Strong-field QED and intense laser impact on new physics

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第五届量子场论及其应用研讨会
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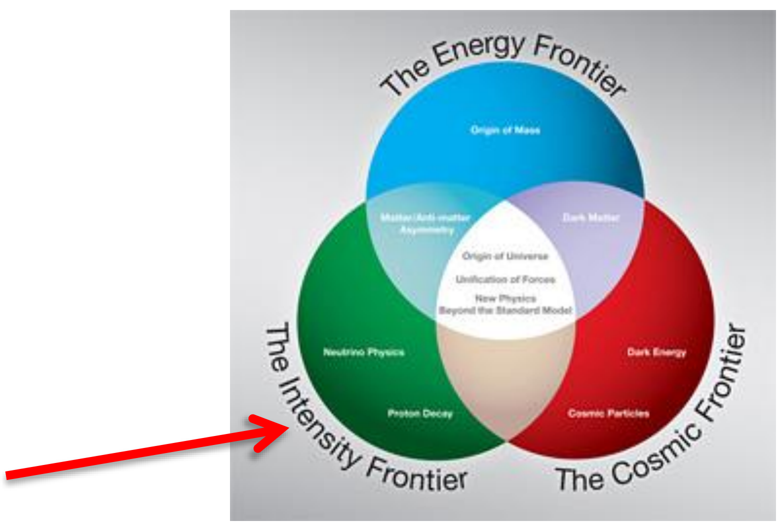
Outline

- Strong-field QED and laser-assisted Compton scattering
- Laser-assisted search for dark particles
- 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

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

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

正负电子对产生的**施温格极限场强**：

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

对应的**激光强度**：

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

Phys. Rev. 82 (1951) 664-679

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

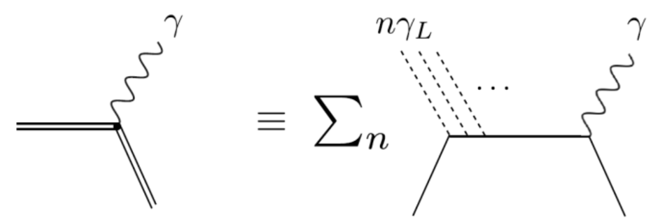
$$2VT\frac{(eE)^2}{(2\pi)^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n\pi\frac{m^2}{eE}\right]$$

- 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)

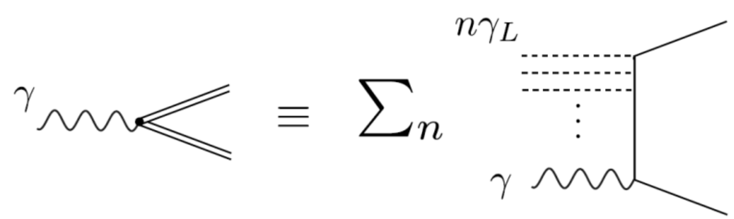
- ➢ the nonlinear Compton scattering

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

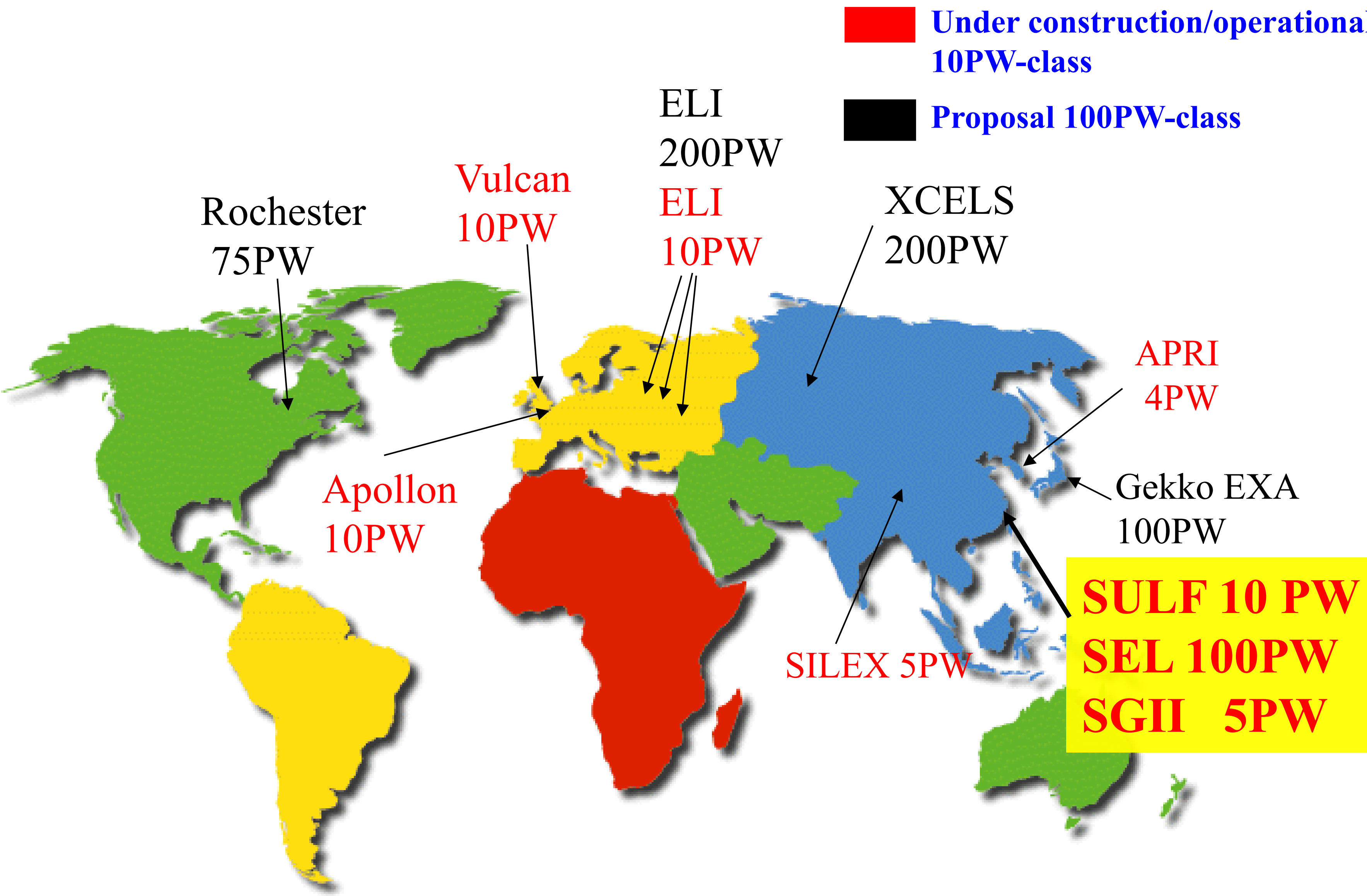


- ➢ the nonlinear Breit-Wheeler production

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

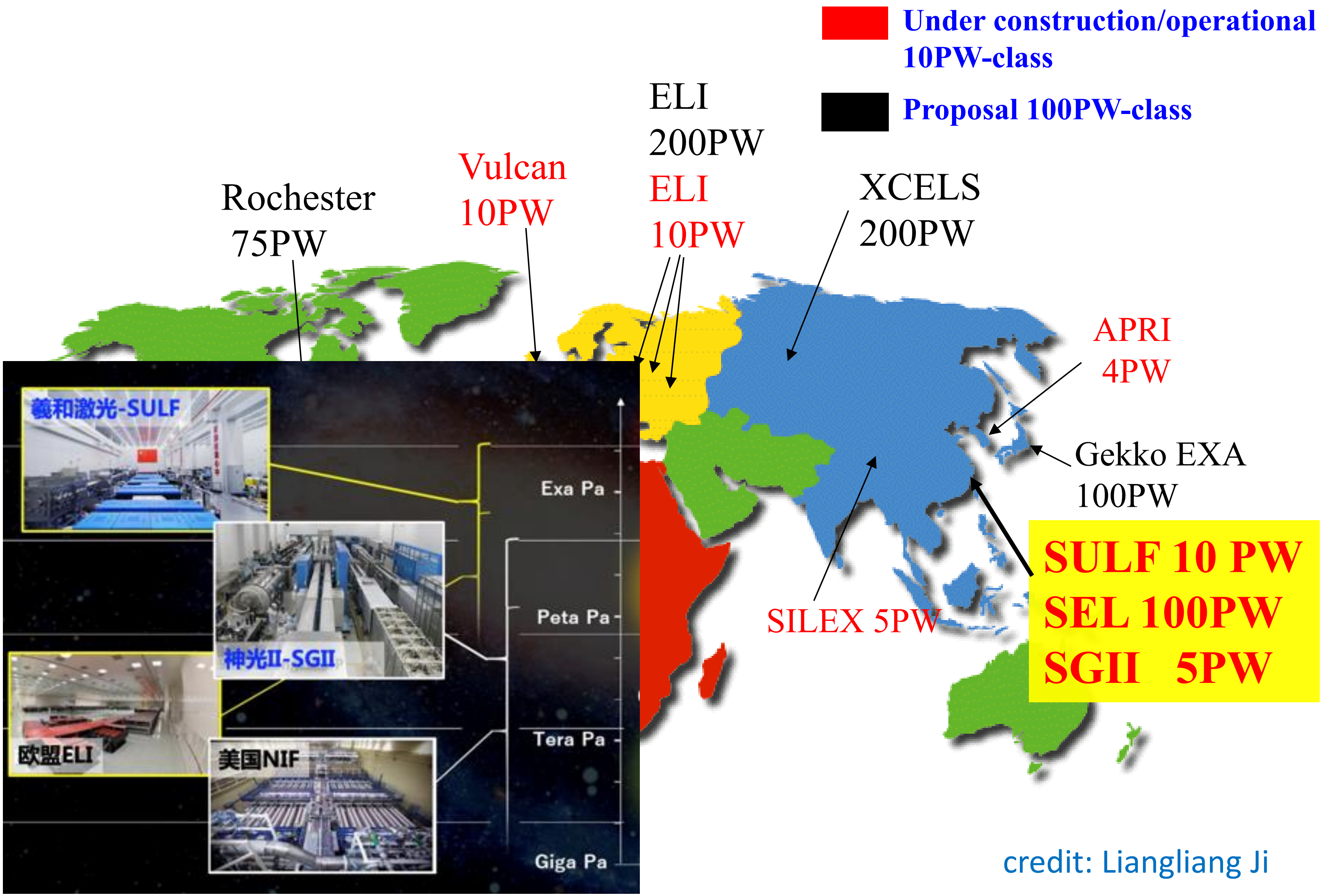


全球10-100PW级超强激光科学装置



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:

1. further studies on non-perturbative and nonlinear QED
2. investigating processes that normally do not occur in vacuum but can be induced under strong fields

Examples:

- 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)

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

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

- effective momentum and mass of the dressed electron

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

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

- High-order (nonlinear) effects in the laser field are 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 $\Phi = ea_1 \cdot y \sin\phi - ea_2 \cdot y \cos\phi$

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

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

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

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

- Finally (Jacobi-Anger expansion)

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

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

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

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

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

B functions

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

- Integrating out the coordinate x

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

- Squared S matrix and scattering cross section

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

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

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

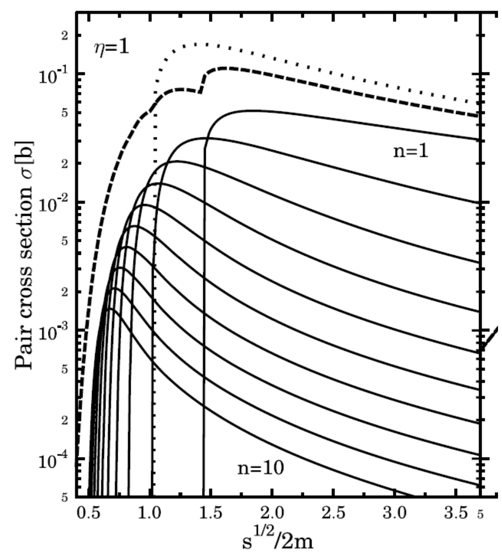
$$u \equiv k \cdot p / k \cdot p' \qquad z = \frac{2nu\boxed{ea}}{s'_n - m_e^{*2}} \left(\frac{s'_n + m_e^{*2} - m_\chi^2}{u} - \frac{s'_n}{u^2} - m_e^{*2} \right)^{1/2}$$

- define an intensity quantity

-- power series expansion of η

$$\boxed{\eta \equiv \frac{ea}{m_e} = \frac{e\varepsilon_0}{\omega_{\mathrm{Lab}} m_e}}$$

- 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): $U(1)_D$

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

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

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

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

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

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

- Consider the nonlinear Compton scattering to DP or ALP

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

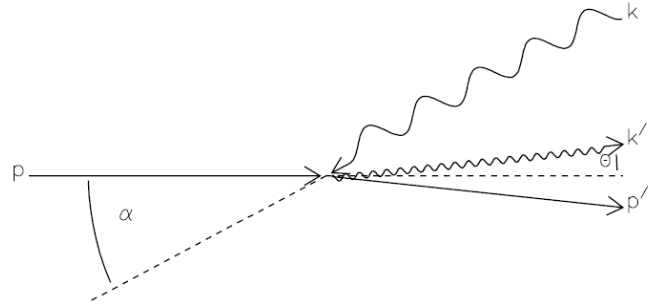
- The new amplitude square

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

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

- Experimental setup (e.g. SLAC)

$E_{Lab} = 46.6\ \mathrm{GeV}$
$\omega_{Lab} = 2.35\ \mathrm{eV}$
$\theta_{Lab} = 17^{\circ}$



- Cross section

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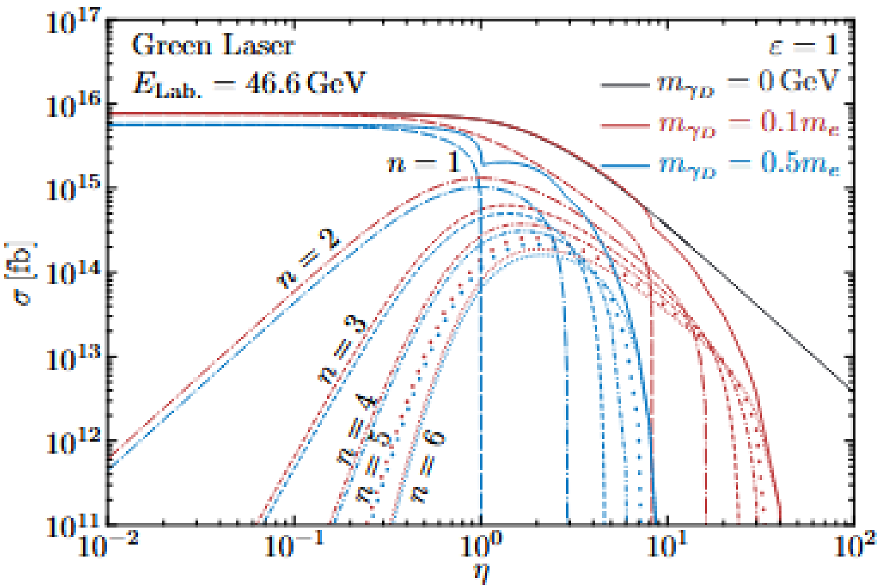
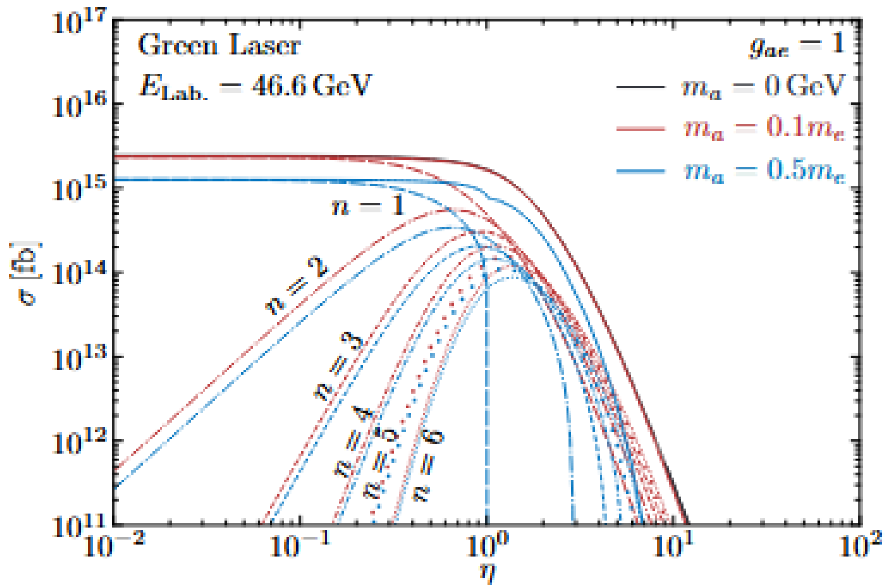
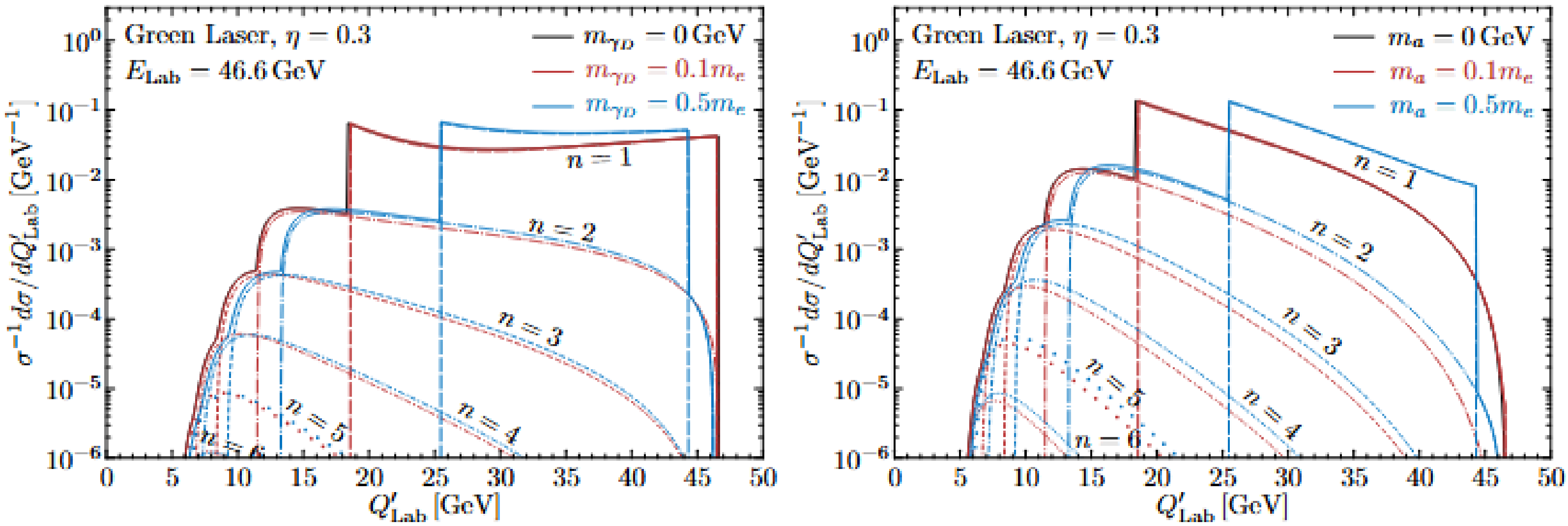




- Distribution of outgoing electron energy: edges



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- Sensitivity of laser-induced Compton scattering to dark particle couplings (SM bkg: $e^- + \text{laser} \to e^- + \nu + \overline{\nu}$)

$$\frac{S}{\sqrt{S+B}}$$

- Complementary to other beam dump and collider experiments

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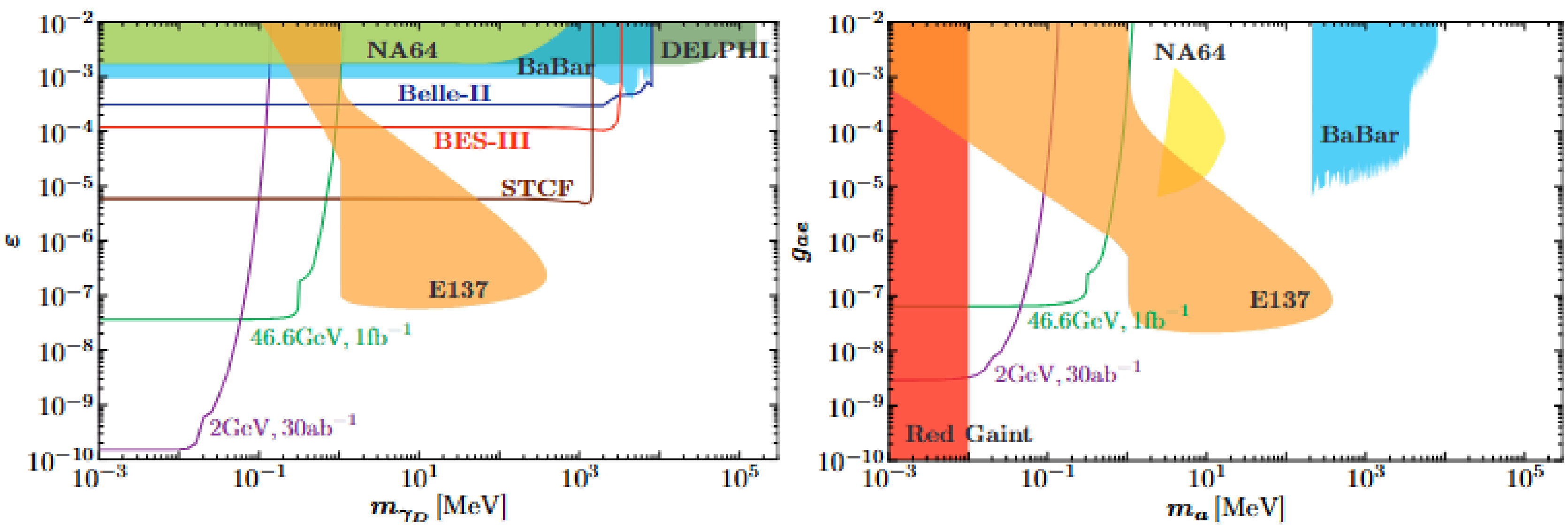

Laser-induced Compton scattering to DM in EFT

Kai Ma, TL, JHEP 07 (2025) 028

- Dirac-type fermionic DM in a leptophilic scenario

$$e^- + \mathrm{laser} \to e^- + \chi + \overline{\chi}$$

$$\begin{aligned}
&\mathcal{O}_{MD} = (\overline{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}\ , \quad \mathcal{O}_{ED} = (\overline{\chi}\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu}\ , \\
&\mathcal{O}_{SS} = (\overline{e}e)\,(\overline{\chi}\chi)\ , \quad \mathcal{O}_{SP} = (\overline{e}e)\,(\overline{\chi}i\gamma_5\chi)\ , \\
&\mathcal{O}_{PS} = (\overline{e}i\gamma_5 e)\,(\overline{\chi}\chi)\ , \quad \mathcal{O}_{PP} = (\overline{e}i\gamma_5 e)\,(\overline{\chi}i\gamma_5\chi)\ , \\
&\mathcal{O}_{VV} = (\overline{e}\gamma^\mu e)\,(\overline{\chi}\gamma_\mu\chi)\ , \quad \mathcal{O}_{VA} = (\overline{e}\gamma^\mu e)\,(\overline{\chi}\gamma_\mu\gamma_5\chi)\ , \\
&\mathcal{O}_{AV} = (\overline{e}\gamma^\mu\gamma_5 e)\,(\overline{\chi}\gamma_\mu\chi)\ , \quad \mathcal{O}_{AA} = (\overline{e}\gamma^\mu\gamma_5 e)\,(\overline{\chi}\gamma_\mu\gamma_5\chi)\ .
\end{aligned}$$

- Sensitivity of laser-induced Compton scattering to the effective cutoff scale

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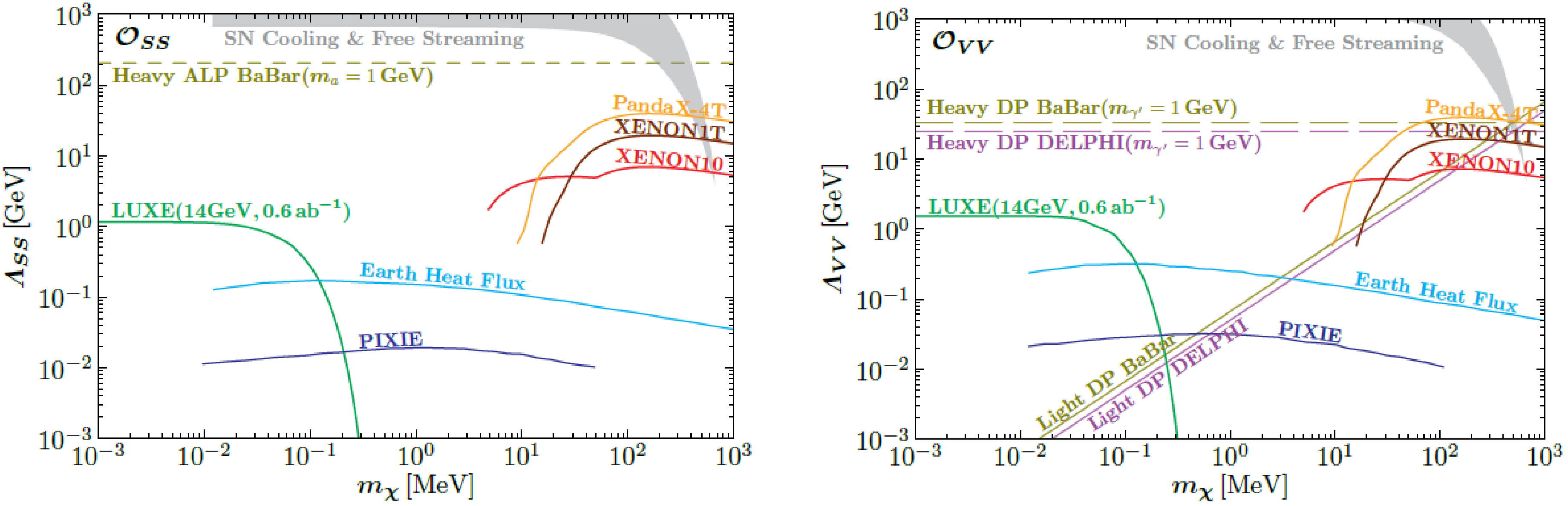

Summary

- 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 dark particles such as invisible dark photon or axion-like particle
- We find that the laser-induced process provides a complementary and competitive search of dark particles lighter than 1 MeV

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Thank you!