*LA-UR-23-30935*

# Axion Magnetic Resonance: A Novel Enhancement in Axion-Photon Conversion

**Chen Sun** (LANL)

May 15, 2024

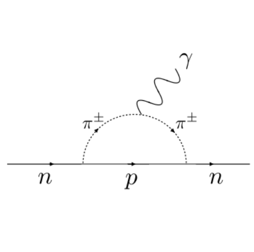
*H. Seong (DESY),* ***CS****, S. Yun (IBS),* *2308.10925*

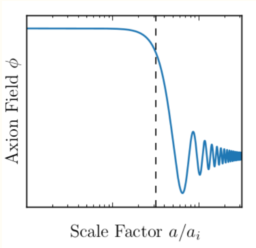
The SM of elementary particle physics is incredibly successful, but...

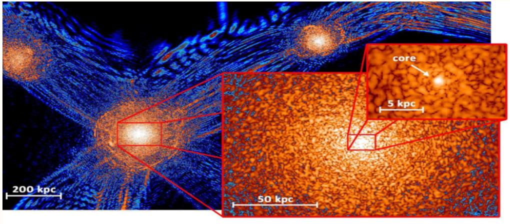
- Why is time reversal preserved in QCD?
- How to UV complete gravity? ($[G_N] = M^{-2}$)
- What is the nature of dark matter?

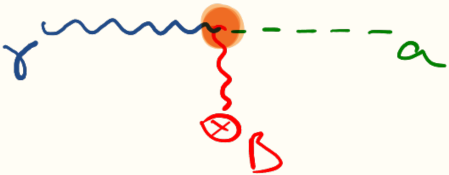
Axions are

- originally motivated by the strong CP problem;
- natural light states that appear in many UV models;
- interesting non-thermal DM candidates.

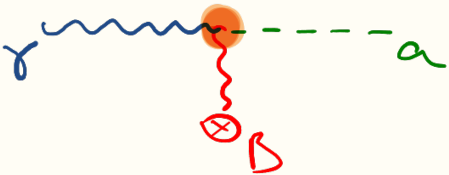


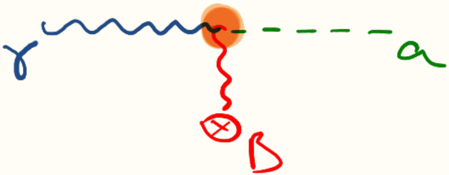



$$g_{a\gamma} a F\tilde{F} \sim g_{a\gamma} a \; \mathbf{E} \cdot \mathbf{B}$$



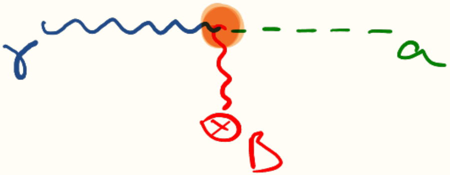

$$g_{a\gamma} a F\tilde{F} \sim g_{a\gamma} a \, \mathbf{E} \cdot \mathbf{B}$$

$$P_{a\gamma} = \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + (m_a^2 - m_\gamma^2)^2/(4\omega^2)} \sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{(m_a^2 - m_\gamma^2)^2}{4\omega^2}}\right) x\right),$$



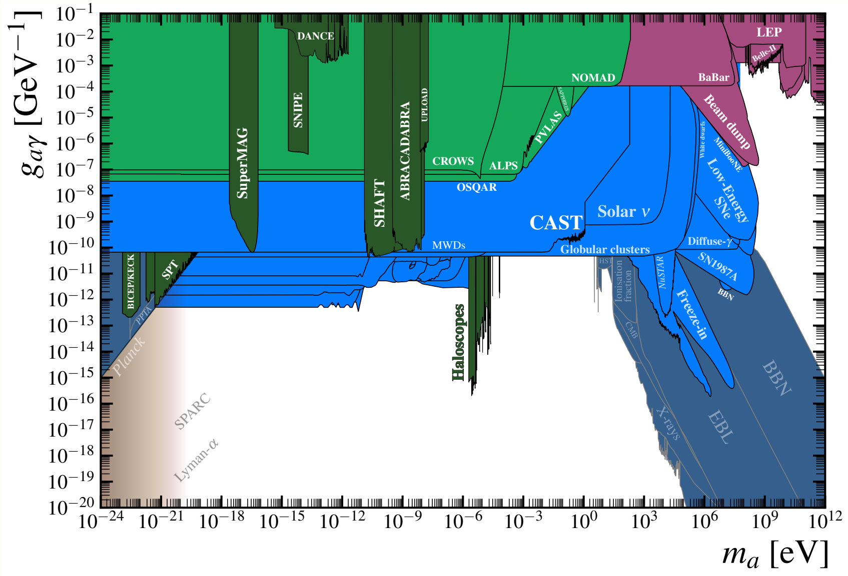

$$g_{a\gamma} a F\tilde{F} \sim g_{a\gamma} a \, \mathbf{E} \cdot \mathbf{B}$$

$$P_{\gamma \to a} \sim (g_{a\gamma} B x)^2$$

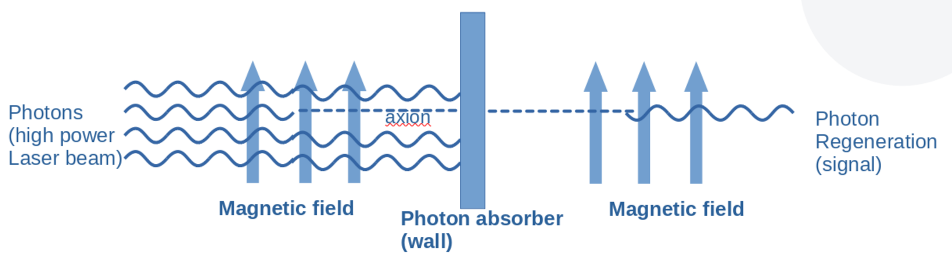


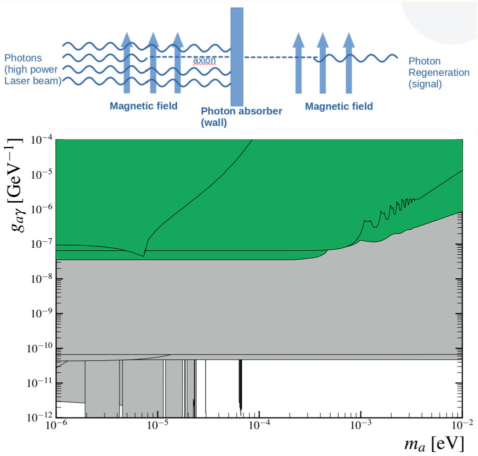

$$g_{a\gamma} a F\tilde{F} \sim g_{a\gamma} a \; \mathbf{E} \cdot \mathbf{B}$$

$$P_{\gamma \to a} \sim \frac{g_{a\gamma}^2 B^2}{m_a^4/(4\omega^2)}$$



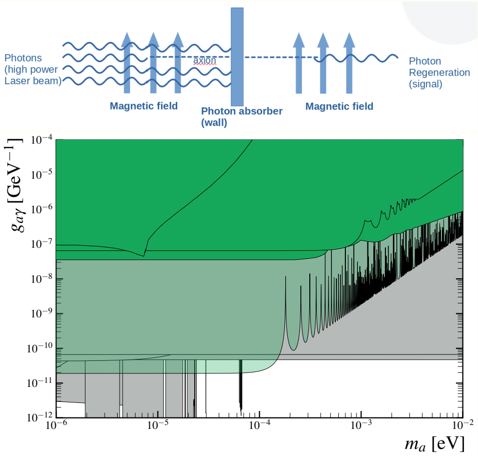

cajohare/AxionLimits


Photons
(high power
Laser beam)
axion
Magnetic field
Photon absorber
(wall)
Magnetic field
Photon
Regeneration
(signal)




ALPS-II:

- 12 pieces of HERA dipole magnet,
  (5.7 kA $\Rightarrow$ 5.3 T)
- 106 m for production, 106 m for regen'
- continuous laser: 1064 nm, 30 W
- optical Fabry-Perot resonator:
  5000 power build-up $\sim$150 kW in prod' cavity
  40000 power build-up in the regen' cavity
- detector: cryogenic superconducting microcalorimeter (TES)
- started data taking on May 23, 2023

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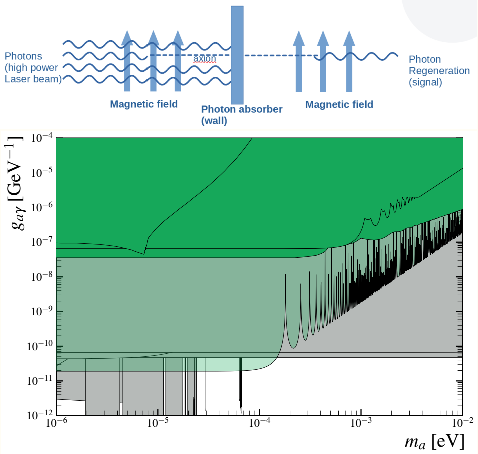
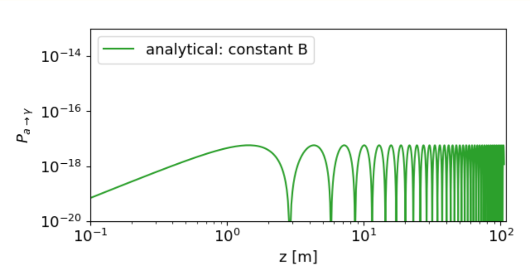
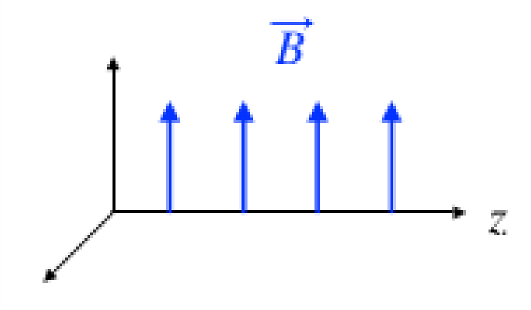
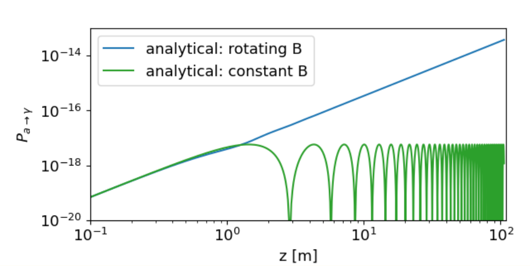


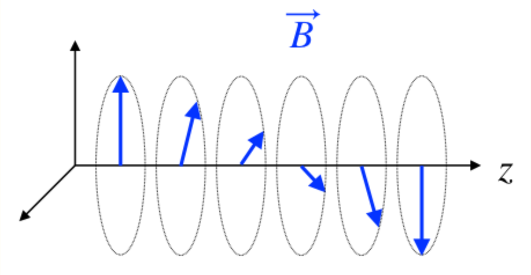

How to lift the $P_{a\gamma} \propto m_a^{-4}$ suppression?




$$P_{a\to\gamma} \simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/(4\omega^2)} \sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}}\right) z\right),$$




$$P_{a\to\gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2/2}{g_{a\gamma}^2 B^2/2 + (m_a^2/2\omega \pm \dot{\theta})^2} \sin^2\left(\left(\frac{1}{2}\sqrt{\frac{g_{a\gamma}^2 B^2}{2} + (\frac{m_a^2}{2\omega} \pm \dot{\theta})^2}\right) z\right),$$

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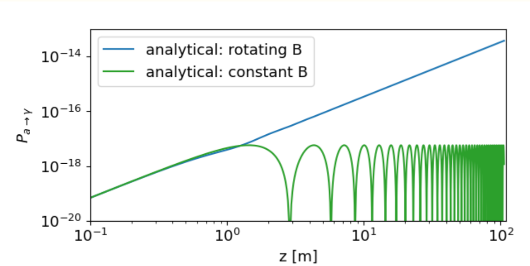


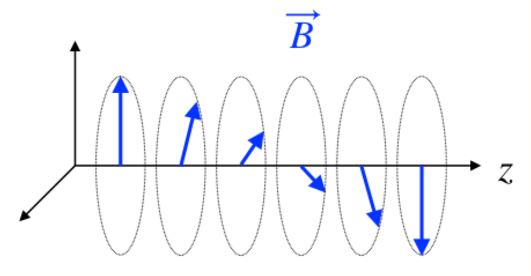


$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta(z) \\ 0 & 0 & g_{a\gamma}\omega B c_\theta(z) \\ g_{a\gamma}\omega B s_\theta(z) & g_{a\gamma}\omega B c_\theta(z) & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x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

*(RK45 or BDF solver)*

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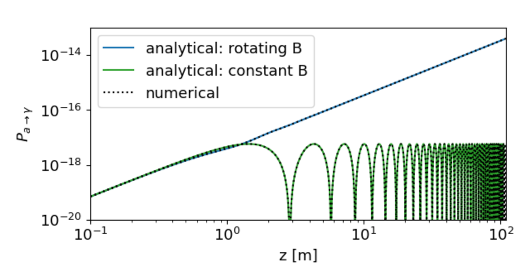


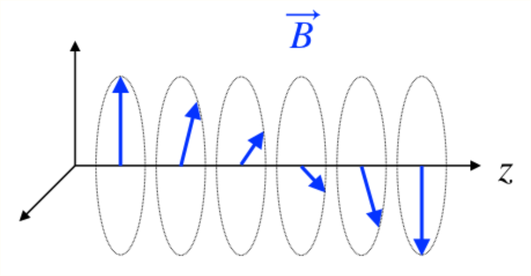


$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta(z) \\ 0 & 0 & g_{a\gamma}\omega B c_\theta(z) \\ g_{a\gamma}\omega B s_\theta(z) & g_{a\gamma}\omega B c_\theta(z) & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x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

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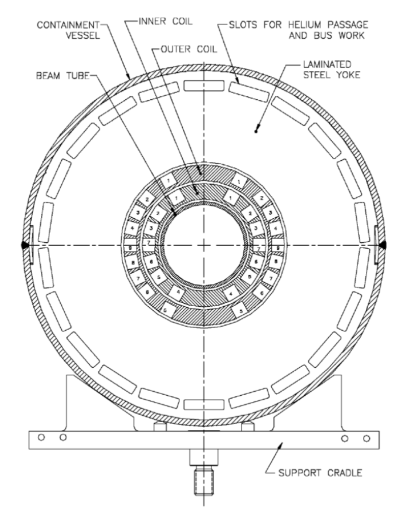
# Experimental Implications

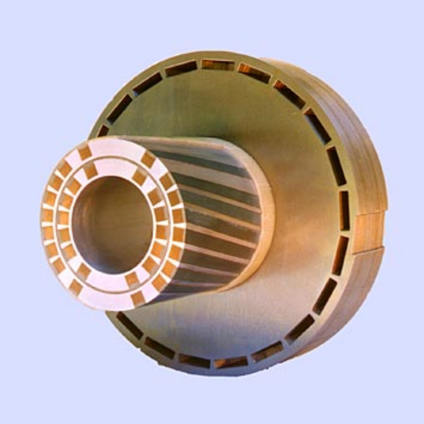



Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

- 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

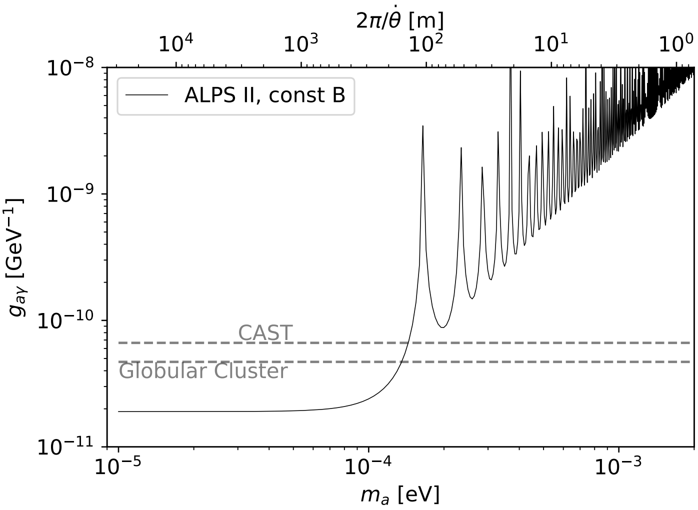


Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

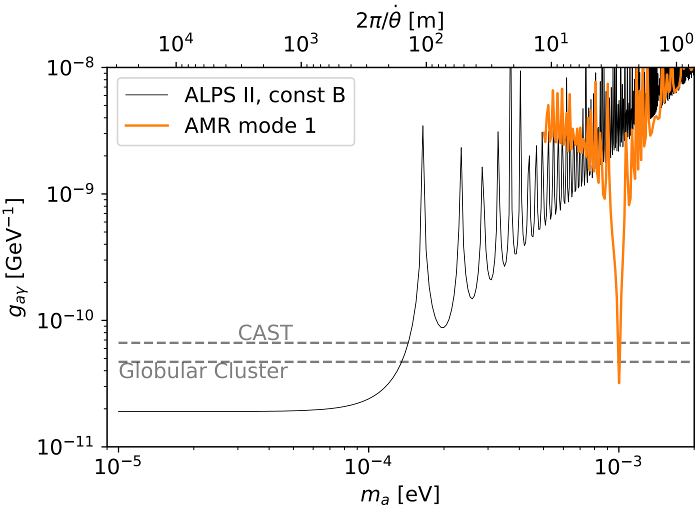
- superconducting dipole magnet $\sim 5$ T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
  ... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding

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

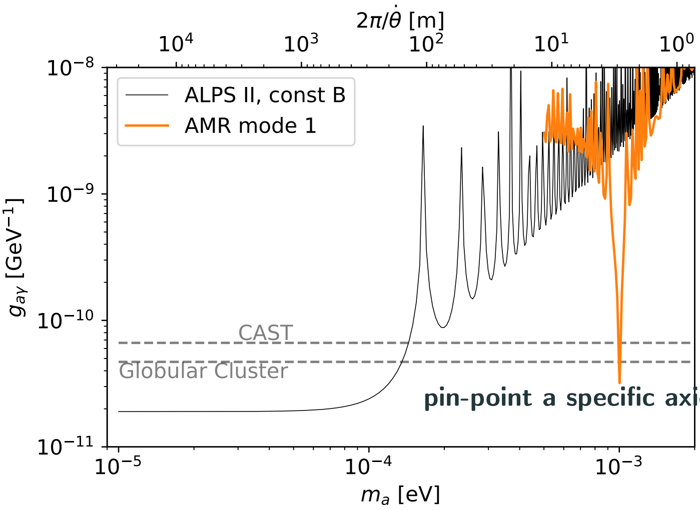
# Experimental Implications – cont'd



# Experimental Implications – cont'd

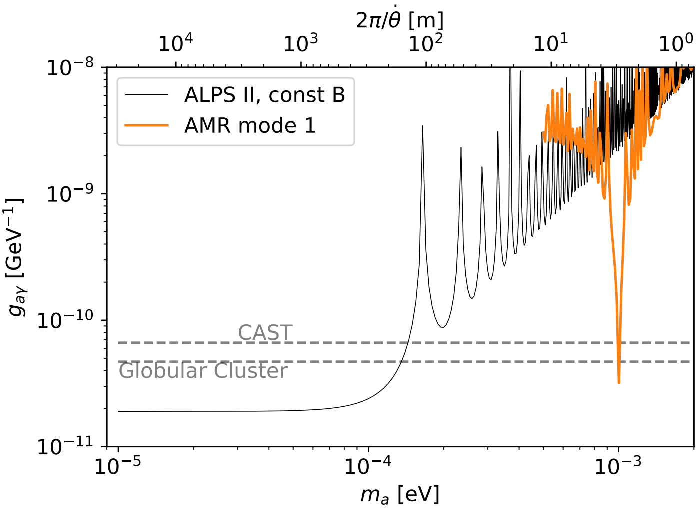


# Experimental Implications – cont'd




**pin-point a specific axion mass!**

# The maximal reach of AMR



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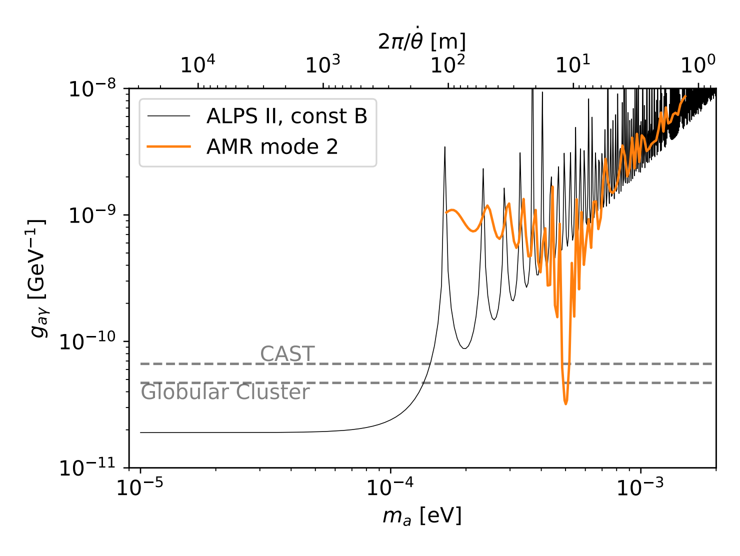

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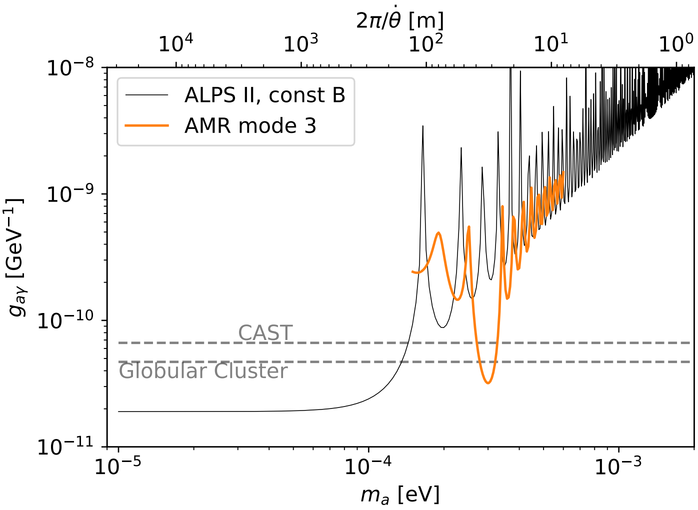

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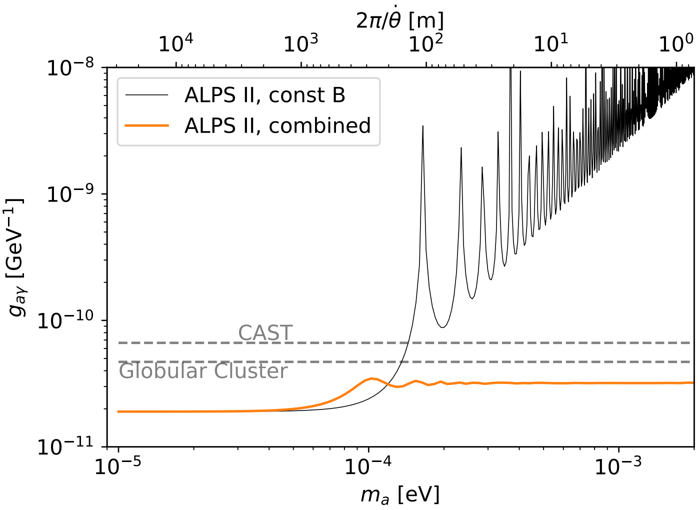


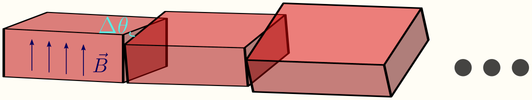
**Unpopular opinion:**

building $\sim 10$ types of magnet each covering one magnetic frequency.

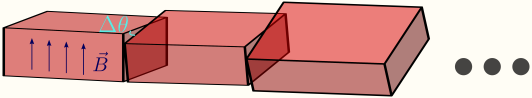
# In an ideal world (where physics budget is not an issue)

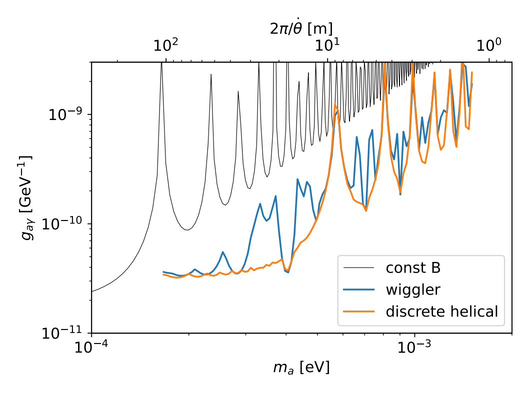
**Unpopular opinion:**

building $\sim 10$ types of magnet each covering one magnetic frequency.



$\Delta\theta$
$\vec{B}$


$\Delta\theta$
$\vec{B}$


$2\pi/\dot{\theta}$ [m]
$10^2$
$10^1$
$10^0$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$g_{a\gamma}$ [GeV$^{-1}$]
$10^{-4}$
$10^{-3}$
$m_a$ [eV]
const B
wiggler
discrete helical

# Conclucsion

- **Axion magnetic resonance** is poised to deepen the experimental reach (*e.g.* ALPS-II) that has great potential to ...
  - **enhance** the axion-photon conversion;
  - **pinpoint** parameter space should any anomaly arises;
  - **scan** parameter space that has never been tested on the ground!

Thank you!

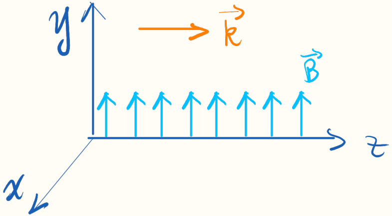
# Thank you!

- https://github.com/ChenSun-Phys/cosmo_axions — axion in cosmic distance (2011.05993)
- https://github.com/ChenSun-Phys/high_z_candles — axion in quasars (2309.07212)
- https://github.com/ChenSun-phys/snr_ghosts — axion stimulated decay by SN remnants (2110.13916)
- https://github.com/ChenSun-phys/ULDM_x_SPARC — axion probed by galaxy rotation curves (2111.03070)
- https://github.com/ChenSun-phys/axion-magnetic-resonance — axion magnetic resonance (2308.10925)
- https://github.com/cajohare/AxionLimits — axion global constraints (O'Hare Repository)

# Backup Slides

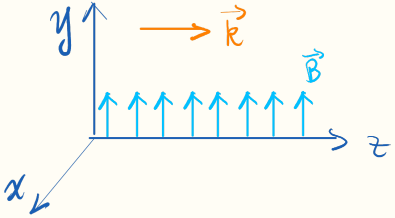
# A Simple Derivation of the Resonance

# The Good'ol Oscillation




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

# The Good'ol Oscillation




$$U^\dagger i\partial_z \begin{bmatrix}\gamma_x\\ \gamma_y\\ a\end{bmatrix} = \frac{1}{2\omega} \underbrace{U^\dagger \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & g_{a\gamma}\omega B\\ 0 & g_{a\gamma}\omega B & m_a^2\end{bmatrix} U}_{\text{diagonal}} \underbrace{U^\dagger \begin{bmatrix}\gamma_x\\ \gamma_y\\ a\end{bmatrix}}_{\text{mass eigenbasis}},$$

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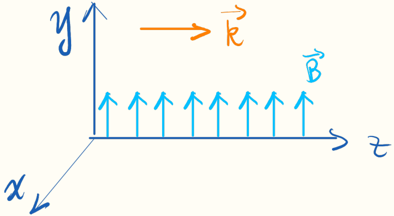


$$i\partial_z U^\dagger \begin{bmatrix}\gamma_x\\ \gamma_y\\ a\end{bmatrix} = \underbrace{\frac{1}{2\omega} U^\dagger \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & g_{a\gamma}\omega B\\ 0 & g_{a\gamma}\omega B & m_a^2\end{bmatrix} U}_{\text{diagonal}} \underbrace{U^\dagger \begin{bmatrix}\gamma_x\\ \gamma_y\\ a\end{bmatrix}}_{\text{mass eigenbasis}},$$

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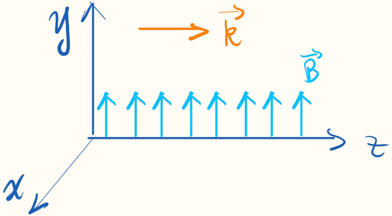
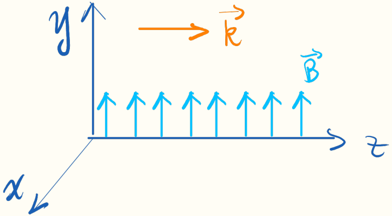


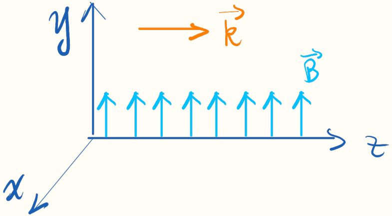

$$i\partial_z \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} = \begin{bmatrix} m_1^2/2\omega & 0 & 0 \\ 0 & m_2^2/2\omega & 0 \\ 0 & 0 & m_3^2/2\omega \end{bmatrix} \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix}$$

# The Good'ol Oscillation



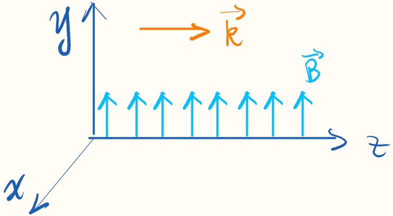

$$\begin{bmatrix}\psi_1\\ \psi_2\\ \psi_3\end{bmatrix} = \begin{bmatrix} e^{-i\frac{m_1^2}{2\omega}z} & 0 & 0\\ 0 & e^{-i\frac{m_2^2}{2\omega}z} & 0\\ 0 & 0 & e^{-i\frac{m_3^2}{2\omega}z}\end{bmatrix}\begin{bmatrix}\psi_1(0)\\ \psi_2(0)\\ \psi_3(0)\end{bmatrix}$$

# The Good'ol Oscillation




$$\begin{bmatrix}\psi_1\\ \psi_2\\ \psi_3\end{bmatrix} \approx \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & \mathrm{e}^{-i\frac{m_a^2}{2\omega}z}\end{bmatrix}\begin{bmatrix}\psi_1(0)\\ \psi_2(0)\\ \psi_3(0)\end{bmatrix}$$

# The Good'ol Oscillation

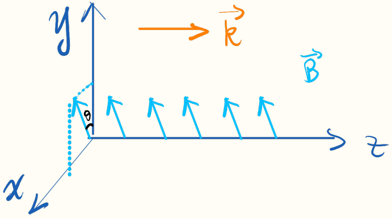



$$\mathcal{M}_{a\to\gamma_y} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} U \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \mathrm{e}^{-i\frac{m_a^2}{2\omega}z} \end{bmatrix} U^\dagger \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$P_{a\to\gamma_y} = |\mathcal{M}_{a\to\gamma_y}|^2$$

$$\simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/4\omega^2} \sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}}\right) z\right),$$

# The Good'ol Oscillation (in arbitrary frame)



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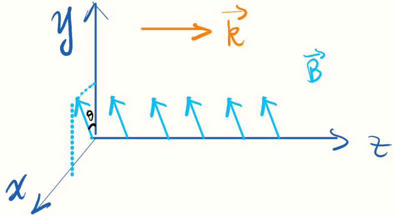


$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y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

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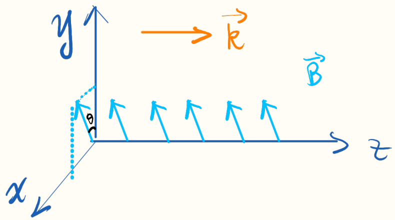


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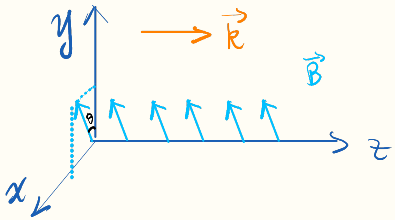
$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

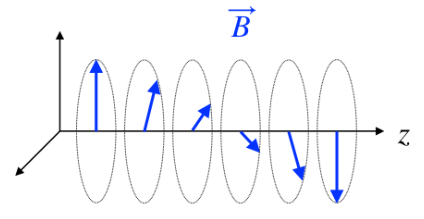
## The Good'ol Oscillation (in arbitrary frame)




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

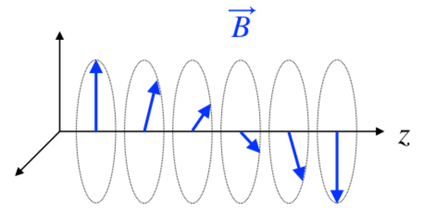
$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \underbrace{\begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V^\dagger} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \underbrace{\begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V}$$

# Helical Magnetic Profile




?

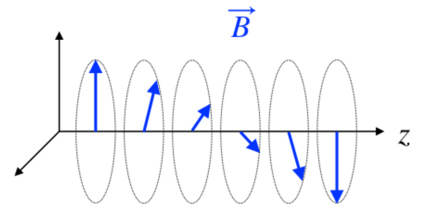
# Helical Magnetic Profile




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

$$\theta = \theta(z)$$

# Helical Magnetic Profile

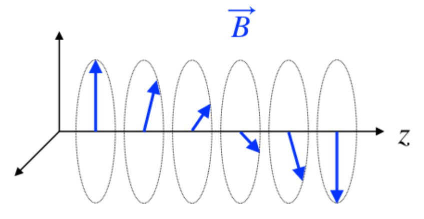



$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y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

$$\theta = \theta(z)$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

# Helical Magnetic Profile




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

$$\theta = \theta(z)$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \underbrace{\begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V^\dagger(z)} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \underbrace{\begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V(z)}$$

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

$$\theta = \theta(z)$$

$$V^\dagger i\partial_z \left( V(z) \begin{bmatrix} \gamma_x' \\ \gamma_y' \\ a' \end{bmatrix} \right) = \left( V^\dagger \begin{bmatrix} 0 & 0 & \frac{g_{a\gamma}B}{2} s_\theta \\ 0 & 0 & \frac{g_{a\gamma}B}{2} c_\theta \\ \frac{g_{a\gamma}B}{2} s_\theta & \frac{g_{a\gamma}B}{2} c_\theta & m_a^2/2\omega \end{bmatrix} V \right) \begin{bmatrix} \gamma_x' \\ \gamma_y' \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} = \left( \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} - V^\dagger i\partial_z V \right) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

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

$$\theta = \theta(z)$$

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

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma_x'' \\ \gamma_y'' \\ a'' \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma_x'' \\ \gamma_y'' \\ a'' \end{bmatrix}$$

$$P_{a\to\gamma} \simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/(4\omega^2)} \sin^2\left(\left(\frac{1}{2}\sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}}\right) z\right),$$

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

$$\theta = \theta(z)$$

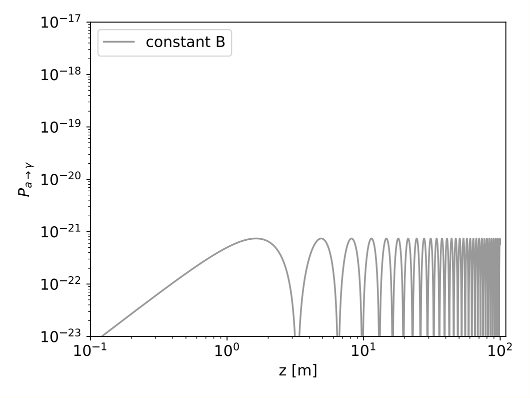
$$P_{a\to\gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2/2}{g_{a\gamma}^2 B^2/2 + (m_a^2/2\omega \pm \dot{\theta})^2} \sin^2\left(\left(\frac{1}{2}\sqrt{\frac{g_{a\gamma}^2 B^2}{2} + (\frac{m_a^2}{2\omega} \pm \dot{\theta})^2}\right) z\right),$$

What if $B(z)$ is not perfectly helical?

# Experimental Implications – B regularity

$$\dot{\theta} = \dot{\theta}(z) \quad \text{is not constant}$$

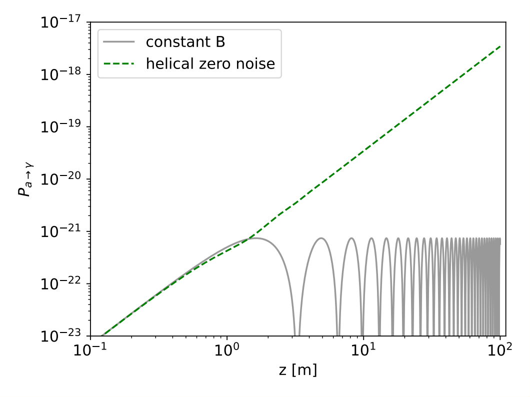
# Experimental Implications – B regularity




A simplified model:

- $\dot{\theta}$ takes $N$ values along the whole baseline
  larger $N \sim$ larger noise frequency
- in each interval, $\dot{\theta}(z) = \bar{\dot{\theta}} + \delta\dot{\theta}(z)$
  larger $\delta\dot{\theta}/\bar{\dot{\theta}} \sim$ larger noise amplitude
- assume $\delta\dot{\theta}/\bar{\dot{\theta}}$ to be gaussian around zero

# Experimental Implications – B regularity

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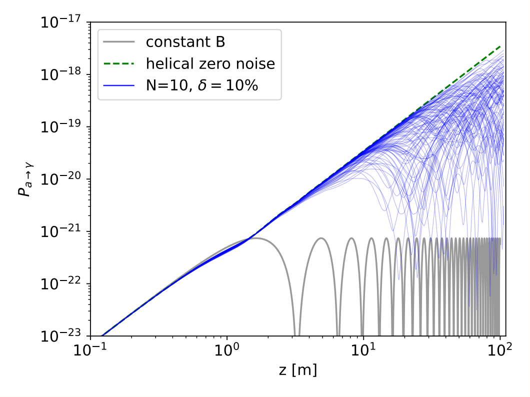


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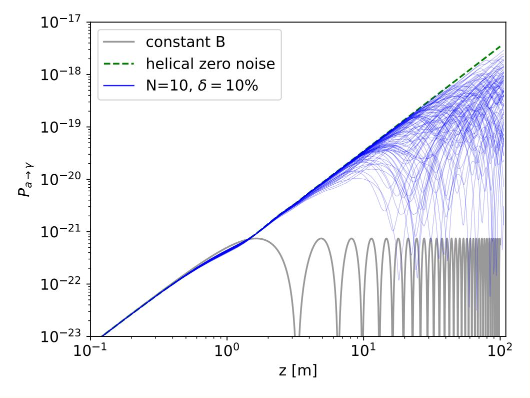


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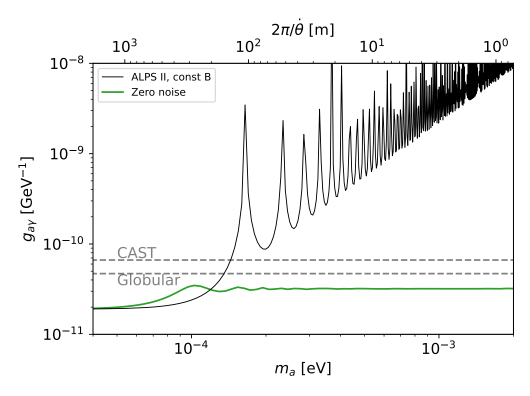
  larger $\delta\dot{\theta}/\bar{\dot{\theta}} \sim$ larger noise amplitude
- assume $\delta\dot{\theta}/\bar{\dot{\theta}}$ to be gaussian around zero

*Repeat same exercise for different* $m_a$

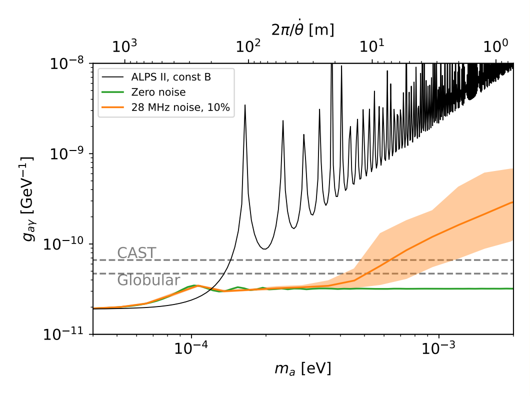
# Experimental Implications – B regularity (cont'd)




A simplified model:

- Zero noise reach: AMR floor

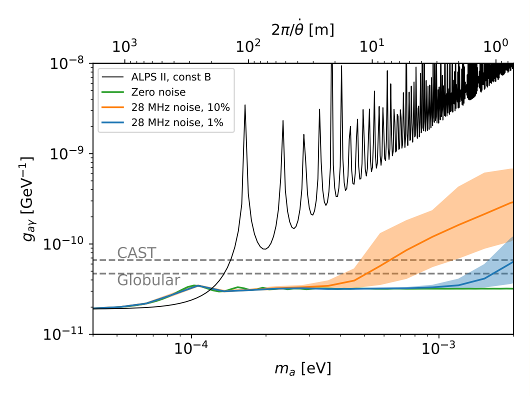
# Experimental Implications – B regularity (cont'd)




A simplified model:

- Zero noise reach: AMR floor
- $N = 10,\ \delta = 10\%$

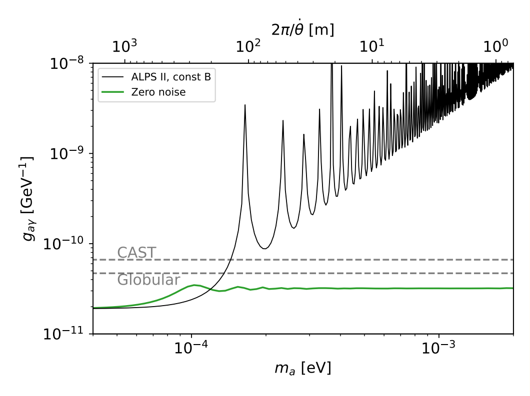
# Experimental Implications – B regularity (cont'd)




A simplified model:

- Zero noise reach: AMR floor
- $N = 10,\ \delta = 10\%$
- $N = 10,\ \delta = 1\%$

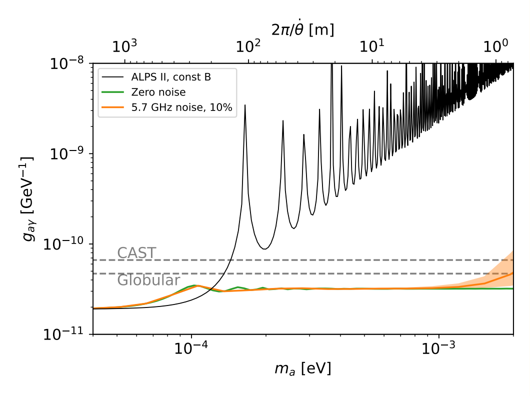
# Experimental Implications – B regularity (cont'd)




A simplified model:

- Zero noise reach: AMR floor
- $N = 10,\ \delta = 10\%$
- $N = 10,\ \delta = 1\%$

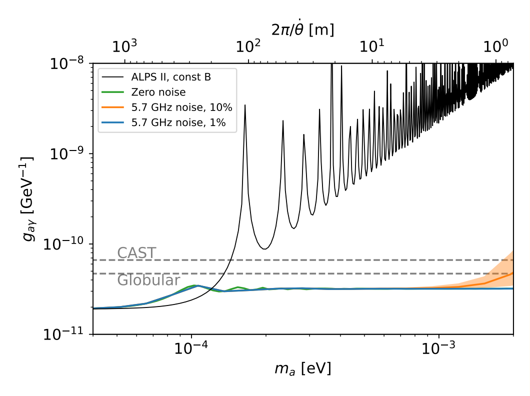
# Experimental Implications – B regularity (cont'd)




A simplified model:

- Zero noise reach: AMR floor
- $N = 10,\ \delta = 10\%$
- $N = 10,\ \delta = 1\%$
- $N = 2000,\ \delta = 10\%$

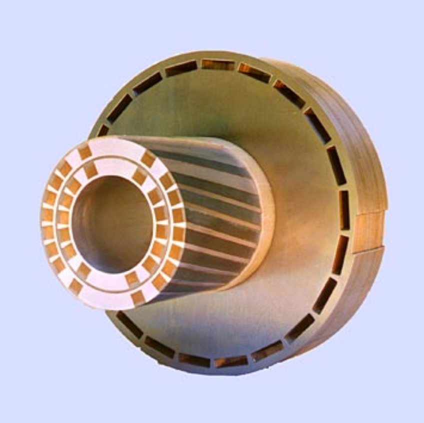
# Experimental Implications – B regularity (cont'd)




A simplified model:

- Zero noise reach: AMR floor
- $N = 10,\ \delta = 10\%$
- $N = 10,\ \delta = 1\%$
- $N = 2000,\ \delta = 10\%$
- $N = 2000,\ \delta = 1\%$

# Experimental Implications – B regularity (cont'd)

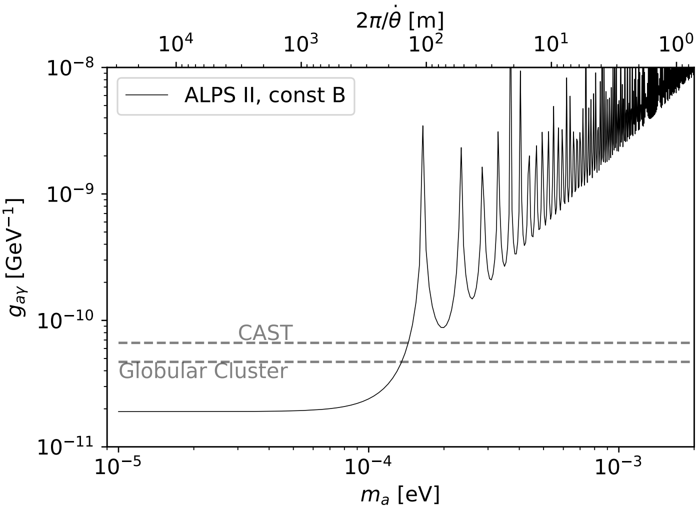


Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

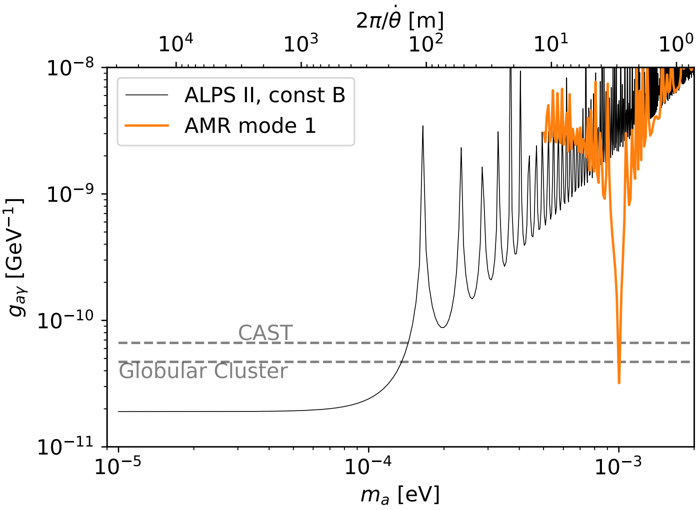
- superconducting dipole magnet $\sim 5$ T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
  ... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding
- sub-percent error in field irregularity easily achieved:
  $\int |\mathbf{B}| dz \approx 10\,\mathrm{T}\cdot\mathrm{m}$
  $\left[ (\int B_x(z) dz)^2 + (\int B_y(z) dz)^2 \right]^{1/2} < 0.05\,\mathrm{T}\cdot\mathrm{m}$

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

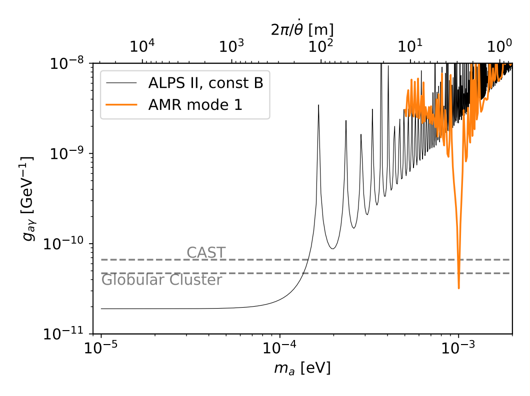
# Extending the Resonance



# Extending the Resonance

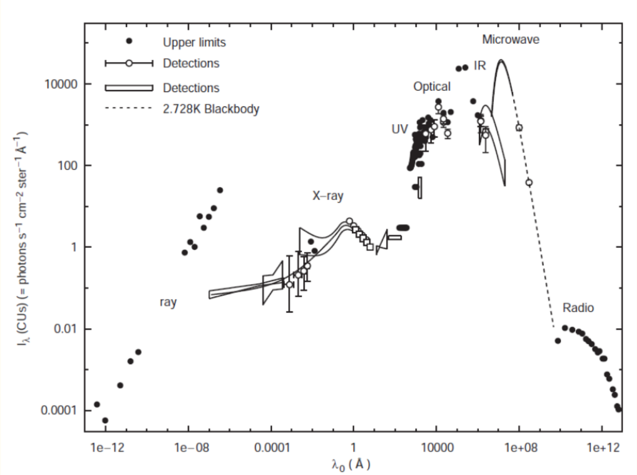


# Extending the Resonance




- Particularly helpful if we want to examine a particular region hinted by astrophysical anomalies
- How do we reach resonance at lower frequencies to scan smaller $m_a$?

# EBL

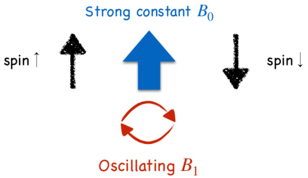



*Cadamuro and Redondo 2011, 1110.2895*

# AMR vs NMR

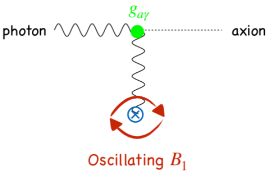
## Axion magnetic resonance (AMR)

### Nuclear magnetic resonance




- Two states: spin ↑↓
- Larmor precession frequency $\omega_0 = \mu B_0$
- Transition in oscillating $B_1$ with $\dot{\theta} = d\hat{B}_1/dt$
- Rabi frequency $\sqrt{(\omega_0 - \dot{\theta})^2 + (\mu B_1)^2}$

### Axion magnetic resonance




- Two state: photon & axion
- Axion momentum transfer $\omega_a = m_a^2/2E$
- Transition in oscillating $B_1$ with $\dot{\theta} = d\hat{B}_1/dt$
- Rabi frequency $\sqrt{(\omega_a - \dot{\theta})^2 + (g_{a\gamma}B/2)^2}$