PROBING CP-VIOLATING PHOTON-PHOTON INTERACTIONS IN CAVITIES

ICHEP 2020

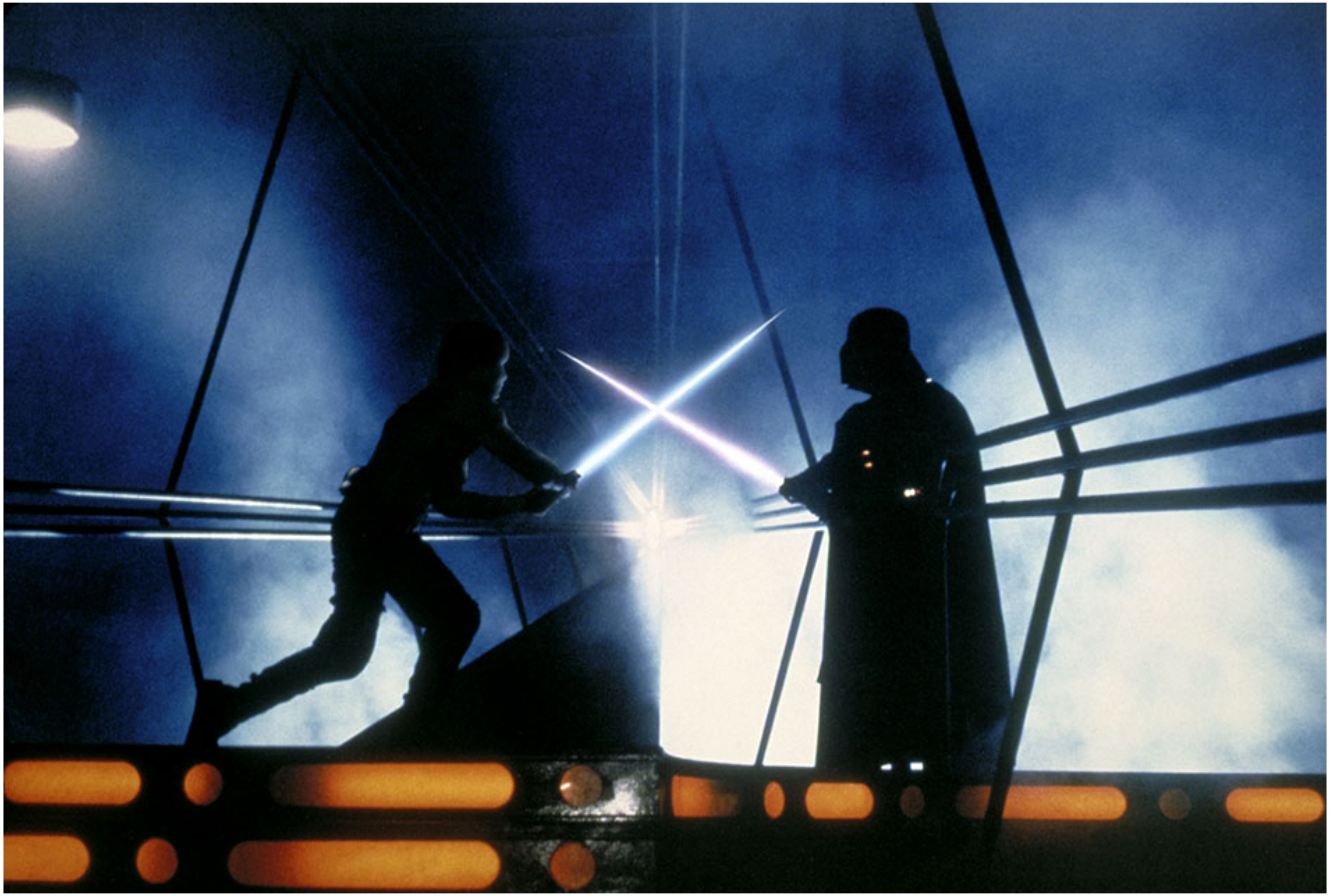
INBAR SAVORAY

WEIZMANN INSTITUTE OF SCIENCE

IN COLLABORATION WITH: M. GORGHETTO, G. PEREZ, Y. SOREQ

PHOTON-PHOTON INTERACTIONS - MOTIVATION

PHOTON-PHOTON INTERACTIONS - MOTIVATION



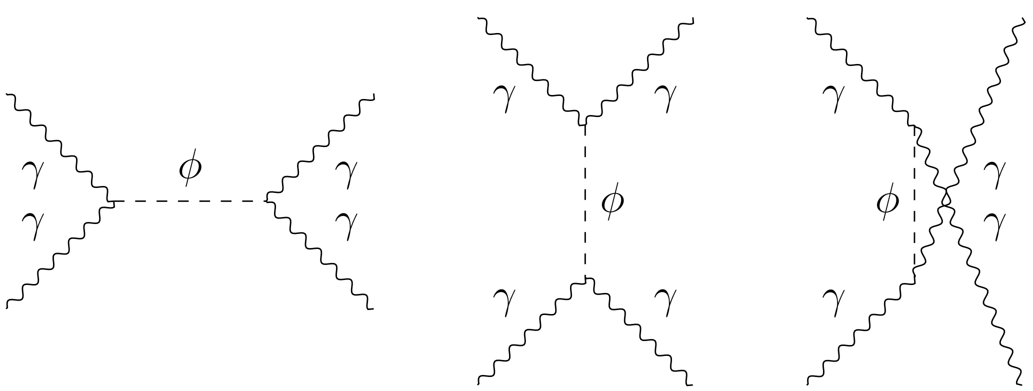
PHOTON-PHOTON INTERACTIONS – MOTIVATION

- The relaxion has both CP-even and CP-odd couplings to photons

$$\mathscr{L}_{\phi\gamma} = -\frac{1}{4} g\phi F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{g}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} .$$

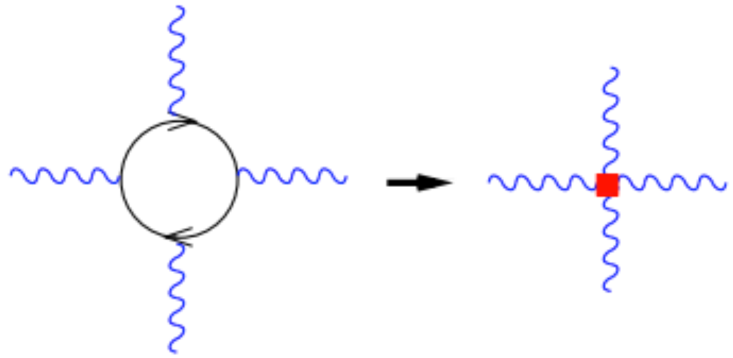
- Could generate effective CPV photon-photon interactions.

$$\mathscr{L}^{\text{eff}}_{\phi\gamma} = \frac{g^2}{32m_\phi^2}\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{\tilde{g}^2}{32m_\phi^2}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2 + \frac{g\tilde{g}}{16m_\phi^2}F_{\rho\sigma}F^{\rho\sigma}F_{\mu\nu}\tilde{F}^{\mu\nu} .$$



- **Within the SM** -
  - CP-conserving - Euler-Heisenberg

$$\mathscr{L}_{EH} = \frac{2\alpha^2}{45m_e^4}\left(4\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + 7\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right) .$$



  - CP-violating - from θ_{QCD} - suppressed by 20 orders of magnitude.

R. Millo and P. Faccioli, PHYSICAL REVIEW D 79, 065020 (2009)

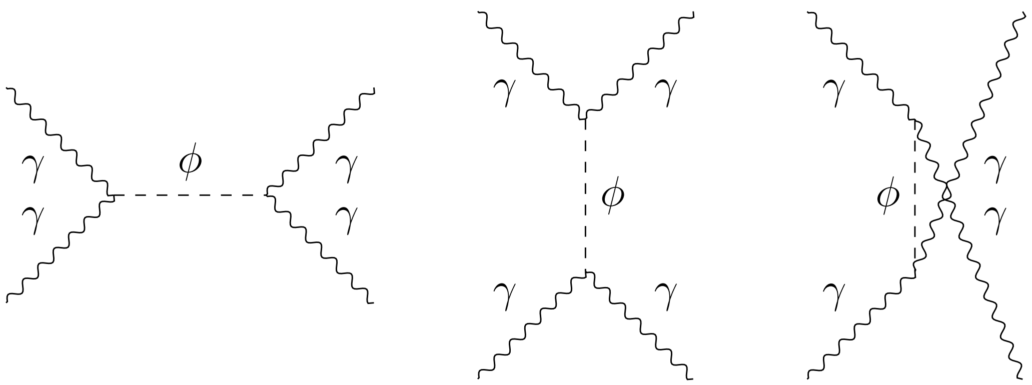
PHOTON-PHOTON INTERACTIONS - MOTIVATION

- The relaxion has both CP-even and CP-odd couplings to photons

$$\mathscr{L}_{\phi\gamma} = -\frac{1}{4} g\phi F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{g}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} .$$

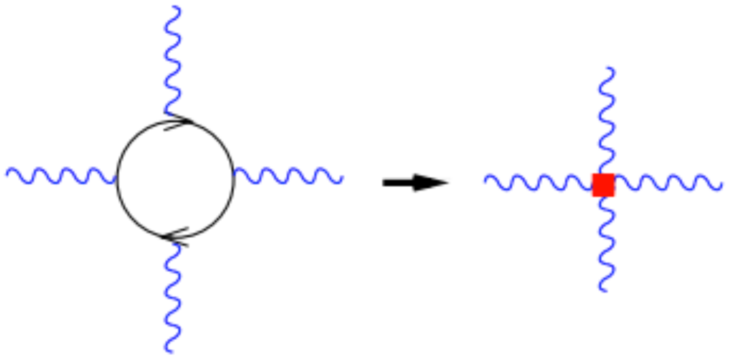
- Could generate effective CPV photon-photon interactions.

$$\mathscr{L}^{eff}_{\phi\gamma} = \frac{g^2}{32m_\phi^2}\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{\tilde{g}^2}{32m_\phi^2}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2 + \frac{g\tilde{g}}{16m_\phi^2} F_{\rho\sigma}F^{\rho\sigma}F_{\mu\nu}\tilde{F}^{\mu\nu} .$$



- **Within the SM** -
  - CP-conserving - Euler-Heisenberg

$$\mathscr{L}_{EH} = \frac{2\alpha^2}{45m_e^4}\left(4\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + 7\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right) .$$



  - CP-violating - from θ_{QCD} - suppressed by 20 orders of magnitude.

CPV photon-photon interactions could probe BSM physics

EXPERIMENTAL CONSTRAINTS

- **High energies** - Light-by-Light scattering at $m_{\gamma\gamma} \sim GeV$
  - LHC with heavy ions $\sigma_{\gamma\gamma\to\gamma\gamma} \approx 1.53 - 1.73\ \sigma^{SM}_{\gamma\gamma\to\gamma\gamma}$
- **Low energies** - constraints on the effective operators

$$\mathscr{L}_8^{\text{eff}} = \alpha_1 \left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \alpha_2 \left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2 + \alpha_3 F_{\rho\sigma}F^{\rho\sigma}F_{\mu\nu}\tilde{F}^{\mu\nu}\,.$$

  - Direct measurements only of CPC operators!
    - Lamb Shift $\alpha_1 \lesssim 10\,\alpha_1^{EH}$
    - Vacuum Birefringence (PVLAS) $-30\,\alpha_1^{EH} \lesssim \alpha_2 - \alpha_1 \lesssim 50\,\alpha_1^{EH}$
  - CPV is constrained by EFT consistency - causality/unitarity

$$\alpha_3^2 \leq 4\alpha_1\alpha_2$$

No direct experimental measurement of low-energy photon CPV

ATLAS, [1904.03536] G. Remmen and N. Rodd , [1908.09845] M. Fouche et al, [1605.04102]

SUPERCONDUCTING RADIO FREQUENCY (SRF) CAVITIES

NON-LINEAR ELECTRODYNAMICS IN A CAVITY

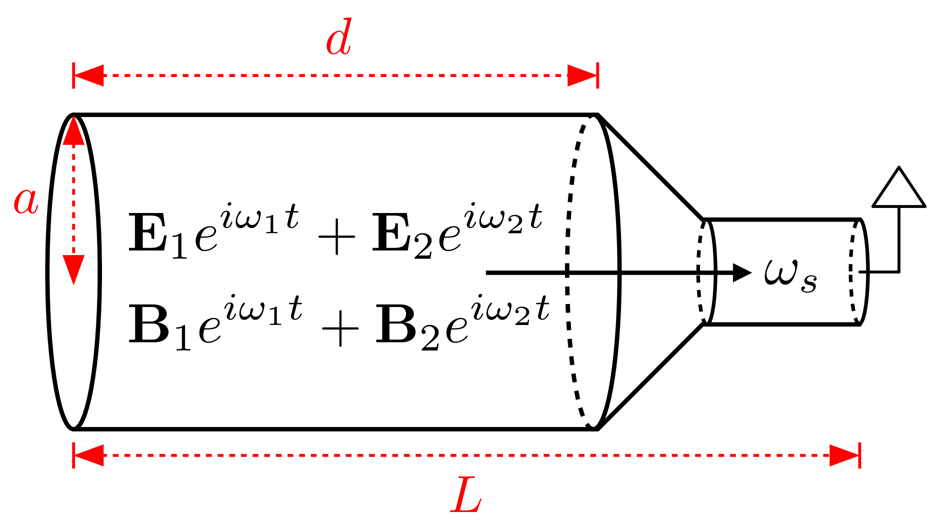
- Start with pump fields - eigenmodes of the cavity

$$\vec{E}_p = \vec{E}_1(x)\sin(\omega_1 t) + \vec{E}_2(x)\sin(\omega_2 t)\,,\ \vec{B}_p = \vec{B}_1(x)\cos(\omega_1 t) + \vec{B}_2(x)\cos(\omega_2 t)$$

- **Nonlinear Maxwell's equations -** pump fields self-interactions as an effective current-

$$\partial_\nu F^{\mu\nu} \approx -J^\mu_\phi(F_p^3)$$

- **Generate a new field** - cubic in the background fields



$$\vec{E}_{NL} \propto \frac{Q}{2\pi\omega}\vec{J}_{NL}(F_p^3)$$

$$\omega_{E_{NL}} = \omega_1, \omega_2, \pm 2\omega_1 \pm \omega_2, \pm \omega_1 \pm 2\omega_2, 3\omega_1, 3\omega_2$$

NON-LINEAR ELECTRODYNAMICS IN A CAVITY

- **Non-linear effects are enhanced** if the self-interactions of the pump fields **excite another resonance mode** of the cavity Es.
  - **Spatial overlap -**

$$E^{s}_{NL} = \frac{Q}{\omega_s}\hat{E}_s \frac{1}{V}\int d^3x \overrightarrow{J}_{NL} \cdot \hat{E}_s$$

  - **Frequency matching -** set the cavity dimensions to match the frequency of E^{s}_{NL} to the eigenfrequency of the resonance mode

$$\omega_s \stackrel{!}{=} \omega_{E^{s}_{NL}} = 2\omega_1 \pm \omega_2 / 2\omega_2 \pm \omega_1 / 3\omega_1 / 3\omega_2$$

Eriksson et al., [physics/0411054]

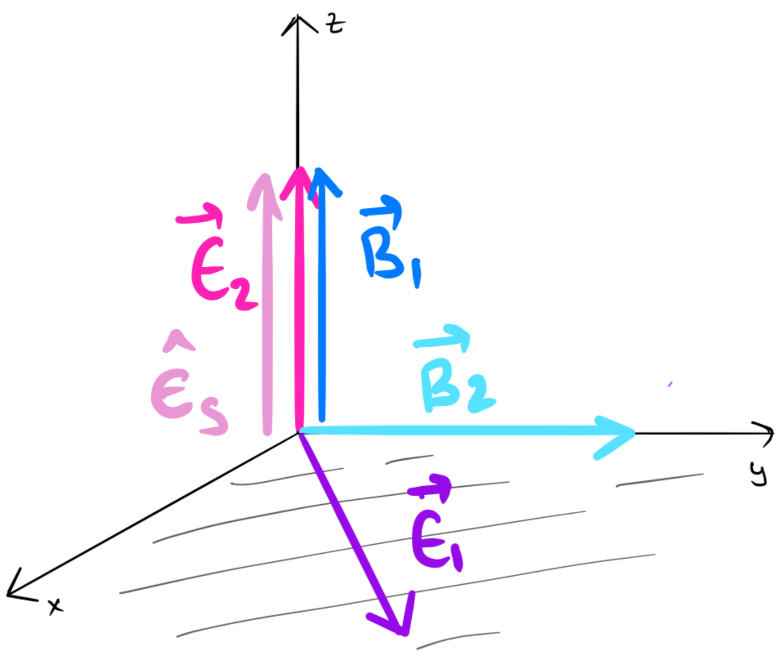
Bogorad et al, [1902.01418]

IDENTIFYING AND ISOLATING CPV INTERACTIONS

- Choose pump & signal modes -

scalar - $F^2 = \frac{1}{2}(E_1^2 + E_2^2 - B_1^2 - B_2^2)$

pseudoscalar - $F\tilde{F} = (\vec{E}_1 \cdot \vec{B}_2 + \vec{E}_2 \cdot \vec{B}_1)$



- The new field in the direction of E2 -
  - **CPV part**

$$\left(\vec{E}_{NL} \cdot \hat{E}_s\right)_{CPV} \propto g\tilde{g}\vec{B}_1 \cdot \hat{E}_2 \partial_t \left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right) + \ldots$$

  - **CPC part**

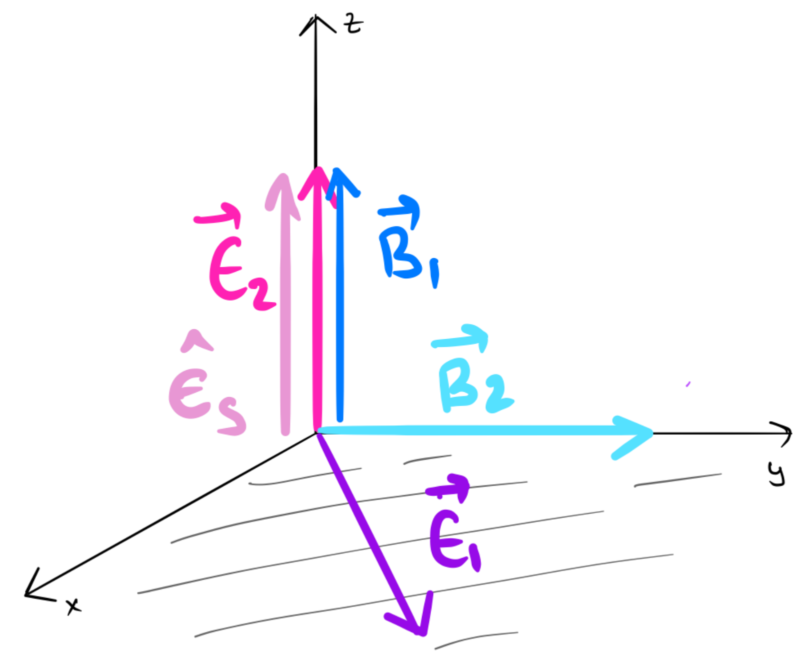
$$\left(\vec{E}_{NL} \cdot \hat{E}_s\right)_{CPC} \propto g^2\vec{E}_2 \cdot \hat{E}_2 \partial_t \left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right) + \ldots$$

IDENTIFYING AND ISOLATING CPV INTERACTIONS

- Choose pump & signal modes -

scalar - $F^2 = \frac{1}{2}(E_1^2 + E_2^2 - B_1^2 - B_2^2)$

pseudoscalar - $F\tilde{F} = (\vec{E}_1 \cdot \vec{B}_2 + \vec{E}_2 \cdot \vec{B}_1)$



- The new field in the direction of E2 -
  - **CPV part**

$\omega_{CPV} = \pm n_{odd}\omega_1 \pm n_{even}\omega_2$

$$\left(\vec{E}_{NL} \cdot \hat{E}_s\right)_{CPV} \propto g\tilde{g}\vec{B}_1 \cdot \hat{E}_2 \partial_t \left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right) + \ldots$$

  - **CPC part**

$\omega_{CPC} = \pm n_{odd}\omega_2 \pm n_{even}\omega_1$

$$\left(\vec{E}_{NL} \cdot \hat{E}_s\right)_{CPC} \propto g^2\vec{E}_2 \cdot \hat{E}_2 \partial_t \left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right) + \ldots$$

Can set cavity geometry s.t only CPV field matches a resonance!

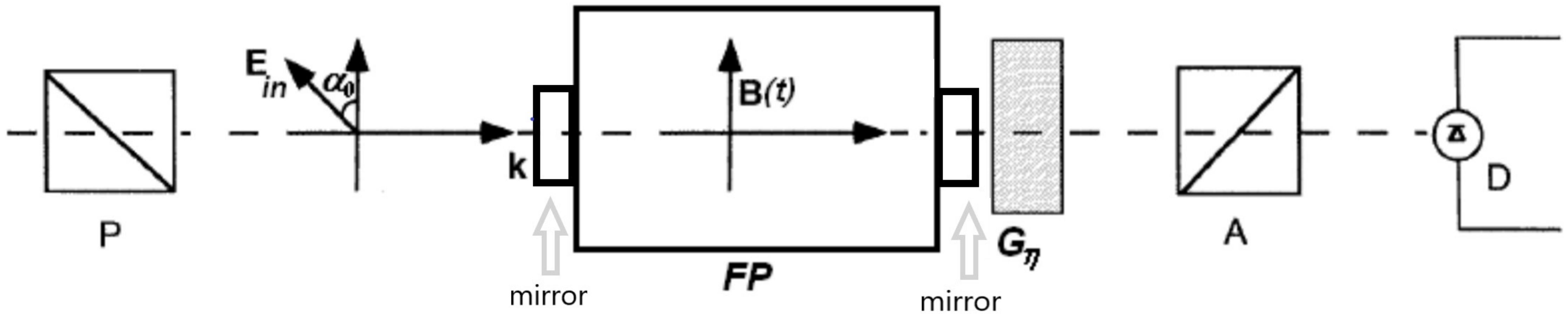
BIREFRINGENCE IN FABRY-PEROT CAVITIES

VACUUM BIREFRINGENCE

- Modified dispersion relation in the presence of a background magnetic field - **non-isotropic vacuum refractive index**

$$\begin{pmatrix} \omega^2 - k^2 & 0 & \pm\omega B\tilde{g} \\ 0 & \omega^2 - k^2 & gB\omega \\ \pm\omega B\tilde{g} & gB\omega & \omega^2 - k^2 - m_\phi^2 \end{pmatrix} \begin{pmatrix} A_\perp \\ A_\parallel \\ \phi \end{pmatrix} = 0$$

- **Induced ellipticity of a probe beam -** if not in an eigenstate (eigen-polarization) of propagation (similarly to neutrino/flavor oscillations)



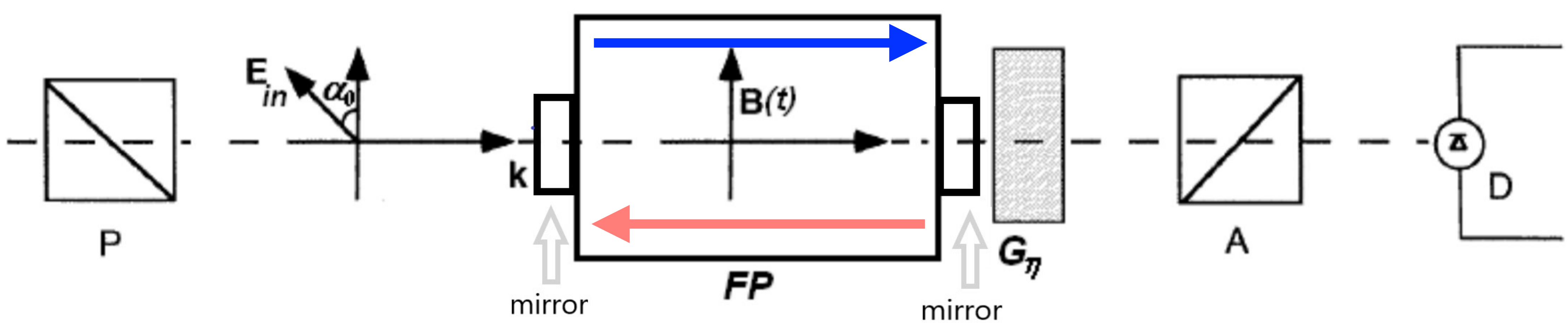
Y. Liao, 0704.1961 J. Redondo, 0807.4329.

CPV VACUUM BIREFRINGENCE

- Signal grows linearly with length of interaction region.
- **PVLAS** - Fabry-Perot cavity - probe laser bounces back and forth between two mirrors - enhancement by $F \sim 10^5$.
- CPV and CPC interactions -

$$\Psi^{CPC}_{\rm EFT} = 8(\alpha_2 - \alpha_1)\omega L B^2 \sin 2\alpha_0, \qquad \Psi^{CPV}_{\rm EFT} = \mp\, 8\alpha_3 \omega L B^2 \cos 2\alpha_0$$

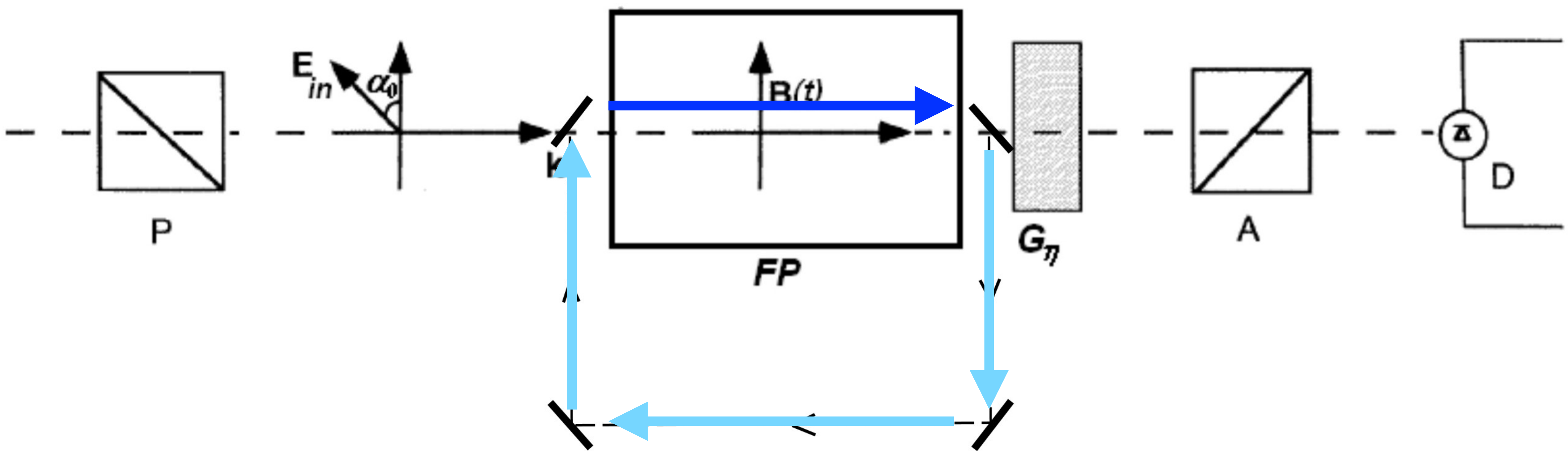
- **CPV accumulated phase cancels out in a round trip!**



PVLAS is insensitive to CPV light-by-light interactions!

PVLAS WITH A RING CAVITY

- **A solution - a ring cavity**, phase is accumulated on one side.



- **Separating CPV and CPC interactions** - modulation by a rotating magnetic field.

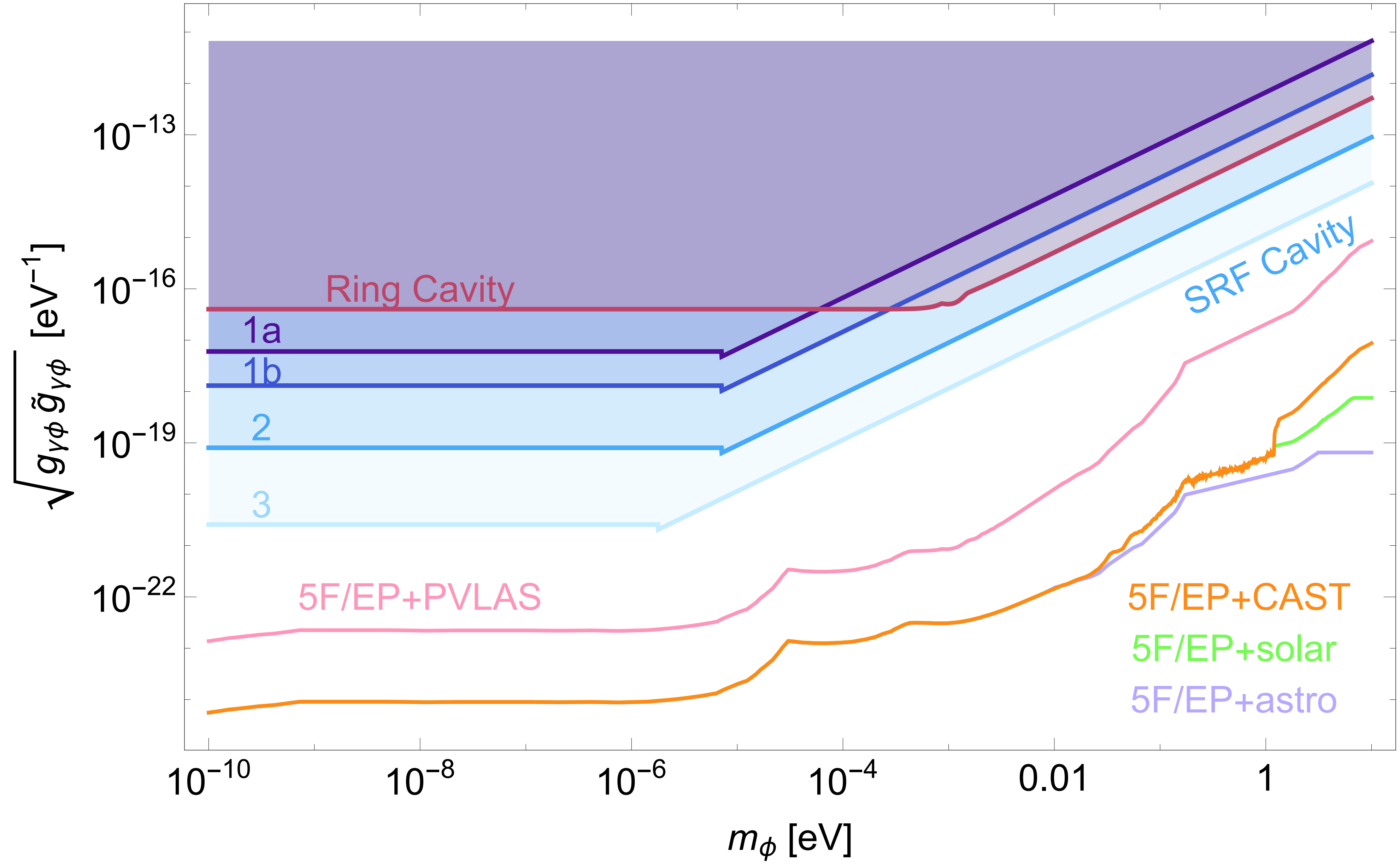
$$\Psi^{CPC}_{\text{EFT}} = 8(\alpha_2 - \alpha_1)\omega L B^2 \sin(2\alpha_0 + \omega_B t), \qquad \Psi^{CPV}_{\text{EFT}} = -8\alpha_3 \omega L B^2 \cos(2\alpha_0 + \omega_B t)$$

CPV and CPC signals can be disentangled by a temporal analysis of the beam intensity.

RESULTS

EXPERIMENTAL PROBE - EXPECTED BOUNDS

- Bounds on the product of CP-odd and CP-even relaxion couplings.

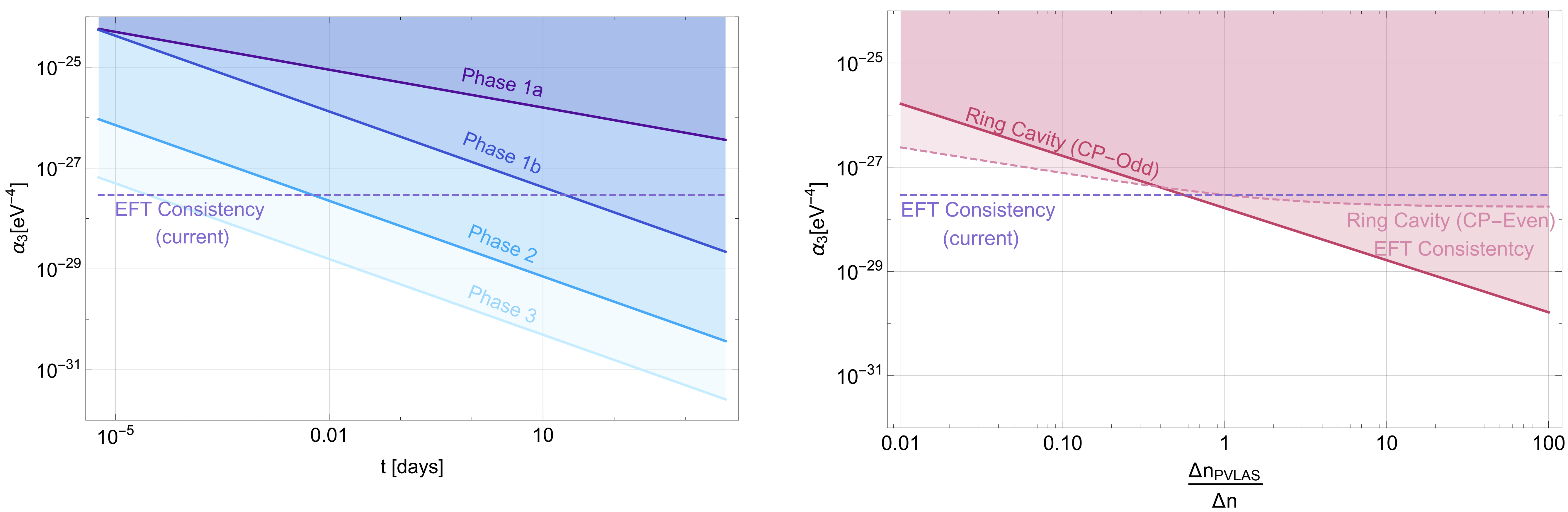


Igor G. Irastorza and Javier Redondo, [1801.08127]

E.G. Adelberger et al, [hep-ph/0307284v1]

EXPERIMENTAL PROBE - EXPECTED BOUNDS

➤ Obtain bounds on a generic dim-8 EFT- $\mathscr{L}^{eff}_{CPV} = \alpha_3 F_{\rho\sigma} F^{\rho\sigma} F_{\mu\nu} \tilde{F}^{\mu\nu}$.



CONCLUSIONS AND FUTURE WORK

- We presented two methods for measuring CPV photon-photon interactions using an SRF cavity and a ring Fabry-Perot cavity (PVLAS-like).
- **CPV interactions can be isolated** from CPC effects according to the frequency of the signal mode(SRF), or temporal dependence (FP).
- Bounds on relaxion-like scalars expected to be weaker than the combination of current scalar and pseudoscalar bounds.
- However, bounds on **effective** CPV photon-photon interactions would **probe theoretically consistent region.**
- Future work - eEDM EFT bound estimation, molecular probes?, CPV in intense laser background.

THANK YOU!

BACKUP SLIDES

BREAKING DOWN THE SIGNAL COMPONENTS

- For our setup, we choose the pump fields such that

$$\vec{E}_1 \cdot \vec{B}_1 = 0\,, \vec{E}_2 \cdot \vec{B}_2 = 0\,,$$
$$\vec{E}_1 \cdot \vec{E}_2 = 0\,, \vec{B}_1 \cdot \vec{B}_2 = 0\,,$$
$$\vec{B}_1 \cdot \vec{E}_2 \neq 0\,, \vec{B}_2 \cdot \vec{E}_1 \neq 0\,.$$
$$\overrightarrow{E_2} \parallel \overrightarrow{B_1} \;\; or \;\; \left(\vec{\nabla}\phi\right)_{\vec{B}_1\times\vec{E}_2} = 0$$

- The projection of the new field onto the direction of E2

$$\vec{J}_\phi \cdot \hat{E}_2 = -\left((\tilde{g}\vec{E} - g\vec{B}) \times \vec{\nabla}\phi\right) \cdot \hat{E}_2 + \partial_t\phi(\tilde{g}\vec{B} + g\vec{E}) \cdot \hat{E}_2$$

$$\phi \sim \left(-\frac{1}{2}g\left(B^2 - E^2\right) + \tilde{g}\left(\vec{B} \cdot \vec{E}\right)\right)$$

BREAKING DOWN THE SIGNAL COMPONENTS

- For our setup, we choose the pump fields such that

$$\vec{E}_1 \cdot \vec{B}_1 = 0\,, \vec{E}_2 \cdot \vec{B}_2 = 0\,,$$
$$\vec{E}_1 \cdot \vec{E}_2 = 0\,, \vec{B}_1 \cdot \vec{B}_2 = 0\,,$$
$$\vec{B}_1 \cdot \vec{E}_2 \neq 0\,, \vec{B}_2 \cdot \vec{E}_1 \neq 0\,.$$
$$\overrightarrow{E_2} \parallel \overrightarrow{B_1} \;\; or \;\; \left(\vec{\nabla}\phi\right)_{\vec{B}_1 \times \vec{E}_2} = 0$$

- The projection of the new field onto the direction of E2

$$\vec{J}_\phi \cdot \hat{E}_2 = -\left((\tilde{g}\vec{E}_1 - g\vec{B}_2) \times \vec{\nabla}\phi\right) \cdot \hat{E}_2 + \partial_t\phi(\tilde{g}\vec{B}_1 + g\vec{E}_2) \cdot \hat{E}_2$$

$$\phi \sim \left(-\frac{1}{2}g\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right) + \tilde{g}\left(\vec{B}_1 \cdot \vec{E}_2 + \vec{B}_2 \cdot \vec{E}_1\right)\right)$$

IDENTIFYING CPV INTERACTIONS

- **CPV part**

$$\left(\vec{J}_\phi \cdot \hat{E}_2\right)_{CPV} \propto g\tilde{g}\left(-\vec{E}_1 \times \vec{\nabla}\left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right)\right) \cdot \hat{E}_2 + g\tilde{g}\left(\vec{B}_2 \times \vec{\nabla}\left(\vec{B}_1 \cdot \vec{E}_2 + \vec{B}_2 \cdot \vec{E}_1\right)\right) \cdot \hat{E}_2$$

$$+g\tilde{g}\vec{B}_1 \cdot \hat{E}_2 \partial_t\left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right) + g\tilde{g}\vec{E}_2 \cdot \hat{E}_2 \partial_t\left(\vec{B}_1 \cdot \vec{E}_2 + \vec{B}_2 \cdot \vec{E}_1\right).$$

$$\boldsymbol{\omega_{CPV} = \pm n_{odd}\omega_1 \pm n_{even}\omega_2}$$

- **CPC part**

$$\left(\vec{J}_\phi \cdot \hat{E}_2\right)_{CPC} \propto g^2\left(\vec{B}_2 \times \vec{\nabla}\left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right)\right) \cdot \hat{E}_2 - \tilde{g}^2\left(\vec{E}_1 \times \vec{\nabla}\left(\vec{B}_1 \cdot \vec{E}_2 + \vec{B}_2 \cdot \vec{E}_1\right)\right) \cdot \hat{E}_2$$

$$+g^2\vec{E}_2 \cdot \hat{E}_2 \partial_t\left(-\frac{1}{2}\left(B_1^2 + B_2^2 - E_1^2 - E_2^2\right)\right) + \tilde{g}^2\vec{B}_1 \cdot \hat{E}_2 \partial_t\left(\vec{B}_1 \cdot \vec{E}_2 + \vec{B}_2 \cdot \vec{E}_1\right).$$

$$\boldsymbol{\omega_{CPC} = \pm n_{odd}\omega_2 \pm n_{even}\omega_1}$$

Separate CPV and CPC effects by frequency components at different polarizations!

EXAMPLE – CYLINDRICAL CAVITY

- Can choose pump eigenmodes -

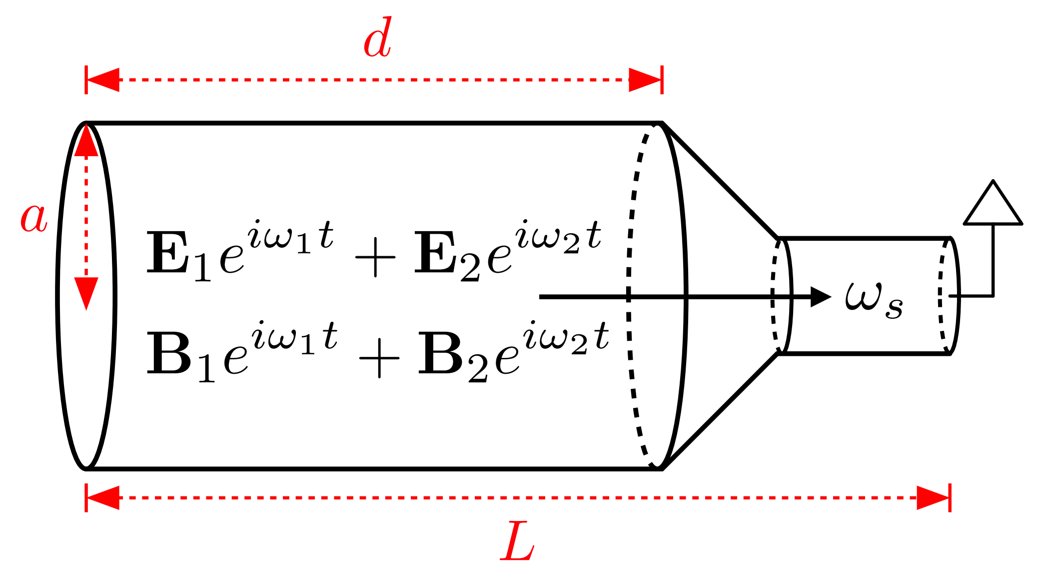
E_1 $\quad E^{TM}_{0p0} = E^{TM}_{0p0}(\rho)\hat{z}\,, \qquad E^{TE}_{0pq} = E^{TE}_{0pq}(\rho, z)\hat{\varphi}\,,$ $\quad E_2$

B_1 $\quad B^{TM}_{0p0} = B^{TM}_{0p0}(\rho)\hat{\varphi}\,, \qquad B^{TE}_{0pq} = B^{TE}_{z_{0pq}}(\rho, z)\hat{z} + B^{TE}_{\rho_{0pq}}(\rho, z))\hat{\rho}\,,$ $\quad B_2$

$$\vec{E}_1 \cdot \vec{B}_1 = 0\,, \vec{E}_2 \cdot \vec{B}_2 = 0\,,$$
$$\vec{E}_1 \cdot \vec{E}_2 = 0\,, \vec{B}_1 \cdot \vec{B}_2 = 0\,,$$
$$\vec{B}_1 \cdot \vec{E}_2 \neq 0\,, \vec{B}_2 \cdot \vec{E}_1 \neq 0\,,$$
$$\vec{E}_s \parallel \vec{E}_2 \quad and \quad : \vec{E}_s \parallel \vec{B}_1 \quad or \quad \left(\vec{\nabla}\phi\right)_{\vec{B}_1 \times \vec{E}_s} = 0$$

- Signal eigenmodes -

1. $E_s = E^{TE}_{0p'q'}$
2. $E_s = E^{TM}_{0p'0}$



EXAMPLE – CYLINDRICAL CAVITY – FILTERING GEOMETRY

- Resonance condition

$$\omega_{npq}^{TM} = \sqrt{\frac{x_{np}^2}{a^2} + \frac{q^2\pi^2}{d^2}}\,, \qquad \omega_{npq}^{TE} = \sqrt{\frac{x'^2_{np}}{a^2} + \frac{q^2\pi^2}{d^2}}$$

- Frequency matching for CPV -

$$E_s = E_{0p'q'}^{TE} \to \omega_{CPV} = 2\omega_{0pq}^{TE} \pm \omega_{0p0}^{TM} \overset{!}{=} \omega_{0p'q'}^{TE}$$

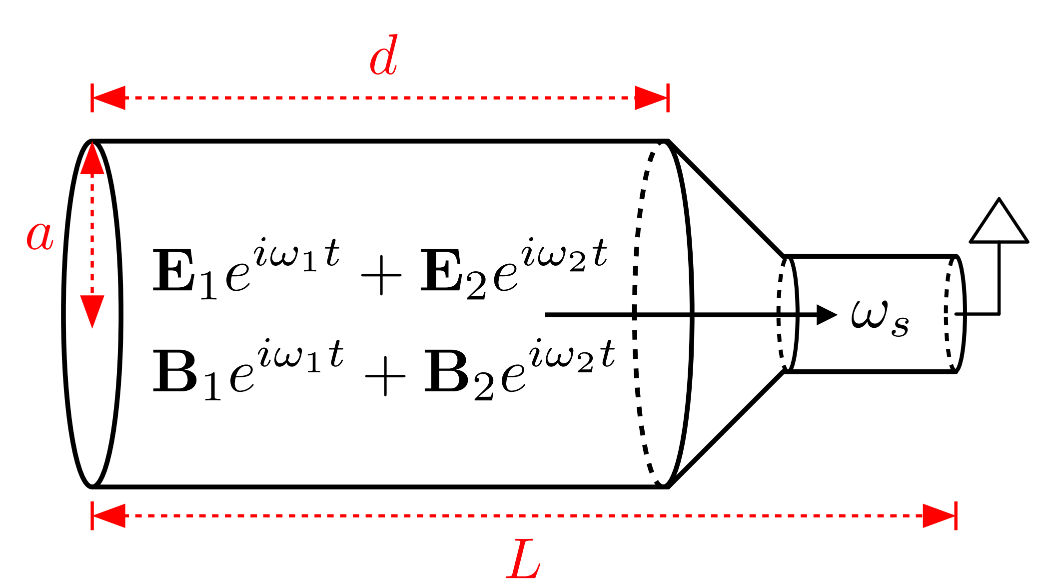
$$E_s = E_{0p'0}^{TM} \to \omega_{CPV} = 2\omega_{0p0}^{TM} \pm \omega_{0pq}^{TE} \overset{!}{=} \omega_{0p'0}^{TM}$$

→ *fix d/a*

- Filtering region - keep only signal

$$\omega_{0p'q'}^{TE} = \sqrt{\frac{x'^2_{0p'}}{a^2} + \frac{q'^2\pi^2}{d^2}} \overset{!}{=} \sqrt{\frac{x'^2_{01}}{r^2} + \frac{\pi^2}{(L-d)^2}}\,.$$

$$\omega_{0p'0}^{TM} = \sqrt{\frac{x_{0p'}^2}{a^2}} \overset{!}{=} \sqrt{\frac{x_{01}^2}{r^2}}$$



EXPERIMENTAL PROBE - SRF CAVITIES

- **Bounds** on the relaxion couplings given by

$$\sqrt{g\tilde{g}}^{\text{lim.}} \sim \left(\frac{TL}{QVE_0^6}\sqrt{\frac{B}{t}}\right)^{\frac{1}{4}} \times \begin{cases} K_0^{-1/2}\omega_s, & m_\phi \ll \omega_s \\ K_\infty^{-1/2}m_\phi, & m_\phi \gg \omega_s\,. \end{cases}$$

- **Cavity parameters** -$T \approx 1.5K, \omega_s \sim 10^8\,Hz \sim 10^{-6}\,eV$
- **Proposed experimental phases**
  1. Phase I - $Q \sim 10^8, a \sim 0.5\,m\,, t \sim 1\ \ day$
     a. B=2Hz
     b. B=1/t

  b. Phase II - $Q \sim 10^{12}, a \sim 0.5\,m\,, t \sim 20\ \ days\,, B = 1/t$

  c. Phase III - $Q \sim 10^{12}, a \sim 2\,m\,, t \sim 1\ \ y\,, B = 1/t$
- **Mode choice** - $E_p = TE_{011} + TM_{030}\,, E_s = TM_{050} \to K_\infty \sim 0.29$

Bogorad et al, [1902.01418]

VACUUM BIREFRINGENCE

- Modified dispersion relation in the presence of a background field - non-isotropic vacuum refractive index.

$$\begin{pmatrix} 1-n^2-16B_0^2 f(\alpha_1,\alpha_2) & \pm 16B_0^2 n\alpha_3 \\ \pm 16B_0^2 n\alpha_3 & 1-n^2-16B_0^2 h(\alpha_1,\alpha_2) \end{pmatrix} \vec{E} = 0 \,. \begin{pmatrix} \omega^2-k^2 & 0 & \pm\omega B\tilde{g} \\ 0 & \omega^2-k^2 & gB\omega \\ \pm\omega B\tilde{g} & gB\omega & \omega^2-k^2-m_\phi^2 \end{pmatrix} \begin{pmatrix} A_\perp \\ A_\parallel \\ \phi \end{pmatrix} = 0$$

- **Induced ellipticity (dispersion) and rotation of polarization plane (absorption) of a probe beam**
  - Scalar mediator -

$$\Psi_\phi = \sin(2\theta-2\theta_s)\frac{\omega L}{4}\frac{B^2(g^2+\tilde{g}^2)}{m_\phi^2}\left(1-\frac{\sin x}{x}\right),$$

$$\zeta_\phi = \sin(2\theta-2\theta_s)\,\omega^2 L\frac{B^2(g^2+\tilde{g}^2)}{m_\phi^4}\sin^2\frac{x}{2}$$

$$x \equiv m_\phi^2 \lambda L/(4\pi)$$

  - EFT -

$$\Psi_{\rm EFT} = \sin(2\theta-2\beta)8\omega L B^2\sqrt{(\alpha_2-\alpha_1)^2+\alpha_3^2}$$

Y. Liao, 0704.1961 J. Redondo, 0807.4329.