Search for Dark Neutrino via Vacuum Magnetic Birefringence Experiment

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Collaborators:
X. Fan (Harvard Univ.), S. Kamioka, S. Asai (Tokyo Univ.) experiment
A. Sugamoto (Ochanomizu Univ., OUJ) theory

PTEP **2017** no. 12, 123B03 (2017), arXiv:1707.03609
(arXiv:1707.03308)

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KEK, Tsukuba

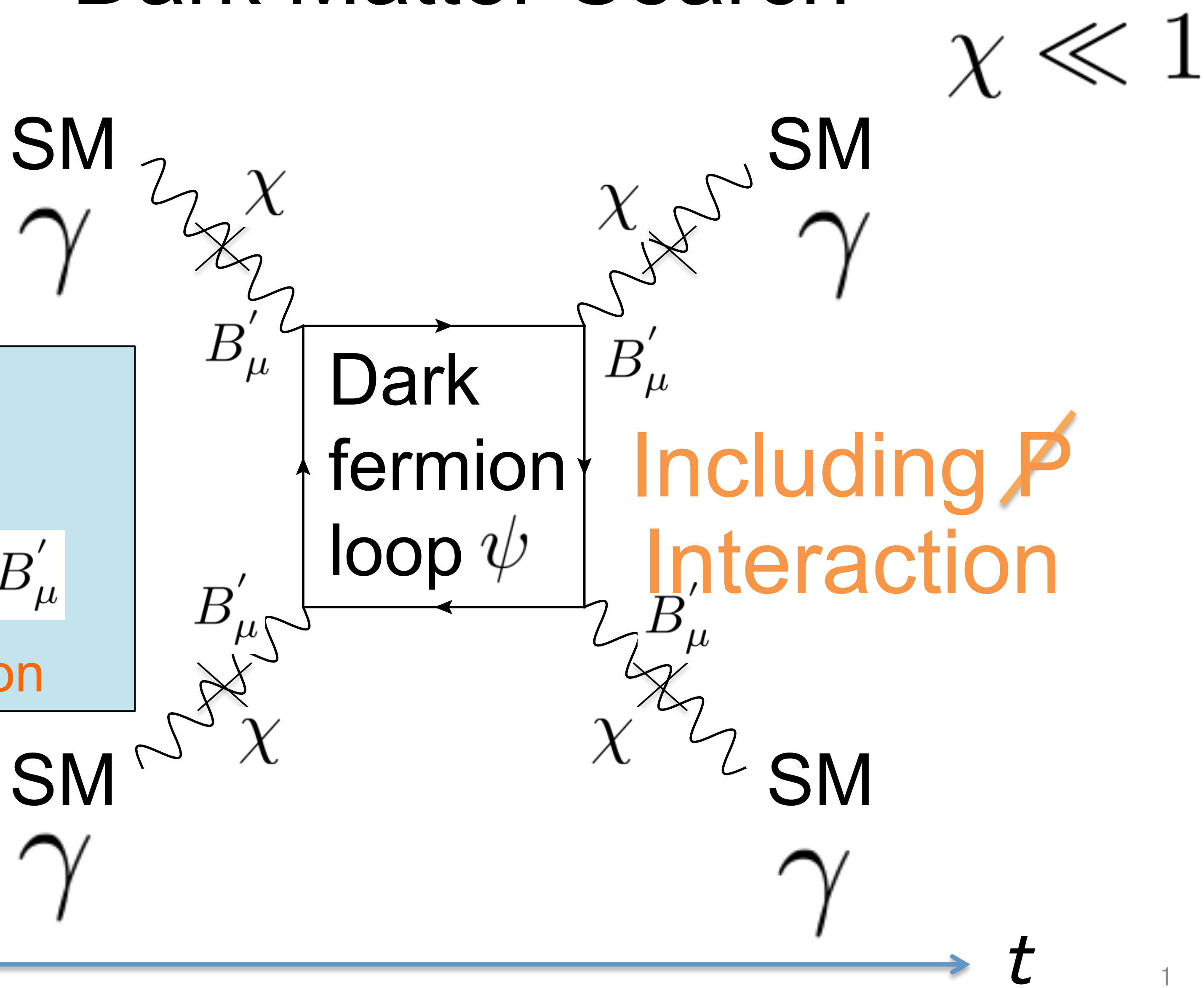
Including Dark Matter as New Physics

Dark Matter Search

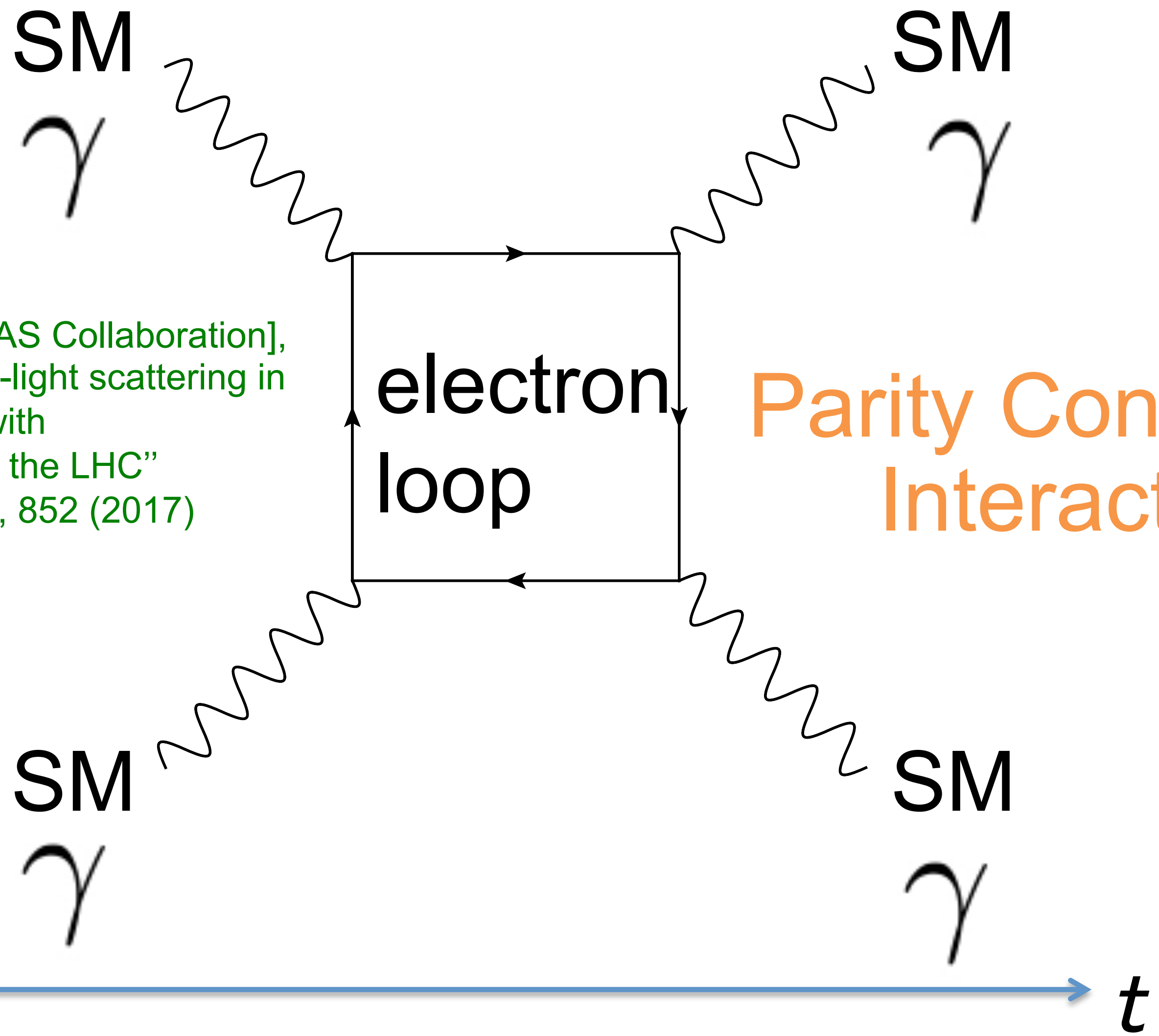
DM:

- $\psi \times 1$
- $\not{P}$ with B'_μ

V-A interaction



cf. QED interaction



M. Aaboud *et al*. [ATLAS Collaboration],
``Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC''
Nature Phys.**13**, no. 9, 852 (2017)

Parity Conserving Interaction

Need to Calculate Effective Lagrangian
→ Vacuum Birefringence Experiment

QED Case

already known

W. Heisenberg, H. Euler, Z. Phys. **98**, 714 (1936)

Heisenberg-Euler Lagrangian:

$$\mathfrak{L} = -\mathfrak{F} - \frac{1}{8\pi^2}\int_0^\infty ds\, s^{-3} \exp(-m^2 s) \times \left[(es)^2 \mathfrak{G} \frac{\mathrm{Re}\,\cosh esX}{\mathrm{Im}\,\cosh esX} - 1 - \tfrac{2}{3}(es)^2 \mathfrak{F} \right]$$

$$X = \sqrt{2(\mathcal{F} + i\mathcal{G})},$$

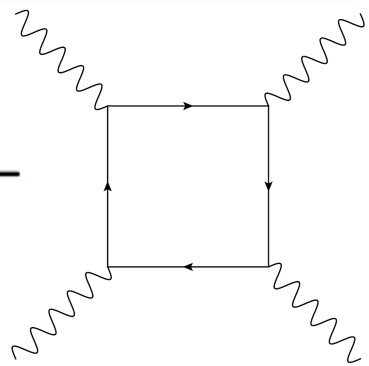
$$\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}\left(\vec{H}^2 - \vec{E}^2\right)$$

$$\mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{H}$$

$$\tilde{F}_{\mu\nu} = \tfrac{1}{2}\epsilon_{\mu\nu\lambda\rho} F^{\lambda\rho}$$

$$= \tfrac{1}{2}(\mathbf{E}^2 - \mathbf{H}^2) + \frac{2\alpha^2}{45}\frac{(\hbar/mc)^3}{mc^2} \times [(\mathbf{E}^2 - \mathbf{H}^2)^2 + 7(\mathbf{E}\cdot\mathbf{H})^2] + \cdots$$

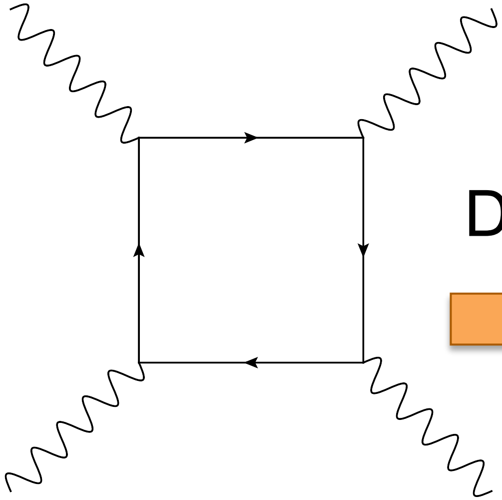
from J. Schwinger, Phys. Rev. **82**, 664 (1951)

$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4} F_{\mu\nu}^2 +$$  $$+ \cdots$$

related to this

- constant background electromagnetic field $F_{\mu\nu}$
- electron 1-loop diagrams

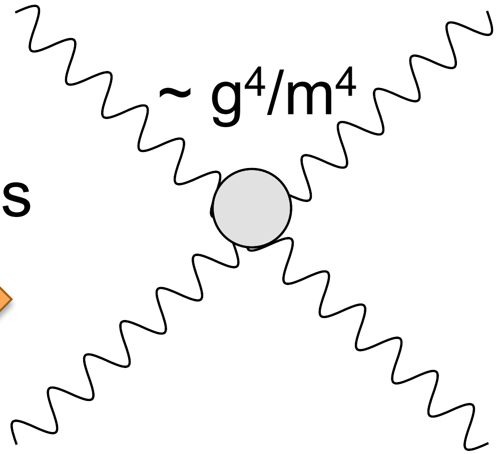
Dark Sector Case (1/3)



Photon Energy

^
^

Dark Fermion Mass



$+ \cdots$
ignore higher dimensional terms

$$\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right)$$

$$\mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = \vec{E} \cdot \vec{B}$$

We calculated here including coefficients a,b,c

$E_\gamma \ll m_{DM}$

$$\mathcal{L}_{\text{eff}} = -\mathcal{F} + a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}$$

Dark Sector Case (2/3)

extra U(1)

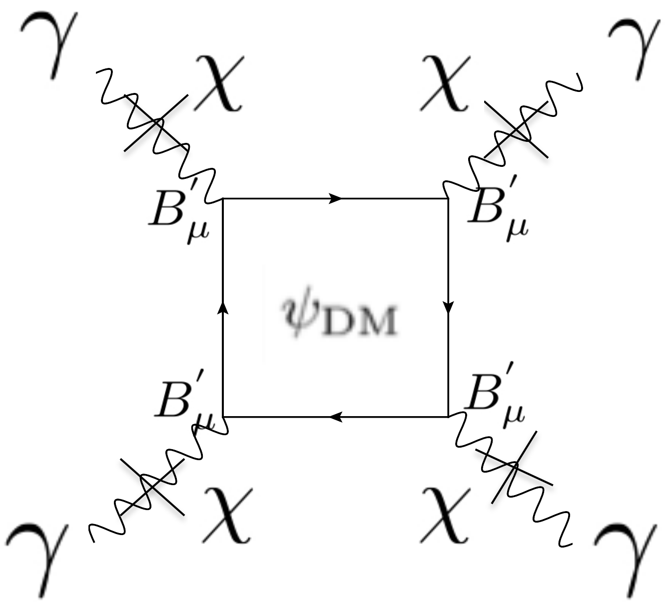
$$\tilde{A}^{\mu} = A^{\mu}_{\mathrm{SM}} + \chi B^{'\mu} \qquad \chi \ll 1$$

photon in our theory (massless)

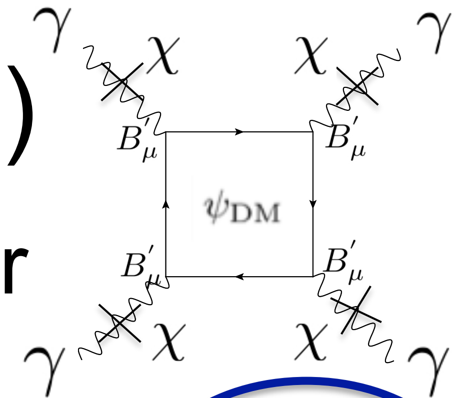
ordinary photon in SM

extra U(1) gauge boson

$$\mathcal{L} = \bar{\psi}_{\mathrm{DM}}[\gamma^{\mu}(i\partial_{\mu} - (g_V + g_A\gamma_5)B^{'}_{\mu}) - m_{\mathrm{DM}}]\psi_{\mathrm{DM}}$$



Dark Sector Case (3/3)



- Effective Lagrangian of Fourth Order

Our work: PTEP **2017** no. 12, 123B03 (2017)

$$\mathcal{L}_{\rm eff} = -\mathcal{F} + \chi^4 (a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G})$$

$\not{P}$

$$\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right) \quad \mathcal{G} = \frac{1}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

$$a = \frac{1}{(4\pi)^2 m^4}\left(\frac{8}{45}\, g_V^4 - \frac{4}{5}\, g_V^2 g_A^2 - \frac{1}{45}\, g_A^4\right)$$

$$b = \frac{1}{(4\pi)^2 m^4}\left(\frac{14}{45}\, g_V^4 + \frac{34}{15}\, g_V^2 g_A^2 + \frac{97}{90}\, g_A^4\right)$$

$$c = \frac{1}{(4\pi)^2 m^4}\left(\frac{4}{3}\, g_V^3 g_A + \frac{28}{9}\, g_V g_A^3\right)$$

c=0 when g_A or g_V is 0

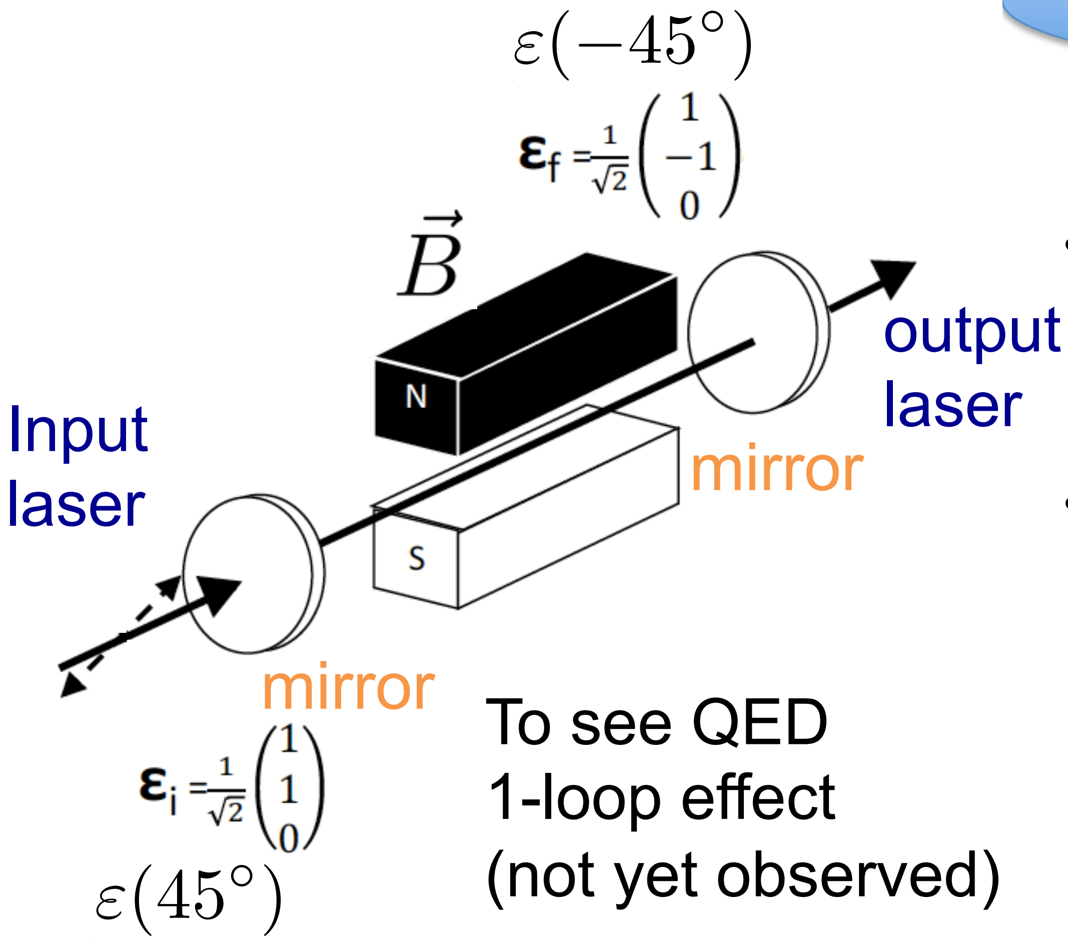
We followed a method developed by Schwinger J. Schwinger, Phys. Rev.**82**, 664 (1951)

Vacuum Magnetic Birefringence Experiment (1/5)

X. Fan *etal.* Eur. Phys. J. D **71**, no. 11, 308 (2017)

- OVAL (Observing Vacuum with Laser) experiment

Conventional



To see QED
1-loop effect
(not yet observed)

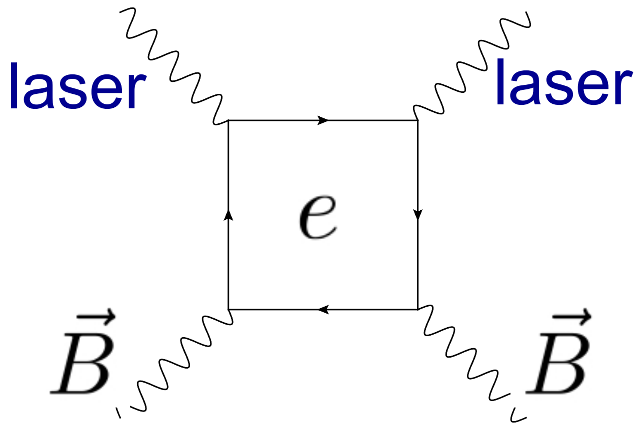
Tabletop experiment

Eur. Phys. J. D (2014) **68**: 16

- BMV experiment

Eur. Phys. J. C (2016) **76**: 24

- PVLAS experiment

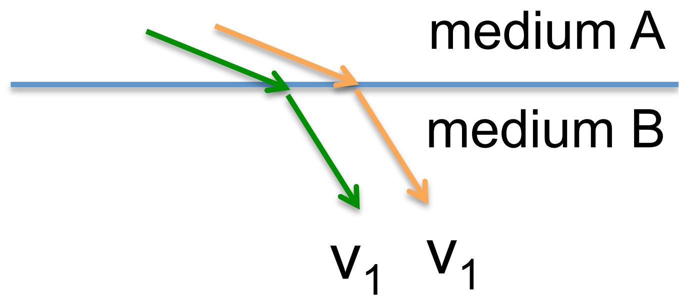


Vacuum Magnetic Birefringence Experiment (2/5)

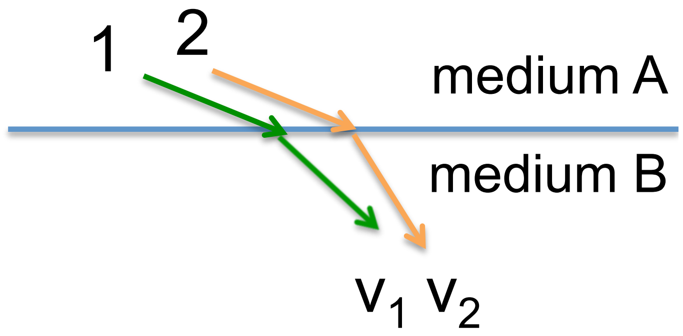
- refractive index: n
- phase velocity: v

  → n = 1/v

refringence:
changing phase velocity of the light



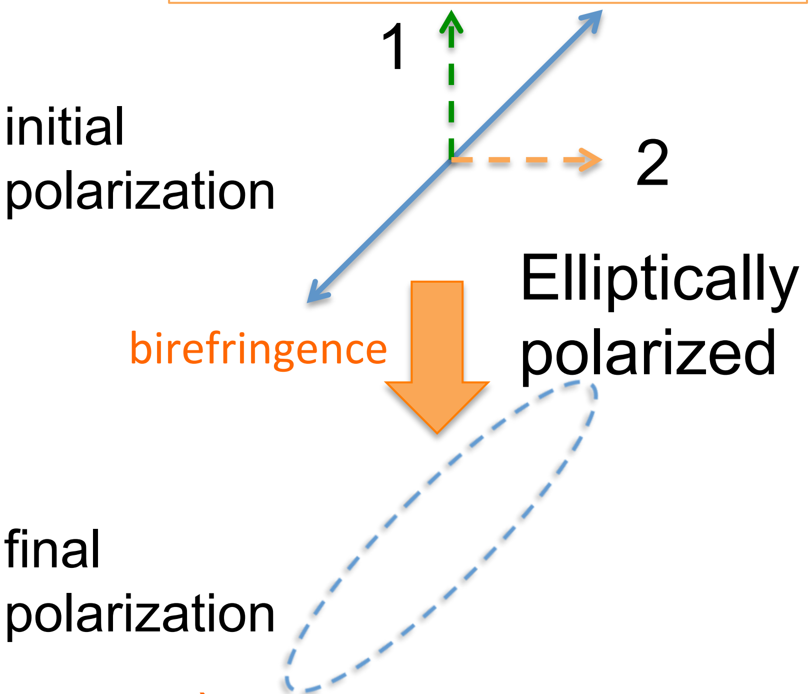
birefringence:
changing phase velocity of 2 light polarizations in different ways



Vacuum Magnetic Birefringence Experiment (3/5)

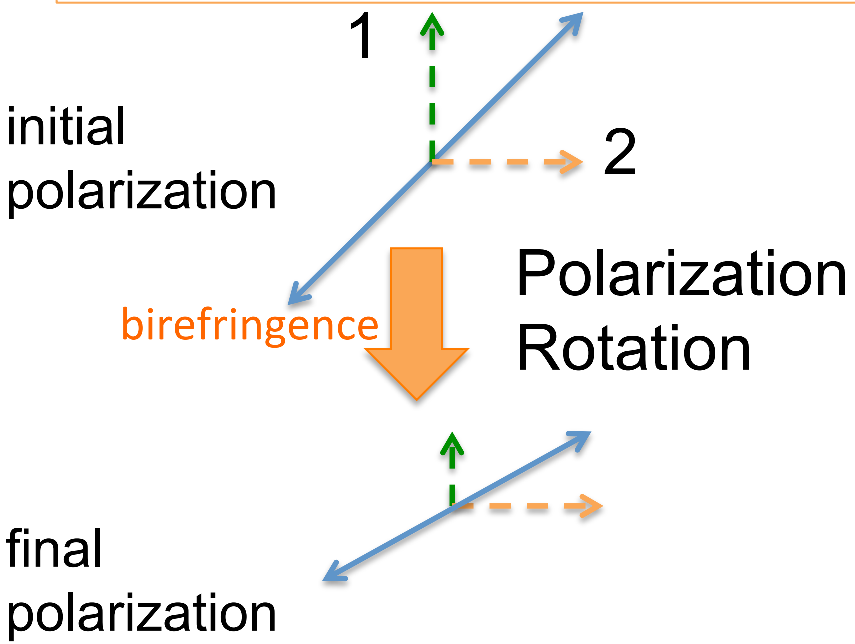
To detect birefringence,
we observe a difference of polarization state

1) Ellipticity



ex)
- QED
- dark sector in our model

2) Direction of the long axis of an ellipse

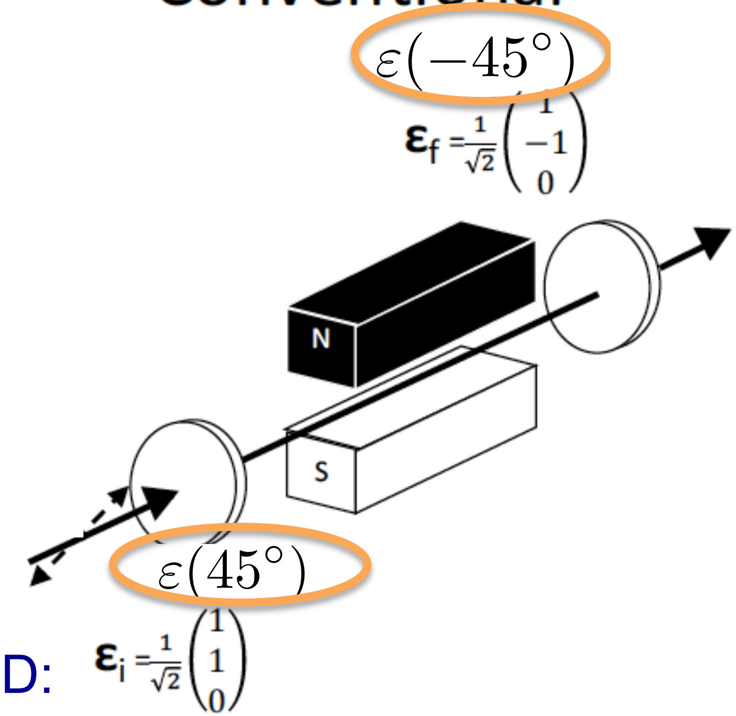


ex) dark sector in our model with $\not{P}$

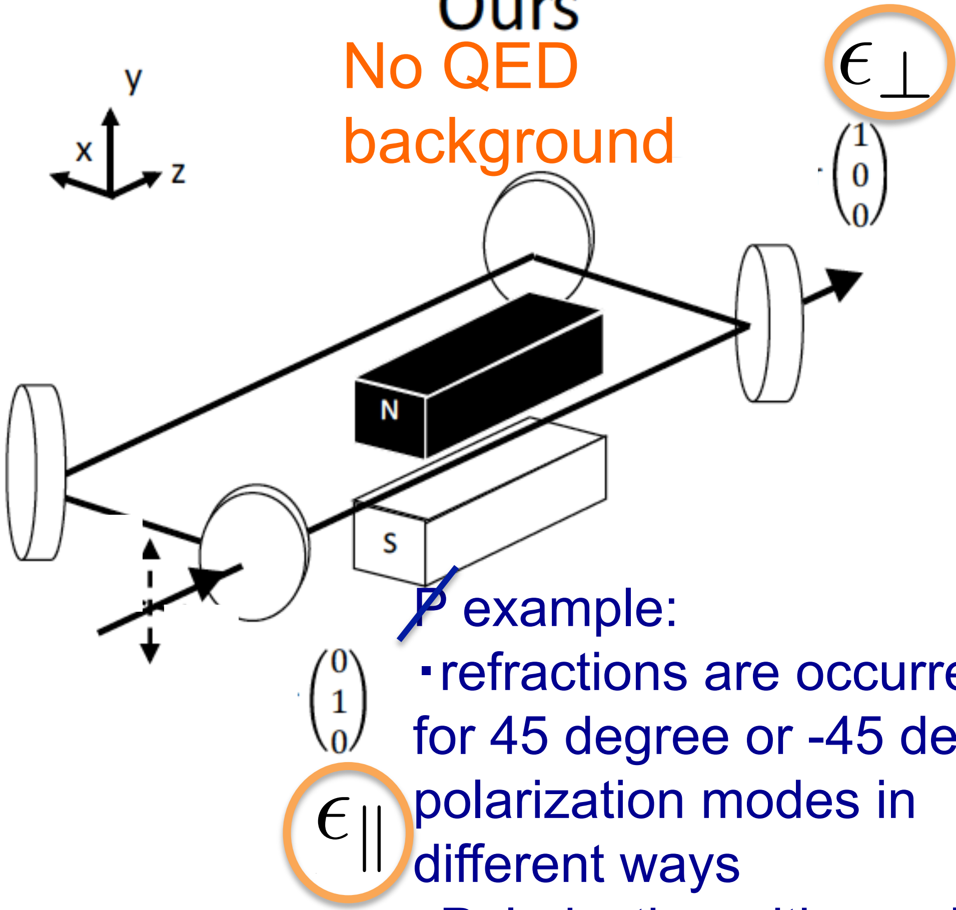
Vacuum Magnetic Birefringence Experiment (4/5)

To detect $\not{P}$ interaction, we propose a new method

Conventional



Ours



QED:

・refractions are occurred for parallel (from magnetic field) or perpendicular polarization modes in different ways

・Polarization with 45 degrees includes both modes.

-> We detect -45 degrees to see reflections

$\not{P}$ example:

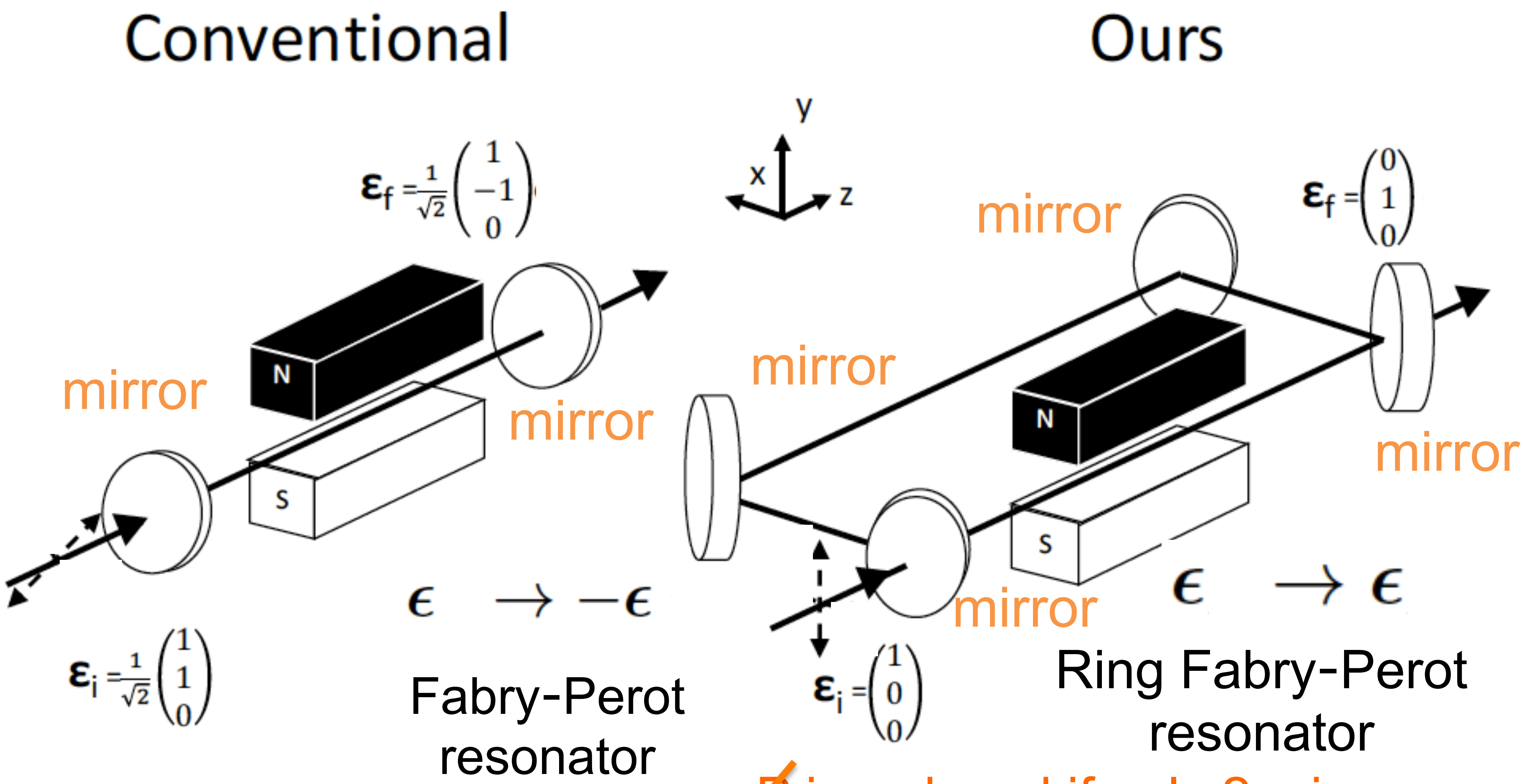
・refractions are occurred for 45 degree or -45 degree polarization modes in different ways

・Polarization with parallel includes both modes.

-> We detect perpendicular to see reflections

Vacuum Magnetic Birefringence Experiment (5/5)

To detect $\not{P}$ interaction, we propose a new method



$\not{P}$ is reduced if only 2 mirrors

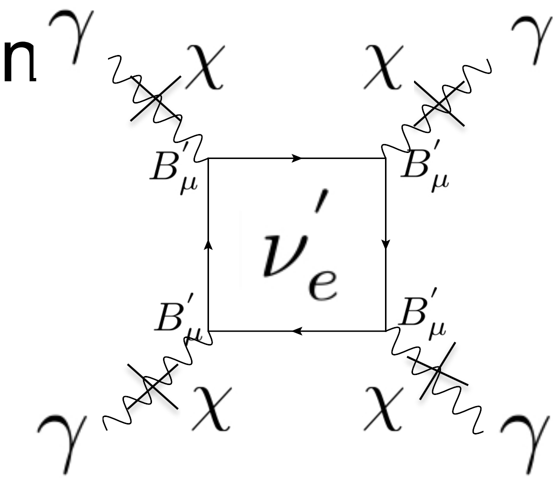
Dark neutrino

$$\mathcal{L} = \bar{\psi}_{\rm DM}[\gamma^{\mu}(i\partial_{\mu} - (g_V + g_A\gamma_5)B_{\mu}^{'}) - m_{\rm DM}]\psi_{\rm DM}$$

We assume g_A = - g_V (= |e|) to obtain the experimental constraint

↓

V – A current: Dark neutrino



We examine the case, having both the electron and the lightest DS neutrino. For the DS search, QED forms the background to the DS signal.

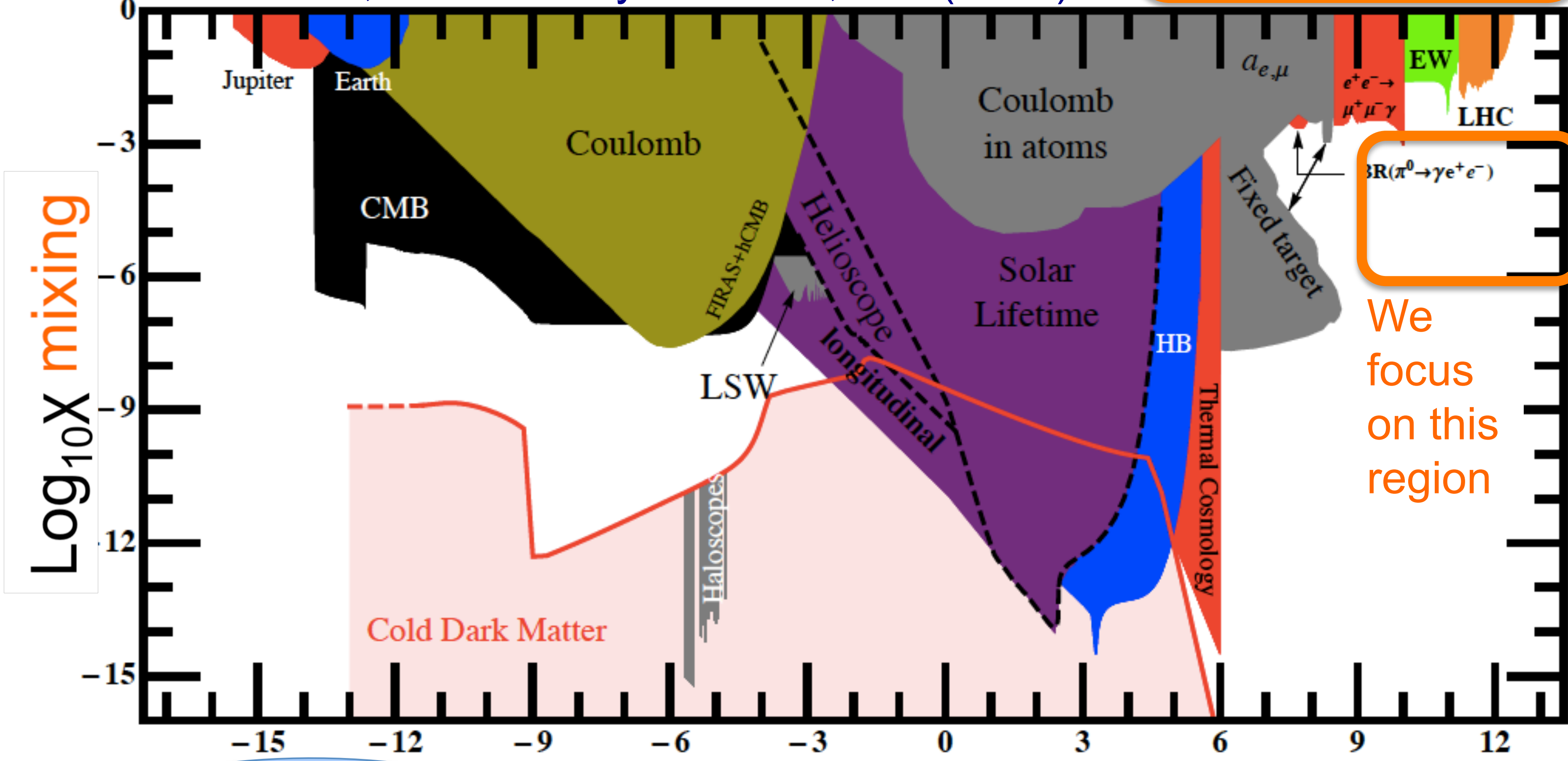
$$a = a_{\rm QED} + \chi^4 a_{{\rm DS}\nu'},\ \ b = b_{\rm QED} + \chi^4 b_{{\rm DS}\nu'},\ \ \text{and}\ c = \chi^4 c_{{\rm DS}\nu'}$$

Allowed region

$$10^{-6} \leq \chi \leq 10^{-3}$$

$$m_{\tilde{B}'} \geq 1\ \mathrm{GeV}$$

J. Jaeckel, Frascati Phys. Ser. 56, 172 (2012)



We focus on this region

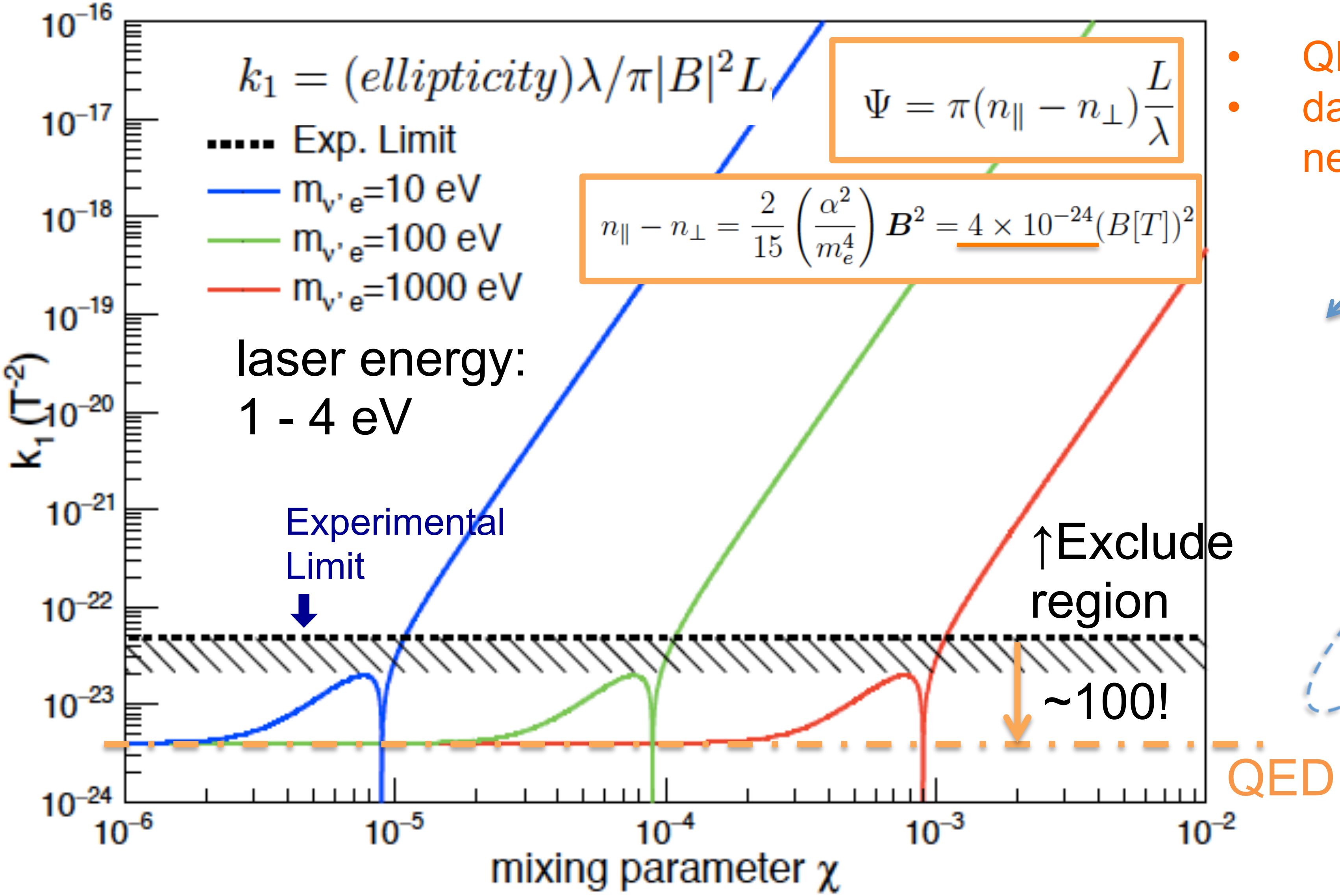
$\mathrm{Log}_{10}\, m_{\tilde{B}'}$ [eV]

GeV

dark photon mass

At VMB experiment, the sensitivity does not depend on dark photon mass

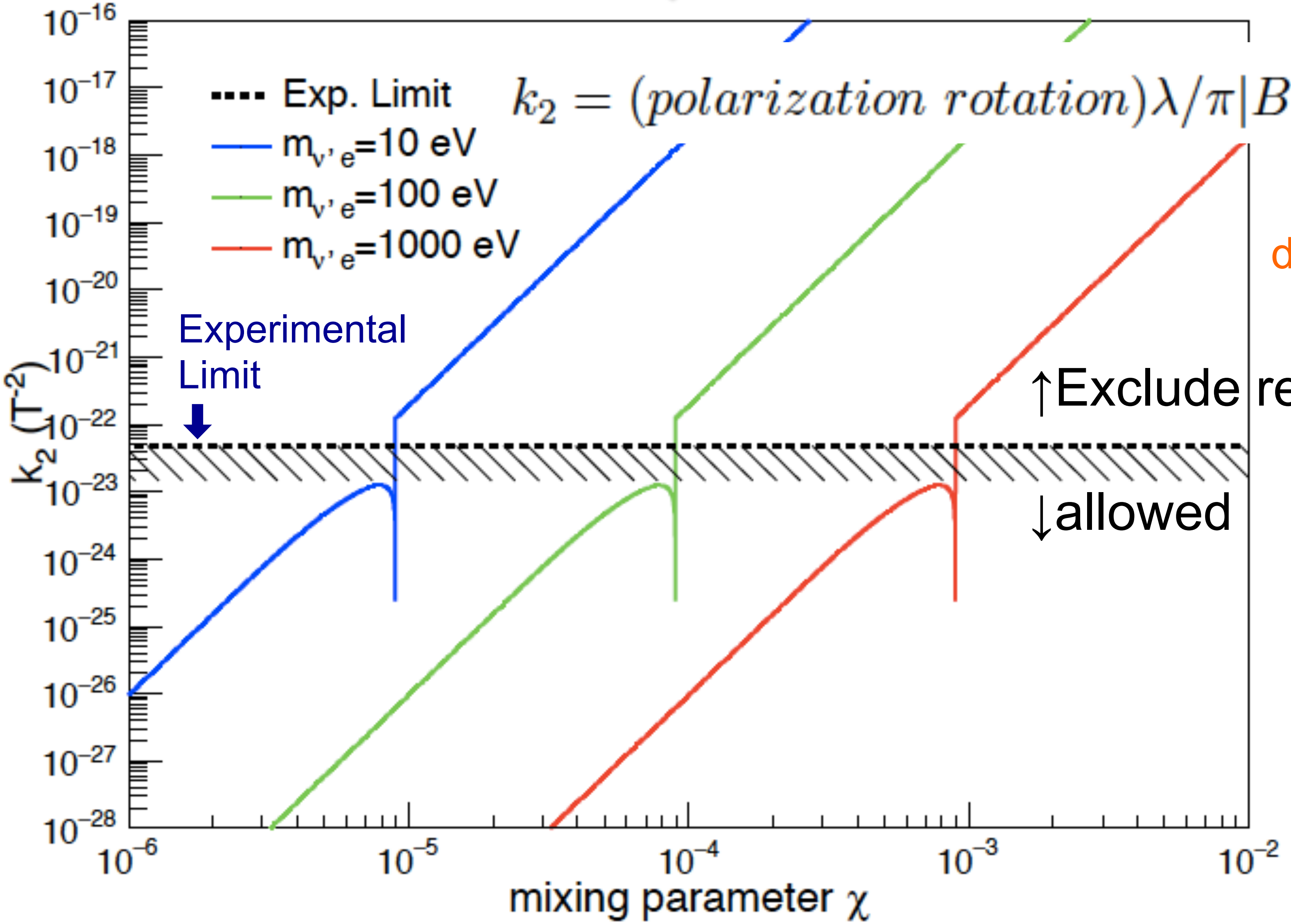
Conventional, QED/Dark neutrino



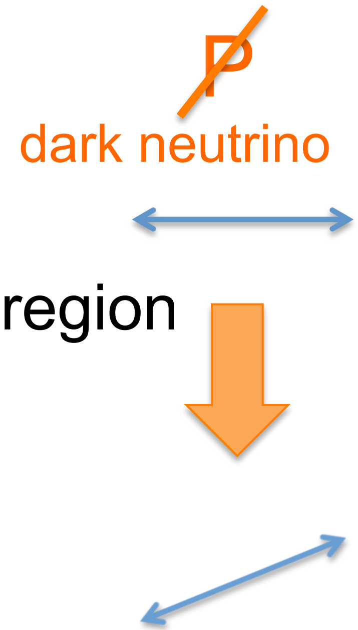
- QED
- dark neutrino

New set up, dark neutrino only

~~P~~ No QED background



$$k_2 = (polarization\ rotation)\lambda/\pi|B|^2 L$$



Summary

1. We considered Parity violated dark sector model, and derived generalized Heisenberg-Euler formula
2. Our focus lay on light-by-light scattering effective Lagrangian of fourth order and gave a result:

$$\mathcal{L}_{\rm eff} = -\mathcal{F} + a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}$$

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right) \quad \mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

$$a = \frac{1}{(4\pi)^2 m^4}\left(\frac{8}{45}\ g_V^4 - \frac{4}{5}\ g_V^2 g_A^2 - \frac{1}{45}\ g_A^4\right)$$

$$b = \frac{1}{(4\pi)^2 m^4}\left(\frac{14}{45}\ g_V^4 + \frac{34}{15}\ g_V^2 g_A^2 + \frac{97}{90}\ g_A^4\right)$$

$$c = \frac{1}{(4\pi)^2 m^4}\left(\frac{4}{3}\ g_V^3 g_A + \frac{28}{9}\ g_V g_A^3\right)$$

3. We focused on Vacuum Magnetic Birefringence Experiment to probe the dark sector and proposed new polarization state and the ring resonator in stead of the usual Fabry-Perot resonator to measure the Parity violated term

Backup

Search for Dark Neutrino via Vacuum Magnetic Birefringence Experiment
20′

We consider a dark matter model where a dark matter candidate couples to photons via an extra U(1) mediator and assume that this dark matter candidate is a fermion and can couple to the mediator with parity violation. We derived a low energy effective Lagrangian including a parity violated term for light-by-light scattering by integrating out the dark matter fermion. Our focus lies on Vacuum Magnetic Birefringence Experiment to probe the dark sector. We propose the ring resonator (3-4 mirrors) with an appropriate polarization state of light in stead of a usual Fabry-Perot resonator (2 mirrors) with a conventional polarization state of light to measure the Parity violated term. We assume that a dark neutrino is a dark matter, i.e. V-A current, and give constraints on model parameters from a current experimental limit. PTEP 2017 no. 12, 123B03 (2017) (arXiv: 1707.03308 [hep-ph]), arXiv:1707.03609 [hep-ph]

Dark Matter Model (1/3)

SM + U'(1)$_{Y'}$ + 1 Complex Scalar

$$\mathcal{L}_S = \left|\left(i\partial_\mu - g_1 Y_s B_\mu - g_1' Y_s' B_\mu'\right) S(x)\right|^2$$

spontaneously broken $\langle S \rangle = v_s/\sqrt{2}$,

$$\mathcal{L}_{\text{mixing}} = \frac{1}{2} m_{B'}^2 \left(\varepsilon^2 B_\mu B^\mu + 2\varepsilon B_\mu B'^\mu + B'_\mu B'^\mu\right)$$

$$m_{B'} = g_1' Y_s' v_s \qquad \varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

$$m_{B'} = g_1' Y_s' v_s$$

Dark Matter Model (2/3)

$$\varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

$$\mathcal{L}_{\text{mixing}} = \frac{1}{2} m_{B'}^2 \left(\varepsilon^2 B_\mu B^\mu + 2\varepsilon B_\mu B'^\mu + B'_\mu B'^\mu \right)$$

mass diagonalization ↓

$$(m_{\tilde{A}})^2 = 0, \ (m_{\tilde{Z}})^2 = \frac{1}{4} v^2 (g_1^2 + g_2^2) + \varepsilon^2 \frac{g_1^2}{g_1^2 + g_2^2 - \alpha'} (m_{B'})^2, \ \text{and}$$

$$(m_{\tilde{B}'})^2 = (m_{B'})^2 \left(1 + \varepsilon^2 \frac{g_2^2 - \alpha'}{g_1^2 + g_2^2 - \alpha'} \right).$$

$$\tilde{A}_\mu = \frac{g_1 A_\mu^3 + g_2 B_\mu}{\sqrt{g_1^2 + g_2^2}} - \varepsilon \frac{g_2}{\sqrt{g_1^2 + g_2^2}} B'_\mu$$

We assume $\epsilon \ll 1$

Dark Matter Model (3/3)

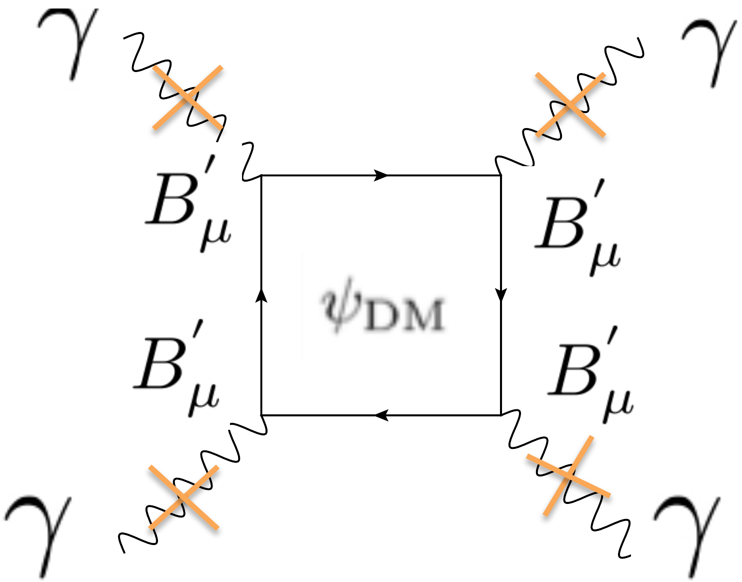
$$\varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

$$\tilde{A}_\mu = \frac{g_1 A_\mu^3 + g_2 B_\mu}{\sqrt{g_1^2 + g_2^2}} - \varepsilon \frac{g_2}{\sqrt{g_1^2 + g_2^2}} B'_\mu$$

$$\chi$$

$$\mathcal{L}'_{\rm eff} = \chi^4 \left\{ a\, \mathcal{F}^2 + b\, \mathcal{G}^2 + ic\, \mathcal{F}\mathcal{G} \right\}$$

$$S_\psi(m) = \int d^4x\, \bar{\psi}_{\rm DM} \left[\gamma^\mu \left(i\partial_\mu - (g_V + g_A \gamma_5) B'_\mu \right) - m \right] \psi_{\rm DM}$$



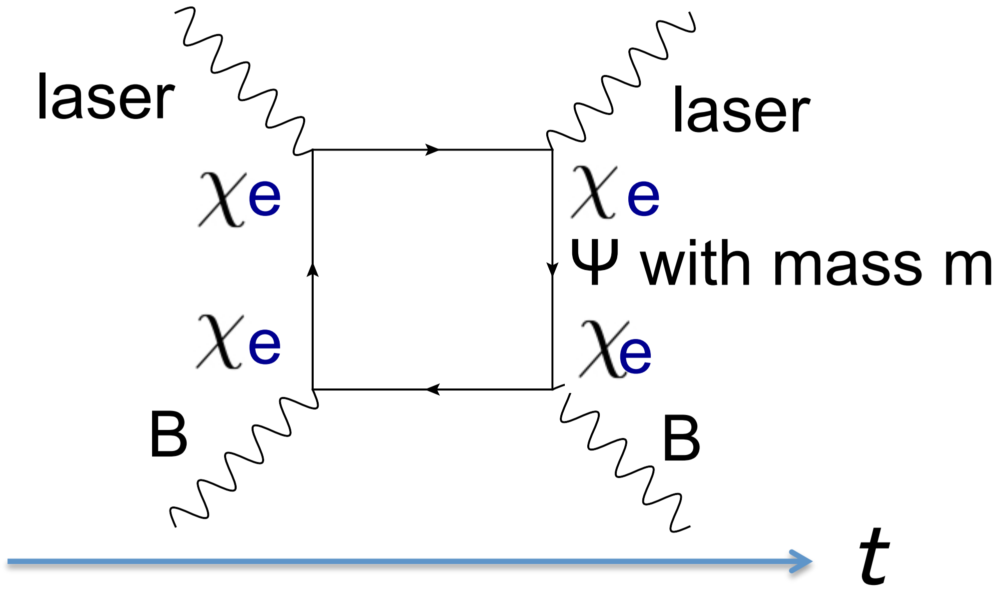
2 conditions

$$h\nu_{\text{laser}} \ll mc^2$$

1 eV

$$\hbar \chi e |\boldsymbol{B}| \ll m^2 c^2$$

10 Tesla, (1 Tesla ~ 200 eV^2)



Vacuum Magnetic Birefringence Experiment: laser beam energy

beam energy 1.16 eV @OVAL experiment

For 2 mirrors system: 1 ~ 4 eV

laser energy itself:
m eV ~ 10 k eV are available
thanks to X-ray Free Electron Laser