Laser plasma wakefield based axion generation and detection

Min Chen, Xiang-Yan An, Jiang-Lai Liu, Liang-Liang Ji, Zhai Bai,
Zheng-Ming Sheng, and Jie Zhang
minchen@sjtu.edu.cn

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

2025-04-17

LPAW, 13–19 Apr 2025 Hotel Continental, Ischia Island (Naples, Italy)

Outline

- Axion – a candidate particle of dark matter being searched for globally
- Modelling axion-photon interaction in a PIC code
- Laser wakefield based axion generation and detection
- Summary

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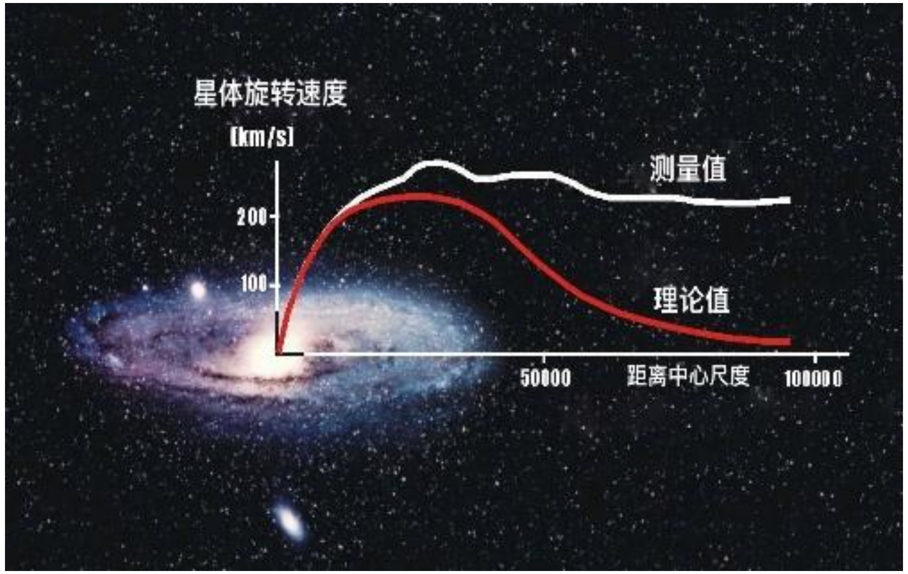
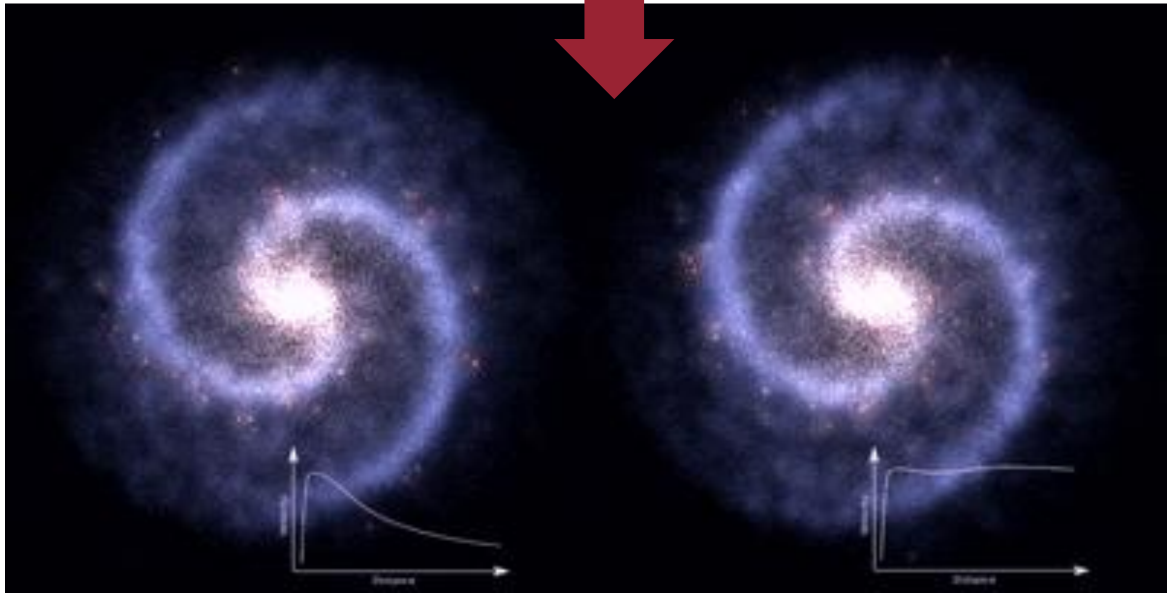
Astronomical evidence for the existence of dark matter

Galaxy Rotation Curves



A large amount of dark matter is needed to provide stronger gravitational force.



Dark matter mainly participates in gravitational interactions. It has very weak interactions with the particles of the Standard Model and is extremely difficult to detect directly. Therefore, it is almost "invisible".

Types of dark matter and their proportions in the universe

candidate types of dark matter

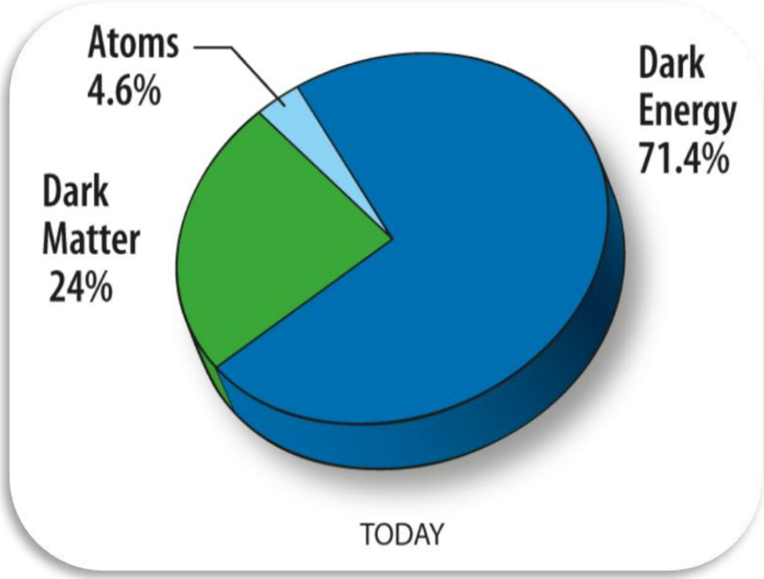
WIMPs

Axions/ALPs

Sterile Neutrinos

Small Black Holes

Mixed Scenario

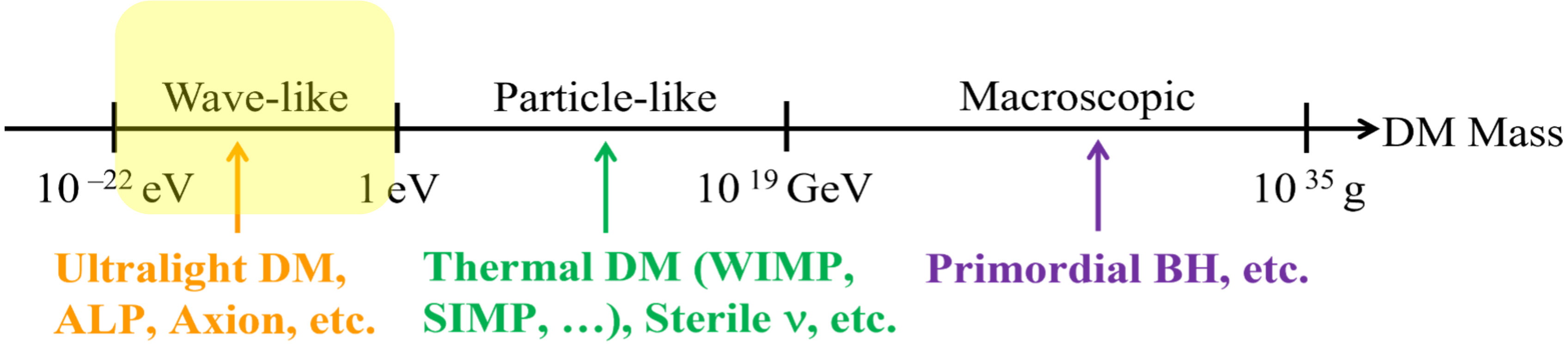


Theoretically well-motivated

1. Correct abundance

2. Stable/Long lived

3. Multiple puzzles hints



Axion in universe

Axion star

PRL **117,** 121801 (2016) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2016

Dense Axion Stars

Eric Braaten,* Abhishek Mohapatra,† and Hong
Department of Physics, The Ohio State University, Columbus,
(Received 8 December 2015; revised manuscript received 8 July 2016; p

If the dark m
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study axion star
theory for axion
pressure of the
about $M_\odot$. If a
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DOI: 10.1103/Ph

REVIEWS OF MODERN PHYSICS, VOLUME 91, OCTOBER–DECEMBER 2019

***Colloquium*: The physics of axion stars**

Eric Braaten
Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

T31, Technische Universität München, Germany

)ctober 2019)

es up the dark matter of the Universe could
s can condense into a bound Bose-Einstei
significant fraction of the axion dark mat
ne efforts to identify the axion as the dark
en up new possibilities. The basic proper
l or bound by self-interactions, are su
vistic field theory with a real scalar fiel
y by a classical nonrelativistic effective f

'hys.91.041002

PHYSICAL REVIEW D **108,** 103038 (2023)

Can planet 9 be an axion star?

Haoran Di* and Haihao Shi
School of Science, East China University of Technology, Nanchang 330013, China

(Received 5 September 2023; accepted 18 October 2023; published 27 November 2023)

The anomalous orbits of trans-Neptunian objects (TNOs) can be explained by the planet 9 hypothesis. We propose that the planet 9 can be an axion star. Axion stars are gravitational bound clusters condensed by QCD axions or axionlike particles (ALPs), which we call axions for brevity. We find that the probability of capturing an axion star by the solar system is the same order of magnitude as the probability of capturing a free floating planet (FFP), and even higher for the case of axion star, with axion star mass $5M_\oplus \approx 1.5 \times 10^{-5} M_\odot$ and $\Omega_{AS}/\Omega_{DM} \simeq 1/10$. Although axion star can emit monochromatic signals through two-photon decay, we find that the frequency of decay photon is either not within the frequency range of the radio telescope, or the decay signal is too weak to be detected. Therefore, if planet 9 is composed by an axion star, it may be difficult to distinguish it from an isolated primordial black hole by spontaneous decay of axion.

PHYSICAL REVIEW D **109,** 043018 (2024)

Axion star explosions: A new source for axion indirect detection

Miguel Escudero,[1,*] Charis Kaur Pooni,[2,†] Malcolm Fairbairn,[2,‡] Diego Blas,[3,4,§] Xiaolong Du,[5,6,∥] and David J. E. Marsh[2,¶]
[1]*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
[2]*Physics, King's College London, Strand, London WC2R 2LS, United Kingdom*
[3]*Grup de Física Teòrica, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[4]*Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain*
[5]*Carnegie Observatories, 813 Santa Barbara Street, Pasadena, California 91101, USA*
[6]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*

Axion laser

PHYSICAL REVIEW LETTERS **120,** 231102 (2018)

Editors' Suggestion

Stimulated Axion Decay in Superradiant Clouds around Primordial Black Holes

João G. Rosa[1,*] and Thomas W. Kephart[2,†]
[1]*Departamento de Física da Universidade de Aveiro and CIDMA, Campus de Santiago, Aveiro 3810-183, Portugal*
[2]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*

(Received 29 September 2017; revised manuscript received 21 March 2018; published 4 June 2018)

The superradiant instability can lead to the generation of extremely dense axion clouds around rotating black holes. We show that, despite the long lifetime of the QCD axion with respect to spontaneous decay into photon pairs, stimulated decay becomes significant above a minimum axion density and leads to extremely bright lasers. The lasing threshold can be attained for axion masses $\mu \gtrsim 10^{-8}$ eV, which implies superradiant instabilities around spinning primordial black holes with mass $\lesssim 0.01\ M_\odot$. Although the latter

universe MDPI

Review

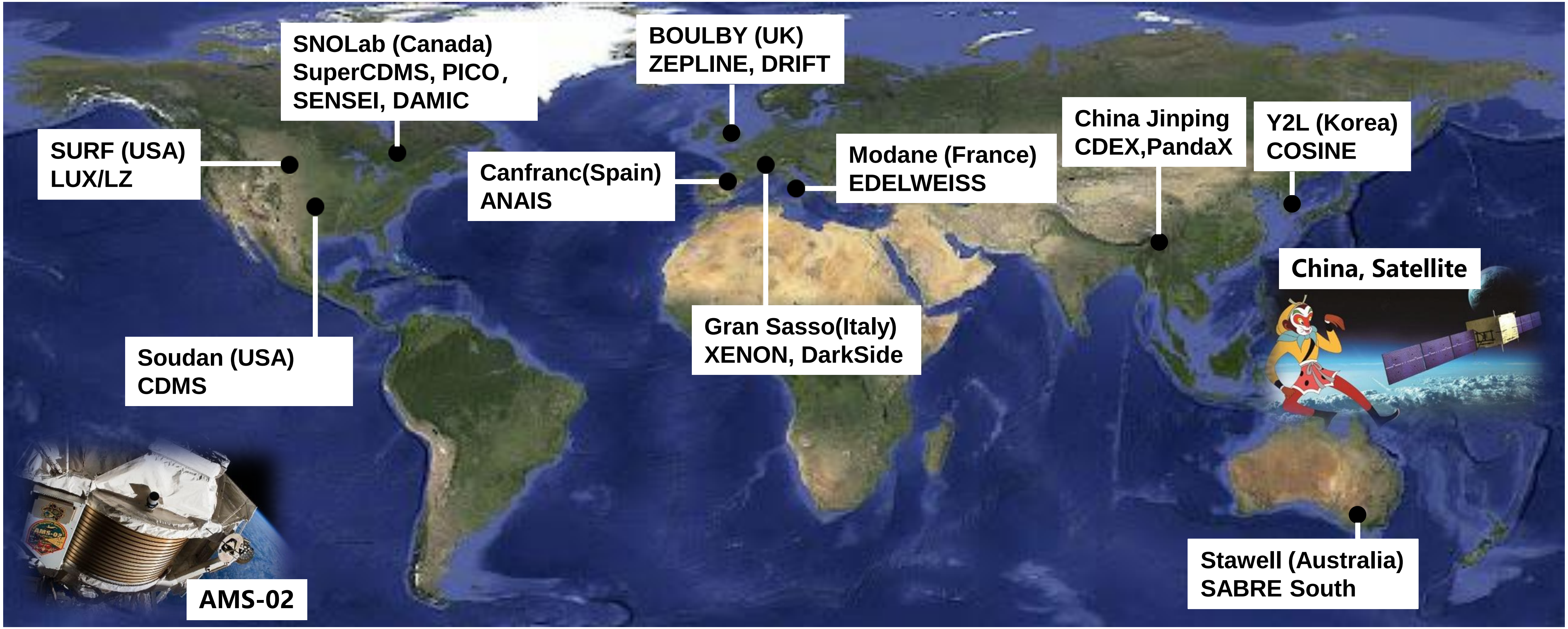
A Review of Axion Lasing in Astrophysics

Liang Chen [1,2,†] and Thomas W. Kephart [3,*,†]

[1] School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China; bqipd@protonmail.com
[2] University of Chinese Academy of Sciences, Beijing 100190, China
[3] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA
* Correspondence: tom.kephart@gmail.com
† These authors contributed equally to this work.

Abstract: Axions can be stimulated to decay into photons by ambient photons of the right frequency or by photons from the decay of neighboring axions. If the axion density is high enough, the photon intensity can be amplified, which is a type of lasing or an axion maser. Here, we review the astrophysical situations where axion lasing can appear and possibly be detected.

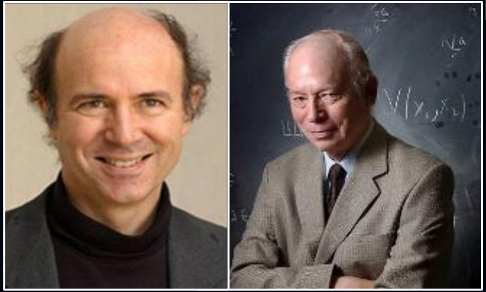
Various detection schemes are being used to search dark matter



A special dark matter candidate particle – axion & its interaction with electromagnetic fields

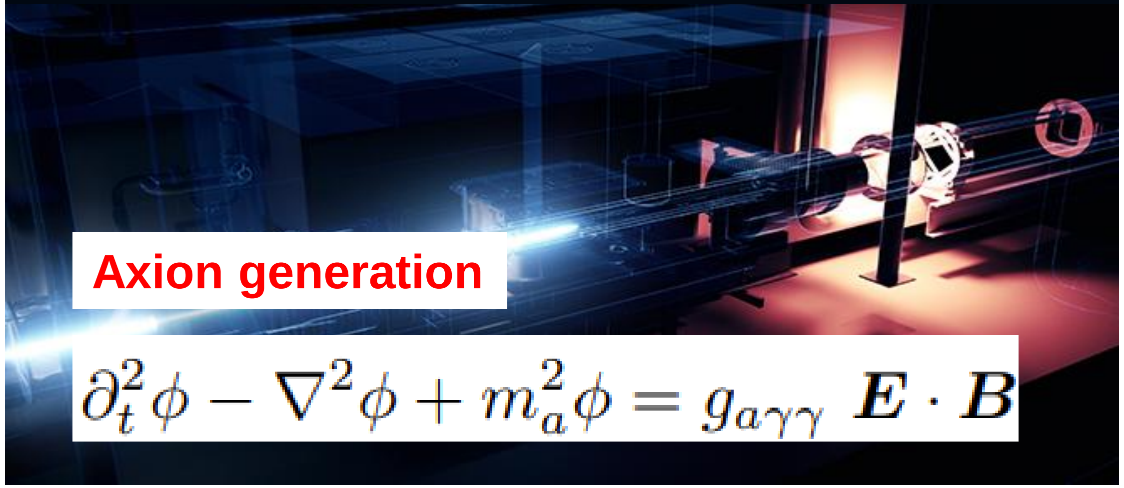
- Axions are theoretically proposed particles that emerge after the introduction of spontaneous symmetry breaking in quantum chromodynamics and possess electromagnetic interactions.

Frank Wilczek　　Steve Weinberg



$$\mathcal{L}_\Theta = \Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu} \to \mathcal{L}_a = \frac{a}{f_a}\frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$$

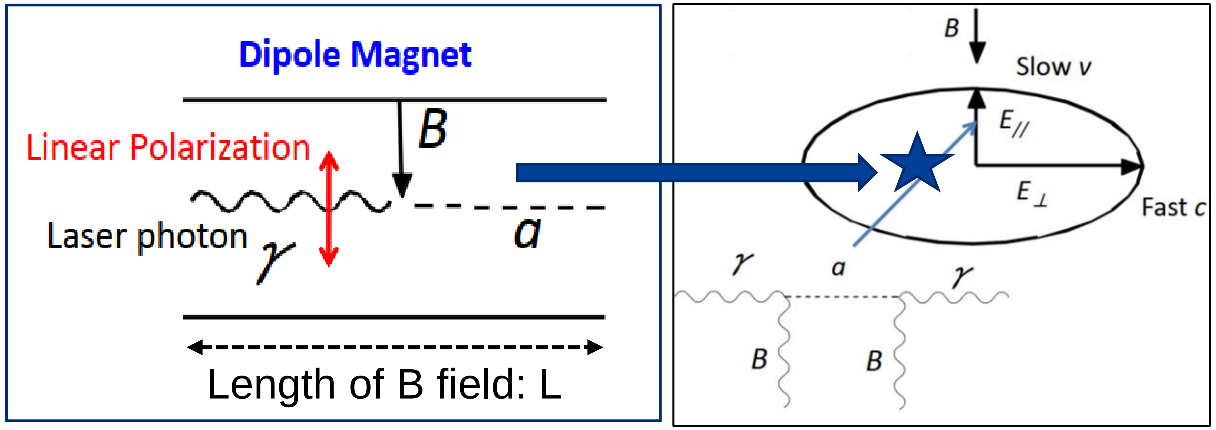
$$\mathcal{L}_{a\gamma\gamma} = -g_r \frac{\alpha}{\pi}\frac{a(x)}{f_a}\vec{E}\cdot\vec{B}$$



Axion generation

$$\partial_t^2\phi - \nabla^2\phi + m_a^2\phi = g_{a\gamma\gamma}\,\boldsymbol{E}\cdot\boldsymbol{B}$$

Primakoff effect



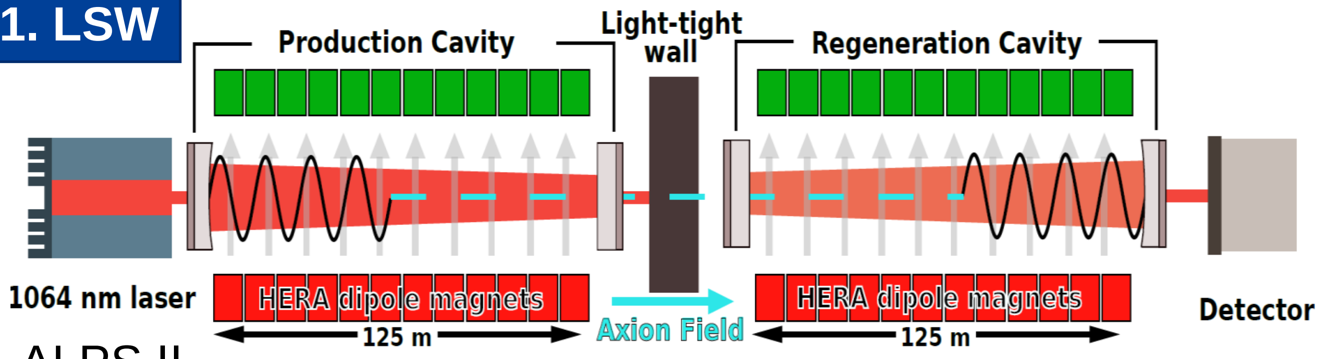
Conversion efficiency $\propto (\boldsymbol{BL})^2$

Lab	B field	length
Fermi：　GammeV	5 T	6 m
CERN: LHC	10 T	10 m

Current existing detection methods of axions

1. Light-shining-through-walls
2. Polarisation of Vacuum with LASe
3. The CERN Axion Solar Telescope

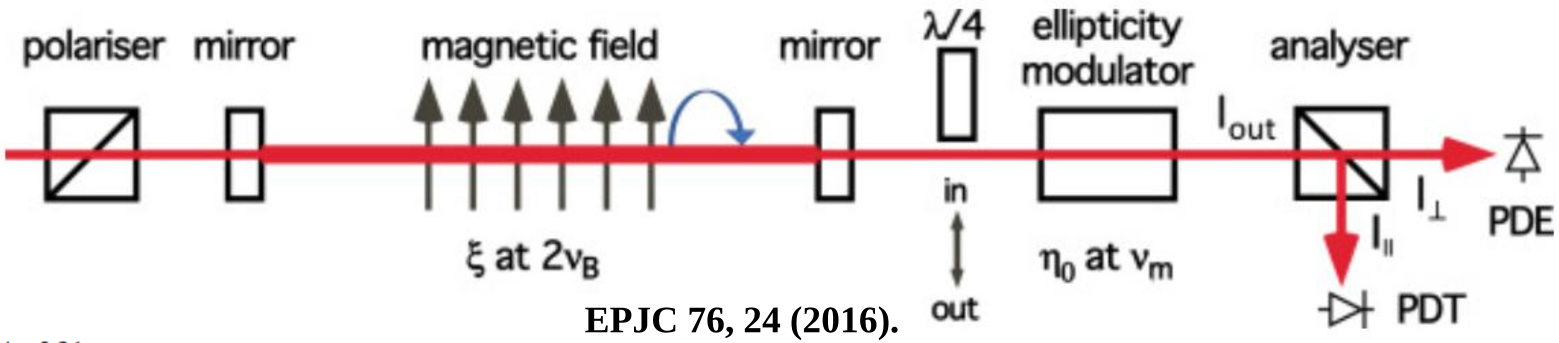
1. LSW



ALPS II
468Tm

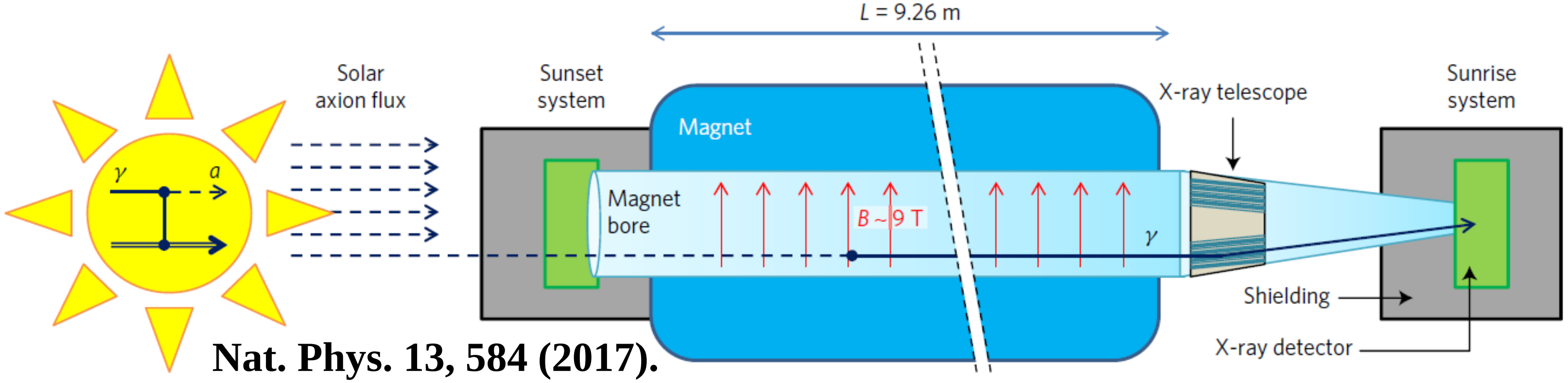
JINST 8, T09001 (2013).
PRD 92, 092002 (2015).

2. PVLAS



EPJC 76, 24 (2016).

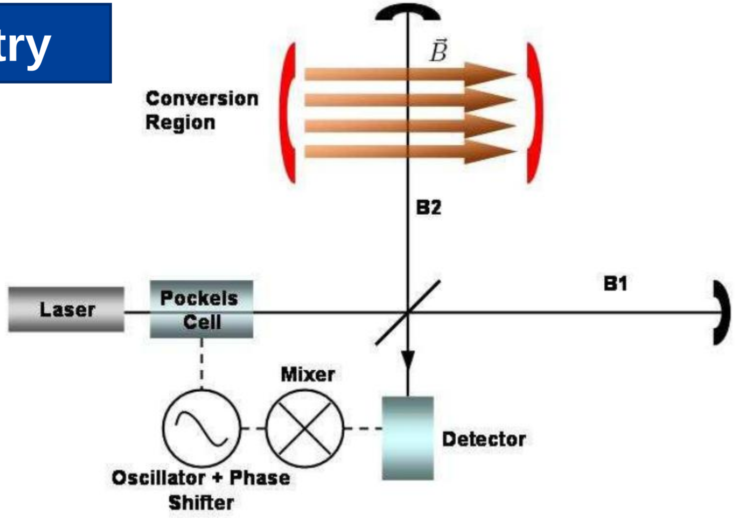
3. CAST, IAXO



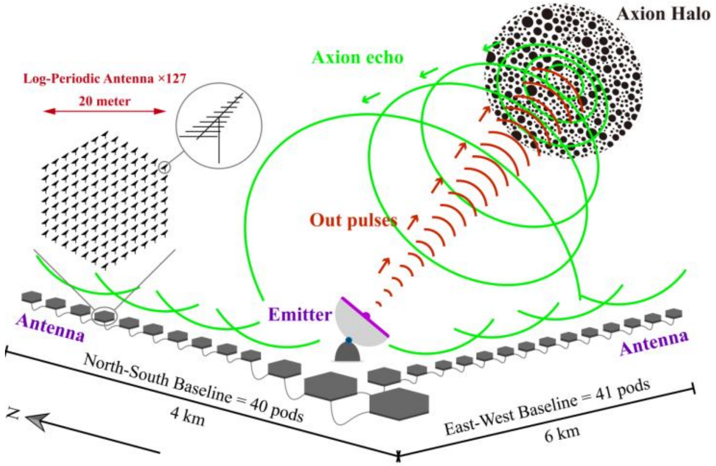
Nat. Phys. 13, 584 (2017).

Current existing detection methods of axions

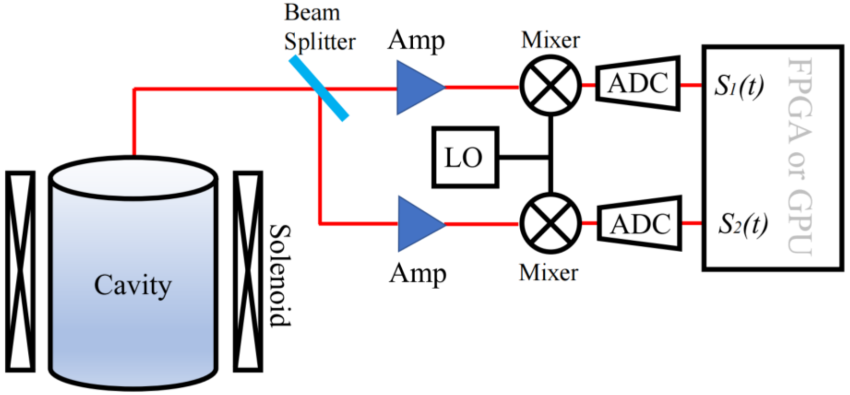
4. Interferometry



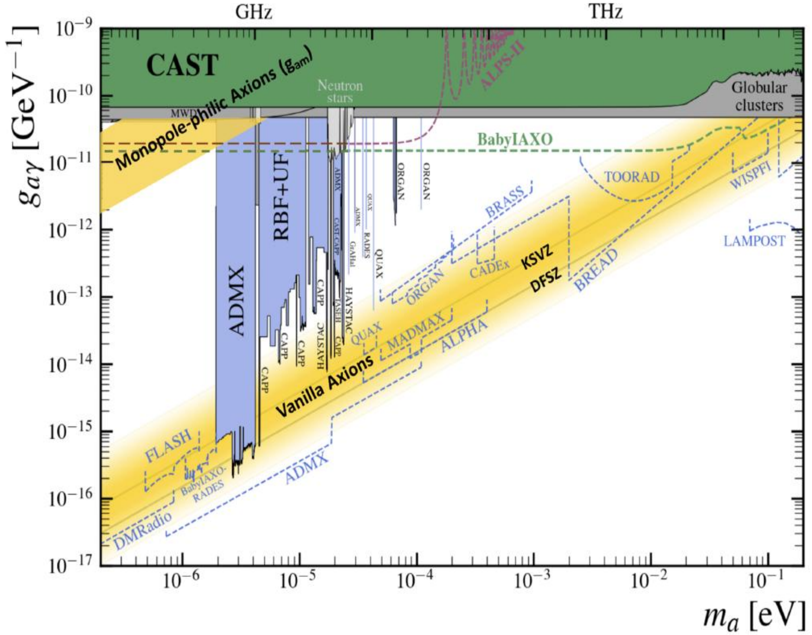
6. Axion Echo



5. Quantum interferometry



Regions which has been excluded



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Developing a simulation tool for axion in plasma

Matter and
Radiation at Extremes
RESEARCH ARTICLE
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Featured

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

Cite as: Matter Radiat. Extremes 9, 067204 (2024); doi: 10.1063/5.0226159
Submitted: 29 June 2024 • Accepted: 21 August 2024 •
Published Online: 20 September 2024

View Online
Export Citation

Xiangyan An,[1,2,3] Min Chen,[1,2,a)] Jianglai Liu,[3] Zhengming Sheng,[1,2,3] and Jie Zhang[1,2,3]

For details, please go to the POSTER session.

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

15 Apr 2025, 17:00
1h 40m
Hotel Continental, Ischia Island (Naples, Italy)

Poster (participant)
Theory and simulati...
Poster Session

Speaker

Xiangyan An (Tsung-Dao Lee Institute, Shanghai Jiao Tong University, China)

Coupling of axion and EM fields

$$\mathcal{L} = \mathcal{L}_{\rm EM} + \mathcal{L}_\phi + \mathcal{L}_{\rm int},$$

$$\mathcal{L}_{\rm EM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + A_\mu j_e^\mu,$$

$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_a^2\phi^2,$$

$$\mathcal{L}_{\rm int} = -\frac{1}{4}g_{\phi\gamma\gamma}\phi F_{\mu\nu}G^{\mu\nu} = g_{\phi\gamma\gamma}\phi \boldsymbol{E}\cdot\boldsymbol{B}$$

Interaction between axion and photon

$$\nabla\cdot\boldsymbol{E} = \rho \boxed{- g_{\phi\gamma\gamma}\boldsymbol{B}\cdot\nabla\phi},$$

$$\nabla\cdot\boldsymbol{B} = 0,$$

$$\nabla\times\boldsymbol{E} = -\partial_t\boldsymbol{B},$$

$$\nabla\times\boldsymbol{B} = \partial_t\boldsymbol{E} + \boldsymbol{j} + \boxed{g_{\phi\gamma\gamma}[(\partial_t\phi)\boldsymbol{B} - \boldsymbol{E}\times\nabla\phi]}$$

Extremely small
How to include it?

Eq. of axion $\partial_t^2\phi - \nabla^2\phi + m_a^2\phi = g_{a\gamma\gamma}\,\boldsymbol{E}\cdot\boldsymbol{B}$

We use field perturbation separation method to describe the axion generated EM field to avoid the numerical noise

Field Perturbation Separation （FPS） method：

Considering $E = E_0 + E_1$， $B = B_0 + B_1$， E_0, B_0 satisfy the Maxwell Eqs. w/o axion $\nabla \times \boldsymbol{B}_0 = \partial_t \boldsymbol{E}_0 + \boldsymbol{j}_0.$

The axion generated E_1, B_1 satisfies:

$$\nabla \cdot \boldsymbol{E}_1 = \frac{\rho_1}{\varepsilon_0} - c g_{a\gamma\gamma} \boldsymbol{B}_0 \cdot \nabla\phi,$$
$$\nabla \cdot \boldsymbol{B}_1 = 0,$$
$$\nabla \times \boldsymbol{E}_1 = -\partial_t \boldsymbol{B}_1,$$
$$\nabla \times \boldsymbol{B}_1 = \frac{\partial}{c^2 \partial t}\boldsymbol{E}_1 + \mu_0 \boldsymbol{j}_1 + \frac{g_{a\gamma\gamma}}{c}[(\partial_t\phi)\boldsymbol{B}_0 - \boldsymbol{E}_0 \times \nabla\phi].$$

We solve two sets of Maxwell Equations at the same time to include the axion generated EM fields.

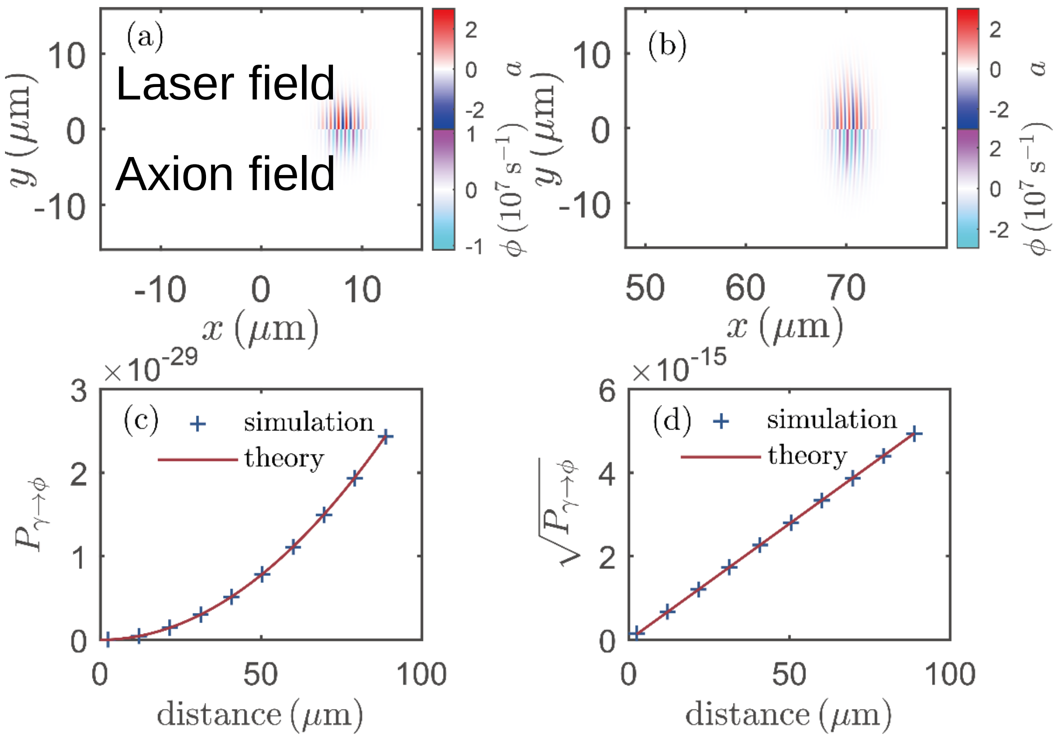
The perturbated current j_1 $\quad \boldsymbol{x} = \boldsymbol{x}_0 + \boldsymbol{x}_1,\ \boldsymbol{p} = \boldsymbol{p}_0 + \boldsymbol{p}_1,\ \boldsymbol{v} = \boldsymbol{v}_0 + \boldsymbol{v}_1,$

The force felt by the particle $(F = E_{x,y,z},\ B_{x,y,z})$：

$$\begin{aligned} F|_{\boldsymbol{x}=\boldsymbol{x}_0+\boldsymbol{x}_1} &= (F_0 + F_1)|_{\boldsymbol{x}=\boldsymbol{x}_0+\boldsymbol{x}_1} = \sum_{ijk} S(\boldsymbol{r}_{ijk} - \boldsymbol{x}_0 - \boldsymbol{x}_1)\left(F_{0,ijk} + F_{1,ijk}\right) \\ &= \sum_{ijk} S(\boldsymbol{r}_{ijk} - \boldsymbol{x}_0) F_{0,ijk} \\ &\quad + \underline{\sum_{ijk}\left[\frac{\partial S(\boldsymbol{r}_{ijk} - \boldsymbol{x})}{\partial \boldsymbol{x}}\Bigg|_{\boldsymbol{x}=\boldsymbol{x}_0} \cdot \boldsymbol{x}_1\right] F_{0,ijk} + \sum_{ijk} S(\boldsymbol{r}_{ijk} - \boldsymbol{x}_0) F_{1,ijk}} \\ &= F_{\text{nop}} + \boxed{F_p} \end{aligned}$$

Perturbation force

Code benchmark: axion generation by a laser field in a background static B field



$$m = 10^{-3}\ \text{eV},\ g_{\phi\gamma\gamma} = 2.65\times 10^{-13}\ \text{GeV}^{-1}.$$

$$\lambda_0 = 800\,\text{nm},\ a_0 = 3,\ B_0 = 423\,\text{T}.$$

The theory prediction of the photon-axion conversion rate

$$P_{\gamma\to\phi} = P_{\phi\to\gamma} \approx \frac{1}{4}\left(g_{\phi\gamma\gamma}B_0 l\right)^2\left[\frac{\sin\left(\kappa l/2\right)}{\kappa l/2}\right]^2, \qquad \text{(natural units)}$$

$$P_{\gamma\to\phi} = P_{\phi\to\gamma} \approx \frac{c}{4\mu_0\hbar}\left(g_{\phi\gamma\gamma}B_0 l\right)^2\left[\frac{\sin\left(\kappa l/2\right)}{\kappa l/2}\right]^2, \qquad \text{(SI units)}$$

Conversion efficiency

$$P_{\gamma\to\phi,\text{sim}} = \frac{H_\phi}{H_\gamma} = \frac{\iint \mathcal{H}_\phi\,\mathrm{d}x\mathrm{d}y}{\iint \mathcal{H}_\gamma\,\mathrm{d}x\mathrm{d}y},$$

$$\mathcal{H}_\phi = \frac{\hbar}{2c}\left(\frac{1}{c^2}\left|\partial_t\phi\right|^2 + \left|\nabla\phi\right|^2 + \frac{m_a^2c^2}{\hbar^2}\phi^2\right),$$

$$\mathcal{H}_\gamma = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{1}{\mu_0}B^2\right).$$

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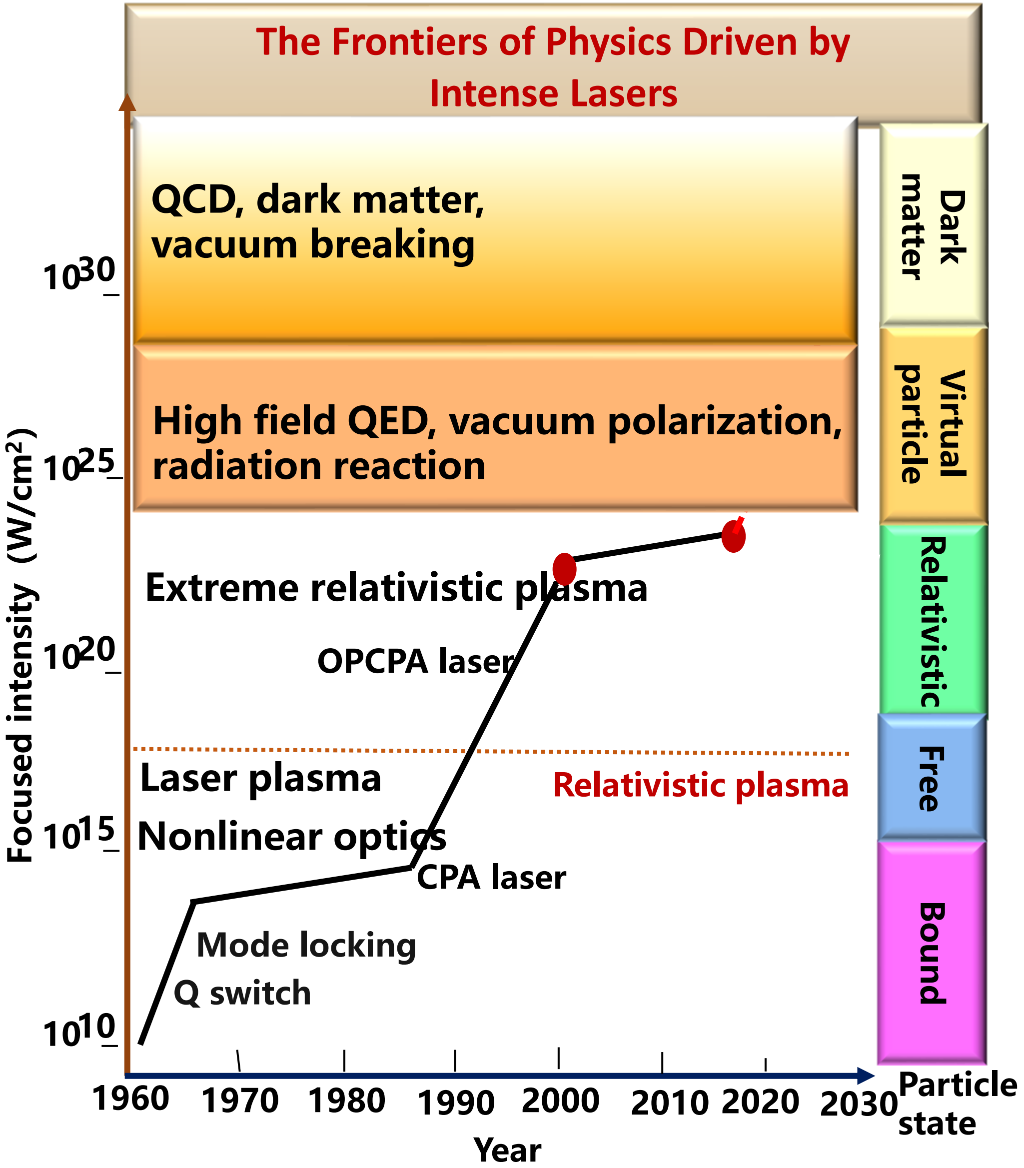
Ultra-strong lasers have the potential to generate axions in a controlled manner, opening the door to the world of dark matter.

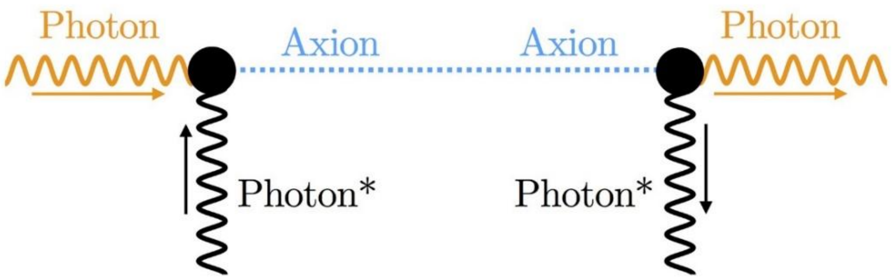


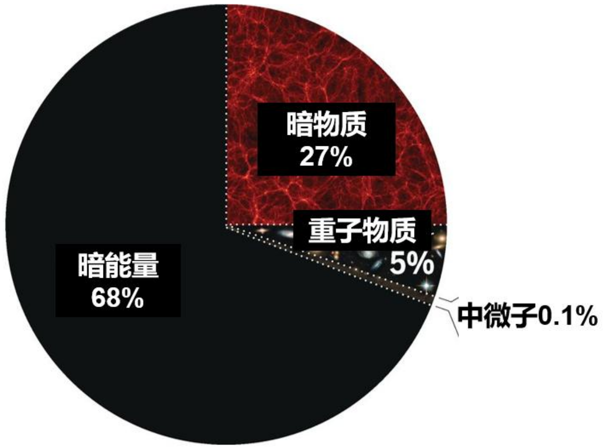
5% Known matter

Intense Laser

95% Unknown matter

Primakoff effect: photon-axion interaction





Frank Wilczek
2004 Nobel Prize

Dark matter → Normal matter

Laser plasma based axion generation and detection

New J. Phys. **20** (2018) 033022 https://doi.org/10.1088/1367-2630/aab475

New Journal of Physics
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IOP Institute of Physics

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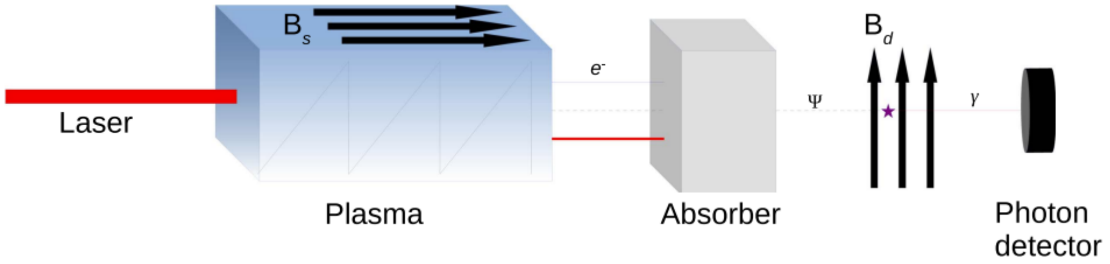
PAPER

Plasma-based wakefield accelerators as sources of axion-like particles

External B field+Wake E field



Phys. Scr. **97** (2022) 105303 https://doi.org/10.1088/1402-4896/ac8b6b

Physica Scripta

PAPER

Axion-like particle generation in laser-plasma interaction

Shan Huang[1,2,4], Baifei Shen[1,3,*], Zhigang Bu[1], Xiaomei Zhang[1,3], Liangliang Ji[1] and Shuhua Zhai[1,2,3]

1 State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, People's Republic of China
2 University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
3 Department of Physics, Shanghai Normal University, Shanghai 200234, People's Republic of China
4 Present address: School of Physics and Astronomy, Tel Aviv University, Tel Aviv-Yafo 6997801, Israel.
* Author to whom any correspondence should be addressed.

PHYSICAL REVIEW LETTERS **120,** 181803 (2018)

Axion-Plasmon Polaritons in Strongly Magnetized Plasmas

H. Terças,* J. D. Rodrigues, and J. T. Mendonça
Instituto de Plasmas e Fusão Nuclear, 1049-001 Lisboa, Portugal
and Instituto Superior Técnico, 1049-001 Lisboa, Portugal

(Received 25 January 2018; revised manuscript received 23 February 2018; published 4 May 2018)

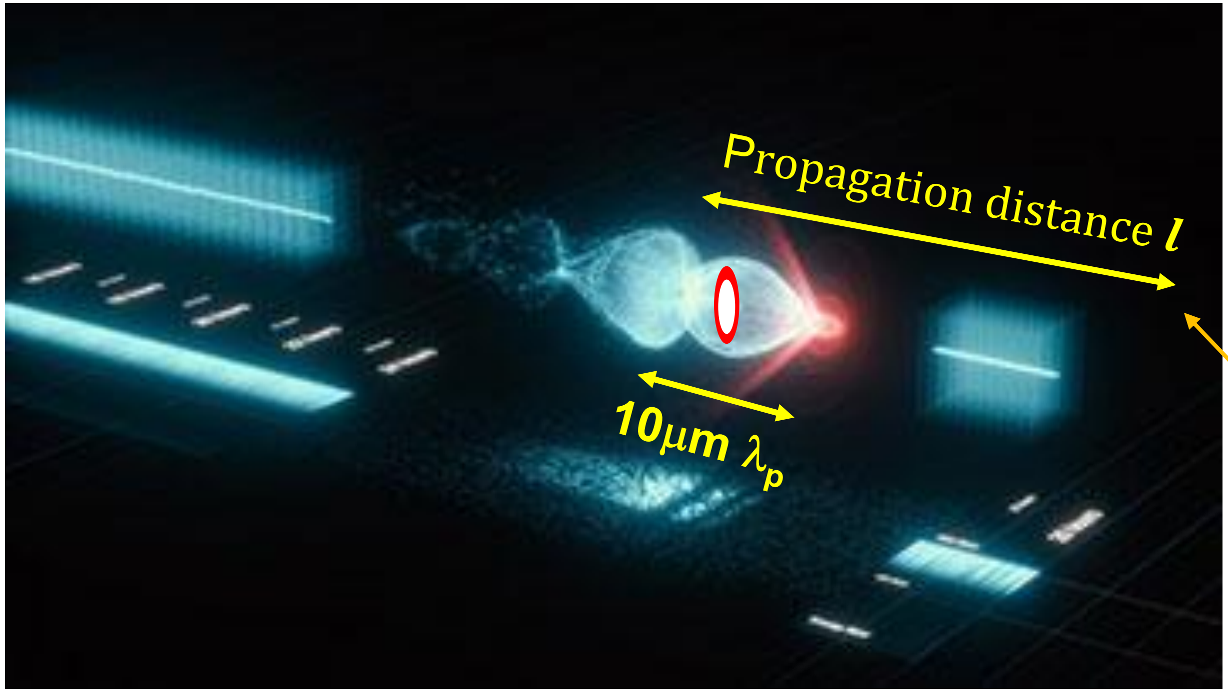
IOP Publishing Physica Scripta
Phys. Scr. **95** (2020) 045601 (7pp) https://doi.org/10.1088/1402-4896/ab5ab5

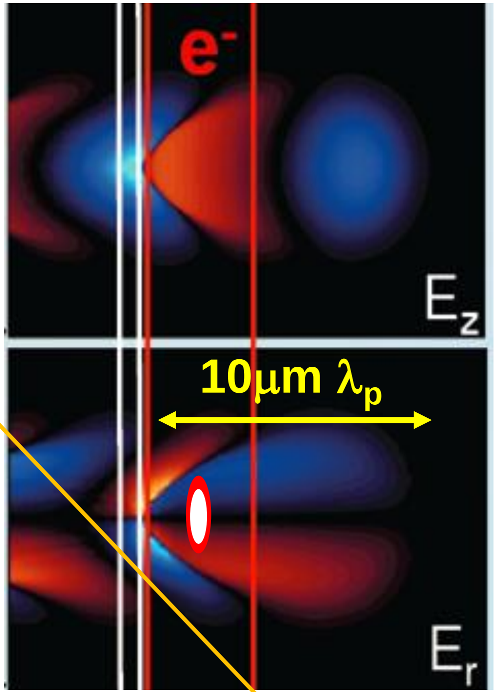
Axion excitation by intense laser fields in a plasma

J T Mendonça[1,3], H Terças[1] and J D Rodrigues[2]

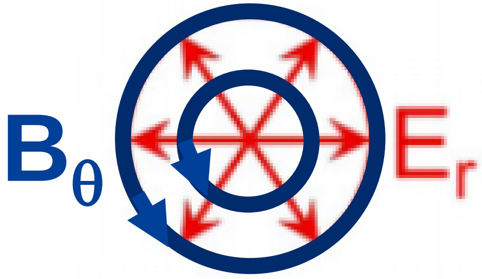
1 IPFN, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
2 Physics Department, Blackett Laboratory, Imperial College London, Prince Consort Road, SW7 2AZ, United Kingdom

Laser plasma wakefield based axion generation





EM fields in wakefield



$$E_z \simeq (k_p\zeta/2)E_0$$
$$E_r \simeq (k_p r/4)E_0$$
$$B_\theta \simeq -(k_p r/4)E_0$$

$$B = \frac{m_e\omega_p}{e}, \quad \omega_p^2 = \frac{ne^2}{\varepsilon_0 m_e}$$

$$P_1 = \frac{c\hbar}{4\mu_0}(g_{a\gamma\gamma}B\boxed{l})^2$$

Typical Magnetic field 300T

$$\partial_t^2\phi - \nabla^2\phi + m_a^2\phi = g_{a\gamma\gamma}\,\boldsymbol{E}\cdot\boldsymbol{B}$$

Advantage: Magnetic intensity and length (**B*l*:10²Tm→10⁵Tm**), conversion efficiency is 6 orders higher， the intense laser also increases the axion amount for another 6 orders.

Axion and secondary EM fields generation

$$\left(\partial_t^2 - \nabla^2 + m_a^2\right)\phi = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B},$$
$$\nabla\times\boldsymbol{E}_1 = -\partial_t\boldsymbol{B}_1,$$
$$\nabla\times\boldsymbol{B}_1 = \partial_t\boldsymbol{E}_1 + g_{a\gamma\gamma}\left[(\partial_t\phi)\boldsymbol{B}_0 - \boldsymbol{E}_0\times\nabla\phi\right]$$

Laser: **y polarized**

N_γ : Envelope of the drive laser

$$\boldsymbol{E}_y = \frac{a_0}{2}N_\gamma(\zeta_0, y, z)e^{\mathrm{i}\xi_0} + \mathrm{c.c.},$$
$$\boldsymbol{B}_z = \frac{a_0k_0}{2\omega_0}N_\gamma(\zeta_0, y, z)e^{\mathrm{i}\xi_0} + \mathrm{c.c.},$$

$\xi_0 = k_0x - \omega_0t$ is the laser phase

Wake fields: **radial polarized**

$$E_x = \frac{k_p\zeta_0}{2}\frac{\omega_p}{\omega_0},\quad E_y = -B_z = \frac{k_py}{4}\frac{\omega_p}{\omega_0},$$
$$B_x = 0,\quad E_z = B_y = \frac{k_pz}{4}\frac{\omega_p}{\omega_0}.$$

The main parts of E, B, *i.e.* E_0, B_0 come from both laser fields & wakefields

The EM fields generated by axions (AREM) are extremely weak and are labeled by E_1, B_1.

Source of axion: E_{Laser} ● B_{Wake} & E_{Wake} ● B_{Laser}

$$S_a = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B} = \frac{g_{a\gamma\gamma}a_0\omega_pk_pz}{2\omega_0}N_\gamma e^{\mathrm{i}\xi_0} + \mathrm{c.c.}$$
$$\left(\partial_t^2 - \nabla^2 + m_a^2\right)\phi = S_a.$$

$$\phi = \varphi(x)N_a(\zeta_0, y, z)e^{\mathrm{i}\xi_a} + \mathrm{c.c.}$$

$$N_a(\zeta_0, y, z) = g_{a\gamma\gamma}a_0\omega_pk_pzN_\gamma/(2\omega_0)$$

$\xi_a = k_ax - \omega_at \approx \xi_0$ is the axion phase

Character of Axion regenerated EM (AREM) field

Description of the axion and AREM fields :Vector potential (A_{1y} & A_{1z})

$$\phi = -\frac{2N_a(\zeta_0, y, z)}{k_a \kappa} \sin(\kappa x/2) \sin(\xi_a + \kappa x/2),$$

$$A_{1,y} = -\frac{g_{a\gamma\gamma} N_a}{k_a \kappa k^{(1)} \kappa_1' \omega_0} (k_a + \omega_a)\, \omega_p \boxed{k_p z} \sin(\kappa x/2) \sin(\kappa_1' x/2) \sin(\boxed{\xi_1^{(1)}} + \kappa_1' x/2),$$

$$A_{1,z} = -\frac{g_{a\gamma\gamma} N_a}{k_a \kappa \omega_0} \sin(\kappa x/2) \Bigg[\frac{(k_a + \omega_a)}{k^{(1)} \kappa_1'} \omega_p \boxed{k_p y} \sin(\kappa_1' x/2) \sin(\boxed{\xi_1^{(1)}} + \kappa_1' x/2)$$
$$- 2a_0 N_\gamma \kappa \omega_0 \left(\frac{\sin(\kappa_0' x/2) \sin(\boxed{\xi_0^{(1)}} + \kappa_0' x/2)}{k_0^{(1)} \kappa_0'} + \frac{\sin(\kappa_2' x/2) \sin(\boxed{\xi_2^{(1)}} + \kappa_2' x/2)}{k_2^{(1)} \kappa_2'} \right) \Bigg],$$

$\kappa = k_0 - k_a$ **matching between laser & axion**

$\xi_\mu^{(1)} = k_\mu^{(1)} x - \omega_\mu^{(1)} t$ is the AREM phase

$\omega_\mu^{(1)} = \mu \omega_0,\ k_\mu^{(s)} = k_a - k_0,\ k_a,\ k_a + k_0$

$\mu = 0, 1, 2$

$$\phi \propto g_{a\gamma\gamma} x \,\mathrm{sinc}(\kappa x/2),$$
$$P_a \propto \phi^2 \propto g_{a\gamma\gamma}^2 x^2 \,\mathrm{sinc}^2(\kappa x/2),$$
$$A_1/a_0 \propto g_{a\gamma\gamma}^2 x^2 \,\mathrm{sinc}(\kappa x/2) \,\mathrm{sinc}(\kappa' x/2).$$

E_1 fields show new frequency components, $0\omega_0$, ω_0, $2\omega_0$

E_1 fields show new spatial modes ($LG_{l,p}$)

PIC simulations: Evolution and spatial distributions of the axion and EM fields

Drive laser: $a_0=5$

$W_{pulse}= w_\perp = 50\lambda_0$ $L_{pulse}= 12\ T_0$

Plasma: $n_e = n_0 + \delta n r_\perp^2$

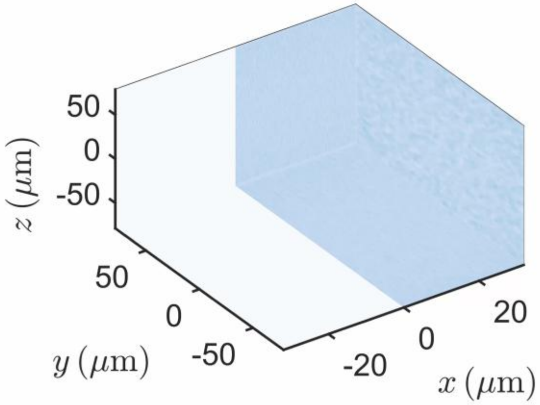
$n_0 = 0.003 n_c,\ n_c = \varepsilon_0 m_e \omega_0^2/e^2$

$\delta n = 4\varepsilon_0 m_e c^2/(e^2/w_\perp^4)$

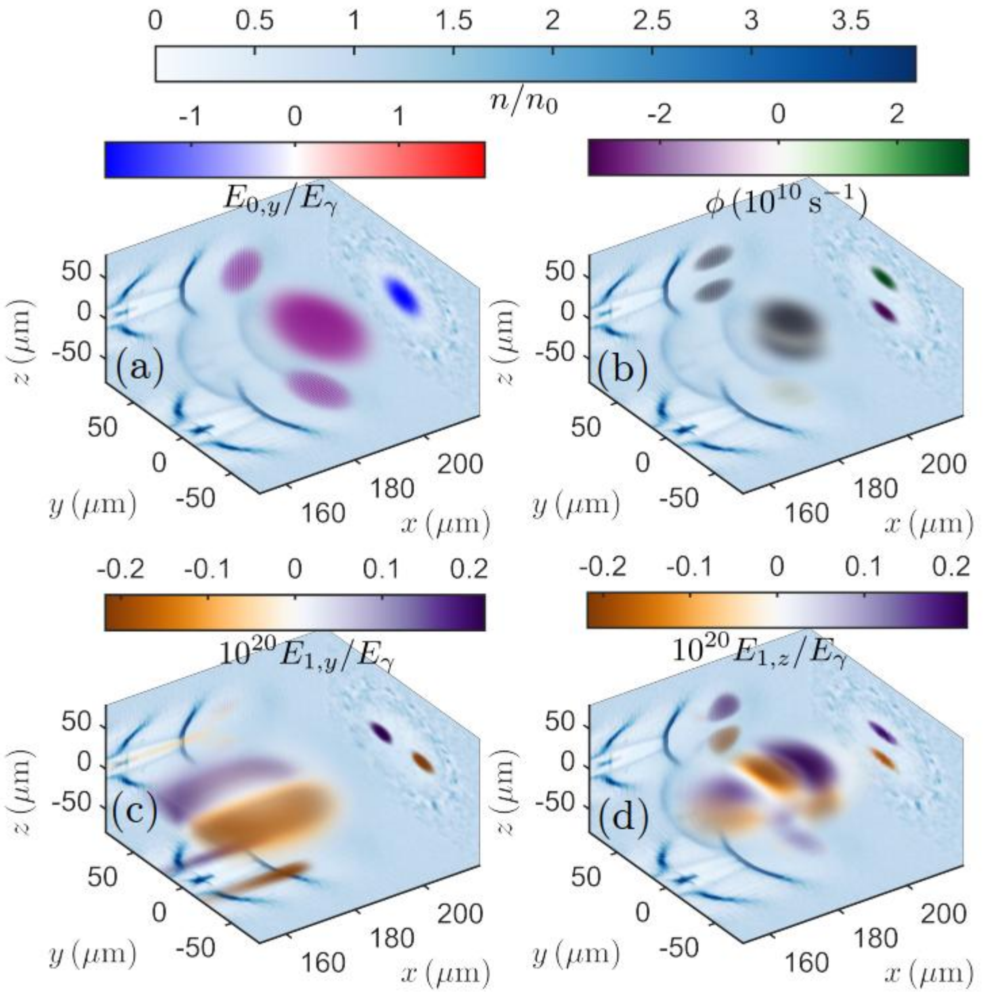
Axion: $m_a = 10^{-6}\,\mathrm{eV}$

$g_{a\gamma\gamma} = 10^{-9}\,\mathrm{GeV}^{-1}$

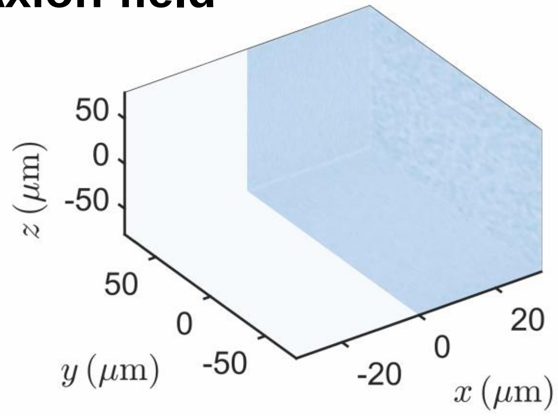
Laser field



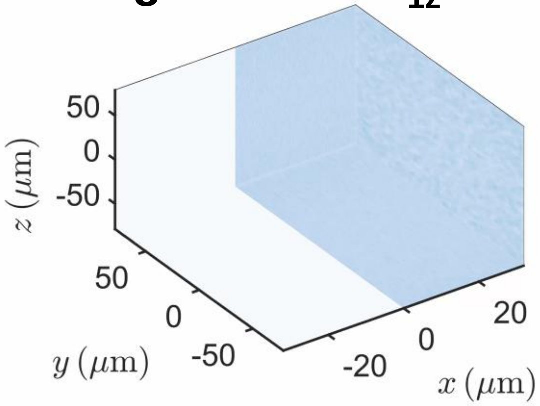
Spatial distributions of the fields



Axion field



Axion generated E_{1z} field



E_1: y and z polarized, high order LG mode

High order LG modes of AREM fields

We decompose the fields of the AREM according to the Laguerre-Gaussian (LG) modes.

$$u_{pl} = a_{pl}\frac{1}{w_\perp}\left(\frac{\sqrt{2}r_\perp}{w_\perp}\right)^{|l|} L_p^{|l|}\left(\frac{2r_\perp^2}{w_\perp^2}\right) e^{-r_\perp^2/w_\perp^2} e^{-\mathrm{i}l\theta}$$

$$\mathcal{C}_{pl} = \int_0^{2\pi} \mathrm{d}\theta \int_0^{\infty} \mathrm{d}r_\perp\, r_\perp A_1 u_{pl}$$

$$A_{1,y,\omega_0} \;:\; \mathcal{C}_{pl} \propto \int_0^{2\pi} \mathrm{d}\theta \sin^2(\theta) e^{-\mathrm{i}l\theta} \neq 0$$

$$l = 0,\ \pm 2$$

$$A_{1,z,0\omega_0} \;:\; \mathcal{C}_{pl} \propto \int_0^{2\pi} \mathrm{d}\theta \sin(\theta) e^{-\mathrm{i}l\theta} \neq 0$$

$$l = \pm 1$$

$$A_{1,z,\omega_0} \;:\; \mathcal{C}_{pl} \propto \int_0^{2\pi} \mathrm{d}\theta \sin(\theta)\cos(\theta) e^{-\mathrm{i}l\theta} \neq 0$$

$$l = \pm 2$$

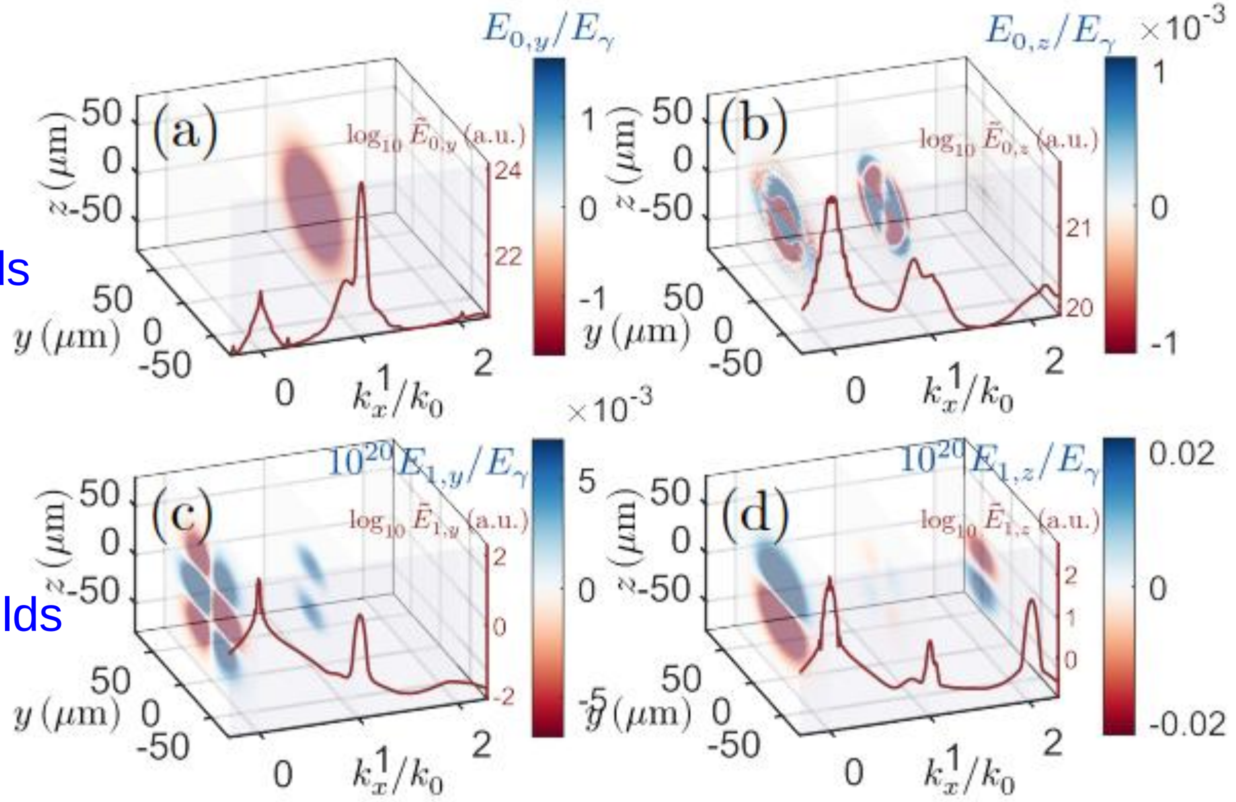
$$A_{\boxed{1,z,2\omega_0}} \;:\; \mathcal{C}_{pl} \propto \int_0^{2\pi} \mathrm{d}\theta \sin(\theta) e^{-\mathrm{i}l\theta} \neq 0$$

$$l = \pm 1$$

Order of EM field, polarization, frequency

Laser & wake fields

AREM fields



Axion generation efficiency along with the guiding length

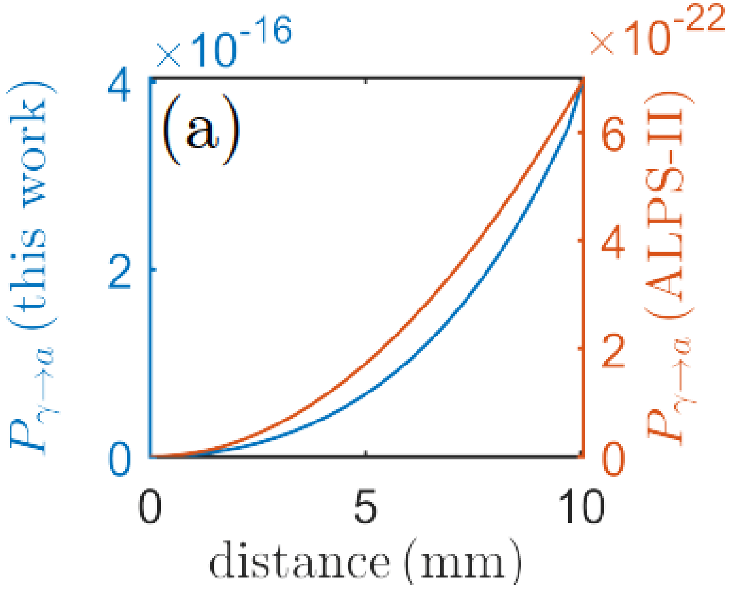
$$\phi \propto g_{a\gamma\gamma} x \,\mathrm{sinc}(\kappa x/2),$$
$$P_a \propto \phi^2 \propto g_{a\gamma\gamma}^2 \boxed{x^2} \mathrm{sinc}^2(\kappa x/2),$$
$$A_1/a_0 \propto g_{a\gamma\gamma}^2 \boxed{x^2} \mathrm{sinc}(\kappa x/2)\,\mathrm{sinc}(\kappa' x/2).$$

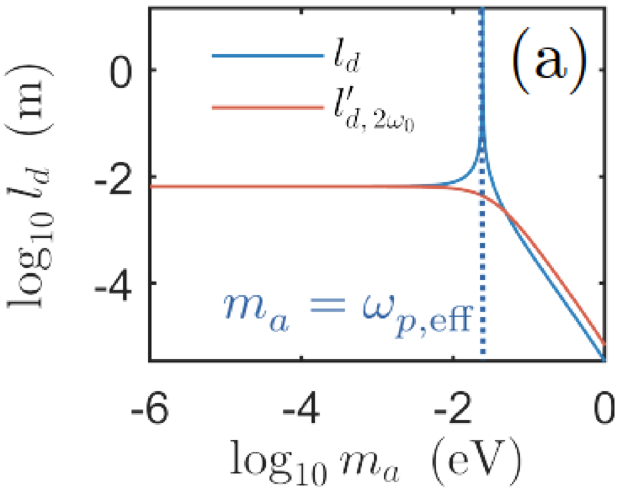
The efficiency can be increased by extending the guiding length. However, even the laser is well guided, photon & axion phase mismatching will limit the axion generation. The maximum distance is limited by:

$x \lesssim l_d \equiv 2\pi/|\kappa|$ Axion mismatch with laser photon

$x \lesssim l'_d \equiv 2\pi/|\kappa|'$ Axion mismatch with AREM photon

Generation efficiency compared with ALPS-II





$$\omega_0^2 = \omega_p^2 + k_0^2$$
$$\omega_{p,\mathrm{eff}}^2 = n_{\mathrm{eff}} e^2/(\gamma_\perp m_e)$$
$$\gamma_\perp = \sqrt{1 + a_0^2/2} = 3.7$$
$$\kappa = \sqrt{\omega_0^2 - \omega_{p,\mathrm{eff}}^2} - \sqrt{\omega_0^2 - m_a^2}$$

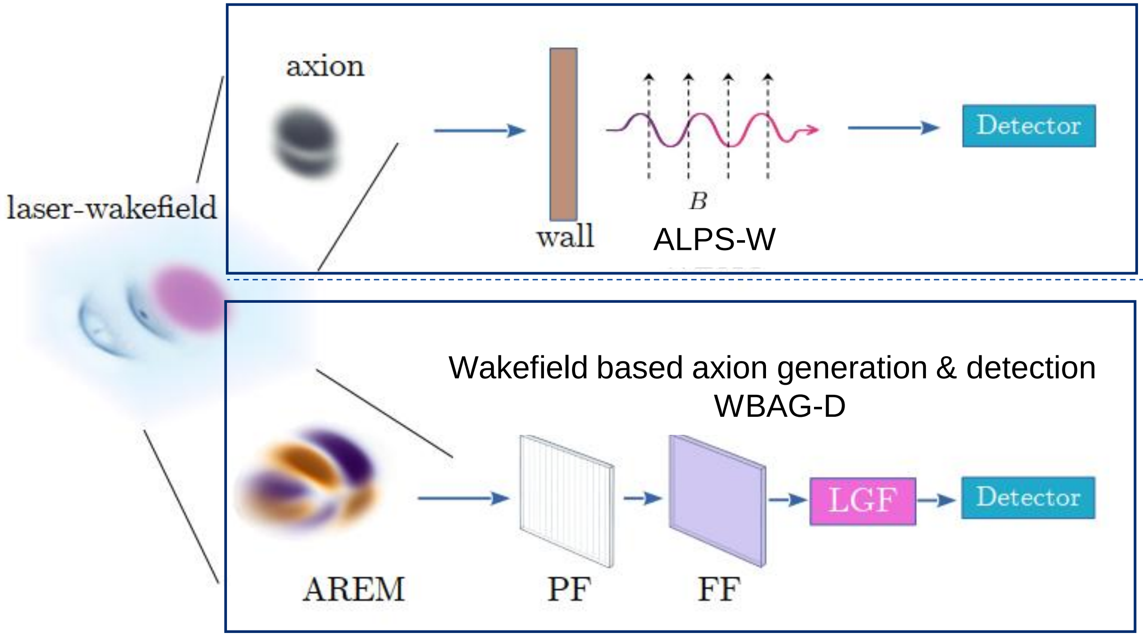
An empty bubble can lower the limitation of the detectable axion mass. Using beam driven?

Detection methods & limitation on the $g_{a\gamma\gamma}$ constraint

Axion generation

Axion detection

- **Meter scale interaction, weak AREM.** N_{ph}~1
  Single photon detection

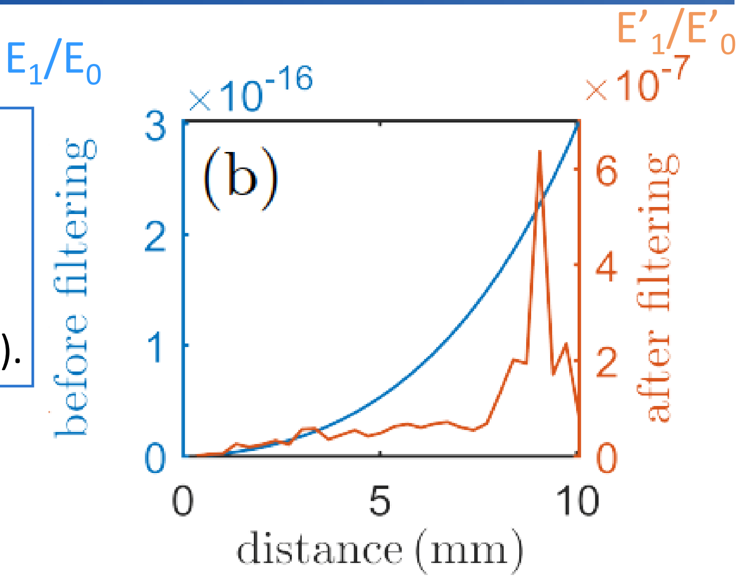


Polarization Filter **Frequency Filter** **Spatial mode Filter**

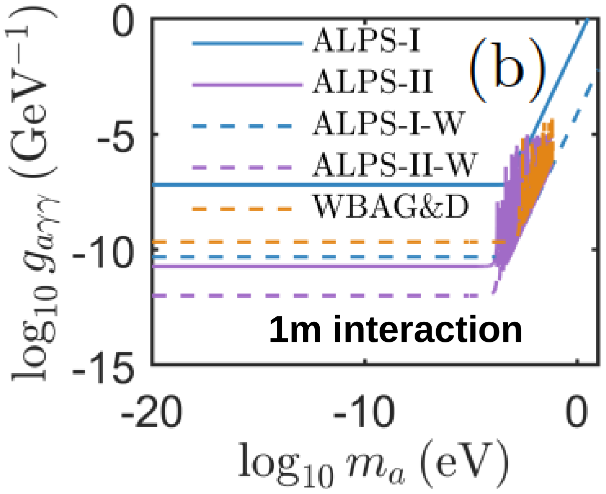
- **Kilometer scale interaction, intense AREM.** N_{ph} >> 1
  AREM detection

In experiments, one should detect E_1. The signal-to-noise ratio ($\varepsilon=E_1/E_0$) can be significantly improved through **triple filtering** (from $10^{-16} \rightarrow 10^{-7}$).

Simulation only runs for 1 cm.



The minimum detectable $g_{a\gamma\gamma}$ depends on the minimum detectable of E_1.



$$\frac{g_{a\gamma\gamma}}{10^{-9}\,\mathrm{GeV}^{-1}} = \left(\frac{\epsilon}{2\times10^{-7}}\right)^{1/2} \frac{1\,\mathrm{cm}}{L} \left(\frac{\sin(\kappa L/2)}{\kappa L/2}\right)^{-1} \left(\frac{\sin(\kappa' L/2)}{\kappa' L/2}\right)^{-1}$$

Summary

- Axion is one of the candidate particles of dark matter. Its coupling with the EM field (Primakoff effect) provides a possible way for intense laser based dark matter searching.
- Plasma wake can support huge E and B fields. When it interacts with a well guided intense laser, axions can be generated. The inverse process can generate secondary EM fields, which shows higher frequency and spatial modes.
- The intense fields from both of the laser and wake make the axion generation efficiency in this scheme is orders of magnitude higher than the existed schemes. It may also be a new application of LWFA.
- For shorter distance (meter long) interaction, the AREM photon number is limited, one should combine the wakefield based axion generation with the LSW scheme to detect the axion. If one wants to use AREM to detect the axions, long distance wake & laser guiding inside the bubble is still required. Beam driven may be a solution. Km level "AWAKE" based axion searching?

Thanks for your attention!

minchen@sjtu.edu.cn