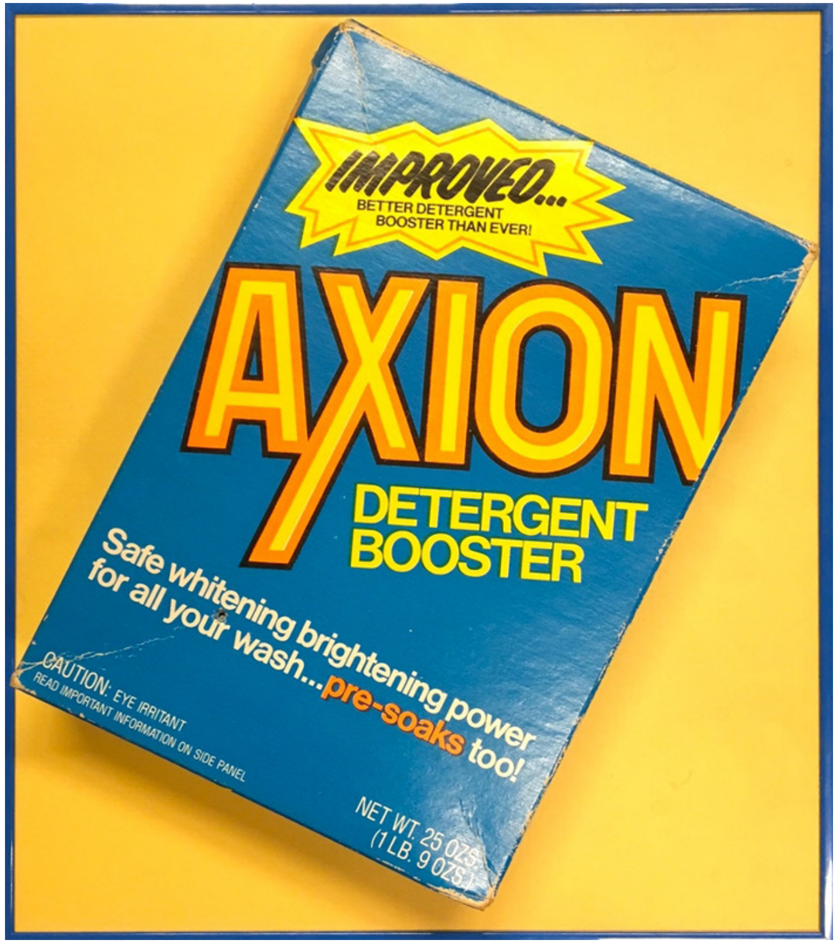
(and way too heavy)

SQWARE

this talk is ***just right***

(meV axion direct detection)

Let’s think about axions



Axion Fact Sheet

~~~~~universal~~~~~

- QUANTUM = boson
- SPIN = 0
- CHARGE = 0
- COLOR = 0

~~~~~model dependent~~~~~

- MASS = ultralight (μeV-meV)
- INTERACTIONS = feeble
  ➔ hard to detect
- LIFETIME = cosmological
  ➔ could be dark matter
- MOTIVATION = it varies
  ➔ strong CP / string axiverse / etc

Let's suppose that axions are dark matter

[https://phys.org/news/2019-05-dark-axions-black-holes-reveal.html
[illustration: ESO / L. Calda]

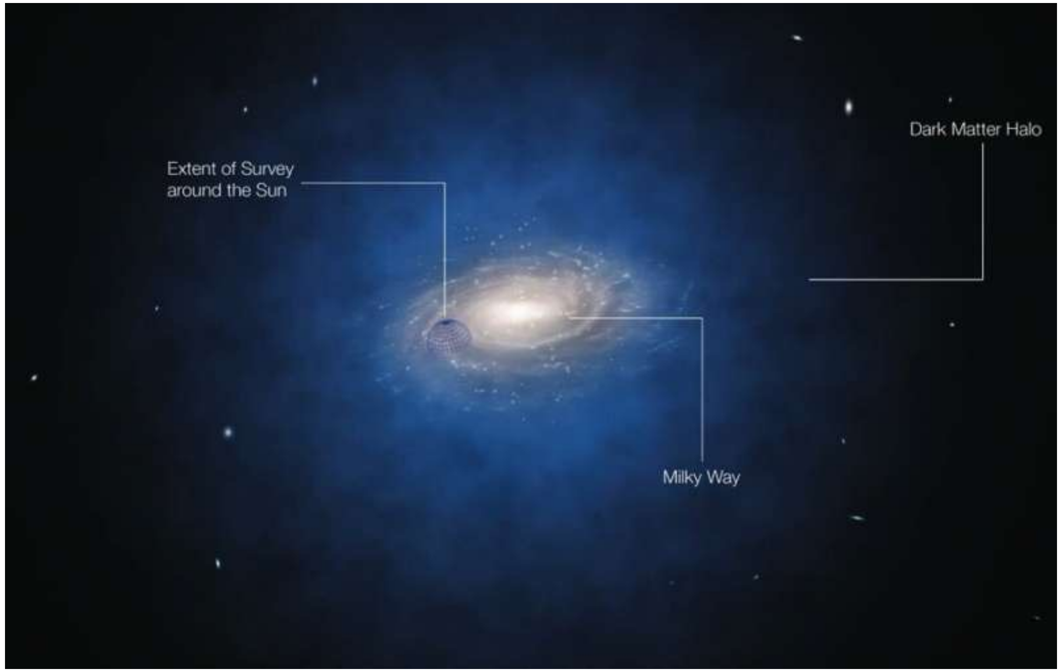
axion dark matter :
by the numbers

$$\rho_{\rm dm} \approx 0.3\,{\rm GeV/cm^3} \quad \text{(near our solar system)}$$

$$n_{\rm dm} \approx \left(0.3\,\mu{\rm m}^{-3}\right)\left(m_{\rm dm}/{\rm meV}\right)^{-1}$$

$$v_{\rm dm} \approx 220\,{\rm km/sec}$$

you hold ~10 trillion meV axions in your hand



modeling non-relativistic DM:
~homogeneous axion field

$$a(\boldsymbol{r}, t) = a_0 \cos(\omega_a t + \varphi_a)$$

$$f_a = \omega_a/2\pi \approx 0.24\,{\rm THz}\,(m_a/{\rm meV})$$

$$a_0 = \sqrt{2\rho_a}/m_a \approx 1.52\,{\rm eV}\,(\rho_a/\rho_{\rm dm})^{1/2}(m_a/{\rm meV})^{-1}$$

$$l_{\rm coh} = 2\pi/m_a v_a \approx 42\,{\rm cm}\,(m_a/{\rm meV})^{-1}(v_a/v_{\rm dm})^{-1}$$

$$t_{\rm coh} = 2\pi/m_a v_a^2 \approx 1.9\,\mu{\rm s}\,(m_a/{\rm meV})^{-1}(v_a/v_{\rm dm})^{-2}$$

For this talk, let's focus on $m_a = 0.5 - 5$ meV.

What makes meV axions so interesting?

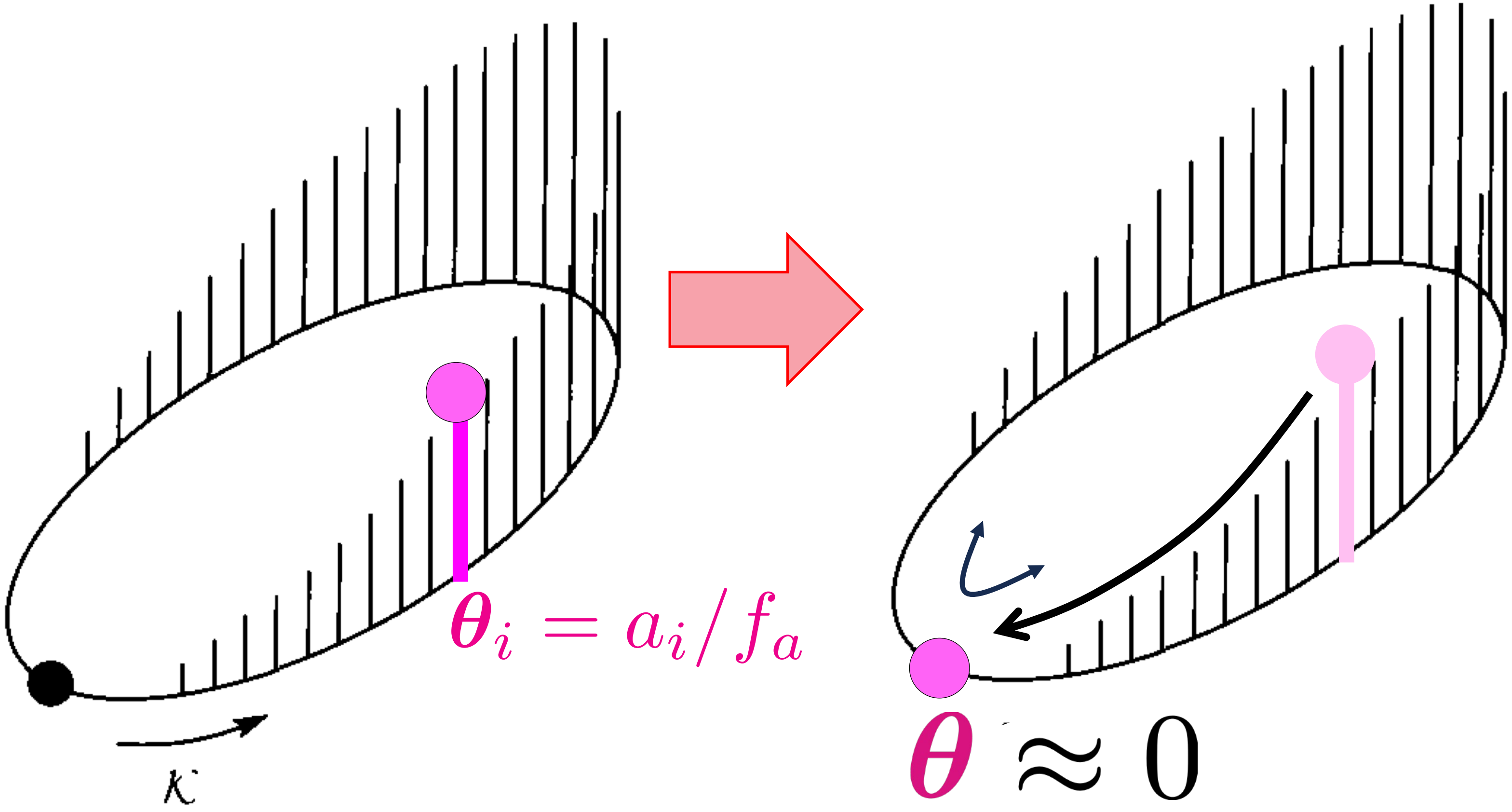
Let's think about production!

Let’s make axions from misalignment

[graphic: Shifman’s book]
[O’Hare review, 2403.17697]

initially away from zero:

relaxes & oscillates around zero:



relic abundance:
(for a QCD axion)

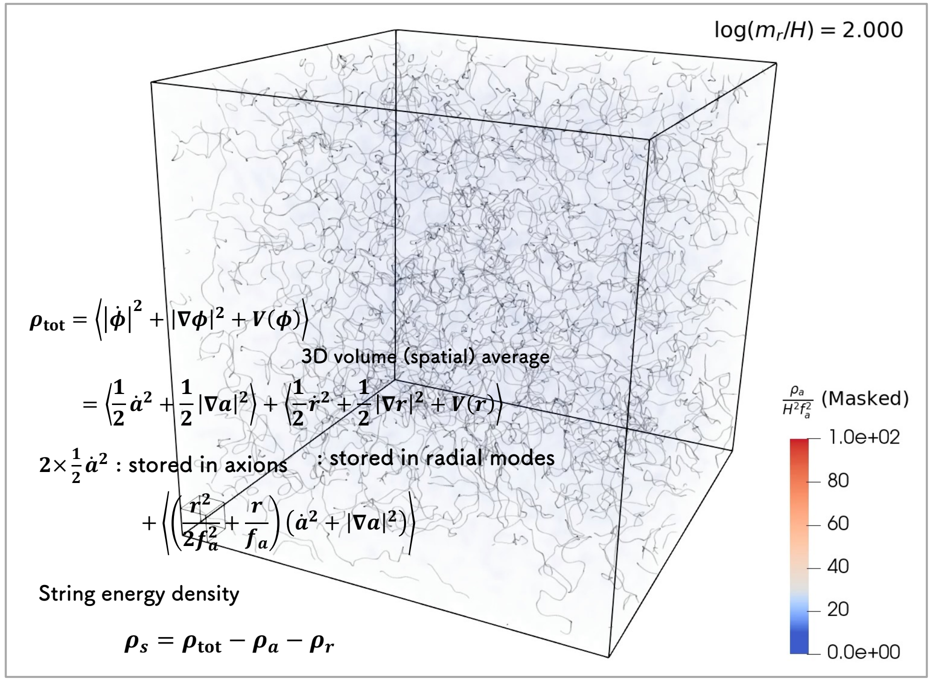
$$\Omega_a h^2 \approx 0.12 \left(\frac{\theta_i}{\pi}\right)^2 \left(\frac{m_a}{0.053\ \mathrm{meV}}\right)^{-7/6}$$

meV-scale mass
=
misalignment production
(nearly) saturates DM

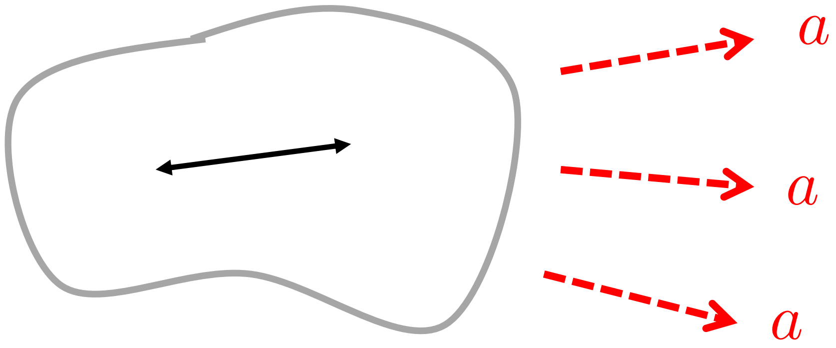
model building = Co, Gonzalez, & Harigaya, 1812.11192
phneo consequences = Arvanitaki et. al. 1909.11665

Let's make axions from defect networks

[graphic: Minho Son, Dark World 2025]
[Kim, Park, Son, 2402.00741]



oscillating loops of axion string are little "antennas" radiating axion particles



$$\Omega_a^{\rm str} h^2 \approx \frac{n_a^{{\rm str},q>1}}{n_a^{{\rm mis},\theta_0=1}} \Omega_a^{{\rm mis},\theta_0=1} h^2 \leq 0.12 \to \begin{cases} m_a \gtrsim 420\ (\mu{\rm eV}) & : \text{ fat-string pre-evolution} \\ m_a \gtrsim 470\ (\mu{\rm eV}) & : \text{ thermal pre-evolution}\ . \end{cases}$$

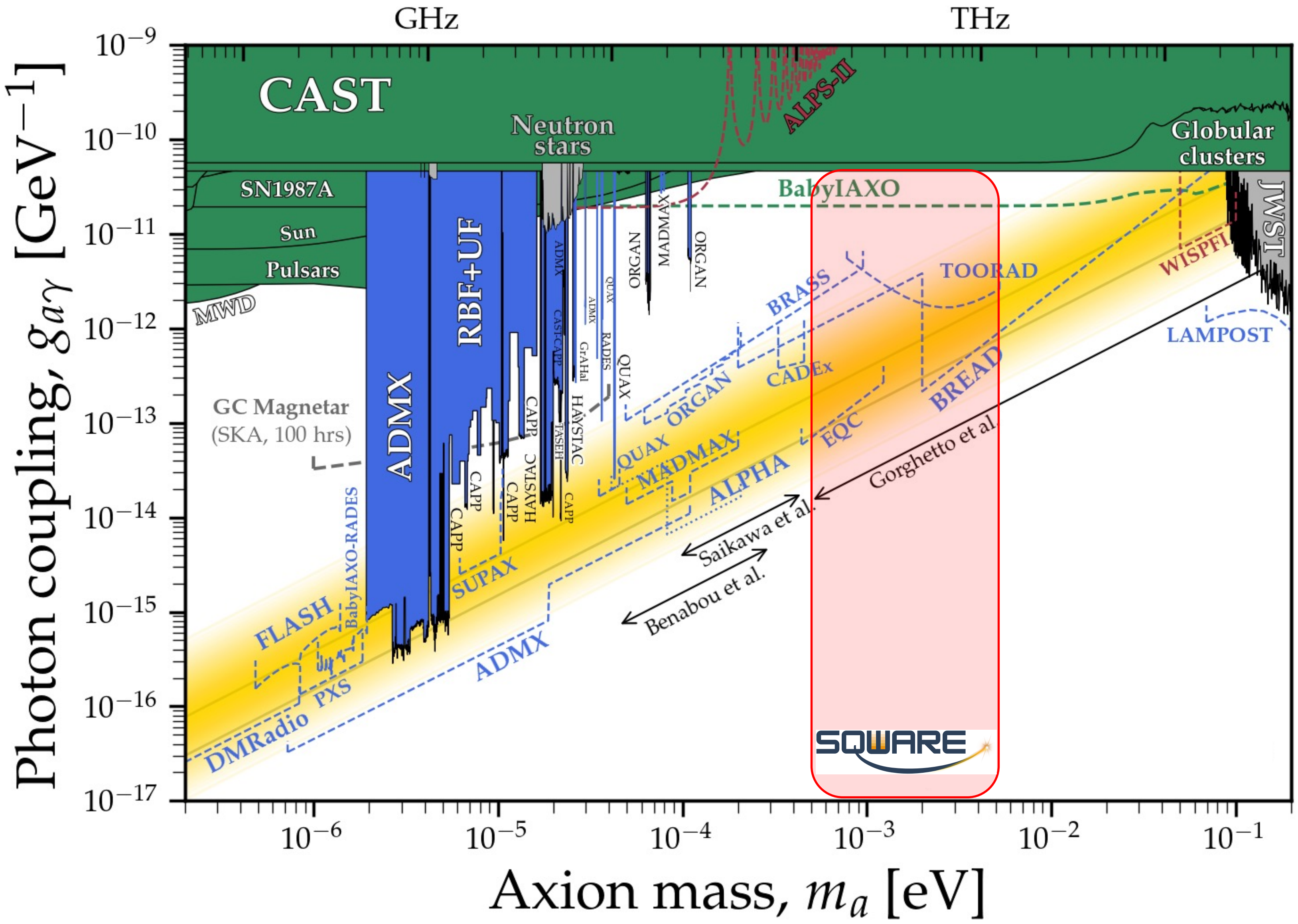
meV-scale mass = axion string production saturates DM

What's the experimental status

of searches for meV axion dark matter?

Let’s look at the big picture

[graphic: Ciran O’Hare]



The meV Gap

there is a lack of coverage to axion dark matter at the meV mass scale

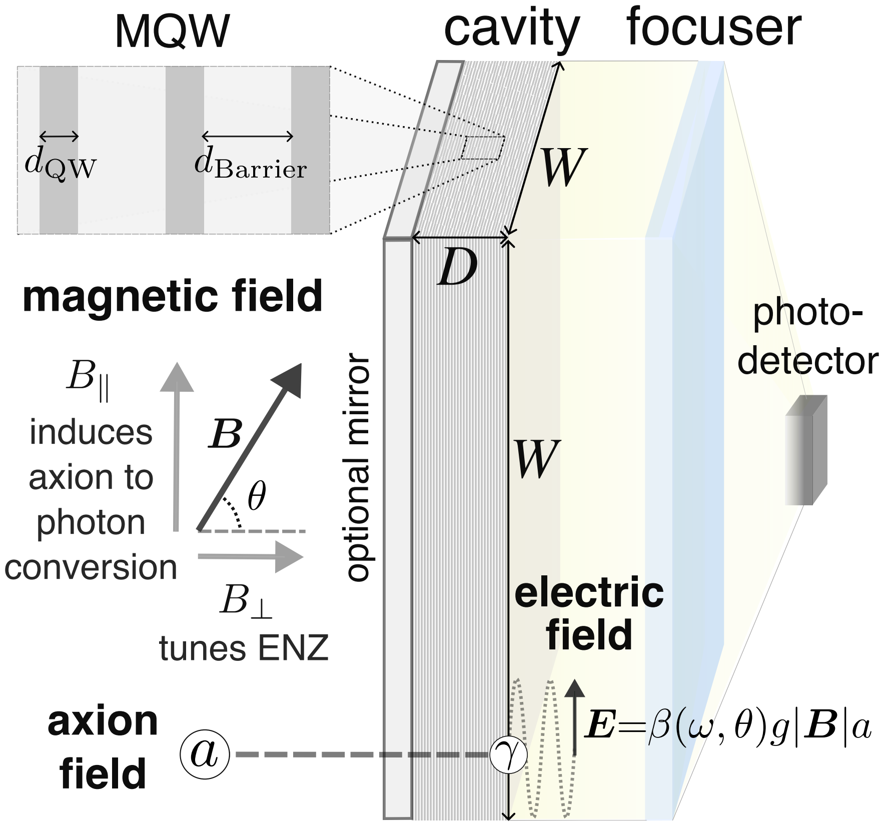
Let's understand why meV is challenging

- **THz photodetection is tough** --- This frequency of EM radiation falls into the gap between detector technologies that optimize for either wave-like or particle-like light
- **THz resonance is tough** --- In general, there is a lack of low-loss, tunable natural THz resonant materials (e.g, phonons, plasmons, etc.).
- **THz tuning is tough** --- Mechanical tuning (needed for scanning across axion masses) is harder to implement at shorter wavelengths.
- **SQWARE's secret ingredient** --- designer ("bespoke") composite material (heterostructure) that allows magnetoplasmonic resonance at THz. Well-studied in the solid state community but new in axions.

Let’s meet the team

[2509.14320 & PRL]

SQWARE



cross-disciplinary collaboration

- ➔ particle physics expertise: AL, Sinha, Xu
- ➔ everybody else are solid state experimentalists

working in Rice’s Smalley-Curl Institute and/or the Rice Center for Quantum Materials

Semiconductor Quantum Well Axion Radiometer Experiment

- ➔ multiple quantum well structure
- ➔ forms magnetoplasmonic cavity
- ➔ vary orientation of applied B-field
- ➔ tunable ENZ point to scan axion masses

So, how does it work?

How are we going to detect
these juicy meV dark axions?

Let's turn the darkness into light

[see talk by Nirmalya Brama (astrophysics)]

assume:
axions interact with electromagnetism

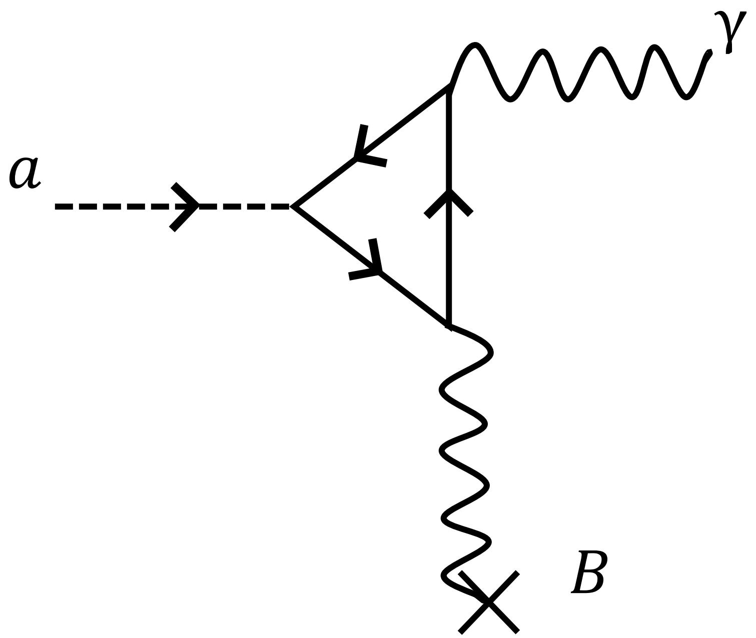
$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

CAST: $g_{a\gamma\gamma} < 0.66 \times 10^{-10}$

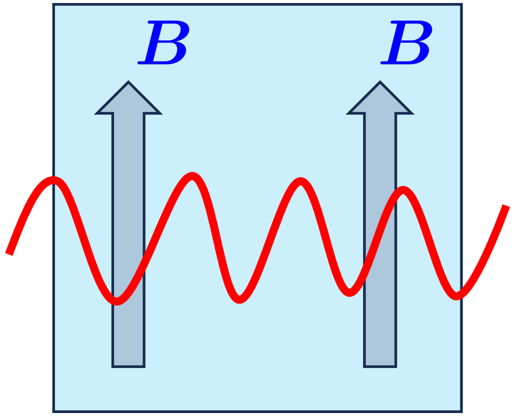
Maxwell's equation:
gets a new "source" term

$$\partial_\mu F^{\mu\nu} = J^\nu - g_{a\gamma\gamma} \tilde{F}^{\mu\nu} \partial_\mu a$$

Inverse Primakoff Effect:
axions convert to photons



Let's estimate the flux



vacuum solution:
assuming a uniform B-field

$$\frac{\partial}{\partial t}\boldsymbol{E}(\boldsymbol{r},t) = -\underbrace{g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial}{\partial t}a}_{\equiv\, \boldsymbol{J}_a(\mathrm{r},t)}$$

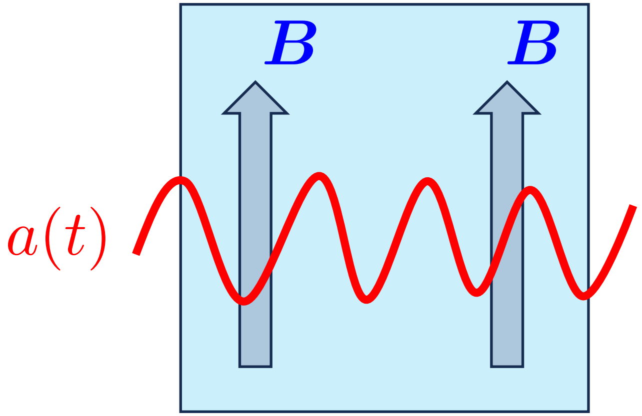
$$\boldsymbol{E}_{\mathrm{ax}} = -\boldsymbol{J}_a/\omega \quad \text{for } \omega = m_a$$

resultant EM radiation:
not very strong .... :(

$$\mathcal{F}_{\mathrm{em}} \approx |\boldsymbol{E}_{\mathrm{ax}}|^2/2\omega$$

$$\mathcal{F}_{\mathrm{em}} \approx (1.7\times 10^{-8}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1})\left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{B}{10\ \mathrm{T}}\right)^2\left(\frac{m_a}{1\ \mathrm{meV}}\right)^{-3}$$

Let's estimate the flux



vacuum solution:
assuming a uniform B-field

$$\frac{\partial}{\partial t}\boldsymbol{E}(\boldsymbol{r},t) = -\underbrace{g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial}{\partial t}a}_{\equiv \boldsymbol{J}_a(\mathrm{r},t)}$$

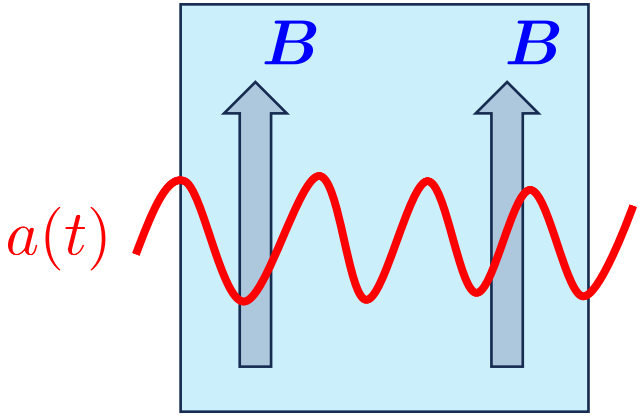
$$\boldsymbol{E}_{\mathrm{ax}} = -\boldsymbol{J}_a/\omega \quad \text{for } \omega = m_a$$

resultant EM radiation:
not very strong .... :(

$$\mathcal{F}_{\mathrm{em}} \approx |\boldsymbol{E}_{\mathrm{ax}}|^2/2\omega$$

$$\mathcal{F}_{\mathrm{em}} \approx (1.7\times10^{-8}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1})\left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{B}{10\ \mathrm{T}}\right)^2\left(\frac{m_a}{1\ \mathrm{meV}}\right)^{-3}$$

Let's not lose hope



vacuum solution:
assuming a uniform B-field

$$\frac{\partial}{\partial t}\boldsymbol{E}(\boldsymbol{r},t) = -\underbrace{g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial}{\partial t}a}_{\equiv \boldsymbol{J}_a(\mathrm{r},t)}$$

$$\boldsymbol{E}_{\mathrm{ax}} = -\boldsymbol{J}_a/\omega \quad \text{for } \omega = m_a$$

$\varepsilon \times$ $\varepsilon^{-1} \times$

Maxwell in a medium:
introduce electric permittivity

resultant EM radiation:
not very strong .... :(

if ε ~ 10^-3 then F_{em} boosted by 10^6!

we want an epsilon-near-zero point

$$\mathcal{F}_{\mathrm{em}} \approx |\boldsymbol{E}_{\mathrm{ax}}|^2/2\omega$$

$$\mathcal{F}_{\mathrm{em}} \approx (1.7\times 10^{-8}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1})\left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{B}{10\ \mathrm{T}}\right)^2\left(\frac{m_a}{1\ \mathrm{meV}}\right)^{-3}$$

$\varepsilon^{-2} \times$ $\varepsilon^{-2} \times$

Let’s think about EM in a material

[emotional support equations]

electromagnetism in materials:
in-medium Maxwell equations

$$\boldsymbol{\nabla} \times \mathbf{H} - \dot{\mathbf{D}} - \mathbf{J}_{\text{free}} = g_{a\gamma\gamma} \mathbf{B} \dot{a} - g_{a\gamma\gamma} \mathbf{E} \times \boldsymbol{\nabla} a$$

Let's think about EM in a material

[emotional support equations]

electromagnetism in materials:
in-medium Maxwell equations

$$\boldsymbol{\nabla} \times \mathbf{H} - \dot{\mathbf{D}} - \mathbf{J}_{\text{free}} = g_{a\gamma\gamma}\mathbf{B}\dot{a} - g_{a\gamma\gamma}\mathbf{E} \times \boldsymbol{\nabla} a$$

linear response theory:
dielectric permittivity tensor

$$\hat{\mathbf{D}} = \left(\mathbb{I} + \hat{\chi}\right) \hat{\mathbf{E}}\ , \quad \text{and} \quad \hat{\mathbf{J}}_{\text{free}} = \hat{\sigma}\, \hat{\mathbf{E}}$$

$$\omega\hat{\mathbf{D}} + i\hat{\mathbf{J}}_{\text{free}} = \omega\hat{\varepsilon}\hat{\mathbf{E}} \quad \text{with} \quad \hat{\varepsilon} = \mathbb{I} + \hat{\chi} + \frac{i}{\omega}\,\hat{\sigma}$$

Let's think about EM in a material

[emotional support equations]

electromagnetism in materials:
in-medium Maxwell equations

$$\boldsymbol{\nabla} \times \mathbf{H} - \dot{\mathbf{D}} - \mathbf{J}_{\text{free}} = g_{\text{a}\gamma\gamma} \mathbf{B} \dot{a} - g_{\text{a}\gamma\gamma} \mathbf{E} \times \boldsymbol{\nabla} a$$

linear response theory:
dielectric permittivity tensor

$$\hat{\mathbf{D}} = \left(\mathbb{I} + \hat{\chi}\right) \hat{\mathbf{E}} \, , \quad \text{and} \quad \hat{\mathbf{J}}_{\text{free}} = \hat{\sigma} \, \hat{\mathbf{E}}$$

$$\omega \hat{\mathbf{D}} + i \hat{\mathbf{J}}_{\text{free}} = \omega \hat{\varepsilon} \hat{\mathbf{E}} \quad \text{with} \quad \hat{\varepsilon} = \mathbb{I} + \hat{\chi} + \frac{i}{\omega} \hat{\sigma}$$

axion dark matter sources radiation
enhanced at small epsilon

$$\omega \hat{\varepsilon} \, \hat{\mathbf{E}} = - g_{\text{a}\gamma\gamma} \mathbf{B}_{\text{ext}} m_{\text{a}} a_0 (2\pi)^4 \delta(\omega - m_{\text{a}}) \delta(\boldsymbol{k})$$

axion-induced electric field:

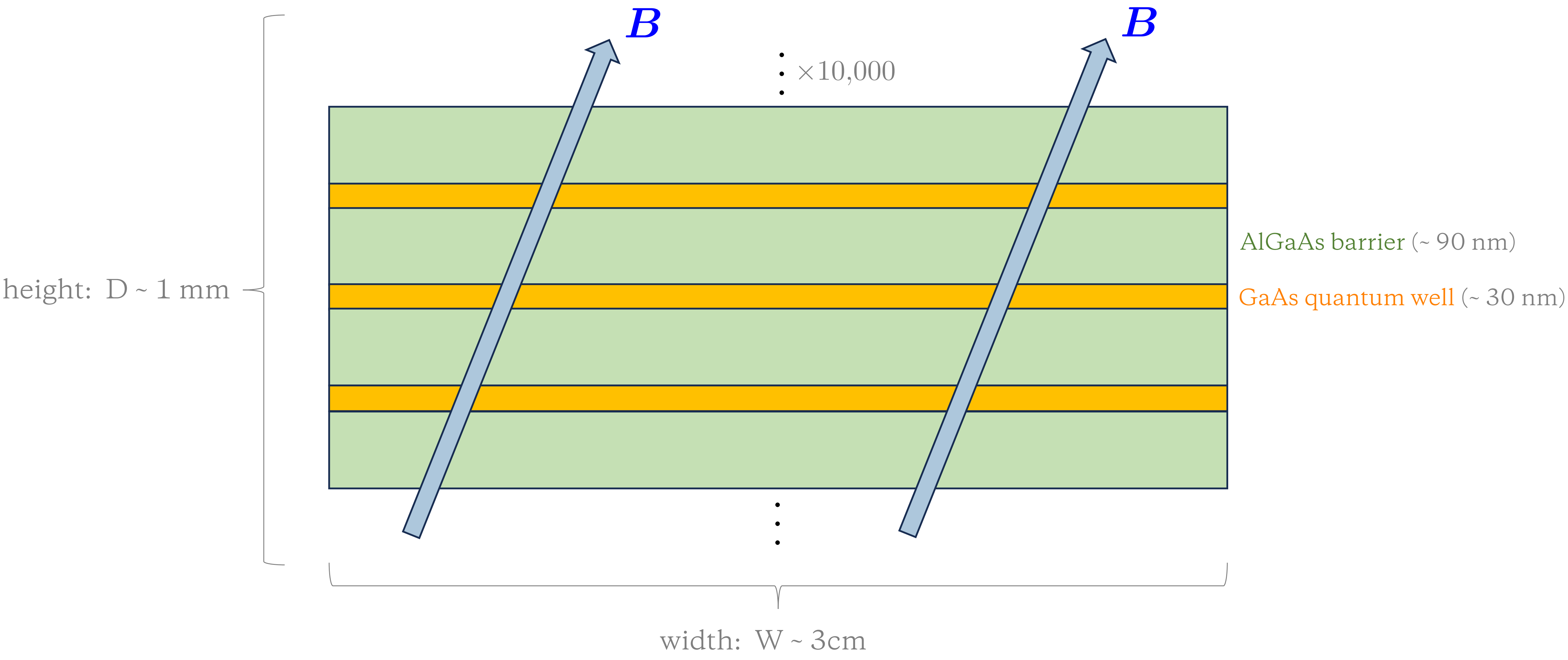
$$\mathbf{E}_{\text{ax}}(\mathbf{r}, t) = - g_{\text{a}\gamma\gamma} a_0 \hat{\varepsilon}^{-1}(\mathbf{0}, m_{\text{a}}) \mathbf{B}_{\text{ext}} \, e^{-i m_{\text{a}} t}$$

enhanced at small epsilon

What kinds of materials allow epsilon-near-zero (ENZ) points?

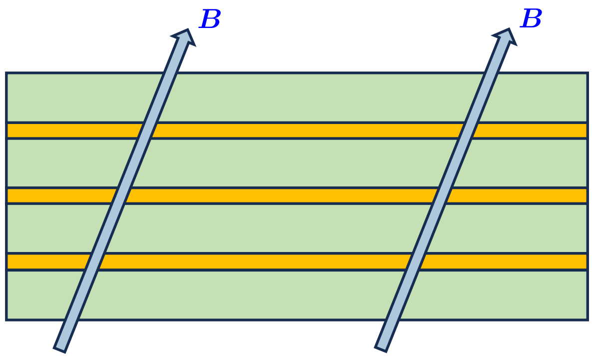
How can we tune the ENZ frequency to scan over axion mass?

Let's think about a stack of multiple quantum wells



Let's think about a stack of multiple quantum wells

[emotional support equations]

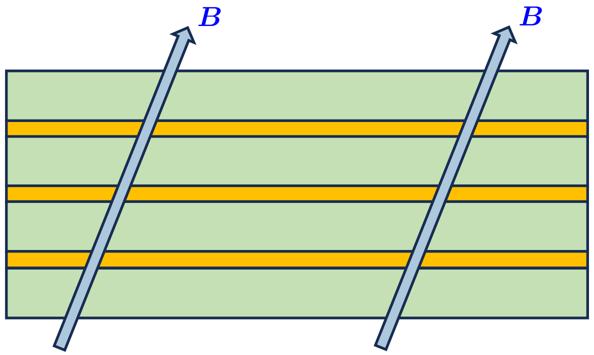


average electric permittivity:
from effective medium theory (EMT)

$$\underbrace{\varepsilon_{\mathrm{MQW}}}_{\sim 0} \approx \frac{\underbrace{\varepsilon_{\mathrm{QW}}}_{<0}\, d_{\mathrm{QW}} + \underbrace{\varepsilon_{\mathrm{Barrier}}}_{>0}\, d_{\mathrm{Barrier}}}{d_{\mathrm{QW}} + d_{\mathrm{Barrier}}}$$

Let's think about a stack of multiple quantum wells

[emotional support equations]



average electric permittivity:
from effective medium theory (EMT)

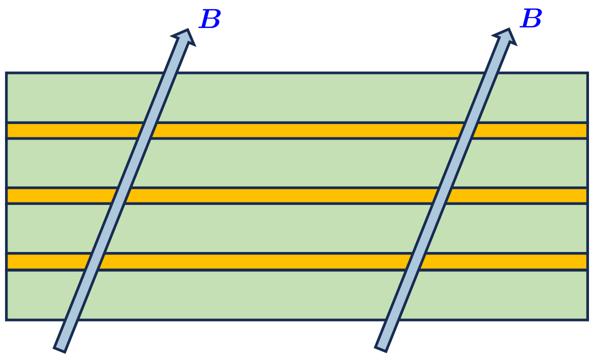
$$\underbrace{\varepsilon_{\mathrm{MQW}}}_{\sim 0} \approx \frac{\overbrace{\varepsilon_{\mathrm{QW}}}^{<0}\, d_{\mathrm{QW}} + \overbrace{\varepsilon_{\mathrm{Barrier}}}^{>0}\, d_{\mathrm{Barrier}}}{d_{\mathrm{QW}} + d_{\mathrm{Barrier}}}$$

for the barrier layers:
well-measured at THz

$$\varepsilon_{\mathrm{Barrier}} \approx 10.6929$$

Let's think about a stack of multiple quantum wells

[emotional support equations]



average electric permittivity:
from effective medium theory (EMT)

$$\varepsilon_{\rm MQW} \approx \frac{\varepsilon_{\rm QW}\, d_{\rm QW} + \varepsilon_{\rm Barrier}\, d_{\rm Barrier}}{d_{\rm QW} + d_{\rm Barrier}}$$

~ 0 < 0 > 0

for the barrier layers:
well-measured at THz

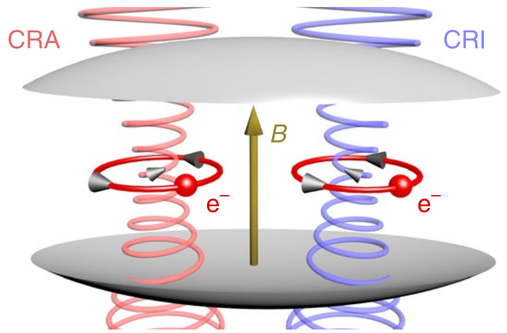
$$\varepsilon_{\rm Barrier} \approx 10.6929$$

for the QW layers:
electron motion restricted to 2D

$$\hat{\varepsilon} = \mathrm{diag}(\varepsilon_{\rm CRA},\ \varepsilon_{\rm CRI},\ \varepsilon_{\perp})$$

(circular polarization basis)

$$\varepsilon_{\rm CRI} = \varepsilon_{\rm bg} + \frac{\mathrm{i}}{\omega}\frac{n_e e^2 \tau / m^*}{1 - \mathrm{i}(\omega - \omega_c)\tau}$$



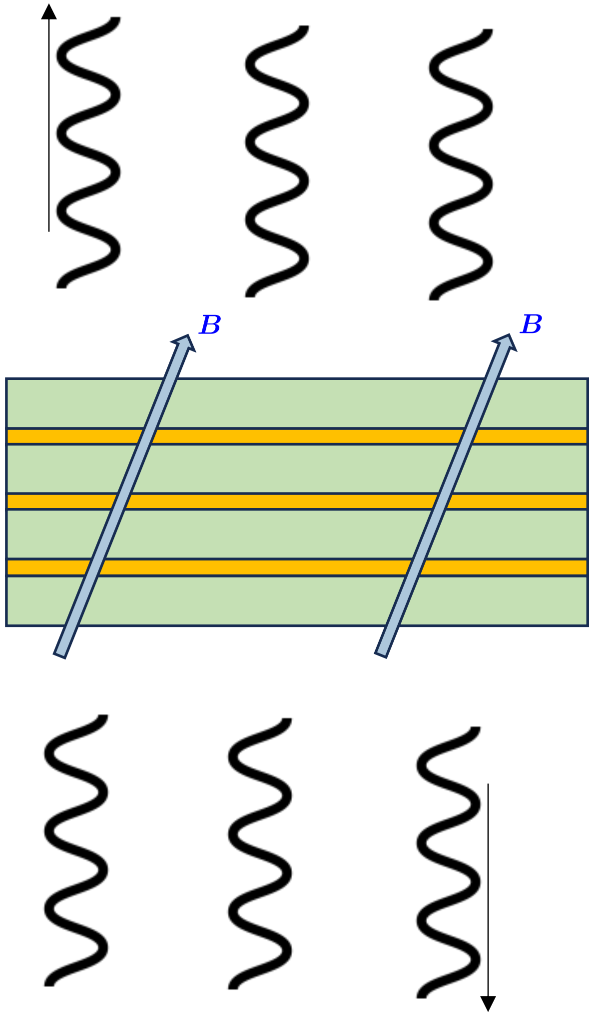
cyclotron frequency:
tune with B-field orientation

$$\omega_c = e|\boldsymbol{B}_{{\rm ext},\perp}|/m^* \approx (0.063\,\mathrm{eV})(B/36\,\mathrm{T})\cos\theta$$

$m^* \approx 0.034\,\mathrm{MeV}$

Let's think about a stack of multiple quantum wells

[Millar, Redondo, Steffen (2017)]



E-field enhancement factor:
for radiation coming out of the MQW

$$\beta = \frac{\|\mathbf{E}_{\rm prop}\|}{E_{\rm vac}} = \frac{\sin\theta}{\sqrt{2}} \left| \frac{1}{\varepsilon_{\rm MQW,CRI}} - 1 \right| \left| 1 + \frac{\rm i}{\sqrt{\varepsilon_{\rm MQW,CRI}}} \cot\frac{\Delta}{2} \right|^{-1}$$

$$\Delta = 2\pi D / \lambda_{\rm med}$$

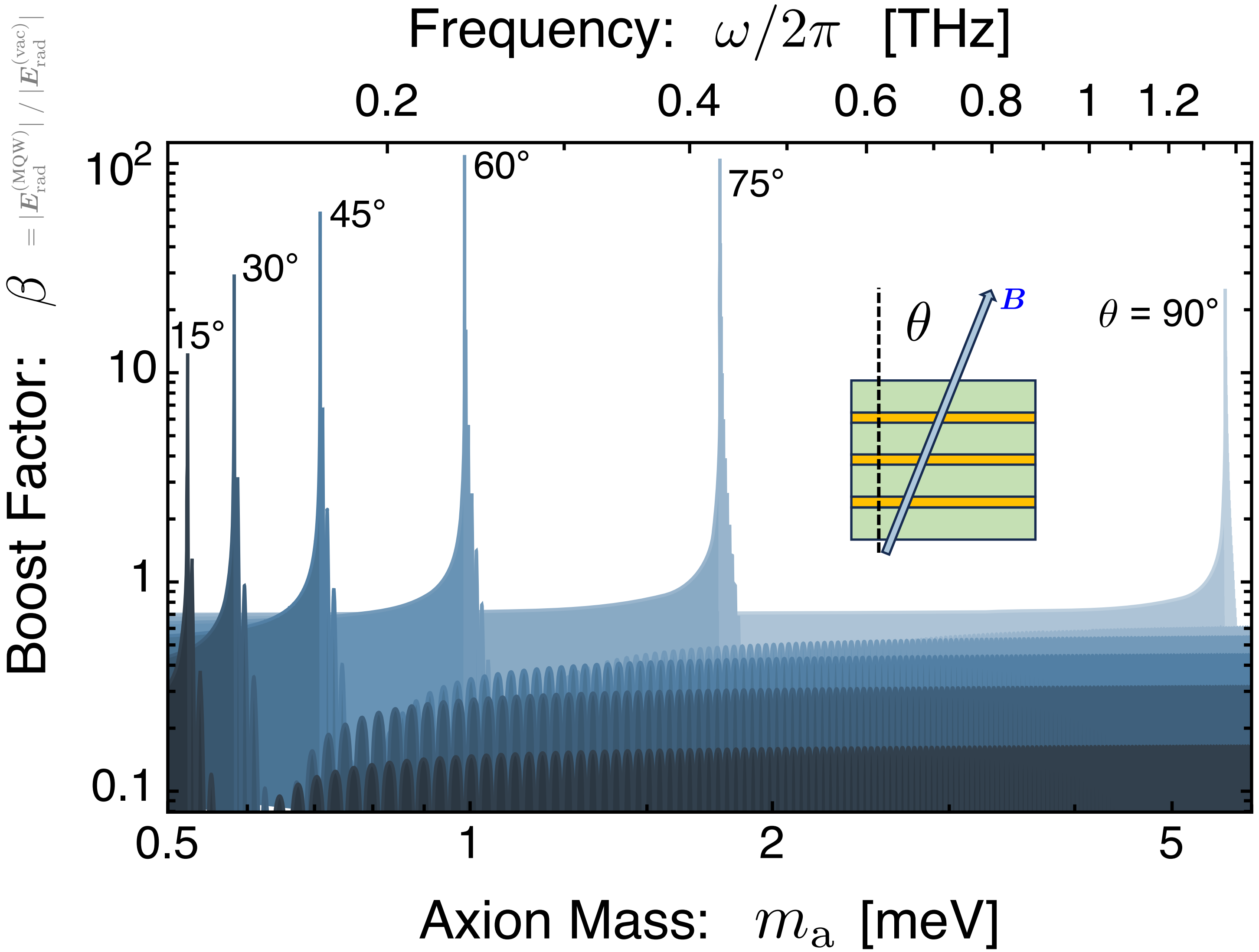
$$\lambda_{\rm med} = 2\pi / m_a \sqrt{\varepsilon_{\rm MQW,CRI}}$$

need to ensure
D <~ λ_{med} / 2

β = "boost factor"
signal ~ β^2

$m^* \approx 0.034\,{\rm MeV}$

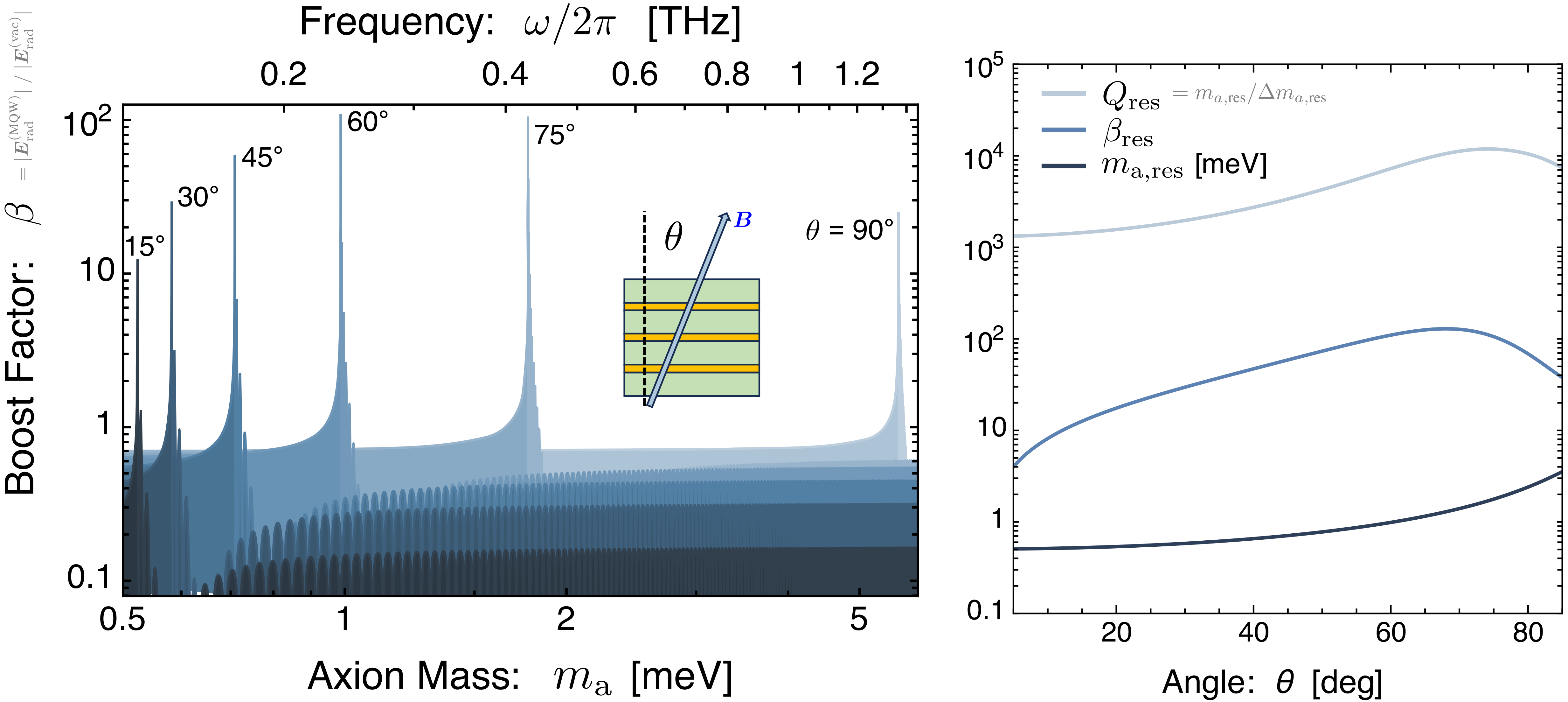
Let's scan over masses by rotating the stack



- B_parallel
  - ➔ the component || to surface
  - ➔ sin θ
  - ➔ creates axion-induced current
- B_perpendicular
  - ➔ the component _|_ to surface
  - ➔ cos θ
  - ➔ controls cyclotron frequency (allows for tuning of axion mass)

$B = 36\,\mathrm{T}$
$\tau = 1.7\,\mathrm{ns}$
$D = 10\,\mathrm{mm}$
$n_e = 3\times 10^{-11}\,\mathrm{cm}^{-2}$

Let's scan over masses by rotating the stack



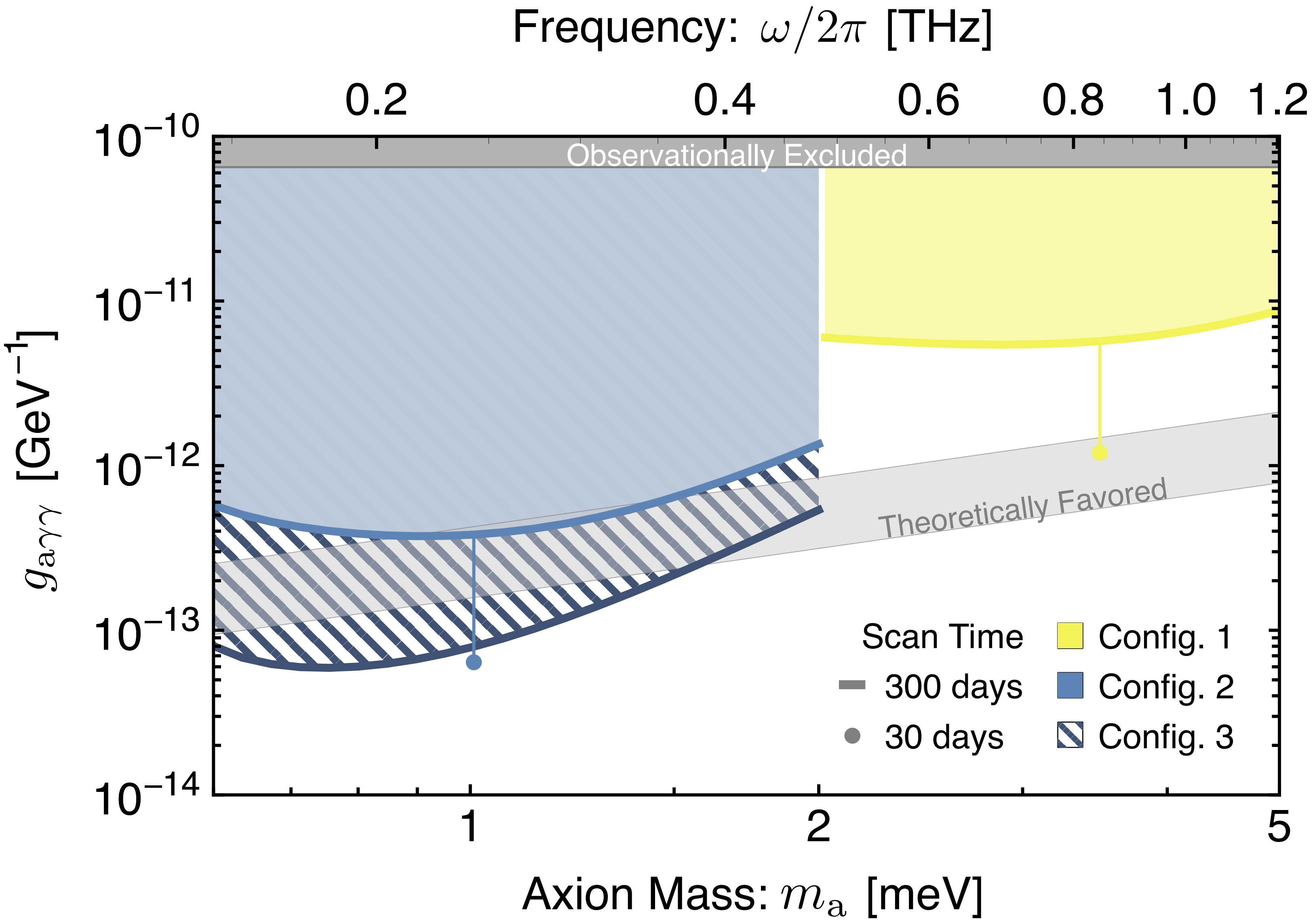
How well could SQWARE do at testing meV axion dark matter?

Let's discuss sensitivity projections

Parameter	Config. 1 (HM)	Config.2 (LM)	Config. 3 (LM-S)
D [mm]	2	10	20
B [T]	36	36	50
τ [ns]	1.7	1.7	4
$\Gamma_{\rm dark}$ [mHz]	1	1	0.1
η [%]	7	20	35

TABLE I. Summary of parameters for three benchmark SQWARE configurations: HM (High Mass), LM (Low Mass), and LM-S (Low Mass Sensitive). As the MQW cavities get thicker and scattering times reduce, larger signal boosts are possible, optimized at lower frequencies. For all scenarios, the temperature $T = 0.3\,\mathrm{K}$, electron density $n_e = 3\times10^{11}\,\mathrm{cm}^{-2}$, quantum well width $d_{\rm QW} = 30\,\mathrm{nm}$, lens efficiency $\eta_{\rm lens} = 100\%$, and total observation time $t_{\rm tot} = 300$ days.

$$g_{a\gamma\gamma} > 5\times10^{-14}\,\mathrm{GeV}^{-1}\left[\frac{36\,\mathrm{T}}{|\boldsymbol{B}|}\right]\left[\frac{100}{\beta(m_a)}\right]\left[\frac{20\%}{\eta}\right]^{\frac{1}{2}} \times\left[\frac{9\,\mathrm{cm}^2}{W^2}\right]^{\frac{1}{2}}\left[\frac{\Gamma_{\rm dark}}{1\,\mathrm{mHz}}\right]^{\frac{1}{4}}\left[\frac{m_a}{1\,\mathrm{meV}}\right]^{\frac{3}{2}}\left[\frac{30\,\mathrm{days}}{t_{\rm obs}}\right]^{\frac{1}{4}}$$



SQWARE -- details

design configurations

Parameter	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
τ [ns]	1.7	1.7	4
W [cm]	3	3	5
D [mm]	2	10	20
d_{Barrier} [nm]	90	150	90
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35
ω_{optimal} [meV]	5.0	1.6	1.1
θ_{optimal} [deg]	86	72	60
β_{optimal}	70	115	390
Q_{optimal} [10^3]	6	10	50
t_{obs} [min]	84	34	7
mirror [yes/no]	no	no	yes

TABLE I. A comparison of parameters for three different configurations for experimental searches, with optimal values yielding the largest signal enhancement in each. As the MQWs get thicker and scattering times reduce, larger signal boosts and higher quality factors are possible and are optimized for lower frequencies. For all scenarios, the temperature $T = 0.3\,\text{K}$, electron density $n_e = 3 \times 10^{11}\,\text{cm}^{-2}$, quantum well width $d_{\text{QW}} = 30\,\text{nm}$, lens efficiency $\eta_{\text{lens}} = 100\%$, and total observation time $t_{\text{obs}} = 300$ days.

MQW structure

- GaAs QWs, Si monolayer doping, AlGaAs barriers
- thickness: $D = N_{\text{layer}}\,(d_{\text{QW}} + d_{\text{Barrier}})$
- optimal: $D \sim \lambda_{\text{med}} / 2 \sim$ 1-10 mm @ THz
- layers: need $N_{\text{layer}} \sim$ 10^5 (a challenge)
- fabrication: molecular beam epitaxy (MBE)
- time scale: weeks-months @ 1 μm/hr growth

High-field magnet

- National High Magnetic Field Lab (NHMFL)
- strength: 36 T & 45 T NMR magnets
- equipped with rotating probe
- high degree of homogeneity ~ good for resonance

Photodetector

- a developing field: the "THz technology gap"
- needs: high efficiency, low dark count rate
- must function in strong B-field & cryogenic temps
- e.g., quantum dot photodetector

SQWARE -- details

design configurations

Parameter	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
τ [ns]	1.7	1.7	4
W [cm]	3	3	5
D [mm]	2	10	20
d_{Barrier} [nm]	90	150	90
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35
$\omega_{\mathrm{optimal}}$ [meV]	5.0	1.6	1.1
$\theta_{\mathrm{optimal}}$ [deg]	86	72	60
β_{optimal}	70	115	390
Q_{optimal} [10^3]	6	10	50
t_{obs} [min]	84	34	7
mirror [yes/no]	no	no	yes

TABLE I. A comparison of parameters for three different configurations for experimental searches, with optimal values yielding the largest signal enhancement in each. As the MQWs get thicker and scattering times reduce, larger signal boosts and higher quality factors are possible and are optimized for lower frequencies. For all scenarios, the temperature $T = 0.3\,\mathrm{K}$, electron density $n_e = 3 \times 10^{11}\,\mathrm{cm}^{-2}$, quantum well width $d_{\mathrm{QW}} = 30\,\mathrm{nm}$, lens efficiency $\eta_{\mathrm{lens}} = 100\%$, and total observation time $t_{\mathrm{obs}} = 300$ days.

MQW structure

- GaAs QWs, Si monolayer doping, AlGaAs barriers
- thickness: $D = N_{\mathrm{layer}}\,(d_{\mathrm{QW}} + d_{\mathrm{Barrier}})$
- optimal: $D \sim \lambda_{\mathrm{med}} / 2 \sim$ 1-10 mm @ THz
- layers: need $N_{\mathrm{layer}} \sim 10^5$ (a challenge)
- fabrication: molecular beam epitaxy (MBE)
- time scale: weeks-months @ 1 μm/hr growth

High-field magnet

- National High Magnetic Field Lab (NHMFL)
- strength: 36 T & 45 T NMR magnets
- equipped with rotating probe
- high degree of homogeneity ~ good for resonance

Photodetector

- a developing field: the "THz technology gap"
- needs: high efficiency, low dark count rate
- must function in strong B-field & cryogenic temps
- e.g., quantum dot photodetector

SQWARE -- details

design configurations

Parameter	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
τ [ns]	1.7	1.7	4
W [cm]	3	3	5
D [mm]	2	10	20
d_{Barrier} [nm]	90	150	90
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35
ω_{optimal} [meV]	5.0	1.6	1.1
θ_{optimal} [deg]	86	72	60
β_{optimal}	70	115	390
Q_{optimal} [10^3]	6	10	50
t_{obs} [min]	84	34	7
mirror [yes/no]	no	no	yes

TABLE I. A comparison of parameters for three different configurations for experimental searches, with optimal values yielding the largest signal enhancement in each. As the MQWs get thicker and scattering times reduce, larger signal boosts and higher quality factors are possible and are optimized for lower frequencies. For all scenarios, the temperature $T = 0.3\,\text{K}$, electron density $n_e = 3 \times 10^{11}\,\text{cm}^{-2}$, quantum well width $d_{\text{QW}} = 30\,\text{nm}$, lens efficiency $\eta_{\text{lens}} = 100\%$, and total observation time $t_{\text{obs}} = 300$ days.

MQW structure

- GaAs QWs, Si monolayer doping, AlGaAs barriers
- thickness: $D = N_{\text{layer}}\,(d_{\text{QW}} + d_{\text{Barrier}})$
- optimal: $D \sim \lambda_{\text{med}} / 2 \sim$ 1-10 mm @ THz
- layers: need $N_{\text{layer}} \sim$ 10^5 (a challenge)
- fabrication: molecular beam epitaxy (MBE)
- time scale: weeks-months @ 1 μm/hr growth

High-field magnet

- National High Magnetic Field Lab (NHMFL)
- strength: 36 T & 45 T NMR magnets
- equipped with rotating probe
- high degree of homogeneity ~ good for resonance

Photodetector

- a developing field: the "THz technology gap"
- needs: high efficiency, low dark count rate
- must function in strong B-field & cryogenic temps
- e.g., quantum dot photodetector

SQWARE -- details

design configurations

Parameter	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
τ [ns]	1.7	1.7	4
W [cm]	3	3	5
D [mm]	2	10	20
d_{Barrier} [nm]	90	150	90
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35
ω_{optimal} [meV]	5.0	1.6	1.1
θ_{optimal} [deg]	86	72	60
β_{optimal}	70	115	390
Q_{optimal} [10^3]	6	10	50
t_{obs} [min]	84	34	7
mirror [yes/no]	no	no	yes

TABLE I. A comparison of parameters for three different configurations for experimental searches, with optimal values yielding the largest signal enhancement in each. As the MQWs get thicker and scattering times reduce, larger signal boosts and higher quality factors are possible and are optimized for lower frequencies. For all scenarios, the temperature $T = 0.3\,\text{K}$, electron density $n_e = 3 \times 10^{11}\,\text{cm}^{-2}$, quantum well width $d_{\text{QW}} = 30\,\text{nm}$, lens efficiency $\eta_{\text{lens}} = 100\%$, and total observation time $t_{\text{obs}} = 300$ days.

MQW structure

- GaAs QWs, Si monolayer doping, AlGaAs barriers
- thickness: $D = N_{\text{layer}} (d_{\text{QW}} + d_{\text{Barrier}})$
- optimal: $D \sim \lambda_{\text{med}} / 2 \sim$ 1-10 mm @ THz
- layers: need $N_{\text{layer}} \sim$ 10^5 (a challenge)
- fabrication: molecular beam epitaxy (MBE)
- time scale: weeks-months @ 1 μm/hr growth

High-field magnet

- National High Magnetic Field Lab (NHMFL)
- strength: 36 T & 45 T NMR magnets
- equipped with rotating probe
- high degree of homogeneity ~ good for resonance

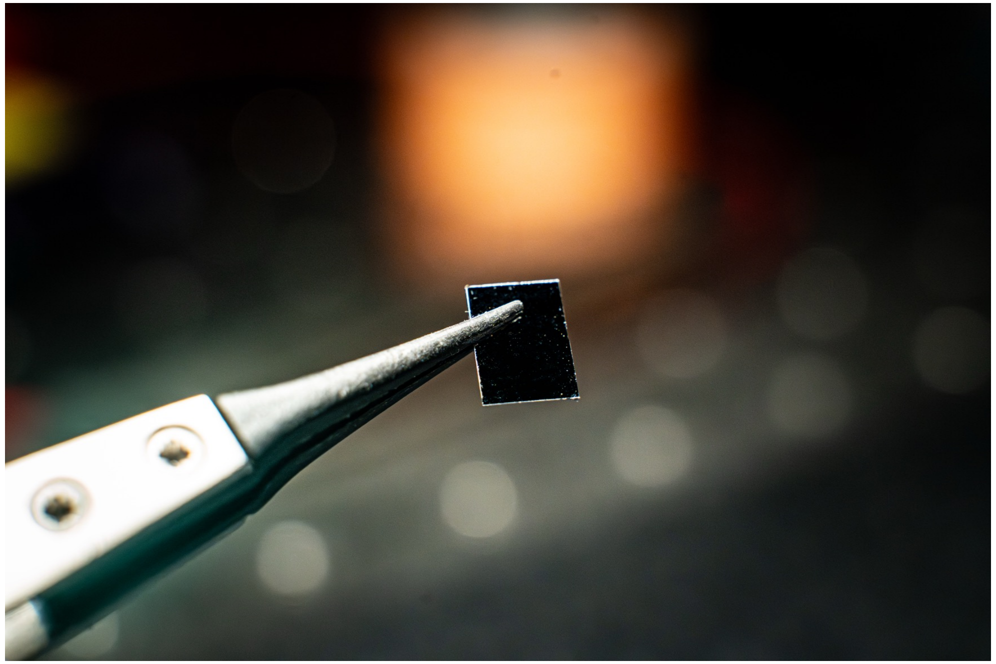
Photodetector

- a developing field: the "THz technology gap"
- needs: high efficiency, low dark count rate
- must function in strong B-field & cryogenic temps
- e.g., quantum dot photodetector

Let's check on the recent progress

[image: Jorge Vidal, Rice Media]

currently testing the dielectric response of two MQW stacks in the lab at Rice



6mm x 9mm, single GaAs QW

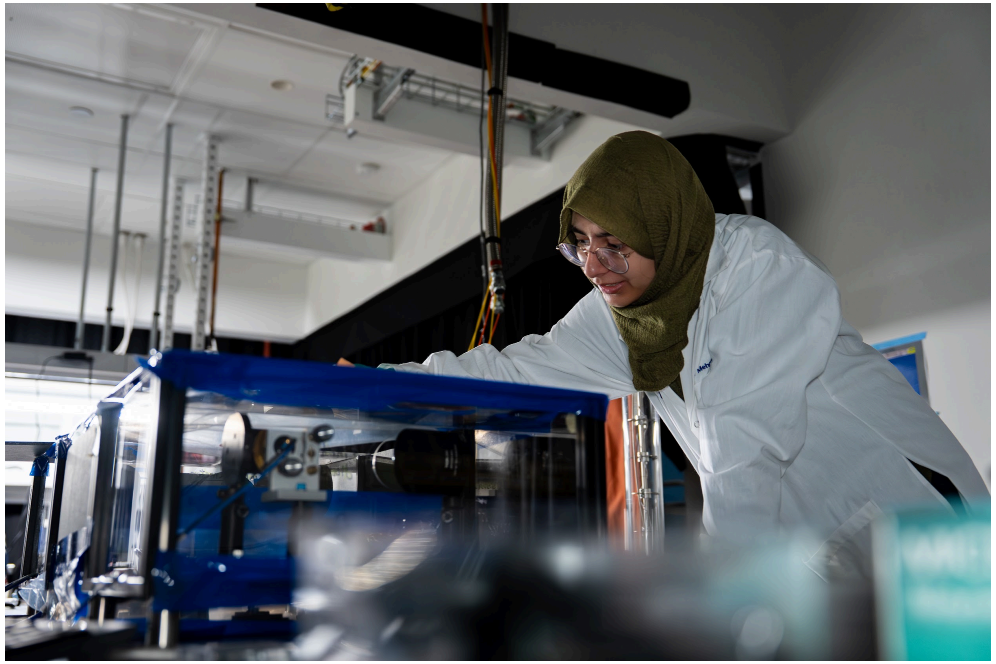
- getting set up: THz TDS system (time-domain spectroscopy), magnet (7T), cryostat (1.6K)
- getting samples: 10 MQW & 30 MQW stacks provided by Manfra group at Purdue University
- goals for August: measure CRI ENZ resonance quality and measure tunability with a B-field

Let’s check on the recent progress

[image: Jorge Vidal, Rice Media]

- next steps:
  - Run 10- & 30-QW samples from 0-7 T to measure ENZ CRI res. quality & tunability. (Summer 2026)
  - Compare with 3D COMSOL sims to test sensitivity to electron density inhomogeneity. (Fall 2026)
  - Run 1, 10, & 30-QW samples up to 36 T at the NHMFL. (Late 2026 / Early 2027)
  - Simulate and manufacture optimal MQW configs. at Purdue, 10x 30-QW stacks. (Summer 2027)
  - Manufacture THz quantum dot photodetectors at NSRC or Rice. (Summer 2027)
  - Combine all of the moving parts at Rice and set a very preliminary constraint. (Late 2027)

Jaanita Mehrani (applied physics PhD student at Rice)

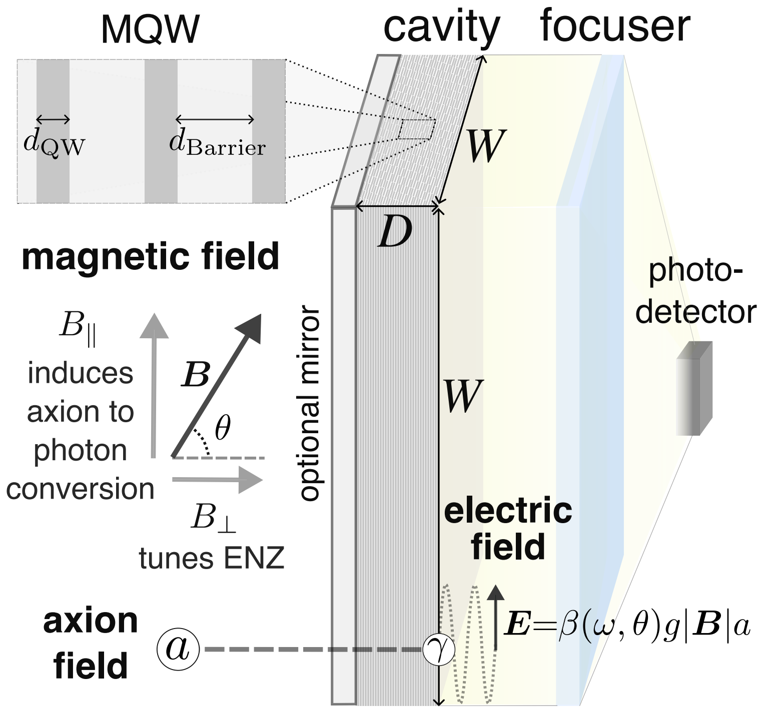


working on the THz optics

… dreaming about graduating (Spring 2028)

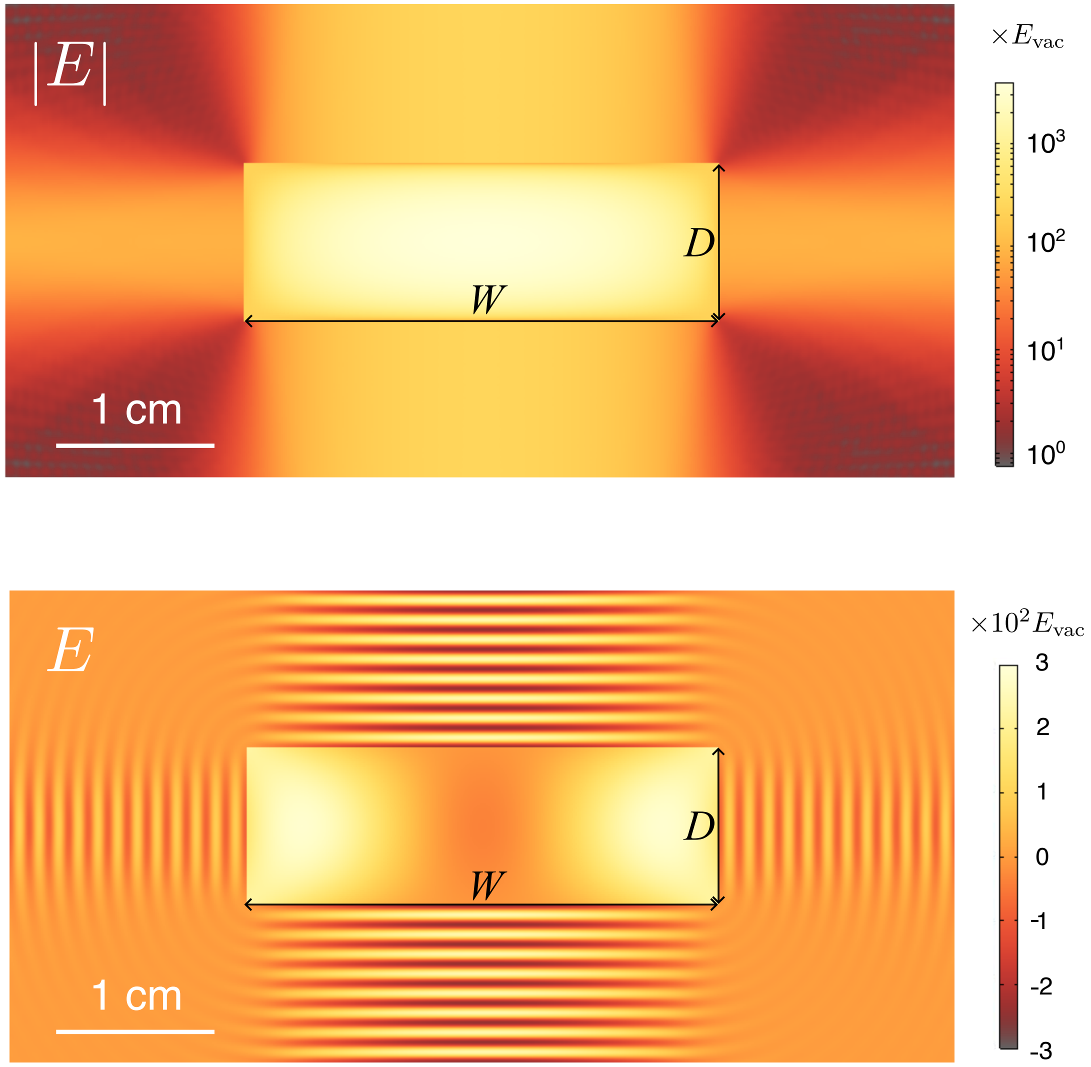
Let me explain … no there is too much, let me sum up

- meV axion dark matter = theoretically compelling
  (post-inflationary production from axion string-wall network)
- but detection = especially challenging
  (meV mass gap … need a tunable resonance at THz)
- “bespoke” materials allow for tunable response
  (using stacks of many nm-thick quantum wells)
- SQWARE team at Rice is gearing up!
  (ask your local material scientists to build their own)



backup slides

Validation w/ COMSOL sims



COMSOL solves the in-medium Maxwell Eqns.

It was used to perform various checks / validations:

- validation of effective medium theory
- validation of large width approximation
- validation of homogenous axion approx.
- validation of homogenous B-field approx.
- validation of homogeneous e-density approx.

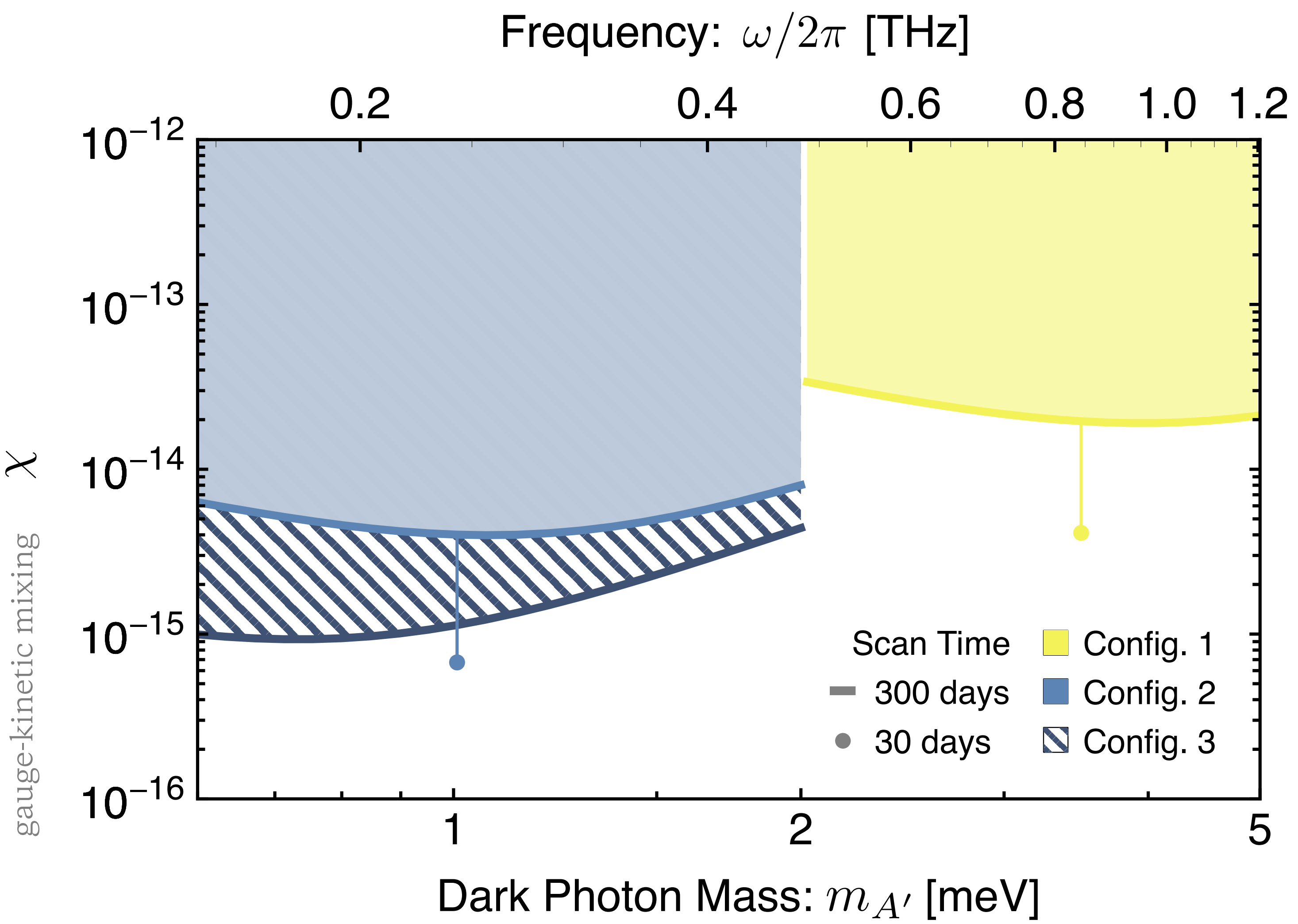
(see discussions in the paper)

Dark photons

Parameter	Config. 1 (HM)	Config.2 (LM)	Config. 3 (LM-S)
D [mm]	2	10	20
B [T]	36	36	50
τ [ns]	1.7	1.7	4
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35

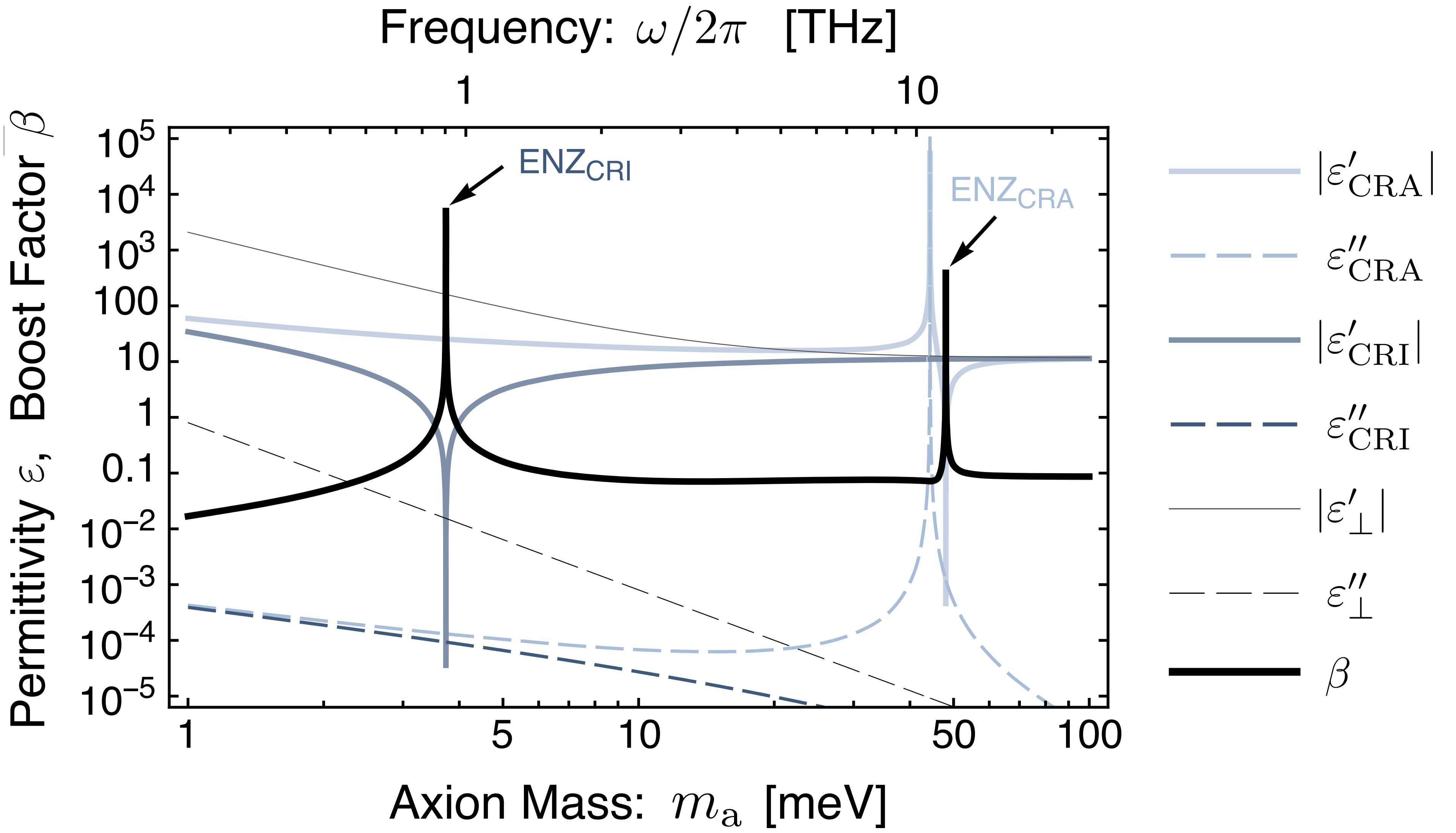
TABLE I. Summary of parameters for three benchmark SQWARE configurations: HM (High Mass), LM (Low Mass), and LM-S (Low Mass Sensitive). As the MQW cavities get thicker and scattering times reduce, larger signal boosts are possible, optimized at lower frequencies. For all scenarios, the temperature $T = 0.3\,\text{K}$, electron density $n_e = 3\times10^{11}\,\text{cm}^{-2}$, quantum well width $d_{\text{QW}} = 30\,\text{nm}$, lens efficiency $\eta_{\text{lens}} = 100\%$, and total observation time $t_{\text{tot}} = 300$ days.

$$\chi > 6\times10^{-16}\left[\frac{100}{\beta(m_{A'})}\right]\left[\frac{0.2}{\eta}\right]^{\frac{1}{2}}\left[\frac{9\,\text{cm}^2}{w^2}\right]^{\frac{1}{2}}\left[\frac{\Gamma_{\text{dark}}}{1\,\text{mHz}}\right]^{\frac{1}{4}}\left[\frac{m_{A'}}{1\,\text{meV}}\right]^{\frac{1}{2}}\left[\frac{30\,\text{days}}{t_{\text{obs}}}\right]^{\frac{1}{4}}$$



ENZ point & boost (inside of a single QW)

$\varepsilon = \varepsilon' + i\varepsilon''$



$B = 36\,\mathrm{T}$
$\theta = 45^\circ$
$\tau = 1.7\,\mathrm{ns}$
$D = 10\,\mathrm{mm}$
$n_e = 3 \times 10^{-11}\,\mathrm{cm}^{-2}$

Let's boost that signal

[derivation: Millar, Redondo, Steffen (2017)]
[plot: SQWARE, 2509.14320]

boost factor:
enhancement in E-field amplitude

$$\beta(\omega,\theta) = \left| -\frac{(1-\varepsilon)\sin(\Delta/2)}{\varepsilon\sin(\Delta/2) + i\sqrt{\varepsilon}\cos(\Delta/2)} \right| \frac{\sin\theta}{\sqrt{2}}$$

$$\Delta = 2\pi D/\lambda_{\text{med}}$$

$$\lambda_{\text{med}} = \lambda_{\text{vac}}/n_{\text{med}}$$

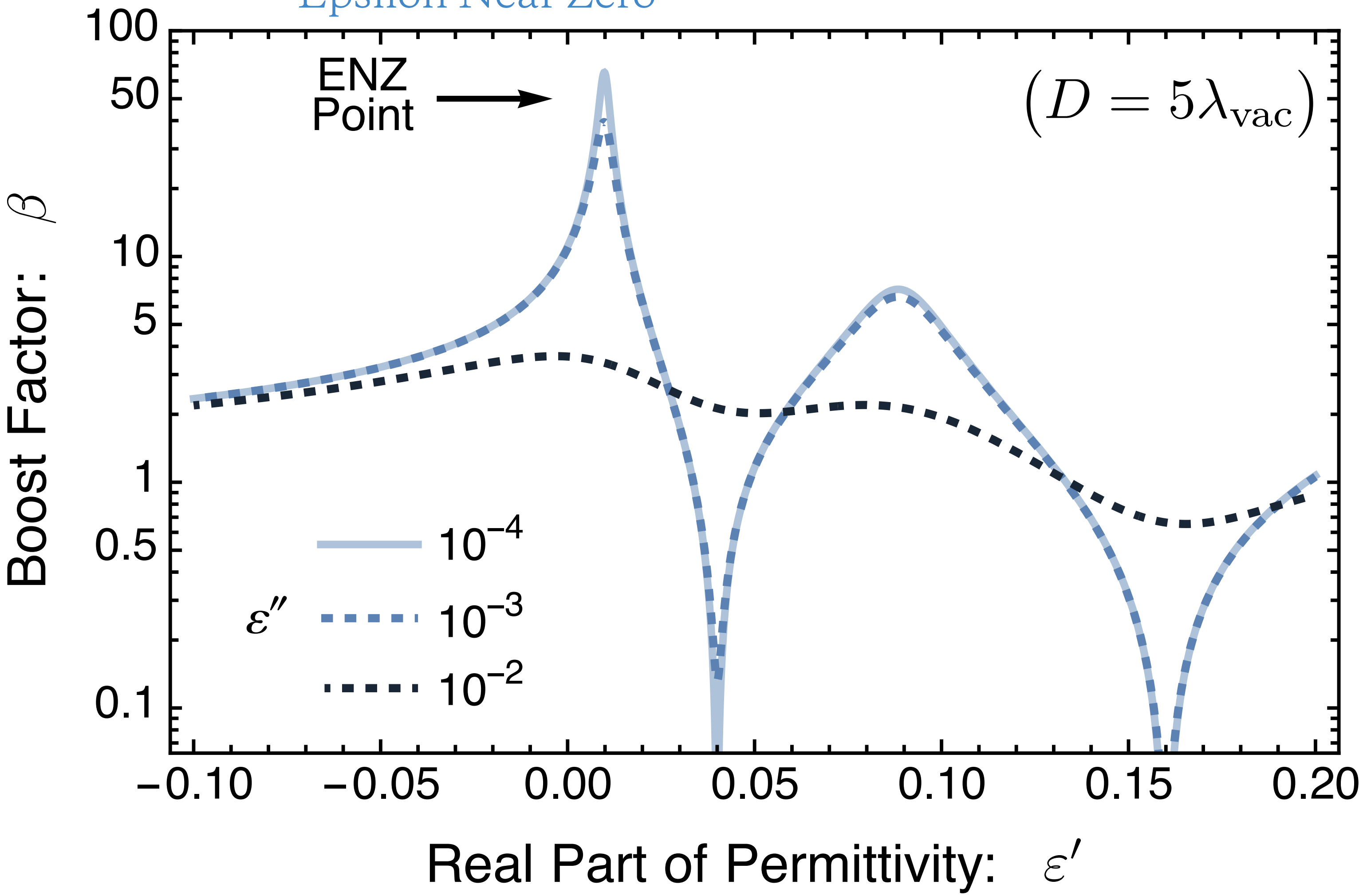
$$\lambda_{\text{vac}} = 2\pi c/\omega$$

$$n_{\text{med}} = \text{Re}[\sqrt{\varepsilon}]$$

$$\varepsilon = \varepsilon' + i\varepsilon''$$

maximal boost:
$\beta = |1/\varepsilon - 1|$ when $\Delta = \pi, 3\pi, 5\pi, \ldots$

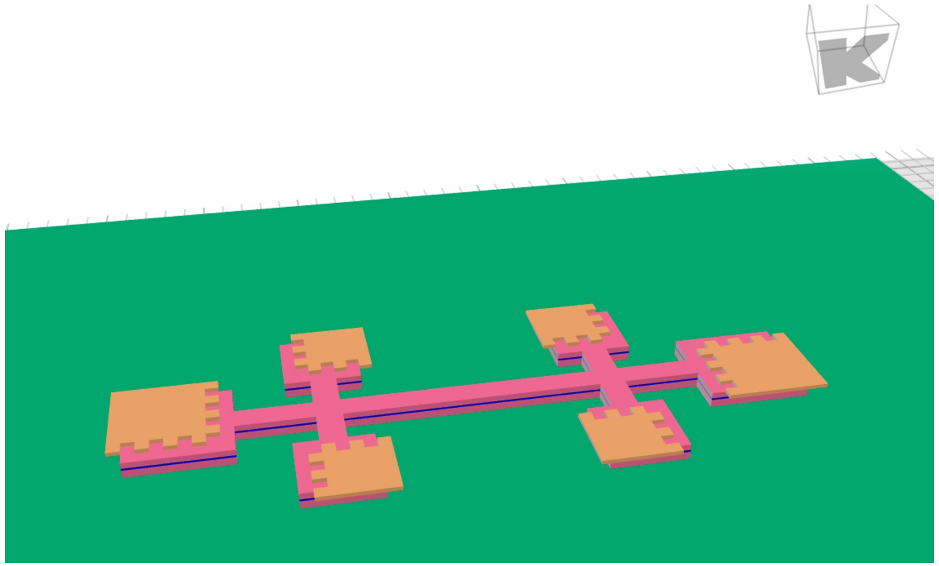
Epsilon Near Zero



Photodetector

- Detecting THz photons is tough.
- Current thinking: use the Komiyama quantum dot detector design (measure the change in conductance of a quantum dot when a photon excites an electron in the QD).
- We're following BREAD's lead … this tech. is part of their proposal.

- People at Rice are beginning the design process (see below), with the idea of possibly doing the fabrication at Rice next year.



SQWARE -- strengths

- **Feasibility and Accessibility:** Multiple Quantum Wells (MQWs) are a mature platform in condensed matter physics, with established, high-quality fabrication techniques including Molecular Beam Epitaxy (MBE). Prototypes can be rapidly realized using widely available infrastructure, making the experiment highly accessible to a broad range of laboratories.
- **Electromagnetic Tunability:** The resonant properties of MQWs can be tuned dynamically and precisely using an external magnetic field, enabling flexible frequency coverage either with simple mechanical adjustment or possibly with no mechanical motion at all.
- **Customizability:** The layered structure of MQWs allows for unprecedented flexibility in device design. Material composition, layer thickness, and doping can be systematically engineered, and complex structures potentially consisting of thousands of layers may be optimized using modern machine learning techniques to maximize signal boost across a targeted frequency range.
- **Reproducibility and Modularity:** MQW-based detectors are inherently modular and reproducible. Any laboratory equipped for MBE growth and standard cryogenics can fabricate and test these devices, enabling parallel efforts and rapid scaling. The compact design obviates the need for large-volume, high-field magnets; low-field and prototype setups can be tailored for various frequency ranges. Moreover, a given sample can be tested in multiple magnets or upgraded setups as new technologies become available.
- **High Sensitivity:** Large electromagnetic boost factors are attainable with high-quality MQW structures, enabling competitive sensitivities with presently achievable materials and fabrication standards.
- **Rapid Scan Rate:** The combination of strong signal enhancement and minimal reliance on mechanical motion allows for high scan rates, facilitating fast coverage of broad axion mass ranges.

SQWARE -- challenges

- **Long Fabrication Times:** High-quality MQW structures, especially those requiring many layers or large surface areas, can require substantial time investments for growth and processing.

1 μm/hr => 3 weeks for D = 1 mm

- **Sample Uniqueness and Value:** Each fabricated sample is a valuable asset, as its properties are fixed post-fabrication and cannot be substantially modified (other than by varying the applied magnetic field). Damage or fabrication error can result in significant loss of effort and resources.
- **Limited Magnet Access:** High-field magnet time is in high demand and can be prohibitively expensive unless dedicated instrumentation is secured. Scheduling access may constrain experimental throughput.
- **Post-Fabrication Inflexibility:** Once the MQW is fabricated, practical tuning is limited primarily to adjustments of the external magnetic field; in situ modifications to layer structure or composition are not possible.