

Axion Magnetic Resonance

and Enhanced Signals

Chen Sun (孙晨)

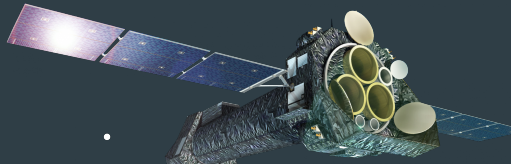
HIAS (杭高院)

Strong CP
DM
UV of Gravity



QCD axion
ALPs.

Macroscopic Wave Behavior



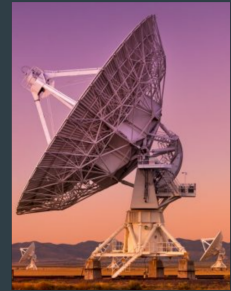
Neutron Stars
Galaxy clusters



NS & BH Mergers



Quasars, SN
BAO

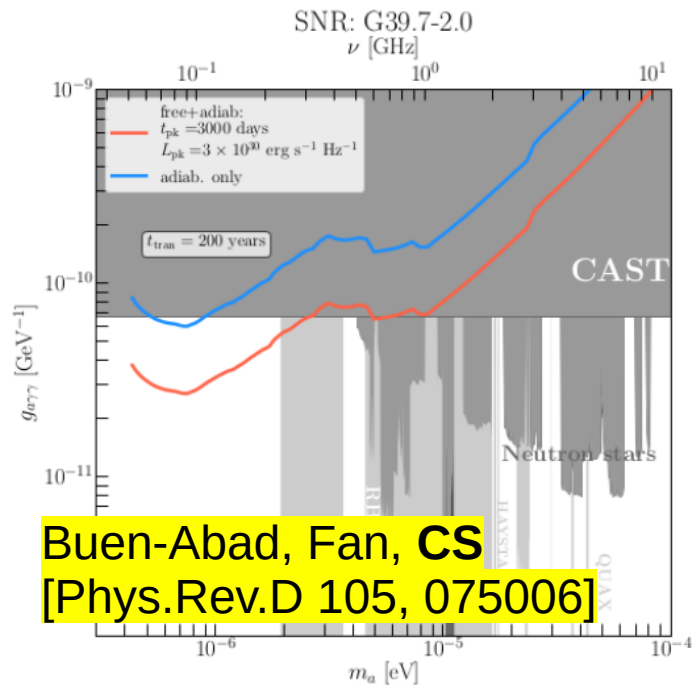


SN Remnant
Galaxy Rotation Curves
Suzuki-Zeldovich

Strong CP
DM
UV of Gravity

QCD axion
ALPs.

Macroscopic Wave Behavior

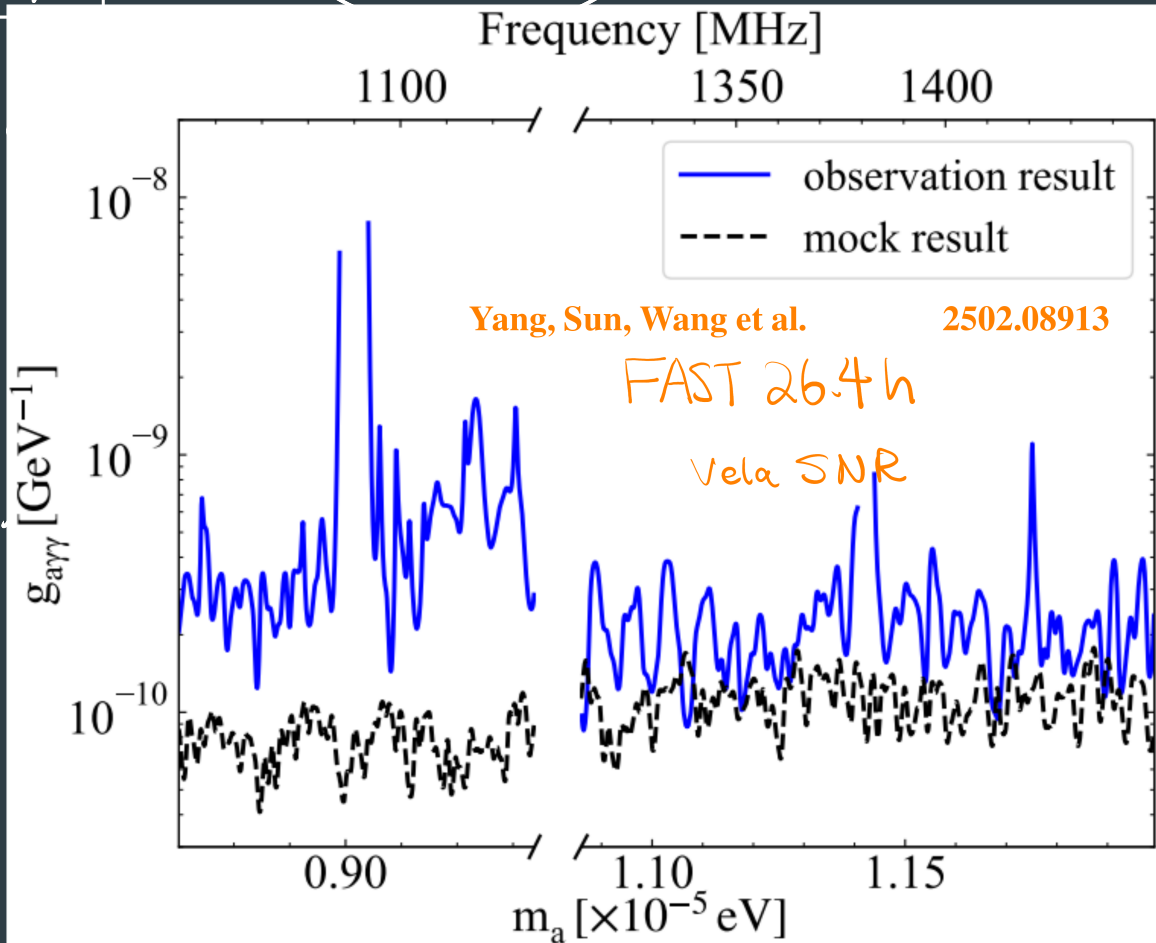
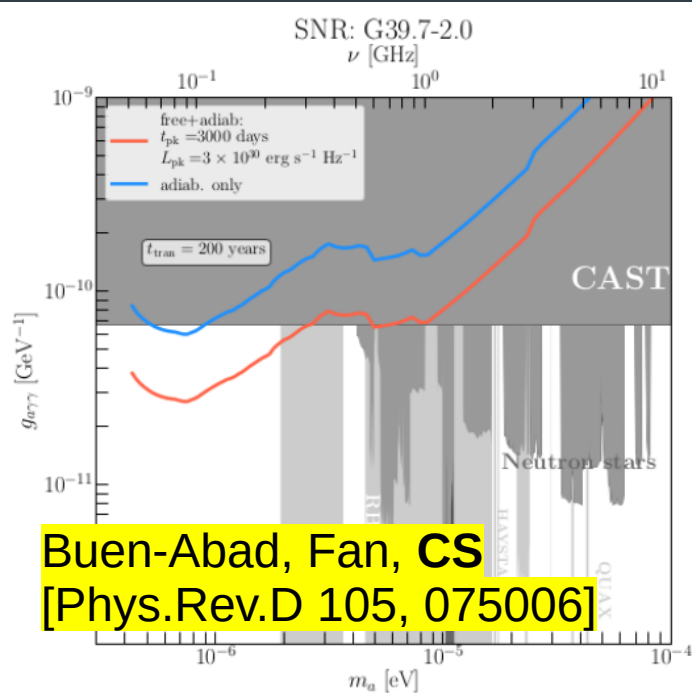


$$\mathcal{M}_{a \rightarrow \gamma\gamma} \rightarrow \mathcal{M}_{a \rightarrow \gamma\gamma} (1 + f_\gamma(p) + f_\gamma(-p))$$

Strong CP
DM
UV of Gravity

QCD axion
ALPs.

Macro

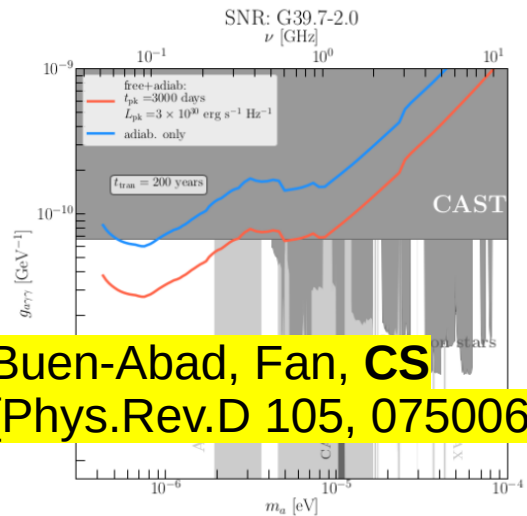


Strong CP
DM
UV of Gravity

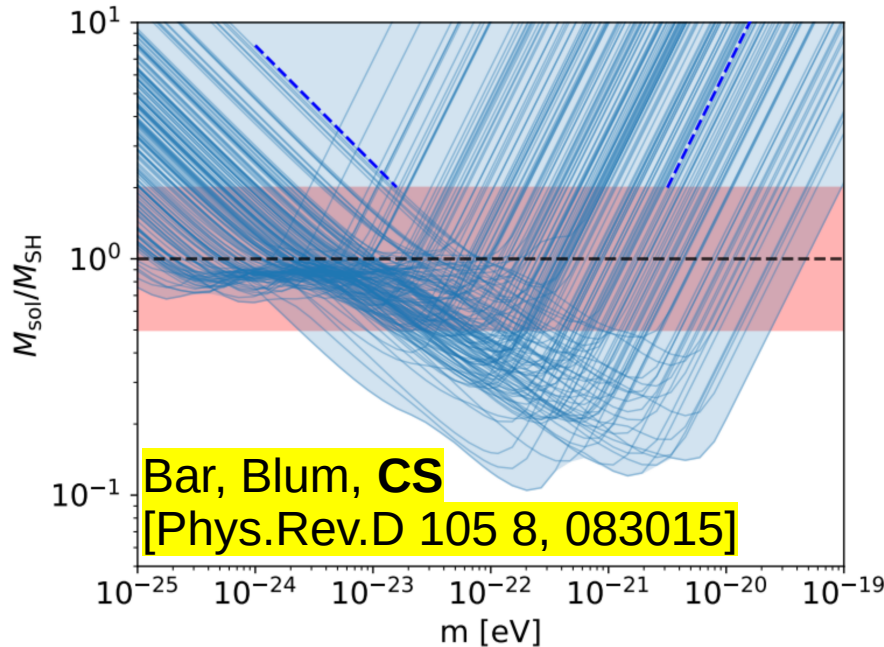


QCD axion
ALPs.

Macroscopic Wave Behavior



Buen-Abad, Fan, CS
[Phys.Rev.D 105, 075006]



Bar, Blum, CS
[Phys.Rev.D 105 8, 083015]

Strong CP
DM
UV of Gravity

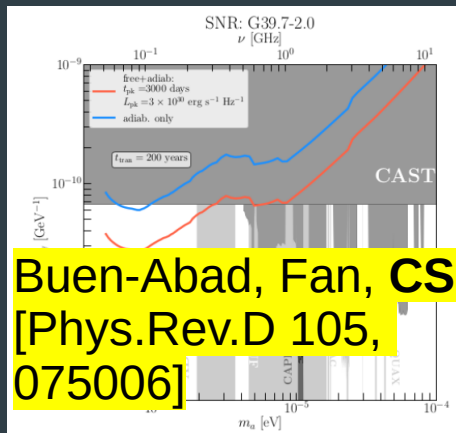


QCD axion
ALPs.

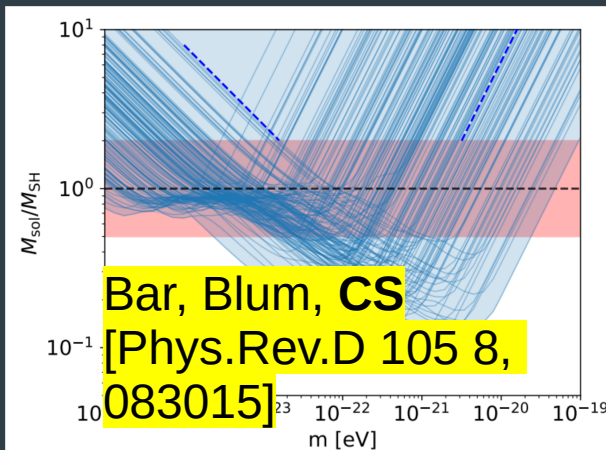
Macroscopic Wave Behavior

Croon, Fan, **CS**
JCAP 04 (2019) 008

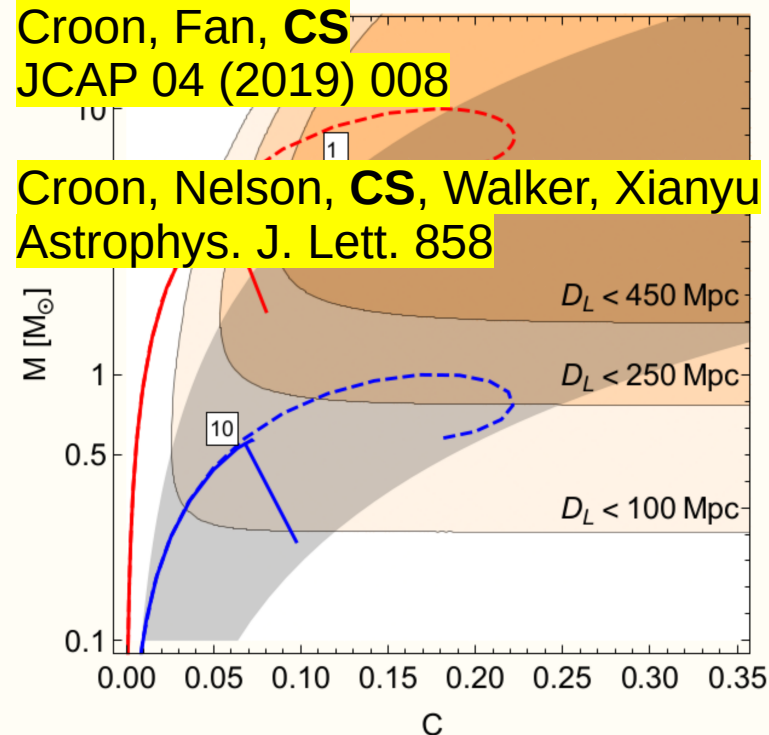
Croon, Nelson, **CS**, Walker, Xianyu
Astrophys. J. Lett. 858

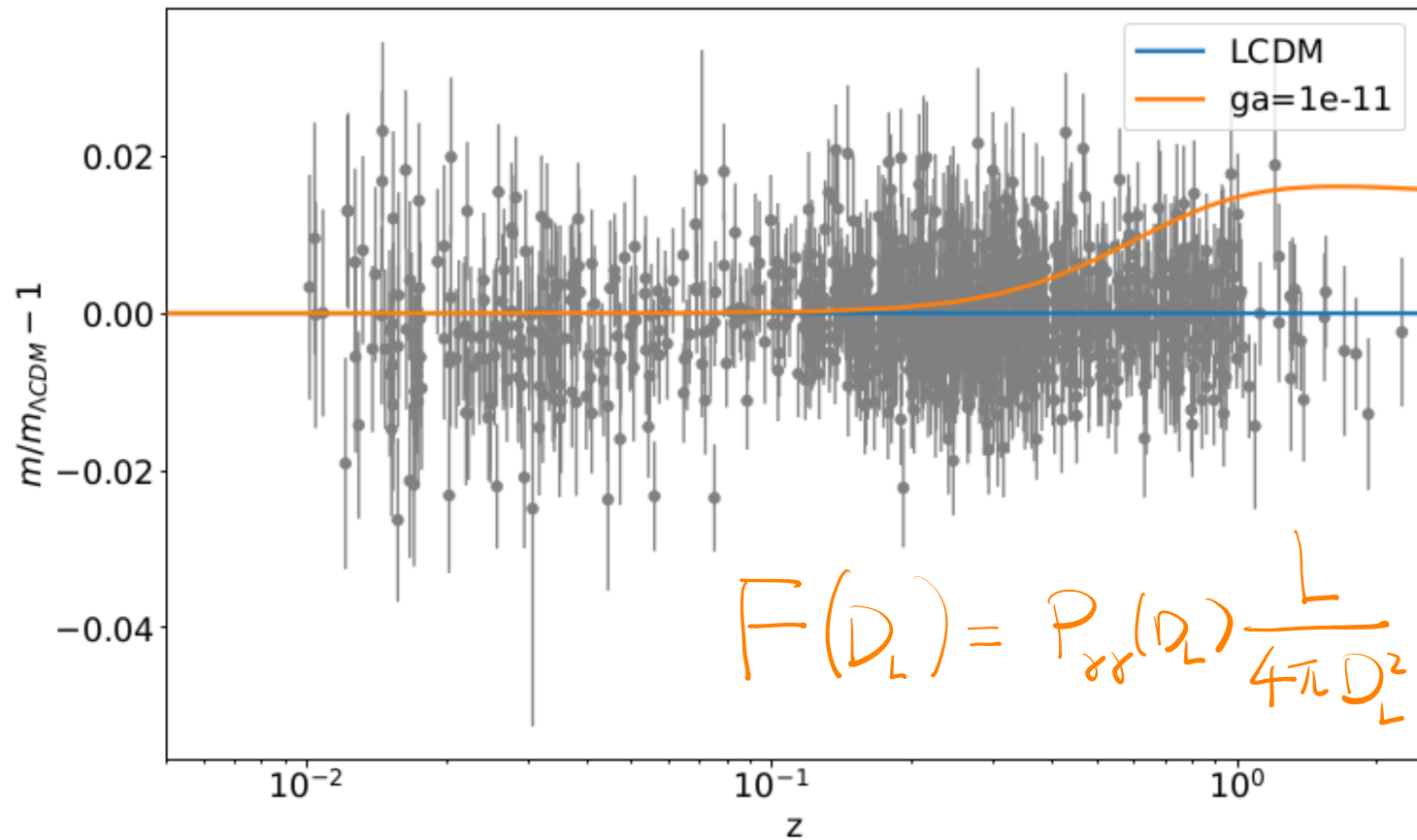


Buen-Abad, Fan, **CS**
[Phys.Rev.D 105,
075006]

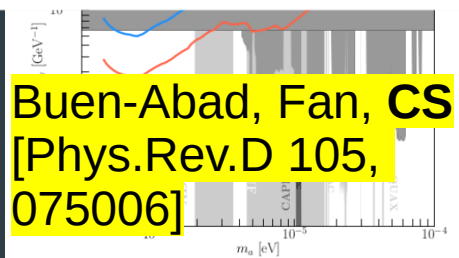


Bar, Blum, **CS**
[Phys.Rev.D 105 8,
083015]

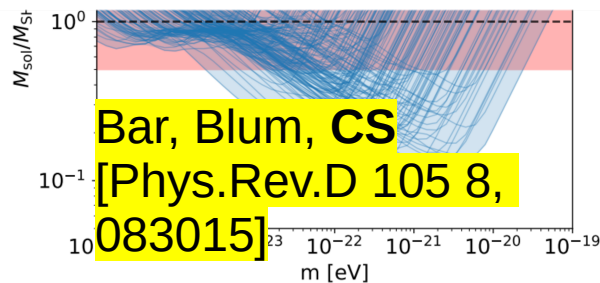




$$F(D_L) = P_{\gamma\gamma}(D_L) \frac{L}{4\pi D_L^2}$$



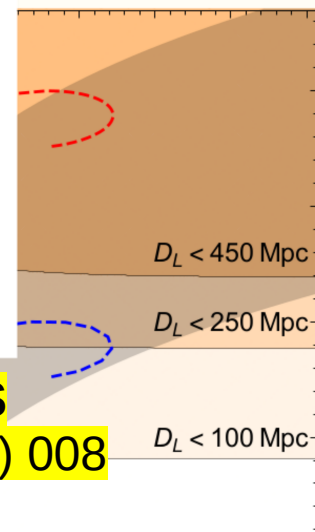
Buen-Abad, Fan, **CS**
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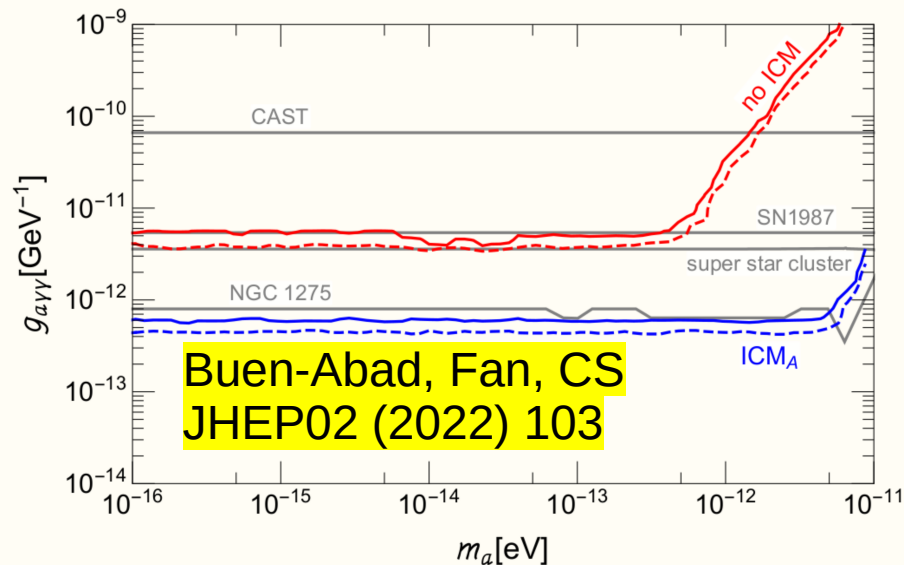
Croon, Nelson, **CS**, Walker, Xianyu
 Astrophys. J. Lett. 858



$D_L < 450 \text{ Mpc}$

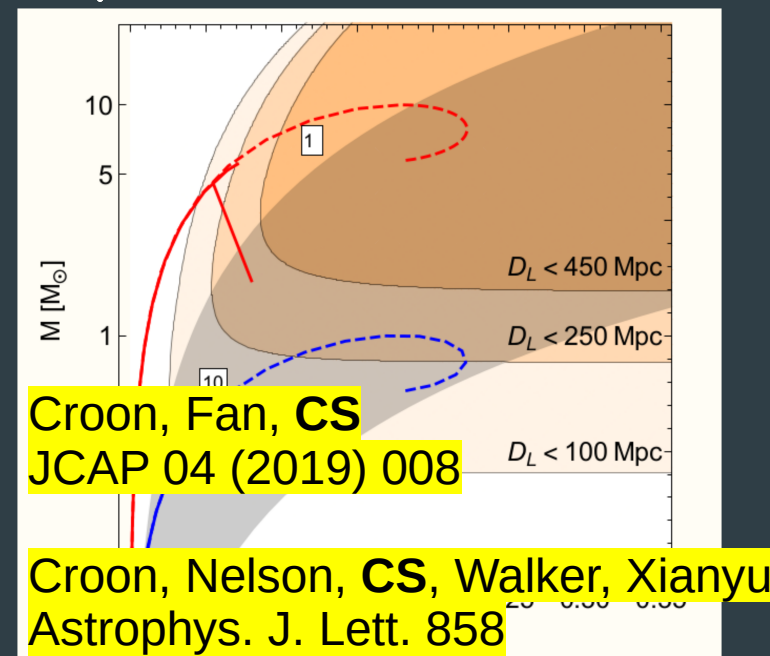
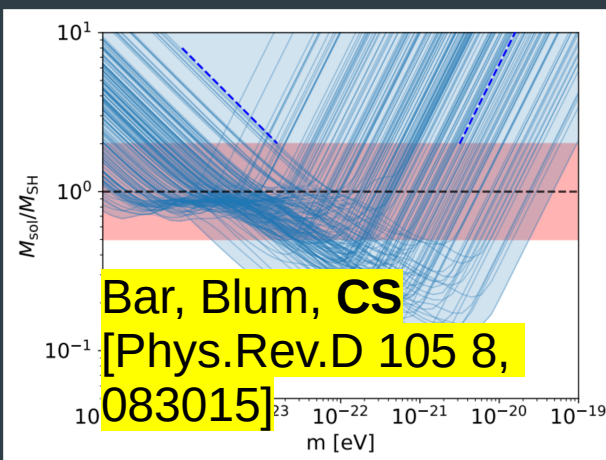
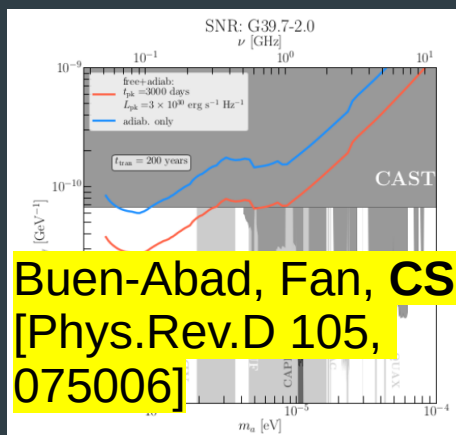
$D_L < 250 \text{ Mpc}$

$D_L < 100 \text{ Mpc}$

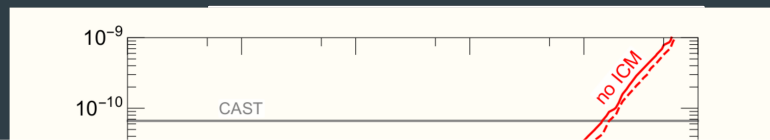


QCD axion
ALPs.

Wave Behavior

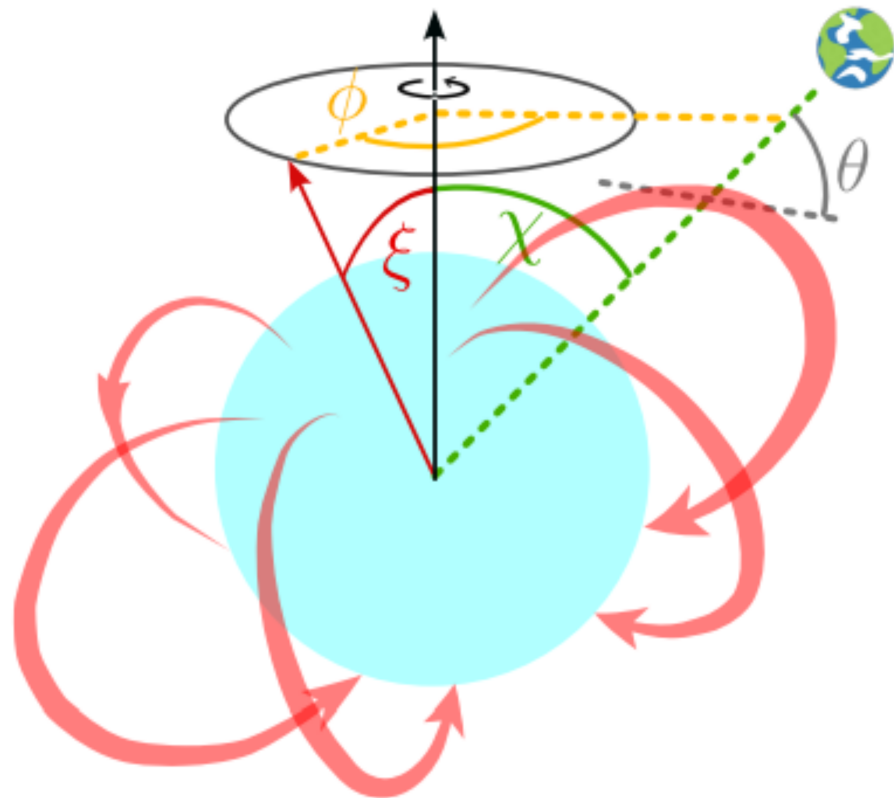


Croon, Nelson, CS, Walker, Xianyu
Astrophys. J. Lett. 858



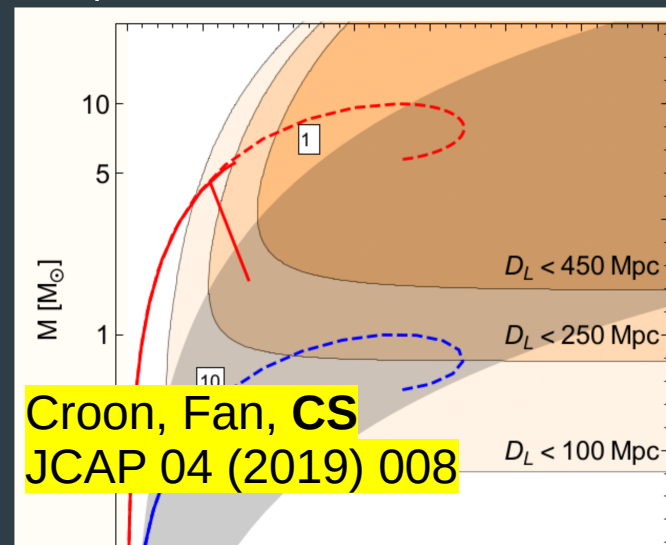
QCD axion
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Wave Behavior



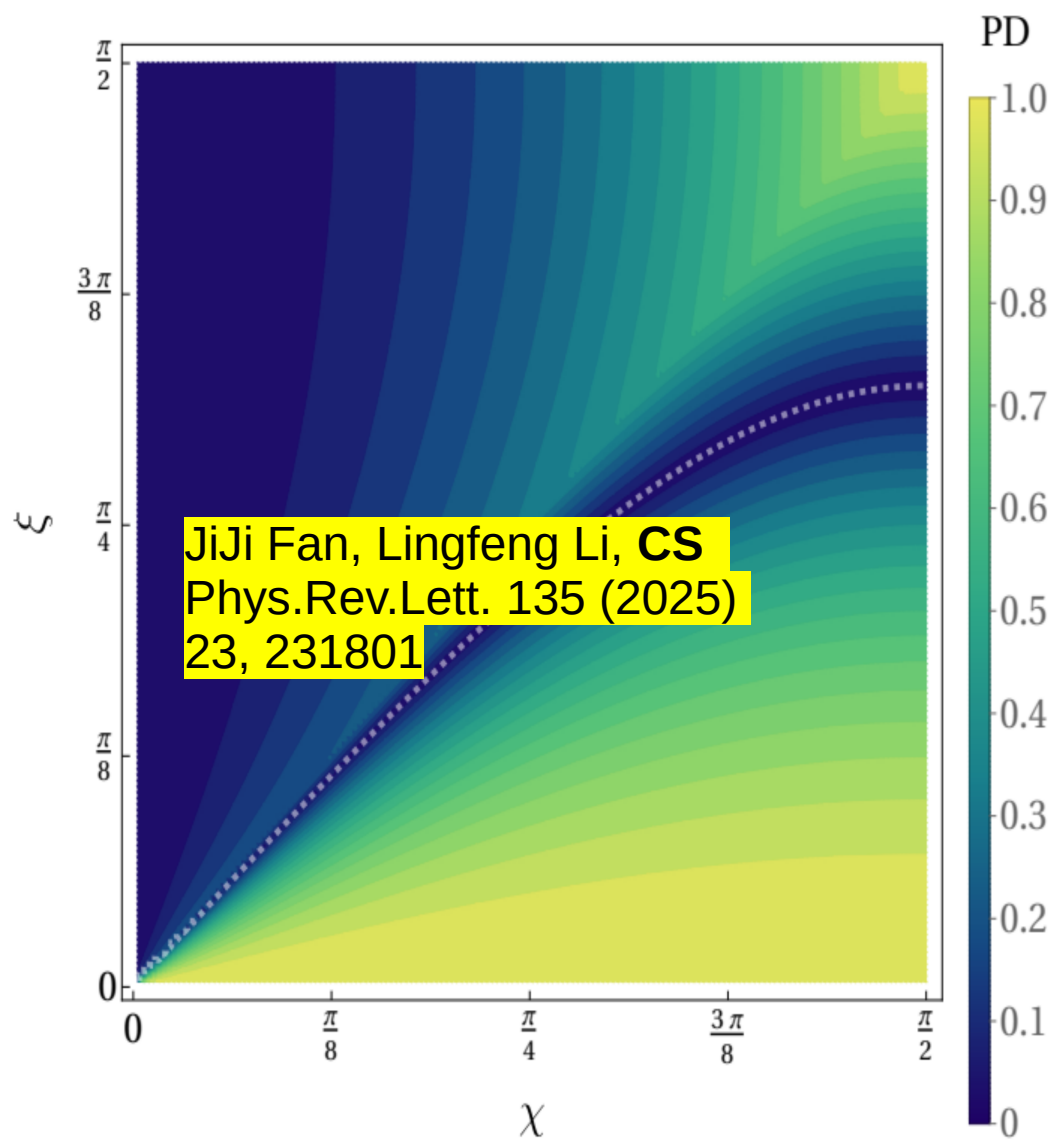
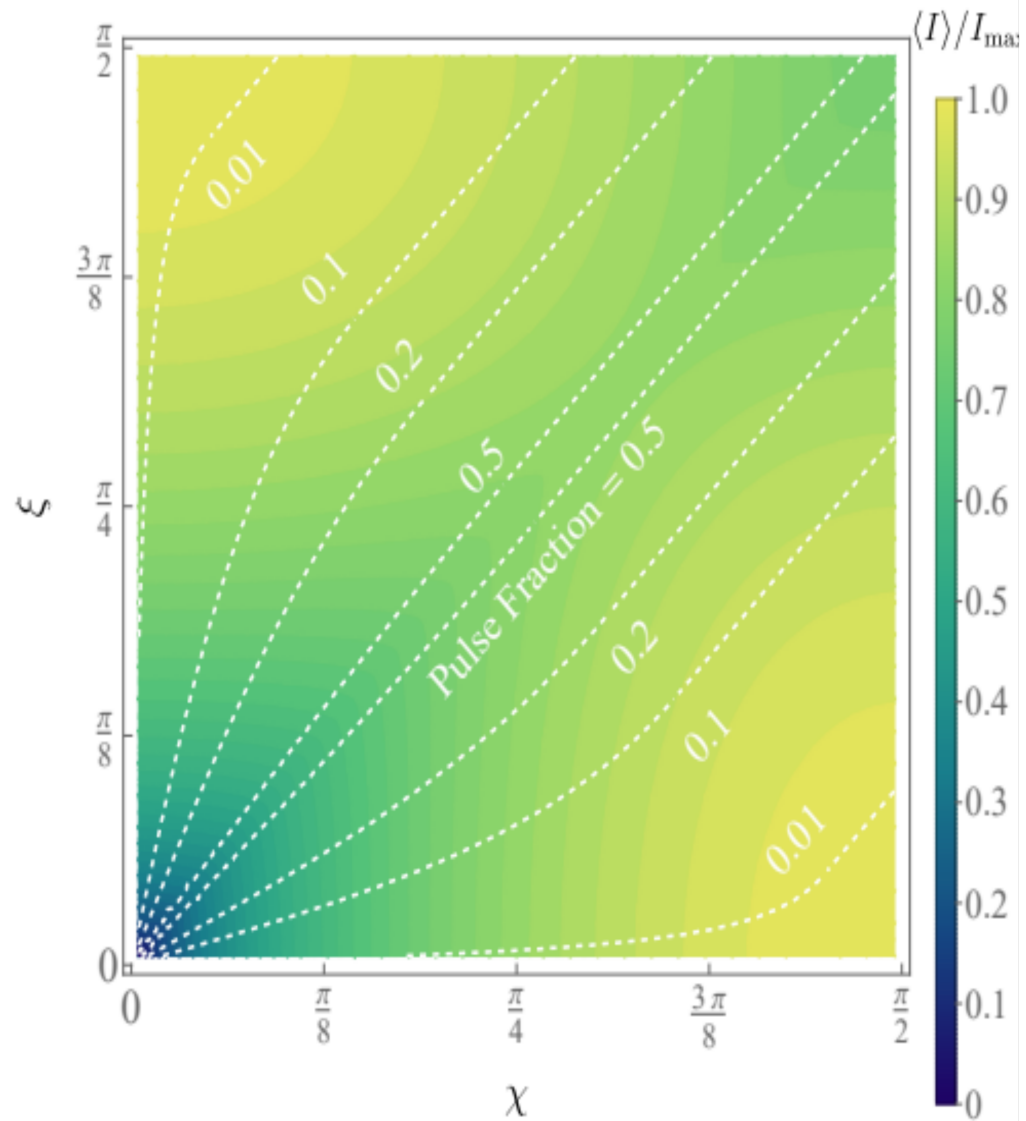
Eachus, Fan, CS
[Phys.Rev.D 105,
075006]

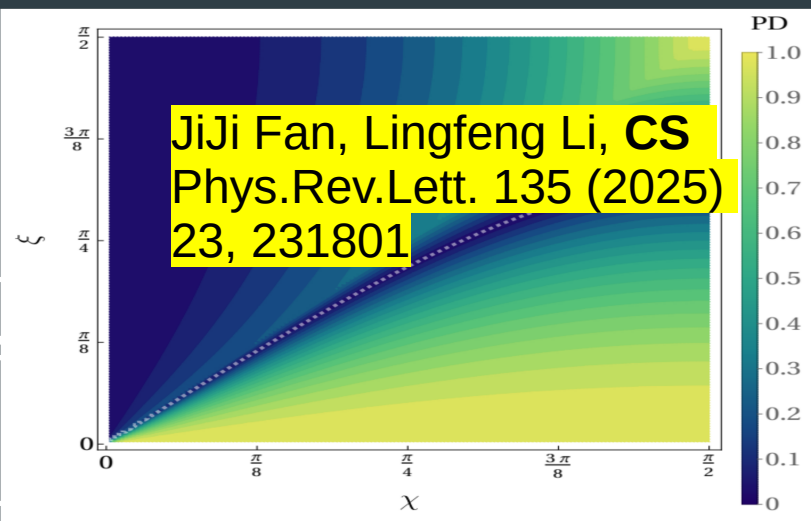
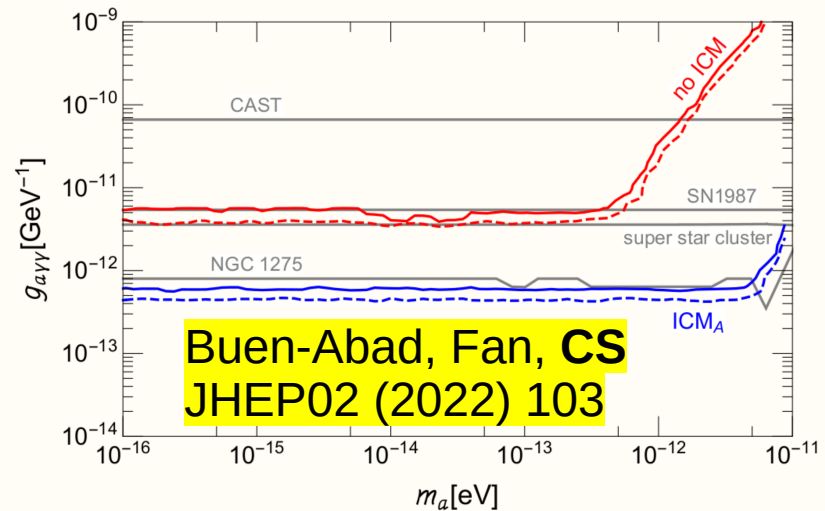
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[Phys.Rev.D 105 8,
083015]



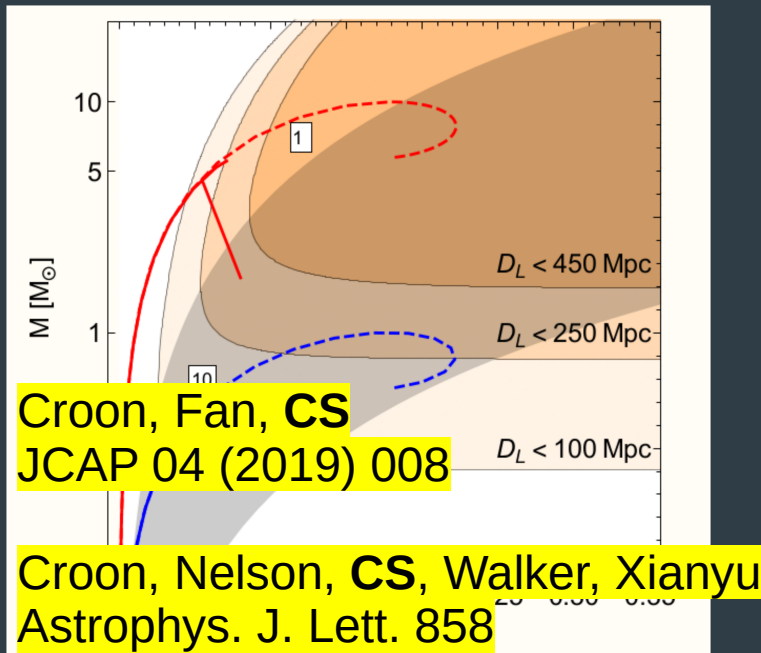
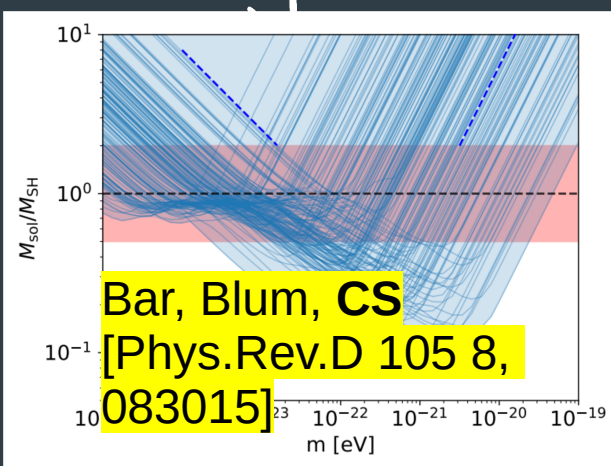
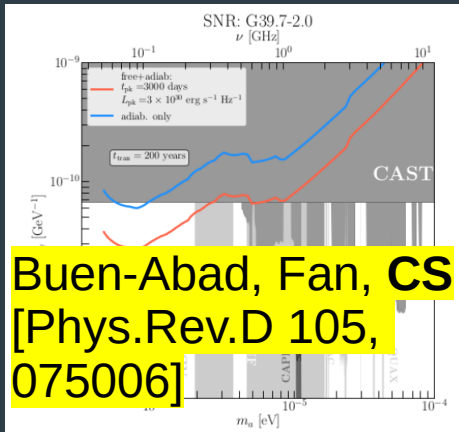
Croon, Fan, CS
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Macroscopic Wave Behavior



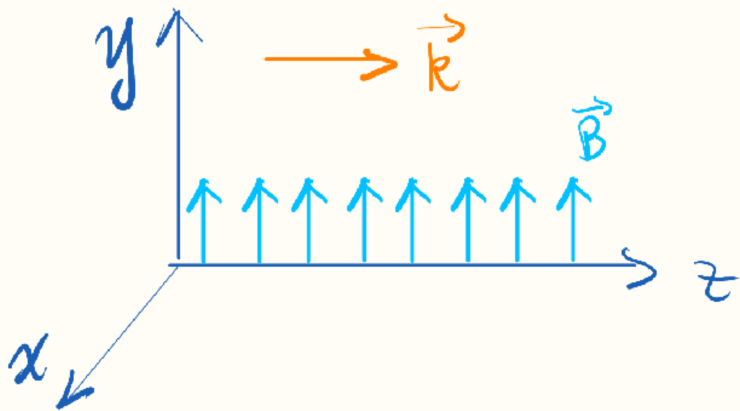
Croon, Nelson, CS, Walker, Xianyu
Astrophys. J. Lett. 858



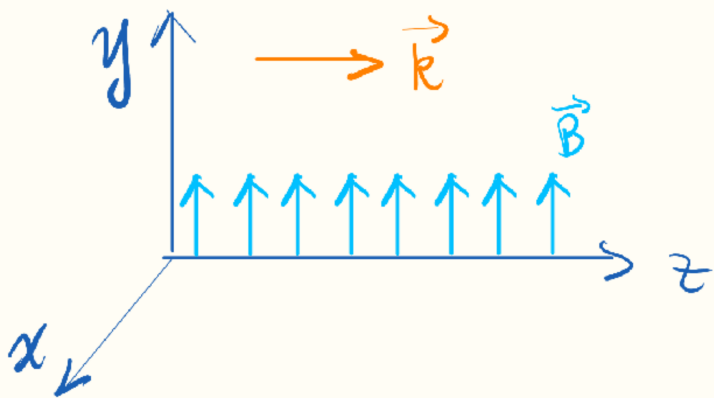
$$\underbrace{g_{ax}}_{M^{-1}} \underbrace{a F_{\mu\nu} F_{\sigma\rho} \epsilon^{\mu\nu\sigma\rho}}_{\text{Dim}-5}$$

1) $a \rightarrow \gamma\gamma$

2) $a \text{ --- } \underbrace{\text{wavy line}}_{\langle B \rangle} \gamma$



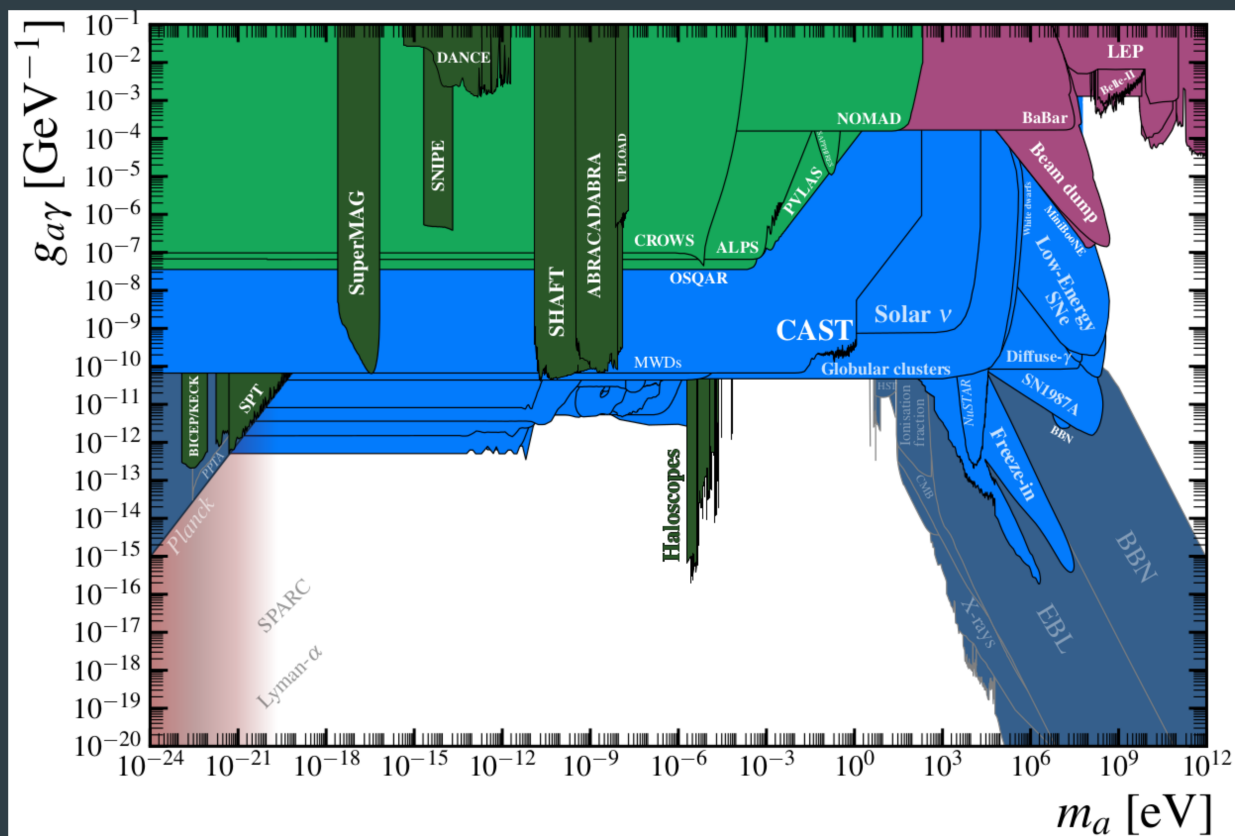
$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_a\gamma\omega B \\ 0 & g_a\gamma\omega B & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix},$$



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

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

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



BAO, SNe, galaxy clusters

Buen-Abad, Fan, CS 2011.05993 (JHEP)

Supernova remnants (radio)

Buen-ABad, Fan, CS 2110.13916 (PRD)

Quasars (UV, X-ray)

Buen-Abad, Fan, CS 2309.07212 (JCAP)

Laboratory Search (laser)

Seong, CS, Yun 2308.10925 (PRD)

Solar axion (X-ray)

Seong, CS, Yun 2408.11103 (JHEP)

Pulsars (X-ray)

Fan, Li, CS 2501.12440 (PRL)

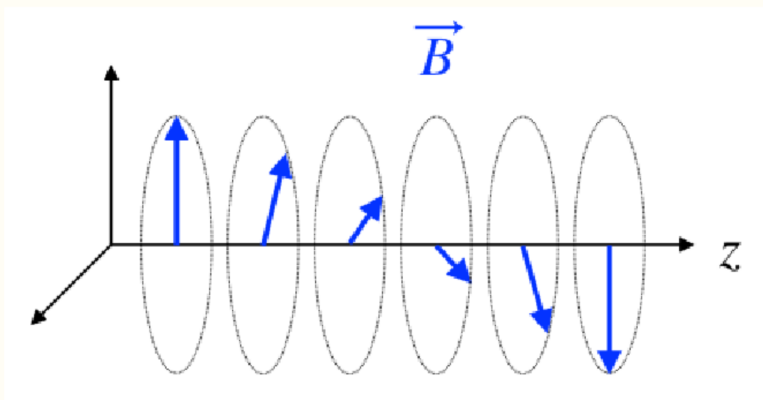
What if $H = H(z)$?

— instantaneous diagonalization

$$[m_1, m_2] = U(z) H(z) U^\dagger(z)$$

$$— i \frac{d}{dz} \psi \rightarrow U \left(i \frac{d}{dz} \psi + \underbrace{U^\dagger i \frac{d}{dz} U}_{\text{extra term.}} \right)$$

extra term.



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

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

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

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

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

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

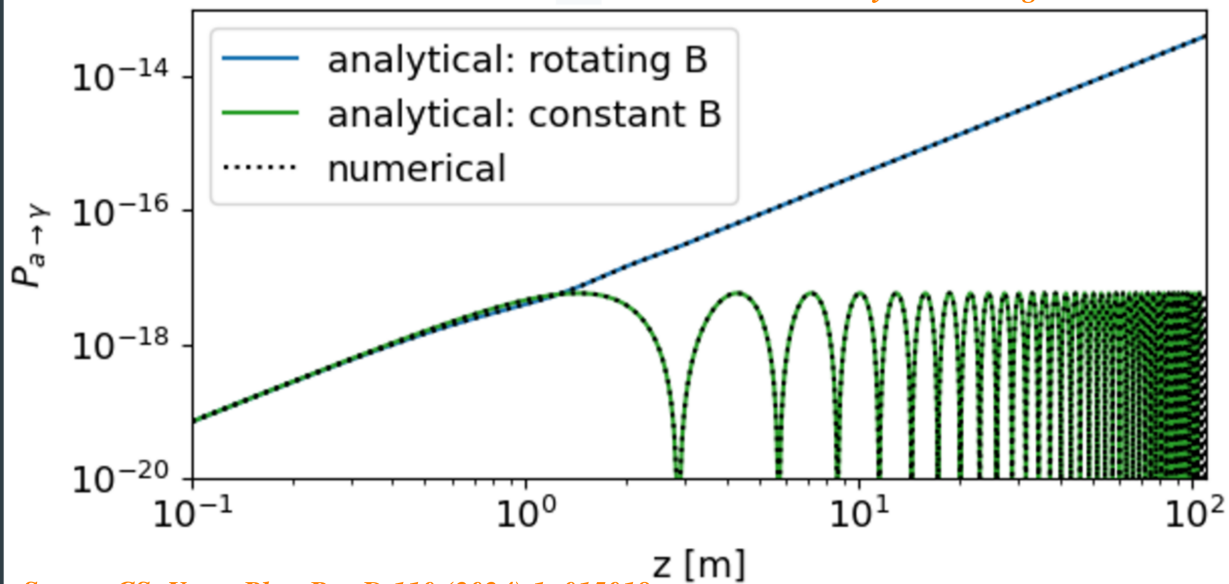
$$i\partial_z \begin{bmatrix} \gamma_x'' \\ \gamma_y'' \\ a'' \end{bmatrix} = \begin{bmatrix} -\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ 0 & \dot{\theta} & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ \frac{g_{a\gamma}B}{2\sqrt{2}} & \frac{g_{a\gamma}B}{2\sqrt{2}} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix}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

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

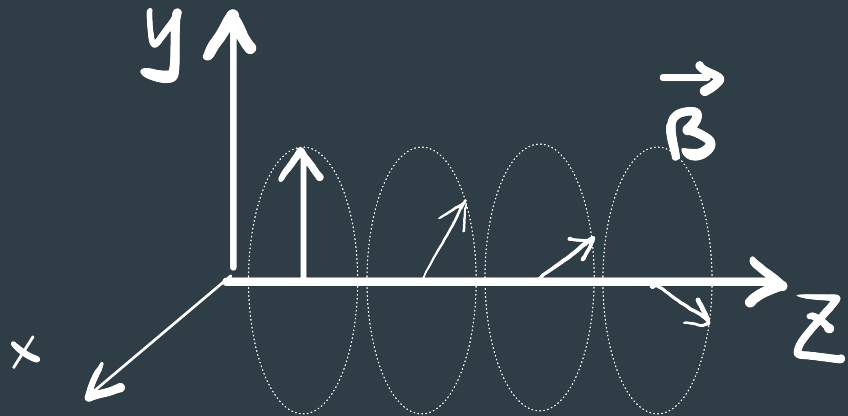
$$i\partial_z \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix} = \begin{bmatrix} -\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ 0 & \dot{\theta} & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ \frac{g_{a\gamma}B}{2\sqrt{2}} & \frac{g_{a\gamma}B}{2\sqrt{2}} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix}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

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

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

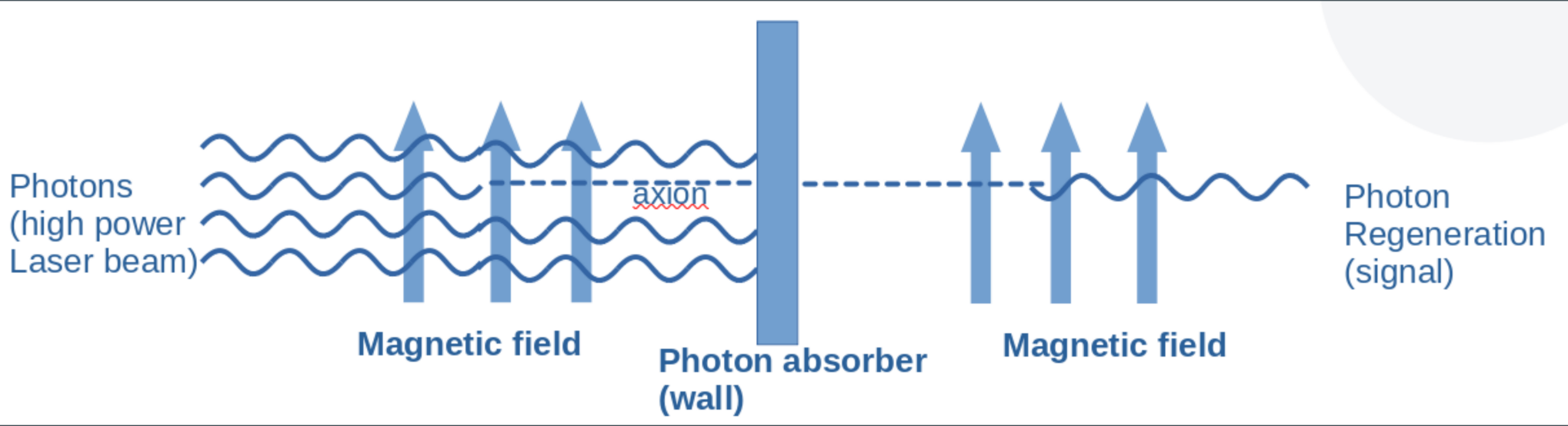


Seong, CS, Yun *Phys.Rev.D* 110 (2024) 1, 015018



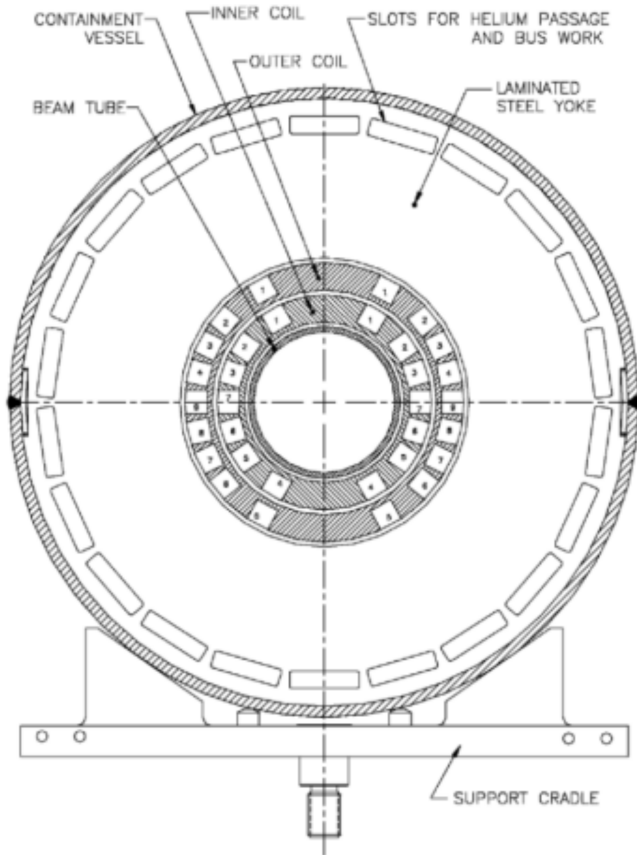
$$P_{a \rightarrow \gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2 / 2}{g_{a\gamma}^2 B^2 / 2 + (m_a^2 / 2\omega \pm \Omega)^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{\frac{g_{a\gamma}^2 B^2}{2} + \left(\frac{m_a^2}{2\omega} \pm \Omega \right)^2} \right) z \right),$$

Experimental Relevance



"Light Shining through Walls"

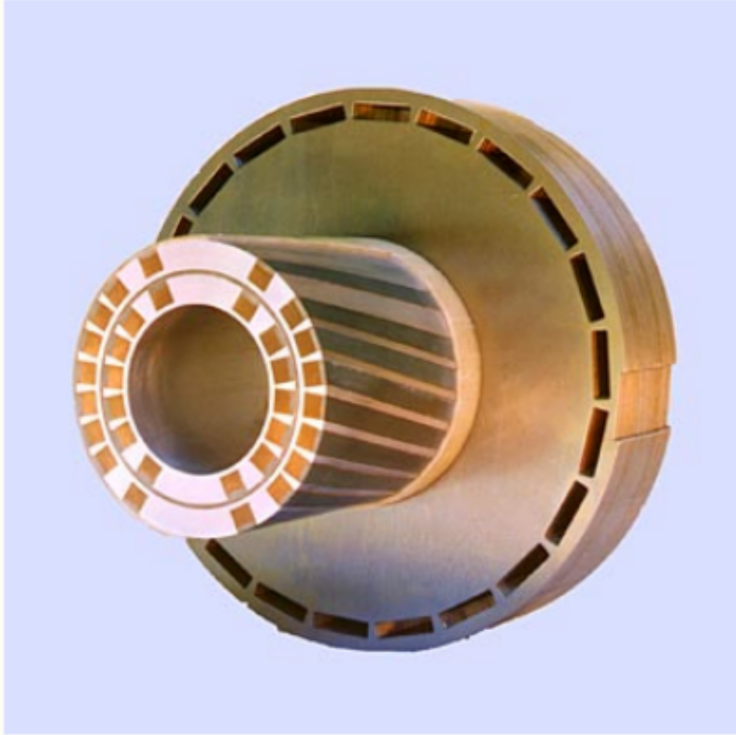
Experimental Implications



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

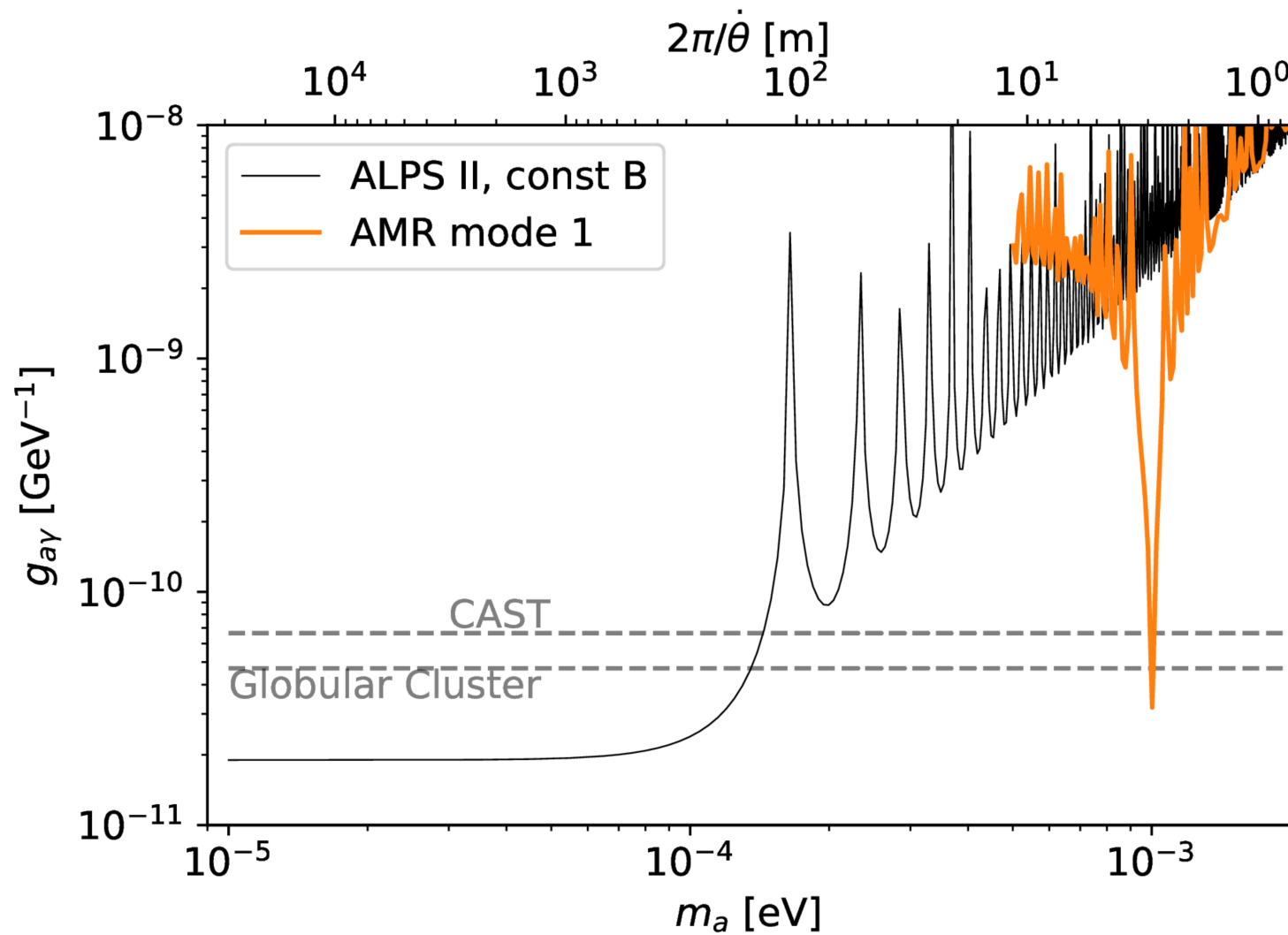
- superconducting dipole magnet ~ 5 T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
... 80-100/130-180 mm apertures

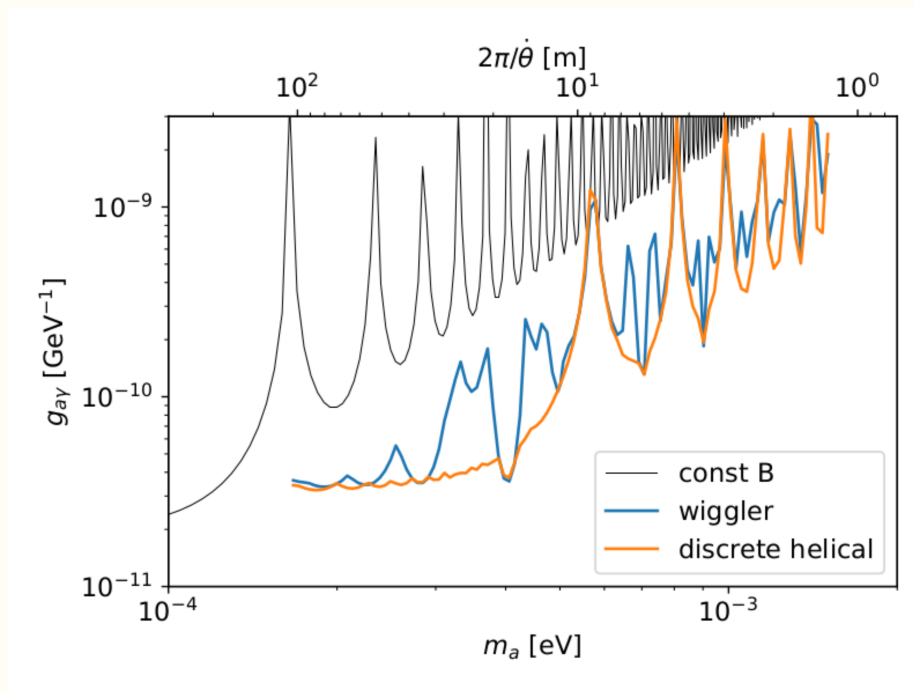
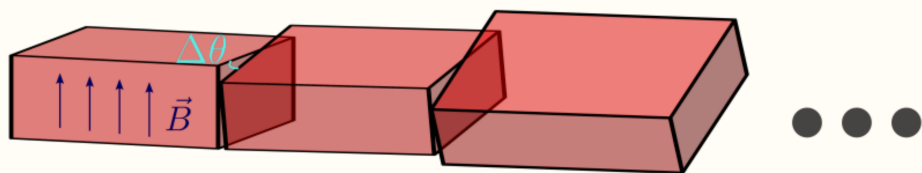
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Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

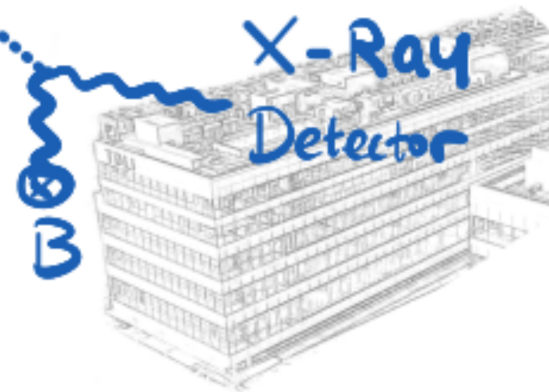
- superconducting dipole magnet ~ 5 T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding







- BNL
- Sumico
- CAST
- IAXO



Resonance

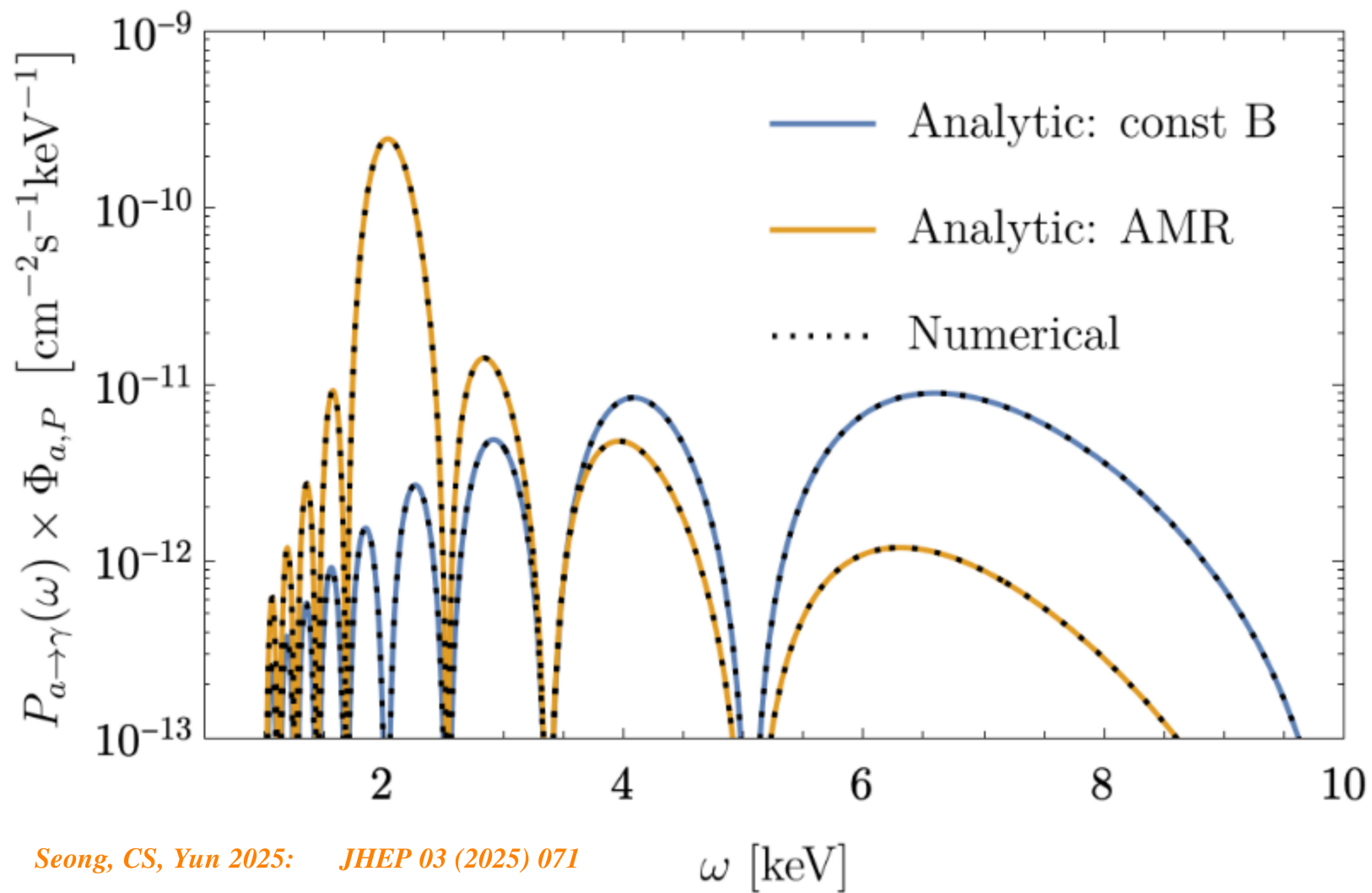
$$\Omega = \frac{m_a^2}{2\omega}$$

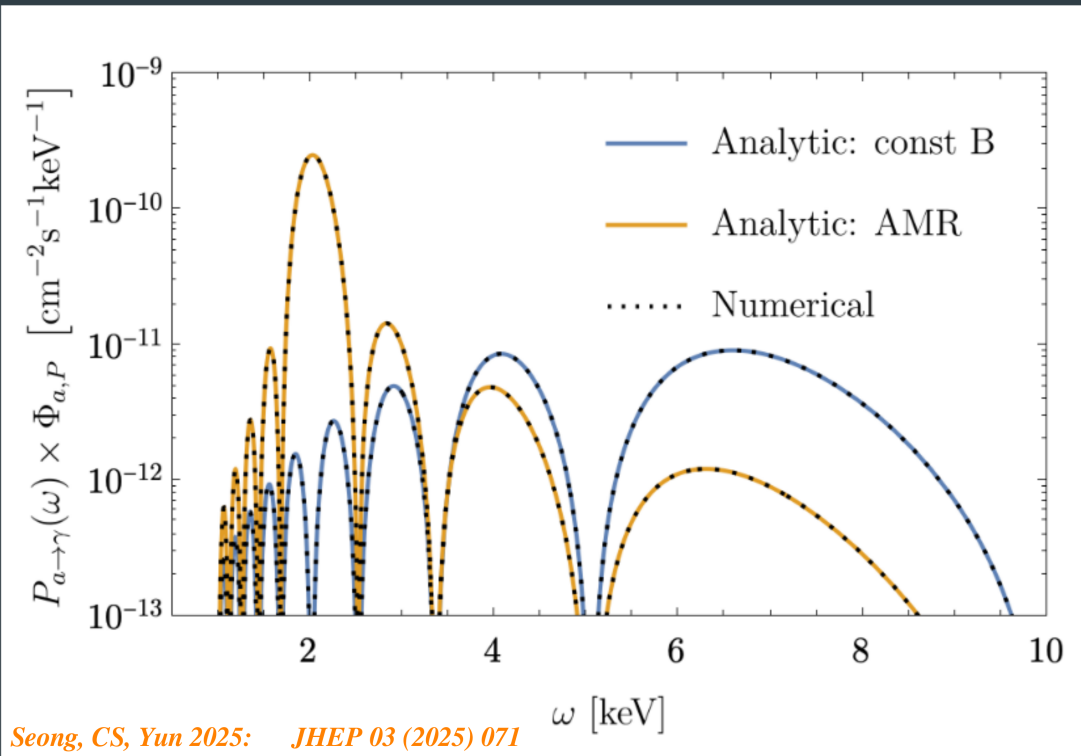
Laser

- ω fixed
- Ω varied

Solar Axion

- ω "varied"
- Ω fixed



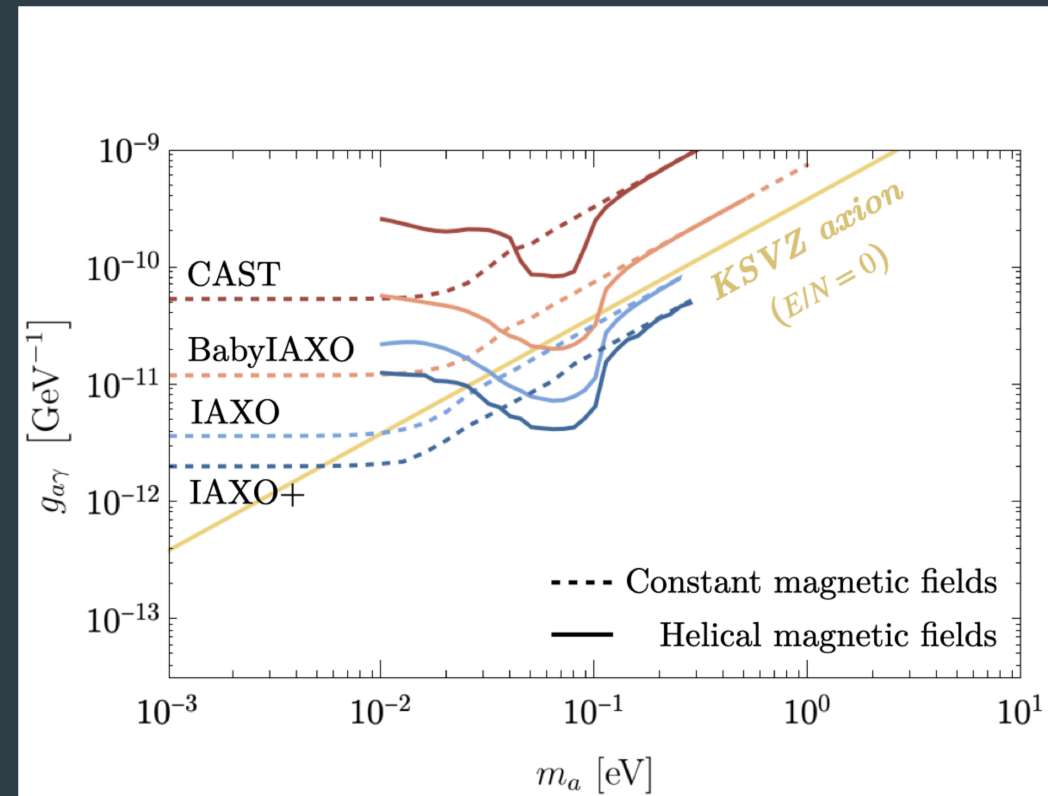


AMR:

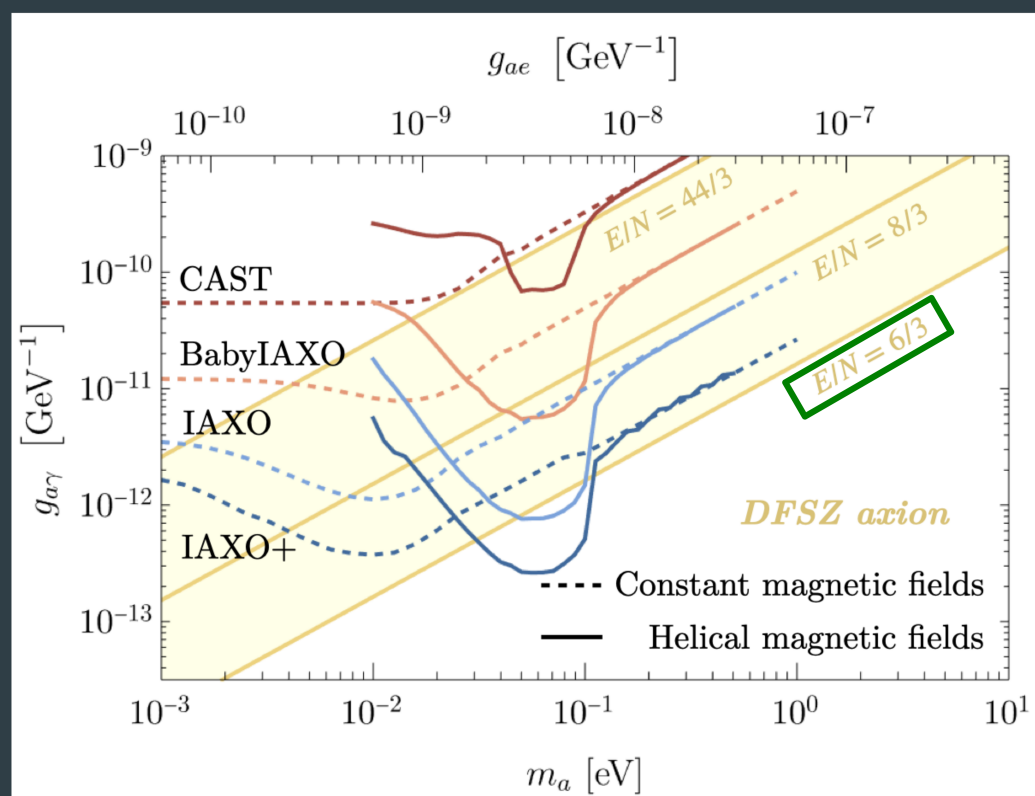
$$\frac{d}{d\omega} P\left(\Omega = \frac{m_a^2}{2\omega}\right) \neq 0$$

plasma frequency:

$$\frac{d}{d\omega} P(m_\gamma = m_a) = 0$$



$$g_{a\gamma} \sim \mathcal{O}(10^{-3} f_a^{-1})$$



$$g_{ae} \sim \mathcal{O}(f_a^{-1})$$

Going beyond AMR

How to make $H = H(t)$?

①

Dark Photon
 $\sim$ $\propto \sin(m_D t)$

$$\mathcal{L} = \frac{a}{f} F \tilde{F}_D$$

$$i \frac{d}{dz} \begin{pmatrix} A_{||} \\ a \end{pmatrix} = \frac{1}{2\omega} \begin{pmatrix} m_\gamma^2 & g\omega B_D \\ g\omega B_D & m_a^2 \end{pmatrix} \begin{pmatrix} A_{||} \\ a \end{pmatrix}$$

② Birefringent Material

mixing of X & O modes

$$i \frac{d}{dz} \begin{pmatrix} A_{\perp} \\ A_{\parallel} \\ a \end{pmatrix} = \frac{1}{2\omega} \begin{pmatrix} m_{\gamma}^2 & \Delta & 0 \\ \Delta & m_{\gamma}^2 & g\omega_B \\ 0 & g\omega_B & m_a^2 \end{pmatrix} \begin{pmatrix} A_{\perp} \\ A_{\parallel} \\ a \end{pmatrix}$$

C.f. Yao, Bi, Yin, and Huang 2601.02115

CS, Wu, Yun

2608.xxxxx

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

Qubit



(Pauli X Gate)

V oscillation

MSW & (Avoided) level crossing

Atomic

Rabi flopping

Nuclear

Nuclear Magnetic Resonance

Axion-photon

Axion Magnetic Resonance

Conclusion

- a) Many UV theories predict low energy d.o.f. that exhibit **wave features**
- b) New astrophysical and cosmological observations **just start to probe** into interesting parameter region by leveraging such features.
 - supernova remnants (radio)
 - galaxy rotation curves (radio, NIR, optical)
 - binary mergers (GW)
 - cosmic distance (X-ray and optical)
 - neutron stars (X-ray spectrum, polarization, and pulsation)
 - ...
- c) There exist **new resonances** to further enhance the signal strength.

Thank you !

感谢垂听

欢迎各位老师来杭高院指导、交流