Laser-assisted search for axion-like particle or dark photon in strong-field QED

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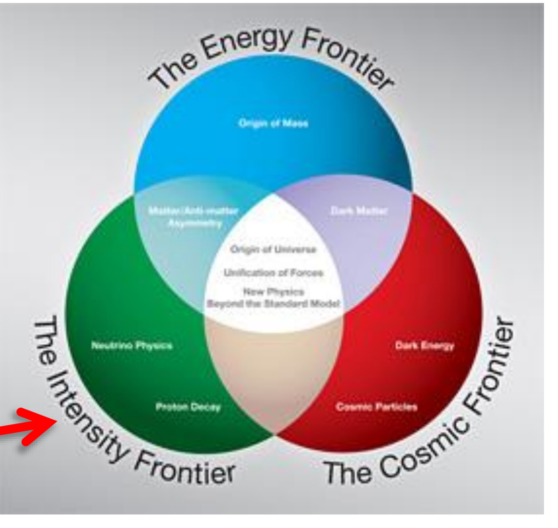
Outline

- Strong-field QED and laser-assisted Compton scattering
- Laser-assisted search for axion-like particle and dark photon
- Summary

Strong-field QED

- The quantum field theory in an external and intense electromagnetic field is regarded as strong-field QED

- An appropriate theory to study high-intensity physics (unlike high-precision domain, e.g. proton decay)



强场量子真空：施温格极限

- In 1951, J. Schwinger showed that at field strengths of $E = \frac{{m_e}^2}{e} \sim 1.32 \times 10^{18}$ V/m, the QED vacuum becomes unstable and decays into electron-positron pairs

$$\boldsymbol{eE_{cr}\lambda_c = mc^2}$$

$$\lambda_c = \hbar/mc = 3.8616 \times 10^{-13}\mathrm{m}$$ 电子康普顿波长

正负电子对产生的**施温格极限场强**：

$$\boldsymbol{E_{cr} = \frac{m^2c^3}{e\hbar} = 1.323 \times 10^{18}\mathrm{V/m}}$$

对应的**激光强度**：

$$\boldsymbol{I_{QED} = 2.1 \times 10^{29}\mathrm{W/cm^2}}$$

Phys. Rev. 82 (1951) 664-679

- The calculation of vacuum decay probability exhibits non-perturbative QED

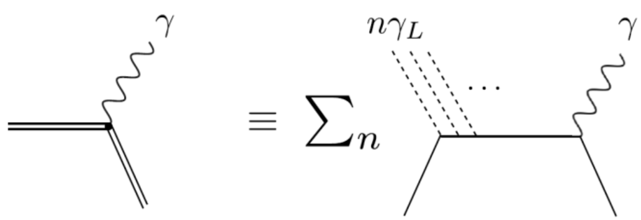
$$2VT\frac{(eE)^2}{(2\pi)^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n\pi\frac{m^2}{eE}\right]$$

- Significant progress has been made in understanding the theory and phenomenology of the Schwinger effect in more realistic backgrounds
- In 1990s, the experiment performed at SLAC observed two strong-field processes in the interaction of an ultra-relativistic electron beam with a terawatt laser pulse

Phys. Rev. Lett. 79, 1626 (1997)
Phys. Rev. D 60, 092004 (1999)

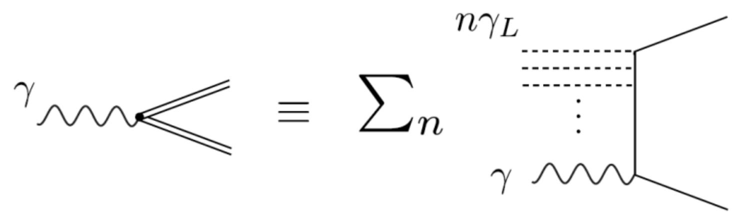
➢ the nonlinear Compton scattering

$$e^{\pm} + n\gamma_L \to e^{\pm} + \gamma$$

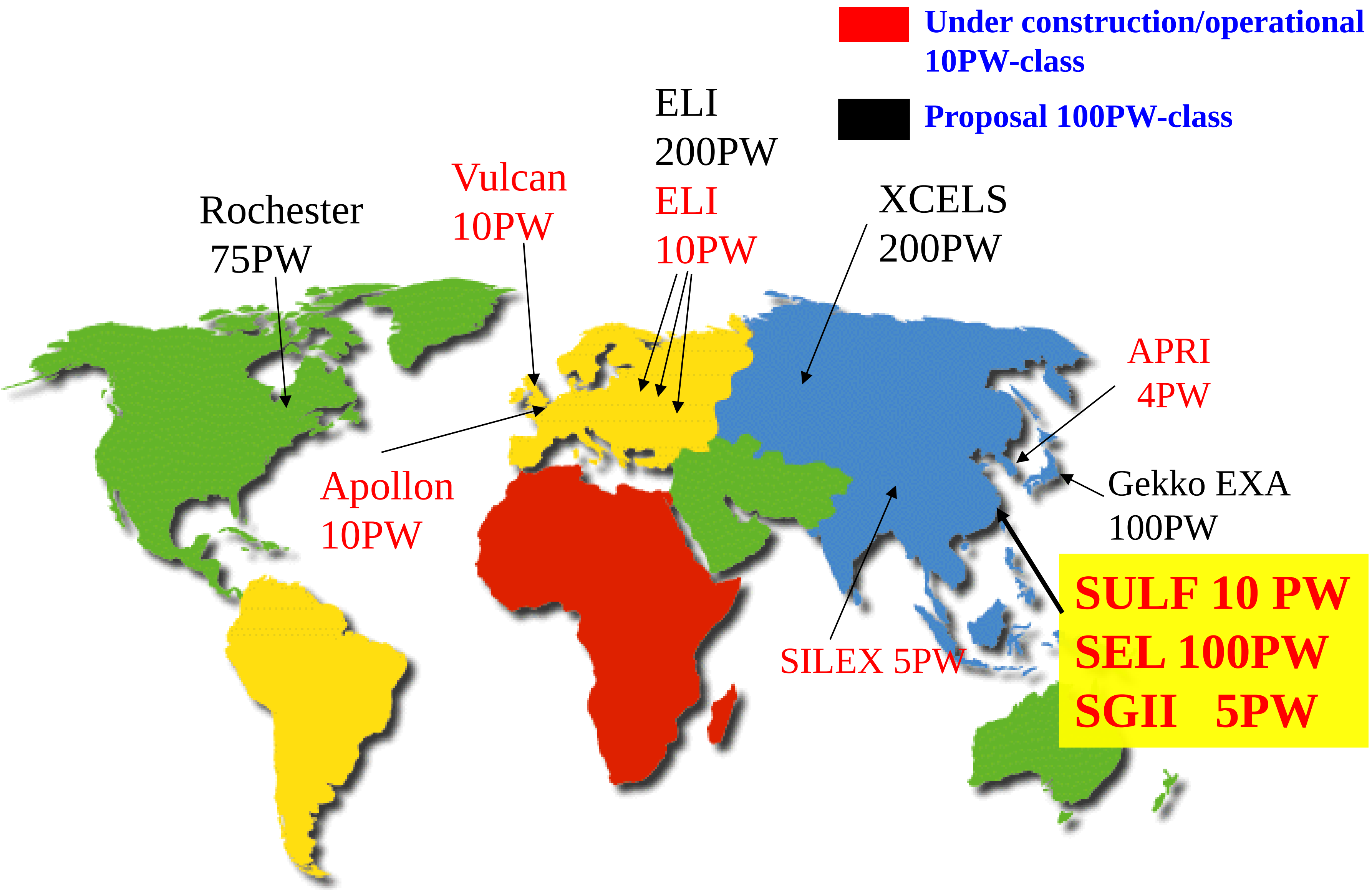


➢ the electron-positron pair production

$$\gamma + n\gamma_L \to e^{+} + e^{-}$$

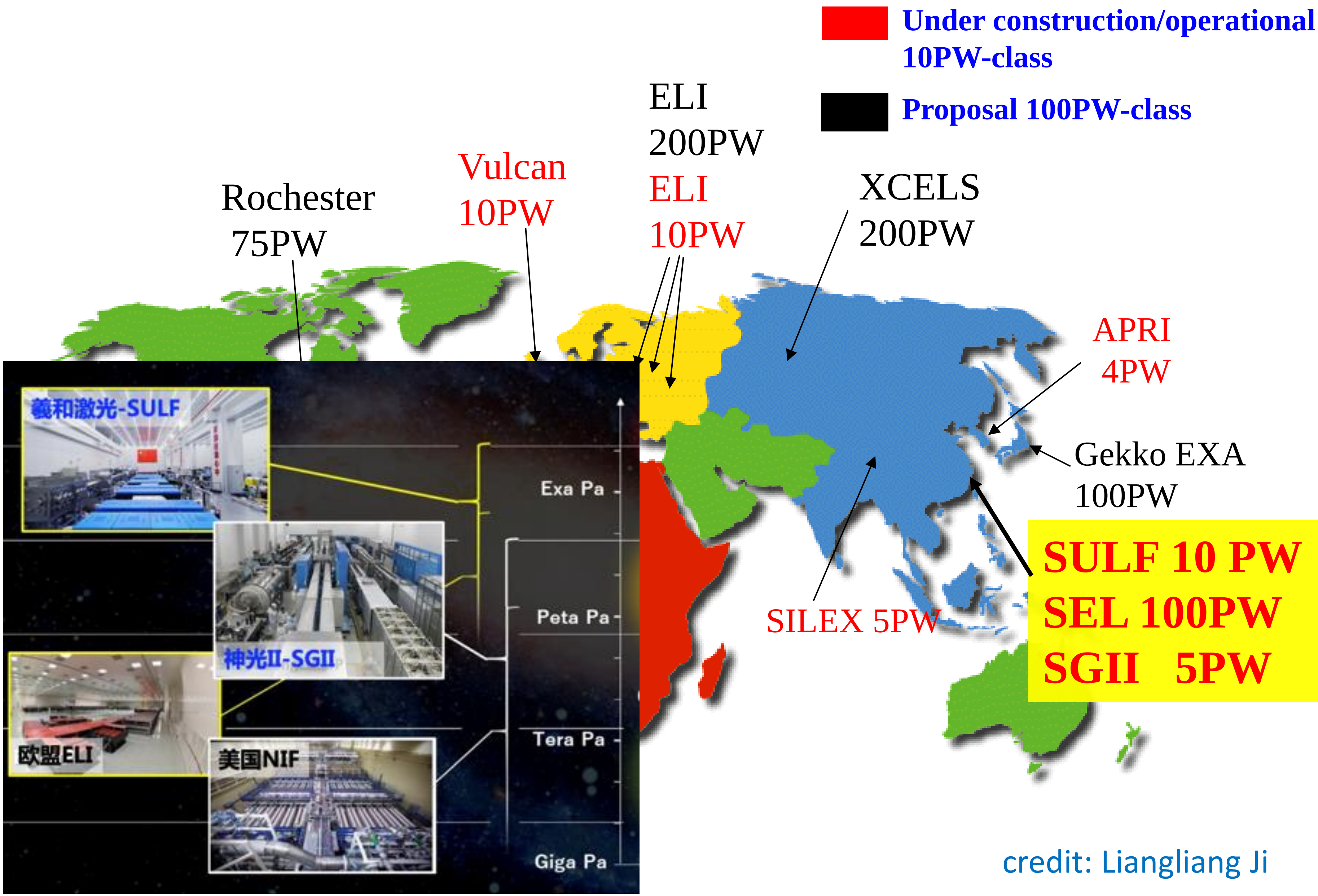


全球10-100PW级超强激光科学装置



credit: Liangliang Ji

全球10-100PW级超强激光科学装置



credit: Liangliang Ji

- Now, the intense electromagnetic field has a lot of applications in atomic physics, nuclear physics and strong-field particle physics (two domains)

- ➢ Neutron stars strongly magnetized
- ➢ Strong magnetic field in high-energy nuclear collisions (e.g. Au-Au at RHIC or Pb-Pb at LHC), CME etc.
- ➢ Transmutation of protons in a laser field
  $p \to n + e^+ + \nu_e$ New J. Phys. 23, 065007 (2021)
- ➢ The first laser excitation of the Th-229 low-energy nuclear transition Phys. Rev. Lett. 132, 182501 (2024)
- ➢ vacuum birefringence, e.g. Shanghai XFEL
- ➢ Search for new physics beyond the SM (this talk)

Laser-induced Compton scattering

- In the presence of an electromagnetic potential, the Dirac equation of a relativistic fermion yields

$$(i\partial\!\!\!/ - Qe A\!\!\!/ - m)\psi(x) = 0$$

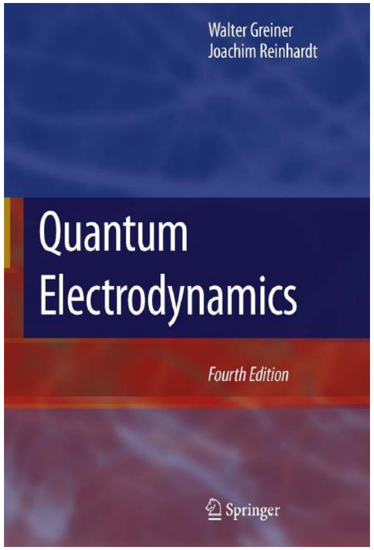
- With circular polarization, the vector potential is

$$A^\mu(\phi) = a_1^\mu \cos(\phi) + a_2^\mu \sin(\phi)\,, \quad \phi = k \cdot x$$

$$a_1^\mu = |\vec{a}\,|(0,1,0,0)\,, \quad a_2^\mu = |\vec{a}\,|(0,0,1,0)$$

$$\boxed{a = \varepsilon_0/\omega}$$

the electric field strength the laser frequency



- The wave function of electron is given by the Volkov state

-- dressed state by the interaction between electron and laser photons

Z. Physik 94, 250 (1935)

$$\psi_{p,s}(x) = \left[1 + \frac{Qe\not{k}\not{A}}{2\left(k \cdot p\right)}\right] \frac{u\left(p, s\right)}{\sqrt{2q^0 V}} e^{iF_1(q,s)}$$

$$F_1(q, s) = -q \cdot x - \frac{\boxed{Qe\left(a_1 \cdot\right.} \left.p\right)}{\left(k \cdot p\right)} \sin\phi + \frac{\boxed{Qe\left(a_2 \cdot\right.} \left.p\right)}{\left(k \cdot p\right)} \cos\phi$$

- effective momentum and mass of the dressed electron

$$q^\mu = p^\mu + \frac{Q^2 e^2 a^2}{2k \cdot p} k^\mu$$

$$q^2 = m_e^2 + Q^2 e^2 a^2 = m_e^{*2}$$

- High-order (nonlinear) effects in the laser field are automatically included

- Consider the laser-induced Compton scattering

$$e^-(p) + n\omega(k) \to e^-(p') + \gamma(k')$$

- The S matrix

$$S_{fi} = ie\frac{1}{\sqrt{2k'^0 V}}\int d^4x e^{ik'\cdot x}\,\overline{\psi_{p',s'}(x)}\not{\epsilon}\psi_{p,s}(x)$$

$$\mathcal{M} = ie\frac{1}{\sqrt{2k'^0 V}}e^{ik'\cdot x}\overline{\psi_{p',s'}(x)}\not{\epsilon}\psi_{p,s}(x)$$

$$= ie\frac{e^{i(k'+q'-q)\cdot x}\boxed{e^{-i\Phi}}}{\sqrt{2^3V^3q^0q'^0k'^0}}\overline{u(p',s')}\left[1-\frac{e\not{A}\not{k}}{2k\cdot p'}\right]\not{\epsilon}\left[1-\frac{e\not{k}\not{A}}{2k\cdot p}\right]u(p,s)$$

$$\Phi = ea_1\cdot y\sin\phi - ea_2\cdot y\cos\phi \qquad y^\mu = \frac{p'^\mu}{k\cdot p'} - \frac{p^\mu}{k\cdot p}$$

- The amplitude can be written as

$$\mathcal{M} = ie\frac{e^{i(k'+q'-q)\cdot x}}{\sqrt{2^3V^3q^0q'^0k'^0}}\sum_{i=0}^{2} C_i\mathcal{M}_i$$

$$\mathcal{M}_0 = \overline{u_2}\not{\varepsilon}u_1 + \overline{u_2}\frac{e^2a^2}{2k\cdot pk\cdot p'}k\cdot\varepsilon\not{k}u_1 \qquad C_0 = e^{-i\Phi}\ ,$$

$$\mathcal{M}_1 = -\overline{u_2}\not{\varepsilon}\frac{e\not{k}\not{a}_1}{2k\cdot p}u_1 - \overline{u_2}\frac{e\not{a}_1\not{k}}{2k\cdot p'}\not{\varepsilon}u_1 \qquad C_1 = \cos\phi\, e^{-i\Phi}$$

$$\mathcal{M}_2 = -\overline{u_2}\not{\varepsilon}\frac{e\not{k}\not{a}_2}{2k\cdot p}u_1 - \overline{u_2}\frac{e\not{a}_2\not{k}}{2k\cdot p'}\not{\varepsilon}u_1 \qquad C_2 = \sin\phi\, e^{-i\Phi}$$

- Look into the phase function

$$\Phi = z\sin(\phi - \phi_0)$$

$$z = e\sqrt{(a_1\cdot y)^2 + (a_2\cdot y)^2}\,,\quad \cos\phi_0 = \frac{ea_1\cdot y}{z}\,,\quad \sin\phi_0 = \frac{ea_2\cdot y}{z}$$

- Then $$e^{-i\Phi} = e^{-iz\sin(\phi-\phi_0)} = \sum_{n=-\infty}^{\infty} c_n e^{-\mathrm{i}n(\phi-\phi_0)}$$

$$c_n = \frac{1}{2\pi}\int_{-\pi}^{\pi} \mathrm{d}\varphi\, e^{-\mathrm{i}z\sin\varphi} e^{in\varphi} = J_n(z)$$

- Finally (Jacobi-Anger expansion)

$$C_0 = e^{-i\Phi} = \sum_{n=-\infty}^{\infty} B_n(z) e^{-\mathrm{i}n\phi} \qquad B_n(z) = J_n(z)\mathrm{e}^{in\phi_0}$$

$$\cos\phi = \frac{1}{2}\Big(e^{i\phi} + e^{-i\phi}\Big)\,, \quad \sin\phi = \frac{1}{2i}\Big(e^{i\phi} - e^{-i\phi}\Big)$$

$$C_1 = \cos\phi\, e^{-i\Phi} = \frac{1}{2}\sum_{n=-\infty}^{\infty}\Big[B_{n+1}(z) + B_{n-1}(z)\Big]e^{-in\phi}$$

$$C_2 = \sin\phi\, e^{-i\Phi} = \frac{1}{2i}\sum_{n=-\infty}^{\infty}\Big[B_{n+1}(z) - B_{n-1}(z)\Big]e^{-in\phi}$$

- Combine $e^{-in\phi}$ with other plane waves

B functions

$$\mathcal{M} = ie \sum_{n=-\infty}^{\infty} \frac{e^{i(k'+q'-q-nk)\cdot x}}{\sqrt{2^3 V^3 q^0 q'^0 k'^0}} \sum_{i=0}^{2} \widetilde{C}_i^n \mathcal{M}_i$$

- Integrating out the coordinate x

$$S_{fi} = ie \sum_{n=-\infty}^{\infty} \frac{(2\pi)^4 \delta^4(k'+q'-q-nk)}{\sqrt{2^3 V^3 q^0 q'^0 k'^0}} \sum_{i=0}^{2} \widetilde{C}_i^n \mathcal{M}_i$$

- Squared S matrix and scattering cross section

$$\left|S_{fi}\right|^2 = e^2 \sum_{n=-\infty}^{\infty} \frac{(2\pi)^4 \delta^4(k' + q' - q - nk)VT}{2^3 V^3 q^0 q'^0 k'^0} \sum_{i,j=0}^{2} \widetilde{C}_i^n (\widetilde{C}_j^n)^\dagger \overline{\mathcal{M}_i \mathcal{M}_j^\dagger}$$

$$\begin{aligned} \sigma &= \frac{|S_{fi}|^2}{VT} \frac{1}{2(1/V)} \frac{1}{\rho_\omega} V \int \frac{d^3 q'}{(2\pi)^3} V \int \frac{d^3 k'}{(2\pi)^3} \\ &= \frac{1}{2\rho_\omega} \frac{e^2}{2q^0} \sum_{n=-\infty}^{\infty} \int d\Pi_2 \boxed{\sum_{i,j=0}^{2} \widetilde{C}_i^n (\widetilde{C}_j^n)^\dagger \overline{\mathcal{M}_i \mathcal{M}_j^\dagger}} \end{aligned}$$

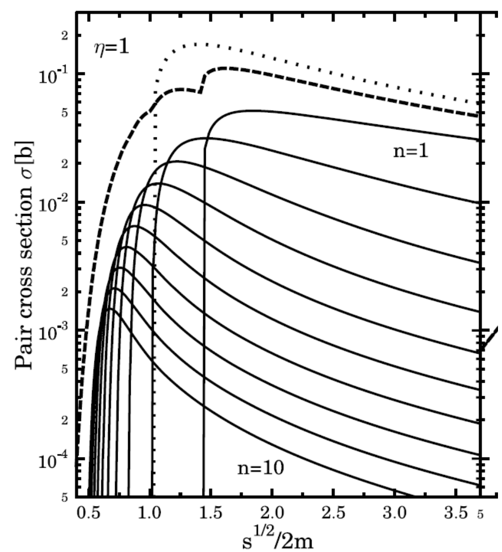
$$\sum_{i,j=0}^{2} \widetilde{C}_i^n (\widetilde{C}_j^n)^* \overline{\mathcal{M}_i \mathcal{M}_j^\dagger} = -4m_e^2 J_n^2(z) + e^2 a^2 \frac{1+u^2}{u} [J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)]$$

$$u \equiv k \cdot p / k \cdot p' \qquad z = \frac{2nu\boxed{ea}}{s_n' - m_e^{*2}} \left(\frac{s_n' + m_e^{*2} - m_\chi^2}{u} - \frac{s_n'}{u^2} - m_e^{*2} \right)^{1/2}$$

- define an intensity quantity $\eta \equiv \dfrac{ea}{m_e} = \dfrac{e\varepsilon_0}{\omega_{\mathrm{Lab}} m_e}$

-- power series expansion of η

- This result is nonperturbative in character and the nonlinear effects become important when $\eta \gtrsim 1$
- The cross section is in unit of barn



Laser-assisted search for dark particles

- dark photon (ALP): $U(1)_D$

$$\mathcal{L}_{\mathrm{DP}} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F_D^{\mu\nu}F_{D\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F_{D\mu\nu} + \frac{1}{2}m_D^2 A_D{}^{\mu}A_{D\mu}$$

$$-e\epsilon J^{\mu}_{\mathrm{EM}}A_{D\mu} = -eQ\epsilon\overline{\psi}\gamma^{\mu}\psi A_{D\mu}$$

- axion-like particle (ALP): pseudo-NG boson

$$\mathcal{L}_{\mathrm{ALP}} \supset c_{ae}\frac{\partial_{\mu}a}{2f_a}\overline{e}\gamma^{\mu}\gamma_5 e$$

$$g_{ae} = c_{ae}m_e/f_a$$

- hypothesis: invisible for m_a or $m_{\gamma_D} < 1$ MeV

- Consider the Compton scattering to DP or ALP

$$e^-(p) + n\omega(k) \to e^-(p') + \gamma_D/a(k')$$

- The new amplitude square

$$\sum_{i,j=0}^{2} \widetilde{C}_i^n (\widetilde{C}_j^n)^* \overline{\mathcal{M}_i^{\gamma_D} \mathcal{M}_j^{\gamma_D \dagger}} = -2(2m_e^2 + m_\chi^2) J_n^2(z) + e^2 a^2 \frac{1+u^2}{u} [J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)]$$

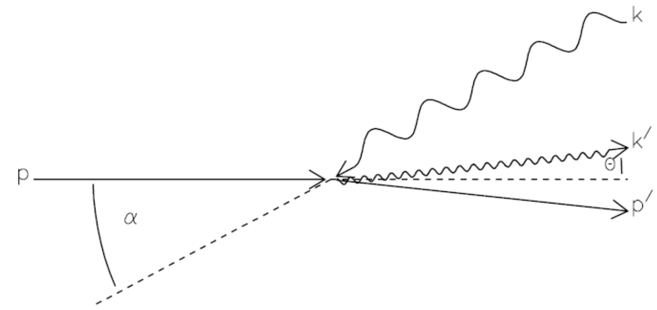
$$\sum_{i,j=0}^{2} \widetilde{C}_i^n (\widetilde{C}_j^n)^* \overline{\mathcal{M}_i^{a} \mathcal{M}_j^{a \dagger}} = -4m_e^2 m_\chi^2 J_n^2(z) + e^2 a^2 \frac{2m_e^2(1-u)^2}{u} [J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)]$$

- Experimental setup (e.g. SLAC)

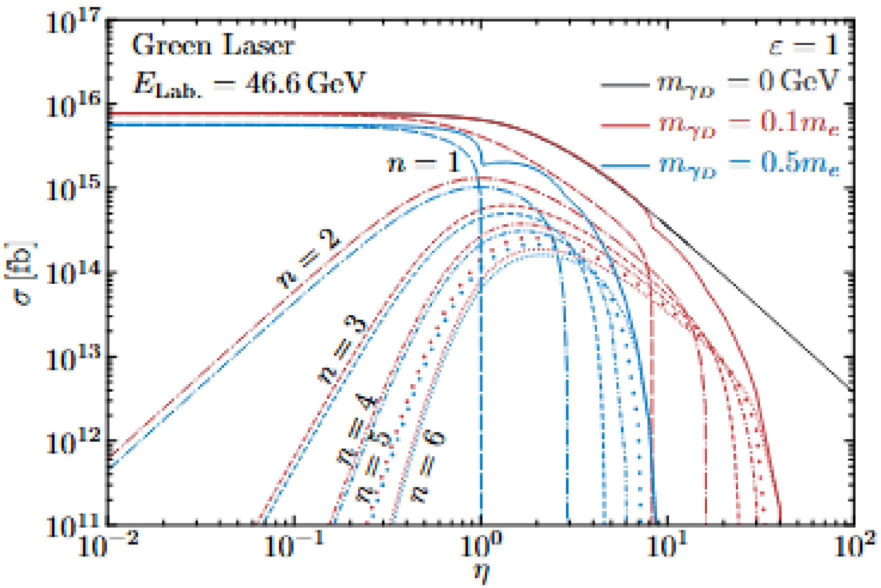
$E_{Lab} = 46.6 \text{ GeV}$

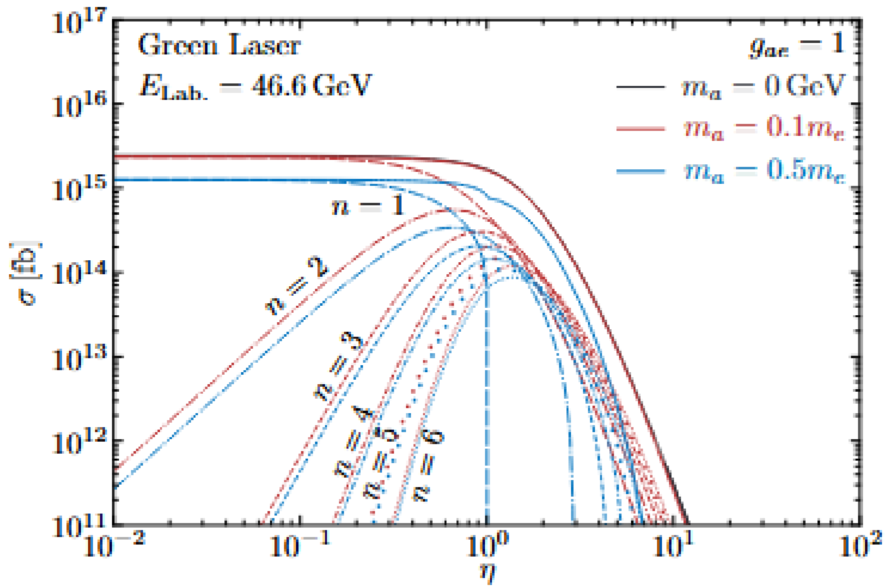
$\omega_{Lab} = 2.35 \text{ eV}$

$\theta_{Lab} = 17^{\circ}$

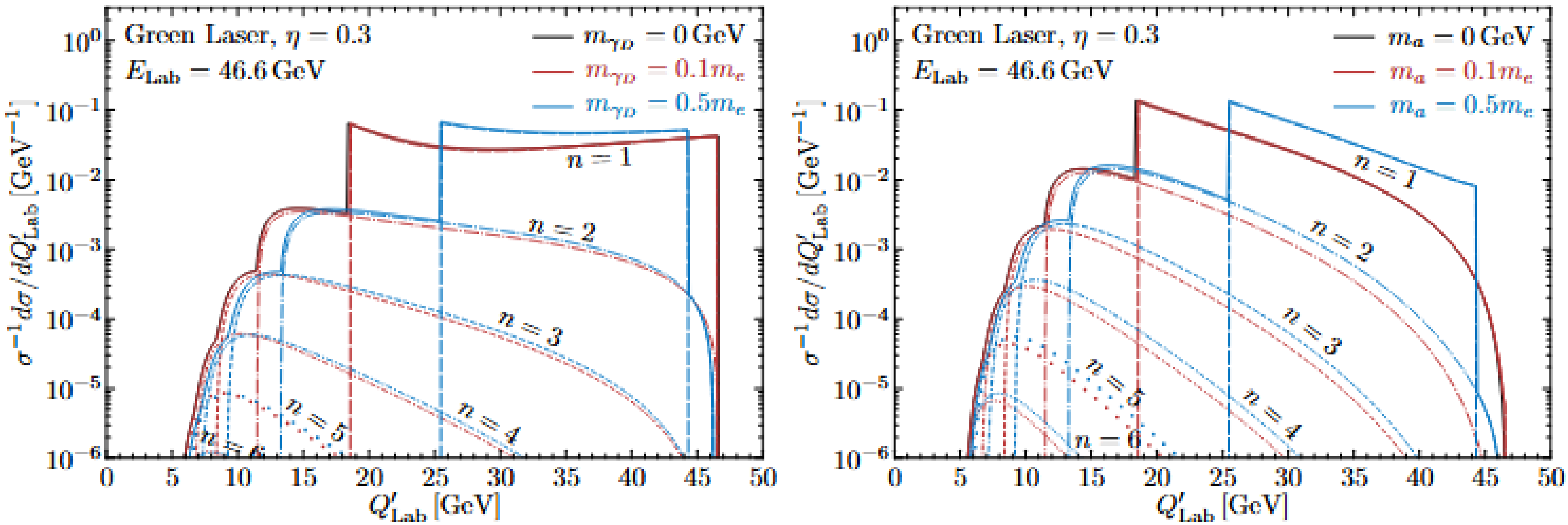


- Cross section

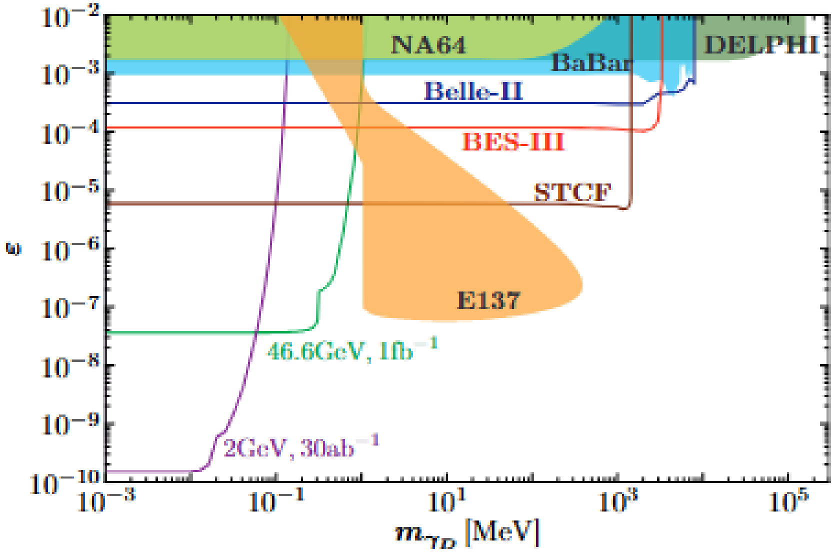


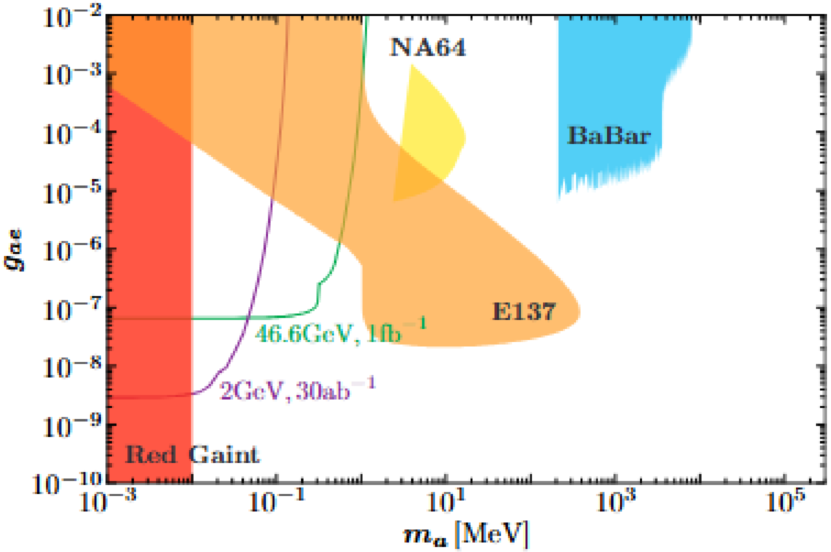


- Distribution of outgoing electron energy: edges



- Sensitivity of laser-induced Compton scattering to dark particle couplings (SM bkg: $e^- + \text{laser} \to e^- + \nu + \overline{\nu}$)
- Complementary to other beam dump and collider experiments





Summary

- The laser of an intense electromagnetic field plays as an important tool to study the strong-field particle physics and search for new physics beyond the SM
- We investigate the laser-induced Compton scattering to invisible dark photon or axion-like particle
- We find that the laser-induced process provides a complementary and competitive search of new dark particles lighter than 1 MeV

Summary

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Thank you!