

CHEN SUN / HIAS-UCAS

# Axion Magnetic Resonance

in the lab, the Sun, and the galaxy

Restoring coherence in axion-photon conversion

# Formalism

Axion–photon mixing, coherence, and magnetic resonance.

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1 Formalism

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2 Laser experiments

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3 Axion helioscopes

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4 DM in galaxies

# Why axions?

01

## Strong CP

The QCD axion lets the CP angle relax.

02

## Dark matter

A light field can behave as cold matter.

03

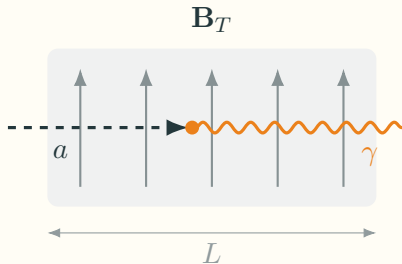
## UV completion

Axion-like particles arise in broader theories.

This talk: use a photon coupling to **make axions visible**.

Lab and solar searches need no axion dark matter assumption.

# Convert axions into light



$$\mathcal{L}_{a\gamma} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

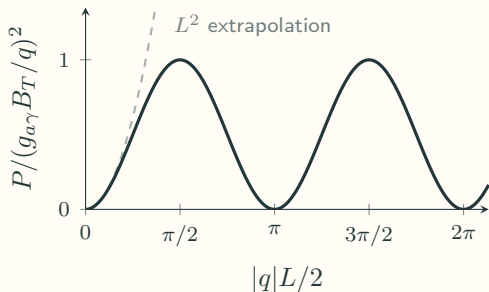
Each segment adds an amplitude.

$$\mathcal{A}_{a \rightarrow \gamma} \simeq \frac{g_{a\gamma} B_T L}{2}$$

If all contributions stay in phase,

$$P_{a \rightarrow \gamma} \propto L^2.$$

# Phase mismatch limits coherent growth



Same energy, different momenta:

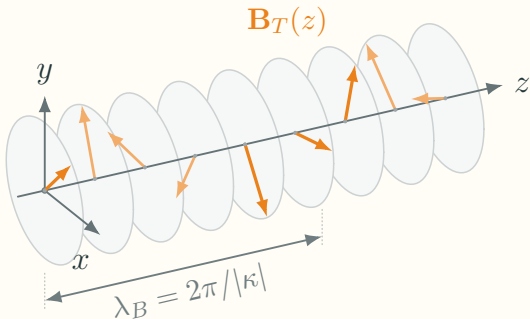
$$q \equiv k_\gamma - k_a \simeq \frac{m_a^2}{2\omega}.$$

$$P \simeq \left( \frac{g_{a\gamma} B_T L}{2} \right)^2 \underbrace{\text{sinc}^2 \left( \frac{qL}{2} \right)}_{\text{phase cancellation}}$$

$\text{sinc } x = \sin x/x$ ; vacuum, weak mixing.

For  $|q|L \gtrsim 1$ , a longer magnet no longer gives steady  $L^2$  growth.

# A rotating field supplies the mismatch



$$\theta(z) = \kappa z + \theta_0, \quad B_z = 0$$

Each gray disk is a transverse  $xy$  plane.

Circular components carry phases

$$B_{\pm}(z) \propto e^{\pm i\kappa z}.$$

Conversion now samples

$$\mathcal{A}_{\pm} \propto \int_0^L dz e^{i(q \pm \kappa)z}.$$

One component stays in phase when  
 $|\kappa| = |q|$ .

# Axion magnetic resonance

In the rotating basis, near one resonance:

$$H_{\text{res}} \simeq \begin{pmatrix} 0 & \Delta_B \\ \Delta_B & q - |\dot{\theta}| \end{pmatrix}, \quad \Delta_B = \frac{g_{a\gamma} B_T}{2\sqrt{2}}.$$

The rotation shifts the photon propagation eigenvalues.

RESONANCE

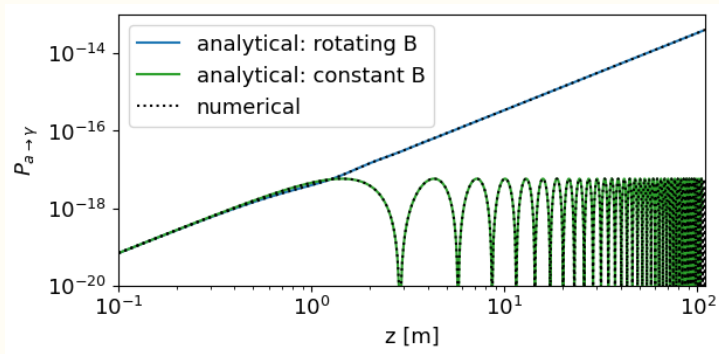
$$\frac{m_a^2}{2\omega} = |\dot{\theta}|$$

$$P_{a \rightarrow \gamma} \simeq \frac{(g_{a\gamma} B_T L)^2}{8}$$

Isolated resonance; small conversion probability.

Restore coherent  $L^2$  growth at a selected axion mass.

# Coherent growth is restored



## Rotating field

$P \propto L^2$  at resonance.

## Constant field

Phase cancellation.

Dotted numerical solution agrees with the analytic result.

# Application to laser experiments

Photon regeneration with resonant magnetic fields.

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1 Formalism

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2 Laser experiments

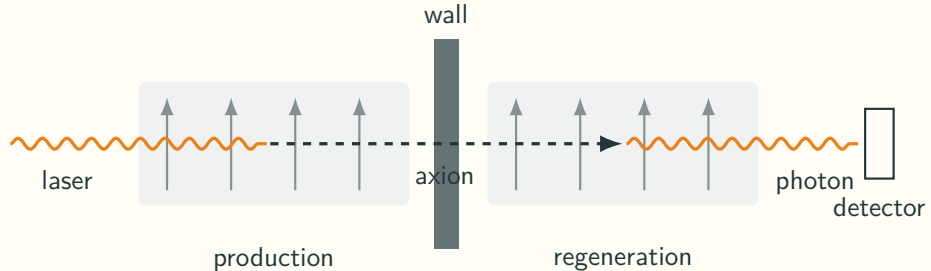
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3 Axion helioscopes

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4 DM in galaxies

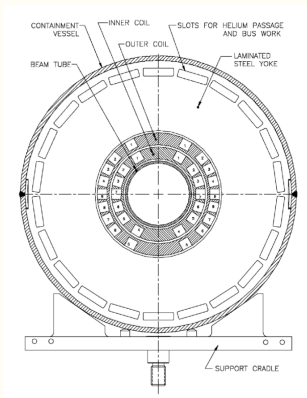
# Lab: light shining through a wall



Two conversions. Restore coherence in both magnets.

Laser photons stop at the wall; axions can pass through.

# Experimental Implications

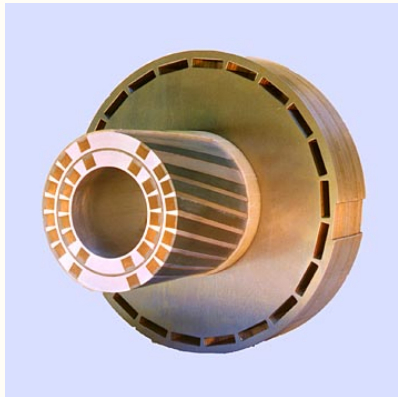


Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

- superconducting dipole magnet  $\sim 5$  T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...  
... 80-100/130-180 mm apertures

10.1016/S0168-9002(02)01940-X

# Experimental Implications

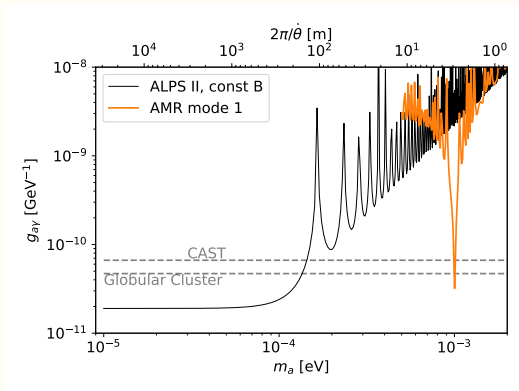


Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

- superconducting dipole magnet  $\sim 5$  T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...  
... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding

*10.1016/S0168-9002(02)01940-X*

# Lab: resonance extends the mass reach



## One helical mode

A localized sensitivity gain.

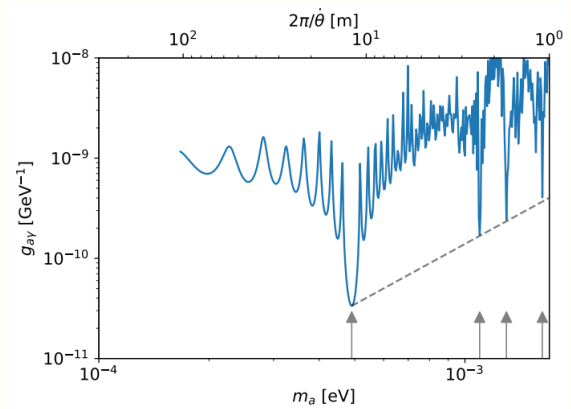
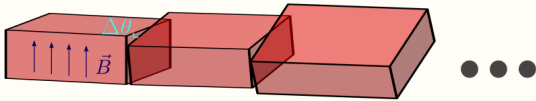
## Scan the mass

Vary the rotation rate:

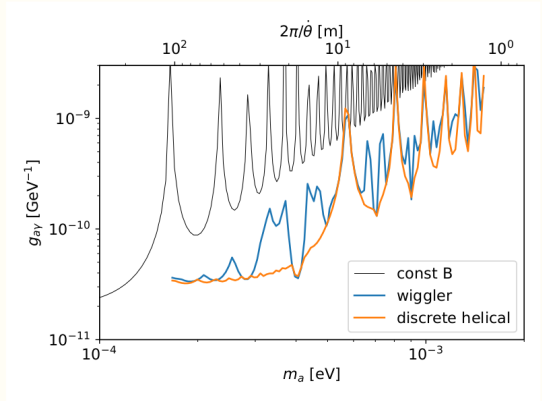
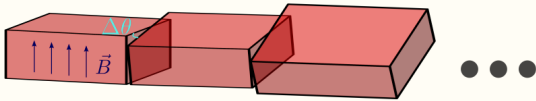
$$m_{a,\text{res}} \propto \sqrt{|\kappa|}.$$

ALPS-II-like projection from the original study.

# Scanning Different Axion Masses



# Scanning Different Axion Masses



# Application to axion helioscopes

Resonant conversion of the solar axion spectrum.

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# One resonance, two ways to scan

$$\dot{\theta} = \frac{m_a^2}{2\omega}$$

$\dot{\theta} = d\theta/dz$  magnetic-field rotation rate

## Laser experiments

Photon energy  $\omega$  fixed

Magnetic rotation  $\dot{\theta}$  varied

Tune the field to scan  $m_a$ .

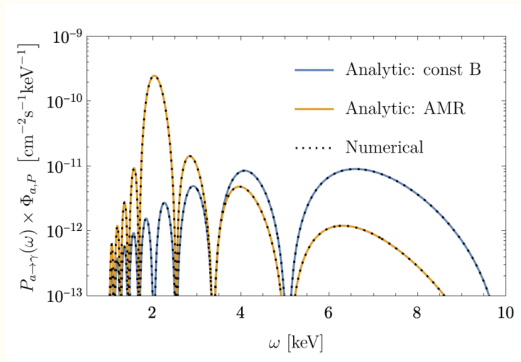
## Axion helioscopes

Photon energy  $\omega$  varied

Magnetic rotation  $\dot{\theta}$  fixed

The Sun supplies the energy range.

# Solar axions scan the resonance



The Sun supplies a broad keV axion spectrum.

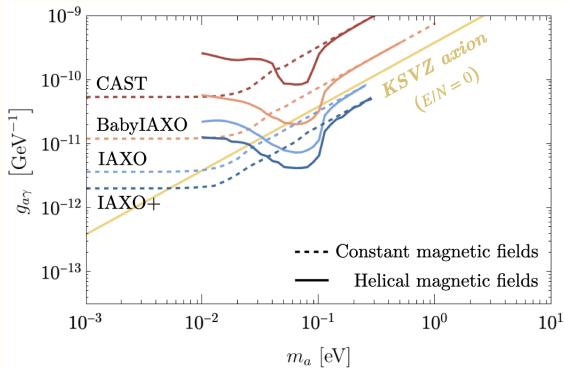
A helioscope converts it into X-rays.

Fix  $\dot{\theta}$ ; resonance selects

$$\omega_{\text{res}} = \frac{m_a^2}{2|\dot{\theta}|}.$$

Plot: conversion probability  $\times$  incident flux.

# Solar: reach toward higher masses



**Dashed:** constant field  
**Solid:** helical field

$$\alpha|0\rangle + e^{i\varphi(t)}\beta|1\rangle$$

Qubit



↯ oscillation

MSW & (Avoided) level crossing

Atomic

Rabi flopping

Nuclear

Nuclear Magnetic Resonance

Axion-photon

Axion Magnetic Resonance

# Application to DM in galaxies

A coherent axion dark matter background supplies a periodic drive.

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$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} m_\gamma^2 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & m_\gamma^2 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}$$

$$i\partial_z \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} = \begin{bmatrix} m_\gamma^2/2\omega & -i\dot{\theta} & 0 \\ i\dot{\theta} & m_\gamma^2/2\omega & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

# Propagation in an axion DM background

$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \begin{bmatrix} m_\gamma^2/2\omega & -i\Delta_{\text{DM}}(z) & 0 \\ i\Delta_{\text{DM}}(z) & m_\gamma^2/2\omega & g_{a\gamma}B/2 \\ 0 & g_{a\gamma}B/2 & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}$$

$$\Delta_{\text{DM}}(z) \simeq g_{a\gamma} \sqrt{\frac{\rho_{\text{DM}}}{2}} \cos(m_{aL}z + \varphi_0)$$

# Resonance Condition

$$\Delta_{a\gamma} \equiv \frac{m_a^2 - m_\gamma^2}{2\omega} = n m_{aL}$$

$$P_{a \rightarrow \gamma}^{(n)}(L) \simeq \left( \frac{g_{a\gamma} B L}{2} \right)^2 J_n^2 \left( \frac{g_{a\gamma} \sqrt{\rho_{\text{DM}}/2}}{m_{aL}} \right)$$

FIRST RESONANCE

$$m_{aL} = 10^{-22} \text{ eV}, \quad \omega = 50 \text{ keV} \quad \Rightarrow \quad m_a \simeq 3.16 \times 10^{-9} \text{ eV}$$

# Enhancement in M82

CS, Si-Yu Wu, Seokhoon Yun, to appear



## WITHOUT RESONANCE

$$P_{a \rightarrow \gamma}^{(0)}(L) = \left( \frac{g_{a\gamma} B}{\Delta_{a\gamma}} \right)^2 \sin^2 \left( \frac{\Delta_{a\gamma} L}{2} \right)$$

## FIRST RESONANCE

$$P_{a \rightarrow \gamma}^{(1)}(L) \simeq \left( \frac{g_{a\gamma} B L}{2} \right)^2 \left( \frac{g_{a\gamma} \sqrt{\rho_{\text{DM}}/2}}{2m_{aL}} \right)^2$$

### M82 benchmark

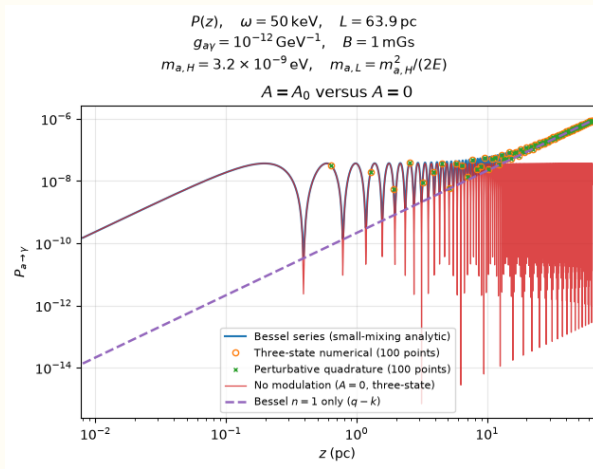
$$B = 10 \mu\text{G}, \quad \omega = 50 \text{ keV}, \quad g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}, \quad \rho_{\text{DM}} = 1 \text{ GeV cm}^{-3}$$

$$m_{aL} = 10^{-22} \text{ eV}, \quad m_a = 3.16 \times 10^{-9} \text{ eV}$$

$$P_{a \rightarrow \gamma}^{(0)} \leq 3.8 \times 10^{-12} \quad \longrightarrow \quad P_{a \rightarrow \gamma}^{(1)} \simeq 5.6 \times 10^{-11} \quad \sim 15 \times$$

$$L = 50 \text{ pc}$$

# Dark matter induced AMR

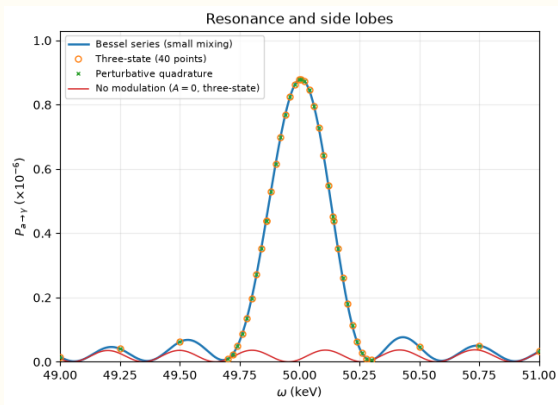


$L = \text{coherence length}$

# Dark matter coherence

$$P(\omega), \quad A = A_0, \quad L = 63.9 \text{ pc}$$

$$m_{a,L} = \frac{m_{a,H}^2}{2 \times 50 \text{ keV}} \quad (\text{fixed})$$



# Including decoherence

Two effects enter our propagation calculation:

01

## Magnetic domains

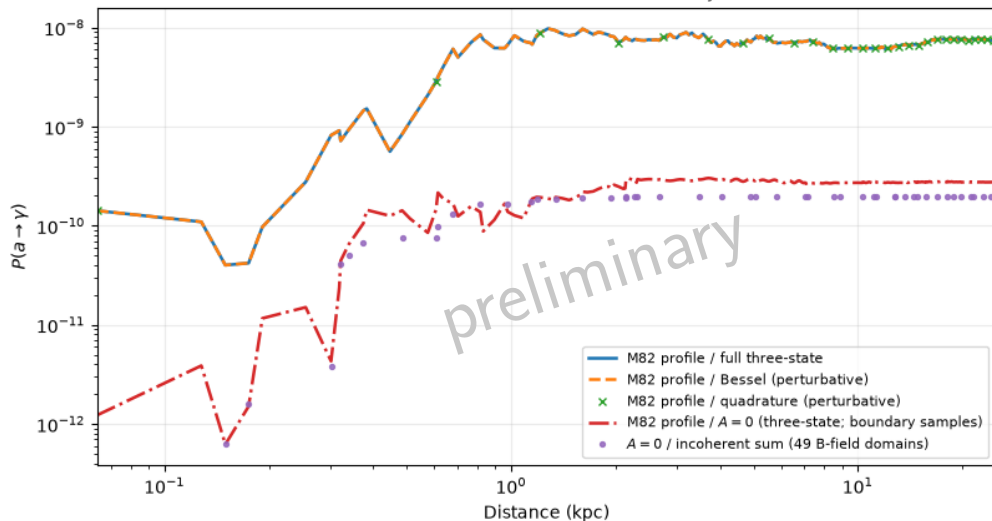
Field directions change between magnetic domains.

02

## Dark matter velocity dispersion

A spread of velocities limits the background coherence.

M82 B profile; 50 keV; modulated versus  $A = 0$   
 All four curves: same 49 B domains + random xy directions



# Takeaways

01

Mismatch destroys coherence

$$\Delta_{a\gamma} L \gtrsim 1$$

02

Restore phase matching

plasma // cavity //  $H(t, \mathbf{x})$

(A)

AMR – Lab search

Laser LSTW experiments

(B)

AMR – Solar axion

Axion helioscope

(C)

AMR – Axion DM

galaxy X-ray