Probing the meV QCD Axion with the SQWARE Quantum Semiconductor Haloscope

TACOS 2025

Jaanita Mehrani, Tao Xu, Andrey Baydin, Michael J. Manfra, Henry O. Everitt, Andrew J. Long, Kuver Sinha, Junichiro Kono, Shengxi Huang

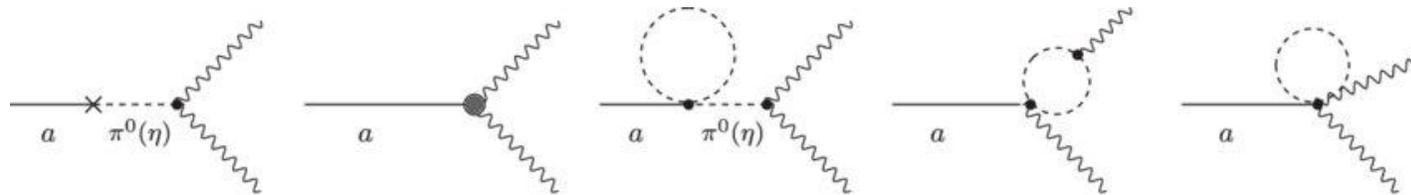**based upon work in**
arXiv:2509.14320

Axions are a promising DM model

- 85% of matter is dark matter!
  - Several theoretical models with unique properties like mass, spin, charge, couplings!
- Axions could additionally solve the strong charge parity problem in quantum chromodynamics (QCD)
  - Peccei-Quinn theory:

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^{a\mu\nu} G^a_{\ \mu\nu} - \frac{g_s^2 \theta}{32\,\pi^2}\, G^{a\mu\nu}\, \tilde{G}^a_{\mu\nu} + \sum_q \bar{q}\,(\, i\slashed{D} - m_q e^{i\theta_q \gamma_5})\, q$$

$$\mathcal{L}_{\mathrm{a}} = \frac{1}{2}\,(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}\, G\tilde{G} + \frac{1}{4}\, g^0_{a\gamma}\, a\, F\tilde{F} + \frac{\partial_\mu a}{2f_a}\, \bar{q} c^0_q\, \gamma^\mu\, \gamma_5\, q - \bar{q}_L M_q q_R + \mathrm{h.\,c.} + \cdots$$
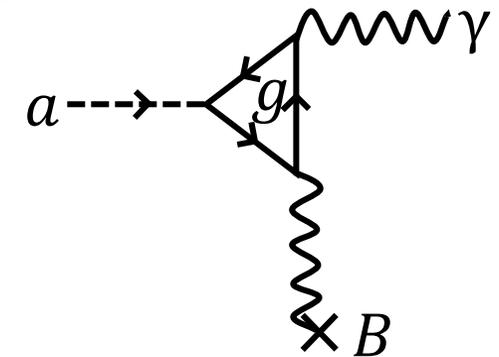
How can we detect axions?

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

which results in the **effective** interaction Lagrangian

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

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

Inverse Primakoff effect

- Maxwell's equations under spatially homogenous axion field a

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

$$\left(\partial_\mu \partial^\mu + m_a^2\right)a = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- To **first order**, axions convert to photons

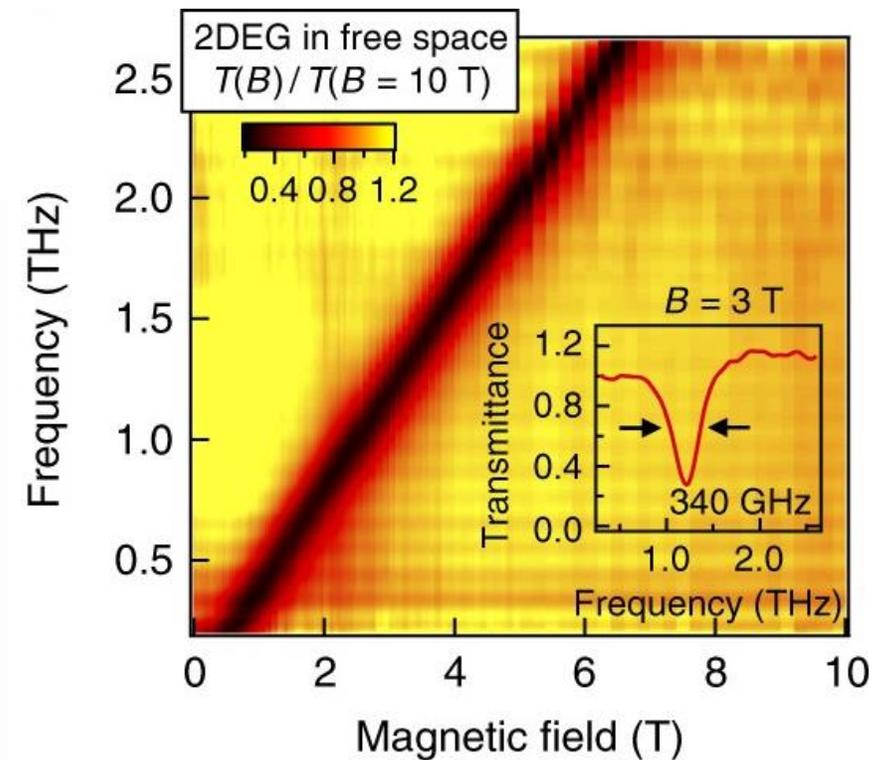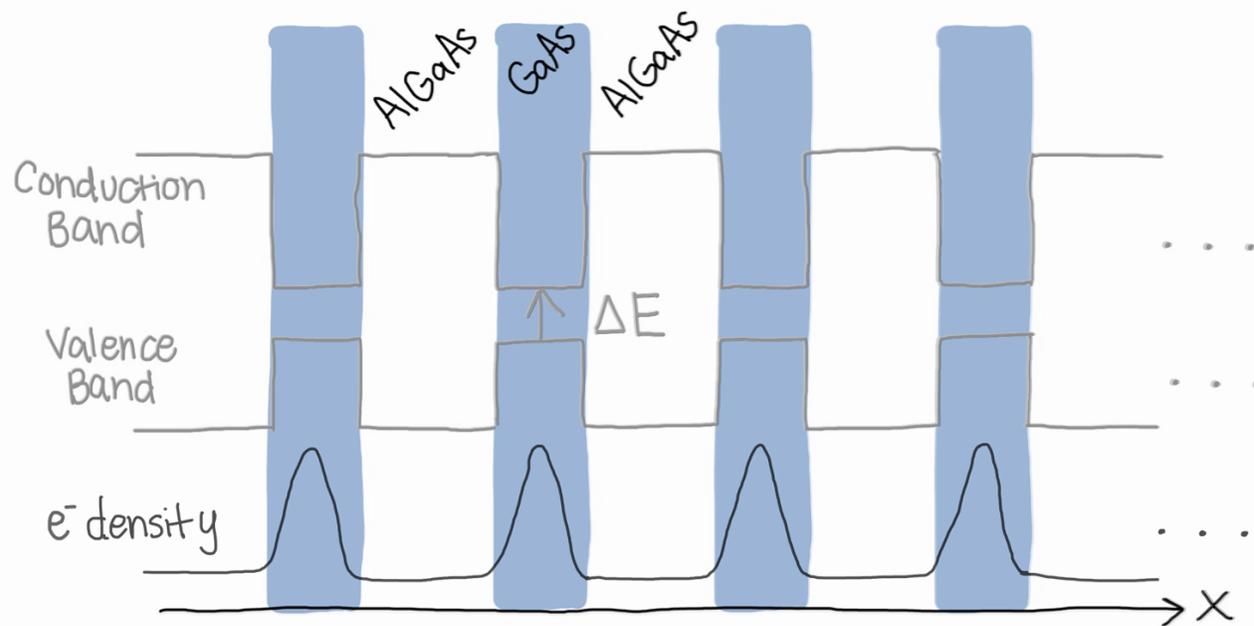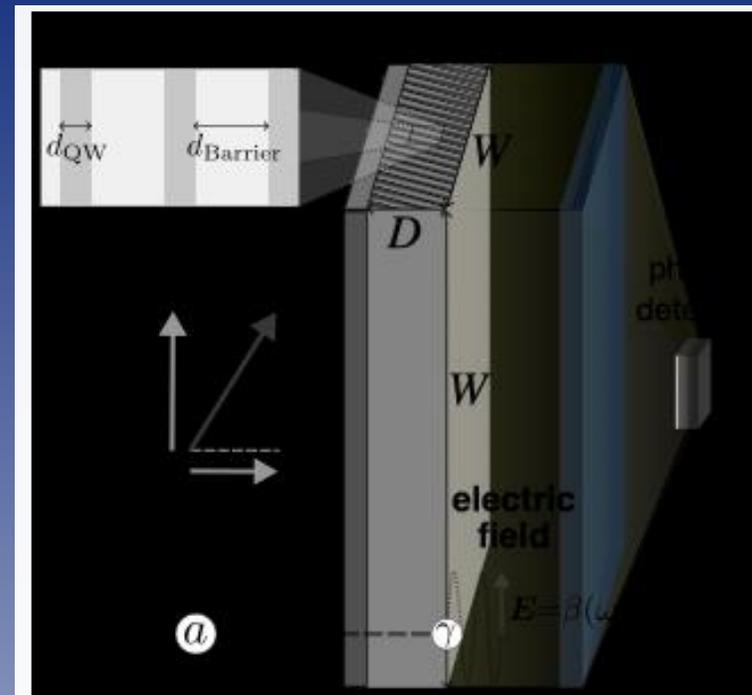$$\hat{\epsilon}\mathbf{E}(t) = -g_{a\gamma}\mathbf{B}_e a_0 e^{-im_a t}$$

Axion Search Strategies

C. O'Hare

Axion Search Strategies

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Axion Search Strategies

Axion-Photon Signal Enhancement

Broadband:
focus photons from large volume

Resonant:
cavities resonate at axion mass

Vacuum
- reduced volume
- reduced quality
- mechanical tuning (moving rods)

ADMX

ALPHA

MADMAX

C. O'Hare

Multiple Quantum Wells (MQW)

- **Low-loss THz plasmonic** resonances that are **electromagnetically tunable**!

Li, X., **Manfra, M.**, **Kono, J**., et. al. *Nature Photonics* (2018)

Semiconductor-Quantum-Well Axion Radiometer Experiment

logo by Haaniya

Material's Plasmonic Response to Axion

- Axion-induced electric field

$$E_{\mathrm{med}} = \frac{E_{\mathrm{vac}}}{\varepsilon} = \frac{g_{\alpha\gamma} B a}{\varepsilon}$$

- Plasmonic cavities generate surface **radiation** with boost β

$$E_{\mathrm{prop}} = \beta E_{\mathrm{vac}}$$

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

$\varepsilon \rightarrow 0$

$\lambda_{\mathrm{med}}/2 = \lambda_{\mathrm{vac}}/2\sqrt{\varepsilon}$

COMSOL Simulation

Mehrani, *arXiv:2509.14320*

Cyclotron Resonance

- A **magnetic field** tunes **ENZ** point with **cyclotron resonance**

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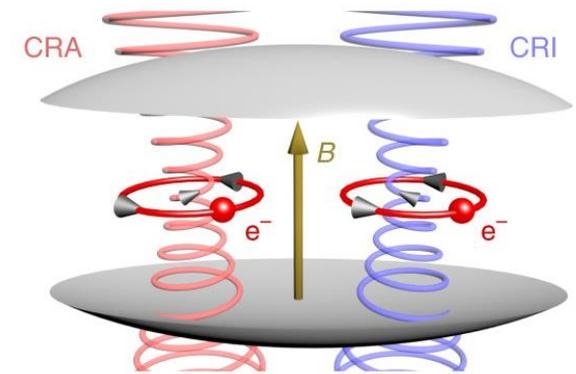
- **Conductivity**

$$\sigma_{\mathrm{CRI}} = \sigma_{xx} - i\,\sigma_{xy} = \frac{\sigma_{\mathrm{DC}}}{1 - i(\omega + \omega_c)\tau}$$

$$\sigma_{\mathrm{CRA}} = \sigma_{xx} + i\,\sigma_{xy} = \frac{\sigma_{\mathrm{DC}}}{1 - i(\omega - \omega_c)\tau}$$

- **Permittivity**

$$\hat{\varepsilon} = \hat{\varepsilon}_{\mathrm{bg}} + i\,\frac{\hat{\sigma}}{\omega\varepsilon_0 d_{\mathrm{QW}}}$$

Li, X., **Kono, J**., et. al.
Nature Photonics (2018)

Permittivity

- **CRI** mode is **lossless**

$$\beta_{\mathrm{CRI}} \gg \beta_{\mathrm{CRA}}$$

- **MQW**s use **effective medium theory (EMT)**

$$\varepsilon_{\mathrm{eff}} = \frac{\varepsilon_{\mathrm{barrier}} d_{\mathrm{Barrier}} + \varepsilon_{\mathrm{QW}} d_{\mathrm{QW}}}{d_{\mathrm{Barrier}} + d_{\mathrm{QW}}}$$

Mehrani, *arXiv:2509.14320*

- COMSOL simulations of boost **validate** EMT:

    layer thickness **<<** λ_{med}

$$\varepsilon_{\mathrm{eff}} = \frac{\varepsilon_{\mathrm{barrier}} d_{\mathrm{Barrier}} + \varepsilon_{\mathrm{QW}} d_{\mathrm{QW}}}{d_{\mathrm{Barrier}} + d_{\mathrm{QW}}}$$

Mehrani, *arXiv:2509.14320*

Detection Principle

- $B_\perp$, normal to MQW surface, **tunes ENZ,** the permittivity component parallel to surface

- $B_\parallel$, parallel to MQW surface, **generates electric field** component parallel to surface

- Lens focuses **radiation from MQW surface** to photodetector

Mehrani, *arXiv:2509.14320*

Experimental Parameters

Realistic ⟵⟶ **Optimistic**

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

Mehrani, *arXiv:2509.14320*

Axion Proposed Sensitivity

Mehrani, *arXiv:2509.14320*

Validating Experimental Conditions

Mehrani, *arXiv:2509.14320*

Finite Surface Area of MQW

- **Smaller** area leads to **reduced collimation** and reduced boost

- **Aspect ratio** of ~**1.5** leads to a **50%** boost

Mehrani, *arXiv:2509.14320*

Finite Axion 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**

Mehrani, *arXiv:2509.14320*

Magnetic Field Inhomogeneity

- The boost is extremely sensitive to the **magnetic field**.
- NMR magnets can reach very high homogeneities (1 ppm/cm).

36 T Magnet at NHMFL

equipped with rotating probe

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.

~ 0.5%/cm

$n \ (10^{11} \ cm^{-2})$

| 3.05 | 2.99 | 2.93 | 2.87 | 2.81 | 2.75 |

1 mm

4 mm

Nano Letters **9** 3 (2019)

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*

Validation Experimental Conditions

Summary: 50% of maximum boost is maintained.
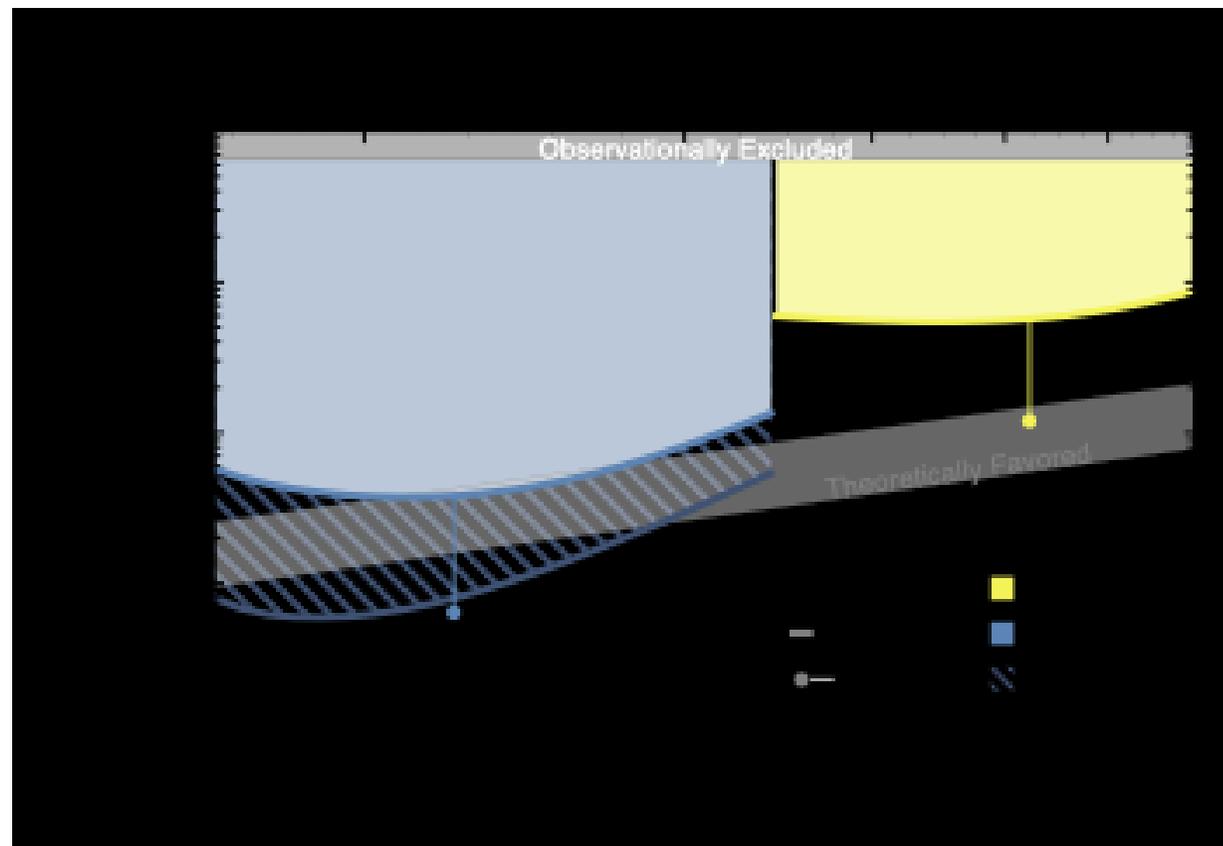
Jaanita Mehrani | Rice University

Conclusion

SQWARE is a new **tabletop, electromagnetically-tunable,** and **highly sensitive** axion detection scheme that may probe **meV axions**.
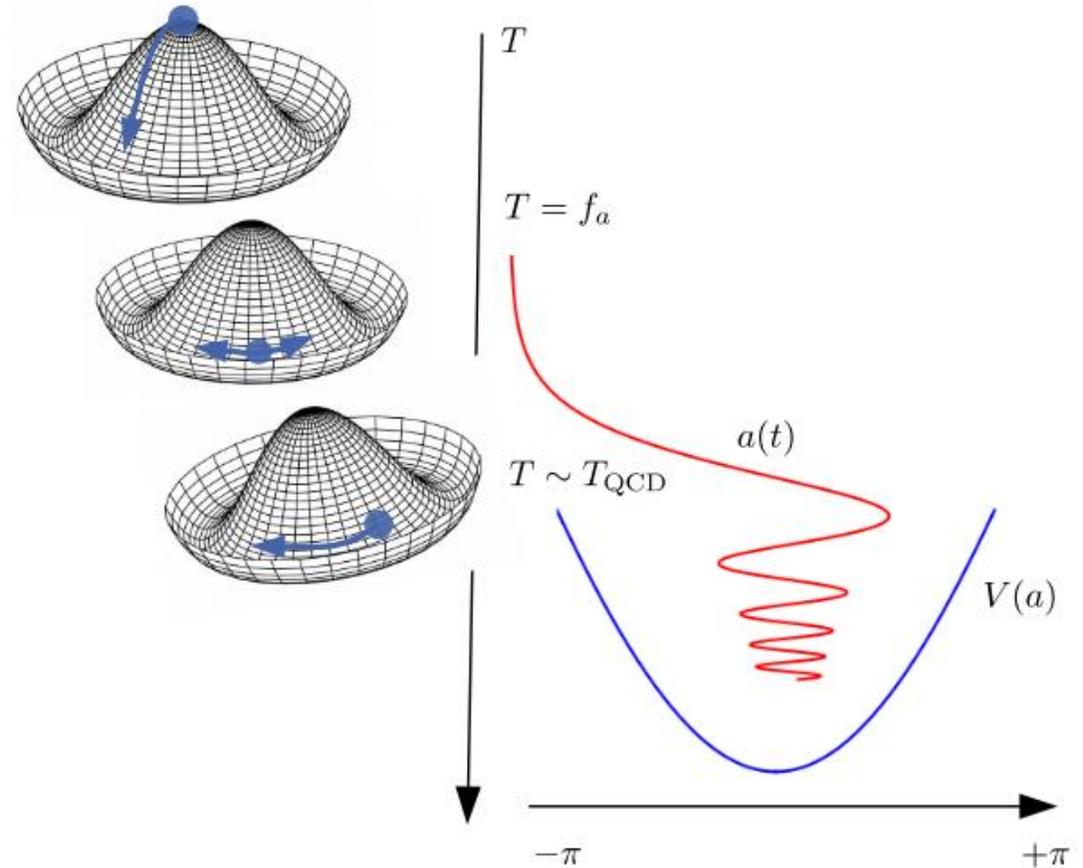
Designer quantum cavities have exciting prospects!!
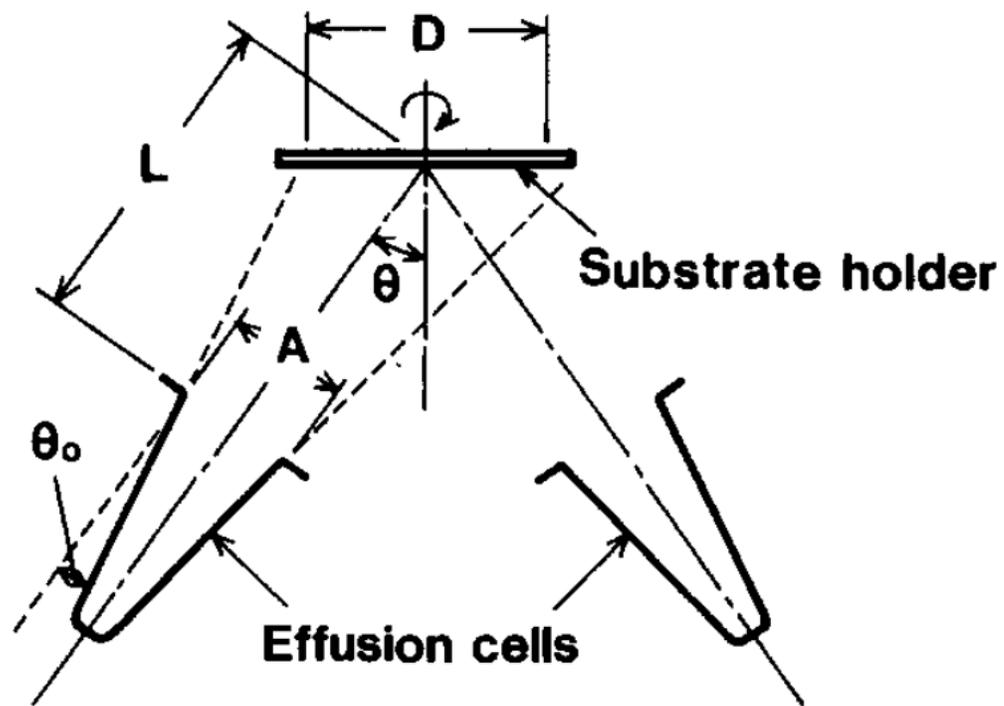

Mehrani, *arXiv:2509.14320*

Acknowledgements

- Co-authors
  - Shengxi Huang (advisor), Jun Kono (advisor), Andrew Long, Henry Everitt, Andrey Baydin, Kuver Sinha (met at TACOS 2 years ago!), Tao Xu, Michael Manfra

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- SCOPE + KONO + CAP lab members!

- TACOS organizers!!!

Conclusion

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

Designer quantum cavities have exciting prospects!!

Thank you for listening!

Mehrani, *arXiv:2509.14320*

Axion Theory

- **Peccei-Quinn Symmetry** is introduced as a **new global symmetry that is spontaneously broken**, which generates **pseudo-goldstone bosons**, called the axion!

- **Pseudo**, since the symmetry wasn't perfect, as there is some **tilt** in the potential, related to **coupling with the gluon fields**.

KIT Andreas Pargner (2019)

Molecular Beam Epitaxy (MBE)

Journal of Crystal Growth **81** 188-192 (1987)

Nature Materials **20** 632-637 (2021)

High Field Magnet

- **Maximum Field:** 45 tesla
- **Bore Diameter:** 32 mm
- **Power:** 30 MW
- **Homogeneity**: 110 ppm
- **Number of input and output leads possible**: 22
- **Frequency**: 0-100 kHz
- **Temperature Range**: 0.3-300K
- **Open for users who would pay for magnet time**: Yes

- **Field strength:** 36 tesla
- **Bore size:** 48 mm
- **Power:** 14 MW
- **Homogeneity**: 100 ppm (in Condensed Matter Configuration)
- **Number of input and output leads possible**: 36
- **Frequency**: 0-1.5 GHz
- **Temperature Range**: 0.3-300K
- **Open for users who would pay for magnet time**: Yes

- Larmor Frequency : 900 MHz
- Field Strength: 21.1T
- Bore size: 105 mm
- Homogeneity : 1 ppb
- Console: Bruker Avance NEO Console
- RF channels- 3 (1H) channels and 2(X) channels
- RF Amplifiers- 2x100W, 1x 500W (1H) and 1x 500W, 1x 1000W (X)
- Gradient amplifiers- Bruker GREAT 60 and IECO 400-350 amplifiers

- **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

Quantum Dot Photodetector

- Tunable resonance using a magnetic field
- Some FET measures the electron excitation as a change in charge, capacitance, or current
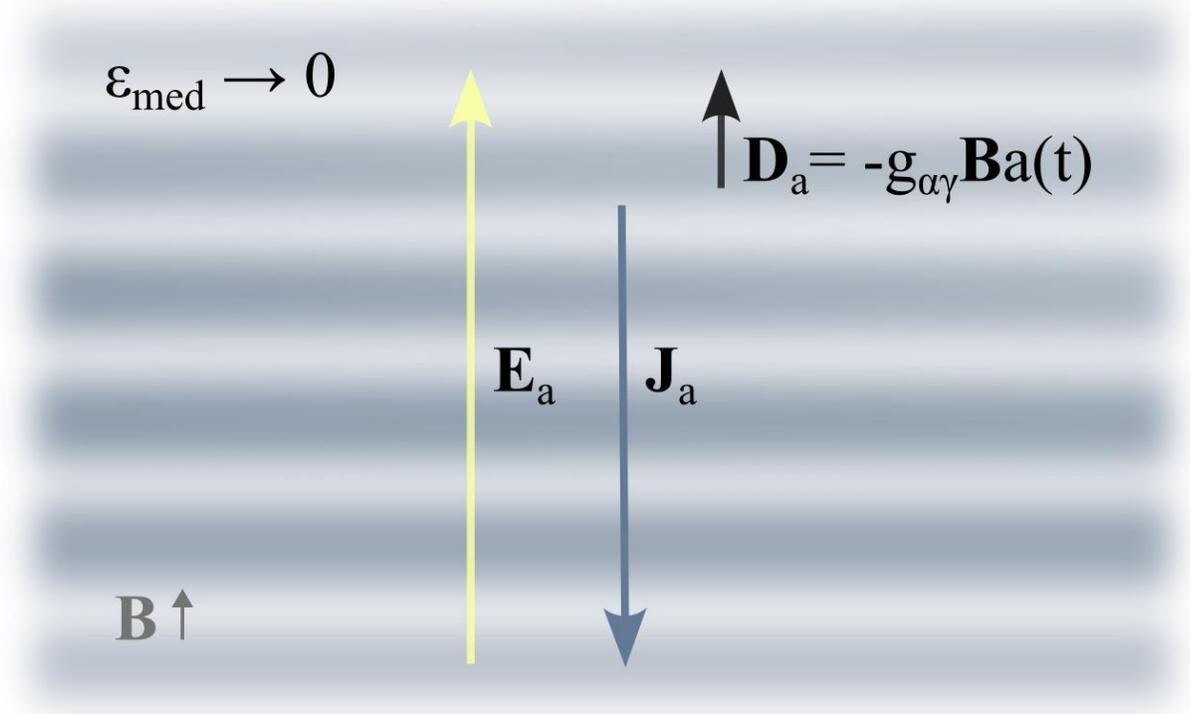- Experimentally tested at 2 meV and 6 meV resonances

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

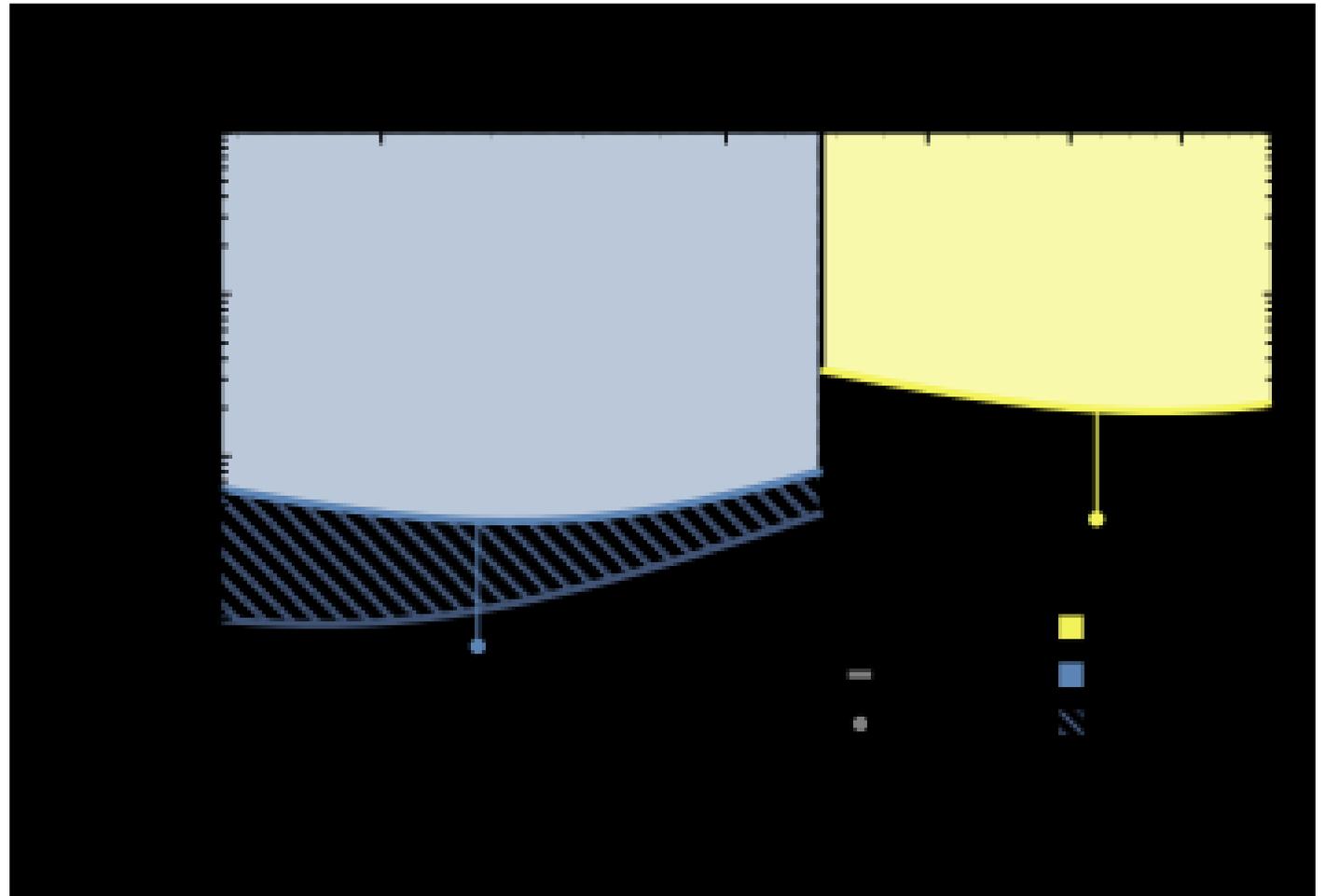# Material Response to Axions

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

$$\mathbf{D}_a = \mathbf{E}_a + \mathbf{P}_a - \frac{i}{\omega}\boldsymbol{J}_a$$

$$= \mathbf{E}_a + \hat{\chi}\mathbf{E}_a - \frac{i\hat{\sigma}}{\omega}\mathbf{E}_a$$

$$= \hat{\epsilon}\mathbf{E}_a = -g_{a\gamma}\mathbf{B}a(t)$$
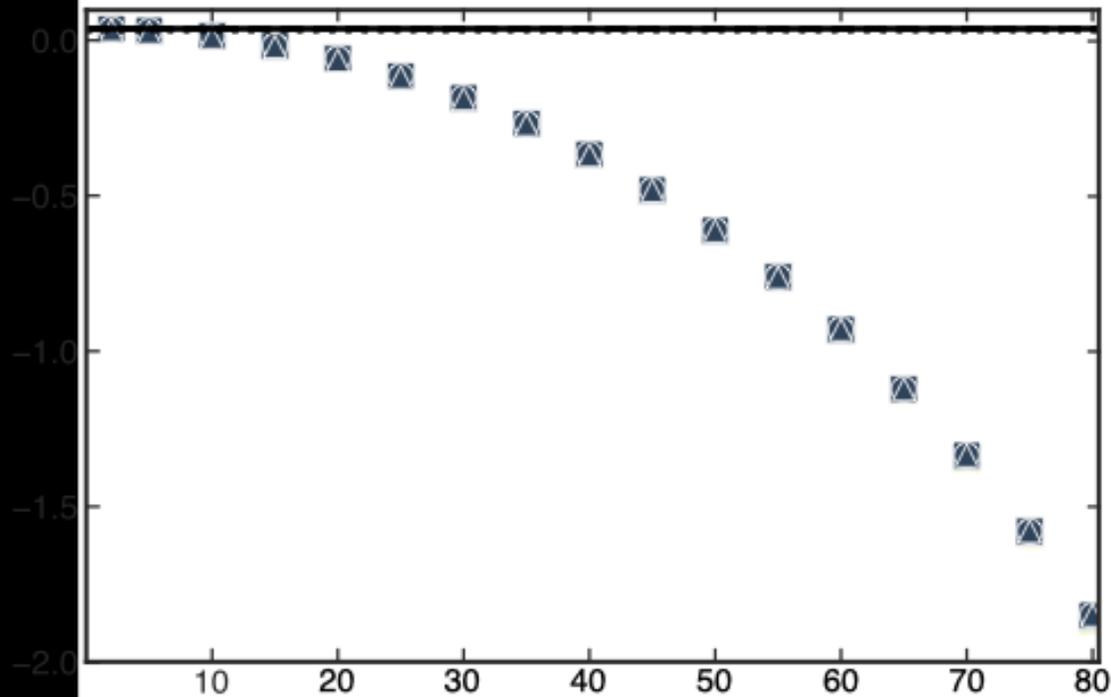
- Plasmonic material ($|\varepsilon| \to 0$)
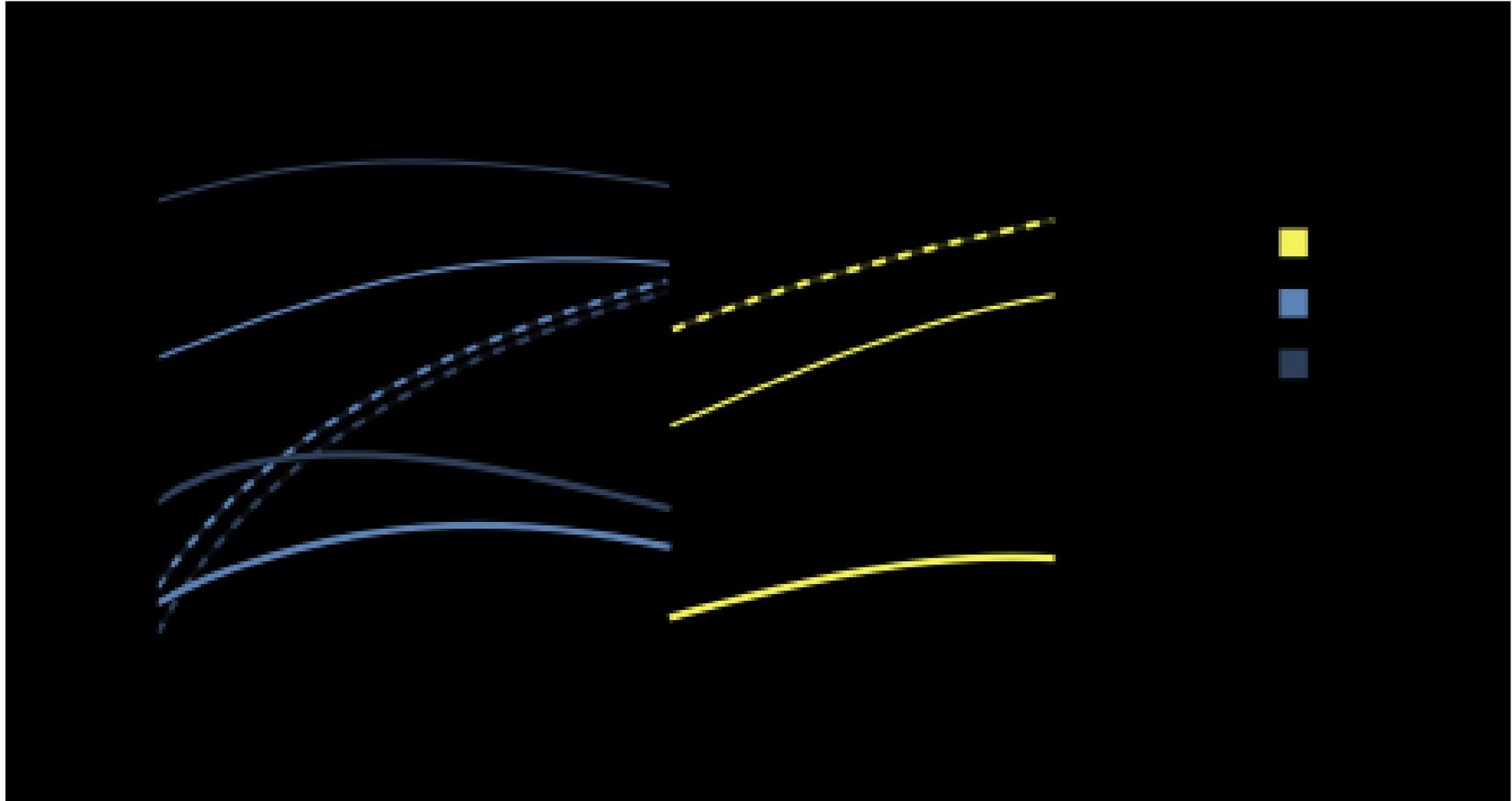
- Mixing parameter χ instead of coupling *g*

EMT (1)

EMT (2)
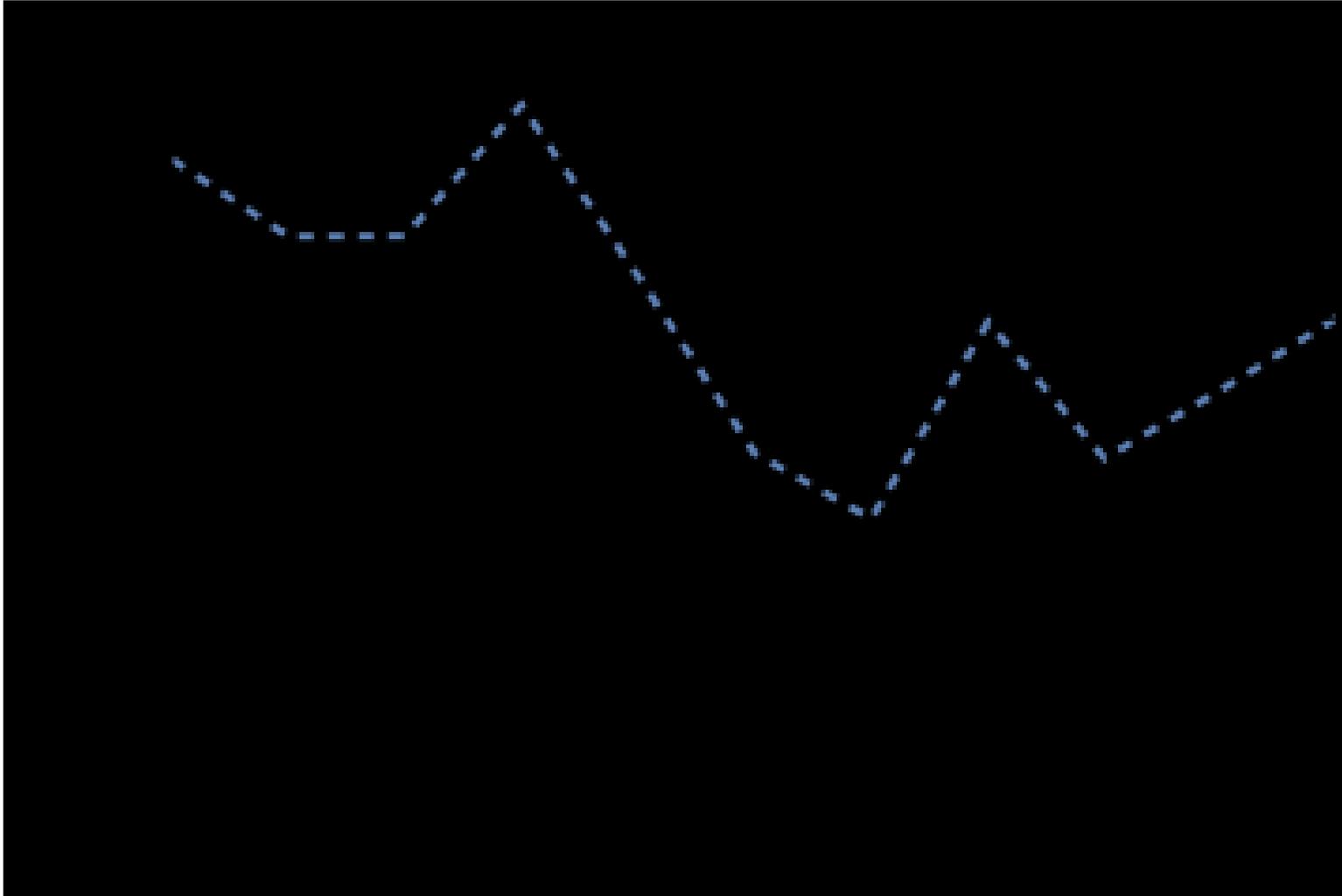
EMT (3)

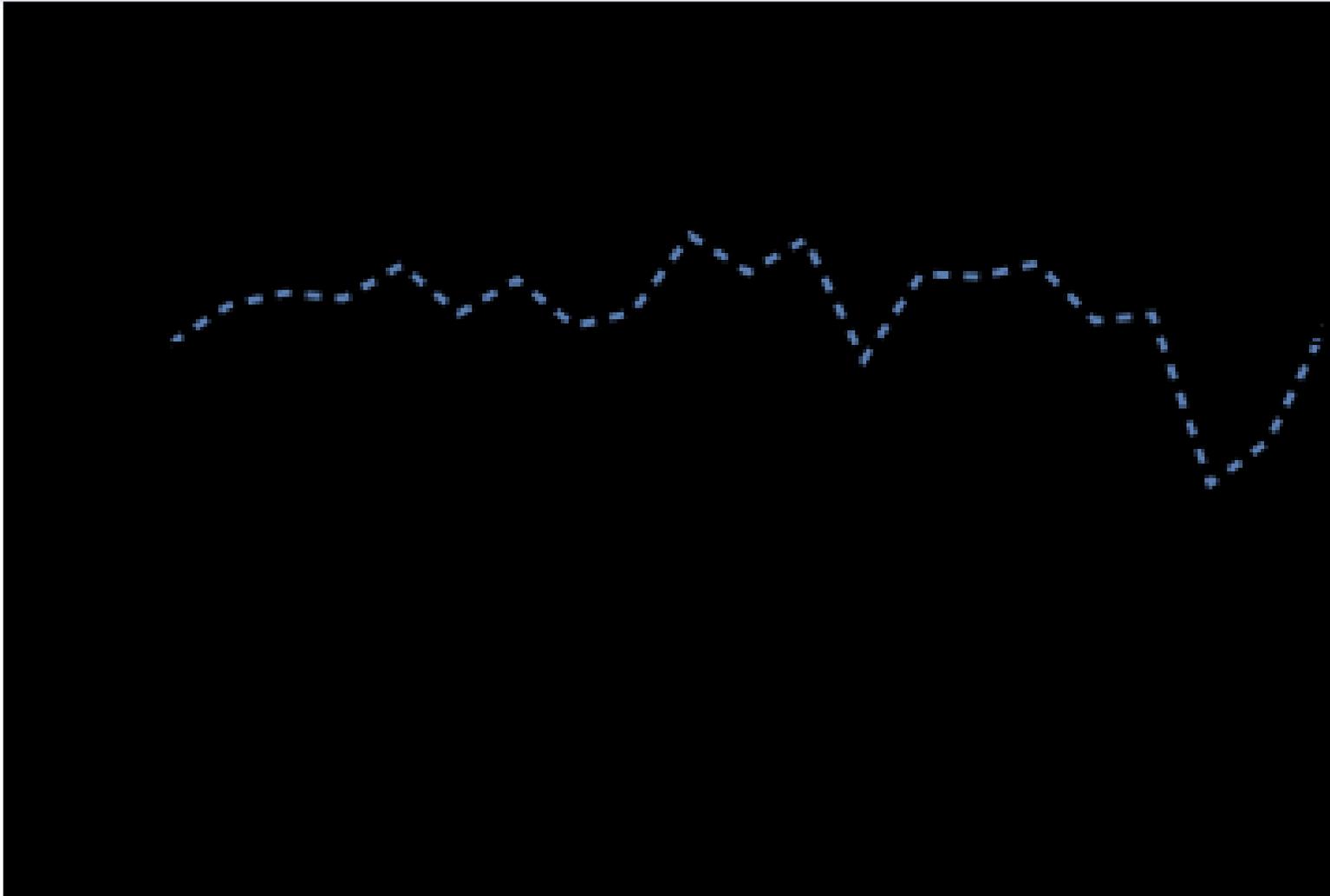# MQW Angle, Quality Factor, and Boost

Surface e⁻ Density Variation

"best side" plotted

Well-to-Well e⁻ Density Variation

"best side" plotted