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Modeling of axion and electromagnetic fields interaction in particle-in-cell simulations

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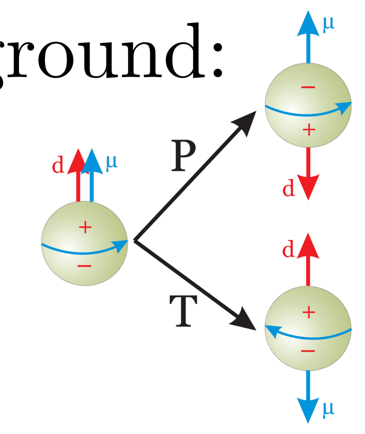
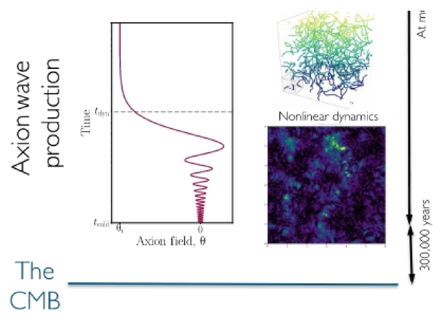
Background:



Strong CP problem → **Axion**(-like particles)

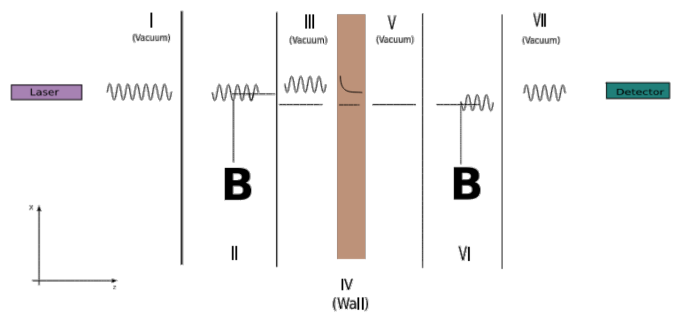
$$\mathcal{L} = \mathcal{L}_{\rm EM} + \mathcal{L}_\phi + \mathcal{L}_{\rm int},$$
$$\mathcal{L}_{\rm EM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + A_\mu j_e^\mu,$$
$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_a^2\phi^2,$$
$$\mathcal{L}_{\rm int} = -\frac{1}{4}g_{a\gamma\gamma}\phi F_{\mu\nu}G^{\mu\nu} = g_{a\gamma\gamma}\phi E\cdot B$$



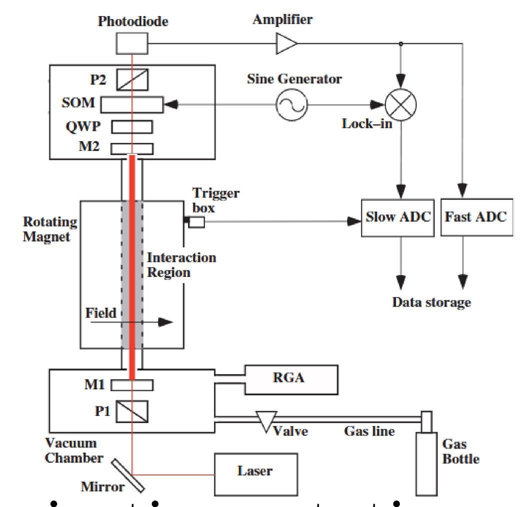
Axion dark matter

$$\left(\frac{\partial^2}{c^2\partial t^2} - \nabla^2 + \frac{m_a^2c^2}{\hbar^2}\right)\phi = \frac{g_{a\gamma\gamma}}{\hbar\mu_0}E\cdot B,$$
$$\nabla\cdot E = \frac{\rho}{\varepsilon_0} - cg_{a\gamma\gamma}B\cdot\nabla\phi,$$
$$\nabla\cdot B = 0,$$
$$\nabla\times E = -\partial_t B,$$
$$\nabla\times B = \frac{\partial}{c^2\partial t}E + \mu_0 j + \frac{g_{a\gamma\gamma}}{c}[(\partial_t\phi)B - E\times\nabla\phi].$$

Traditional detection:

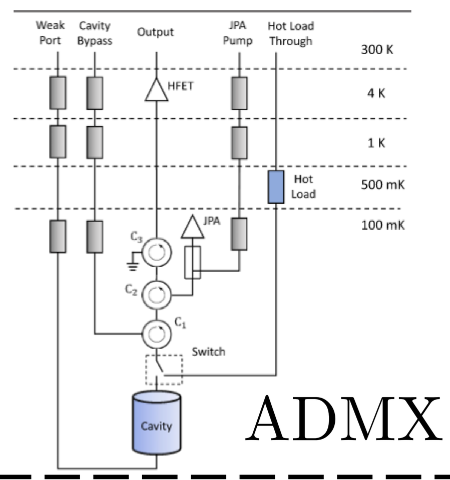


Light shining through a wall



Polarization rotation

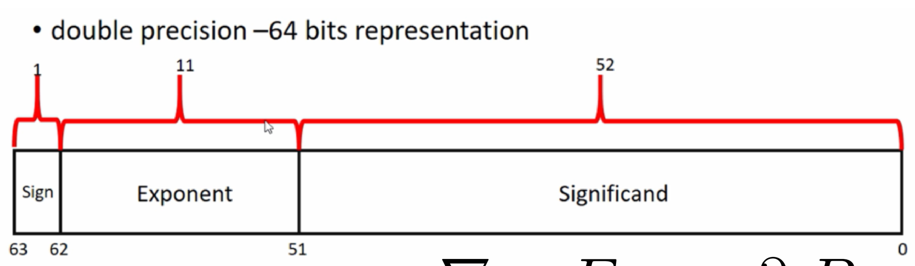
The CERN Axion Solar Telescope (CAST)



ADMX

Necessity of field perturbation sepraration (FPS)

$E(10^{14}\,\mathrm{V/m})$ ↓ generate ϕ ↓ re-generate $E_1\,(10^{-13}\,\mathrm{V/m})$



$$\nabla\times E = -\partial_t B,$$
$$\nabla\times B = \partial_t E + \mu_0 j + g_{a\gamma\gamma}[(\partial_t\phi)B - E\times\nabla\phi].$$

$E_0\&E_1$ in the code →

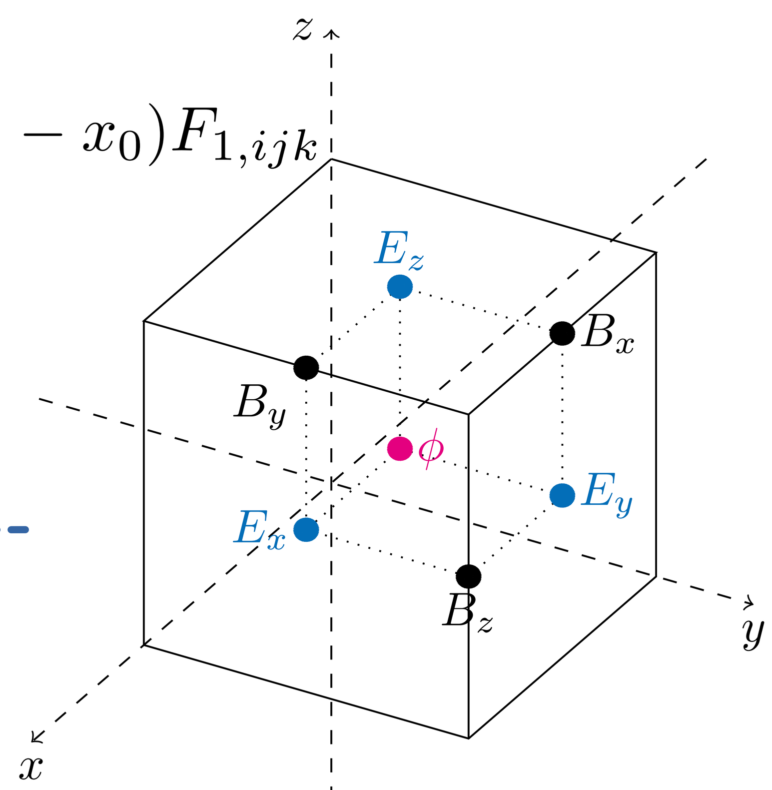
$$\nabla\times E_0 = -\partial_t B_0,$$
$$\nabla\times B_0 = \partial_t E_0 + \mu_0 j_0.$$
$$\nabla\times E_1 = -\partial_t B_1,$$
$$\nabla\times B_1 = \partial_t E_1 + \mu_0 j_1 + g_{a\gamma\gamma}[(\partial_t\phi)B_0 - E_0\times\nabla\phi].$$

Perturbation on the particle motion

$$\frac{\mathrm{d}x_1}{\mathrm{d}t} = v_1,\quad \frac{\mathrm{d}p_1}{\mathrm{d}t} = q\left(E_\mathrm{p} + v_0\times B_\mathrm{p} + v_1\times B_\mathrm{nop}\right),\quad v_1 = \frac{\partial v}{\partial p}\cdot p_1 = \frac{c}{\gamma_0^3}\left[\gamma_0^2 u_1 - u_0\left(u_0\cdot u_1\right)\right],$$

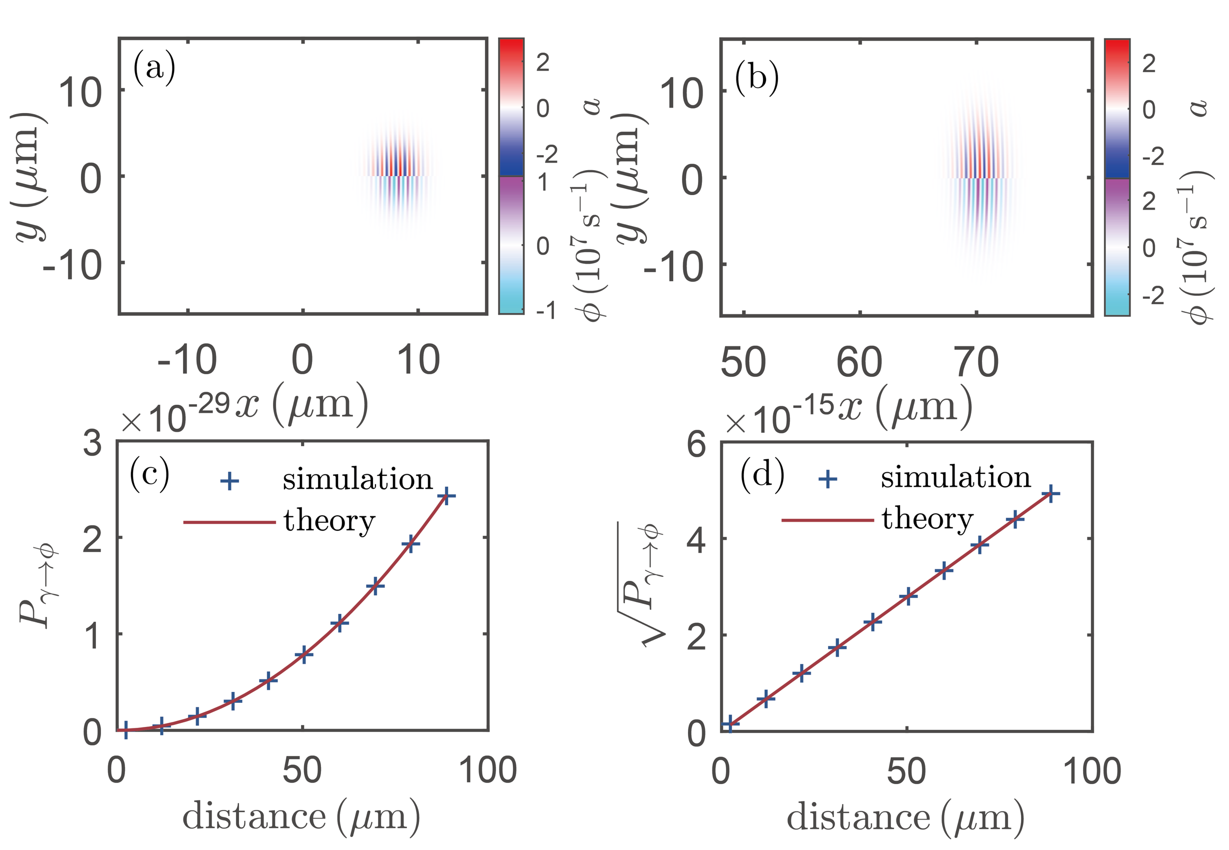
$$F|_{x=x_0+x_1} = (F_0+F_1)|_{x=x_0+x_1} \approx \sum_{ijk} S(r_{ijk}-x_0)F_{0,ijk} + \sum_{ijk}\left[\left.\frac{\partial S(r_{ijk}-x)}{\partial x}\right|_{x=x_0}\cdot x_1\right]F_{0,ijk} + \sum_{ijk} S(r_{ijk}-x_0)F_{1,ijk}$$

$$(j_0+j_1)_{ijk} = \frac{q}{\Delta V}\left[S(r_{ijk}-x_0-x_1)\left(v_0+v_1\right)\right] \approx \frac{q}{\Delta V}S(r_{ijk}-x_0)v_0 + \frac{q}{\Delta V}\left[\left.\frac{\partial S(r_{ijk}-x)}{\partial x}\right|_{x=x_0}\cdot x_1\right]v_0.$$

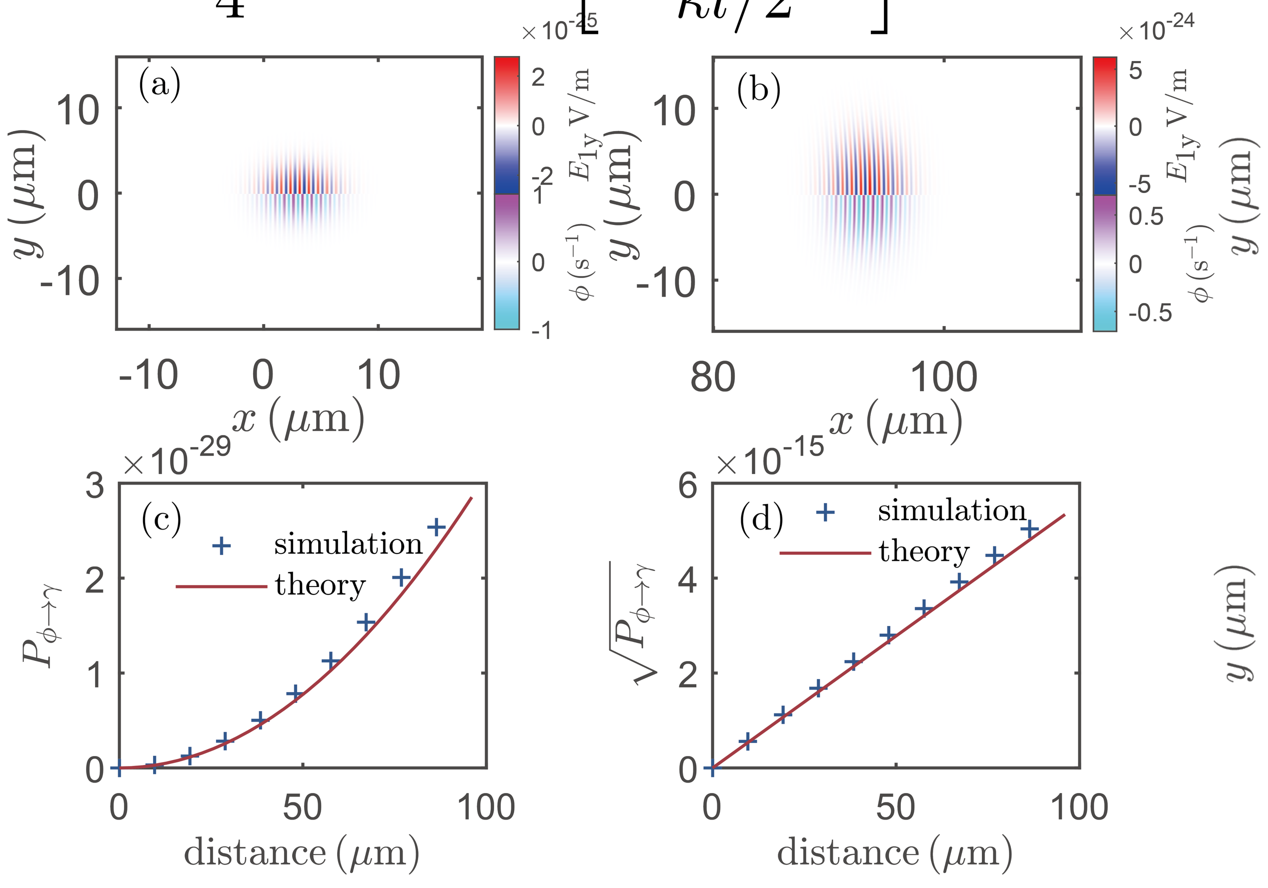


Benchmarks:

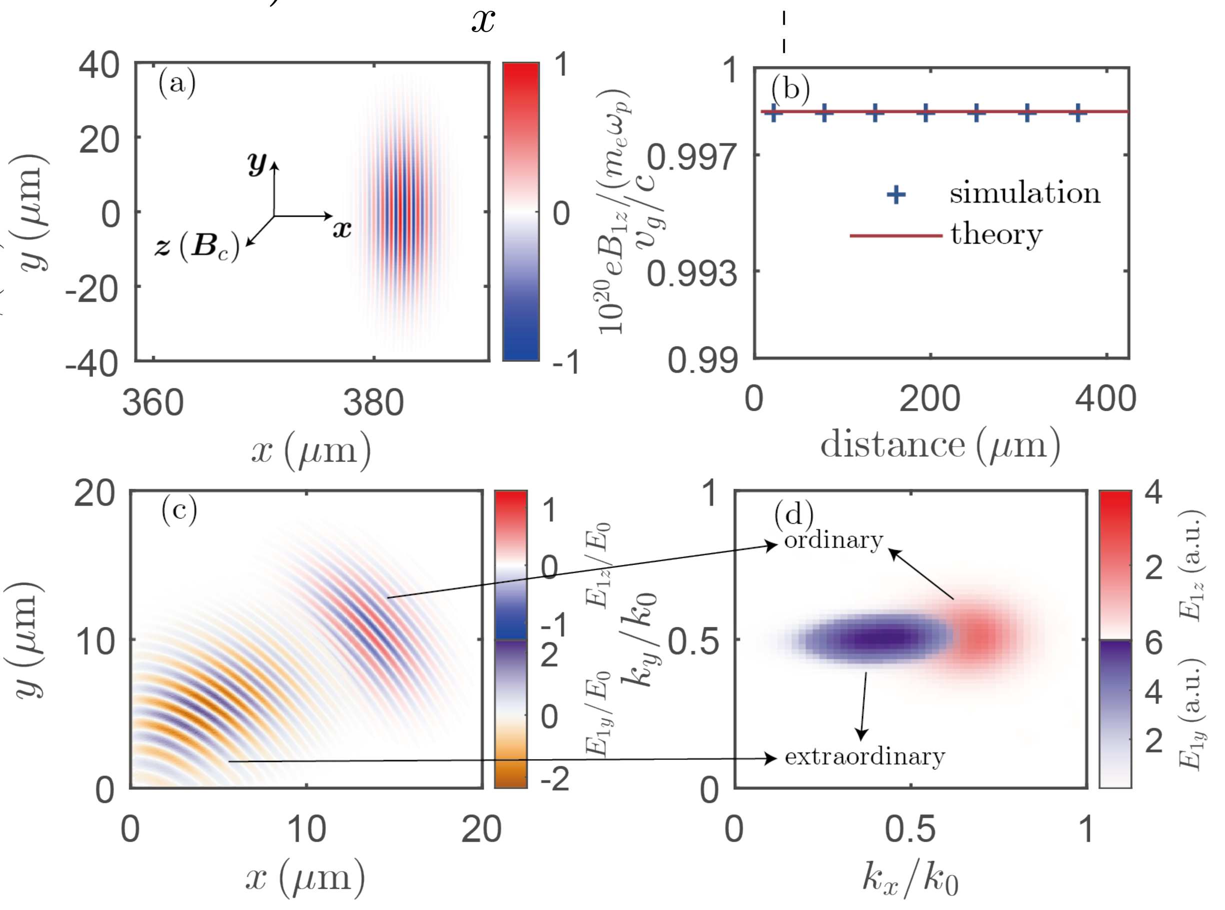
In a constant magnetic field: $P_{\gamma\to\phi} = P_{\phi\to\gamma} \approx \frac{1}{4}\left(g_{a\gamma\gamma}B_0 l\right)^2\left[\frac{\sin(\kappa l/2)}{\kappa l/2}\right]^2,$ (natural units)



Axion generation



Axion conversion



FPS model (birefringence)
Weak laser in strong background

Summary:

1)Model the axion field and its interaction with EM field in the PIC code.

2)Use the FPS model to handle the weak modulation of axion on EM fields.

3)Benchmark of the axion generation, conversion, and FPS model.

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