Probing Virtual Axion–Like Particles From Light Polarization

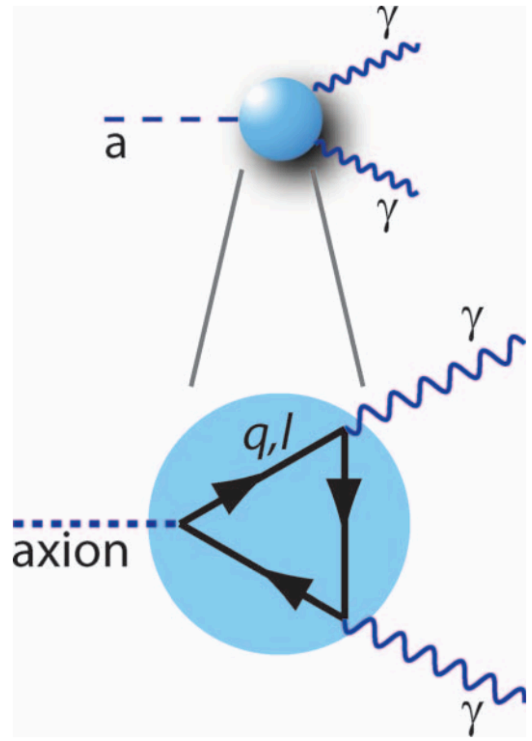
Soroush Shakeri

Isfahan University of Technology (IUT), Isfahan, IRAN

M. Zarei, S. Shakeri, M. Sharifian, M. Abdi, D. J.E. Marsh, S.Matarrese, JCAP 06 (2022) 06, 012

S. Shakeri, F. Hajkarim [arXiv:2209.13572] 27 Sep 2022

Axion — Photon Interaction



$$g_{a\gamma} \equiv \frac{c_{a\gamma}}{2\pi f_a}$$

$$c_{a\gamma} \equiv \alpha_{em}(E/N - 1.92)$$

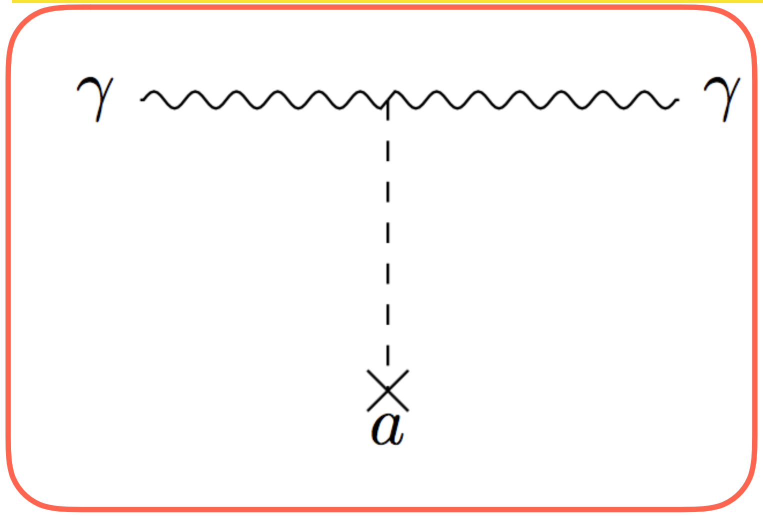
Model Independent Parameter

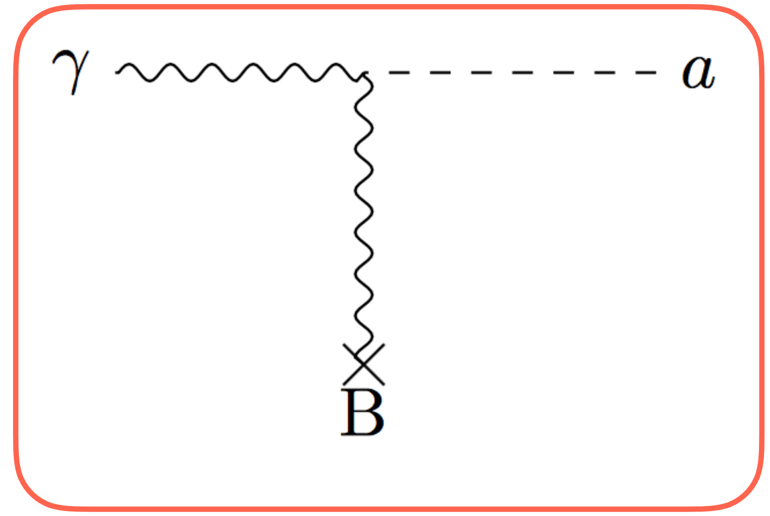
Model Dependent Parameter

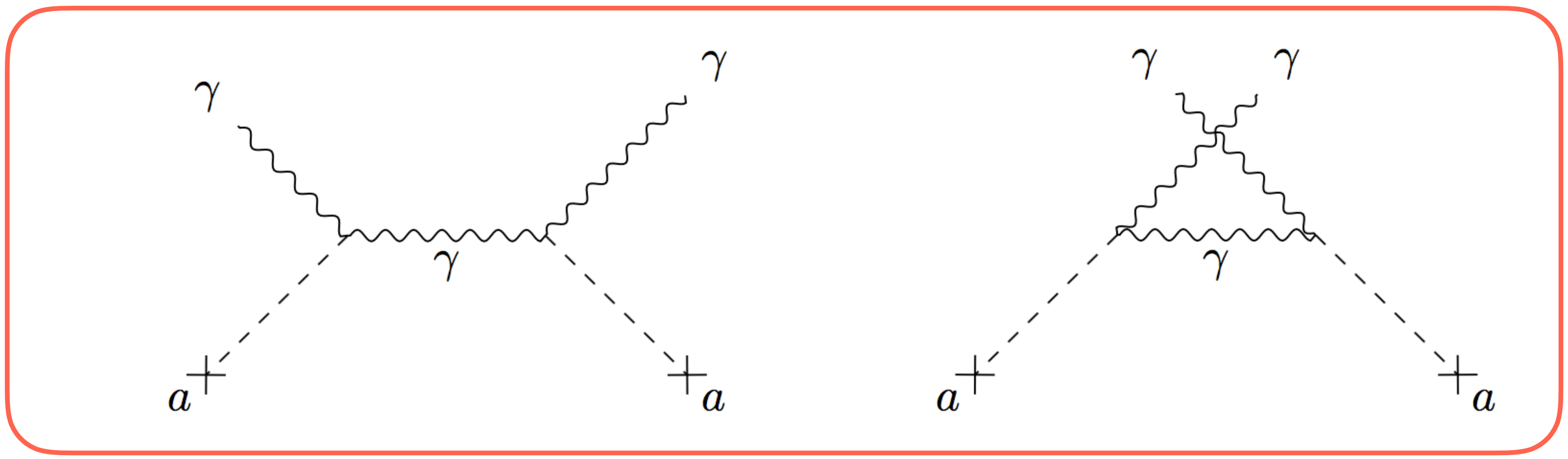
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right) + \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

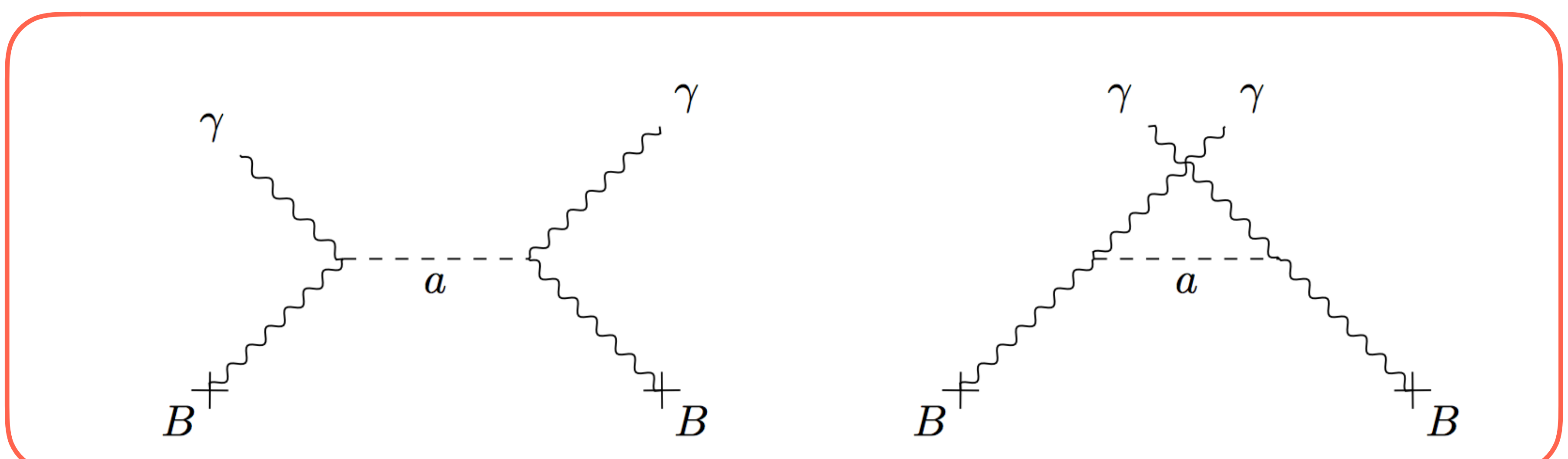
We are going to consider :

Axion — Photon Interaction and Scattering processes



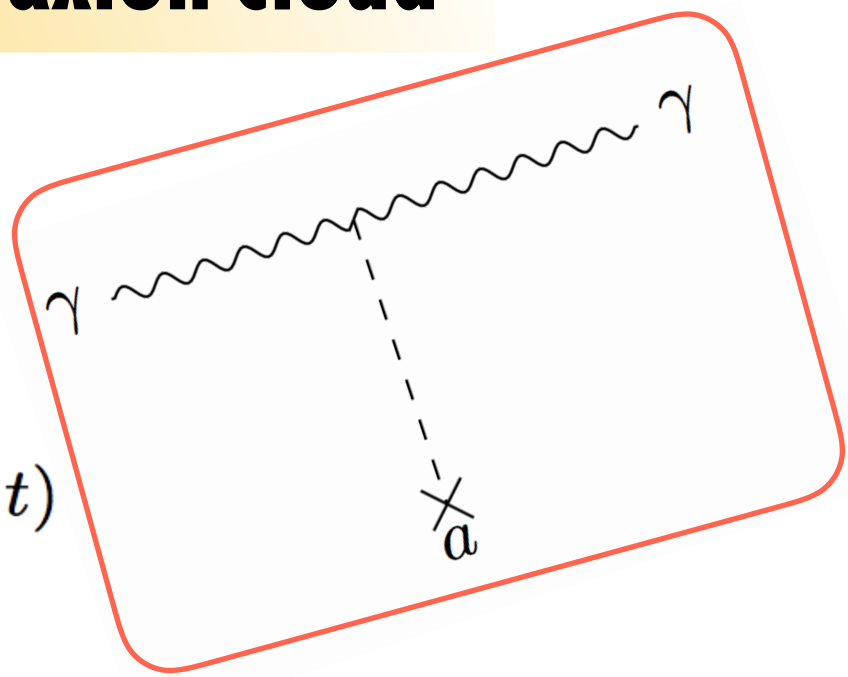






Linear Polarization Angle due to axion cloud

$$\ddot{\boldsymbol{A}} - \nabla^2 \boldsymbol{A} = g_{a\gamma}(\dot{a}\nabla \times \boldsymbol{A} + \dot{\boldsymbol{A}} \times \nabla a)$$



$$\boldsymbol{A}(t, \boldsymbol{x}) = \sum_{\pm} \int \frac{d^3k}{(2\pi)^3} A^{\pm}(k) \boldsymbol{e}^{\pm}(\hat{\boldsymbol{k}}) e^{(ik\cdot x - i\omega_{\pm}t)}$$

The photon dispersion relation in a axion background

$$k^2 = \omega_\gamma^2 - |\vec{k}|^2 \approx \pm g_{a\gamma} \left[\omega_\gamma \dot{a} - \vec{k} \cdot \vec{\nabla} a\right] \quad \Rightarrow \quad w_{\pm} \simeq k \pm \frac{g_{a\gamma}}{2} \frac{da}{dt}$$

S. M. Carroll, et al. Phys. Rev. D41 (1990) 1231.

D. Harari and P. Sikivie, Phys. Lett. B 289 (1992) 67–72.

Rotation of Polarization Plane

$$\Delta\phi = \frac{1}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} (w_+ - w_-)dt = \frac{g_{a\gamma}}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} \frac{da}{dt} dt$$

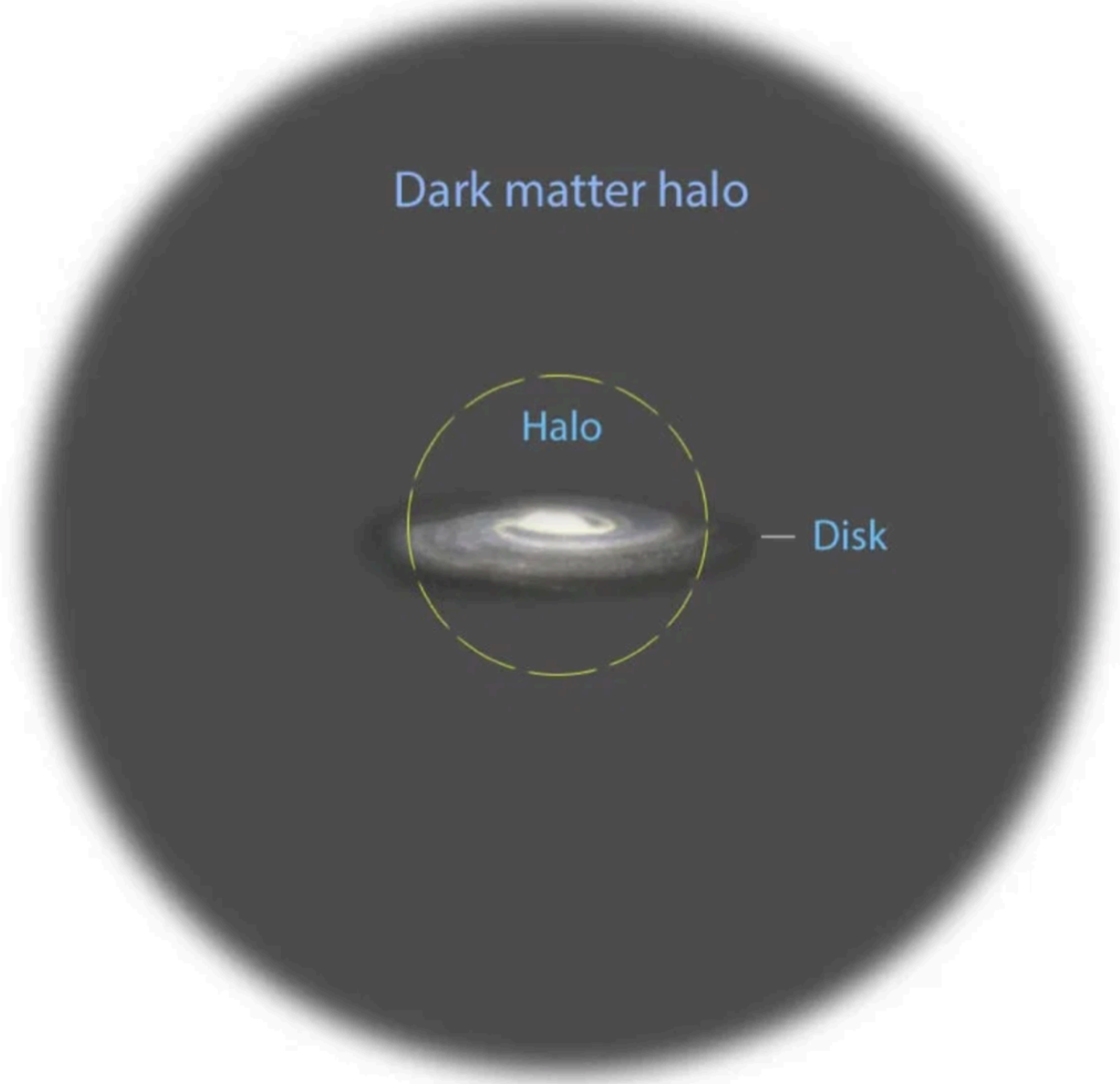
$$= \frac{g_{a\gamma}}{2}[a(t_{\rm obs}, \boldsymbol{x}_{\rm obs}) - a(t_{\rm emit}, \boldsymbol{x}_{\rm emit})],$$

Coherently Oscillating Axion Field & Time Dependent Polarization Angle

$$a(\vec{r},t) \equiv \Re e\left(a_0(r)\ e^{i(\mathbf{p}\cdot\mathbf{r}-\omega t)}\right) \equiv a_0(r)\cos\left[m_a t + \delta(r)\right]$$

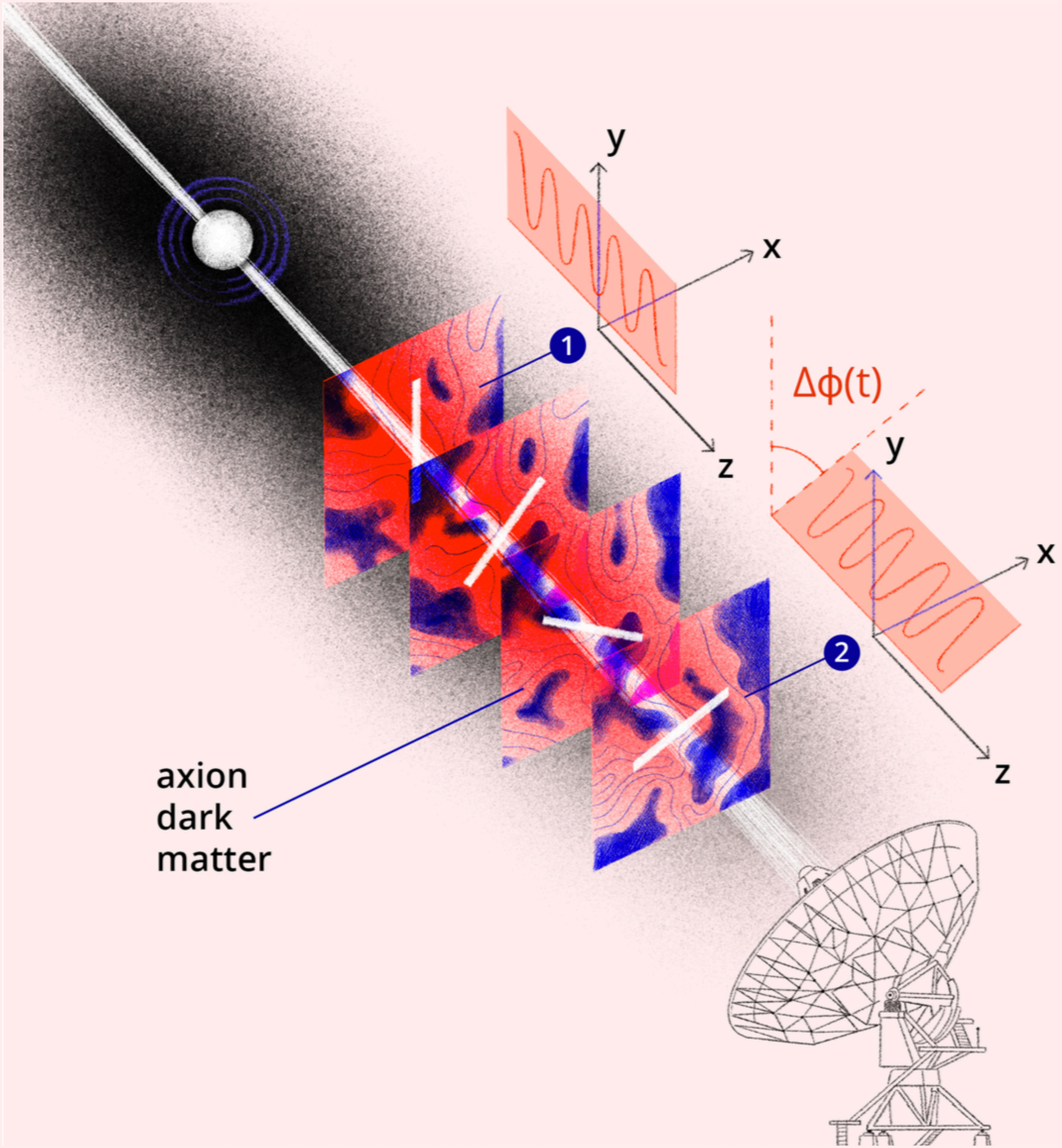
Local DM Density $\rho_{DM} = \frac{1}{2}m_a^2 a^2 \sim 0.4\frac{\text{GeV}}{\text{cm}^3}$

$$T \simeq \frac{2\pi}{m_a} \simeq 4.2\times 10^{-9}\left(\frac{10^{-6}\text{eV}}{m_a}\right)s$$



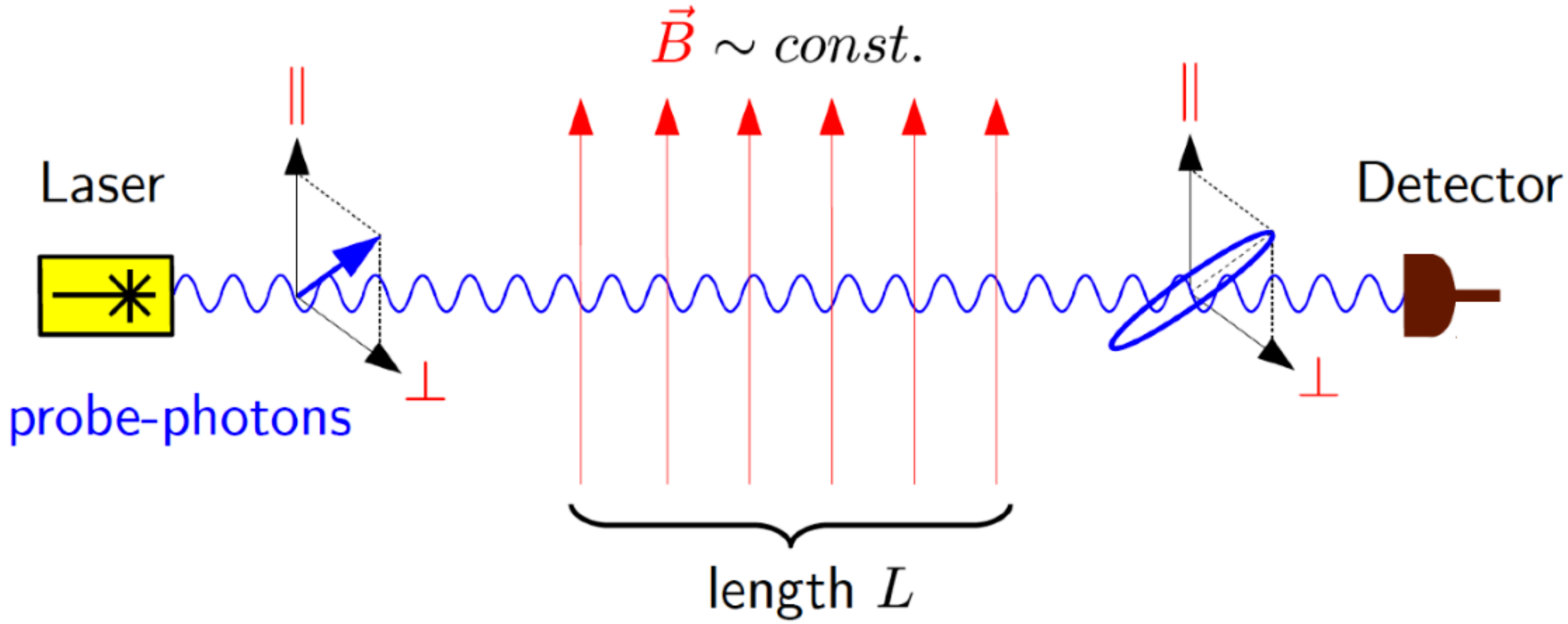
Milky Way model

Credit : Logan Zillmer



ArXiv: 2201.03422

Photon propagation in a cold **axion background** in the presence of a **magnetic field.**



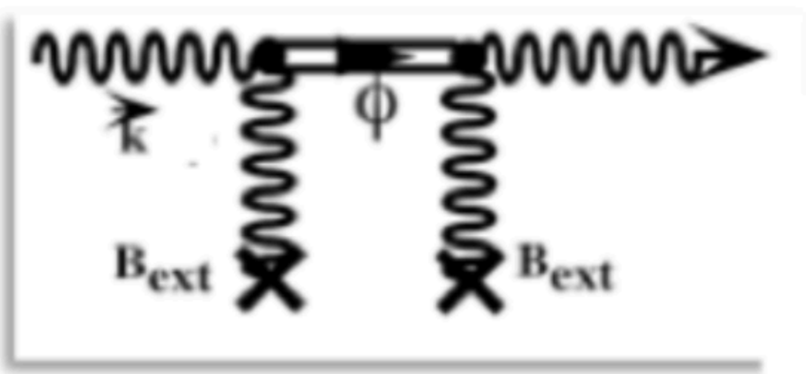
Pseudoscalar ϕ: $\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4} g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$

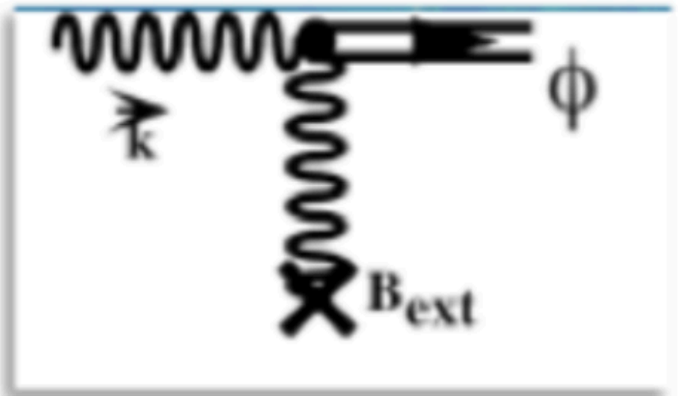
[*Sikivie* (1983)], [*Maiani et al.* (1986)], [*Raffelt, Stodolsky* (1988)], ...

$$\tilde{n} = n + i\kappa$$

Dispersion

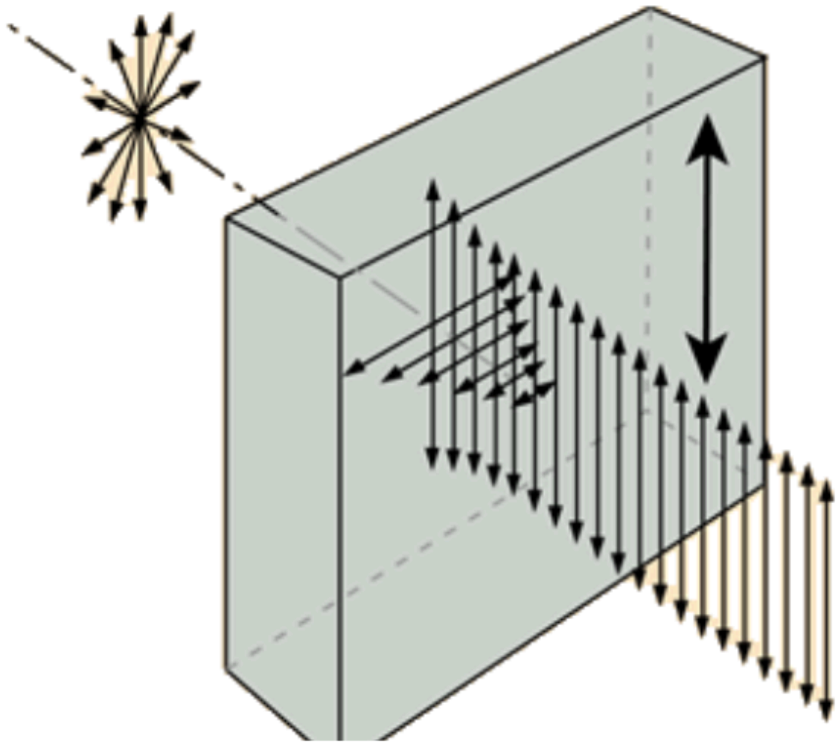
Absorbtion

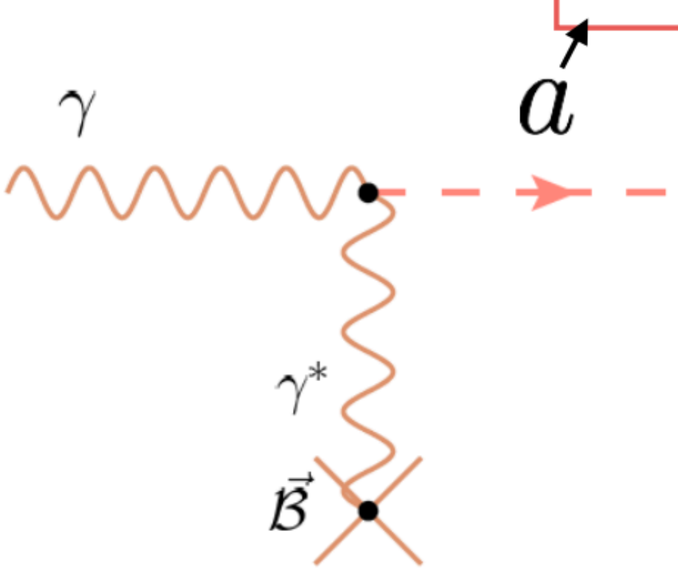


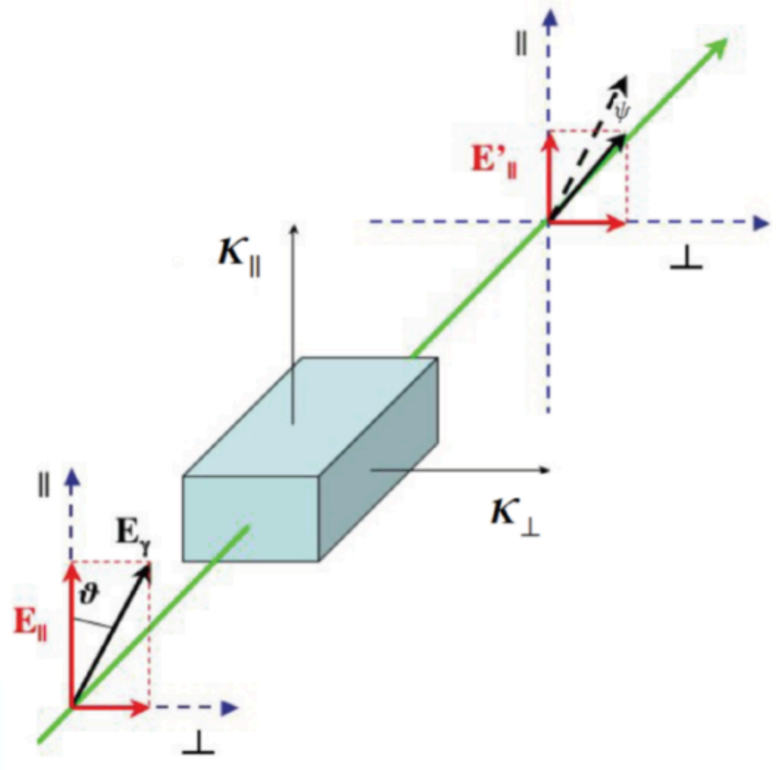


Axion-Photon Interaction Polarization Consequences

Dichroism







Angle of polarization plane

$$\psi = \frac{\pi \Delta\kappa L}{\lambda} \sin 2\vartheta,$$

Linear polarization → ***Light Amplitude Absorption*** → **Rotation of Polarization Plane**

Axion–photon conversion rate in the presence of a uniform magnetic field

$$P_{\gamma\to a} = (\Delta_M r)^2 \left(\frac{\sin(\Delta_{osc} r/2)}{\Delta_{osc} r/2}\right)^2$$

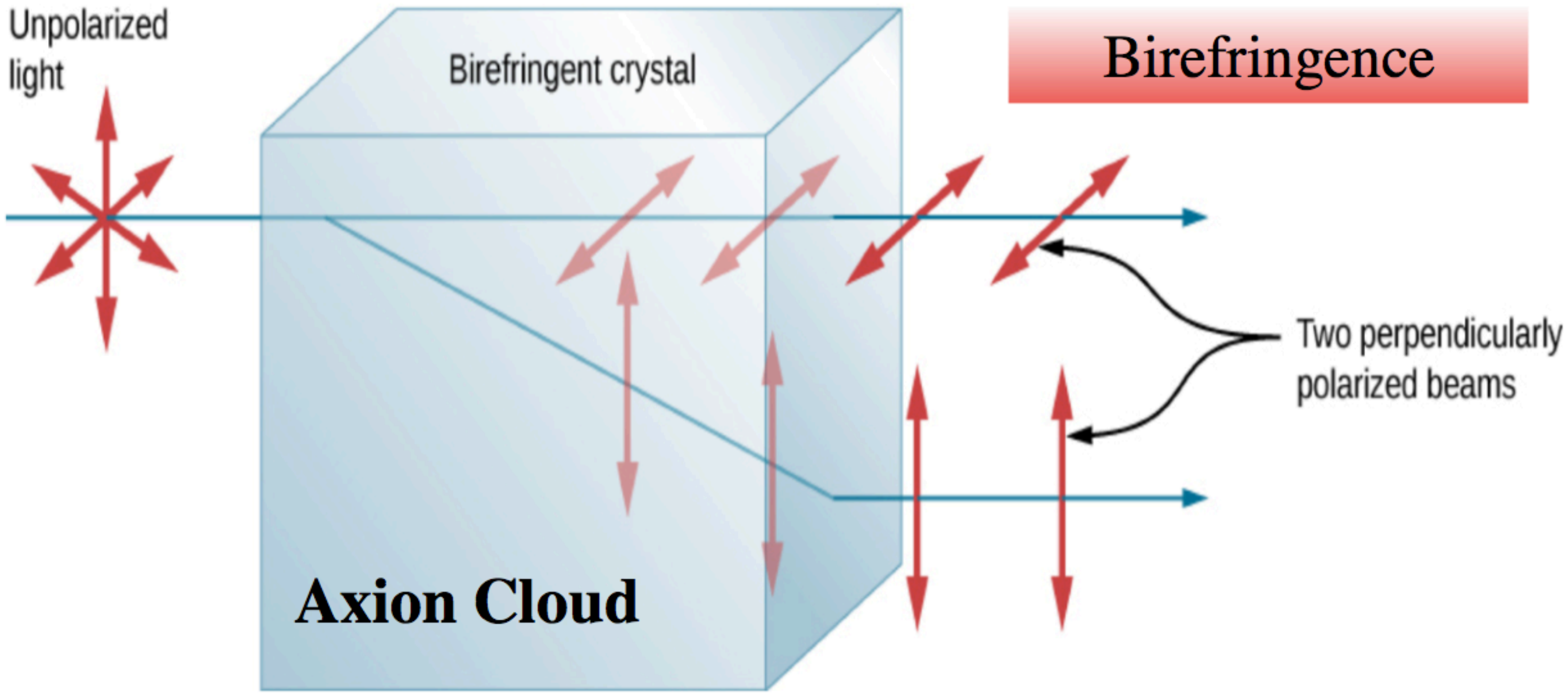
$$\Delta_{osc} = \sqrt{(\Delta_a - \Delta_p + \Delta_{QED})^2 + (2\Delta_M)^2}\,,$$

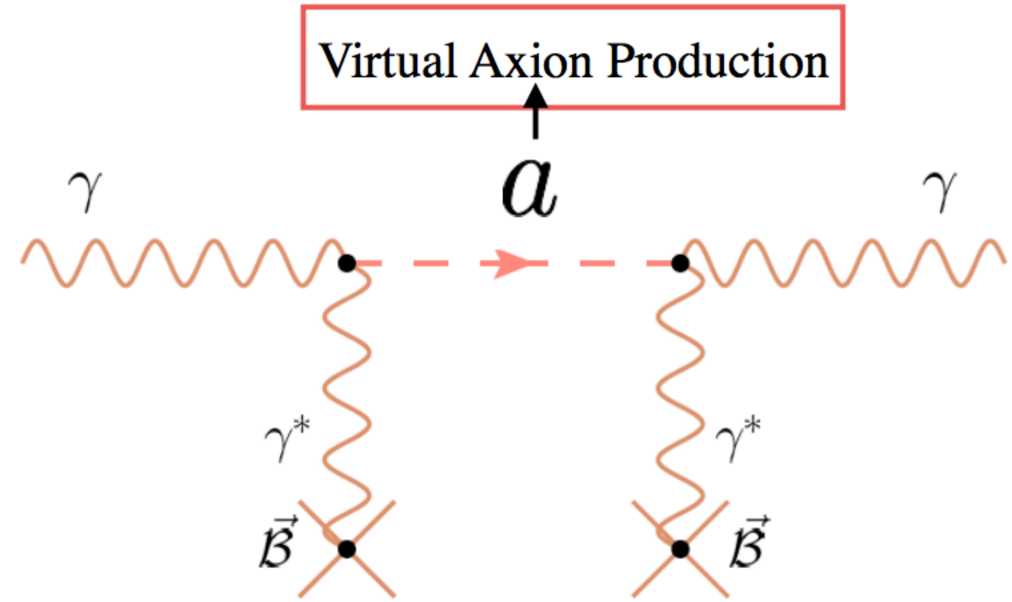
$$\Delta_p = \frac{\omega_p^2}{2\omega_\gamma} \qquad \Delta_a = \frac{m_a^2}{2\omega_\gamma} \qquad \Delta_M = \frac{g_{a\gamma} B}{2}$$

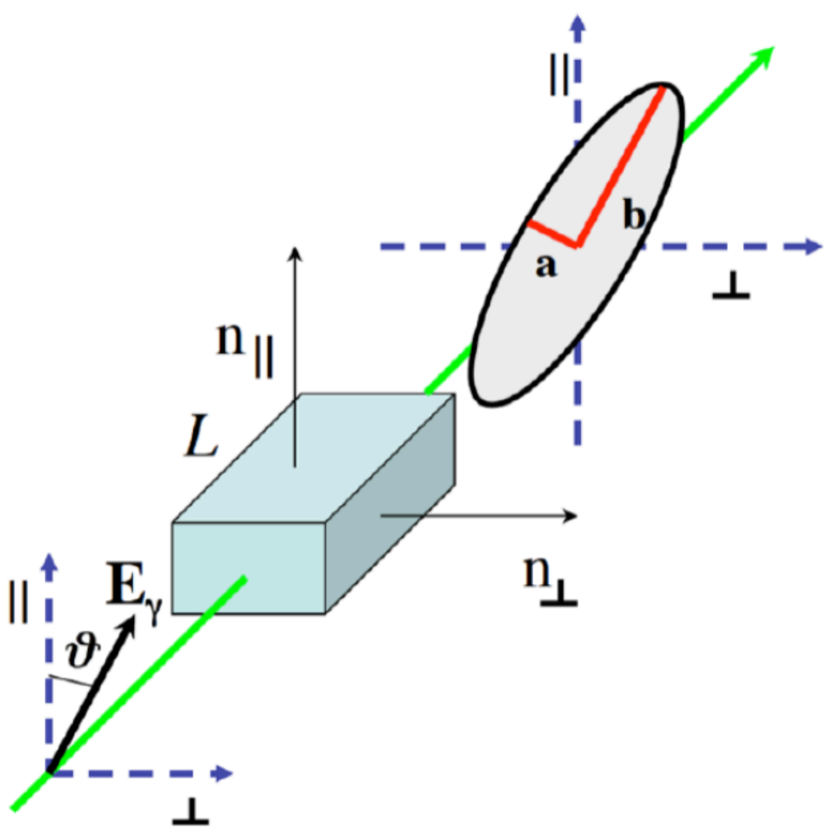
$$\Delta_{QED} = \frac{7\alpha\omega_\gamma}{90\pi}\left(\frac{B}{B_c}\right)^2$$

$B_c = m_e^2/e = 4.42 \times 10^{13} G$ is the QED critical magnetic field.

Axion-Photon Interaction Polarization Consequences



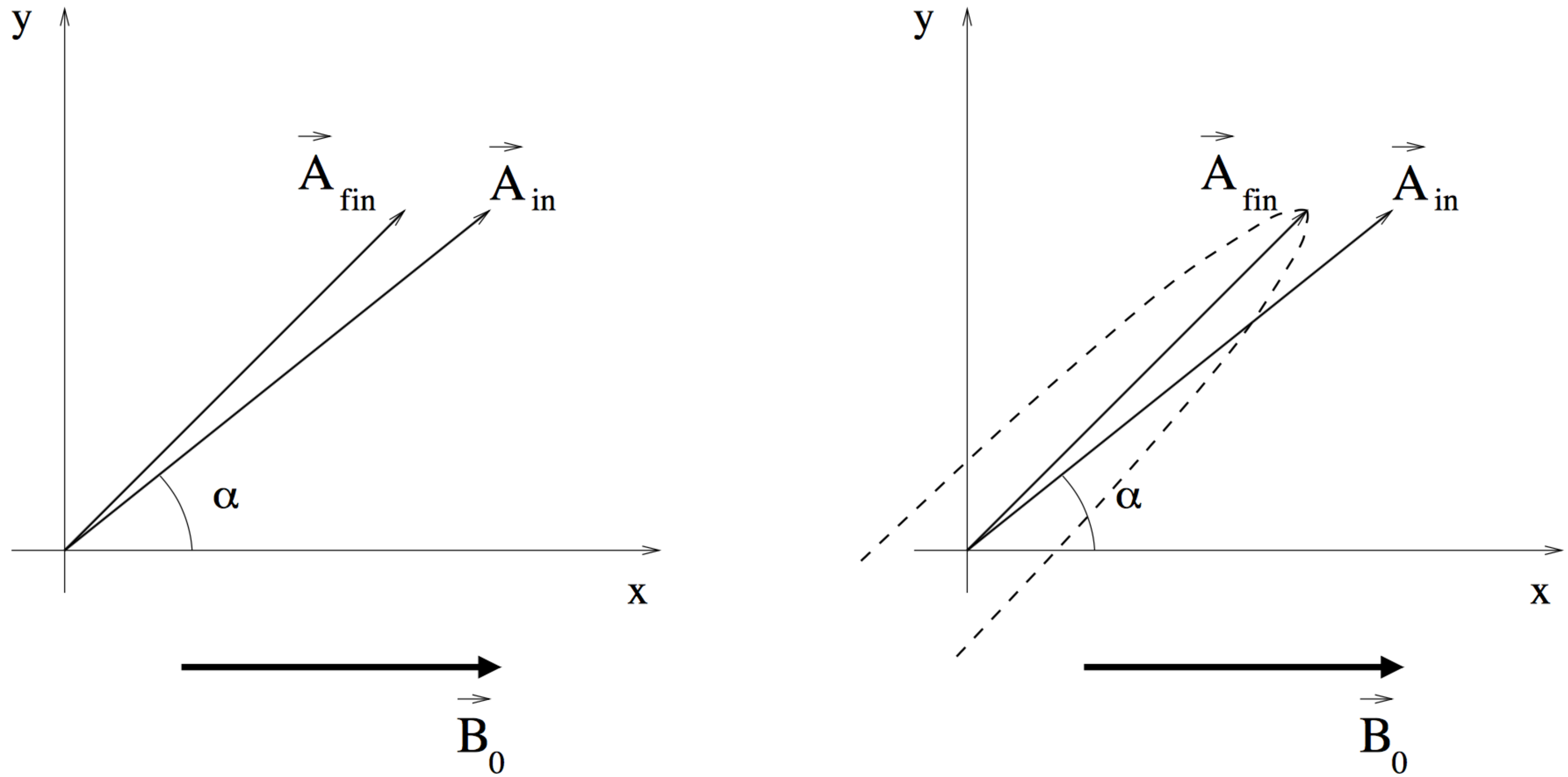




Ellipticiy

$$\epsilon = \frac{\pi \Delta n L}{\lambda} \sin 2\vartheta,$$

Linear polarization → ***Parity -violation interaction*** → **Circular polarization**



light traveling in the z−direction

$$\mathcal{A}_y \to \mathcal{A}_y \quad , \quad \mathcal{A}_x \to [1 - \frac{1}{2}p(L) + i\phi(L)]\mathcal{A}_x$$

$$\Delta\psi = \frac{1}{4} P_{\gamma\to a} \sin 2\alpha, \qquad \varepsilon(L) = \frac{1}{2}|\phi(L)| \sin(2\alpha)$$

Pierre Sikivie, Rev.Mod.Phys. 93 (2021) 1, 015004
Maiani et al., 1986; Raffelt and Stodolsky, 1988

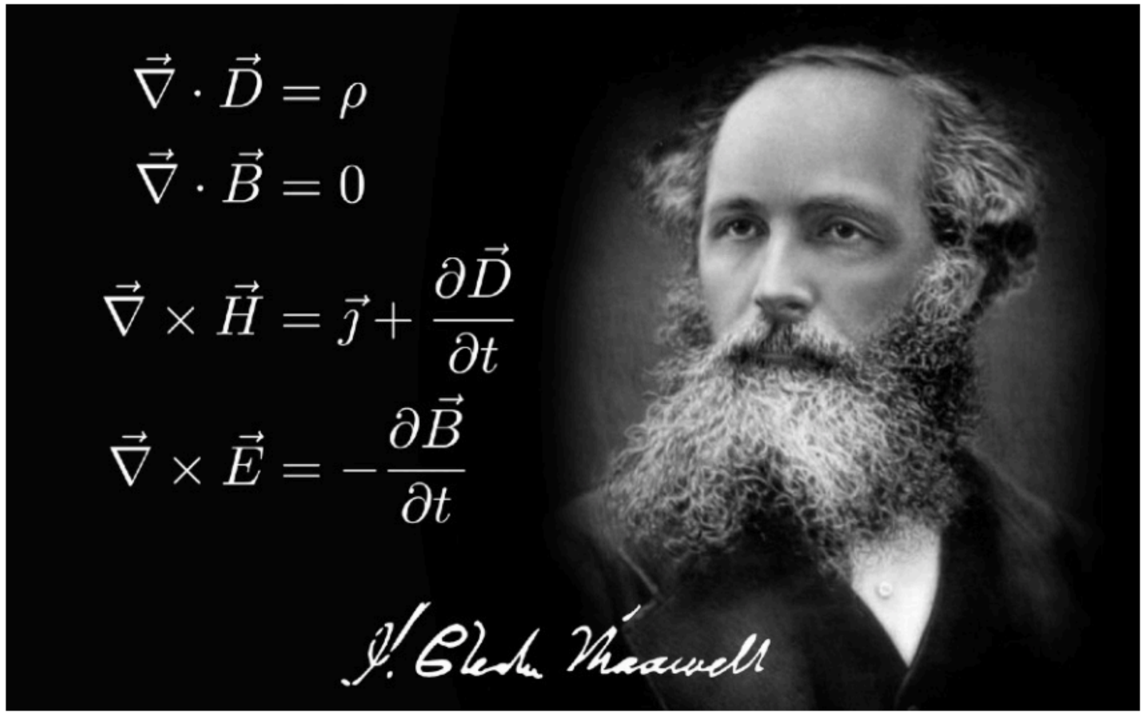
In order to enhance the polarization signal

(i) Using ultrahigh magnetic field

(ii) Using moderate magnetic field but increasing the interaction length

(iii) Using a huge numbers (high-intensity beams) of photons in order to increase interaction rate

Axion as a Virtual Particle



Axion Electrodynamics

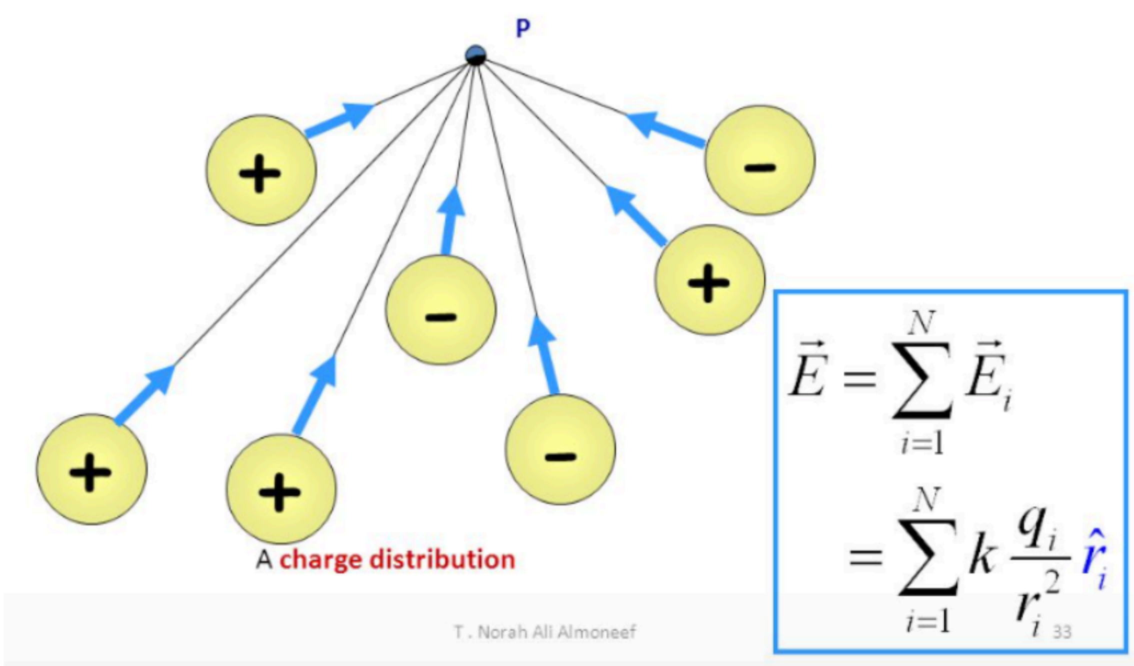
$$\nabla\cdot\vec{E}=-\frac{1}{f}\nabla a\cdot\vec{B}$$

$$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

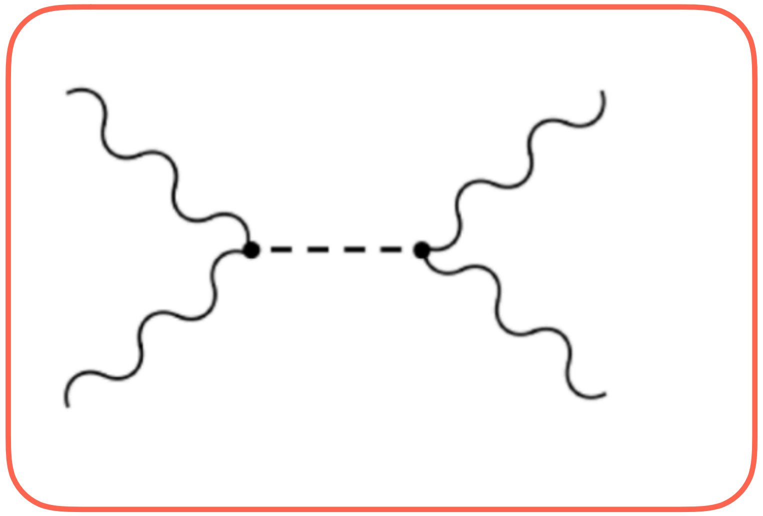
$$\nabla\cdot\vec{B}=0$$

$$\nabla\times\vec{B}=\frac{\partial\vec{E}}{\partial t}+\frac{1}{f}(\dot{a}\vec{B}+\nabla a\times\vec{E})$$

Nonlinear corrections to Maxwell Eqs



superposition principle

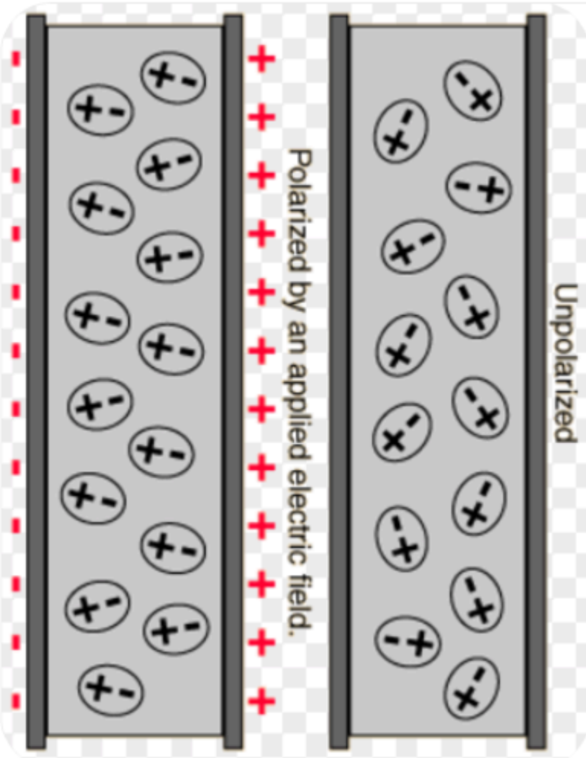


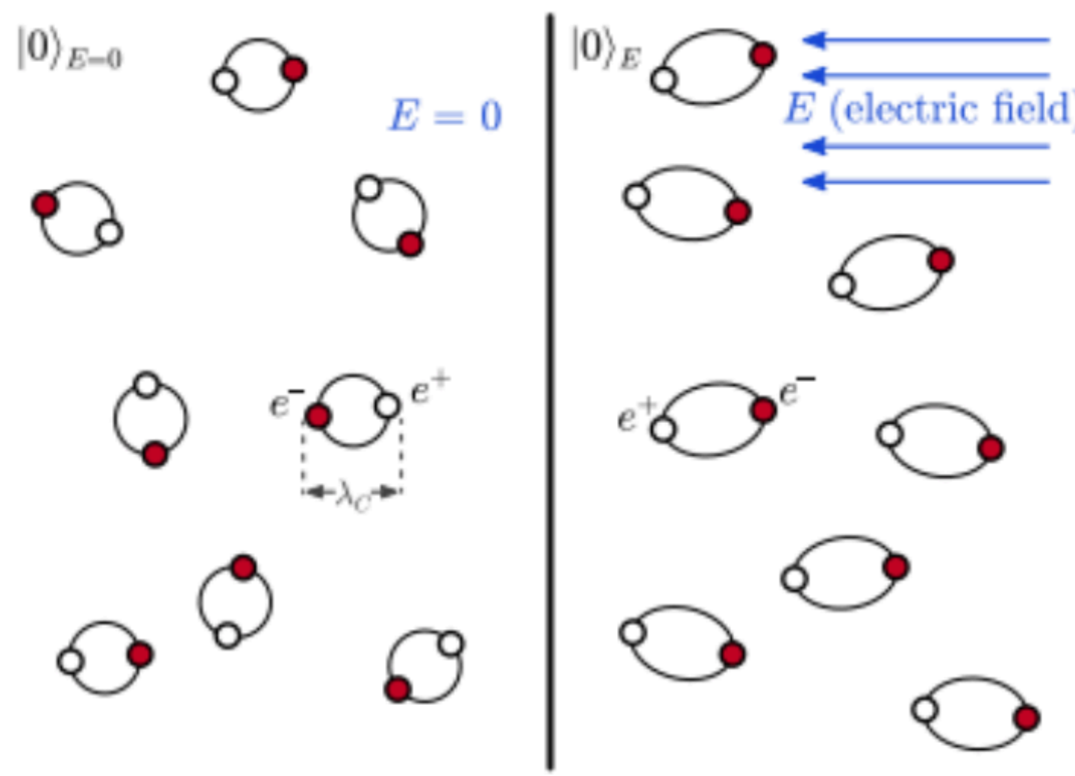
light-by-light scattering due to virtual ALPs

F. Moulin, D. Bernard, 1, F. Amiranoff, Z. Phys. C72, 607–611 (1996).
D. Bernard, Nucl.Phys.B Proc.Suppl. 72 (1999) 201–205.

QED Vacuum birefringence as background noise

for Virtual Axions





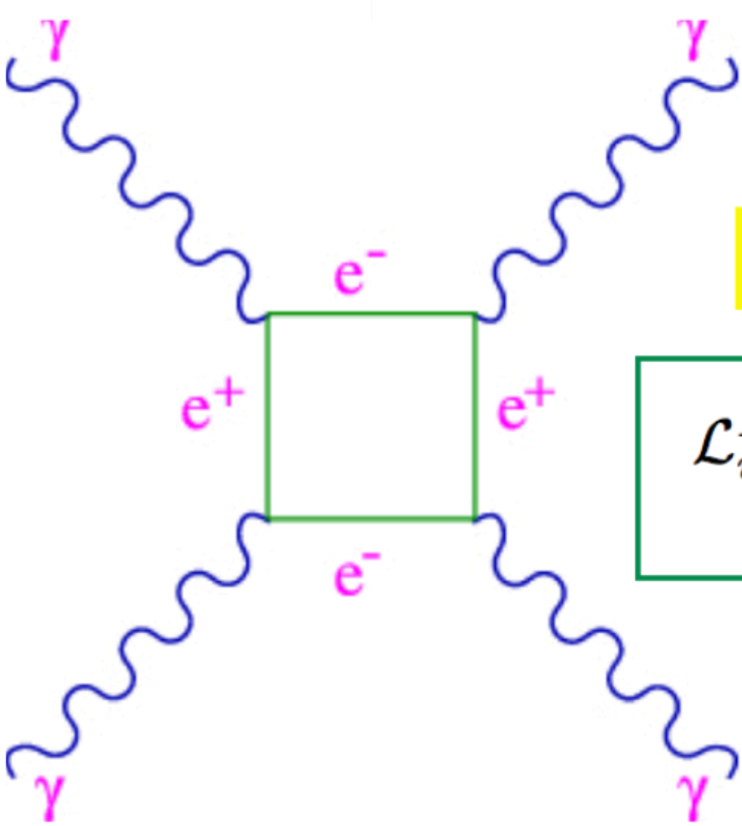
2 refractive index

$$\Delta n = n_{\parallel} - n_{\perp}$$

$$\Delta n = 3A_e B_0^2 = \frac{\alpha}{30\pi}\left(\frac{B}{\mathcal{B}_c}\right)^2$$

nonlinearity

$$(\ \mu(E,B)\ ,\ \varepsilon(E,B)\ )$$



Euler-Heisenberg(EH) Lagrangian

$$\mathcal{L}_{int}^{EH} = \frac{\alpha^2}{90 m_e^4}\left[(\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu})^2 + \frac{7}{4}(\mathcal{F}_{\mu\nu}\widetilde{\mathcal{F}}^{\mu\nu})^2\right]$$

Werner Heisenberg (1901-76)
Foto from 1933 (Wikipedia)

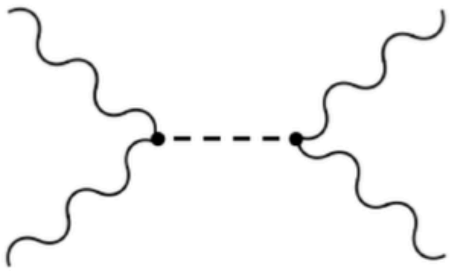
Hans Euler (1909-41)
Foto ca. 1935 (H. Wergeland)

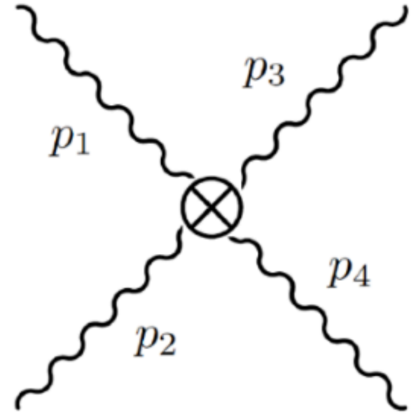
F. Sauter, Z. Phys. 69, 742 (1931).
J. Schwinger: On Gauge Invariance and Vacuum Polarization, Phys. Rev. 82, 664 (1951).

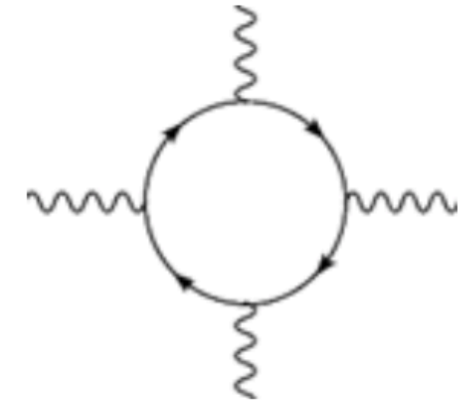
$\omega \ll m_a$

QED as a Background noise for Axions in Light-Light Scattering

$\omega \ll m_e$



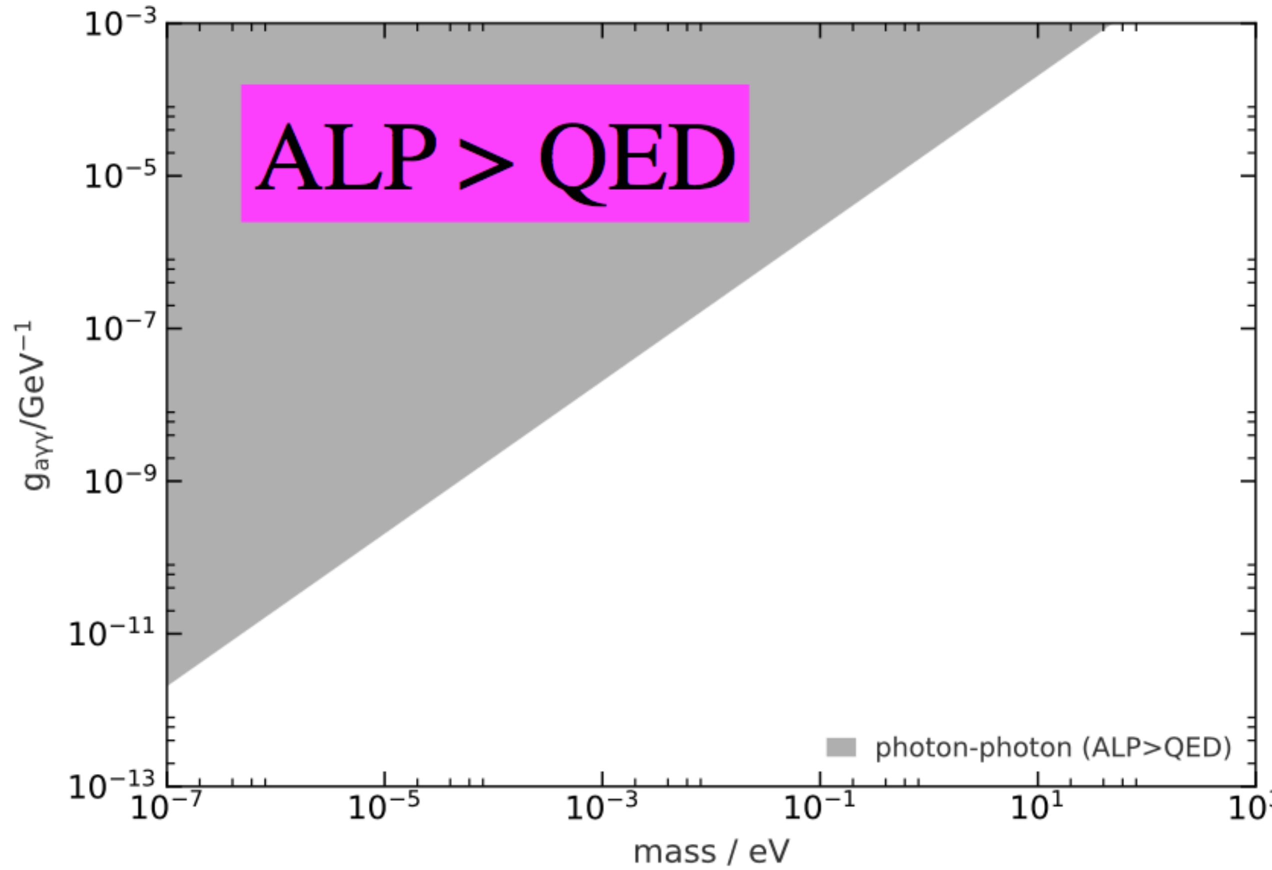




$$\mathcal{L}_{a,\mathrm{eff}} = \frac{g^2_{a\gamma\gamma}}{32 m_a^2}(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2$$

$$\mathcal{L}^{EH}_{int} = \frac{\alpha^2}{90 m_e^4}\left[(\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu})^2 + \frac{7}{4}(\mathcal{F}_{\mu\nu}\widetilde{\mathcal{F}}^{\mu\nu})^2\right]$$

$$\left(\frac{g_{\phi\gamma\gamma}}{m_\phi}\right) \gtrsim 0.73 \times \left(\frac{\alpha}{m_e^2}\right) = \frac{2.05 \times 10^{-5}}{(eV)(GeV)}$$



Moreover, close to the resonance ($\omega \simeq m_a$) the ALP vacuum effect surpasses the virtual electron-positron effect in an even wider parameter region

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Probing virtual axion-like particles by precision phase measurements

Moslem Zarei,[a,b,c] **Soroush Shakeri,**[a,c,d] **Mohammad Sharifian,**[a,c]
Mehdi Abdi,[a] **David J.E. Marsh**[e] **and Sabino Matarrese**[b,f,g,h]

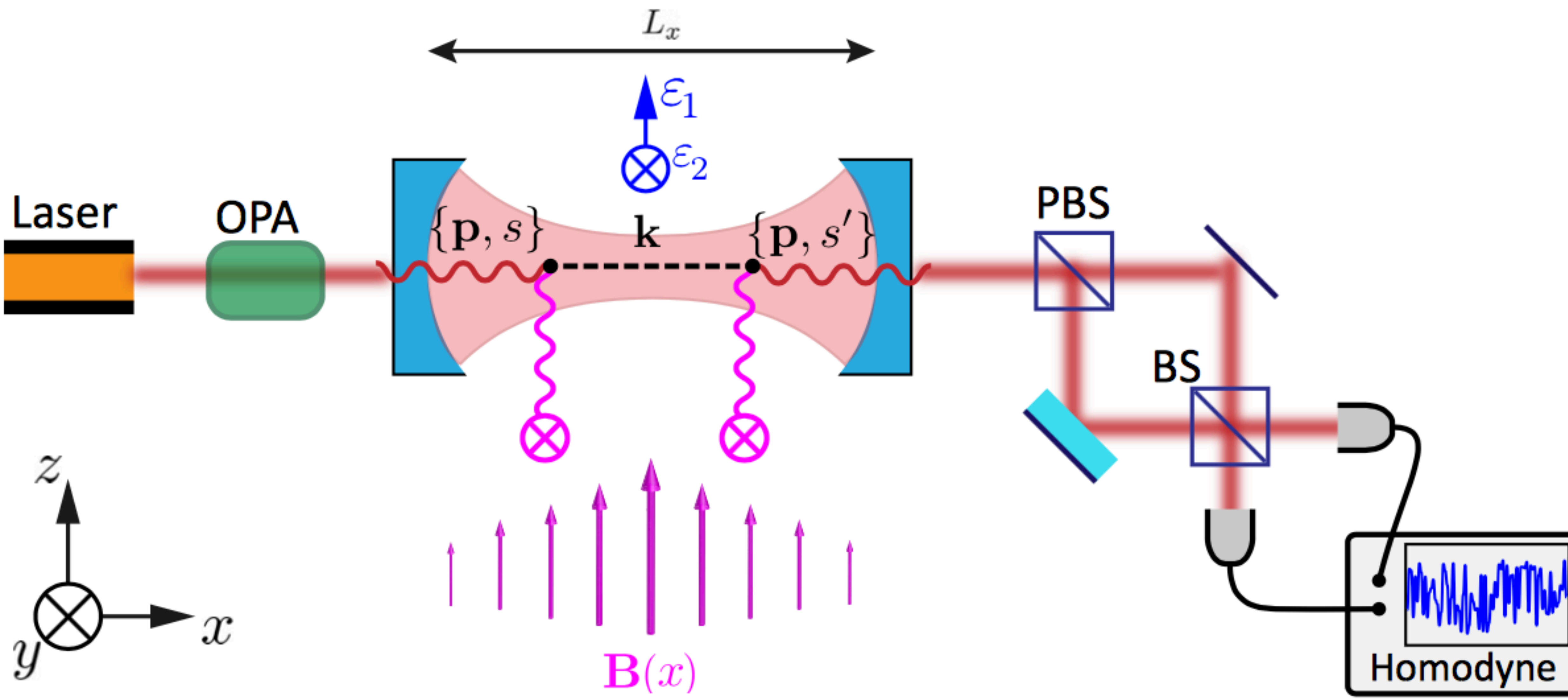
[a]Department of Physics, Isfahan University of Technology,
Isfahan 84156-83111, Iran
[b]Dipartimento di Fisica e Astronomia "G. Galilei", Università degli Studi di Padova,
via Marzolo 8, I-35131, Padova, Italy
[c]ICRANet-Isfahan, Isfahan University of Technology,
Isfahan 84156-83111, Iran
[d]School of Astronomy, Institute for Research in Fundamental Sciences (IPM),
P.O. Box 19395-5531, Tehran, Iran
[e]King's College London,
Strand, London, WC2R 2LS, U.K.
[f]INFN Sezione di Padova,
via Marzolo 8, I-35131, Padova, Italy
[g]INAF-Osservatorio Astronomico di Padova,
vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[h]Gran Sasso Science Institute,
viale F. Crispi 7, I-67100, L'Aquila, Italy

ArXiv ePrint: 1910.09973

Received December 15, 2021
Accepted May 3, 2022
Published June 10, 2022

The scheme of our proposed experiment to probe Virtual Axions

we propose a novel experiment based on the forward scattering of photons via virtual Ahs exchange from an inhomogeneous magnetic field inside a cavity



$$H_{\gamma B} = \sum_{s,s',\mathbf{p}} \mathcal{F}^{\mathbf{p}} (\boldsymbol{\varepsilon}^{s'} \cdot \hat{\mathbf{b}})(\boldsymbol{\varepsilon}^{s} \cdot \hat{\mathbf{b}})\, a^{\dagger}_{s'}(\mathbf{p}) a_s(\mathbf{p})$$

Phase difference between two cavity modes $\overline{\delta\phi} \approx \mathcal{F}_r \tau$

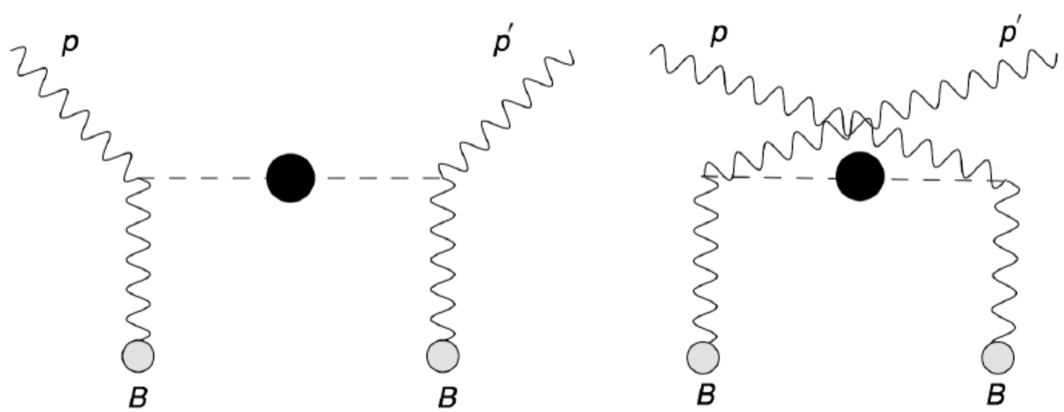
quantizating the photon field inside the cavity

$$A_\nu(x)=A_\nu^+(x)+A_\nu^-(x)=\sum_s\sum_{\mathbf{p}}\frac{1}{\sqrt{\omega_{\mathbf{p}}V}}\left[i\sin\left(p_x x+\frac{p_x L_x}{2}\right)a_s(\mathbf{p})e^{ip_y y}e^{ip_z z}e^{-i\omega_{\mathbf{p}}t}\varepsilon_\nu^s(\mathbf{p})+\text{h.c.}\right],$$

$$\mathbf{p}=(p_x,p_y,p_z)=\left(\frac{\pi l_1}{L_x},\frac{2\pi l_2}{L_y},\frac{2\pi l_3}{L_z}\right)\ \text{with}\ l_2,l_3=0,\pm1,\pm2,\cdots\ \text{and}\ l_1=0,1,2,\cdots,$$

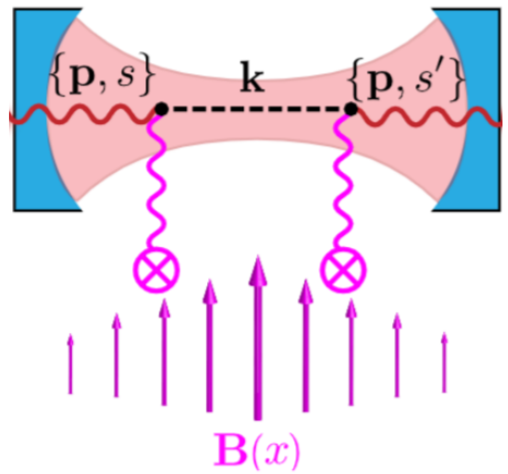
K. Kakazu and Y.S. Kim, , Phys. Rev. A 50 (1994) 1830 .

Forward Scattering of photons from magnetic field inside the cavity



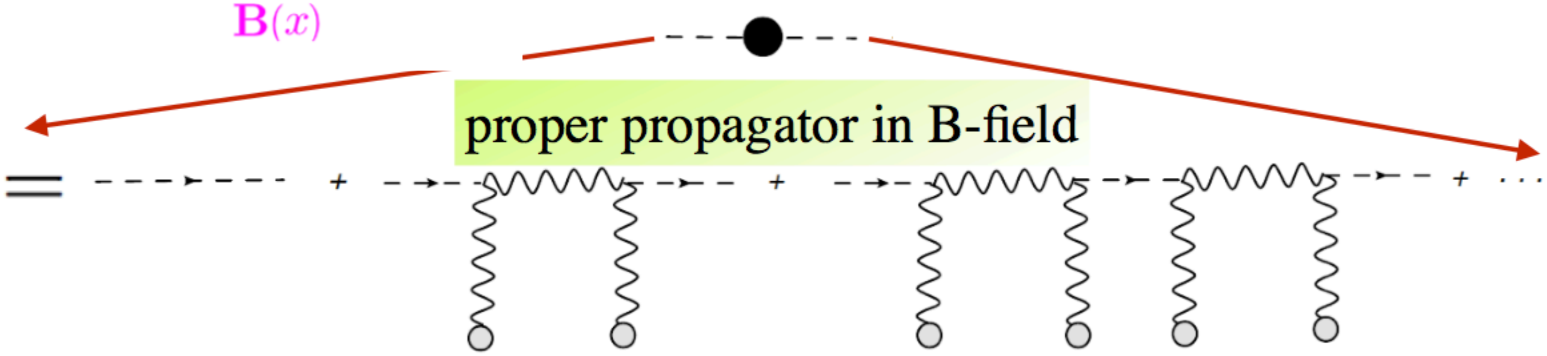
$$H_{\gamma B}(t)=\frac{g_{a\gamma\gamma}^2}{2V}\sum_{s,s'}\sum_{\mathbf{p},\mathbf{p}'}\sqrt{\omega_{\mathbf{p}}\omega_{\mathbf{p}'}}\int dt'dx'd^2\mathbf{x}'_\perp\,dx\,d^2\mathbf{x}_\perp\frac{d^4k}{(2\pi)^4}D(k)$$
$$\times[\boldsymbol{\varepsilon}^{s'*}(\mathbf{p}')\cdot\mathbf{B}(x')][\boldsymbol{\varepsilon}^s(\mathbf{p})\cdot\mathbf{B}(x)]$$
$$\times a_{s'}^\dagger(\mathbf{p}')a_s(\mathbf{p})\Bigg[\sin\left(p'_x x+\frac{p'_x L_x}{2}\right)\sin\left(p_x x'+\frac{p_x L_x}{2}\right)$$
$$\times e^{-i\mathbf{k}\cdot\mathbf{x}'}e^{-i\mathbf{p}'_\perp\cdot\mathbf{x}_\perp}e^{i\mathbf{k}\cdot\mathbf{x}}e^{i\mathbf{p}_\perp\cdot\mathbf{x}'_\perp}e^{-i(-k^0+\omega_{\mathbf{p}})t'}e^{-i(k^0-\omega_{\mathbf{p}'})t}$$
$$+\sin\left(p'_x x'+\frac{p'_x L_x}{2}\right)\sin\left(p_x x+\frac{p_x L_x}{2}\right)$$
$$\times e^{-i\mathbf{k}\cdot\mathbf{x}'}e^{-i\mathbf{p}'_\perp\cdot\mathbf{x}'_\perp}e^{i\mathbf{k}\cdot\mathbf{x}}e^{i\mathbf{p}_\perp\cdot\mathbf{x}_\perp}e^{-i(-k^0-\omega_{\mathbf{p}'})t'}e^{-i(k^0+\omega_{\mathbf{p}})t}\Bigg]$$

Axion interaction with a Spatially harmonic magnetic field profile



$$\mathbf{B}(x) = \mathbf{B}_0 \cos\left(x/\ell\right)$$

$\Pi_B =$



$$\mathrm{Im}\Pi_B = -\omega_{\mathbf{k}}\Gamma_B$$

$$H_{\gamma B} = \sum_{s,s',\mathbf{p}} \mathcal{F}^{\mathbf{p}} (\boldsymbol{\varepsilon}^{s'} \cdot \hat{\mathbf{b}})(\boldsymbol{\varepsilon}^{s} \cdot \hat{\mathbf{b}})\, a^\dagger_{s'}(\mathbf{p}) a_s(\mathbf{p})$$

$$\mathcal{F}^{\mathbf{p}} \equiv \mathcal{F}^{\mathbf{p}}_r + i\mathcal{F}^{\mathbf{p}}_i$$

$\hat{\mathbf{b}}$ is a unit vector pointing in the direction of magnetic field

$$\mathcal{F}^{\mathbf{p}}_r = G_a \int dk_x \frac{\omega_{\mathbf{p}}(p_x^2 - k_x^2 - m_a^2)\mathcal{P}(k_x, p_x)}{(p_x^2 - k_x^2 - m_a^2)^2 + (\omega_{\mathbf{p}}\Gamma_B)^2}$$

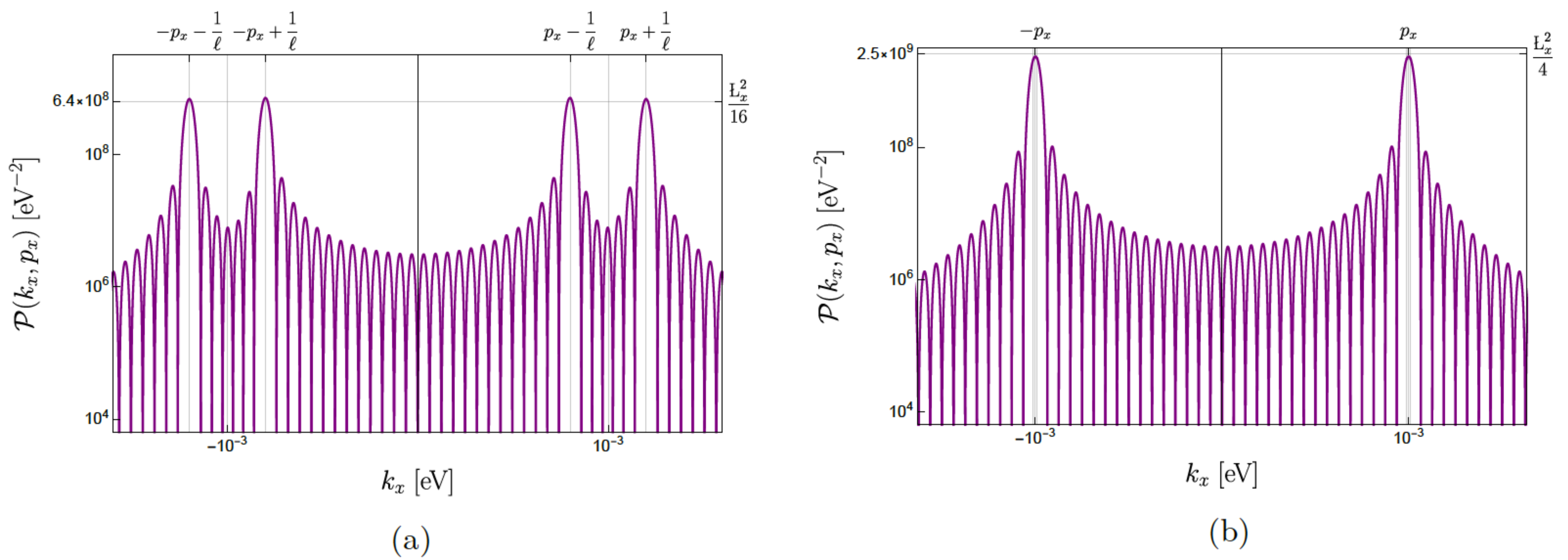
$$\mathcal{F}^{\mathbf{p}}_i = G_a \int dk_x \frac{\omega_{\mathbf{p}}^2\,\Gamma_B\,\mathcal{P}(k_x, p_x)}{(p_x^2 - k_x^2 - m_a^2)^2 + (\omega_{\mathbf{p}}\Gamma_B)^2}$$

$$G_a \equiv g^2_{a\gamma\gamma} B_0^2 / 2\pi L_x$$

Resonance Enhancement of Birefringence Signal

$$\mathcal{P}(k_x,p_x)=\frac{1}{4}\left[(-1)^{l_1}\left(\frac{\sin(\frac{L_x}{2}\Delta_1)}{\Delta_1}+\frac{\sin(\frac{L_x}{2}\Delta_2)}{\Delta_2}\right)-\left(\frac{\sin(\frac{L_x}{2}\Delta_3)}{\Delta_3}+\frac{\sin(\frac{L_x}{2}\Delta_4)}{\Delta_4}\right)\right]^2$$

$\Delta_1=k_x+p_x+\frac{1}{\ell}$, $\Delta_2=k_x+p_x-\frac{1}{\ell}$, $\Delta_3=k_x-p_x+\frac{1}{\ell}$, $\Delta_4=k_x-p_x-\frac{1}{\ell}$, and $l_1=p_xL_x/\pi$



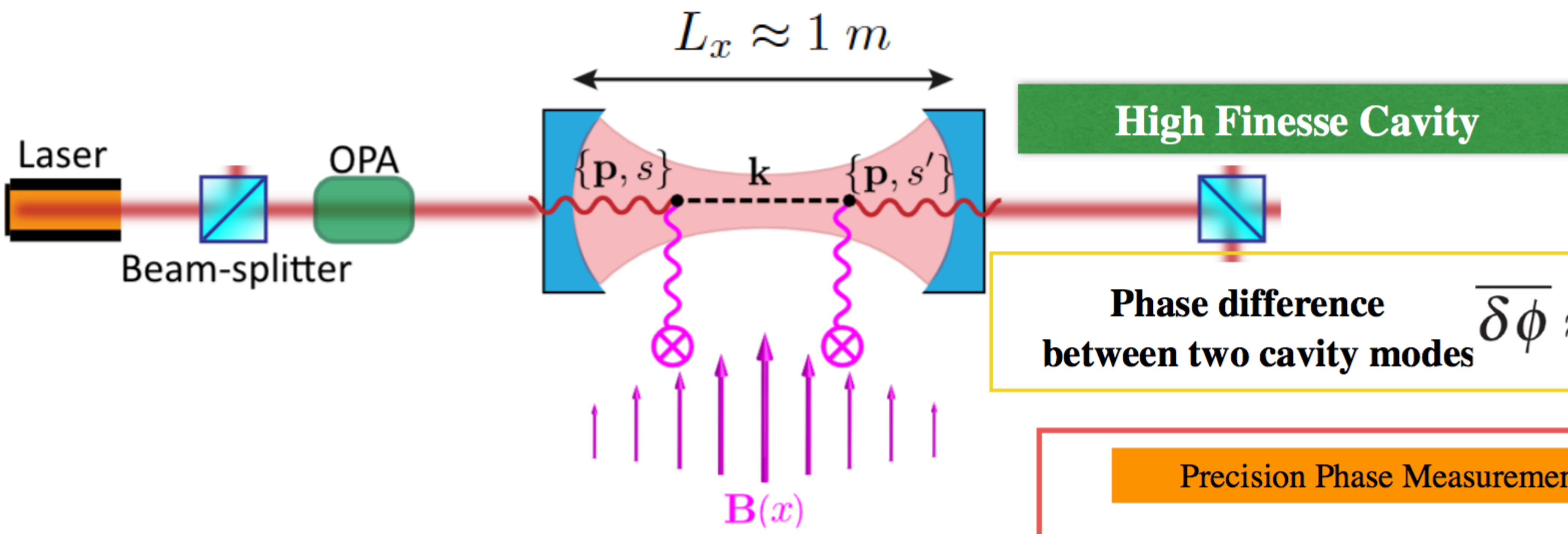
(a) The profile function of $\mathcal{P}(k_x,p_x)$ for a 2 cm cavity which is pumped by $p_x=10^{-3}$ eV photons and exposed to a magnetic field with $\ell=0.05\ L_x$. There are four distinct peaks on $\pm p_x\pm\frac{1}{\ell}$. (b) The same profile function with $\ell=L_x$.

In the Presence of a Uniform Magnetic Field

$$\mathcal{F}^{\mathbf{p}} = -\frac{g_{a\gamma\gamma}^2 B_0^2 \omega_{\mathbf{p}}}{2} \left(\frac{m_a^2 + i\omega_{\mathbf{p}}\Gamma_{B_0}}{m_a^4 + (\omega_{\mathbf{p}}\Gamma_{B_0})^2} \right)$$

$$\Gamma_{B_0} = g_{a\gamma\gamma}^2 B_0^2 L_x / 8$$

Cavity detection scheme



Phase difference between two cavity modes $\overline{\delta\phi} \approx \mathcal{F}_r \tau$

By using a Fabry-Perot cavity

$$L_{eff} = \frac{2FL}{\pi}$$

$F = 10^5$ cavity finesse

Precision Phase Measurements

$$\delta\mathcal{F}_r = \frac{e^{-r}}{\sqrt{N_{\text{ph}} N_{\text{exp}}}} \cdot \frac{\pi c}{2FL}$$

average pulse photon number $N_{\text{ph}} = 10^{14}$,

repetition of the experiment $N_{\text{exp}} = 10^6$

squeezing parameter up to r = 1.73

run of the experiment takes about $\tau_{\text{exp}} \sim \tau$. In our scenario using the above-mentioned number of repetitions $N_{\text{exp}} = 10^6$ and a cavity with the length and finesse of $F = 10^5$ and $L_x = 1$ m, respectively, examining each ALP mass needs about $N_{\text{exp}}\tau_{\text{exp}} \approx 17$ minutes. Therefore, by our scheme one examines about 2500 ALP masses in a period of one-month experiment.

Cavity modes, FSR, The width of the modes

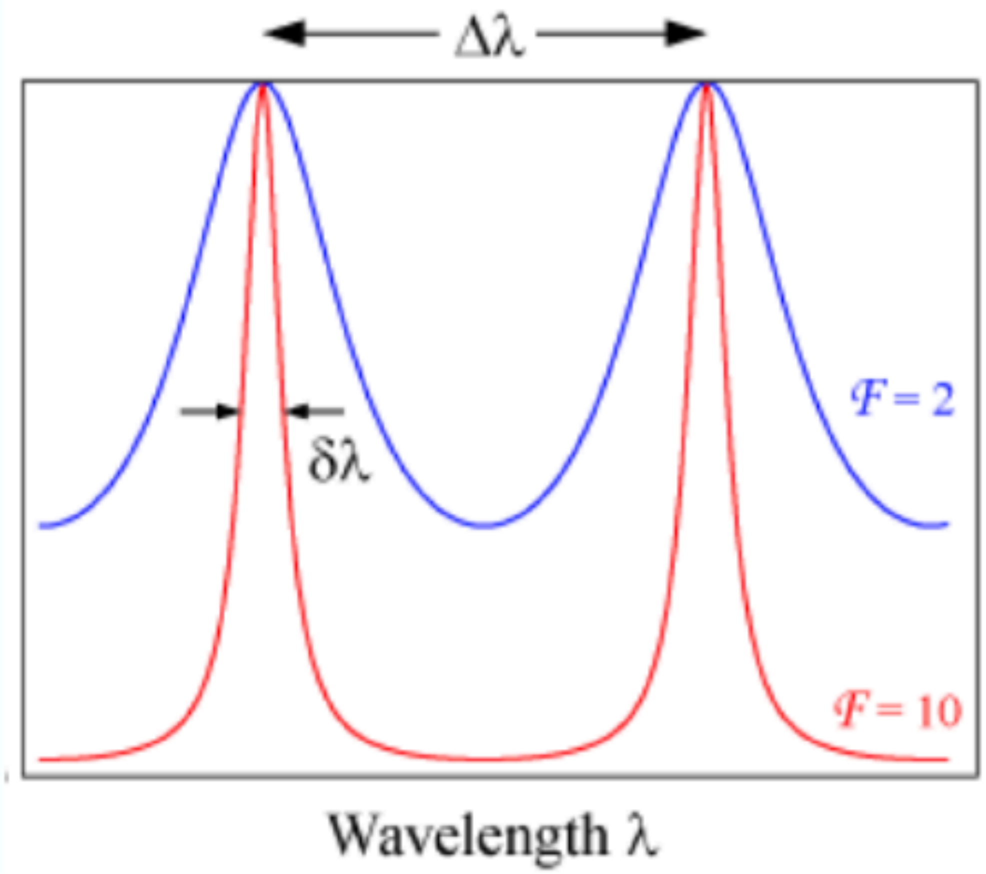
Moreover, practical considerations of optical cavities enforce us to use laser frequencies of the range $0.03\ \text{eV} \leq \omega_L \leq 3\ \text{eV}$ and due to the resonance condition $\omega_{\mathbf{p}} \simeq \frac{\ell}{2}(m_a^2 + \frac{1}{\ell^2})$ the best performance of the scheme is limited to a mass range of $6 \times 10^{-4}\ \text{eV} \leq m_a \leq 6 \times 10^{-3}\ \text{eV}$

cavity modes $\omega_n = n\pi c/L$ with $n = 1, 2, 3, \cdots$

free spectral range (FSR) $\Delta_{\text{FSR}} = \pi c/L$

$L_x \approx 1\ m$

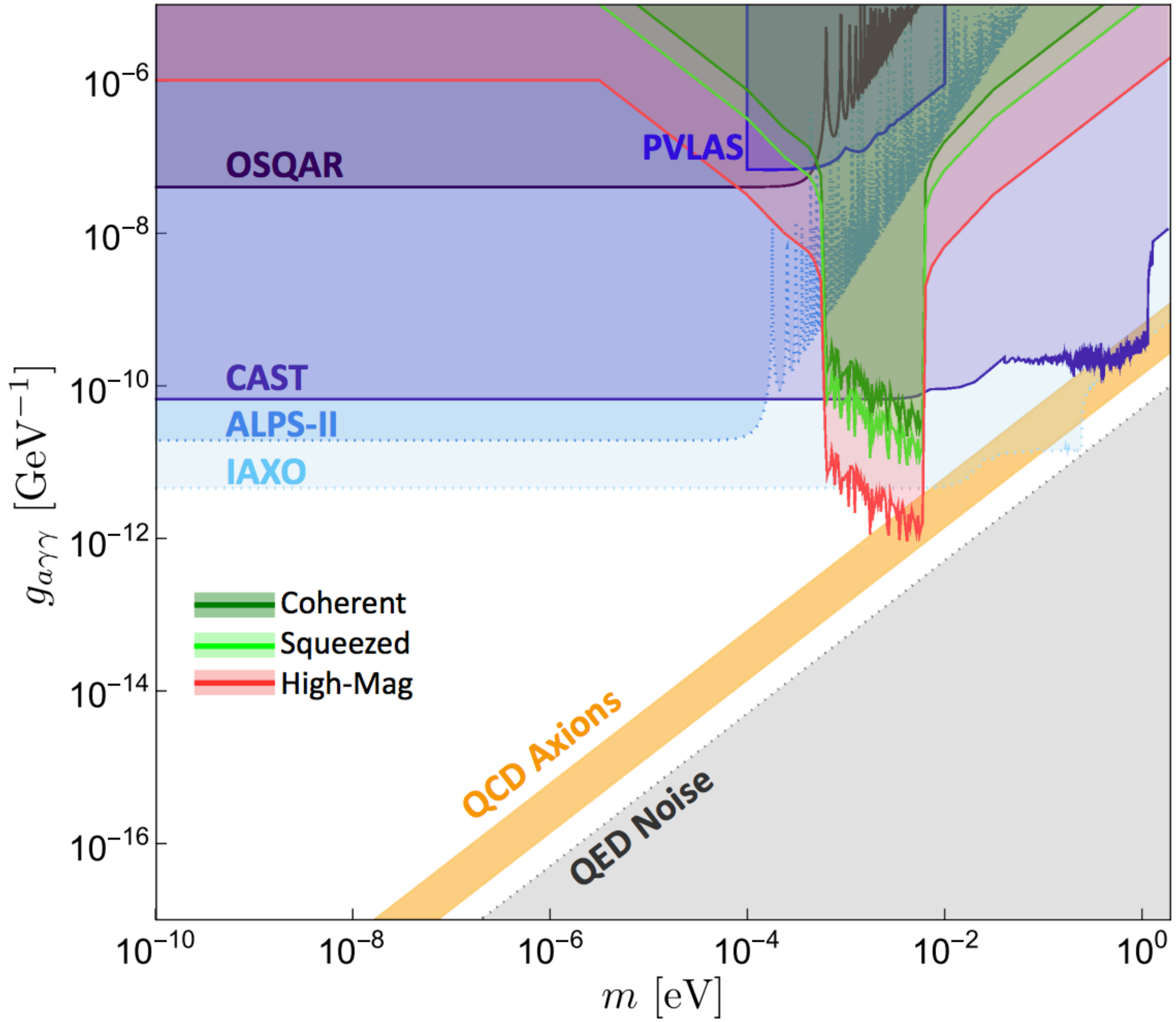
$(\Delta_{\text{FSR}} \approx 6.2 \times 10^{-7}\ \text{eV})$



The width of the cavity modes

$$\Delta\nu = \nu_{fsr}/\mathcal{F}$$

Exclusion Region Resonance Birefringence Signal



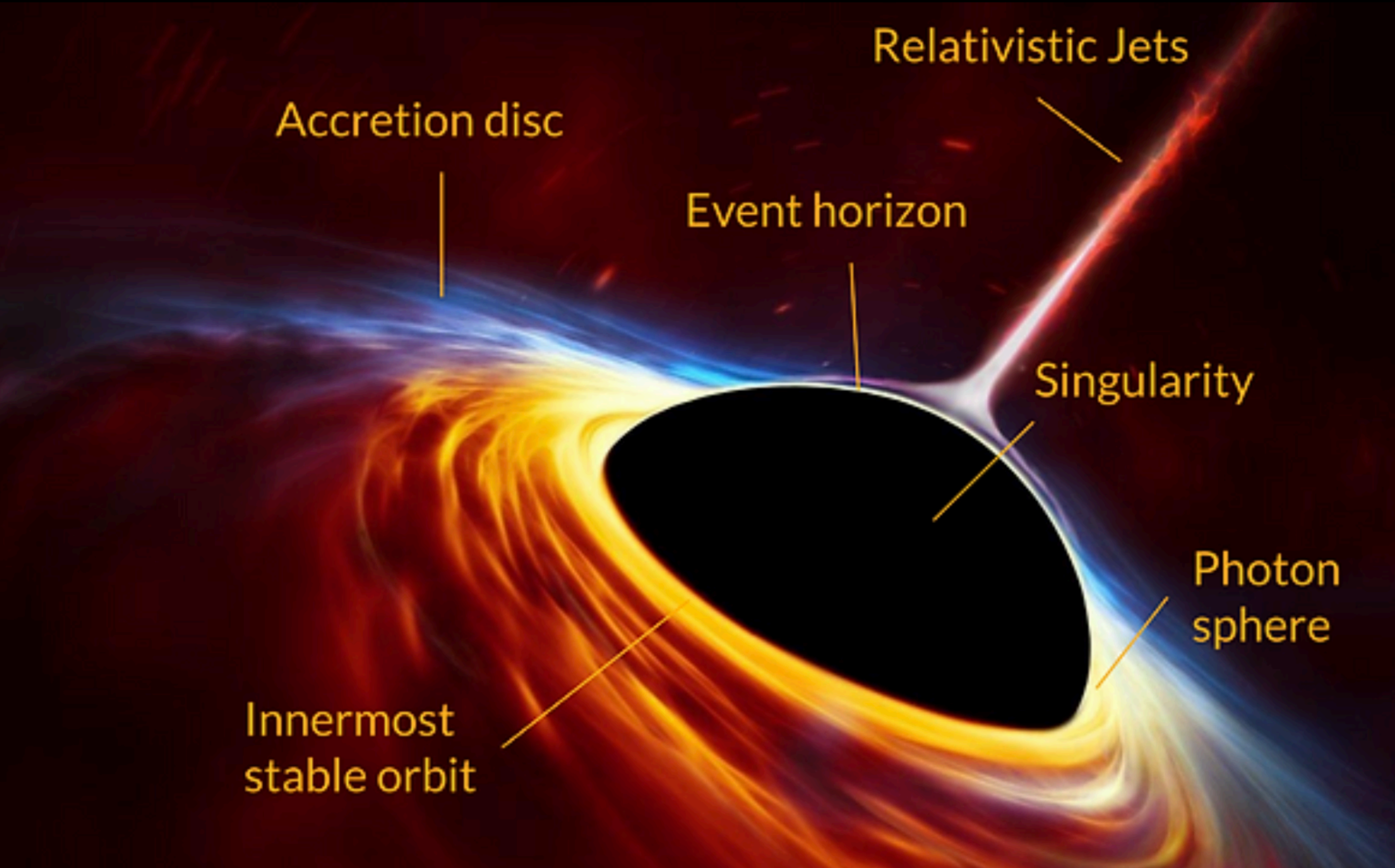
Different stages

(i) Coherent light pump and moderate magnetic fields $(B_0 = 10\ \mathrm{T})$.

(ii) Squeezed state (r = 1.73) and moderate magnetic field $(B_0 = 10\ \mathrm{T})$

(iii) Squeezed state and ultrahigh magnetic field (B_0 = 100 T).

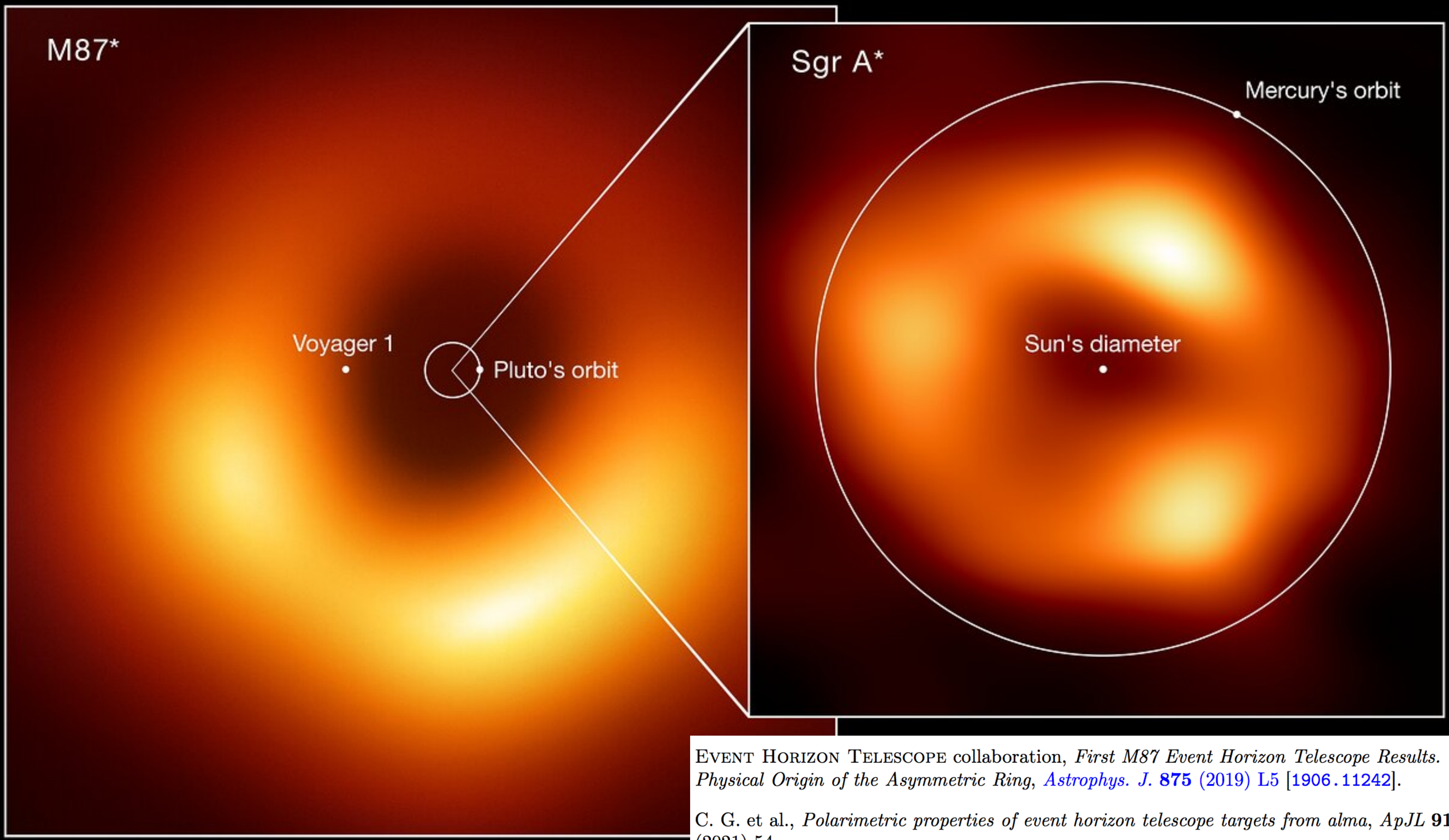
M. Zarei, S. Shakeri, M. Sharifian, M. Abdi, D. J.E. Marsh, S.Matarrese, JCAP 06 (2022) 06, 012 [arXiv:1910.09973]



Probing Axions via Light Circular Polarization and Event Horizon Telescope

S. Shakeri & F. Hajkarim [arXiv:2209.13572] 27 Sep 2022

Axion – Photon Around Supermassive Black Holes (SMBHs)

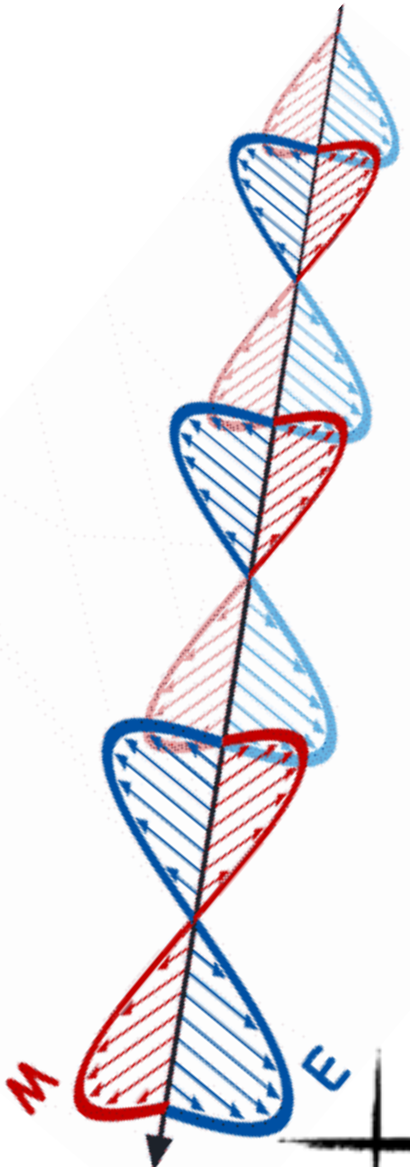


Event Horizon Telescope collaboration, *First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring*, *Astrophys. J.* **875** (2019) L5 [1906.11242].

C. G. et al., *Polarimetric properties of event horizon telescope targets from alma*, *ApJL* **910** (2021) 54.

E. C. et al., *First m87 event horizon telescope results. vii. polarization of the ring*, *ApJL* **910** (2021) 48.

E. C. et al., *First m87 event horizon telescope results. viii. magnetic field structure near the event horizon*, *ApJL* **910** (2021) 43.



Light polarization

1-Intrinsic to the emission process

2- Due to the propagation effect

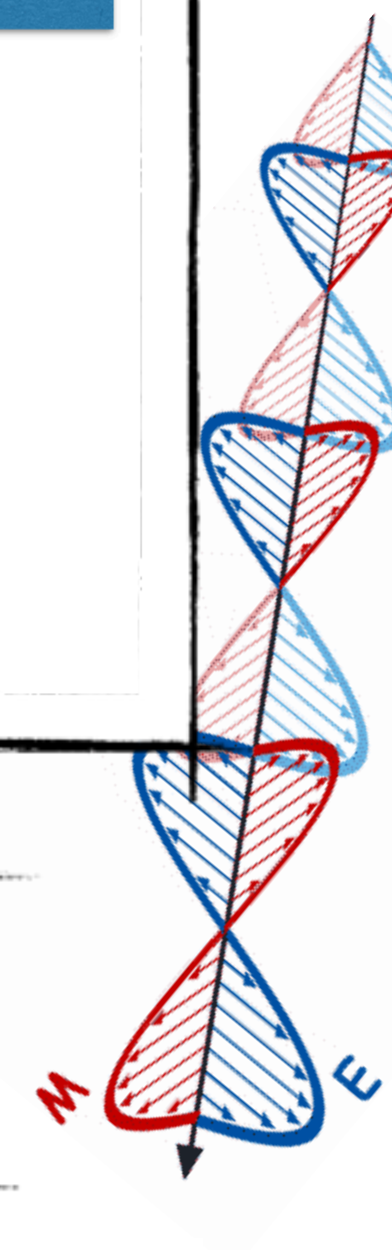
- It has known for many years ;

1-The Synchrotron emission, Bremsstrahlung, curvature radiation …(Intrinsic)

2-The Compton scattering, plasma effect,.. (propagation effect)

Can produce linear **polarization**

BUT
Usual scattering process (like usual Compton scattering) can’t produce circular polarization



Axion–Photon Interaction ←

Circular polarization can be produced by

1-Parity violating interactions

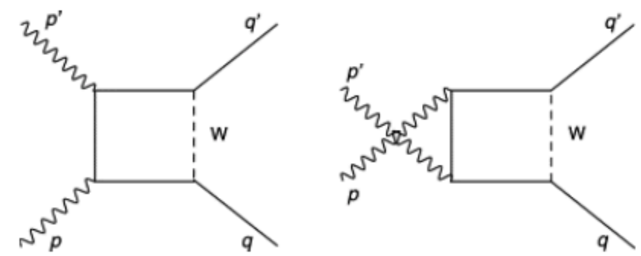
2- Intrinsic asymmetric distribution of left- and right- handed components in target beams

3-The presence of an anisotropic background in the medium

Circular Polarization Sources

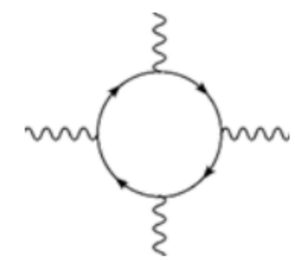
Compton scattering in a background whether the external magnetic field or noncommutative space time

Photon-neutrino interaction



Photon-photon scattering -nonlinear QED effects

Axion-photon interaction



Photon-Gravition Interaction

E. Bavarsad, M. Haghighat, Z. Rezaei, R. Mohammadi, I. Motie and M. Zarei, Generation of circular polarization of the CMB , Phys. Rev. D 81 (2010) 084035 [arXiv:0912.2993].

S. Shakeri, M. Haghighat and S.-S. Xue, Nonlinear QED effects in X-ray emission of pulsars, JCAP 10 (2017) 014 [arXiv:1704.04750] .

S. Shakeri, S.Z. Kalantari and S.-S. Xue, Polarization of a probe laser beam due to nonlinear QED effects , Phys. Rev. A 95 (2017) 012108 [arXiv:1703.10965].

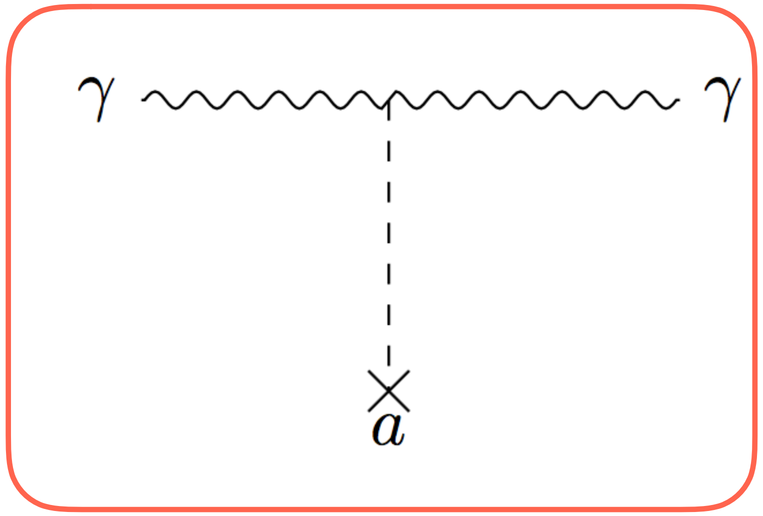
Circularly Polarized EM radiation from GW Binary Sources, S.shakeri, A. Allahyari

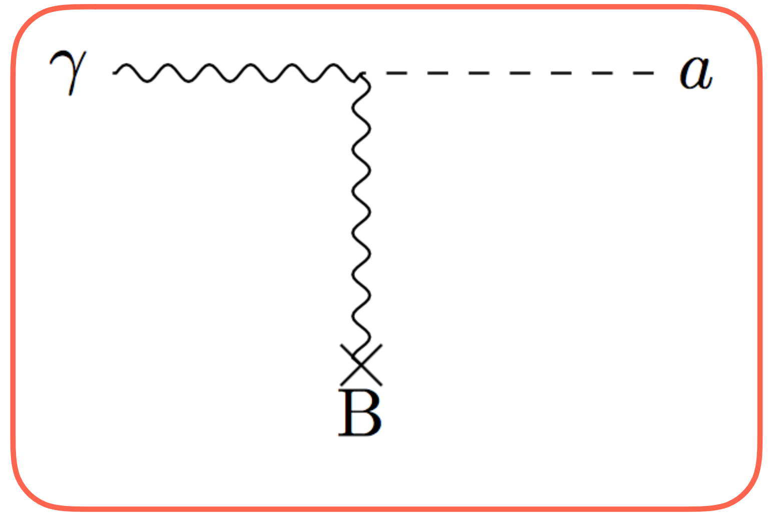
JCAP11(2018)042 [arXiv:1808.05210]

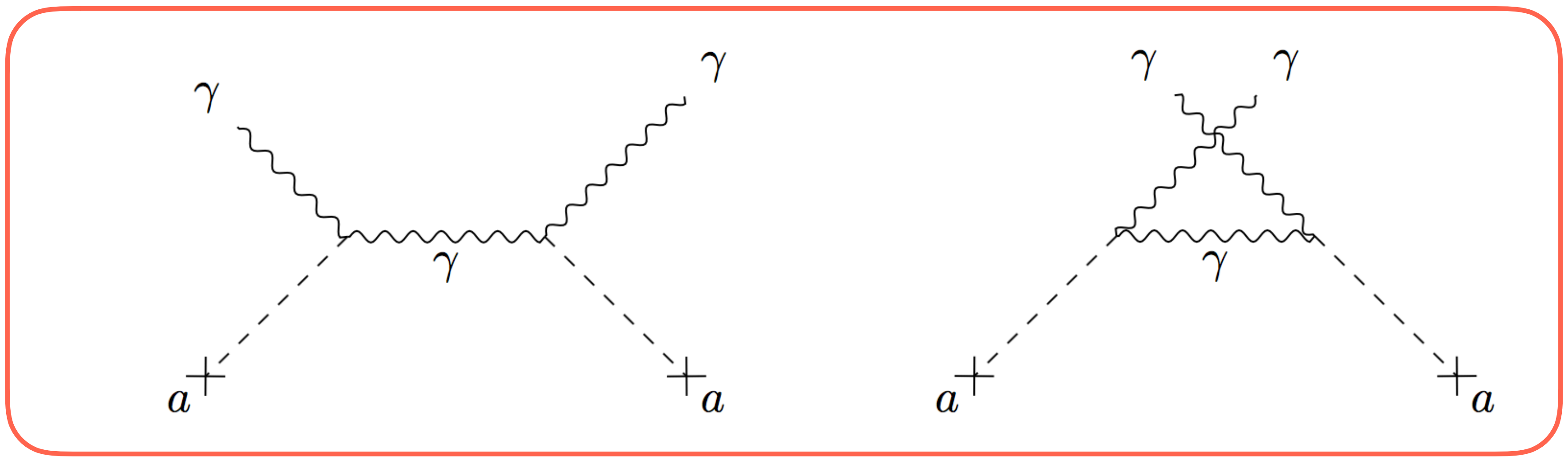
S. Shakeri, David J. E. Marsh, She-Sheng Xue, Light by Light Scattering as a New Probe for Axions[arXiv:2002.06123]

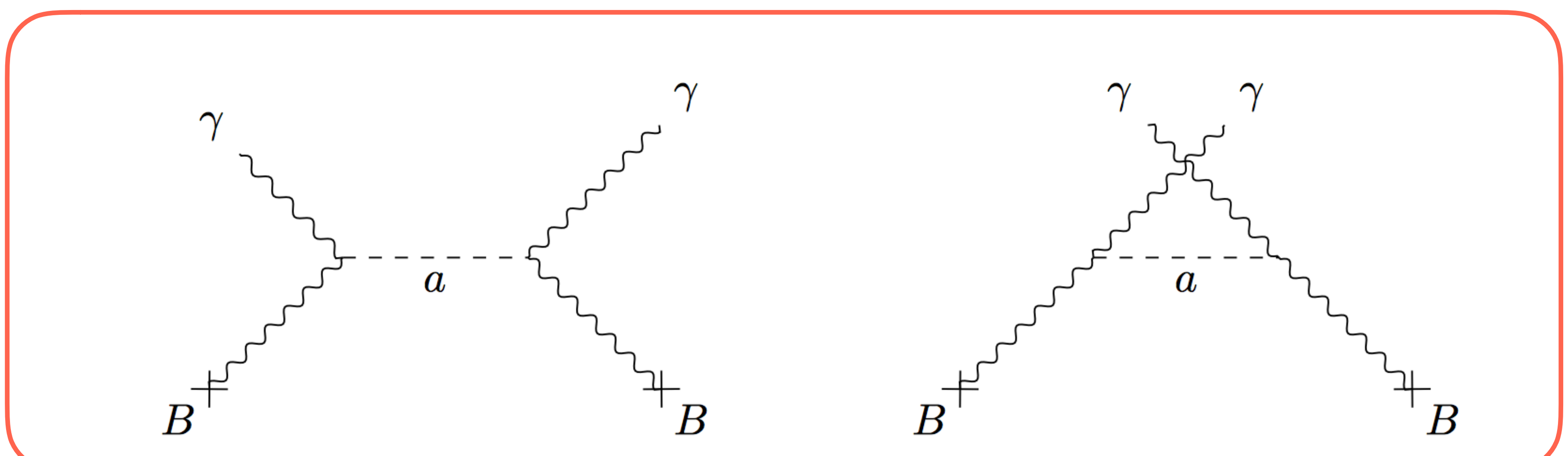
Moslem Zarei, S.Shakeri, Mohammad Sharifian, Mehdi Abdi, David J. E. Marsh, Sabino Matarrese
Probing Virtual Axion-Like Particles by Precision Phase Measurements, JCAP06(2022)012 [Arxiv:1910.09973]

We consider the Polarization effects of below processes assuming the Physical condition around SMBH M87

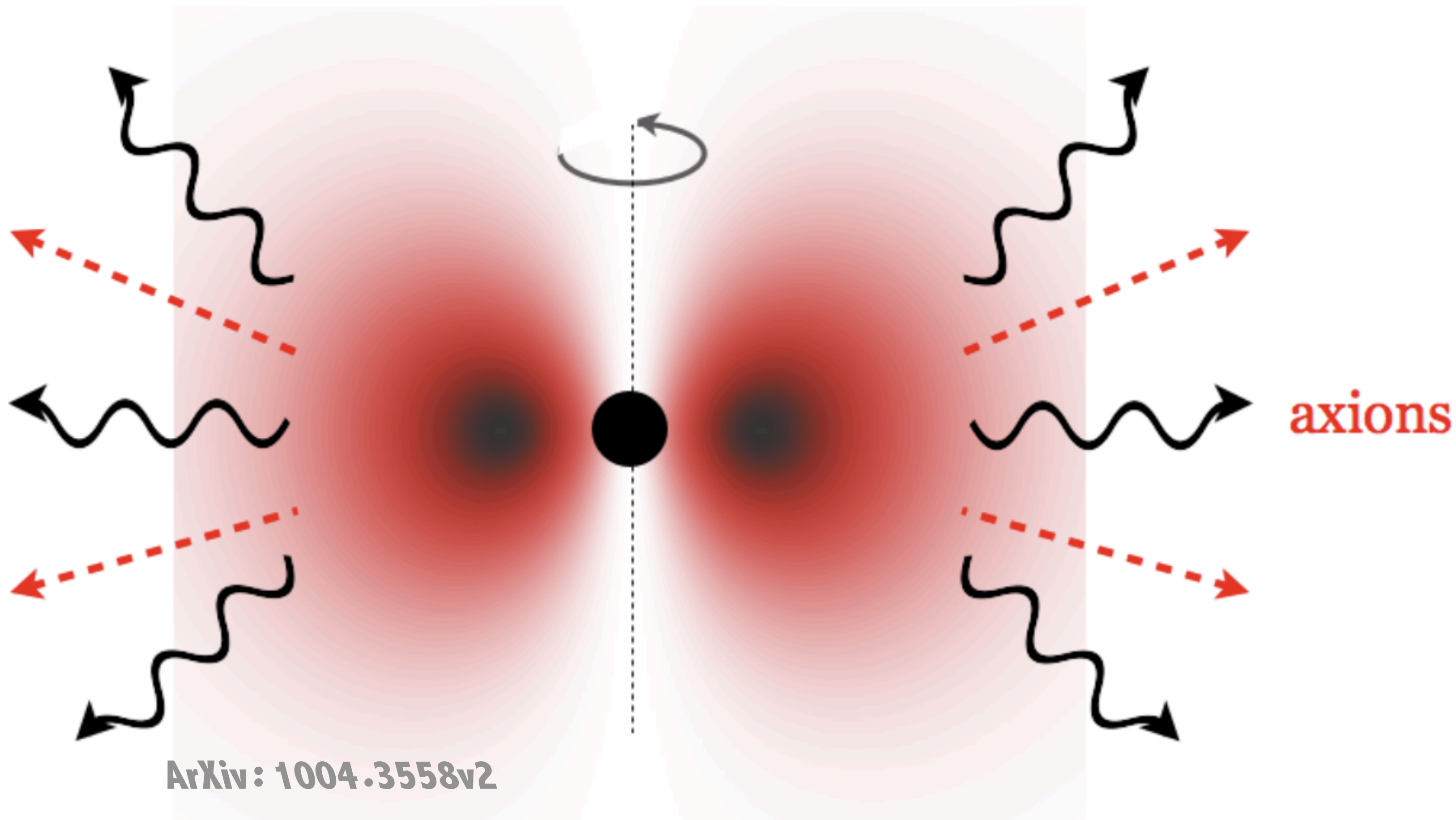








Axion Density near a SMBH



$$(\rho_{\rm DM})_{\rm max} = \frac{1}{2} m_a^2 a^2|_{\rm max} = \frac{1}{2} m_a^2 f_a^2 \approx 3.83 \times 10^{11} \left(\frac{m_a}{10^{-20}{\rm eV}}\right)^2 \left(\frac{f_a}{10^{16}{\rm GeV}}\right)^2 \left[\frac{\rm GeV}{\rm cm^3}\right]$$

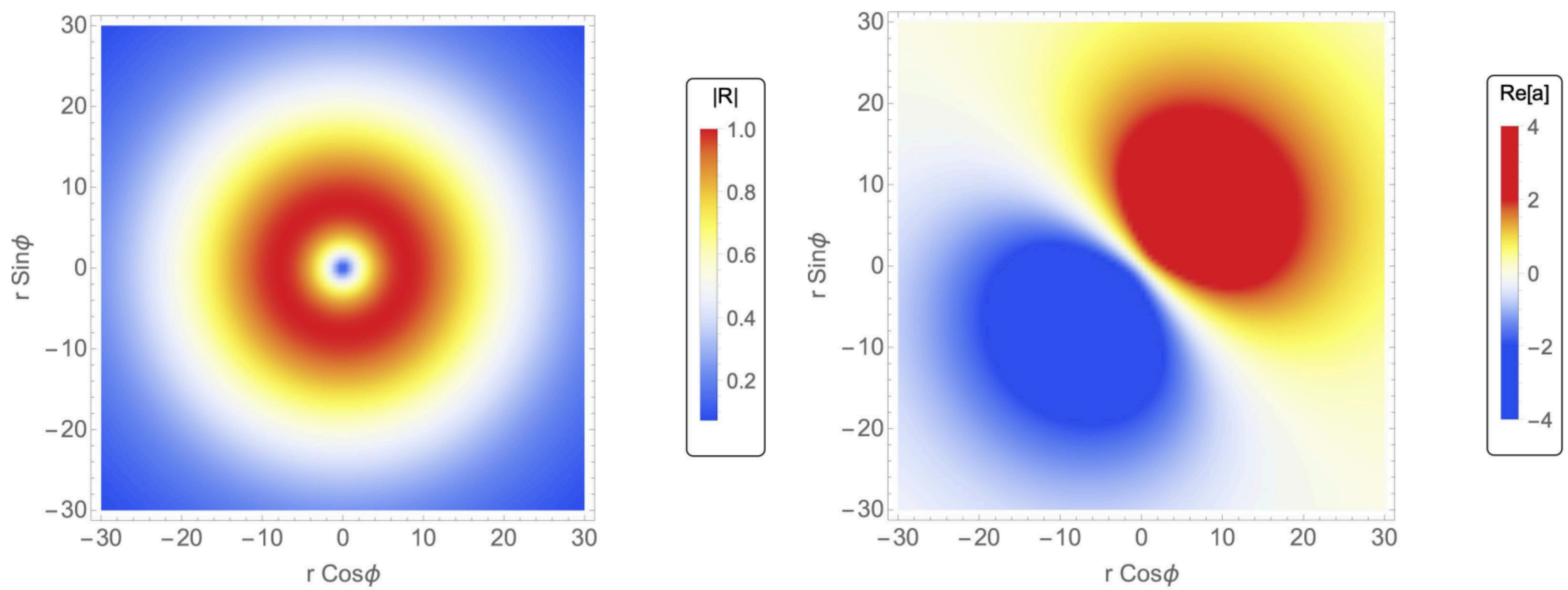
$$r_g \equiv GM_{BH} = 2.97 \times 10^{-4}{\rm pc} \left(\frac{M_{BH}}{6.2 \times 10^9 M_\odot}\right)$$

The emission region $\sim 5 r_g$

$$M_{BH} \approx 6.2 \times 10^9 M_\odot$$

The electron density $n_e \sim 10^4 \ {\rm cm}^{-3}$

Axion Field around the BH



Axion field around the black hole is shown. The left and right panels are for the radial part of axion field $|R|$ (scaled to its maximum) and its real part $\mathrm{Re}[a]$ scaled to its numerical factor at $\theta = \pi/2$ from Eqs. **(1)** and **(2)** with $l = 1$, respectively. The radial distance has been scaled to $r_{cloud} \sim 8$ which means that $M_{BH} m_a^2 = 0.25$.

$$\Box\, a = m_a^2 a$$

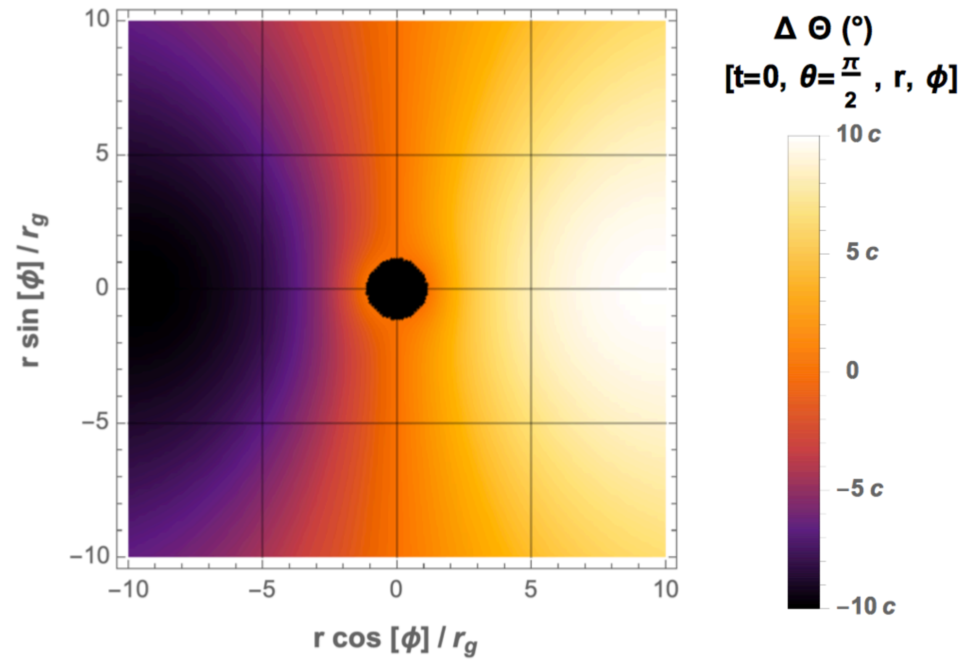
$$a(t, r, \theta, \phi) = e^{im\phi} S_{lm}(\theta) e^{-i\omega t} R_{nl}(r)\,, \qquad \textbf{(1)}$$

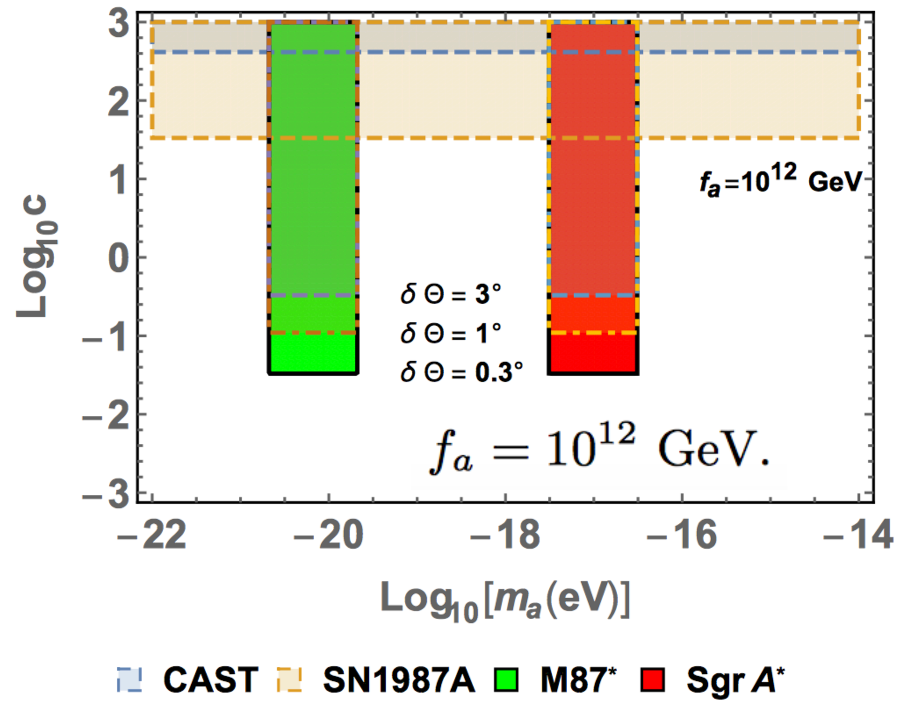
$$R_{nl}(r) = A_{nl}\mathrm{g}(\tilde{r})\,, \quad \mathrm{g}(\tilde{r}) = \tilde{r}^l e^{-\tilde{r}/2} L_n^{2l+1}(\tilde{r})\,, \quad \tilde{r} = \frac{2rM_{\mathrm{BH}}m_a^2}{l+n+1}\,. \qquad r_{cloud} \sim \frac{l+n+1}{M_{\mathrm{BH}}m_a^2}$$

$$a(t, r, \theta, \phi) = \sqrt{\frac{3M_{\mathrm{S}}}{4\pi \mathcal{I}_2 M_{\mathrm{BH}}}} (M_{\mathrm{BH}} m_a)^2 \mathrm{g}(\tilde{r}) \cos(\phi - \omega_R t) \sin\theta\,, \qquad \textbf{(2)}$$

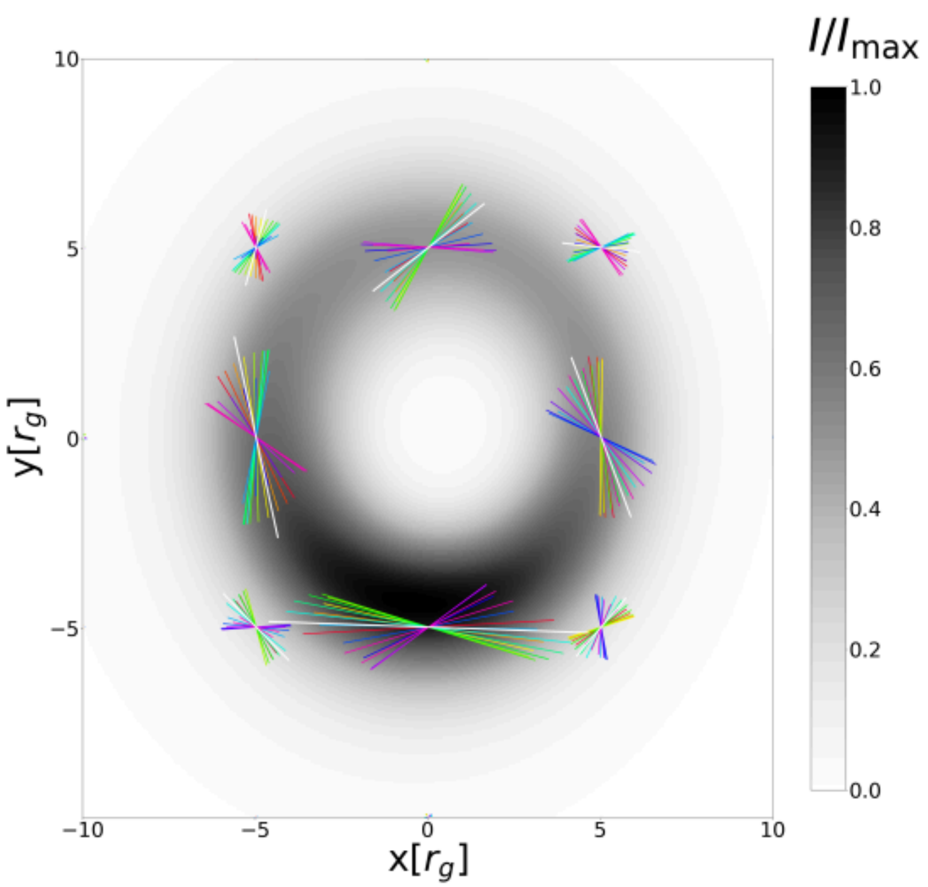
S. Shakeri and F. Hajkarim [arXiv:2209.13572]

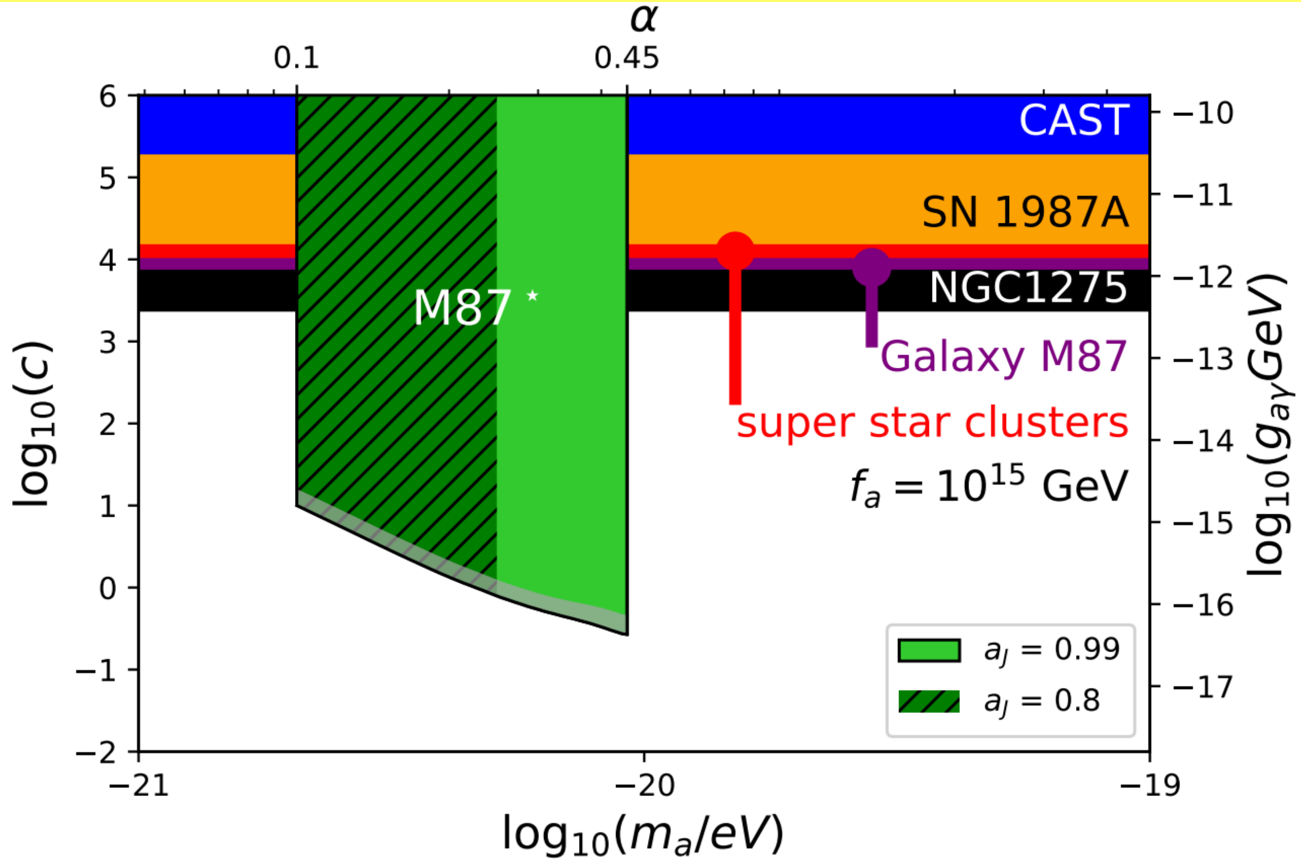
Previous Studies : Linear Polarization & Axion





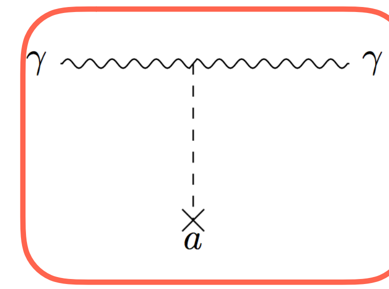
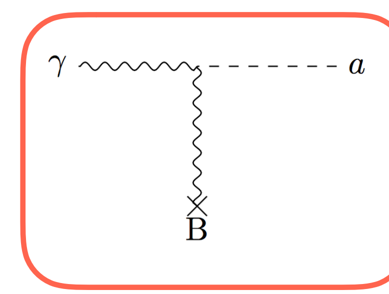
Y. Chen, J. Shu, X. Xue, Q. Yuan and Y. Zhao, Phys. Rev. Lett. 124 (2020) 061102 [1905.02213]





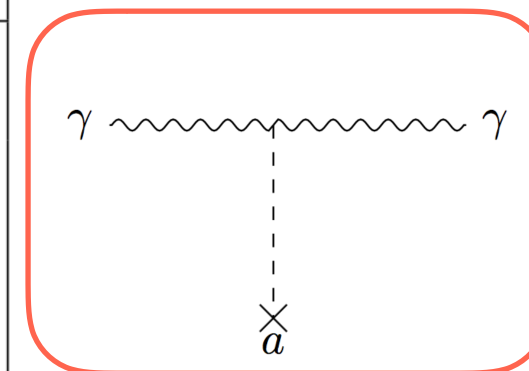
Y. Chen, Y. Liu, R.-S. Lu, Y. Mizuno, J. Shu, X. Xue et al. Nature Astron. 6 (2022) 592 [2105.04572]

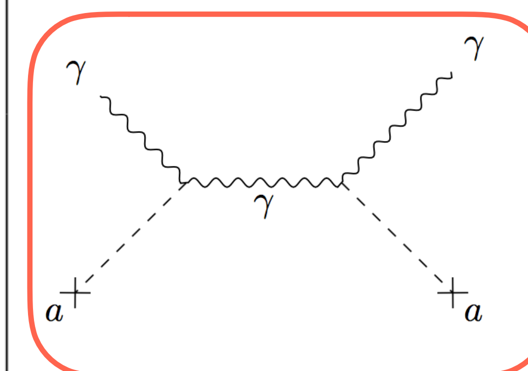
Polarization Angle Δψ of Linearly Polarized Emission

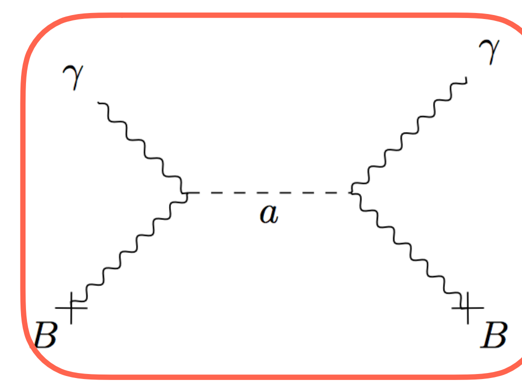
Physical Process	The Axion Polarization Angle
Propagation of Photons in an Axion Background	$\Delta\psi = g_{a\gamma}\Delta a\left(\vec{r}, t\right)$ 
Axion-photon Conversion in a Magnetic Field	$\Delta\psi = \frac{1}{4}P_{\gamma\to a}\sin 2c$ 

Sources of Circular Polarization

Physical Process	Form of the Axion Polarization Term
Axion Induced Propagation Effect	$\Pi_V = \frac{2\pi g_{a\gamma}\dot{a}}{\omega_\gamma} + \mathcal{O}(g_{a\gamma}^2)$
Scattering of Photon from Axion	$\Pi_V = 8 g_{a\gamma}^2 a_0^2 \frac{\omega_\gamma}{m_a^2 - 4\omega_\gamma^2} \left(\mathbf{p}_x^2 + \mathbf{p}_y^2\right) r$
Photon Scattering from a Magnetic Field	$\Pi_V = \frac{\omega_\gamma g_{a\gamma}^2}{m_a^2} \left(B_x^2 + B_y^2\right) r$

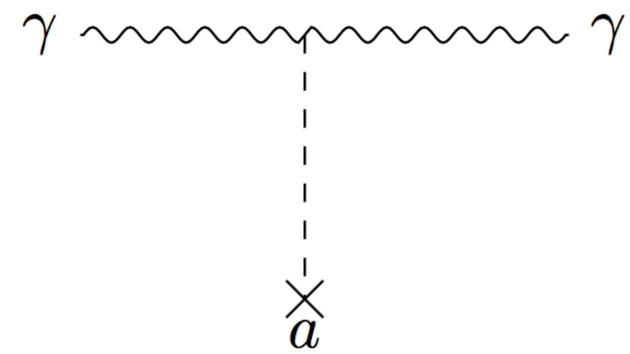






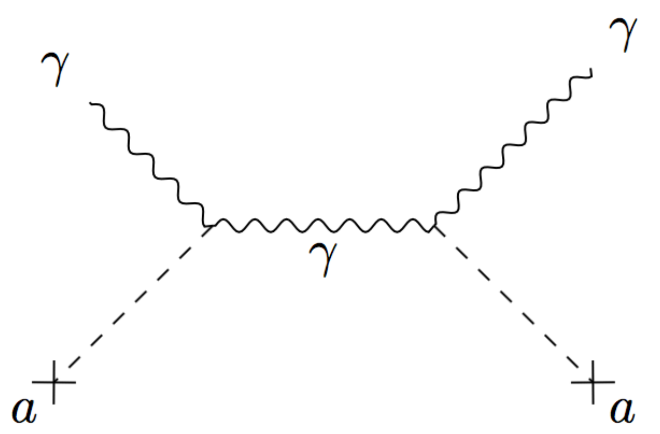
Axion Induced Circular Polarization

$$\Pi_{\rm V} \equiv \frac{V}{I} \equiv \frac{|\dot{A}_+|^2 - |\dot{A}_-|^2}{|\dot{A}_+|^2 + |\dot{A}_-|^2} = \frac{1}{2}(\omega_+^2 - \omega_-^2) \simeq \frac{2\pi g_{a\gamma}\dot{a}}{\omega_\gamma} + \mathcal{O}(g_{a\gamma}^2)$$



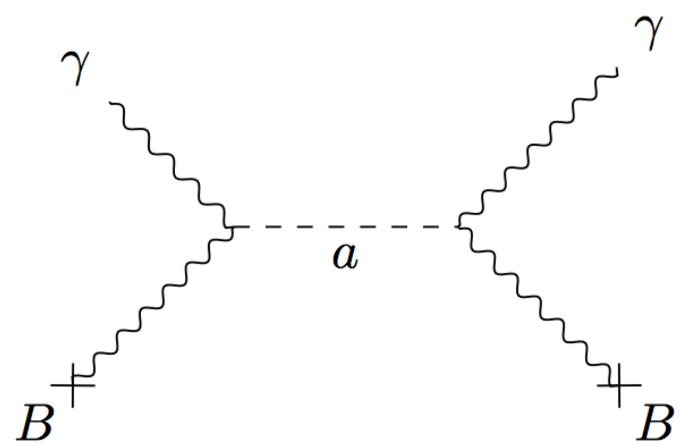
$$\Pi_{\rm V} = \frac{2\pi g_{a\gamma}\dot{a}}{\omega_\gamma} = 5.41 \times 10^{-19}\, c_{a\gamma} \left(\frac{m_a}{10^{-20}{\rm eV}}\right) \left(\frac{230{\rm GHz}}{\nu_\gamma}\right) \sin(\phi - m_a t) \sin\theta\,,$$

$$\Pi_{\rm V} \equiv \frac{|V|}{I} = |\sin(\Omega t)| \approx |\Omega| t = 4.94 \times 10^{-25} c_{a\gamma}^2 \left(\frac{r}{r_g}\right)$$



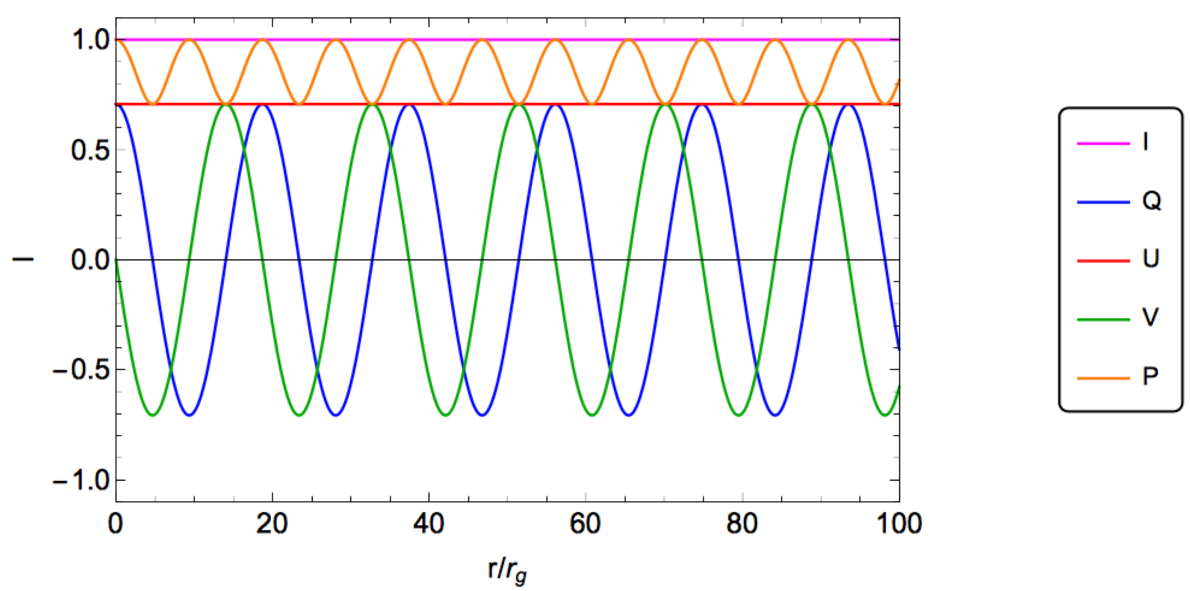
$$\Omega \approx 1.62 \times 10^{-30} c_{a\gamma}^2 \left(\frac{m_a}{10^{-20}{\rm eV}}\right)^2 \left(\frac{230{\rm GHz}}{\nu_\gamma}\right) s^{-1}$$

Dominant Contribution of Circular Polarization



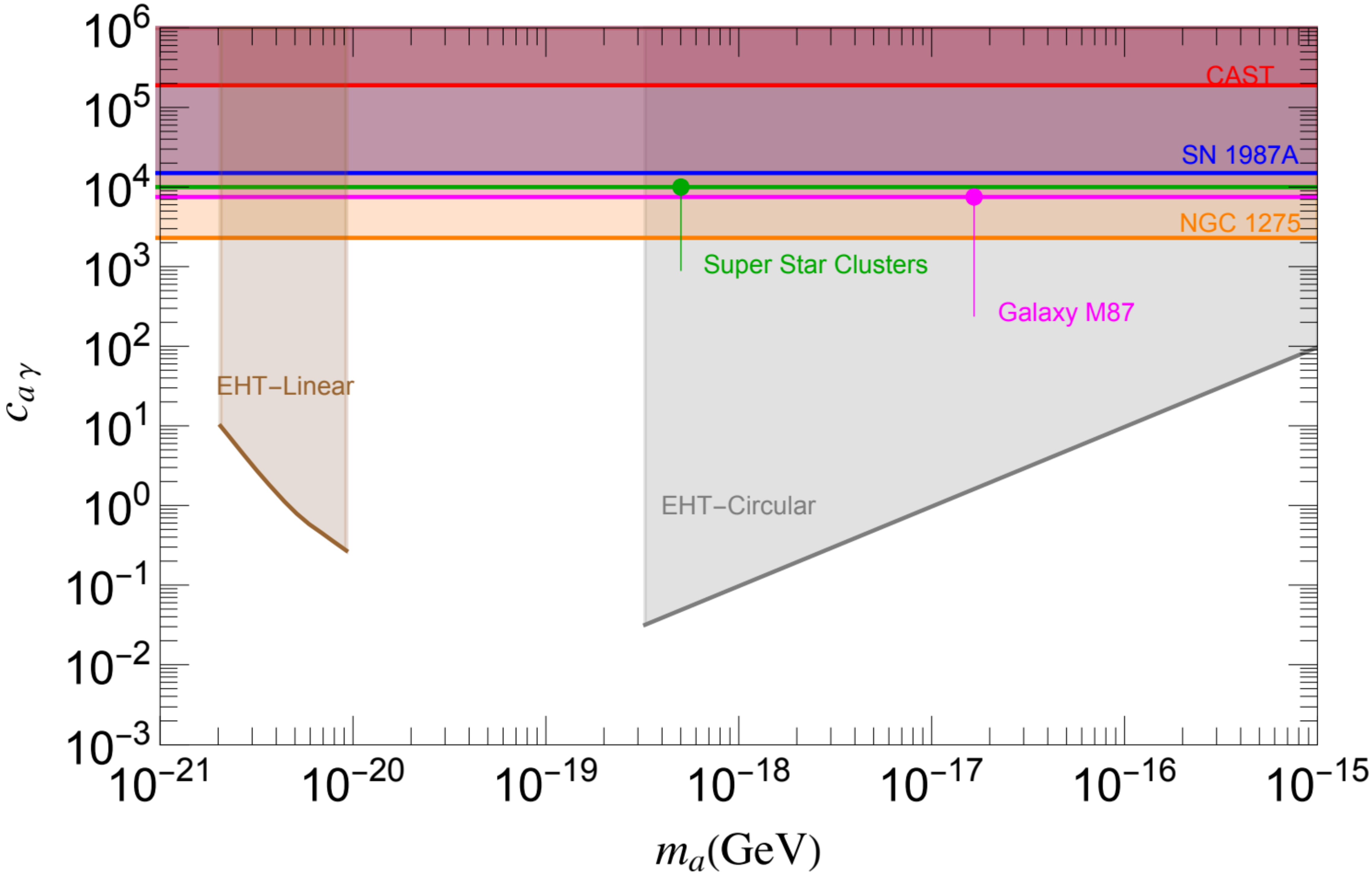
$$\Pi_{\rm V} \equiv \frac{|V|}{I} = |\sin(\Omega t)| \approx |\Omega| t = 0.85 \left(\frac{c_{a\gamma}}{0.1}\right)^2 \left(\frac{\nu_\gamma}{230\rm GHz}\right) \left(\frac{10^{-19}\rm eV}{m_a}\right)^2 \left(\frac{B_0}{1\rm G}\right)^2 \left(\frac{r}{r_g}\right)$$

From ALMA data we have only a conservative upper bound on the measurement of the circular polarization of M87* at 230 GHz which is around **0.8%**



The initial conditions are $I_0 = 1$, $Q_0 = 1/\sqrt{2}$, $U_0 = 1/\sqrt{2}$ and $V_0 = 0$.

Bound Obtain from Circular Polarization of Light from M87



S. Shakeri & F. Hajkarim [arXiv:2209.13572] 27 Sep 2022


Thank you for
your attention