

Probing the meV QCD Axion with the SQUIRE Quantum Semiconductor Haloscope

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Andrew J. Long, Kuver Sinha, Junichiro Kono, Shengxi Huang

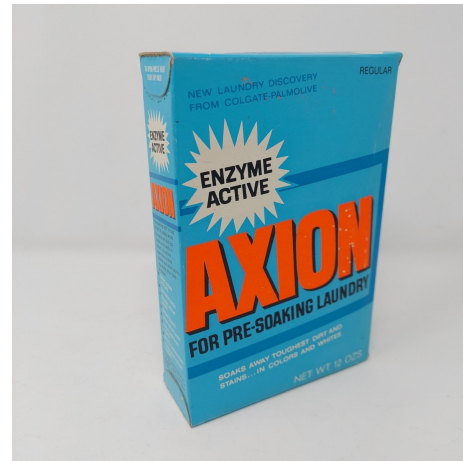


based upon work in
[arXiv:2509.14320](https://arxiv.org/abs/2509.14320)



Axions are a promising DM model

- Several theoretical dark matter models with unique properties of mass, spin, charge, couplings!
- Axions could additionally solve the strong charge parity problem in quantum chromodynamics (QCD)



How can we detect axions? with photons!

- Axions can couple to photons under different models (KSVZ/DFSZ)

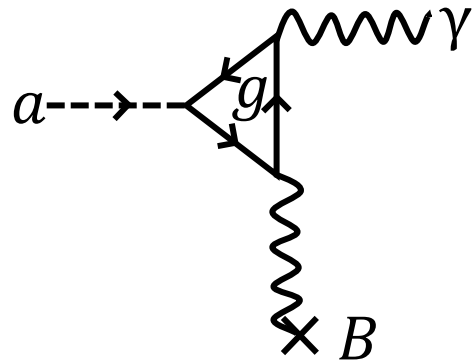
$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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- Inverse Primakoff effect: axions can convert into photons in a magnetic field

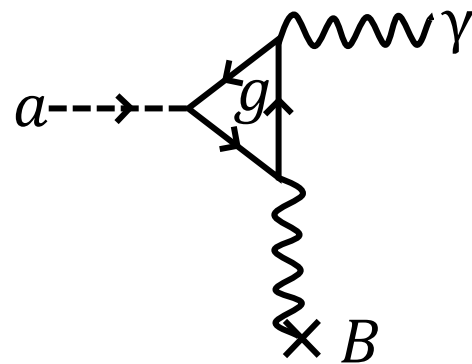


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Inverse Primakoff effect

- Classical Maxwell's equations are modified under axion field a

$$\begin{aligned}\partial_\mu F^{\mu\nu} &= J^\nu - g_{a\gamma} \tilde{F}^{\mu\nu} \partial_\mu a \\ (\partial_\mu \partial^\mu + m_a^2) a &= -\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}\end{aligned}$$

Inverse Primakoff effect

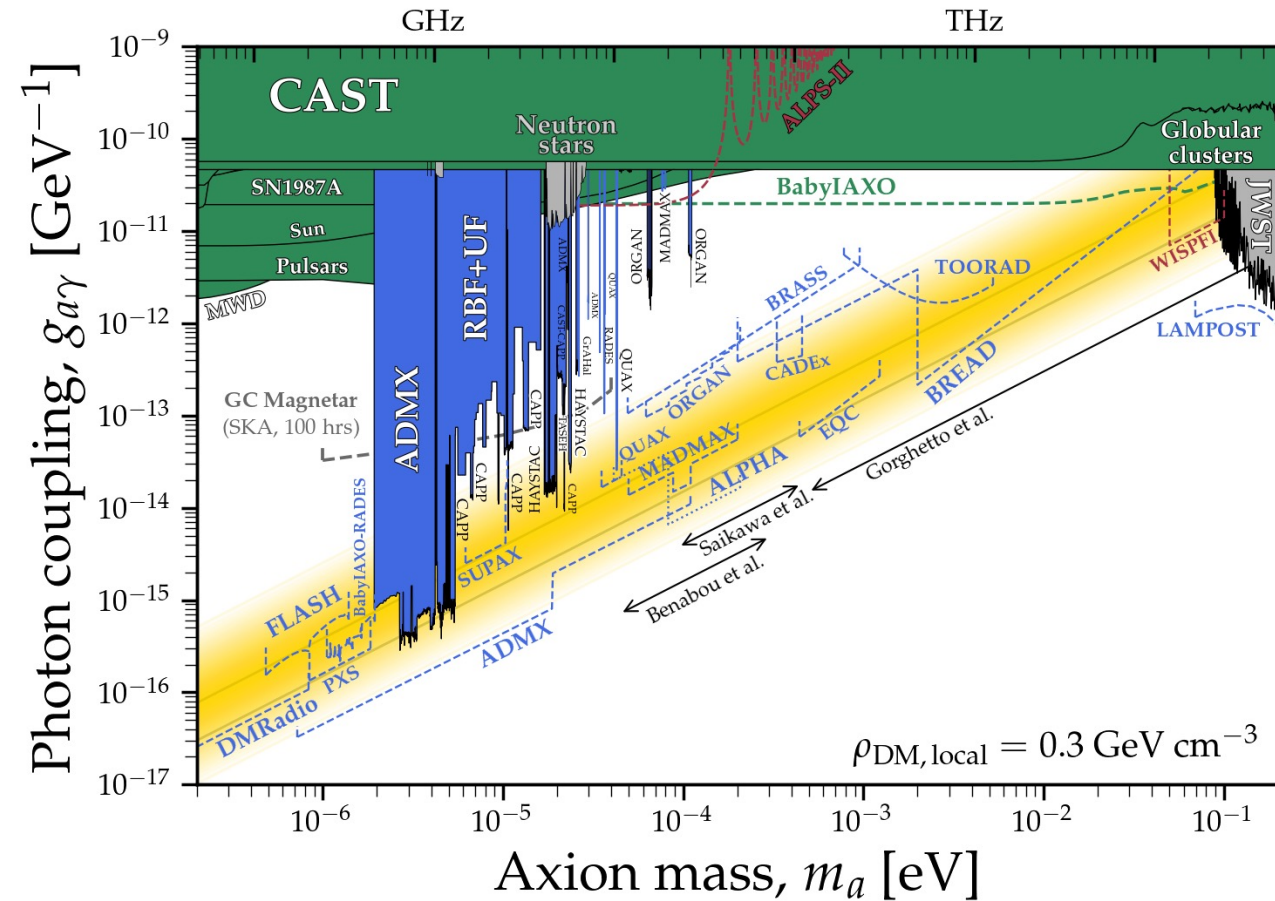
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- To first order, axions convert to photons

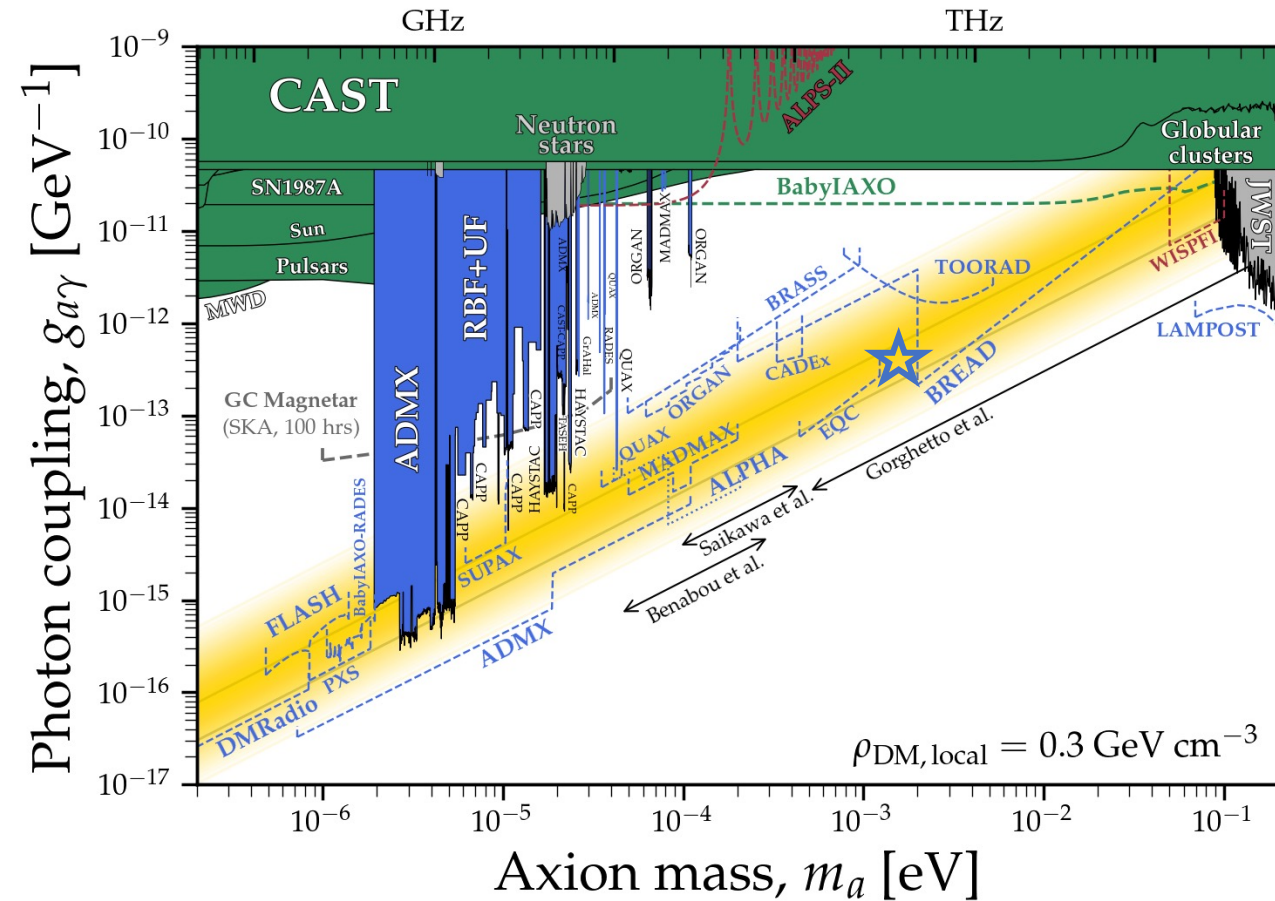
$$\hat{\epsilon}\mathbf{E}(t) = -g_{a\gamma}\mathbf{B}ae^{-im_a t}$$

Axion Search Strategies



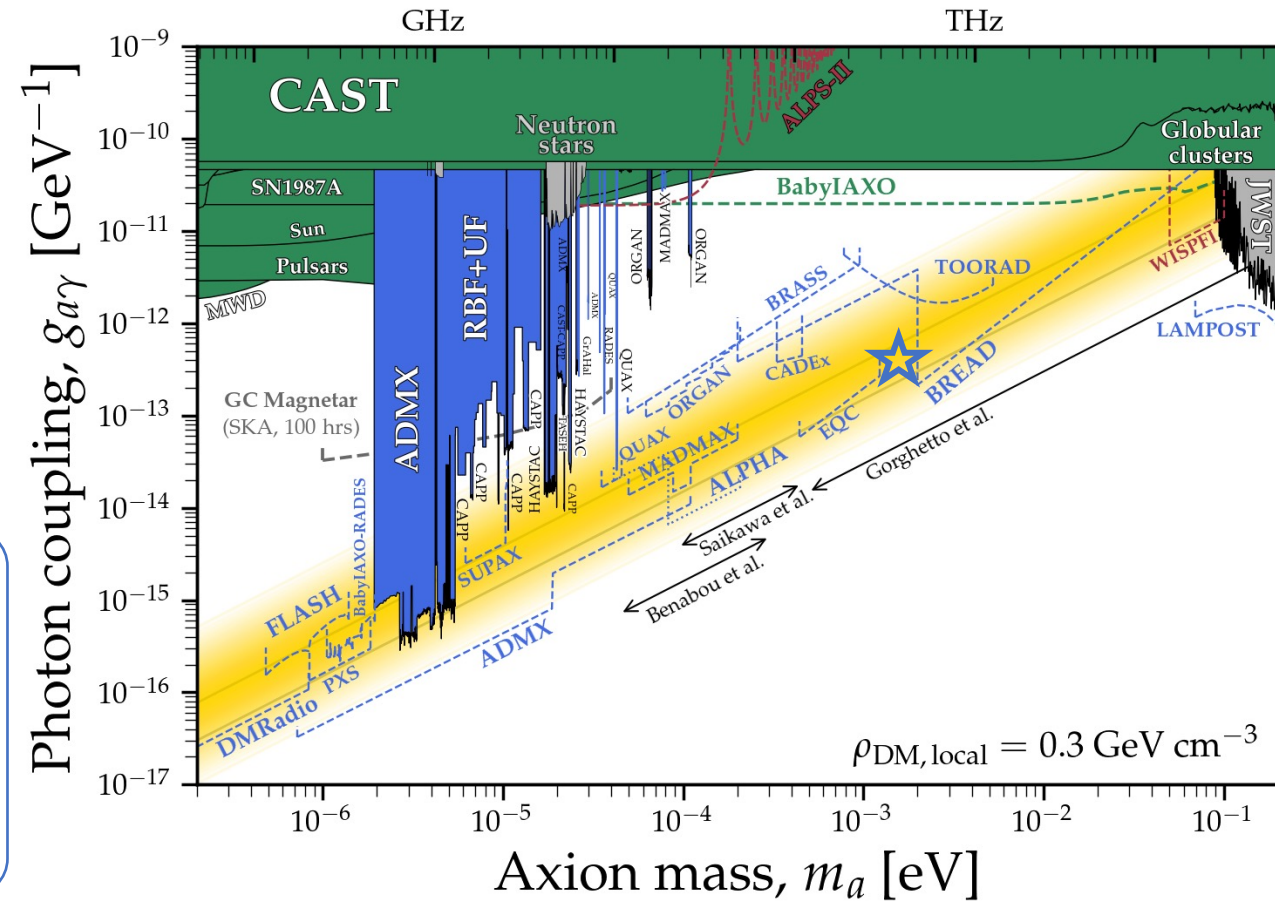
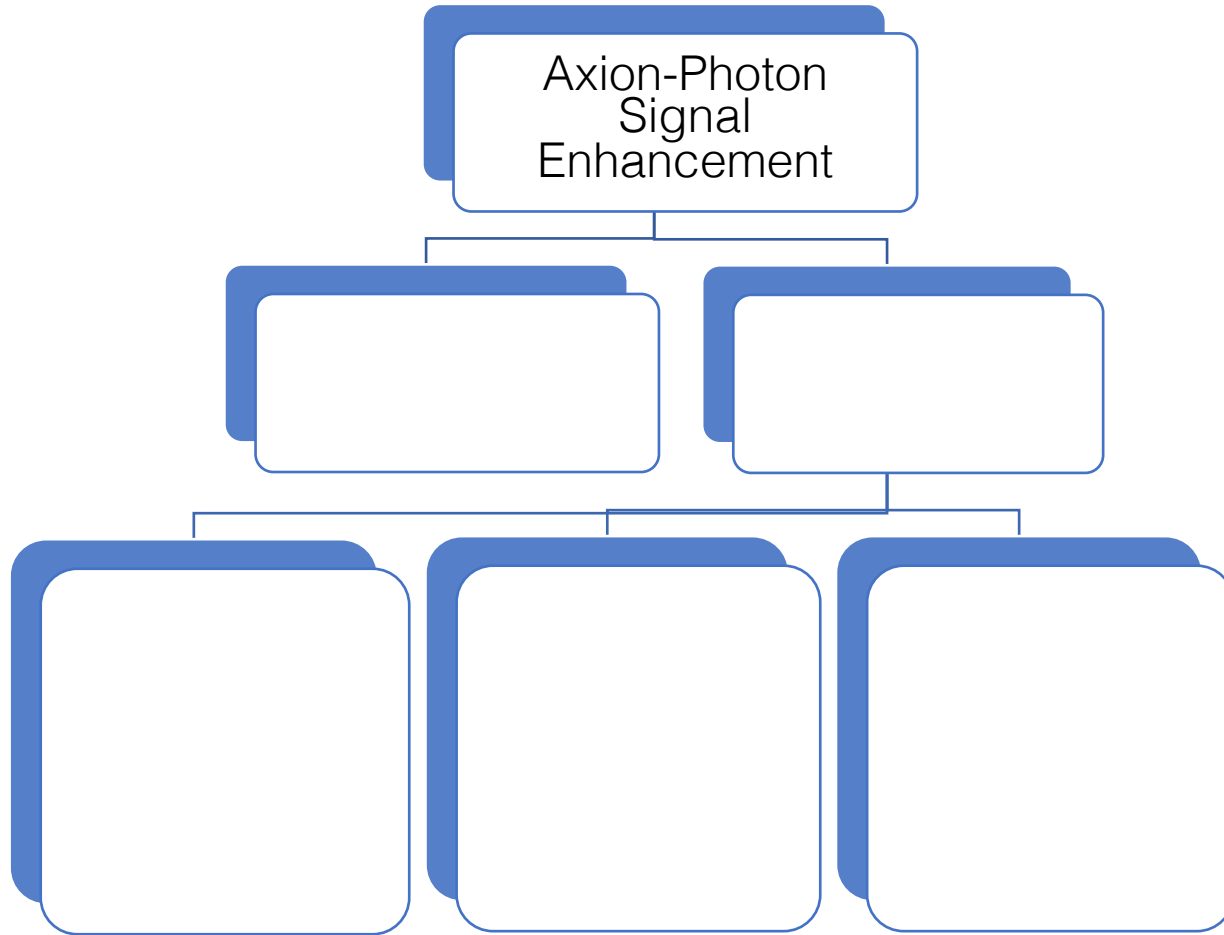
C. O'Hare

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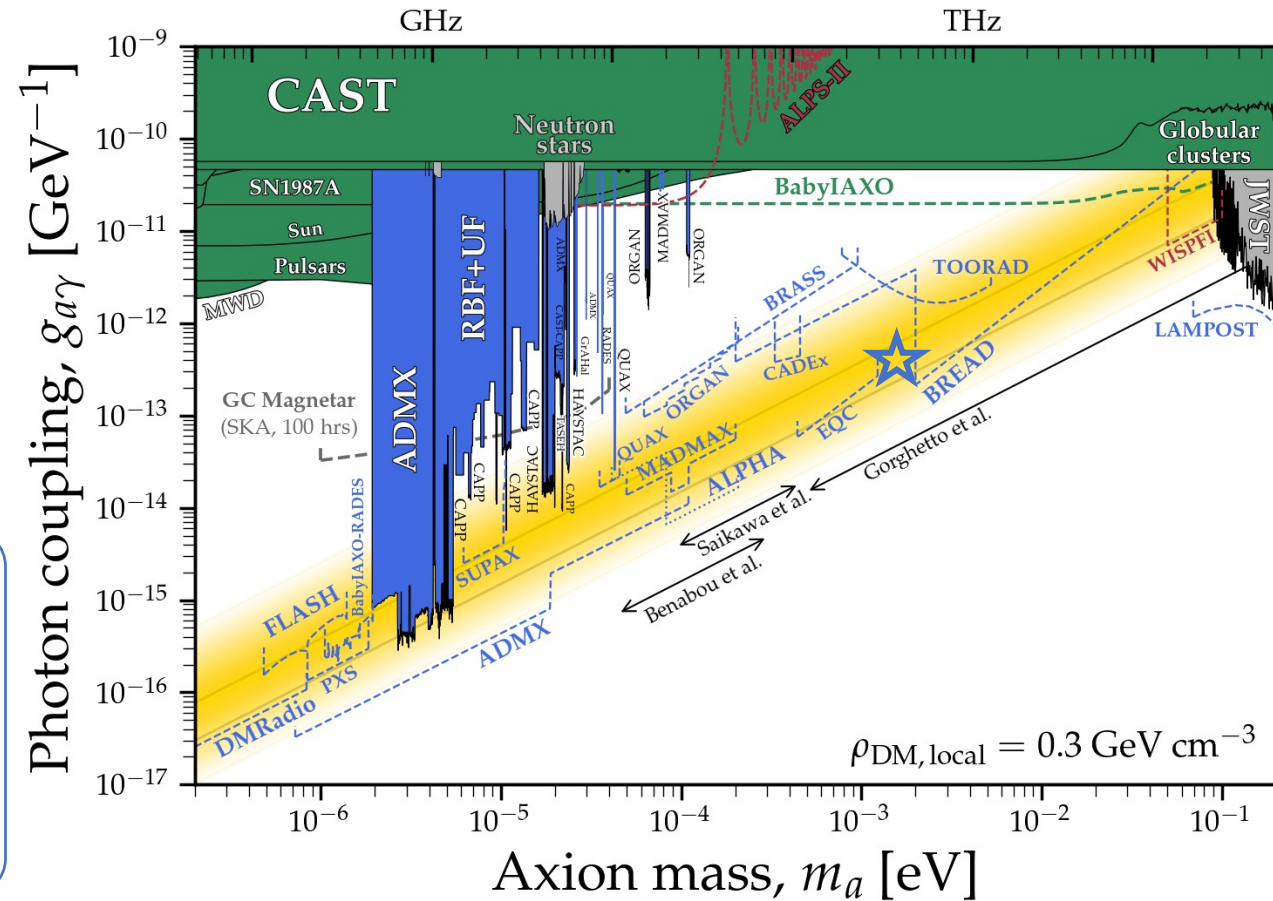
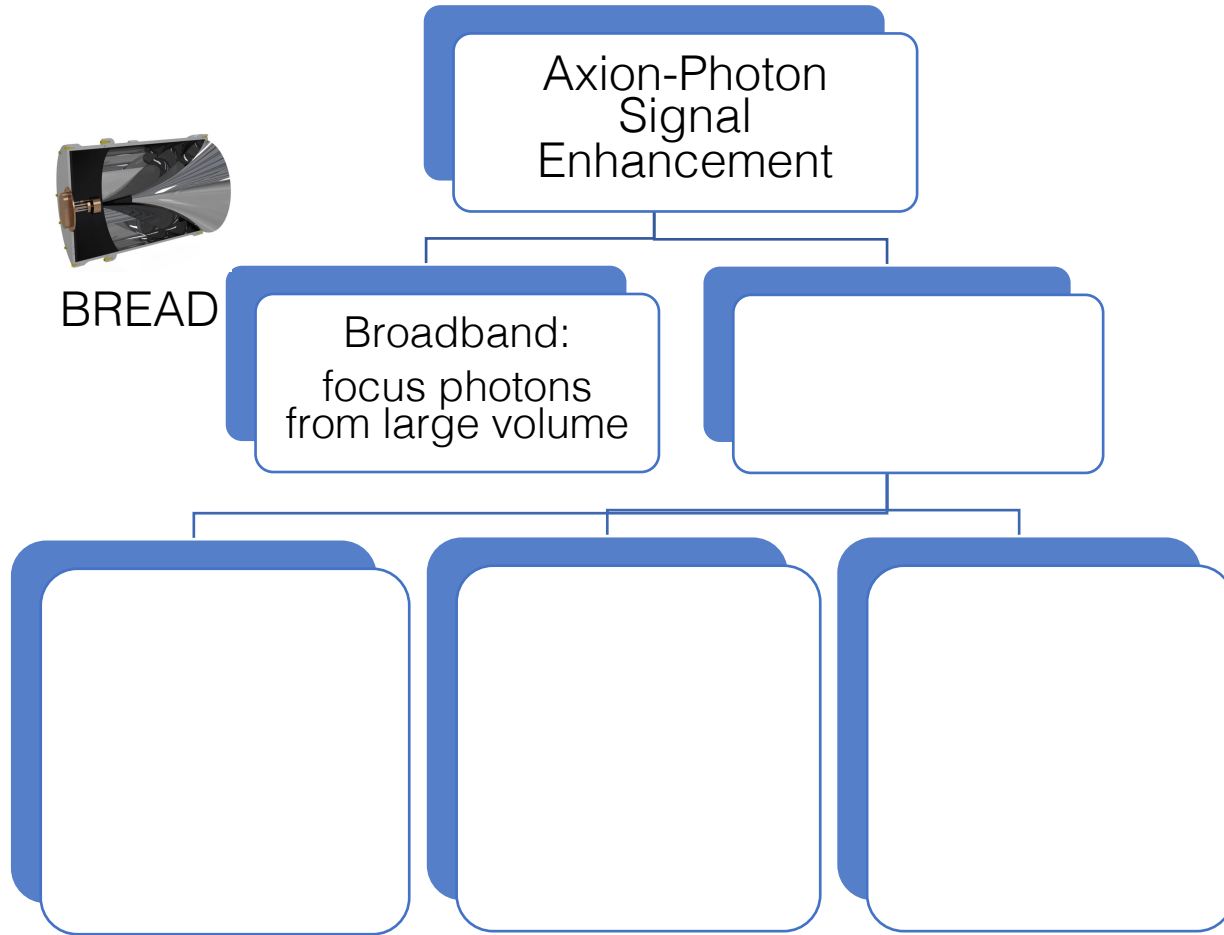
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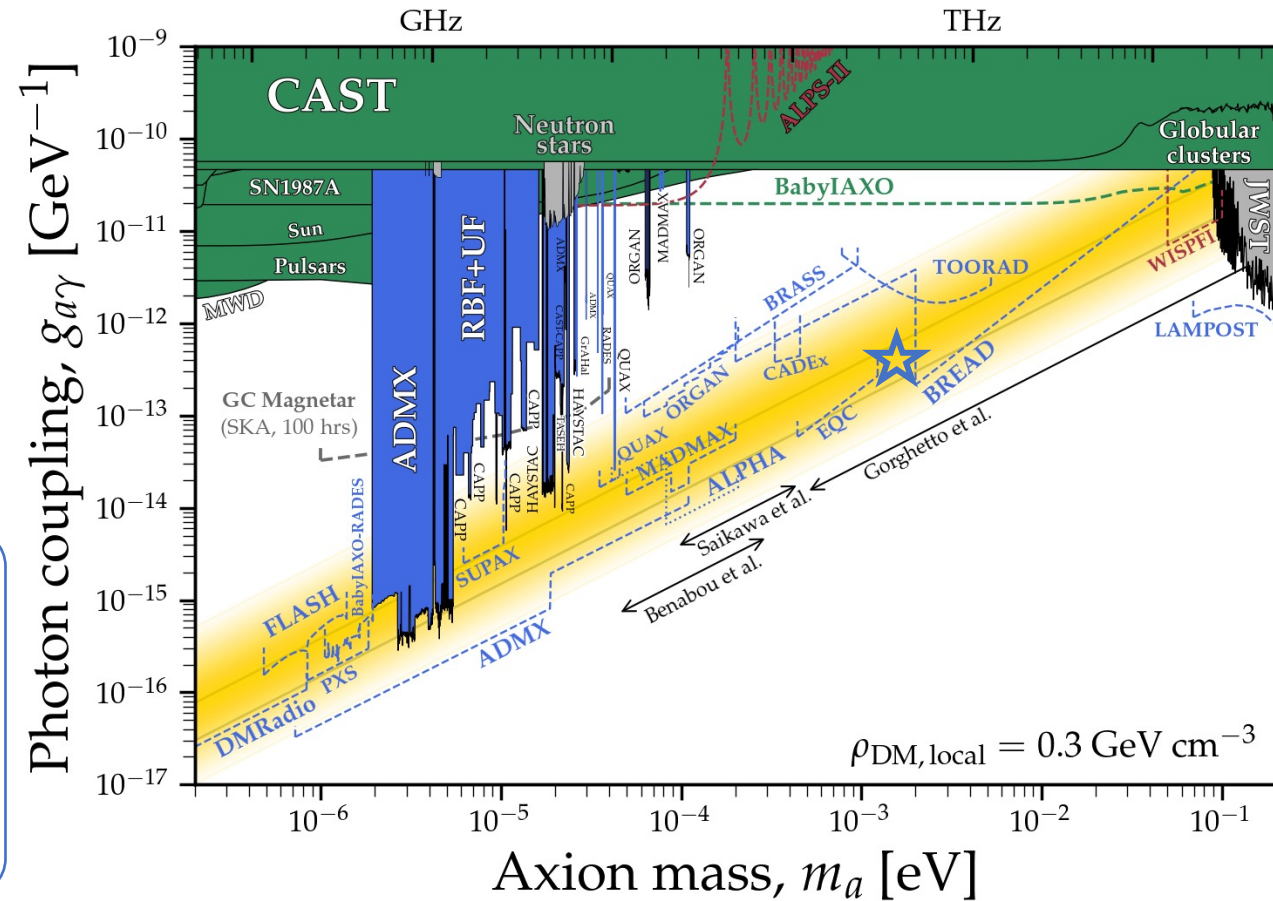
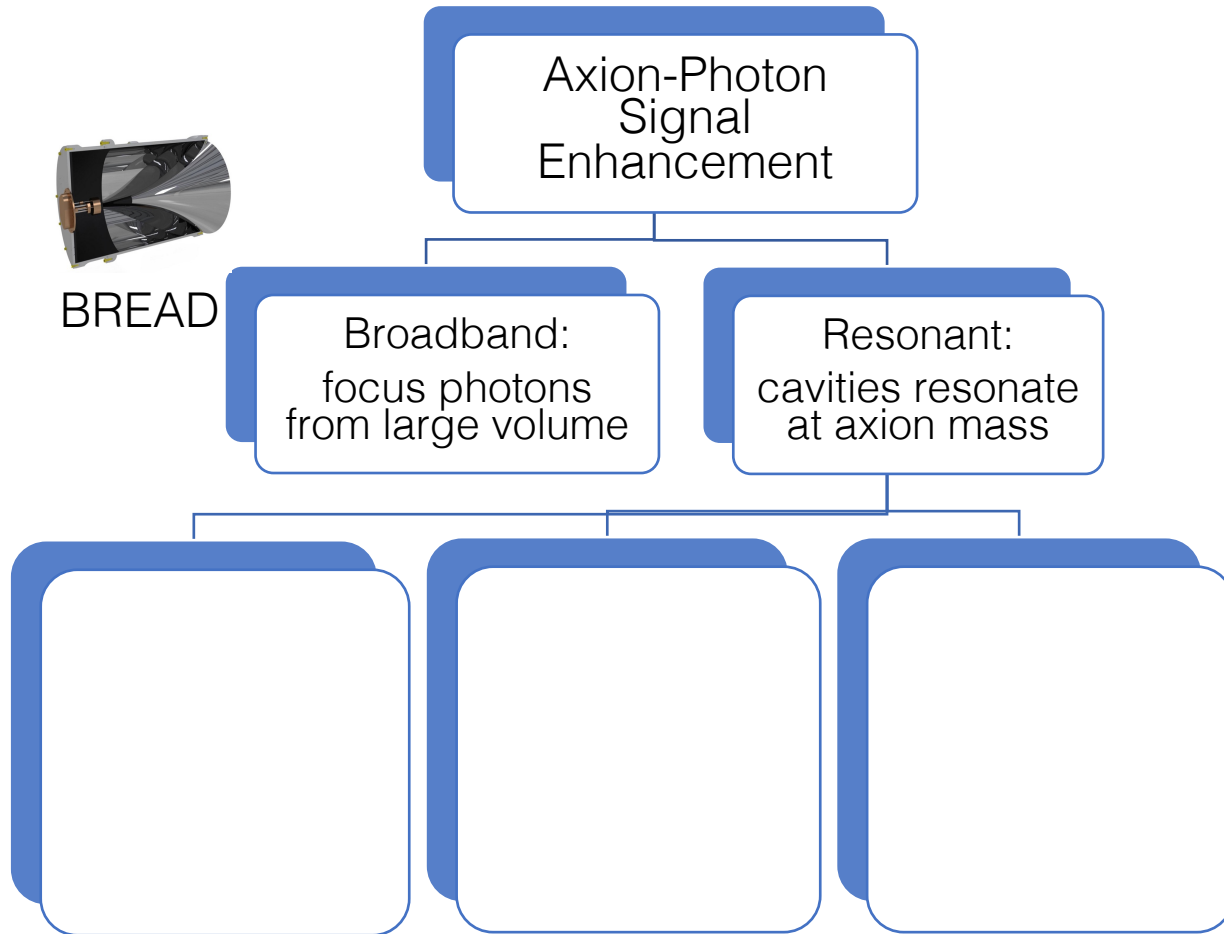
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Material Resonances Enhance Axion-Photon Conversion

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$$\lambda_{\text{med}} = \frac{\lambda_{\text{vac}}}{\tilde{n}} \rightarrow \infty$$

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Momentum Match

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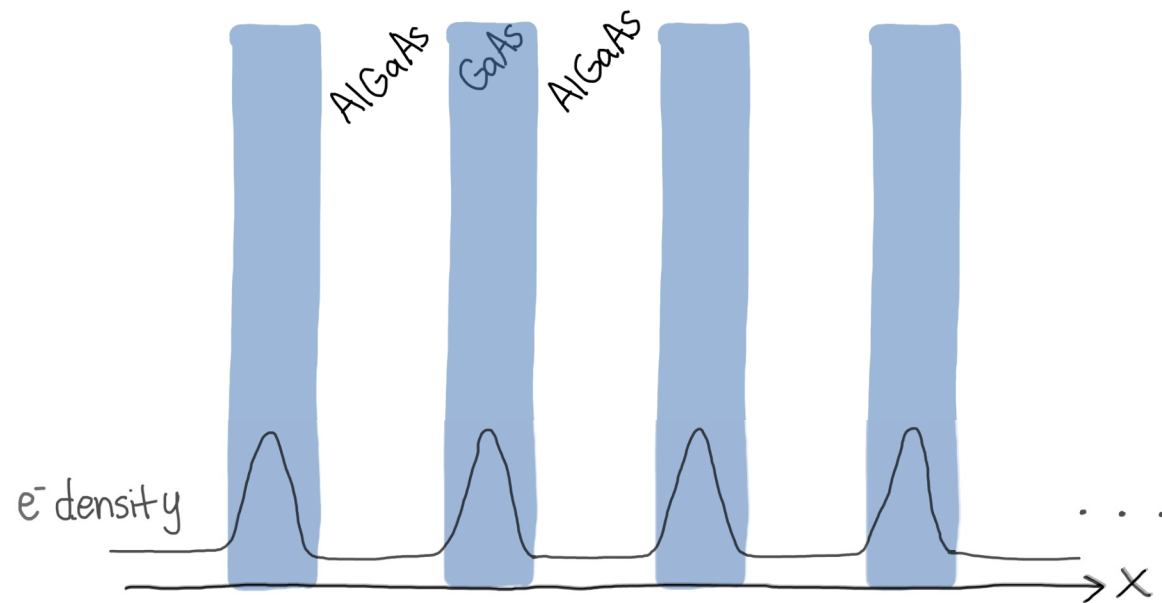
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light hybridizing with matter, gaining effective mass

Multiple Quantum Wells (MQW)!

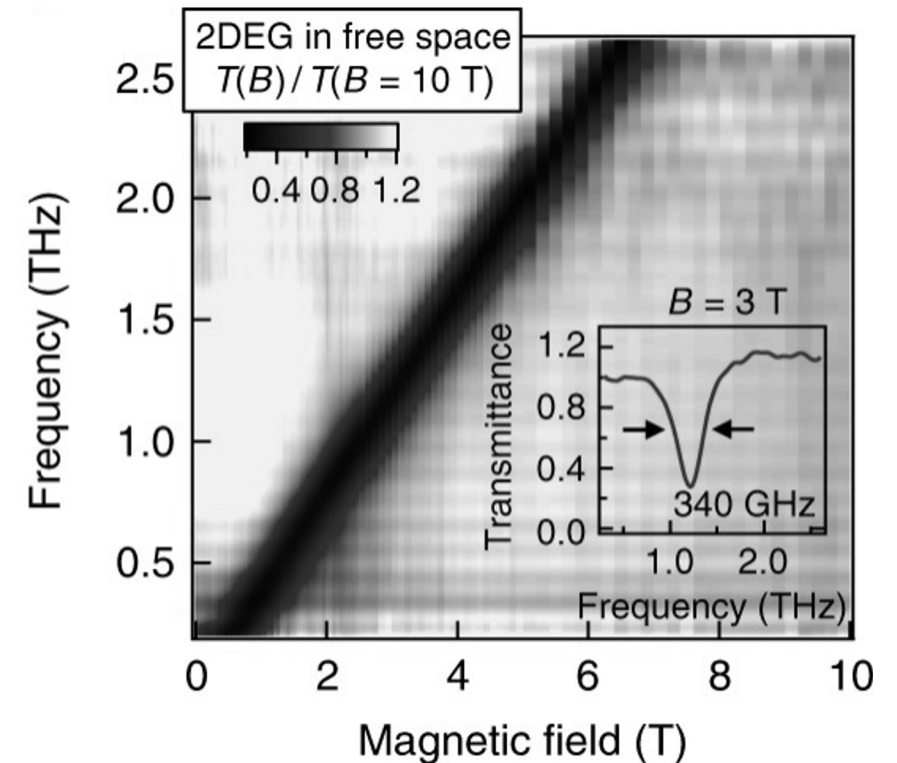
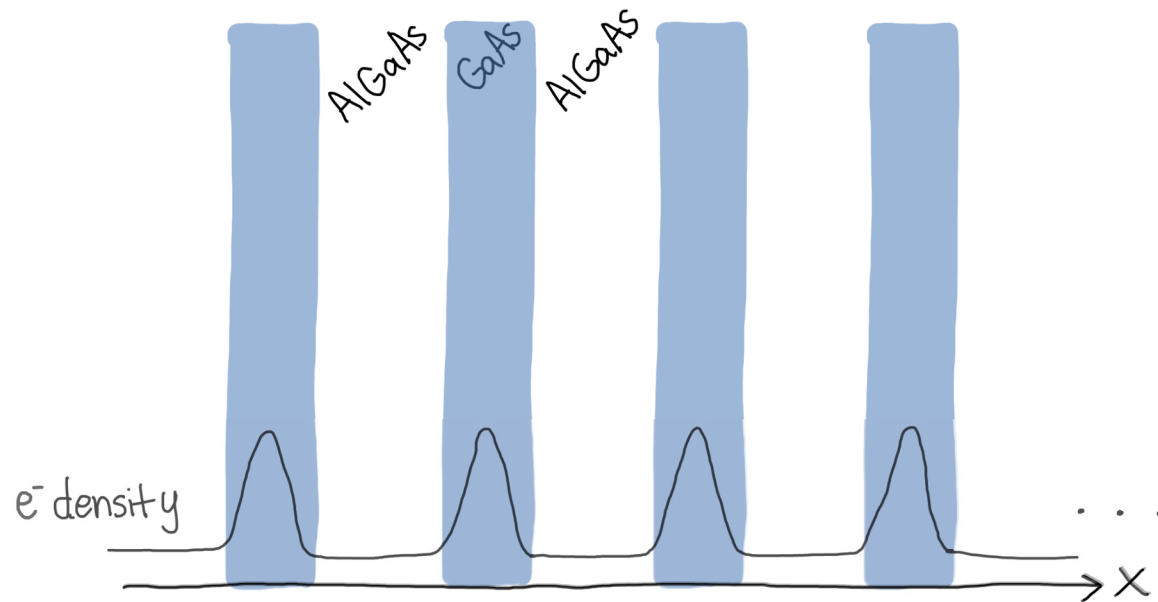
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- Low-loss THz plasmonic resonances that are electromagnetically tunable...



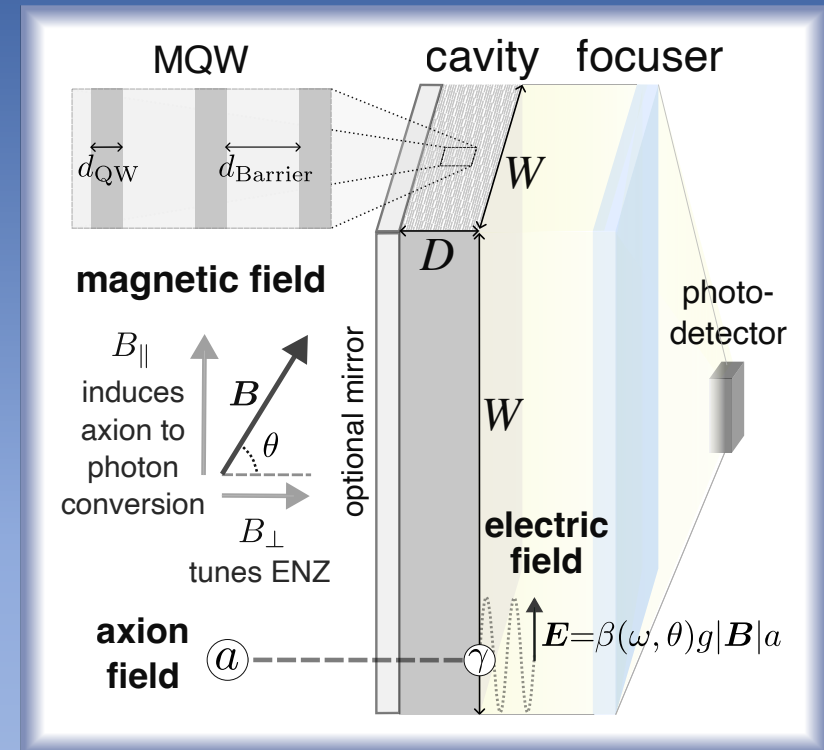
Multiple Quantum Wells (MQW)!

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Li, X., [Manfra, M.](#), [Kono, J.](#), et. al.
Nature Photonics (2018)

Semiconductor-Quantum-Well Axion Radiometer Experiment

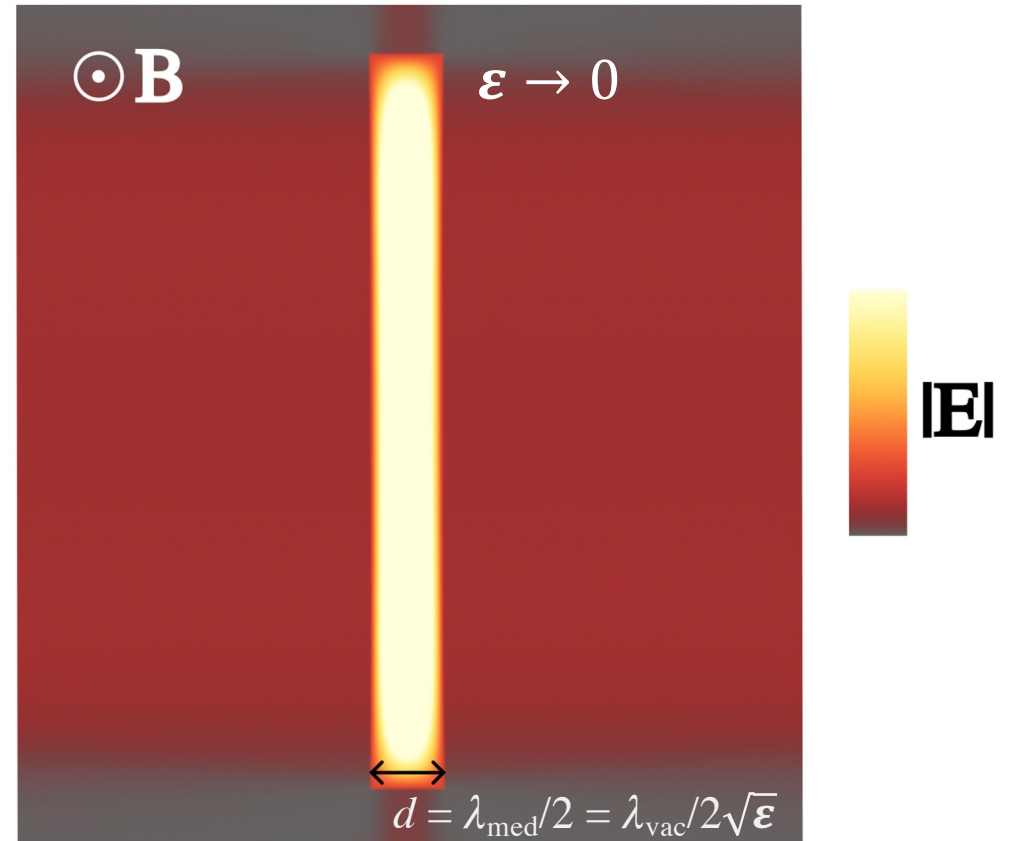


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Axion Response from MQW Cavity

- Axion-induced electric field

$$E_{\text{vac}} = g_{\alpha\gamma} B a$$



COMSOL Simulation

Mehrani, arXiv:2509.14320

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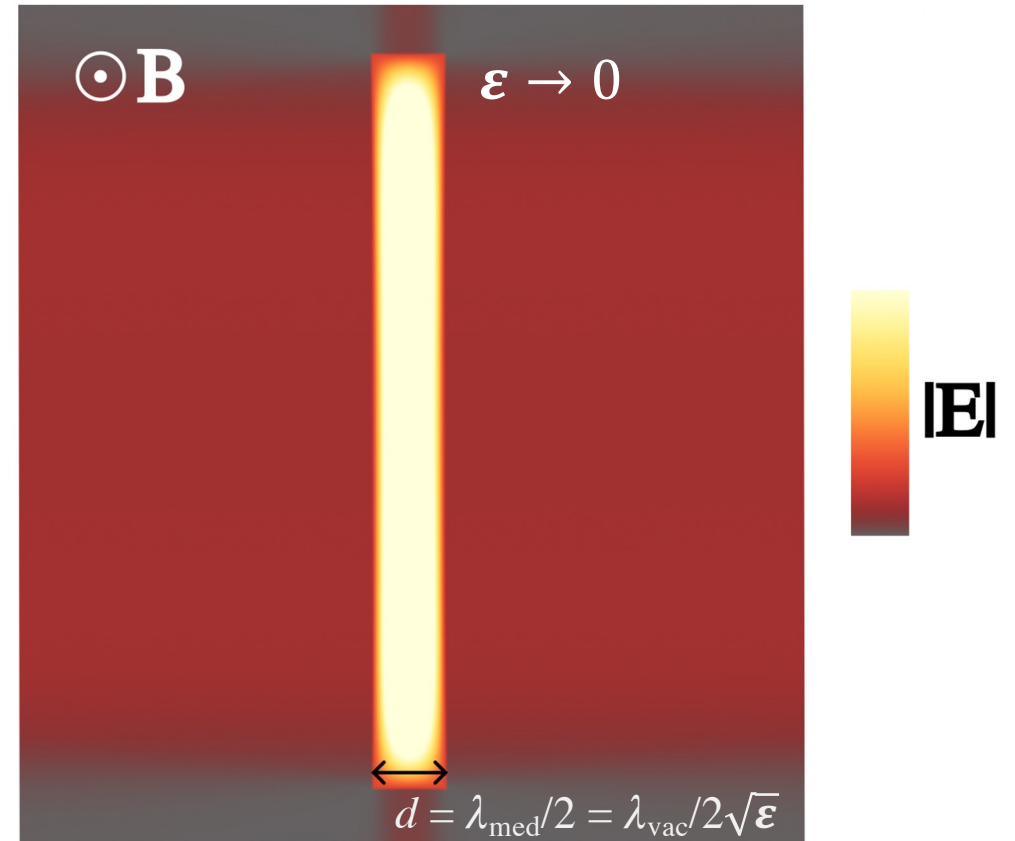
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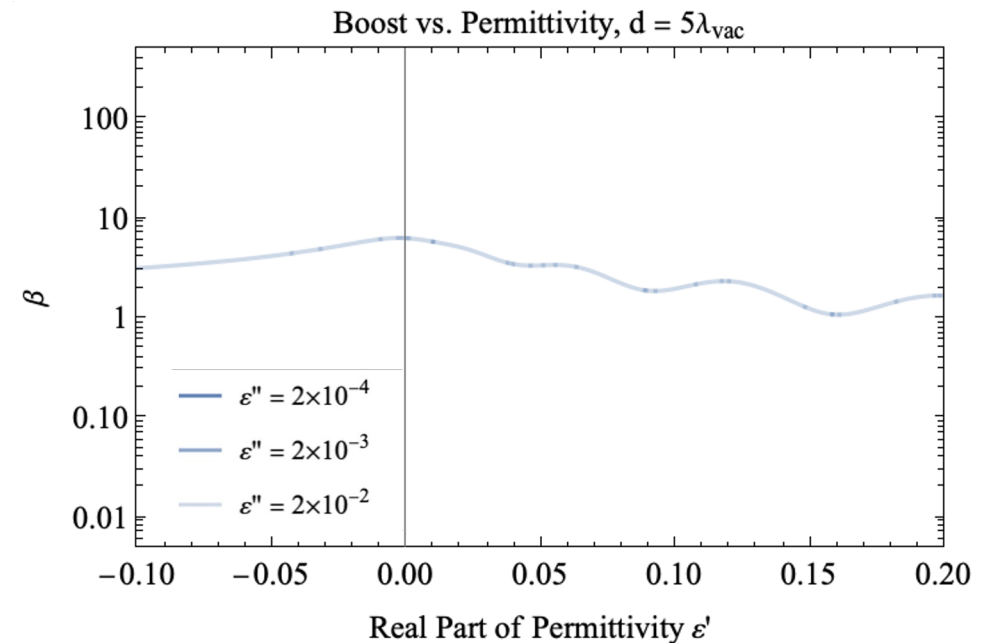
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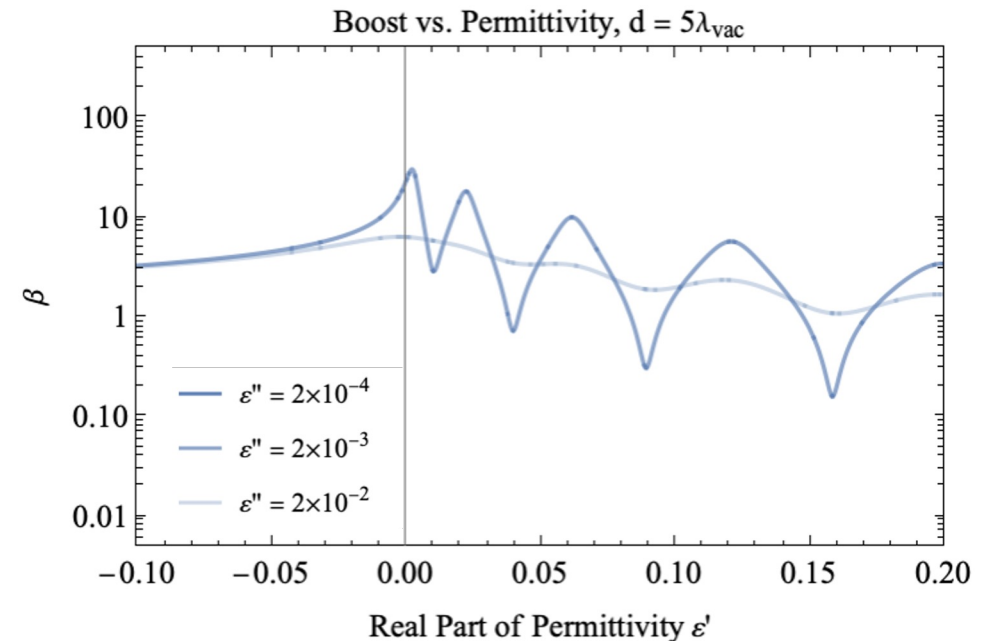
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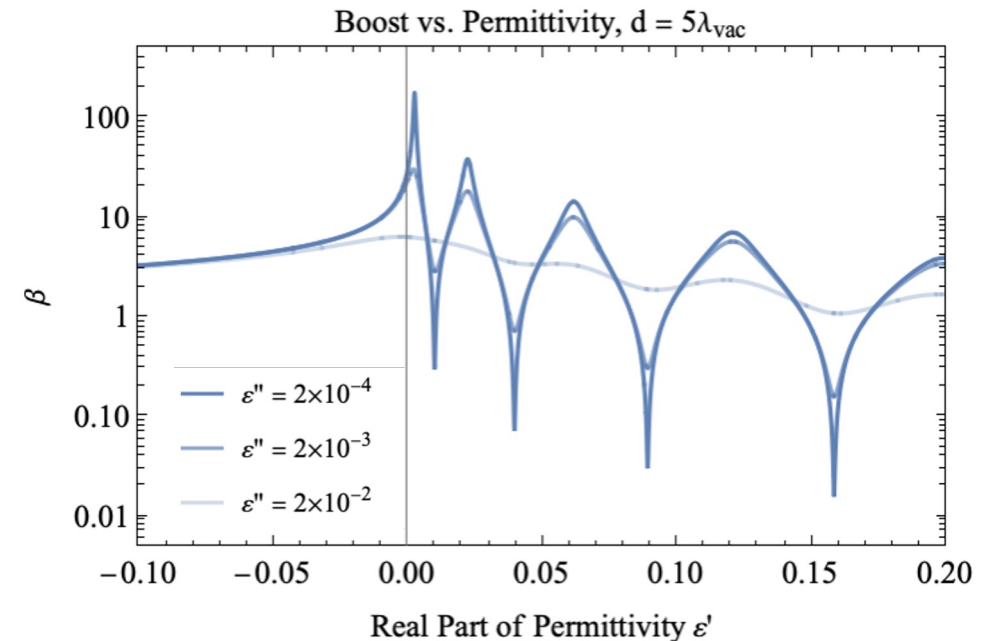
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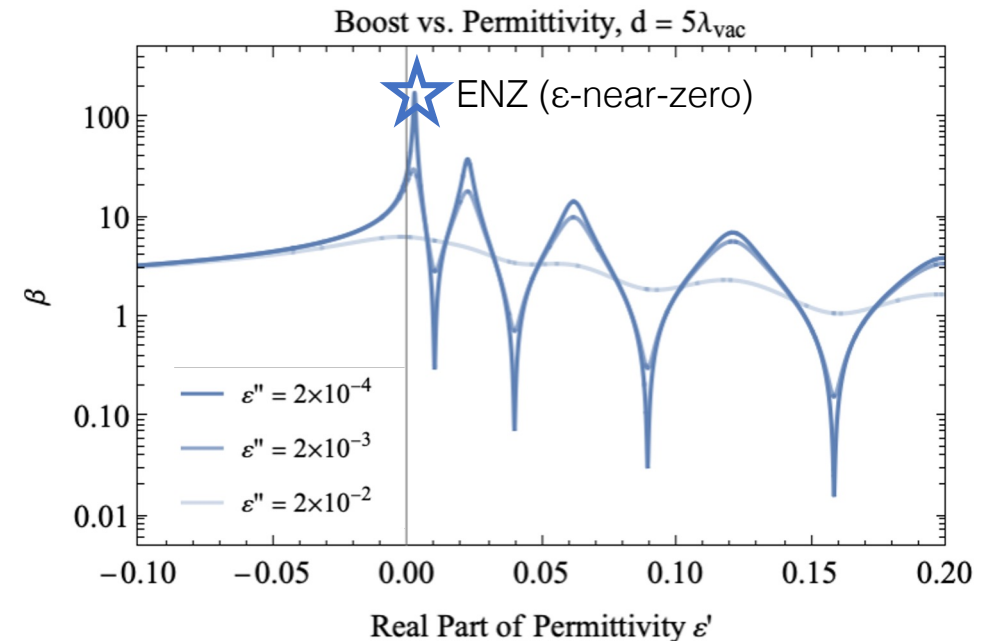
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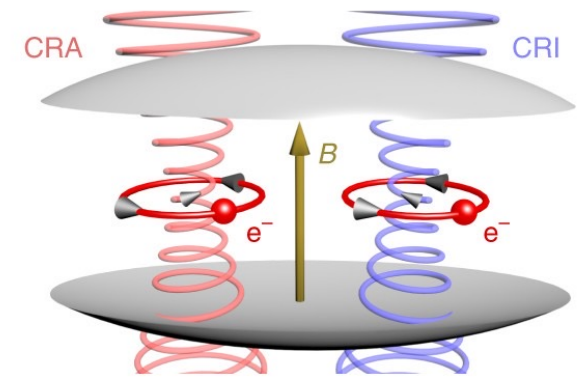


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ENZ Tunability in MQW

- A magnetic field tunes the ENZ point with cyclotron resonance

$$\hat{m}^* \cdot \frac{d\mathbf{v}}{dt} + \hat{m}^* \cdot \frac{\mathbf{v}}{\tau} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad \mathbf{J} = ne\mathbf{v} = \hat{\sigma} \cdot \mathbf{E}$$



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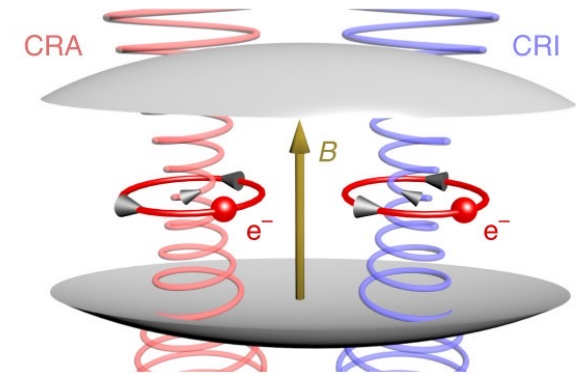
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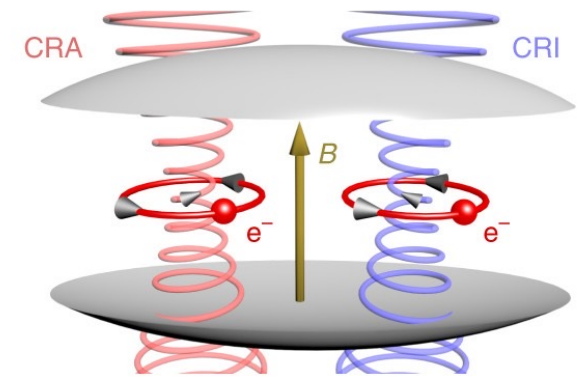
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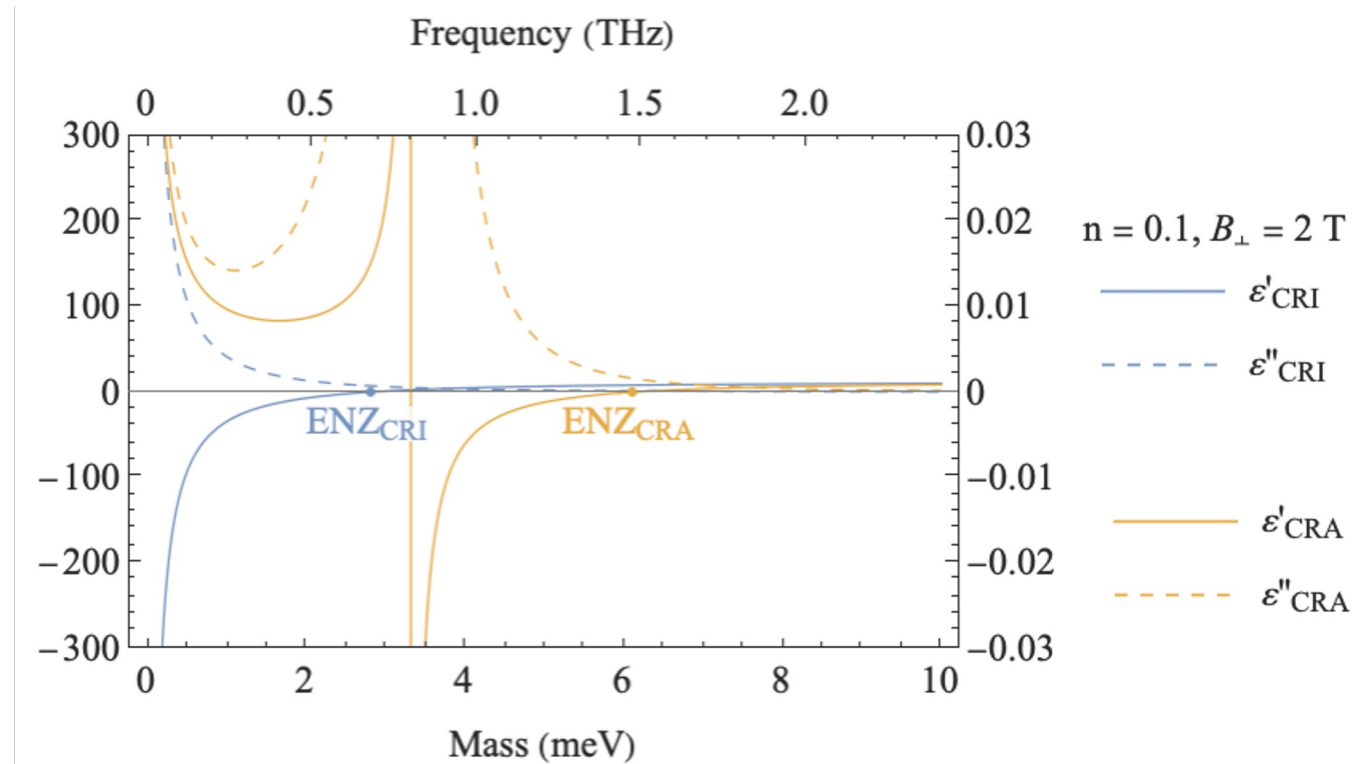
- Permittivity

$$\hat{\epsilon} = \hat{\epsilon}_{\text{bg}} + i \frac{\hat{\sigma}}{\omega \epsilon_0 d_{\text{QW}}}$$



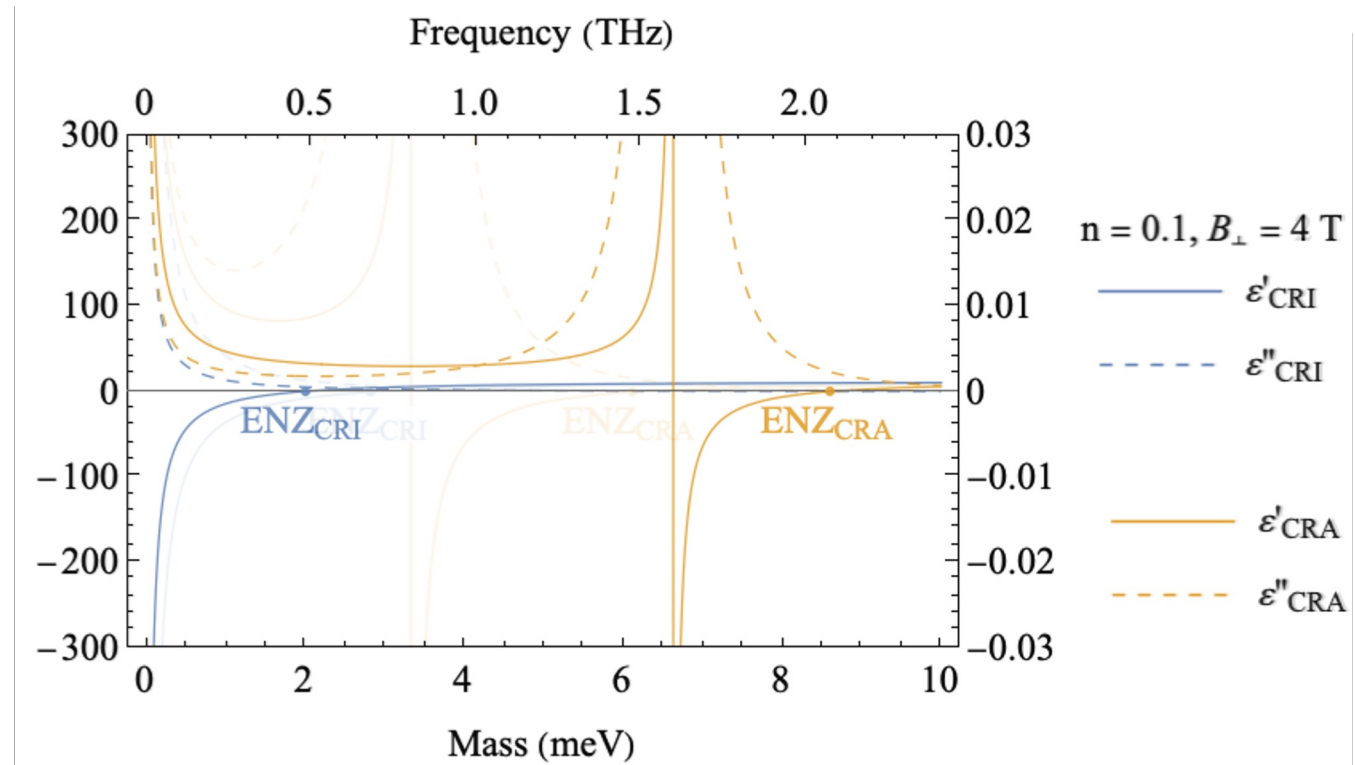
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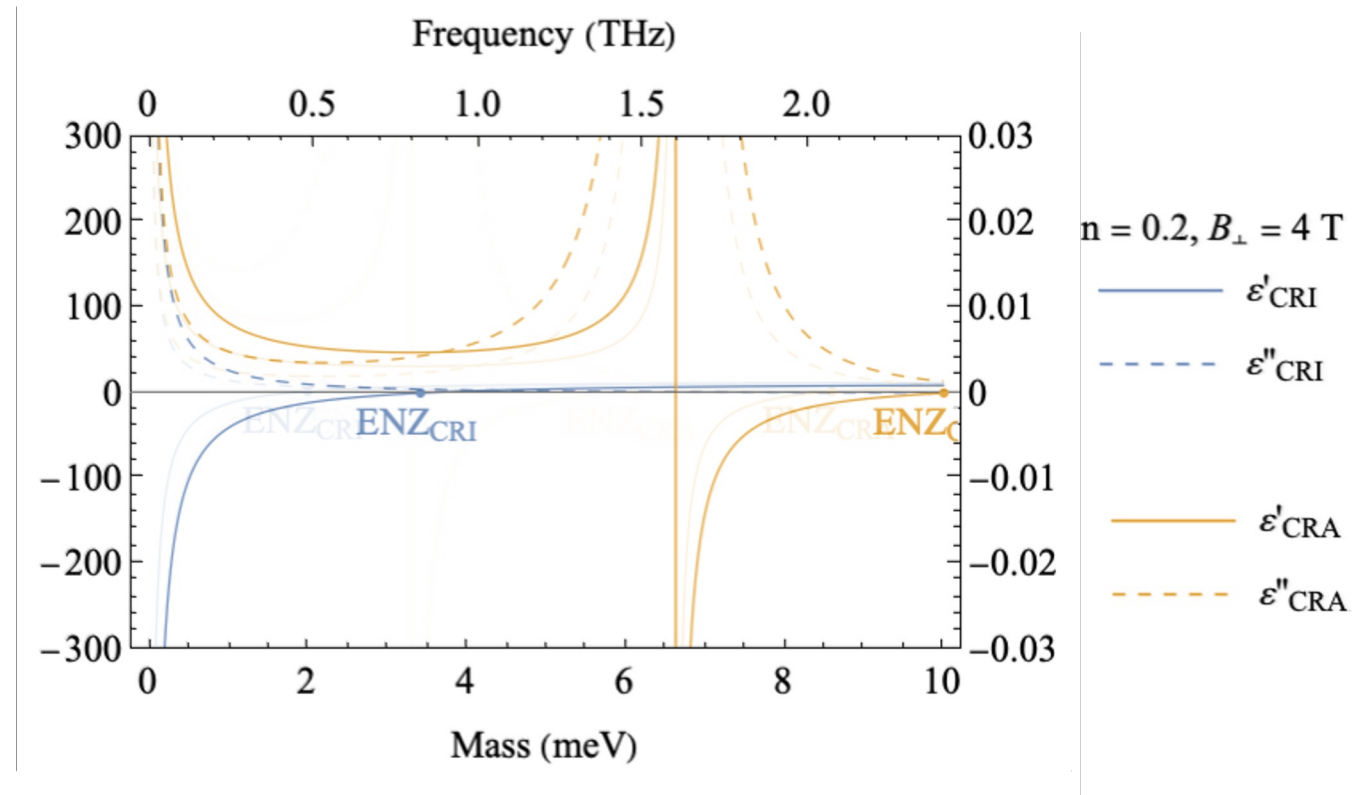
Mehrani, arXiv:2509.14320

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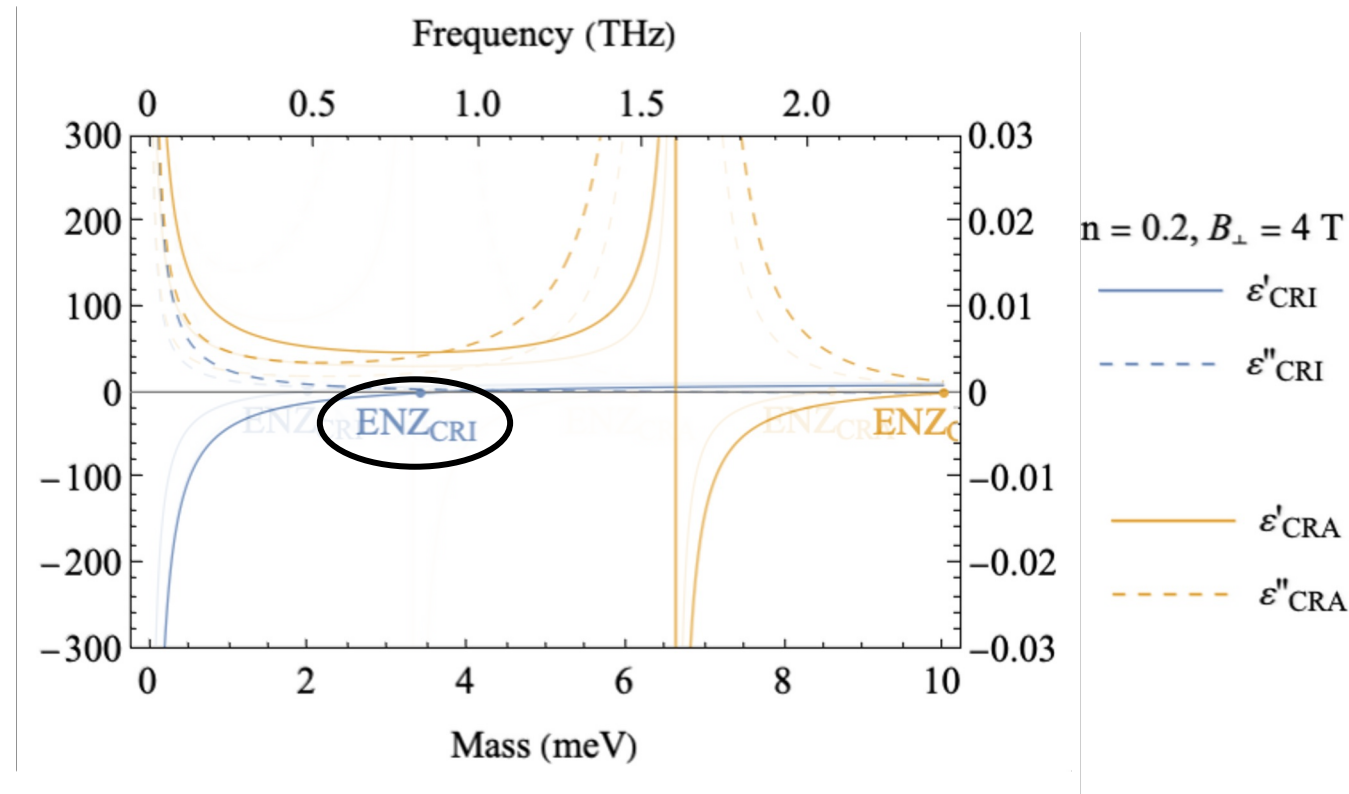


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ENZ Tunability in MQW

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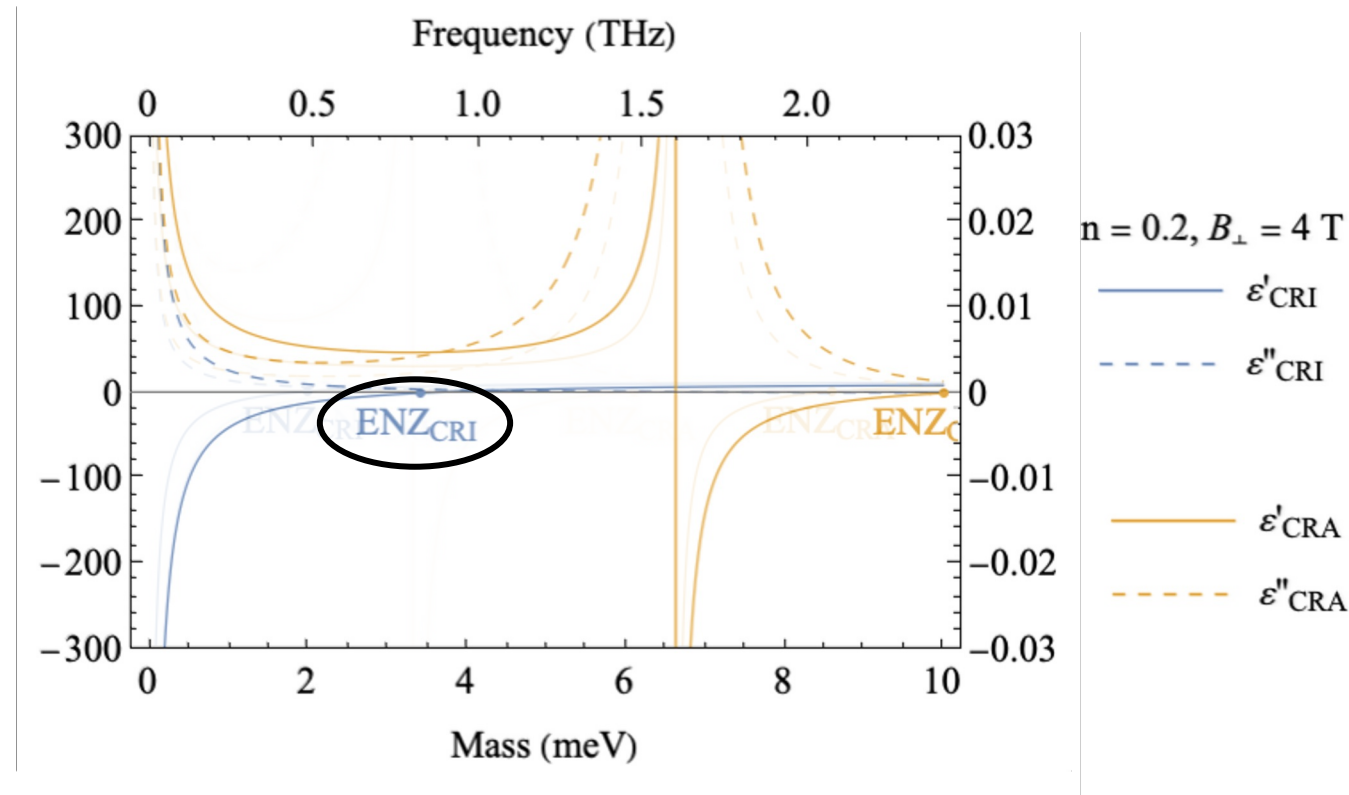
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- MQWs use effective medium theory (EMT)

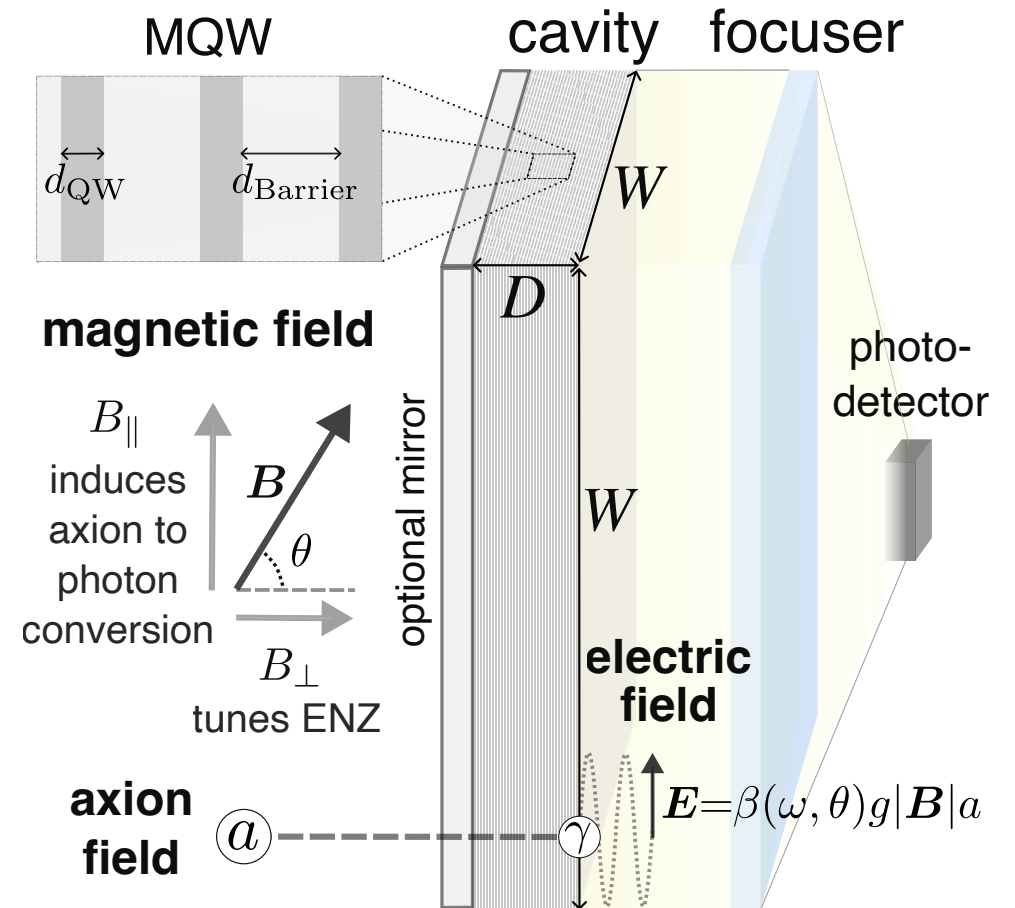
$$\epsilon_{\text{eff}} = \frac{\epsilon_{\text{barrier}} d_{\text{Barrier}} + \epsilon_{\text{QW}} d_{\text{QW}}}{d_{\text{Barrier}} + d_{\text{QW}}}$$



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Dual Magnetic Field Control

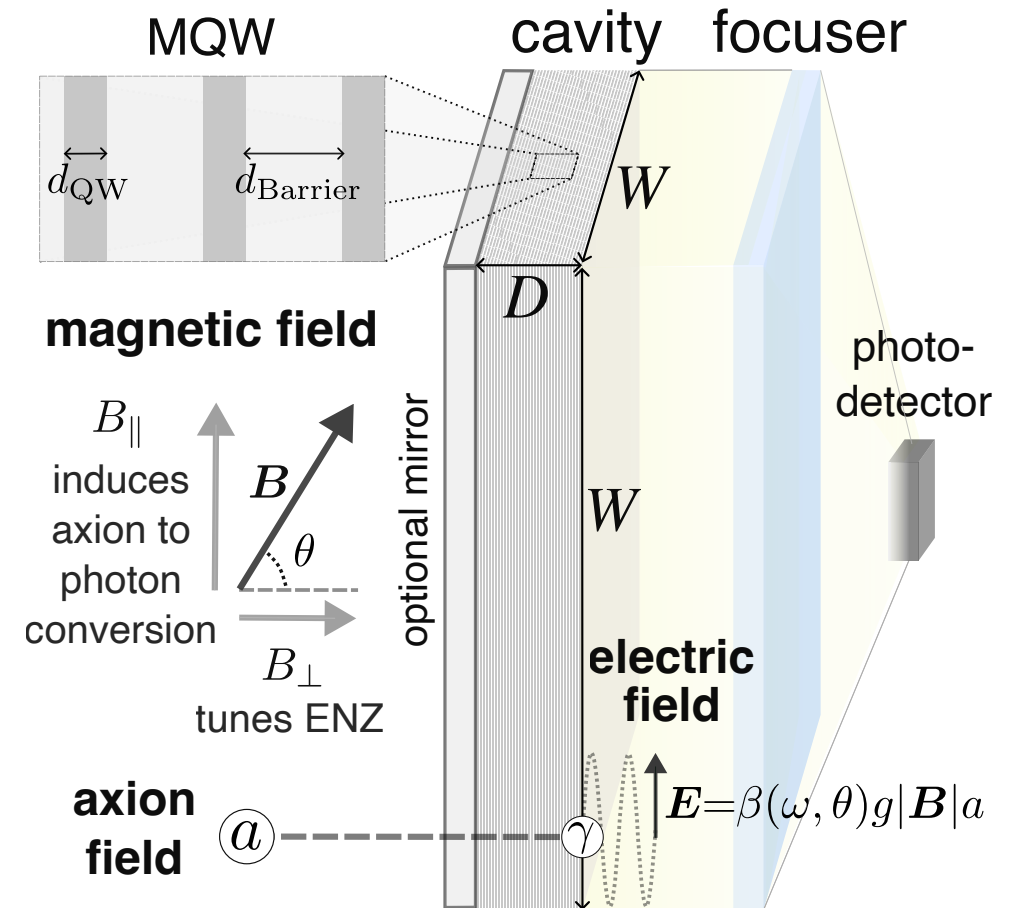
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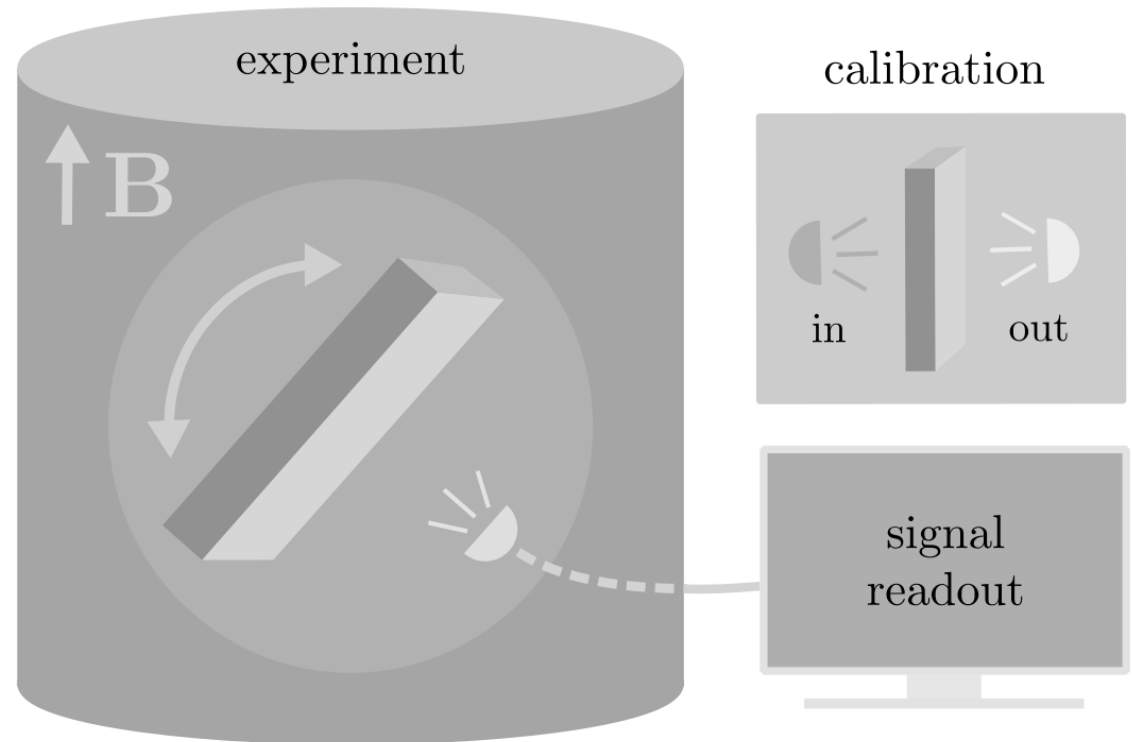
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- \mathbf{B}_{\parallel} , parallel to MQW surface, generates electric field component parallel to surface



Mehrani, arXiv:2509.14320

Dual Magnetic Field Control

- \mathbf{B}_{\perp} , normal to MQW surface, tunes the ENZ, the permittivity component parallel to surface
- \mathbf{B}_{\parallel} , parallel to MQW surface, generates electric field component parallel to surface
- Tuning by tilting θ .



Mehrani, arXiv:2509.14320

Experimental Parameters

Parameter	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
T [K]	0.3	0.3	0.3
n [10^{11} cm $^{-2}$]	3	3	3
τ [ns]	1.7	1.7	4
w [cm]	3	3	5
d [mm]	2	10	20
d_{QW} [nm]	30	30	30
d_{Barrier} [nm]	90	150	90
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35

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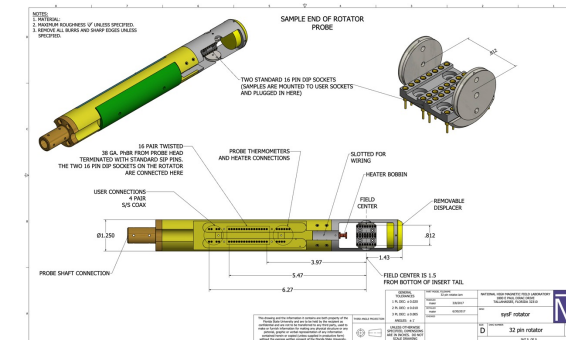
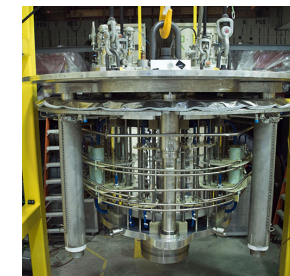
Experimental Parameters: Magnetic field

Realistic ←————→ Optimistic

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η [%]	7	20	35

NATIONAL HIGH
MAGNETIC
FIELD LABORATORY

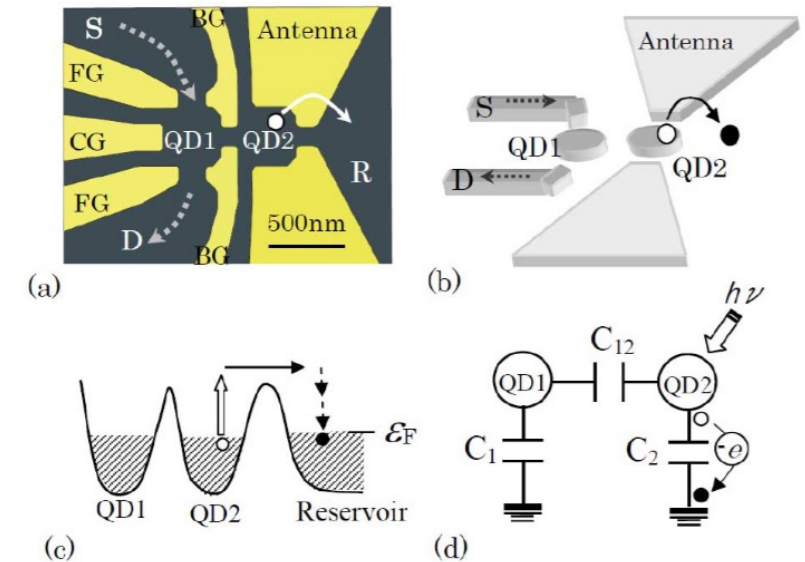
- **Field strength:** 36 tesla
- **Bore size:** 40 mm
- **Power:** 14 MW
- **Homogeneity:** 1 ppm (in NMR Configuration)
- **Number of input and output leads possible:** 36
- **Frequency:** 0-1.5 GHz
- **Temperature Range:** 0.3-300K
- **Uniformity Over 10 mm DSV:** 1 ppm (NMR configuration)
- **Open for users who would pay for magnet time:** Yes



Mehrani, arXiv:2509.14320

Experimental Parameters: Photodetector

Parameter	Realistic ←————→ Optimistic		
	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
T [K]	0.3	0.3	0.3
n [10^{11} cm^{-2}]	3	3	3
τ [ns]	1.7	1.7	4
w [cm]	3	3	5
d [mm]	2	10	20
d_{QW} [nm]	30	30	30
d_{Barrier} [nm]	90	150	90
Γ_{dark} [mHz]	1	1	0.1
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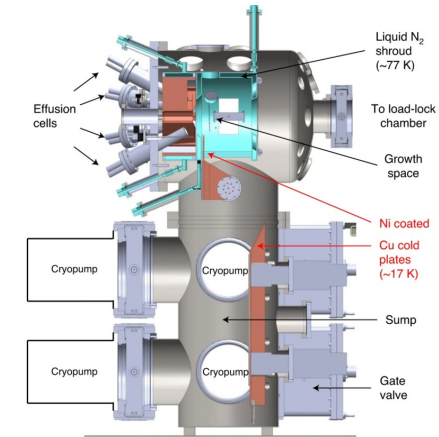
Komiyama S., IEEE Journal of Selected Topics in Quantum Electronics (2011)

Mehrani, arXiv:2509.14320

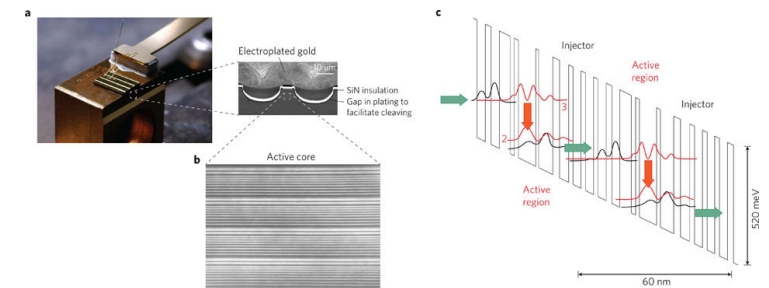
Experimental Parameters: MQW

Parameter	Realistic ←————→ Optimistic		
	Config. 1	Config. 2	Config. 3
B [T]	36	36	50
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Mehrani, arXiv:2509.14320



Nature Materials 20 632-637 (2021)

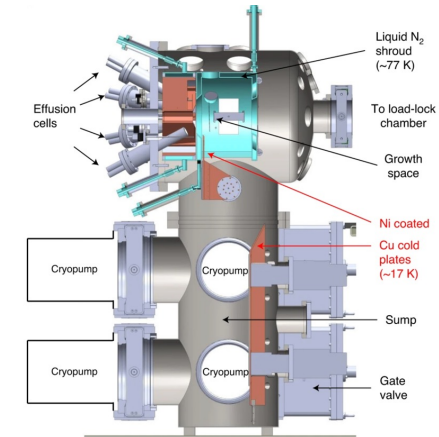


Nature Photonics 6 432-439 (2012)

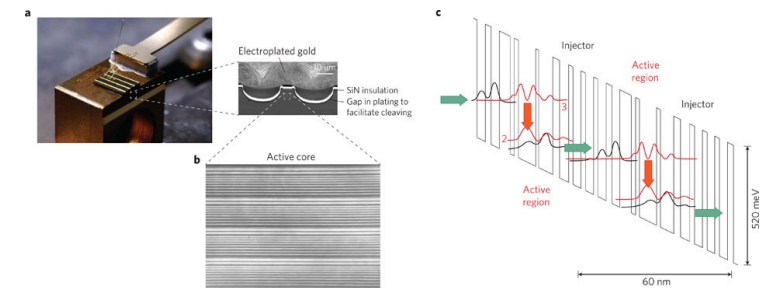
Experimental Parameters: MQW

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Mehrani, arXiv:2509.14320

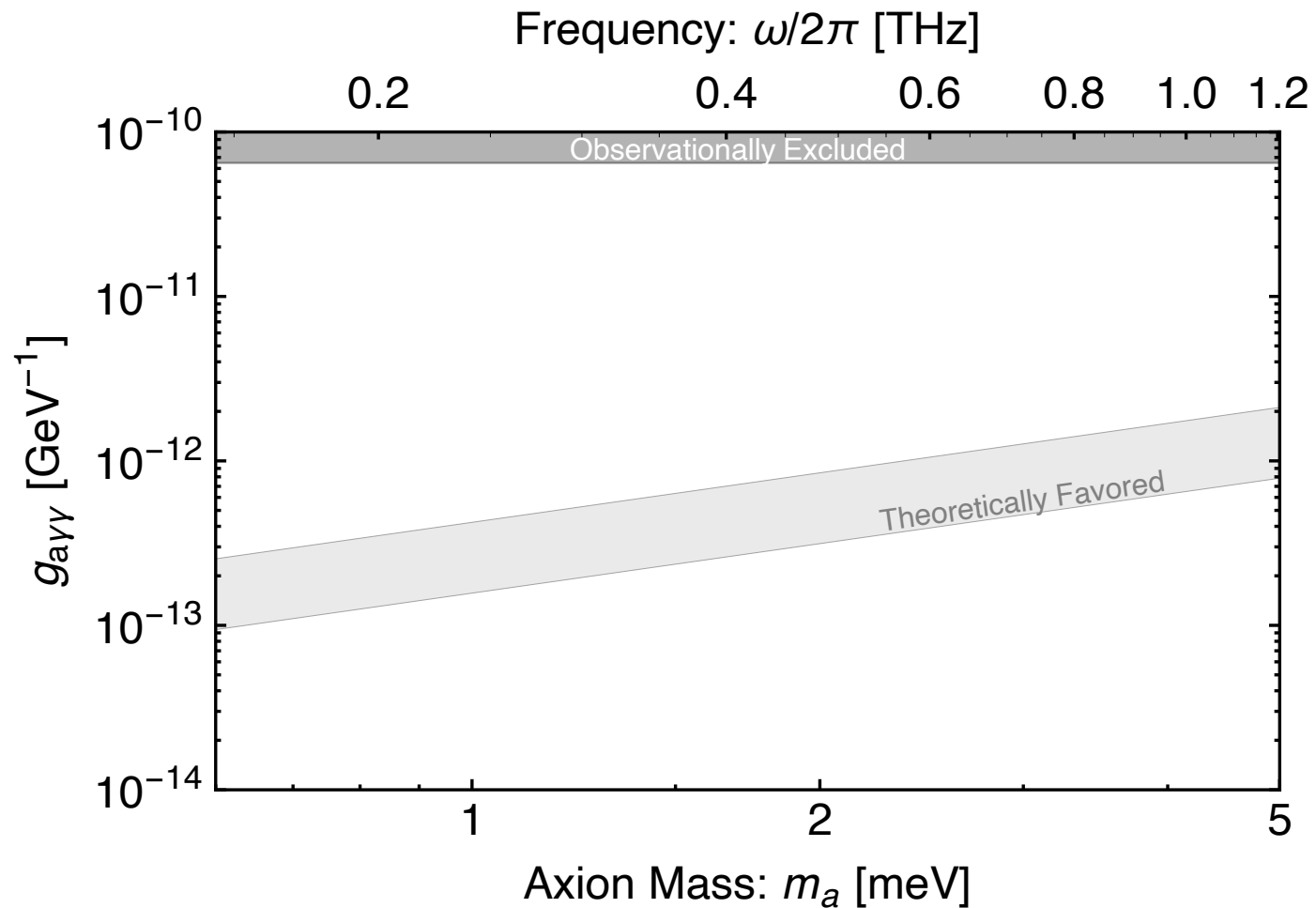


Nature Materials 20 632-637 (2021)



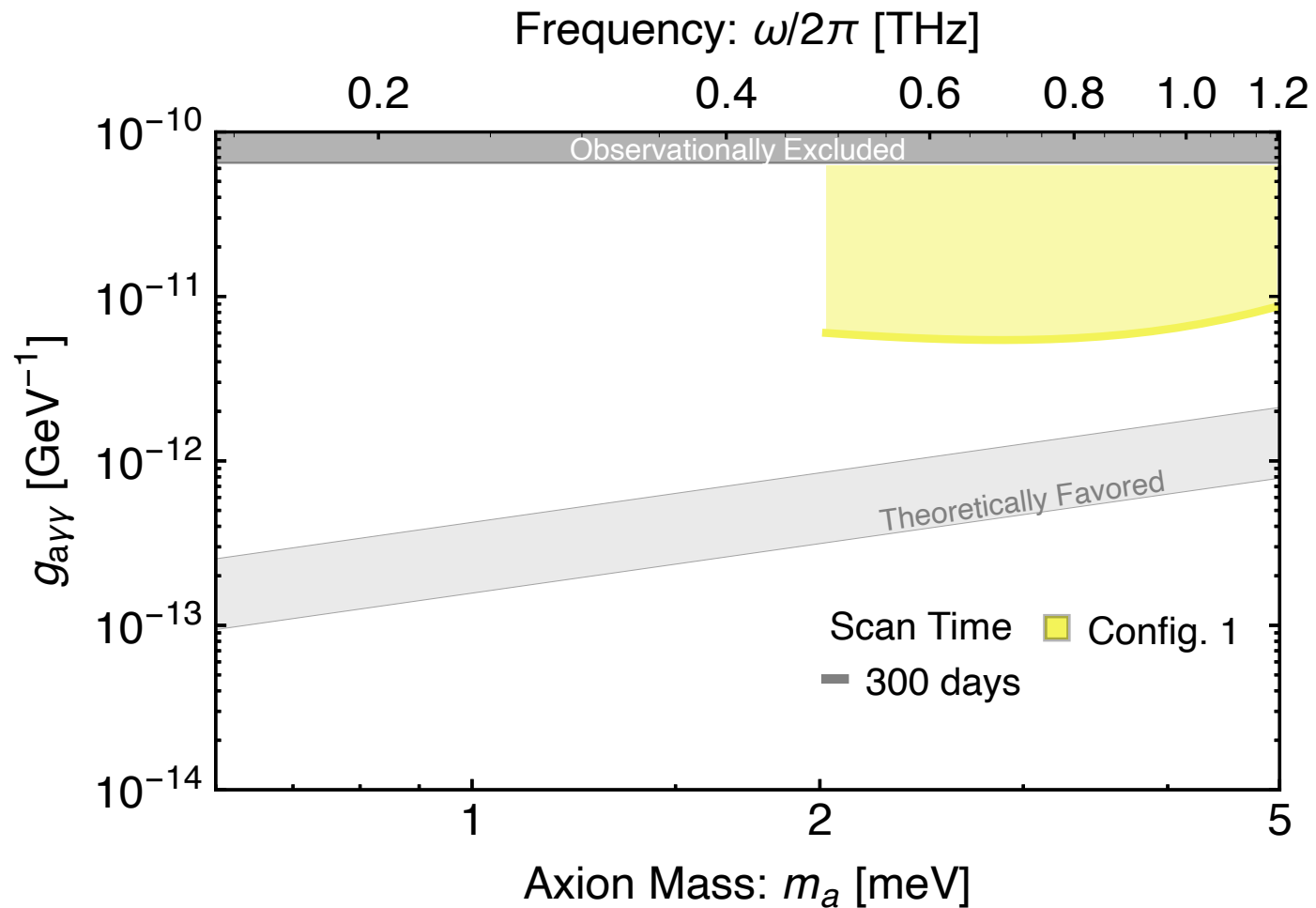
Nature Photonics 6 432-439 (2012)

Axion Proposed Sensitivity



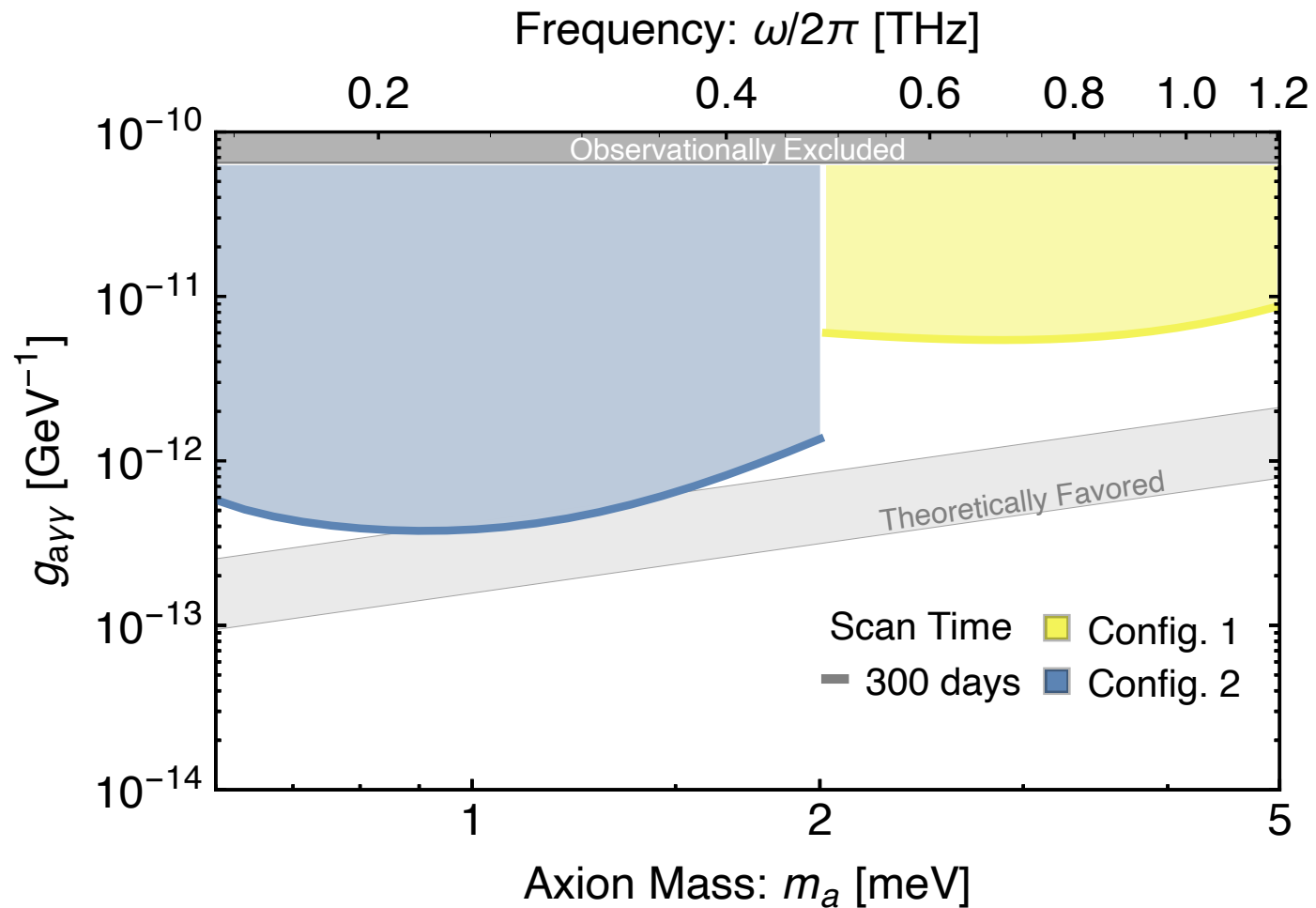
Mehrani, arXiv:2509.14320

Axion Proposed Sensitivity



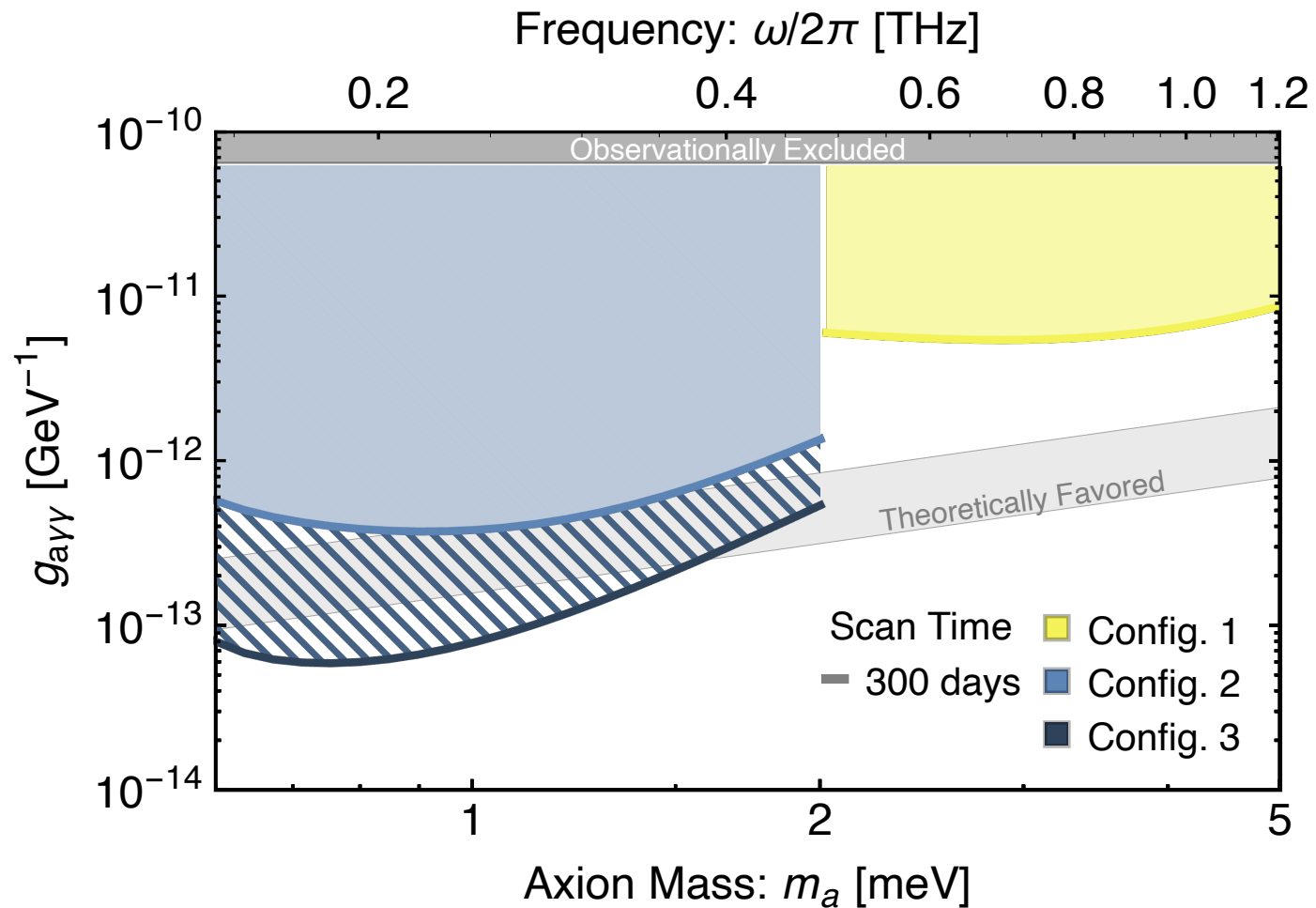
Mehrani, arXiv:2509.14320

Axion Proposed Sensitivity



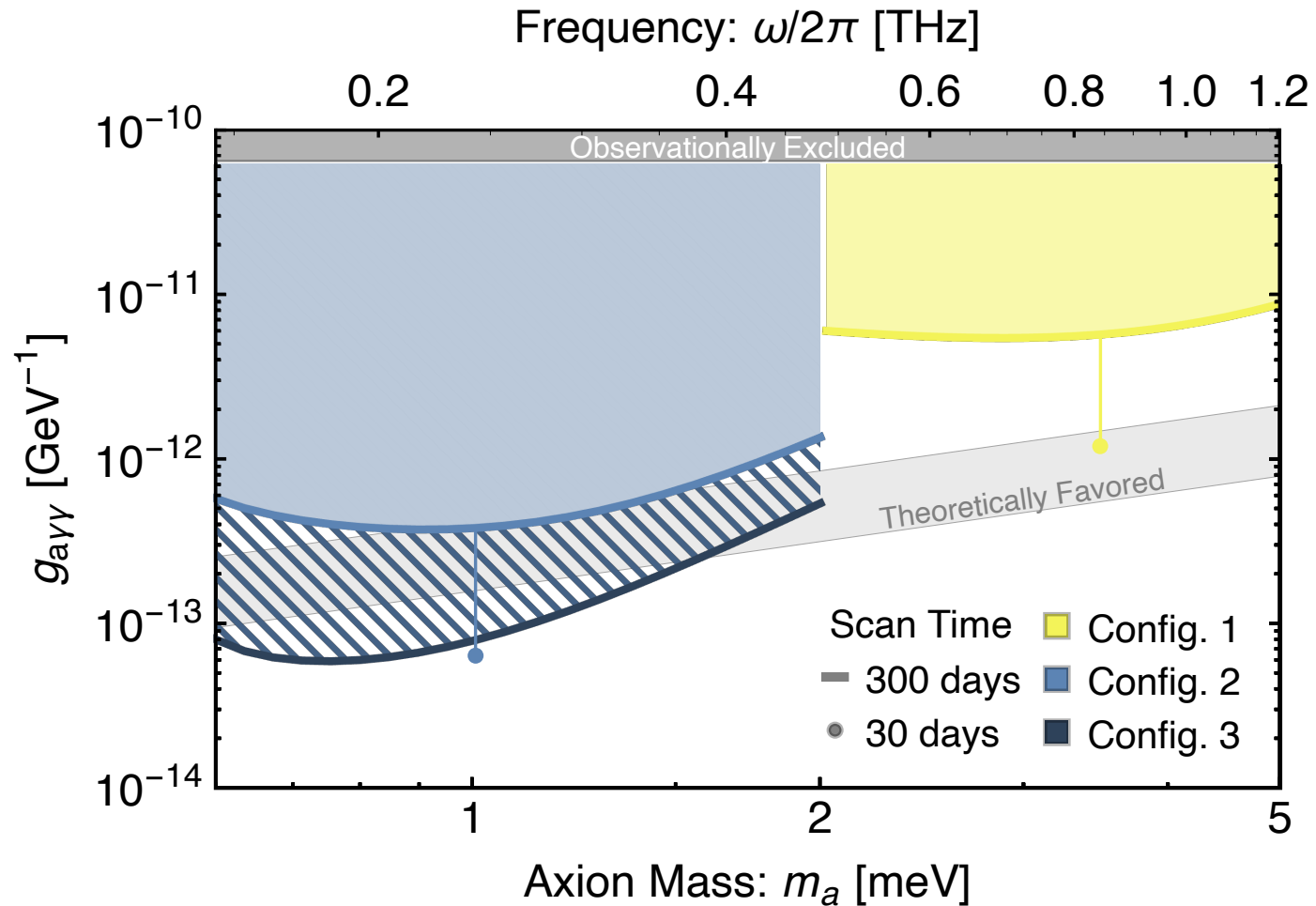
Mehrani, arXiv:2509.14320

Axion Proposed Sensitivity



Mehrani, arXiv:2509.14320

Axion Proposed Sensitivity

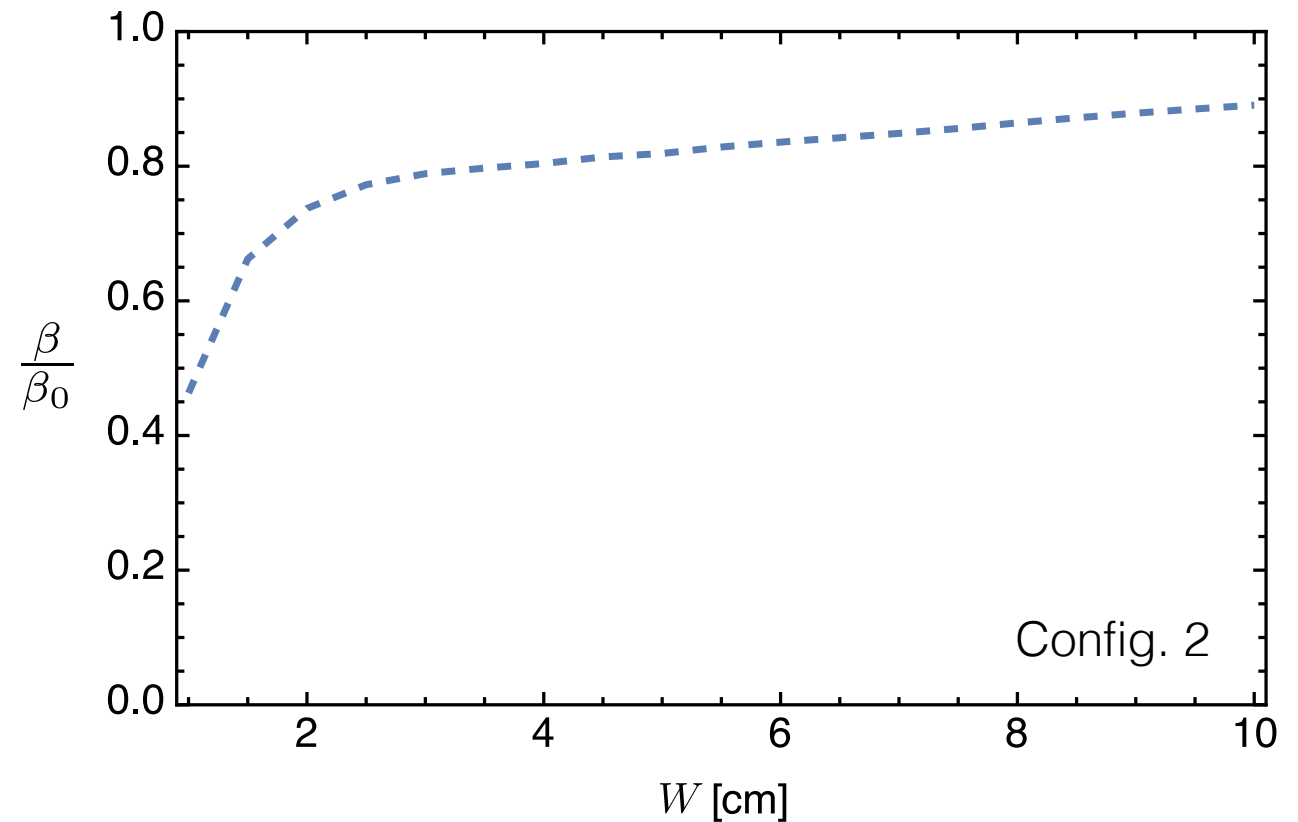


Mehrani, arXiv:2509.14320

Simulating Experimental Conditions in COMSOL

Finite MQW area reduces collimation of surface radiation.

- Aspect ratio of at least ~ 1.5 for 50% boost.

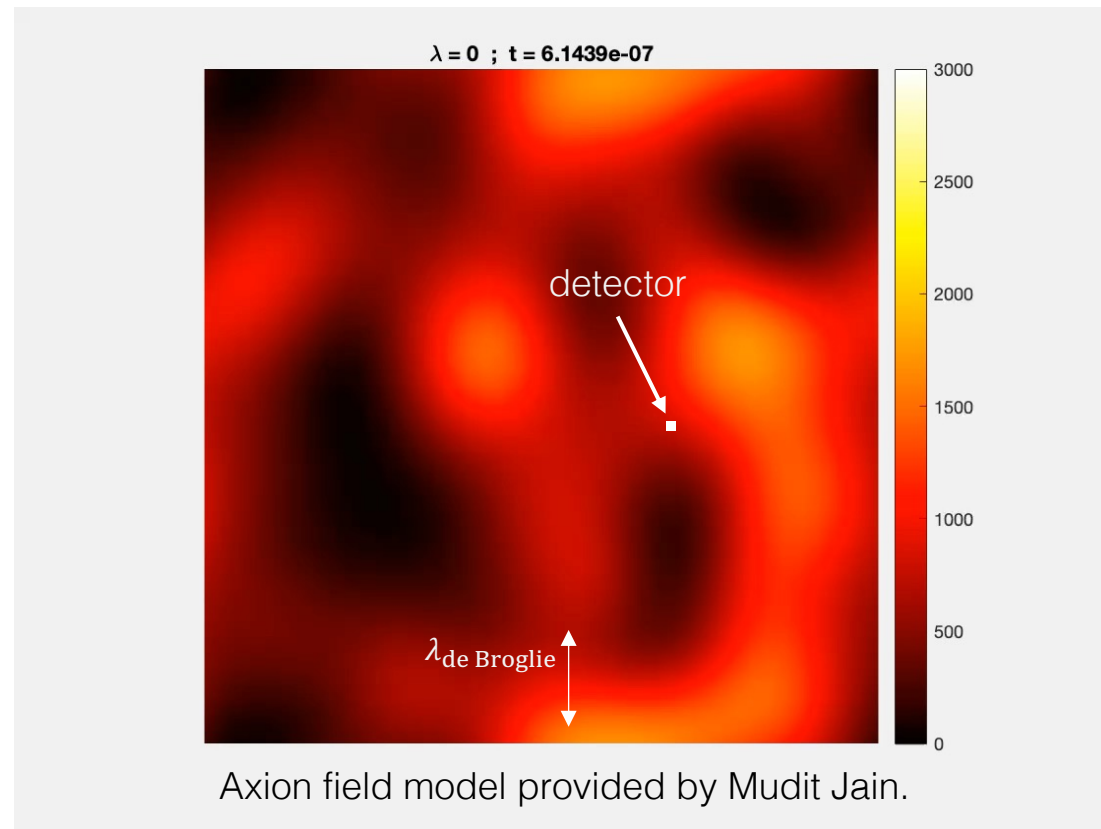


Mehrani, arXiv:2509.14320

Finite axion coherence can reduce photon coherence.

1 meV axion has a 40 cm coherence length ($\lambda_{\text{de Broglie}}$) and 2 μs coherence time

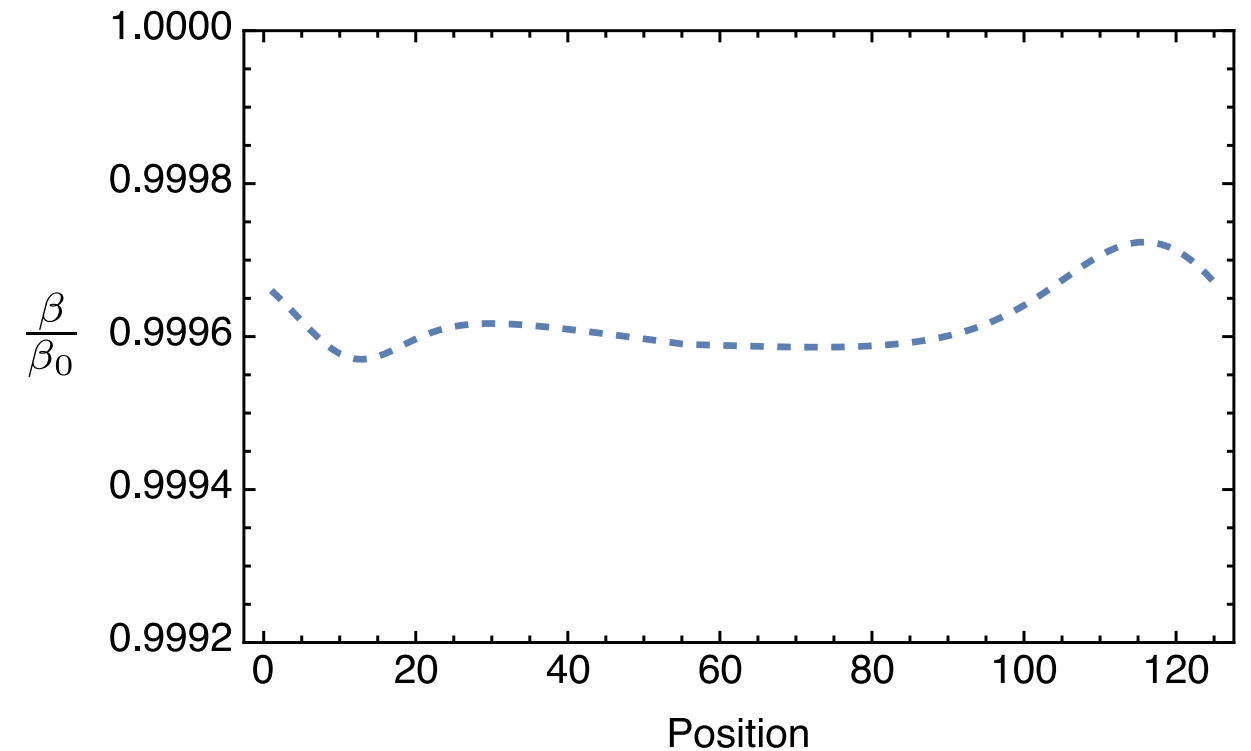
- Detector size is on the order of a few cm
- Detector response is on the order of ns



Finite axion coherence can reduce photon coherence.

- No significant reduction in boost.

Config. 2



Mehrani, arXiv:2509.14320

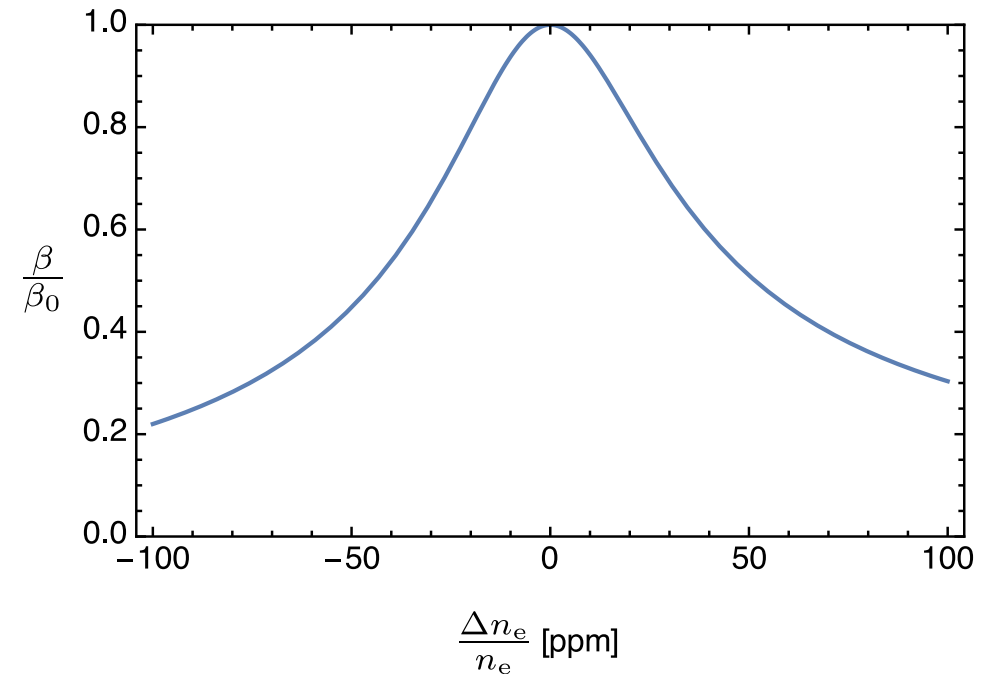
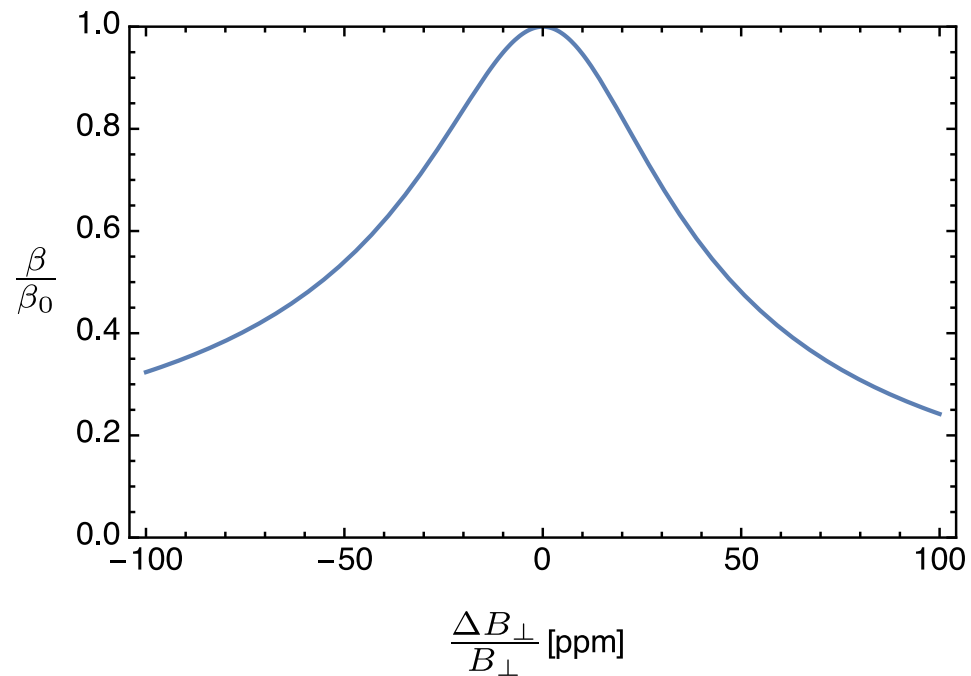
Magnetic field and electron density inhomogeneities broaden resonance.

- The boost is extremely sensitive to B field and e⁻ density.

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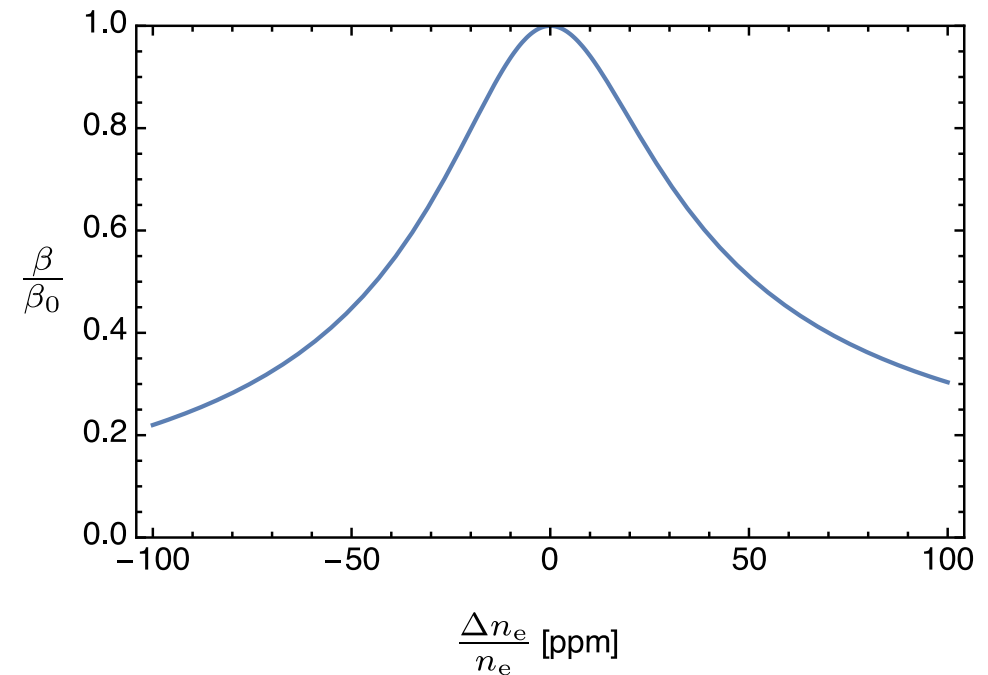
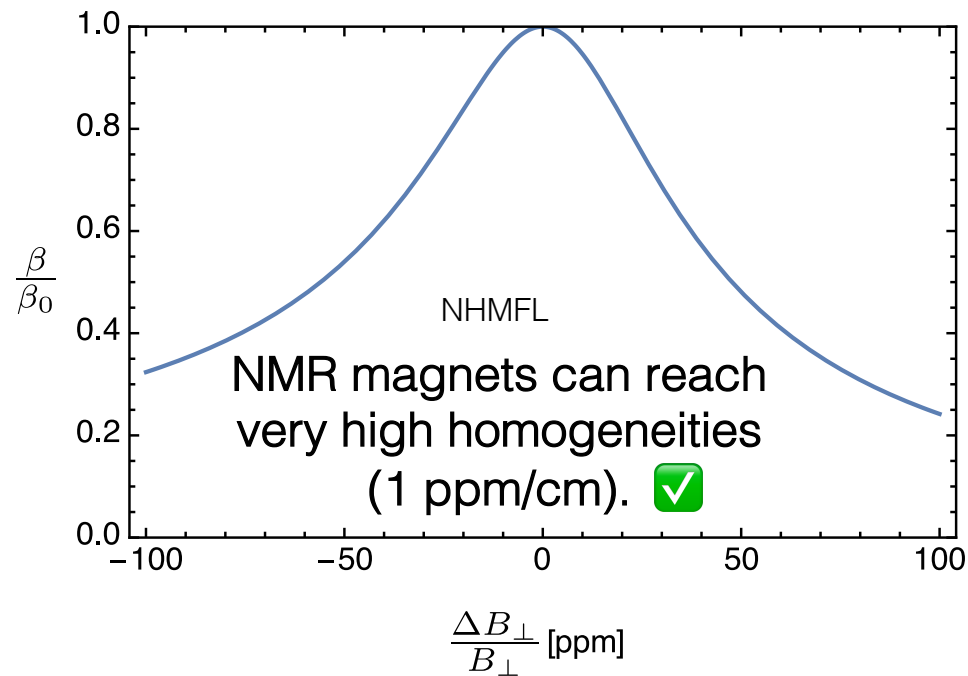


Mehrani, arXiv:2509.14320

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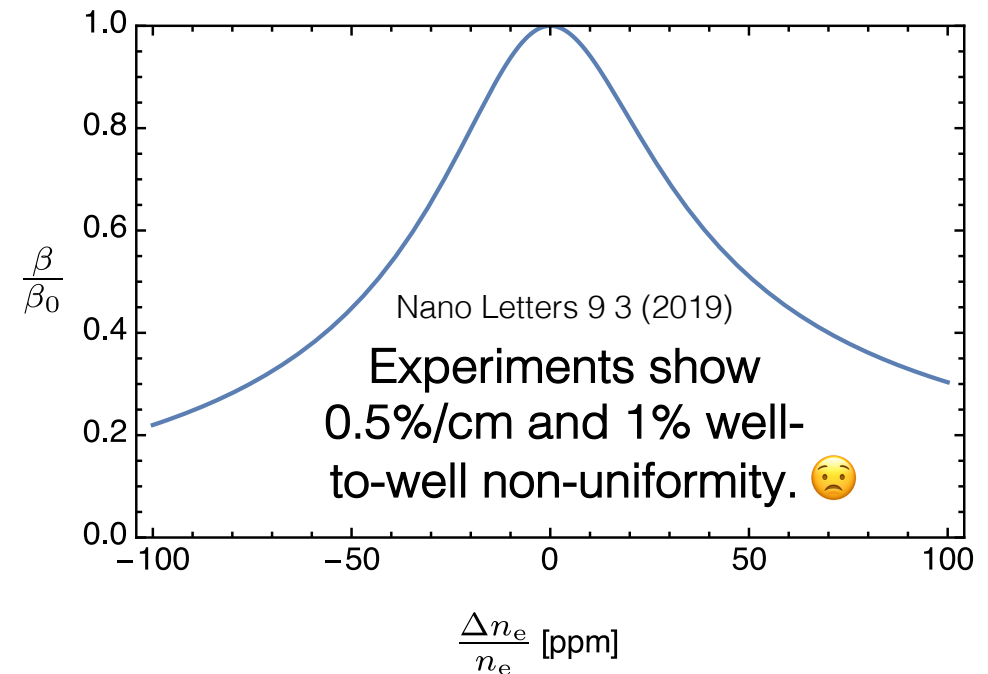
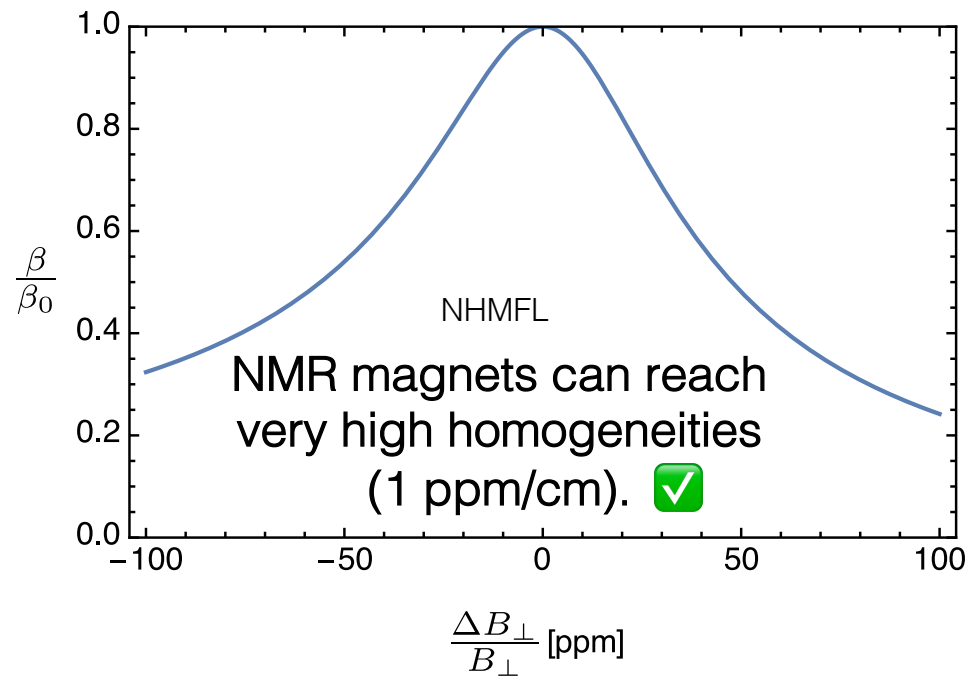


Mehrani, arXiv:2509.14320

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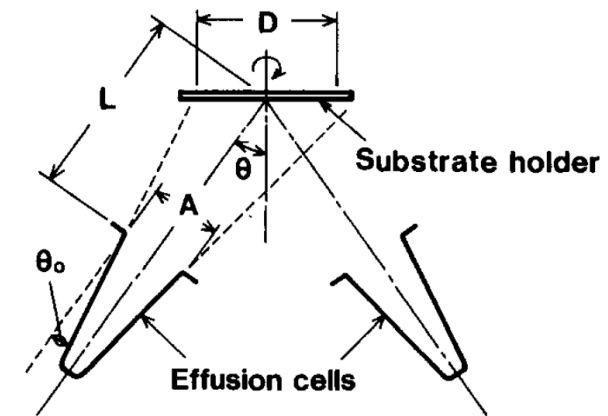
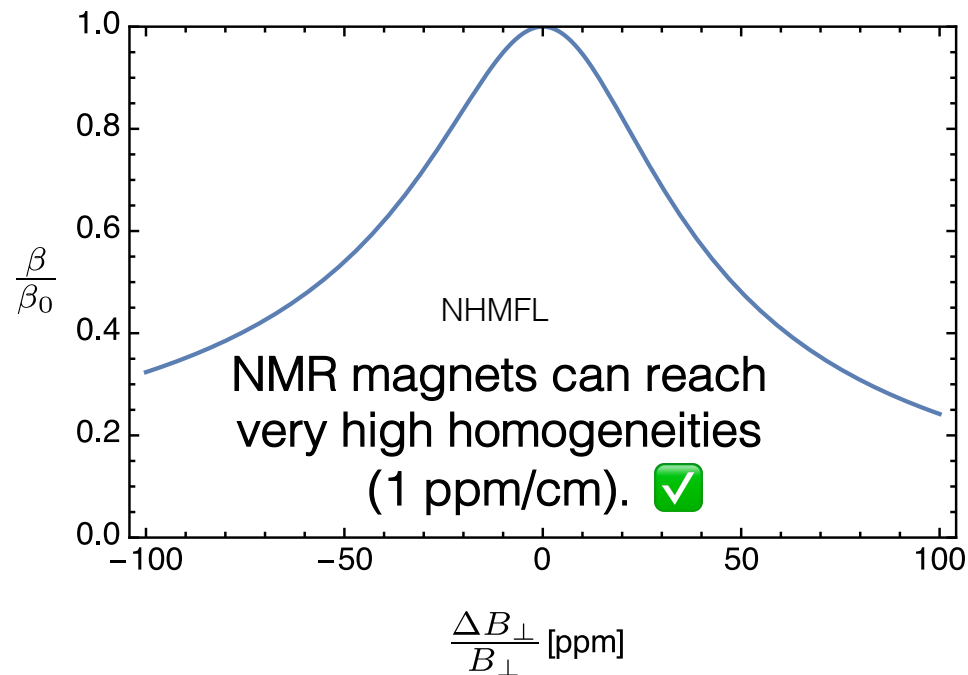


Mehrani, arXiv:2509.14320

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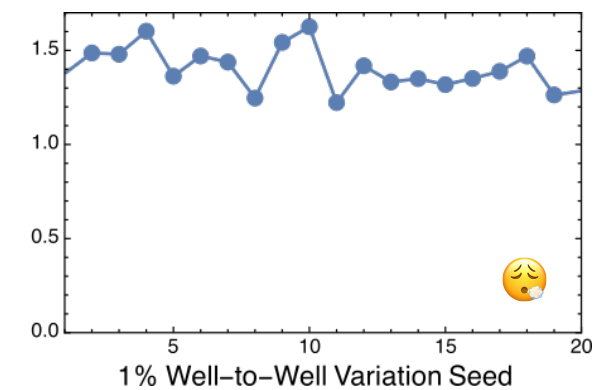
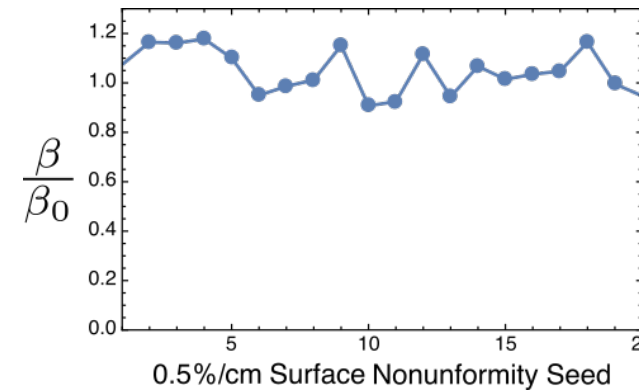
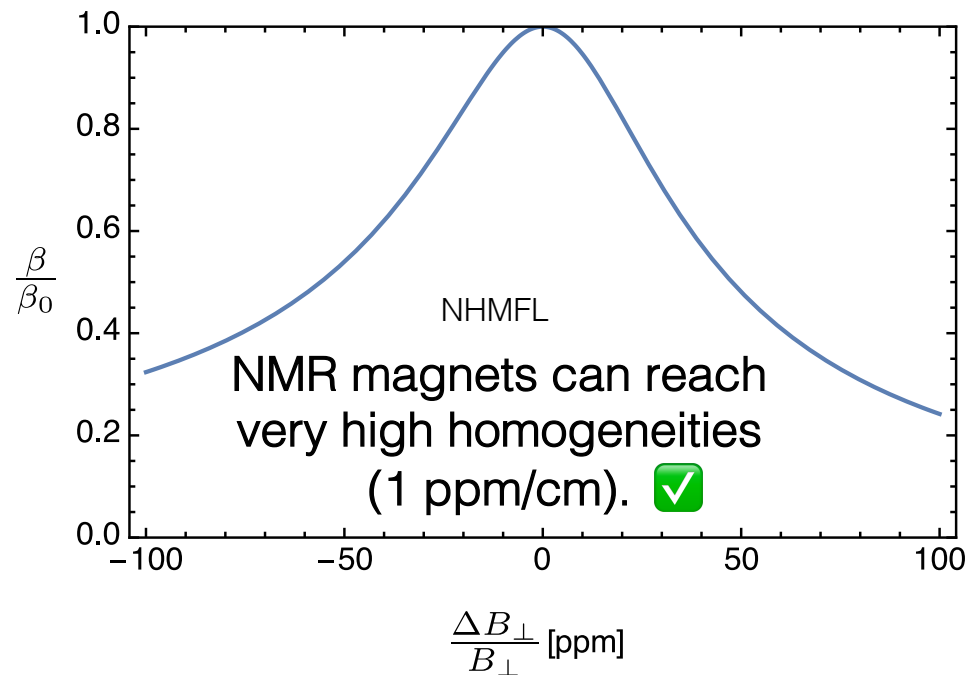
Journal of Crystal Growth 81 188-192 (1987)

Mehrani, arXiv:2509.14320

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Config. 2

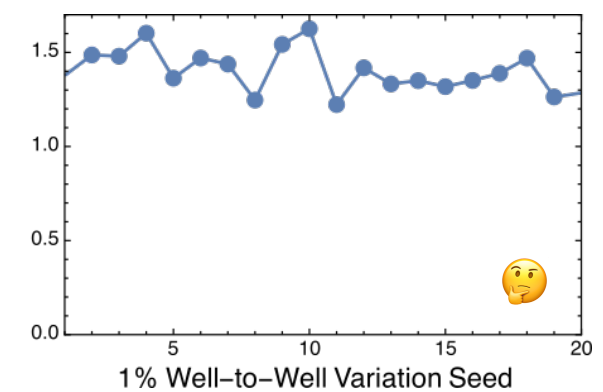
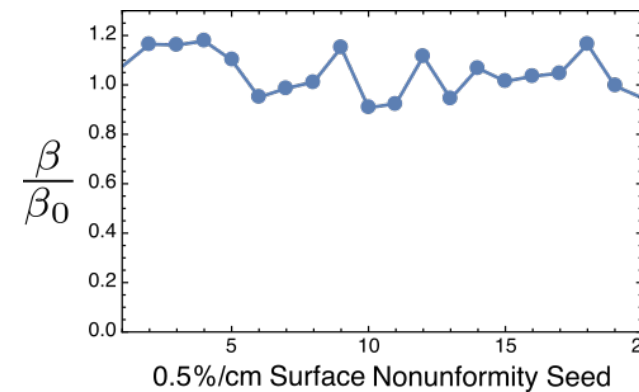
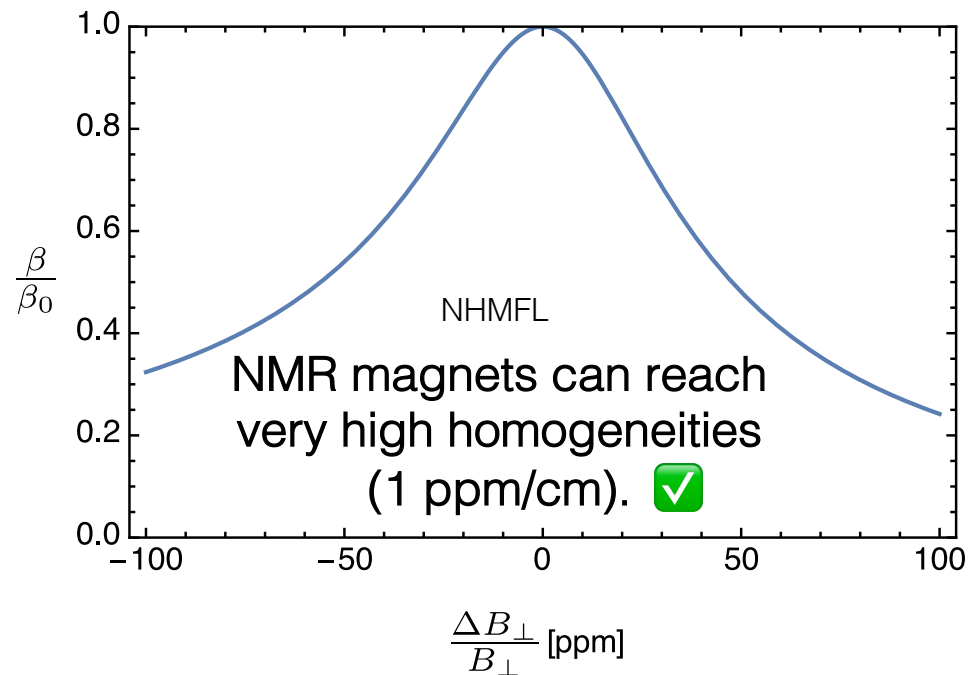


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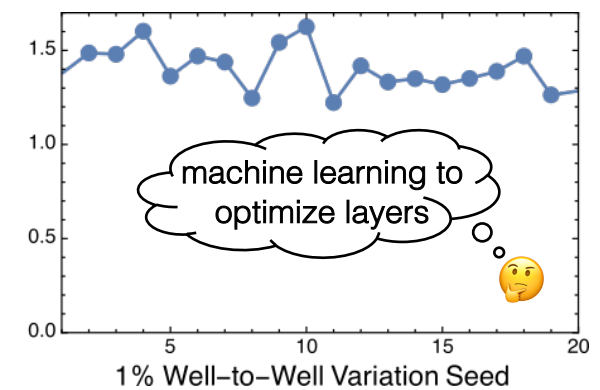
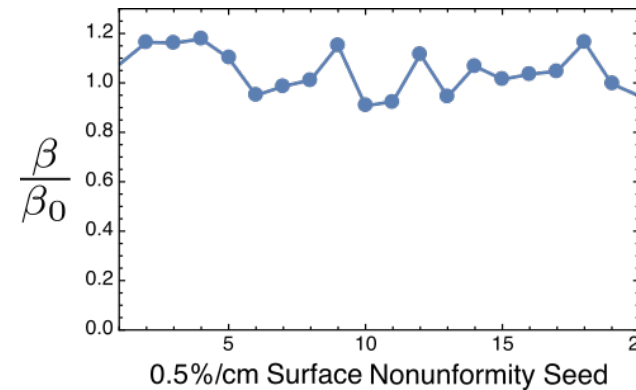
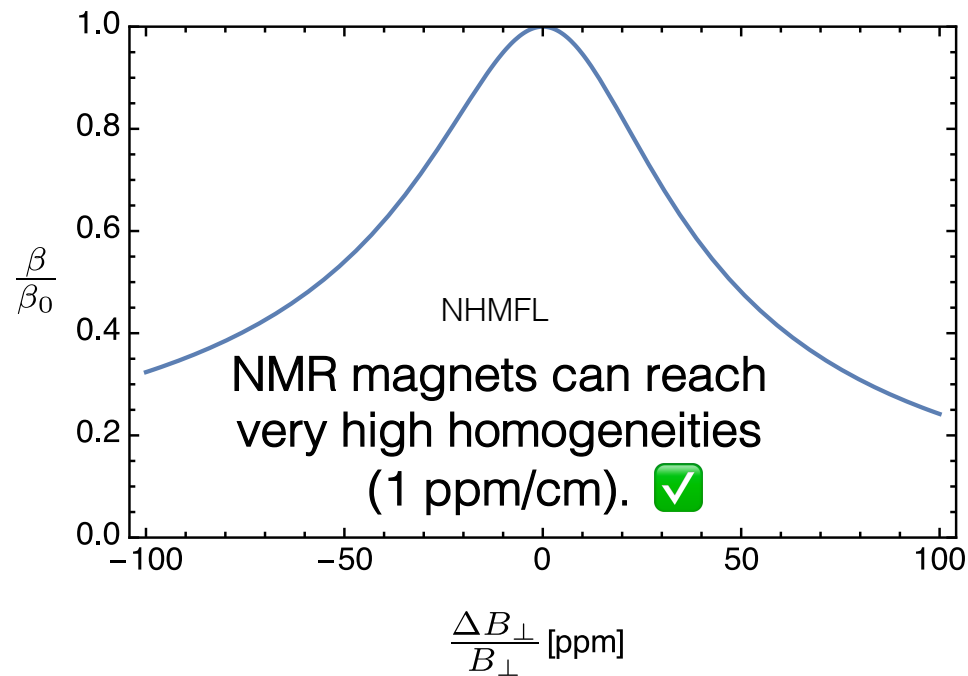


Mehrani, arXiv:2509.14320

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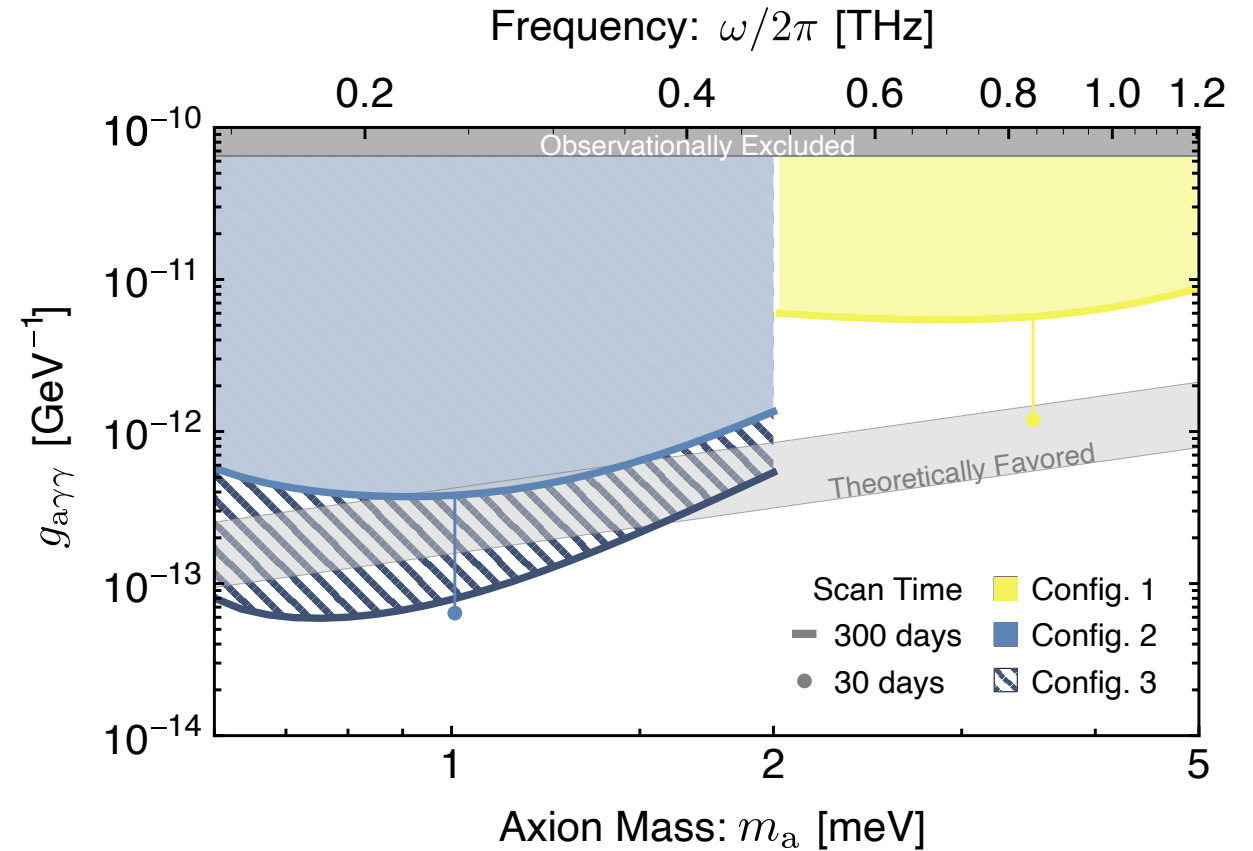
Mehrani, arXiv:2509.14320

Validation Experimental Conditions

Summary: 50% of maximum boost is maintained when testing a variety of experimental conditions.

Conclusion

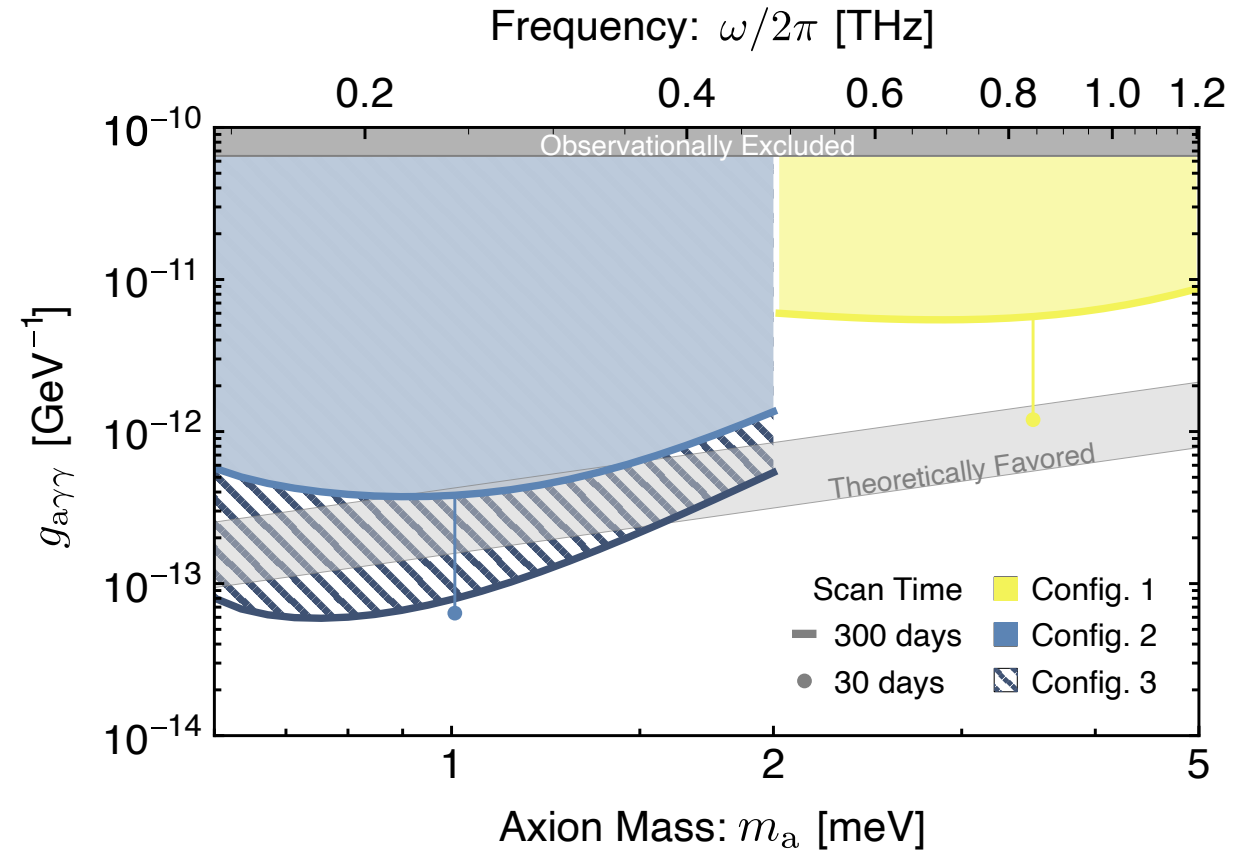
SQWARE is a new tabletop, electromagnetically-tunable, and highly-sensitive axion detection scheme that may probe meV axions.



Conclusion

SQWARE is a new tabletop, electromagnetically-tunable, and highly-sensitive axion detection scheme that may probe meV axions.

We are working on material characterization experiments and Config-0 design that could give preliminary constraints!



Acknowledgements

Co-authors

- Shengxi Huang (advisor), Jun Kono (advisor), Andrew Long, Henry Everitt, Andrey Baydin, Kuver Sinha, Tao Xu, Michael Manfra

Helpful discussions!

- Alexey Belyanin, Amin Mustafa, Mudit Jain, Dorian Amaral, R. C. Woods

SCOPE + KONO + CAP lab members!

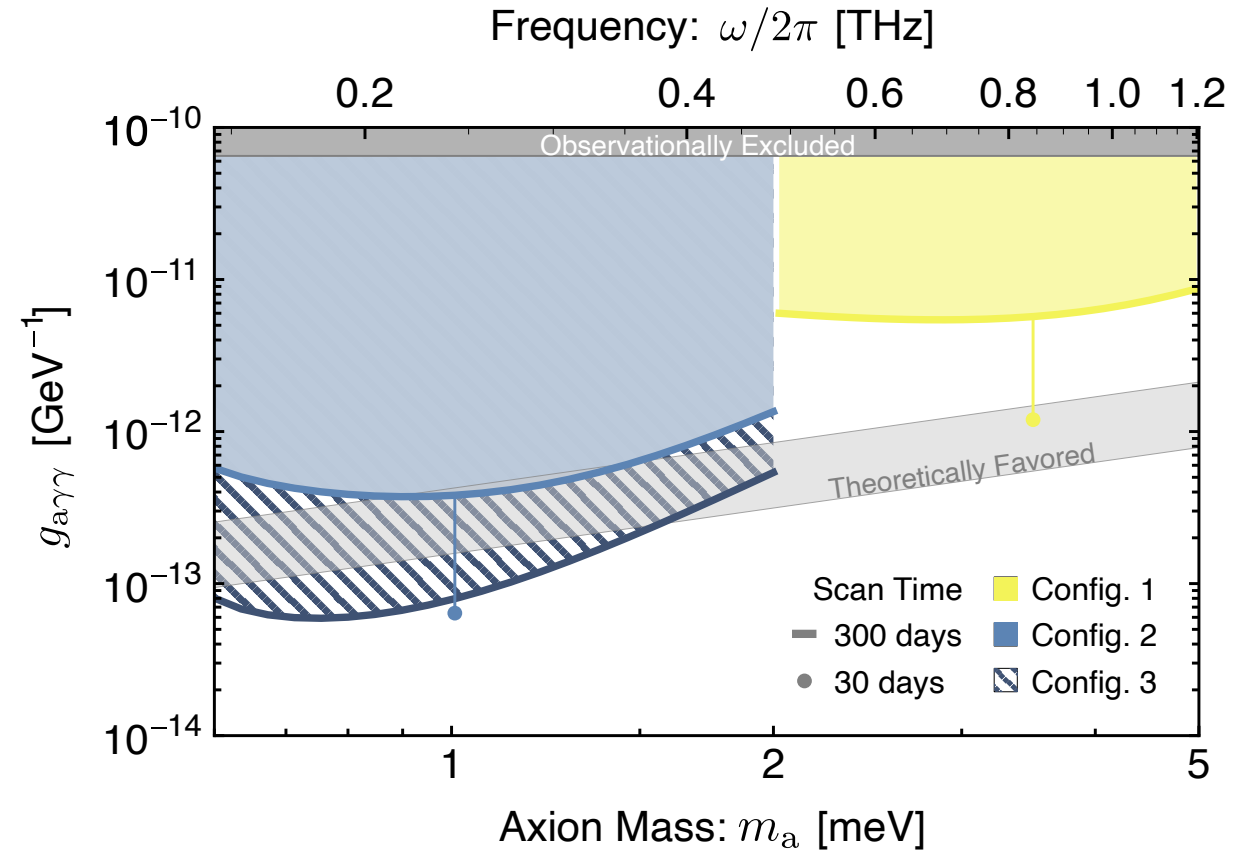
Pheno 2026 organizers!



Conclusion

SQWARE is a new tabletop, electromagnetically-tunable, and highly-sensitive axion detection scheme that may probe meV axions.

We are working on material characterization experiments and Config-0 design that could give preliminary constraints!



Thank you for listening!

Mehrani, arXiv:2509.14320

Config-0 Preliminary Estimates

- 2000 layers (200 μm) \sim 10x state-of-the-art ($N = 166$) MQWs
- 10 T field, e^- density = $4.5 \times 10^{11}/\text{cm}^2$
- CRA polarization (lower loss at higher frequency)
- $\beta \cos\theta = 20$ at 16 meV (compare 70 at 4 meV for Config 1)

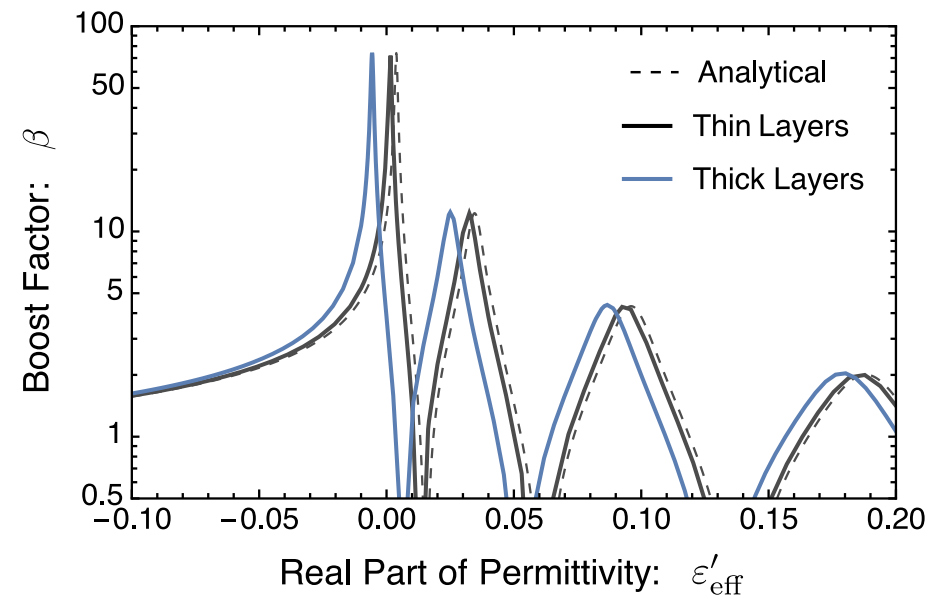
$$g > 1.4 \times 10^{-13} \text{GeV}^{-1} \left[\frac{36 \text{ T}}{|\mathbf{B}| \cos\theta(m_a)} \right] \left[\frac{100}{\beta(m_a)} \right] \left[\frac{0.2}{\eta} \right]^{\frac{1}{2}} \left[\frac{9 \text{ cm}^2}{W^2} \right]^{\frac{1}{2}} \left[\frac{\Gamma_{\text{dark}}}{1 \text{ mHz}} \right]^{\frac{1}{4}} \left[\frac{m_a}{1 \text{ meV}} \right]^{\frac{3}{2}} \left[\frac{30 \text{ days}}{t_{\text{obs}}} \right]^{\frac{1}{4}}$$

- Working on $N = 100$ with optimal layer density configuration (machine learning integrated in COMSOL)

Effective Medium Theory (EMT) is valid when layer thickness $\ll \lambda_{\text{med}}$.

$$\epsilon_{\text{eff}} = \frac{\epsilon_{\text{barrier}}d_{\text{Barrier}} + \epsilon_{\text{QW}}d_{\text{QW}}}{d_{\text{Barrier}} + d_{\text{QW}}}$$

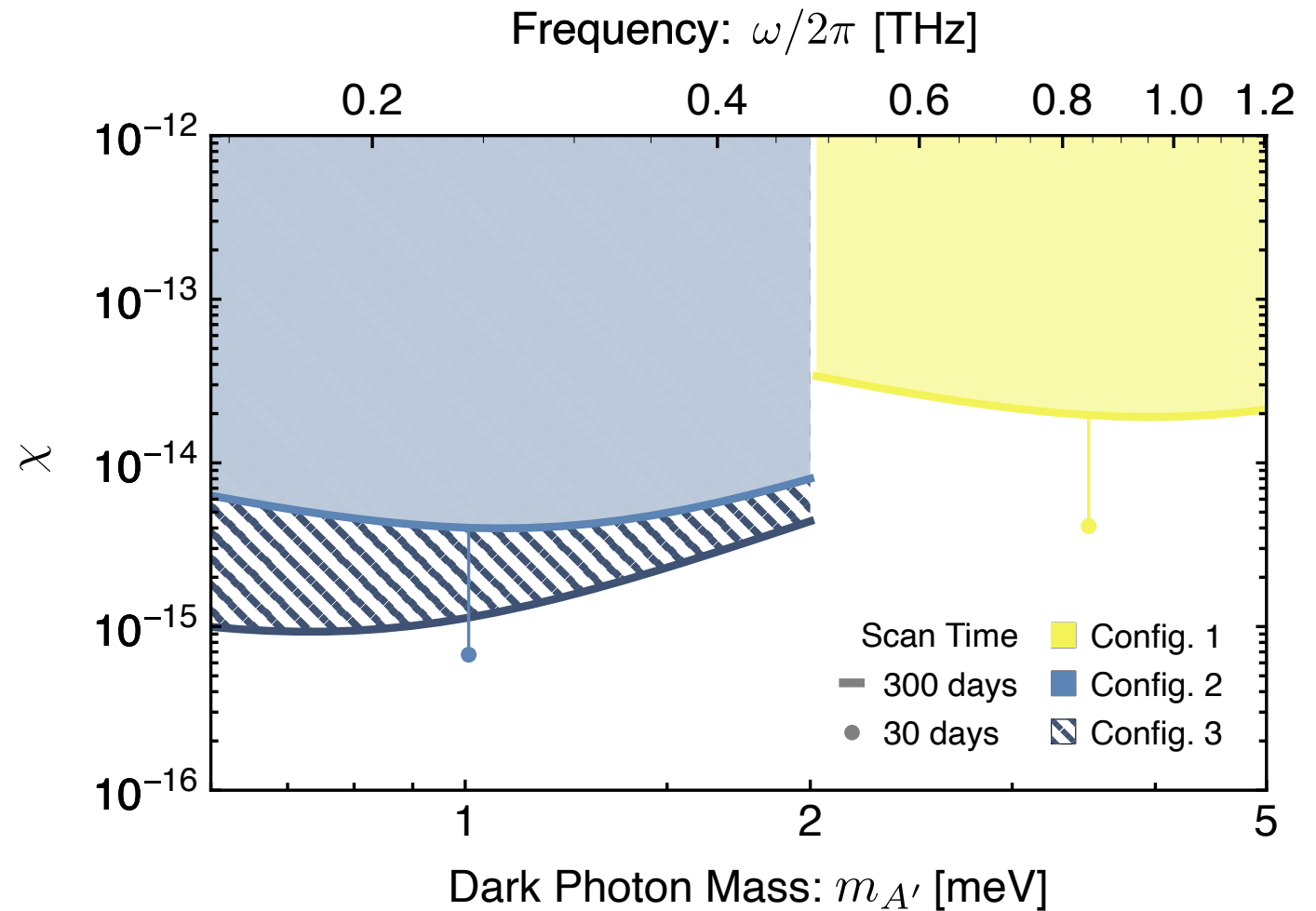
- COMSOL simulations of boost validate EMT.



Mehrani, arXiv:2509.14320

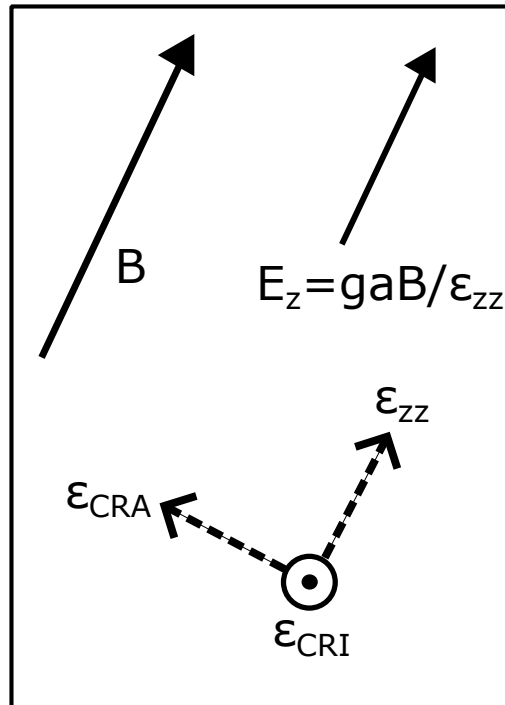
Dark Photon Proposed Sensitivity

- Dark photon mixes with massless photon
- Parallel magnetic field component irrelevant
- Mixing parameter χ instead of coupling g

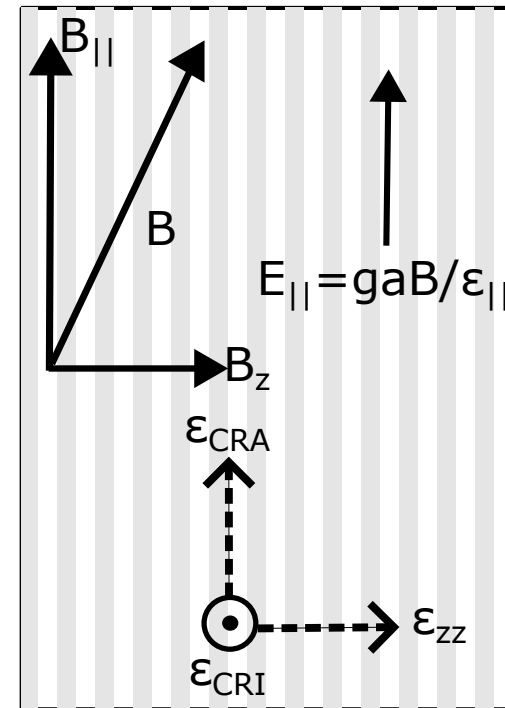


Why we don't use bulk semiconductor?

Bulk Doped Semiconductor

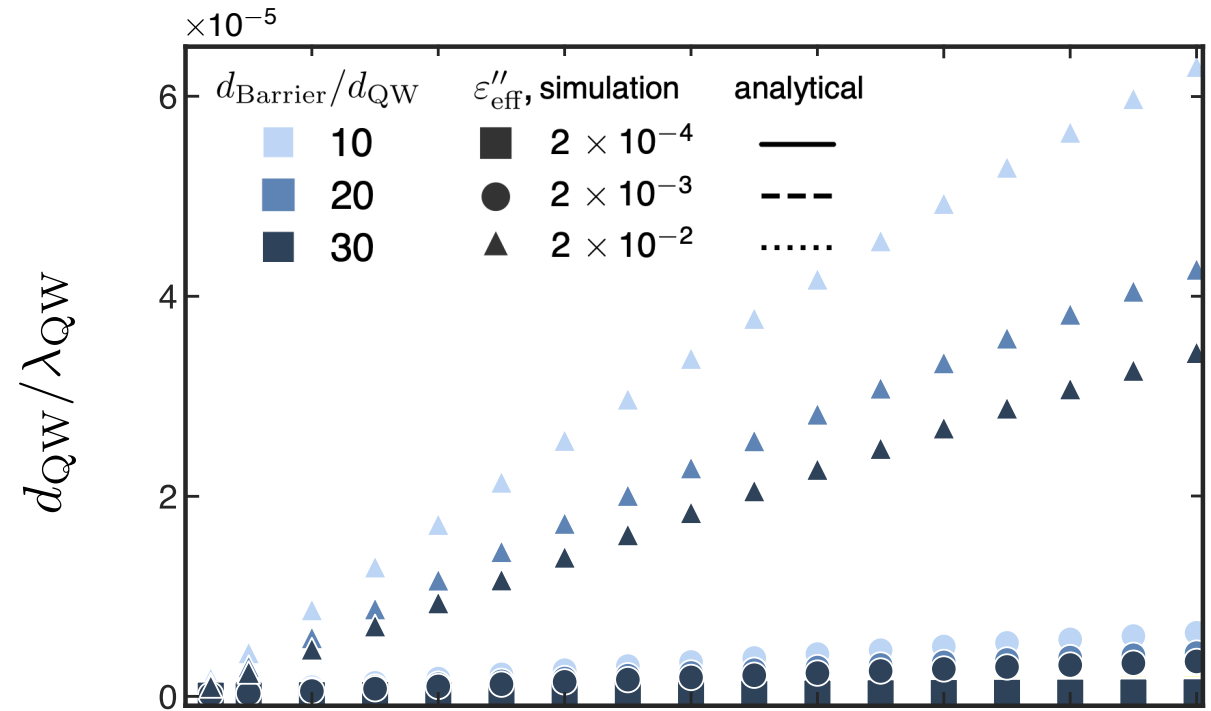
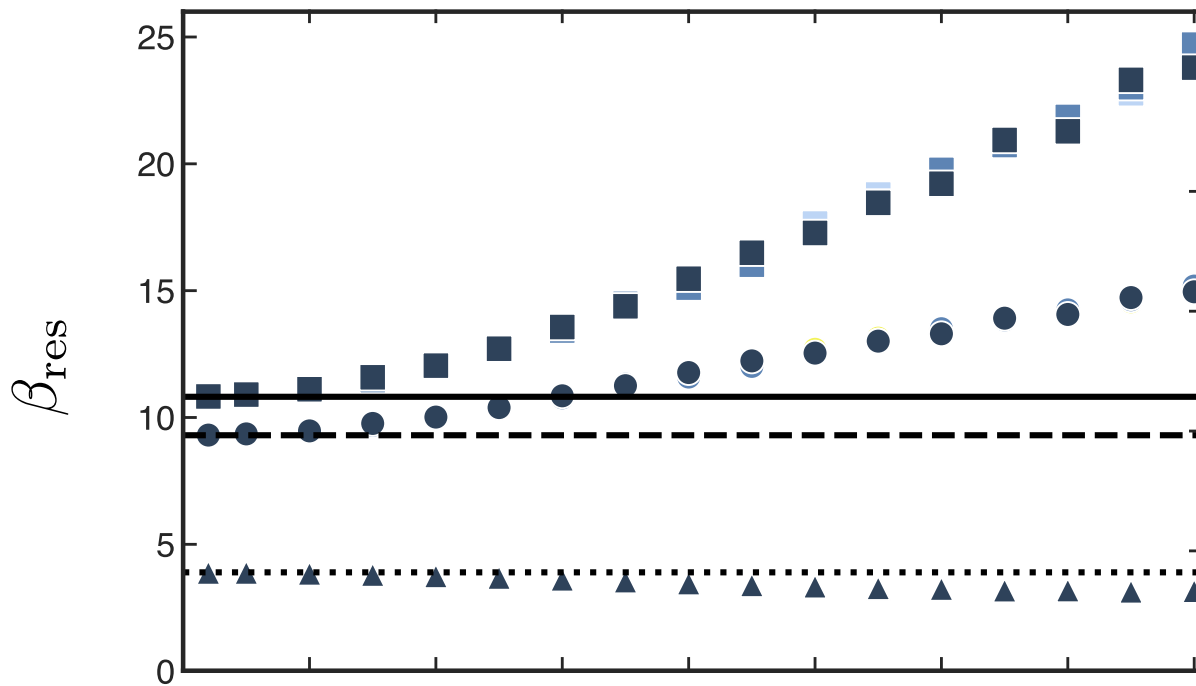


MQW (2DEGs)

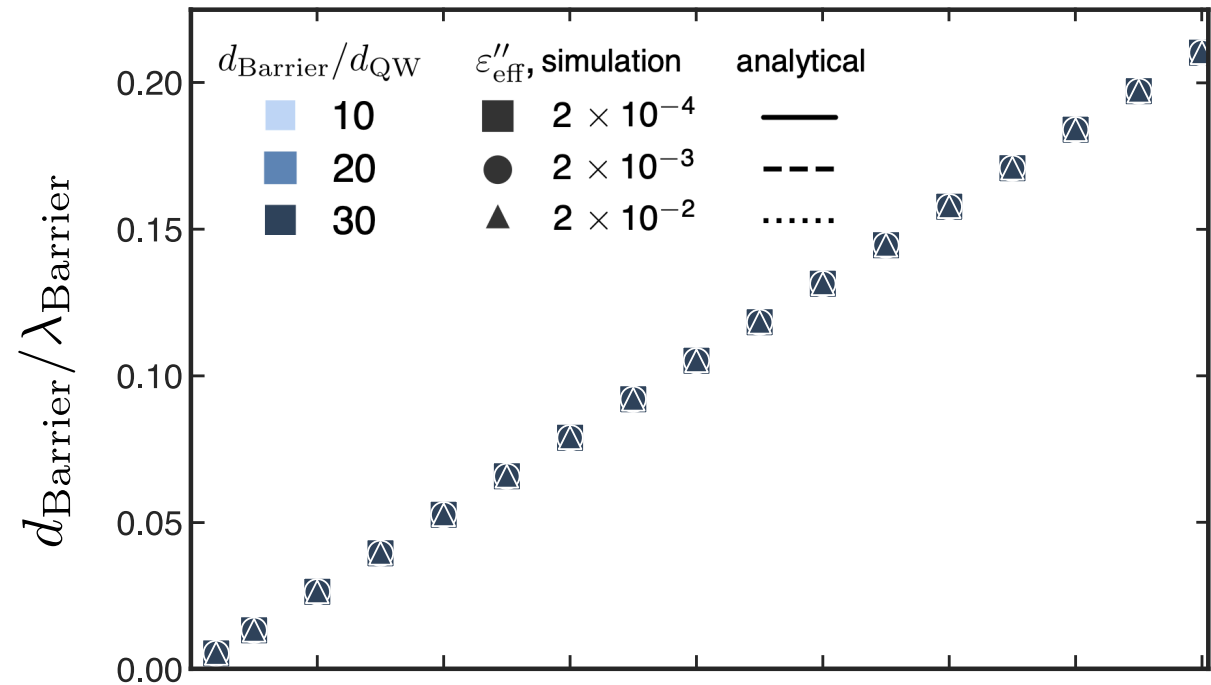
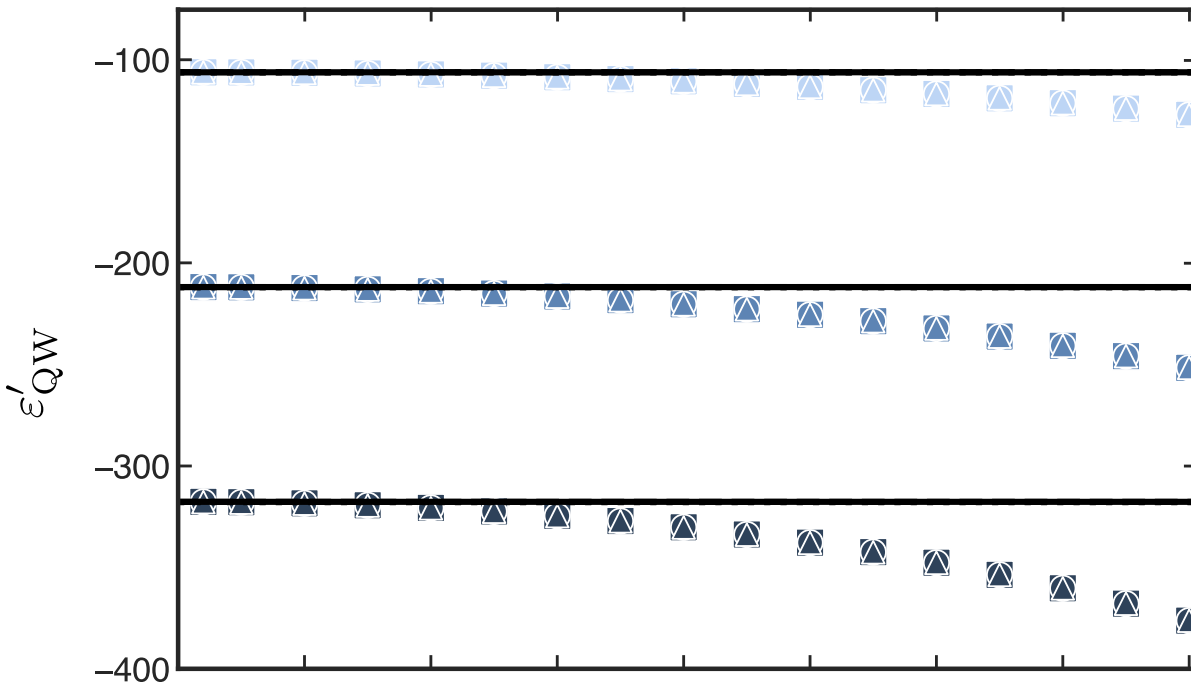


$E_z = gaB_z/\epsilon_{zz}$ is negligible here compared to $E_{||}$ (on resonance)

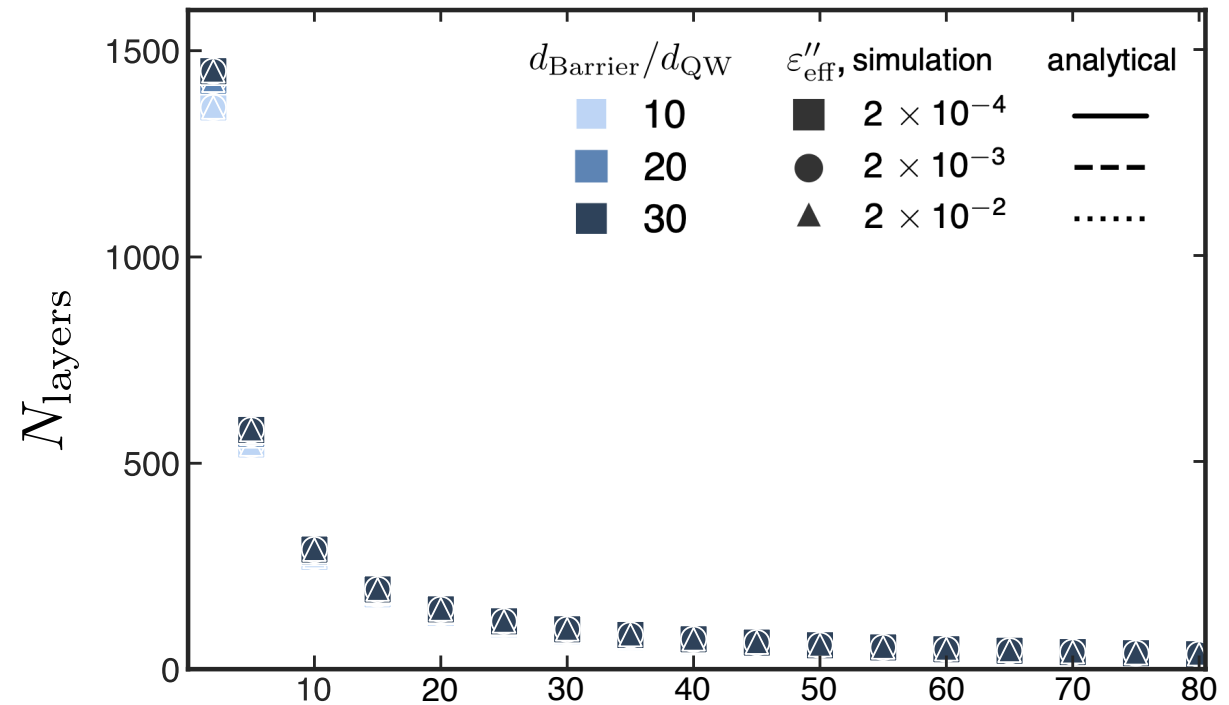
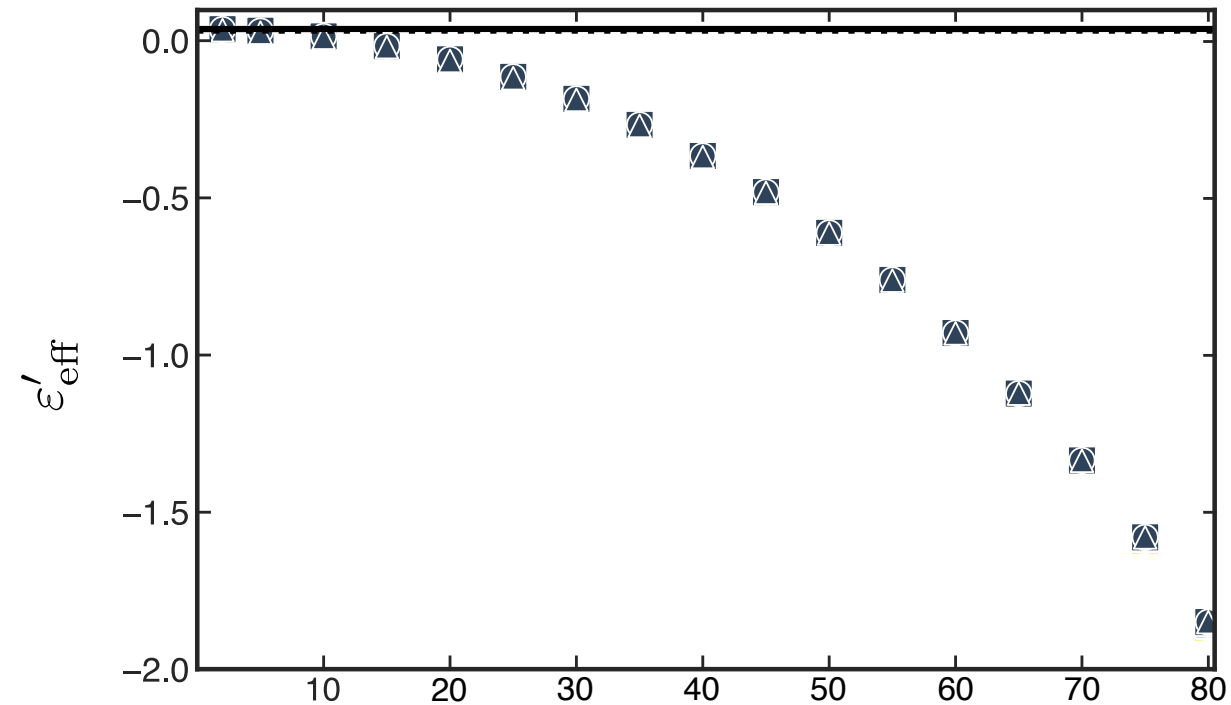
EMT (1)



EMT (2)

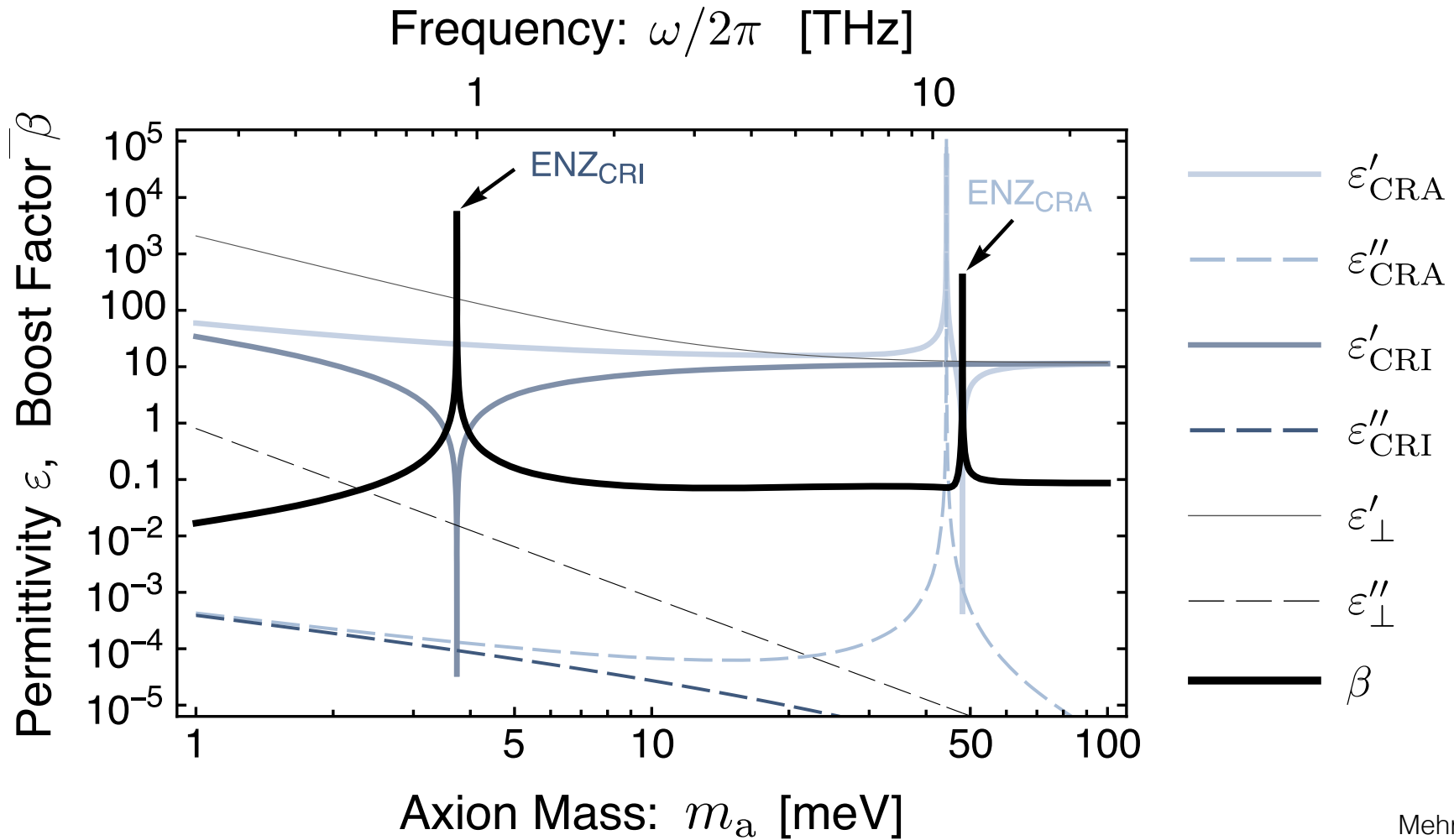


EMT (3)



QW Permittivity and Boost

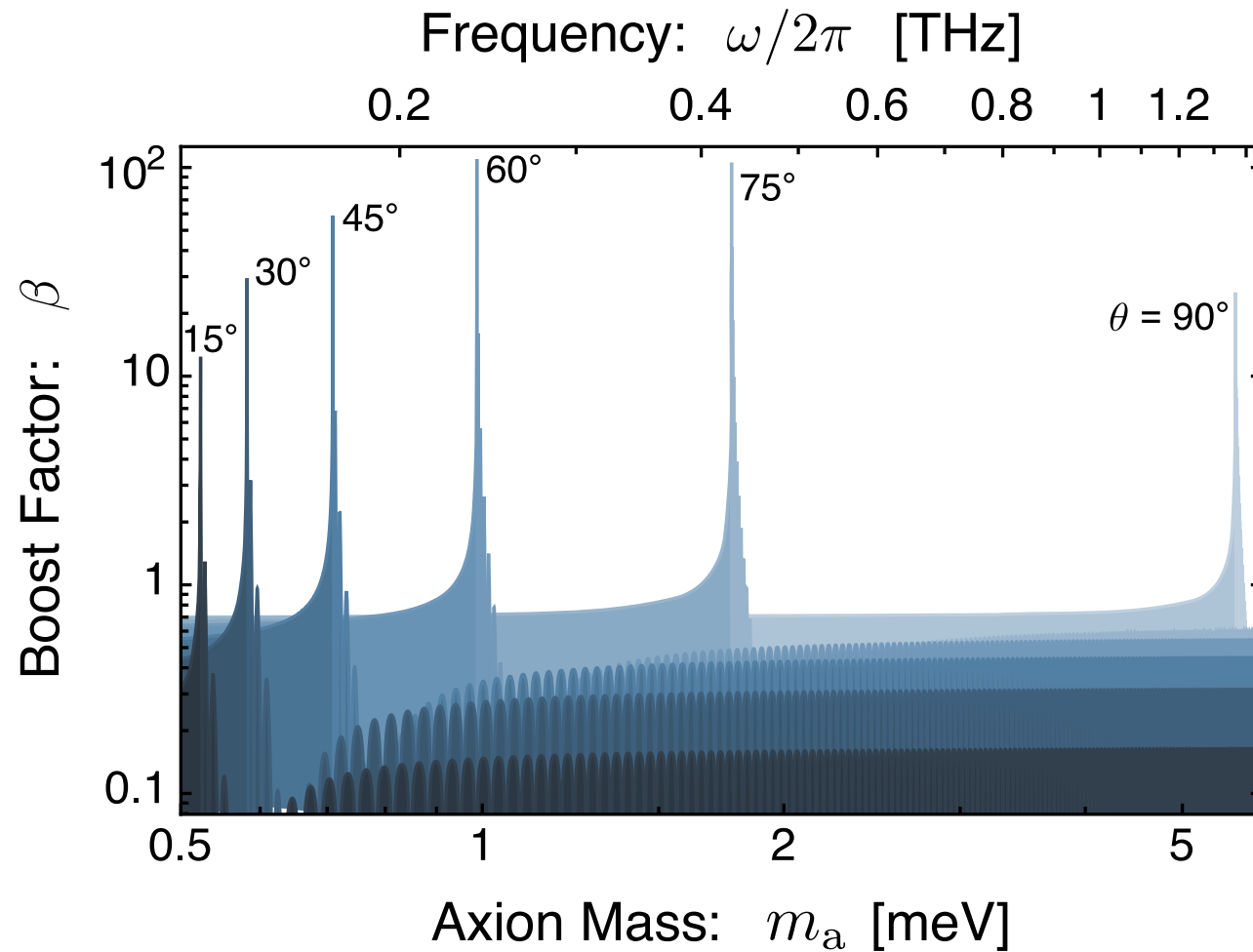
Config. 2



Mehrani, arXiv:2509.14320

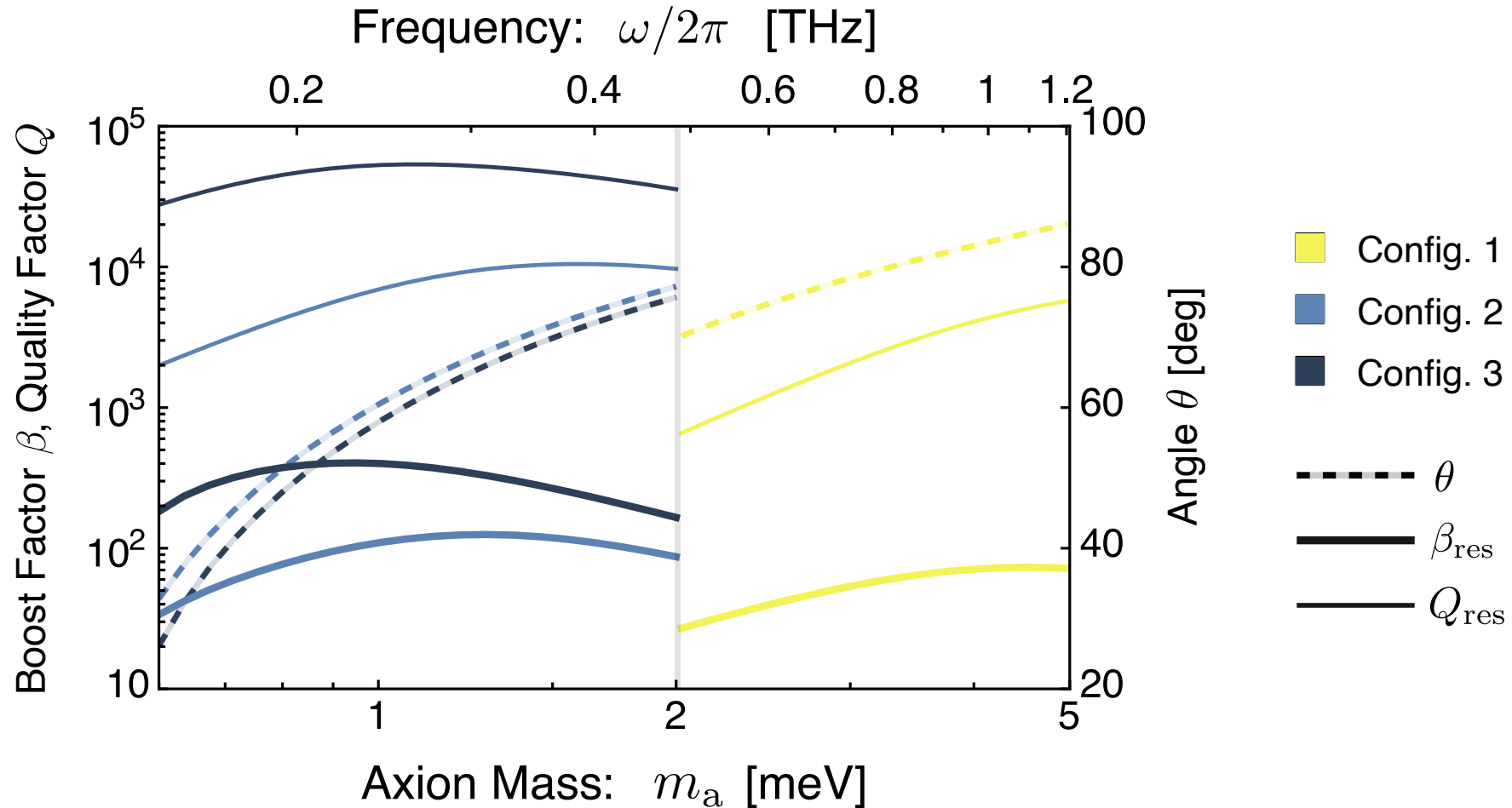
MQW Angle and Boost

Config. 2



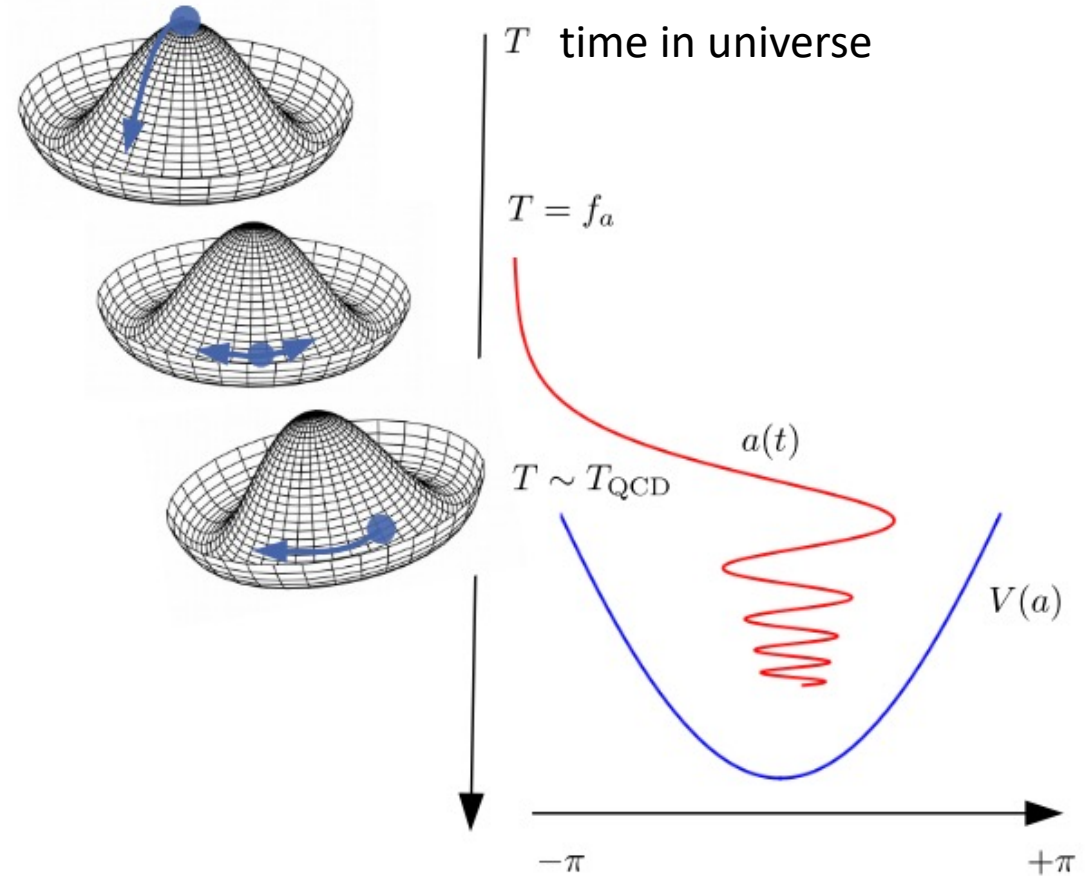
Mehrani, arXiv:2509.14320

MQW Angle, Quality Factor, and Boost



Axion Theory

- Peccei-Quinn Symmetry is a global $U(1)$ symmetry which is spontaneously broken, generating a pseudo-goldstone boson: the axion!
- Tilt in the potential, due to coupling with gluon fields through either standard model quarks with PQ charge (DFSZ model) or exotic quarks (KSVZ).



KIT Andreas Pargner (2019)

Axion Theory

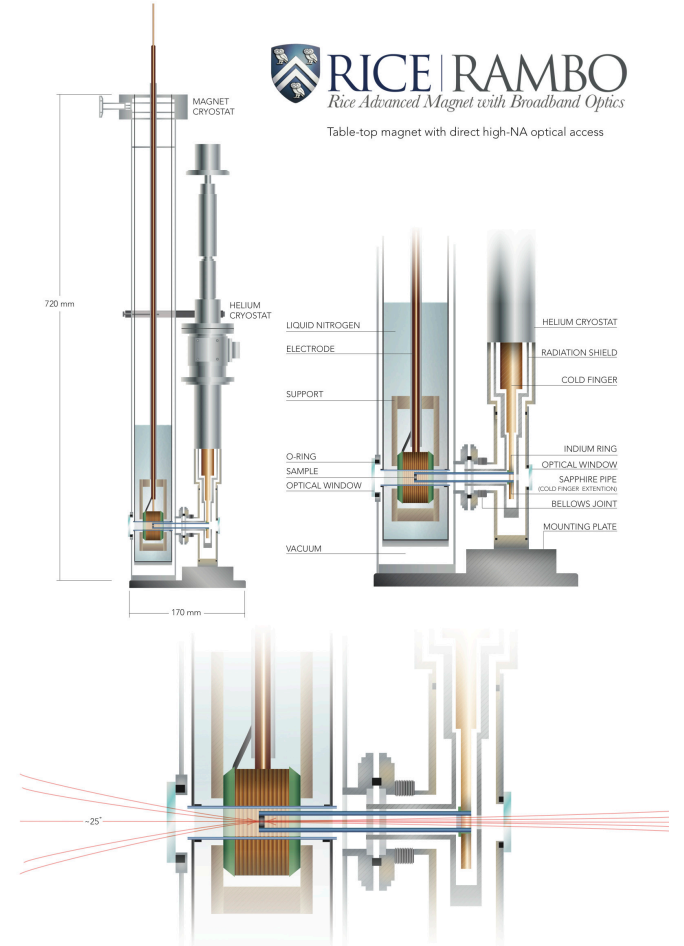
- Post-inflation axion
 - The misalignment angle is a statistical average from all the Horizons.
- Pre-inflation axion
 - The misalignment angle is a quantum fluctuation and is stretched out by inflation.

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \rho - g_{a\gamma} \mathbf{B} \cdot \nabla a, \\ \nabla \times \mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma} (\mathbf{B} \dot{a} - \mathbf{E} \times \nabla a), \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} + \dot{\mathbf{B}} &= 0, \\ \nabla^2 a + m_a^2 a &= g_{a\gamma} \mathbf{E} \cdot \mathbf{B}.\end{aligned}$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - J^\mu A_\mu + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

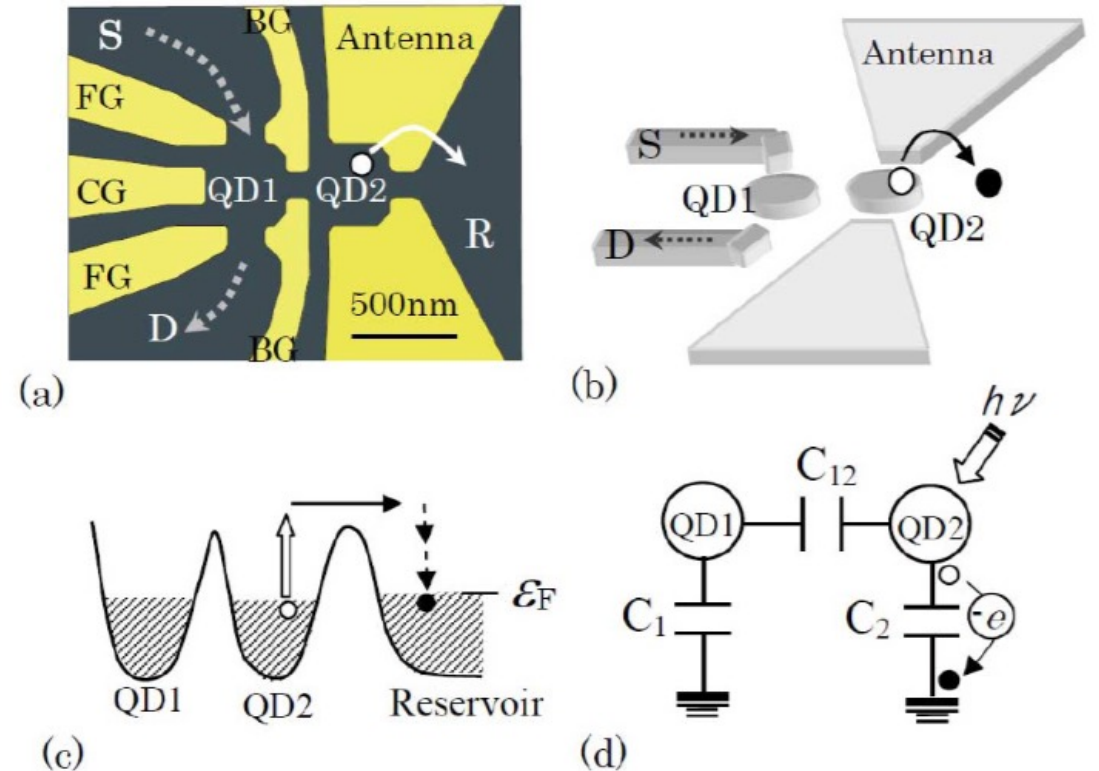
Magnets at Rice

- Oxford 10 T Continuous
 - Constrain QCD axion with thinner prototype for higher frequencies at lower magnetic fields
- RAMBO 30 T Pulsed
 - Characterization of MQW



Quantum Dot (QD) Photodetector

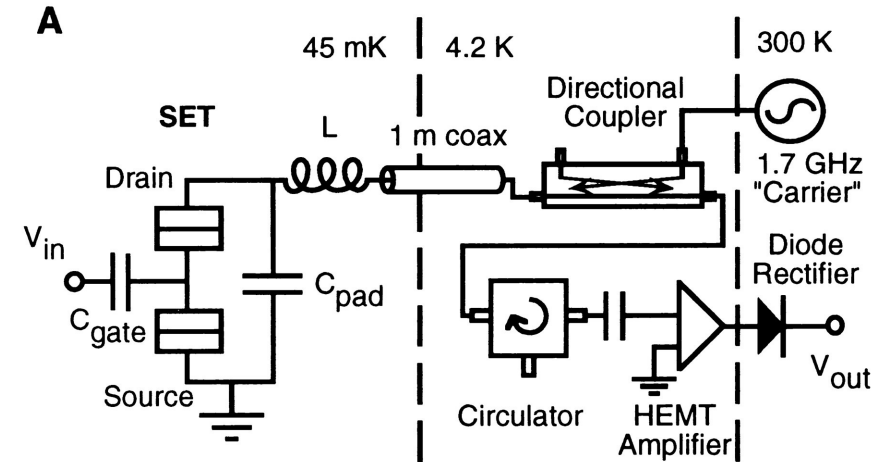
- Coulomb Blockade: Photon exciting a QD is measured as a change in capacitance within a circuit
- QD Landau level system is tunable with a magnetic field (cyclotron resonance)!
- Experimentally tested at 2 meV and 6 meV resonances



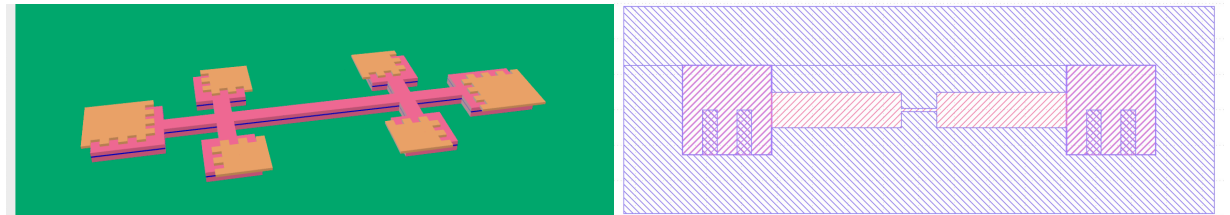
Komiyama S., IEEE Journal of Selected Topics in Quantum Electronics (2011)

Quantum Dot (QD) Photodetector

- Improvements with RF-SET
 - Using RF instead of DC conductance in circuit
 - Removing $1/f$ noise and better impedance matching
- Useful for broad range axion experiments



Science 280,1238-1242 (1998).



KLayout Designs

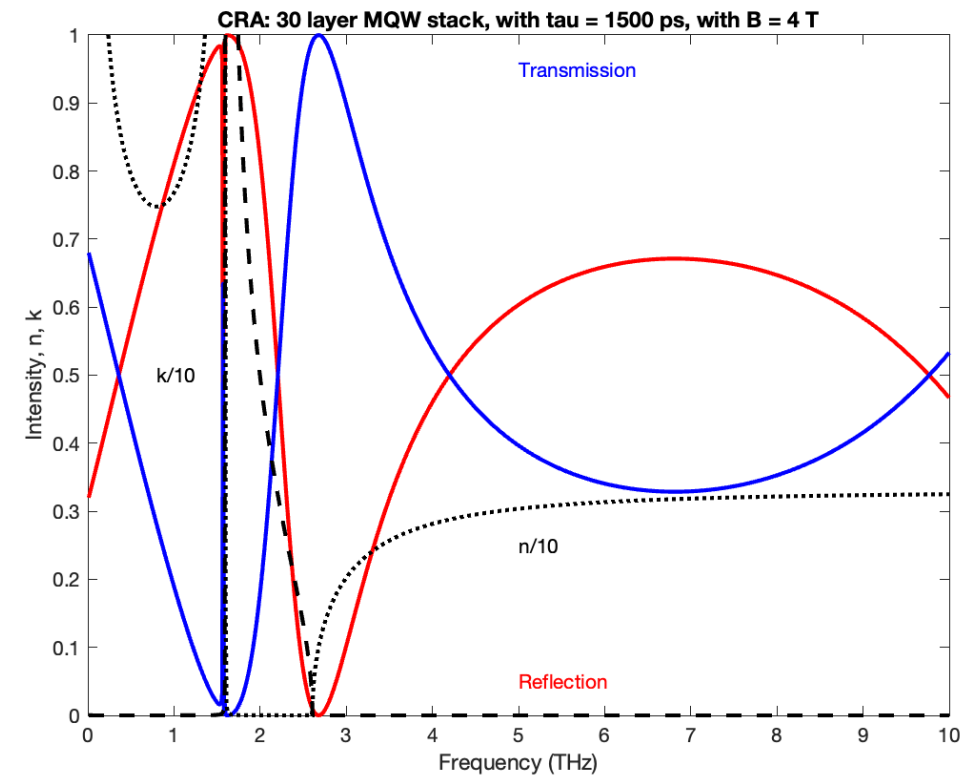
Axions are a promising DM model

- Several theoretical dark matter models with unique properties of mass, spin, charge, couplings!
- Axions could additionally solve the strong charge parity problem in quantum chromodynamics (QCD)
 - Peccei-Quinn theory:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} - \frac{g_s^2 \theta}{32 \pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} + \sum_q \bar{q} (i \not{D} - m_q e^{i\theta_q \gamma_5}) q$$
$$\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 + \frac{a}{f_a} \frac{g_s^2}{32 \pi^2} \mathbf{G} \tilde{\mathbf{G}} + \frac{1}{4} g_{a\gamma}^0 a F \tilde{F} + \frac{\partial_\mu a}{2 f_a} \bar{q} c_q^0 \gamma^\mu \gamma_5 q - \bar{q}_L M_q q_R + \text{h. c.} + \dots$$

Multiple Quantum Wells

- Studying ENZ resonance and homogeneity of multiple quantum wells at high magnetic fields
- Using pulsed THz transmission to characterize ENZ
- TMM simulations on the right

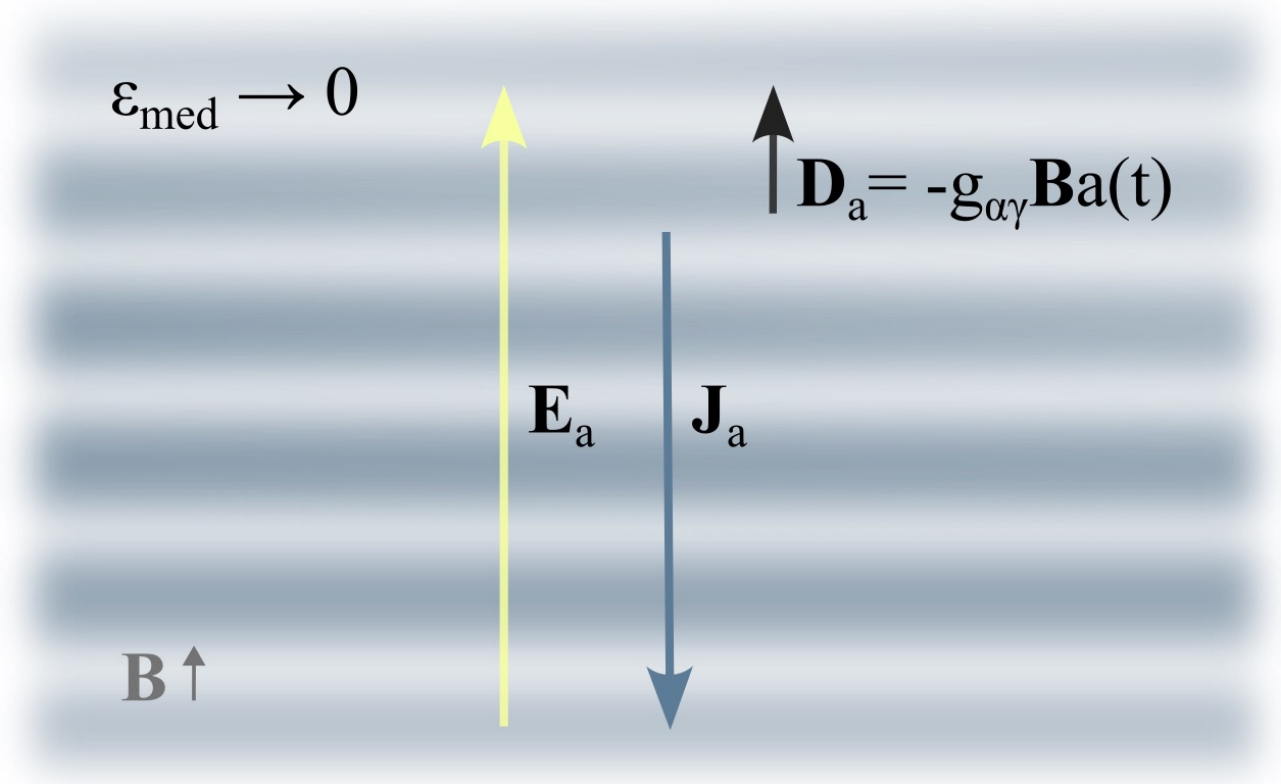


Material's Plasmonic Response to Axion

- Material response ($\hat{\epsilon}$)

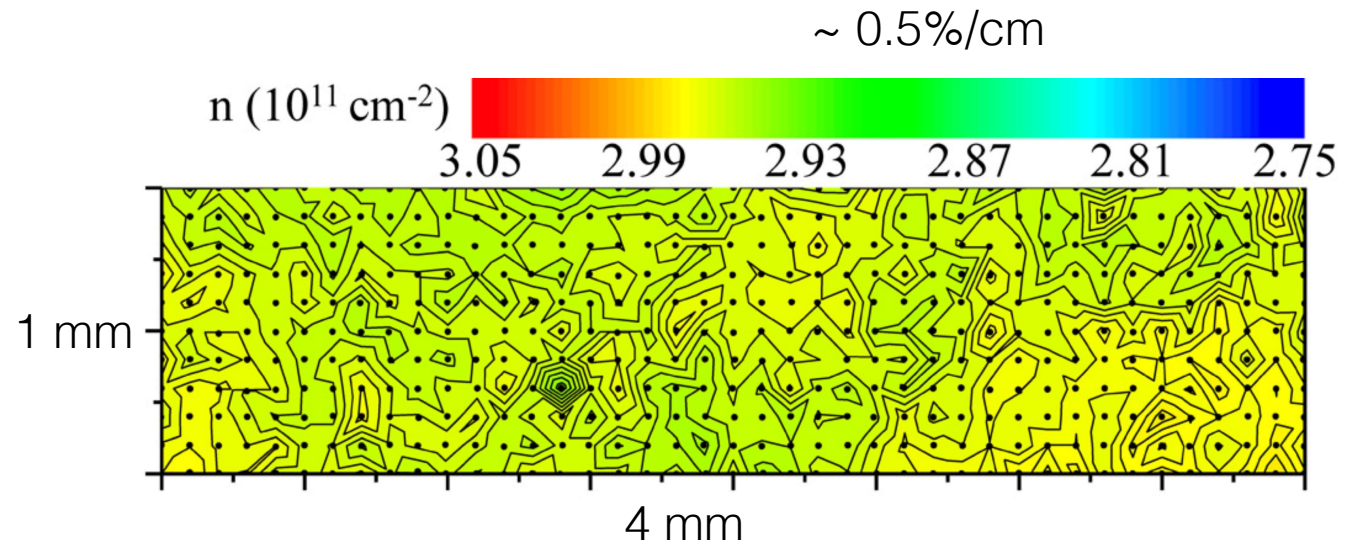
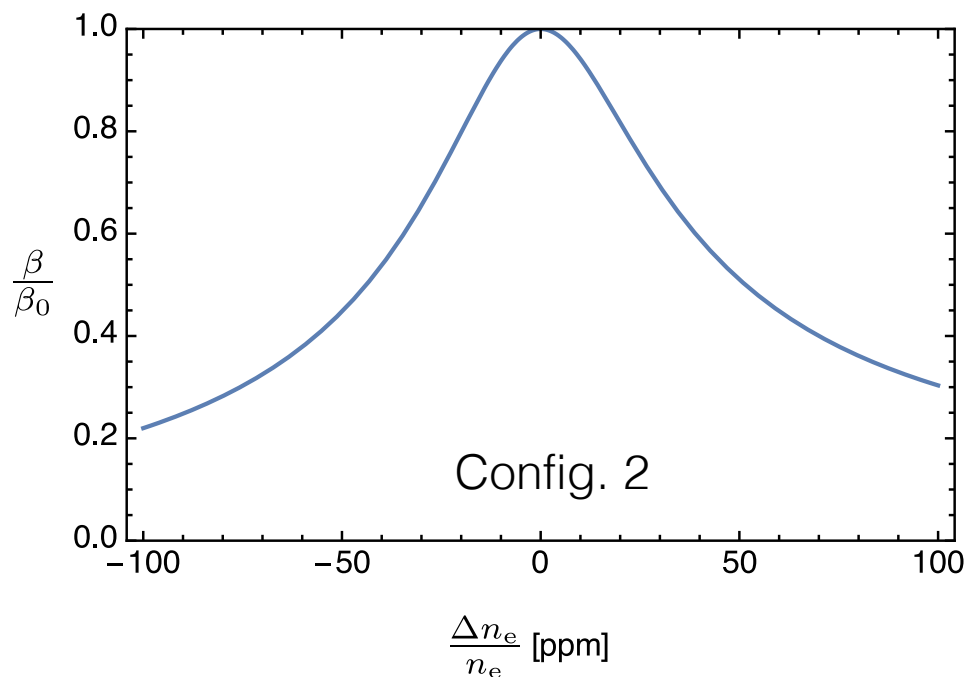
$$\begin{aligned}\mathbf{D}_a &= \mathbf{E}_a + \mathbf{P}_a - \frac{i}{\omega} \mathbf{J}_a \\ &= \mathbf{E}_a + \hat{\chi} \mathbf{E}_a - \frac{i\hat{\sigma}}{\omega} \mathbf{E}_a \\ &= \hat{\epsilon} \mathbf{E}_a = -g_{\alpha\gamma} \mathbf{B}_a(t)\end{aligned}$$

- Plasmonic material ($|\epsilon| \rightarrow 0$)



Electron Density Non-Uniformity

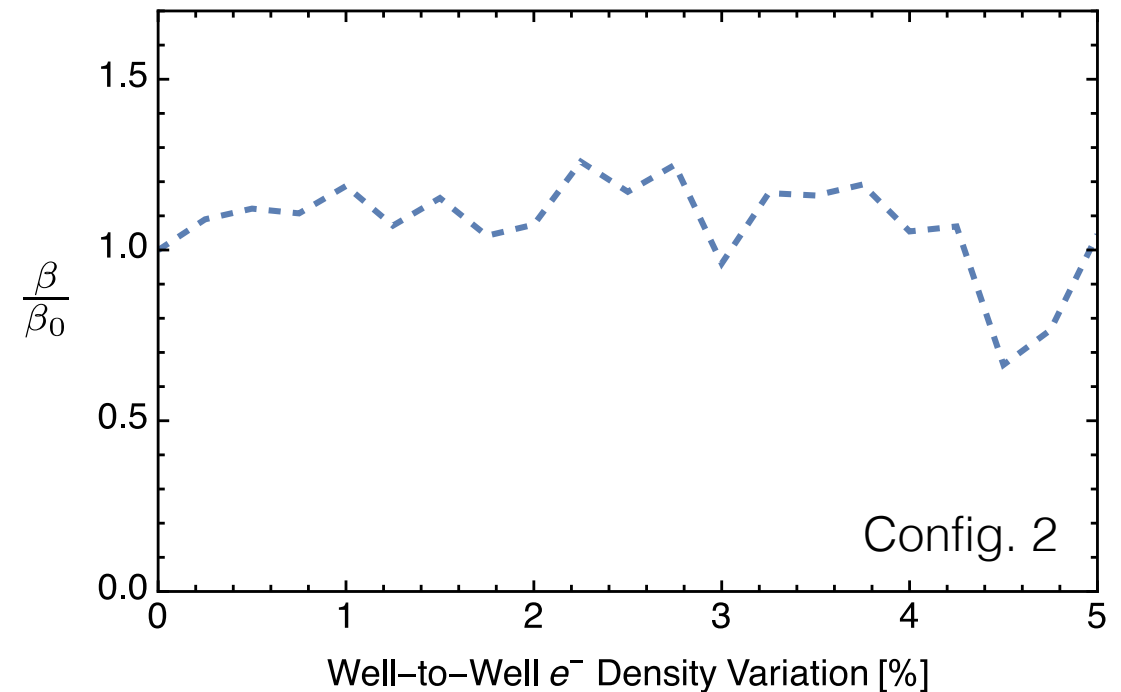
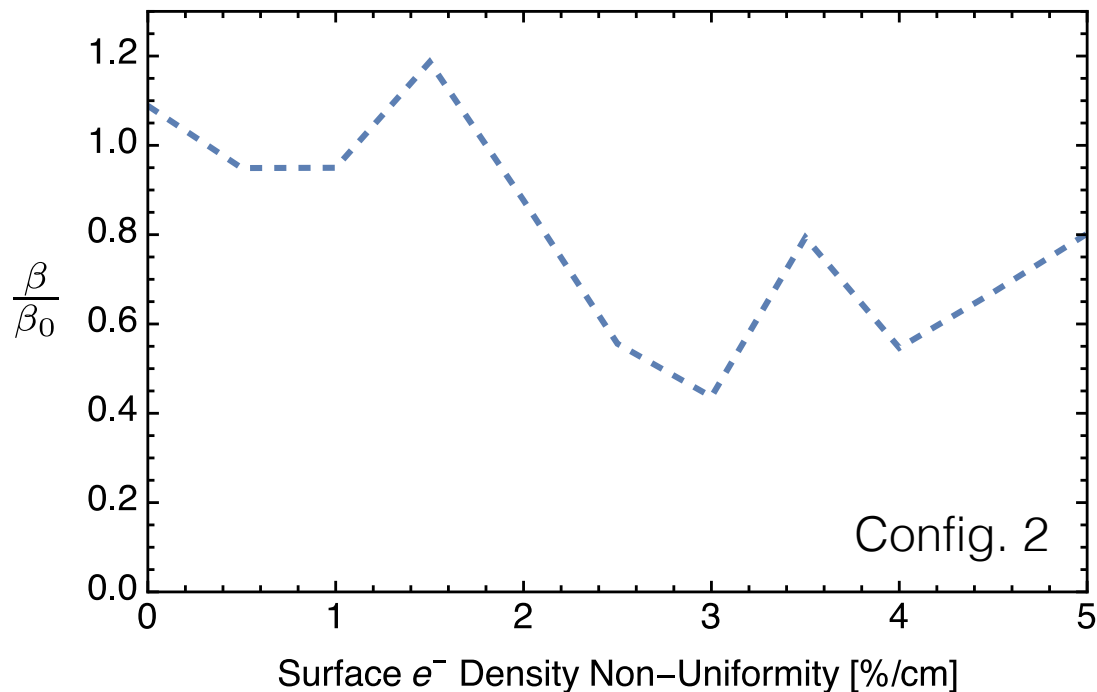
- The boost is extremely sensitive to the electron density.
- Experiments show 0.5%/cm and 1% well-to-well non-uniformity.



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Electron density Non-Uniformity

- EMT comes to the rescue! Randomization across surface and well-to-well maintains boost (“best side” of MQW plotted).



Mehrani, arXiv:2509.14320