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Coherent Axion Production through Laser Crystal Interaction

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Based on arXiv:2412.05073

OUTLINE

1. Introduction
2. Coherent Axion Production
3. Layer Stacking and Conversion Probability
4. Experimental Design and Result Estimation
5. Summary and Discussion

Based on arXiv:2412.05073

1.1 Axion and Axion-Like-Particles (ALP)

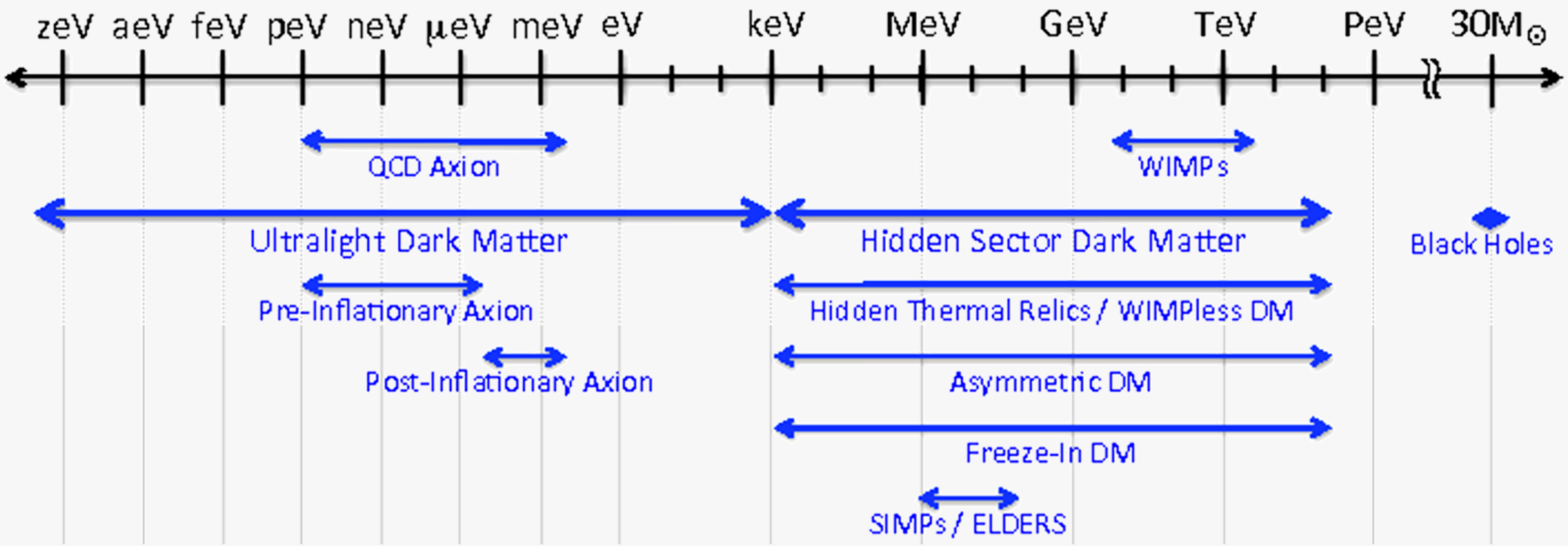


Fig: Some dark matter candidates and their mass range.

- Dark matter explains a lot of problems in cosmology and astrology, but we don’t know its nature yet.
- Axion solve strong CP problem and dark matter problem simultaneously, making it a hot candidate.
- In researches, axion-like-particles (ALP) are often considered, which have wider parameter space.

1.1 Axion and Axion-Like-Particles (ALP)

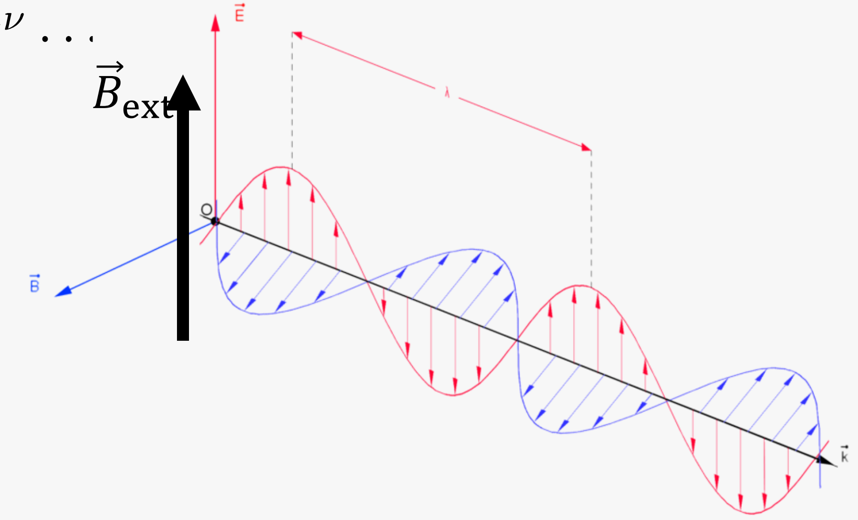
- Axion couples to ordinary matter. We consider its coupling to photon here.

$$\mathcal{L}_{\text{axion}} \supset \underbrace{\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}}_{\text{photon channel}} + \underbrace{g_{aee} a \bar{e} i \gamma_5 e}_{\text{electron channel}} + \underbrace{4\pi g_{aGG} a G_{\mu\nu} \tilde{G}^{\mu\nu}}_{\text{gluon channel}} \cdots$$

photon channel

electron channel

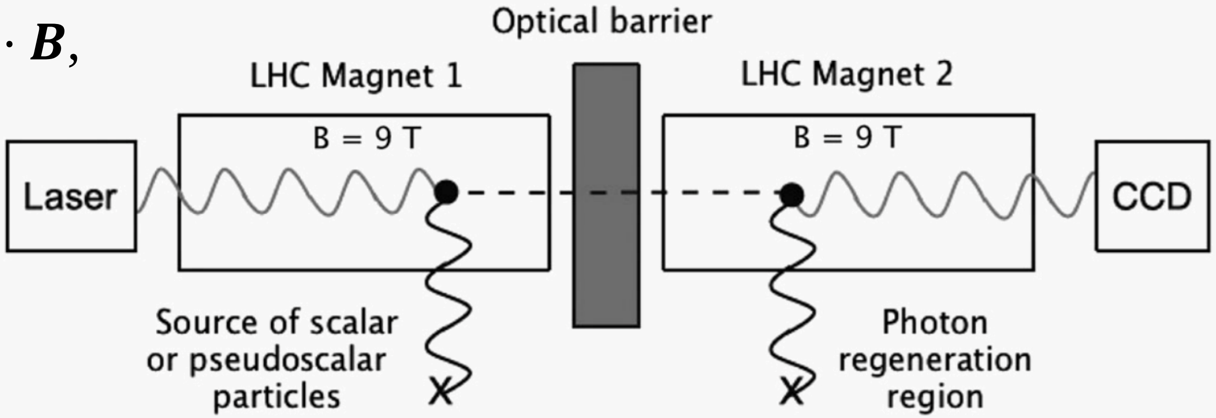
gluon channel



- Field equation for axion:

$$\left(\partial_t^2 - \nabla^2 + m_a^2\right) a = \boxed{g_{a\gamma\gamma} \boldsymbol{E} \cdot \boldsymbol{B}}$$

We can use laser and magnetic field to get nonzero $\boldsymbol{E} \cdot \boldsymbol{B}$, and generate axion.
(Light-Shining-Through-Wall experiment, LSW)



- Conversion probability: $P_{a\leftrightarrow\gamma} \approx \frac{1}{4} g_{a\gamma\gamma}^2 (BL)^2$

1.2.1 CERN Axion Solar Telescope (CAST)

- In sun, photon interact with nucleus and generate axion, whose energy corresponds to X-ray.
- Axion arrive on earth, traverse magnetic field and converts to photon, and then be detected.
- Same mechanism as light-shining-through-wall experiments.

- How to increase magnetic field?

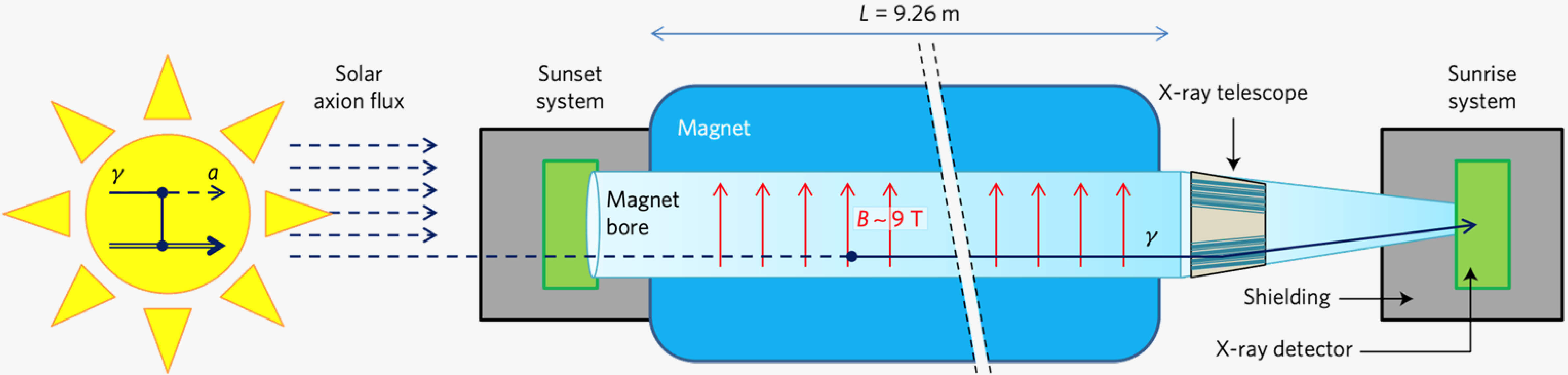


Fig: Experiment design for CAST. Taken from [3]。

[3] V. Anastassopoulos, et al., Nat. Phys. 13, 584(2017)

1.2.2 Cryogenic Dark Matter Search, CDMS

● Strong electric field in crystal can be used for axion detection.
● When axion wavelength match the crystal lattice constant, there is coherent enhancement✣.
● Solar axion interacts with crystal for detection.

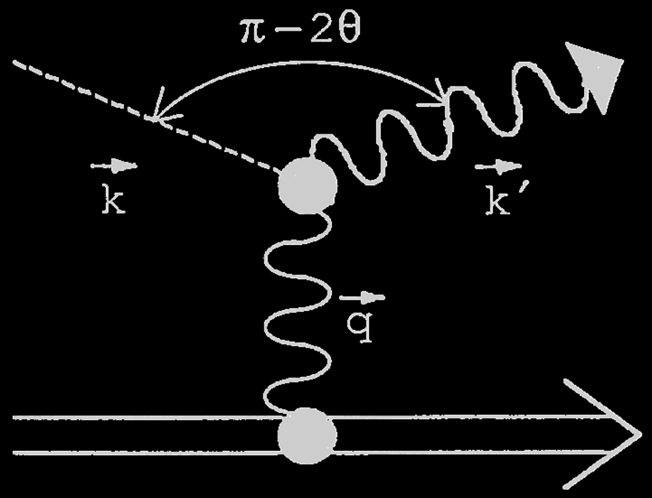
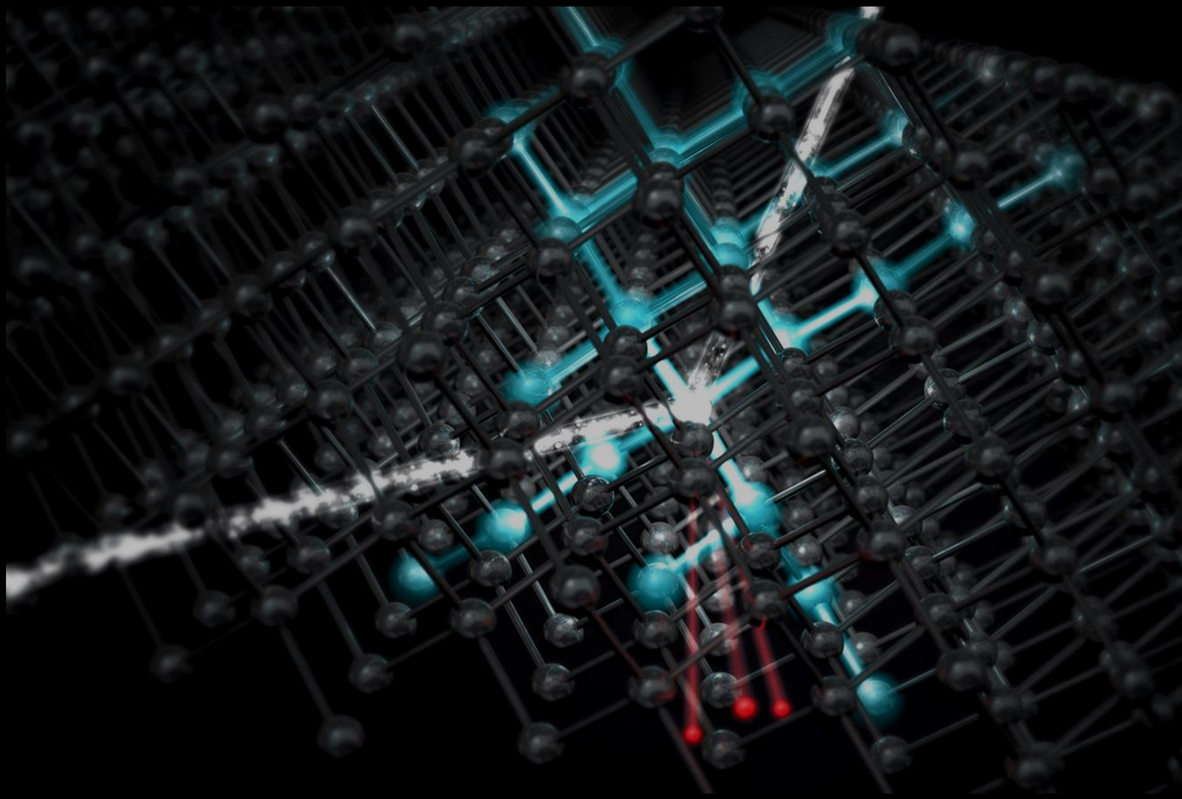


Fig:Axion interact with nuclei[4].



Fig： Conceptual figure for CDMS

[4] R. J. Creswick, et al., PLB 427, 235(1998)

✣ Detailed explanation later

1.3 Axion Coupling Constraints

- Indirect search, direct space axion search and direct lab axion search are complement to each other.

- Currently, <u>terrestrial experiments</u> give much weaker constraints than other two approaches.

- We want to propose new schemes for axion production.

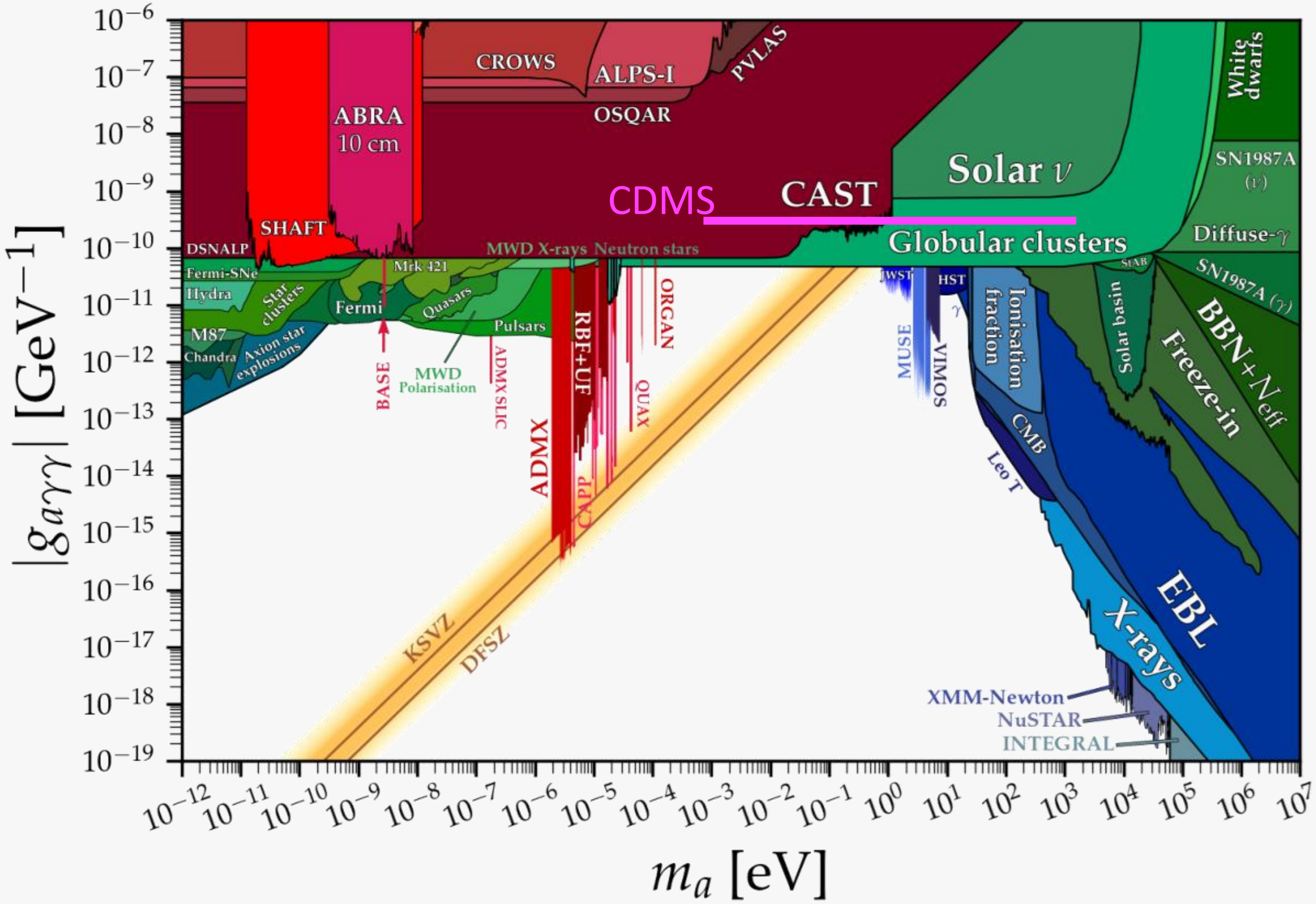


Fig: Constraints for axion parameters from different studies. Taken from [5].

[5] https://cajohare.github.io/AxionLimits/

OUTLINE

1. Introduction
2. Coherent Axion Production

2.1 Bragg Scattering

- X-ray can be scattered by crystal lattice. When Bragg condition, $n\lambda = 2d\sin\theta$, is satisfied, the scattered waves from different lattice undergo coherent superposition.

- A more general condition is:

$$\boldsymbol{k}_{\text{out}} - \boldsymbol{k}_{\text{in}} = \boldsymbol{G} \equiv \frac{2\pi}{d}(i_1, i_2, i_3)$$

e.g., if $\boldsymbol{G} = \frac{2\pi}{d}(0,1,0)$, the phase difference between two adjacent lattices in the y-direction is 2π, while the phases of adjacent lattices in the x- and z-directions are identical.

- If $\boldsymbol{k}_{\text{out}}$ represents the momentum for axion, there can be coherent enhancement, same as Bragg scattering.

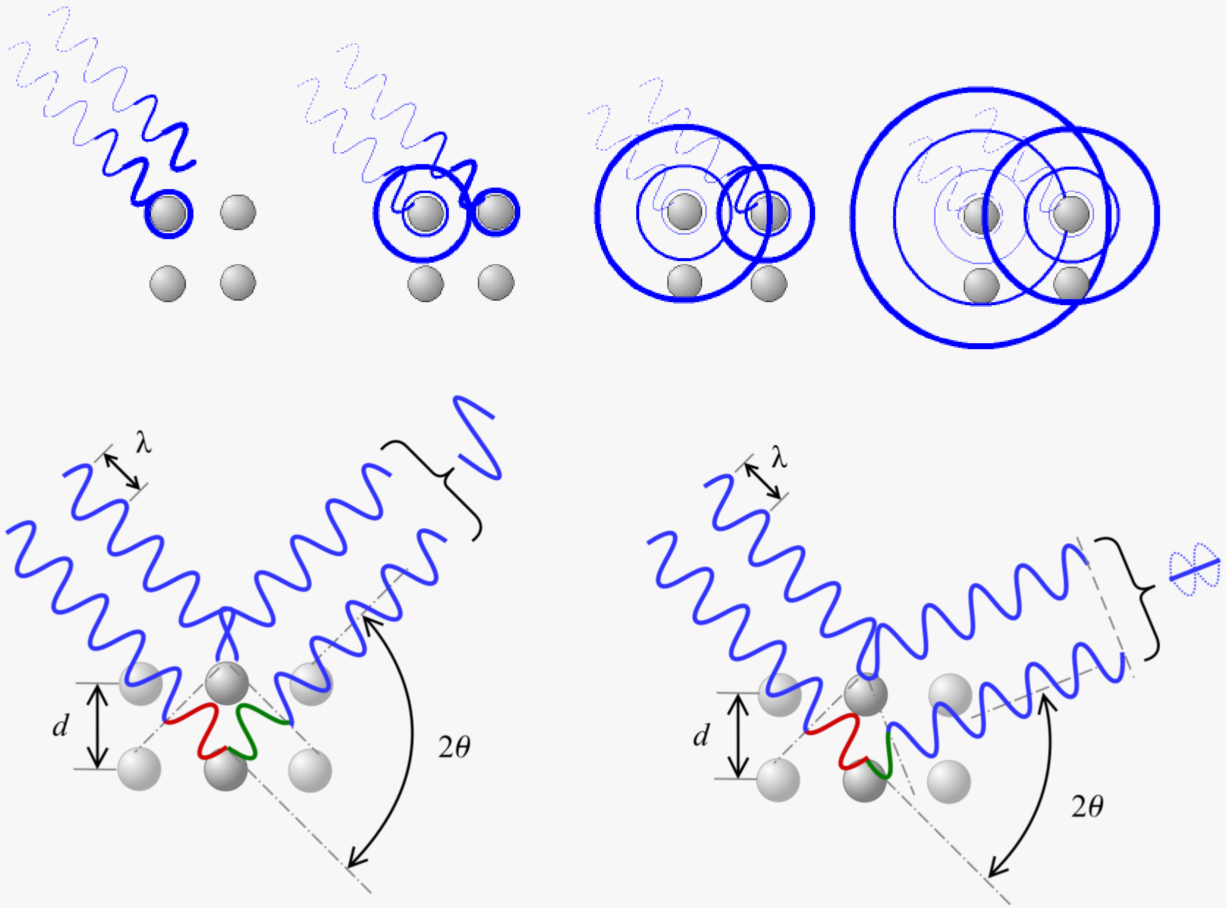
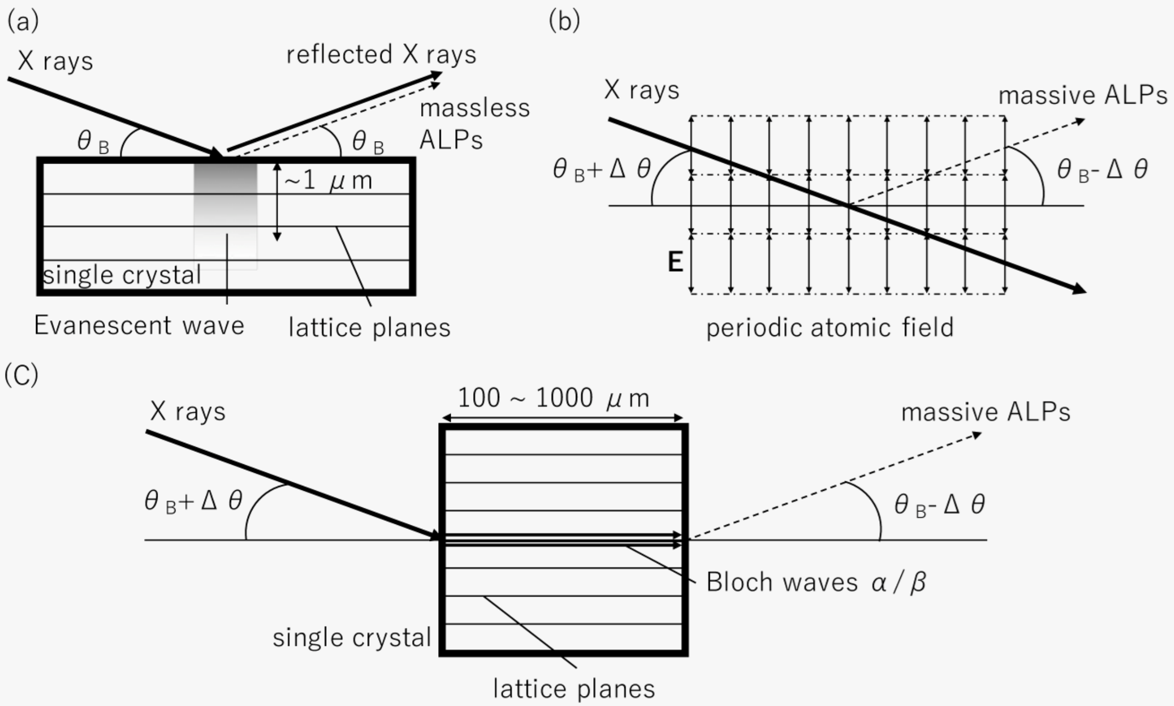
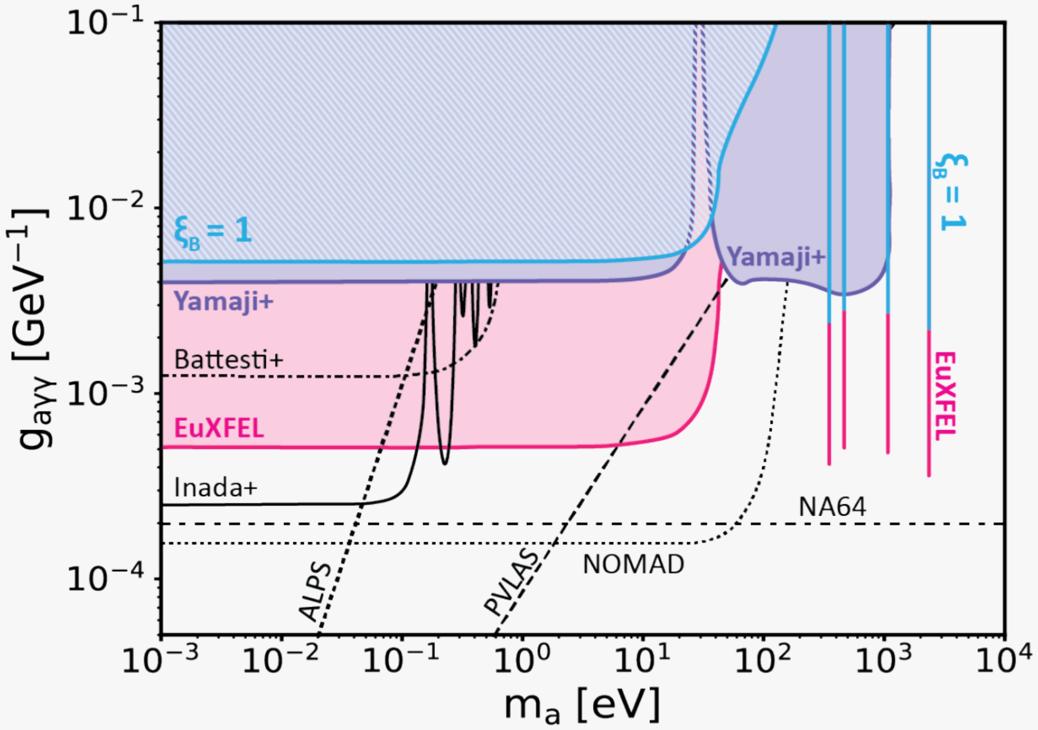


Fig: Schematic figure for Bragg scattering.

2.1 Bragg Scattering——Axion

●When X-ray satisfies Bragg condition, the axion production will enhance coherently.
●Due to reflection or absorption, X-ray only enters crystal for milli-meter or micro-meter, much shorter than typical LSW experiments(O(10m))
●This approach give weaker constraints on axion parameters.





Left: Schemes for axion production with X-ray. Taken from PRD**96**, 115001(2017);
Right: Estimated exclusion line with EuXFEL parameters. Taken from PRL**134**, 17333(2025).

2.2 Optical Light and Ionic Crystal

- Due to reflection or absorption, X-ray only enters crystal for milli-meter or micro-meter

- For larger interaction length, we consider optical light and transparent crystal. Optical laser also has much larger photon number.

- Optical light cannot identify electric field inside atom, we choose ionic crystal* （CaF_2 as example）。

- Optical light energy is low, we can only choose:

$$\boldsymbol{k}_{\mathrm{a}} - \boldsymbol{k}_{\mathrm{L}} = \boldsymbol{G} \equiv \frac{2\pi}{d}(0, \epsilon, 0)$$

i.e., the phases of two adjacent lattices in the x- and z-directions are identical, while those in the y-direction are <u>approximately identical</u>.

** Ionic crystal is still charge neutral, optical light can only faintly resolve its electric dipole moment.*

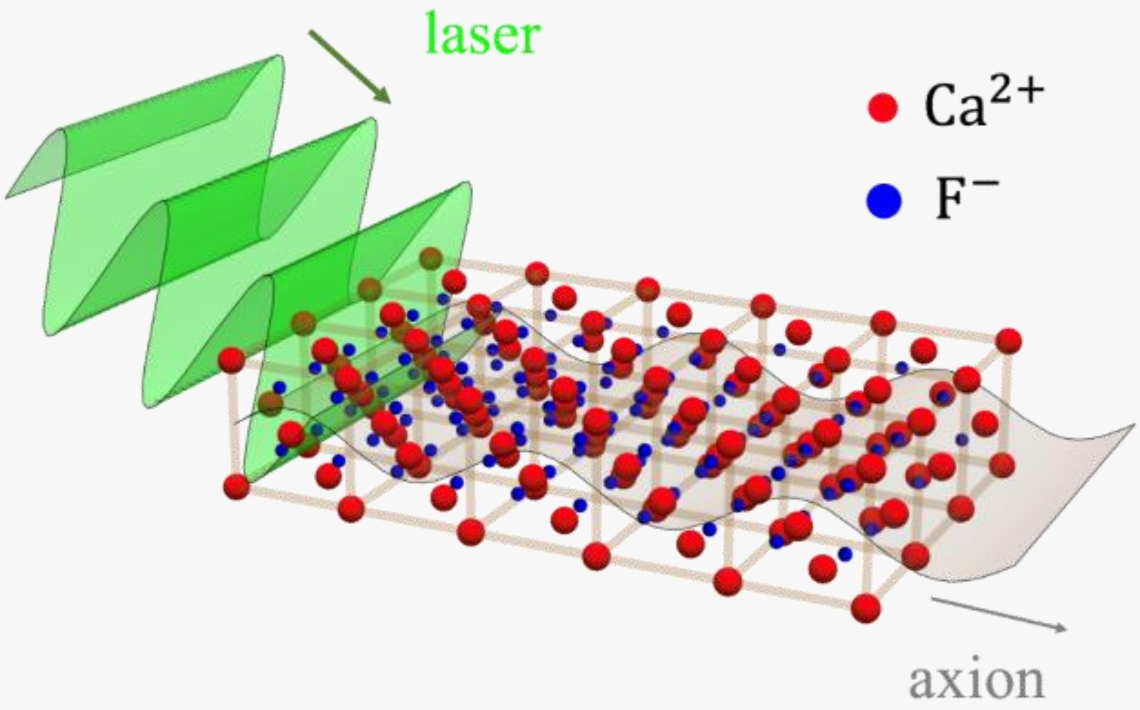


Fig: Axion production through laser-axion interaction

	Optical	X-ray
Interaction length	✓	×
Photon number	✓	×
Spatial resolution	×	✓

TAB: pros and cons for optical light and X-ray

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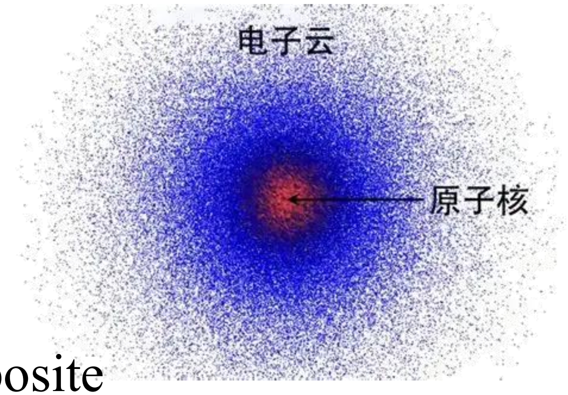
3.0* Damping of Long Wavelength



- Axion wave function is proportional to $a(t,x) \propto \sum_s Q_s \exp[-\mathrm{i}\Delta \boldsymbol{k} \cdot \boldsymbol{r}_s]$
- The wavelength λ of optical light is long and it's difficult to distinguish two close opposite charges. The wave function will be damped by order $\mathcal{O}(d/\lambda)$, where d is the distance between the two charges.
- For charge neutral atom, it can be regarded as point-like nucleus and spherical symmetric electric cloud. The axion wave function will be damped by order $\mathcal{O}(R^2/\lambda^2)$, where r is the atom radius.

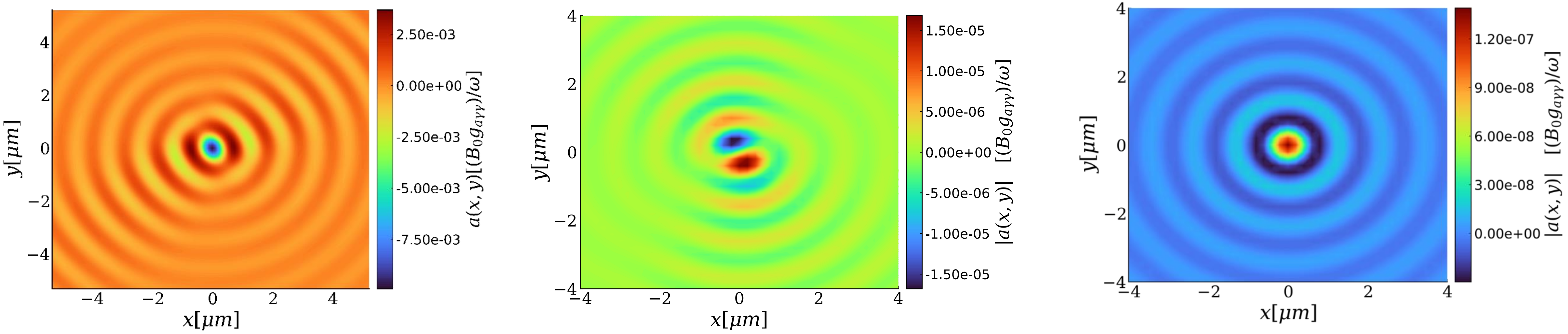


***Fig**: Axion wave function for laser interacting with ion and atom. Left: single positive charge; Middle: two closely positioned opposite charges; Right: charge-neutral atom.*

3.1 Phase Mismatch

● The axion waves from each crystal cell should be coherently superposed.

● The phase of axion waves will shift transversally.

● When the phase shift from two cells reaches π, the axion wave will be coherently destructed.

● The transversal length for π in phase corresponds to half wavelength, which is ~ $0.5\mu m$ for optical light, which is a very thin film.

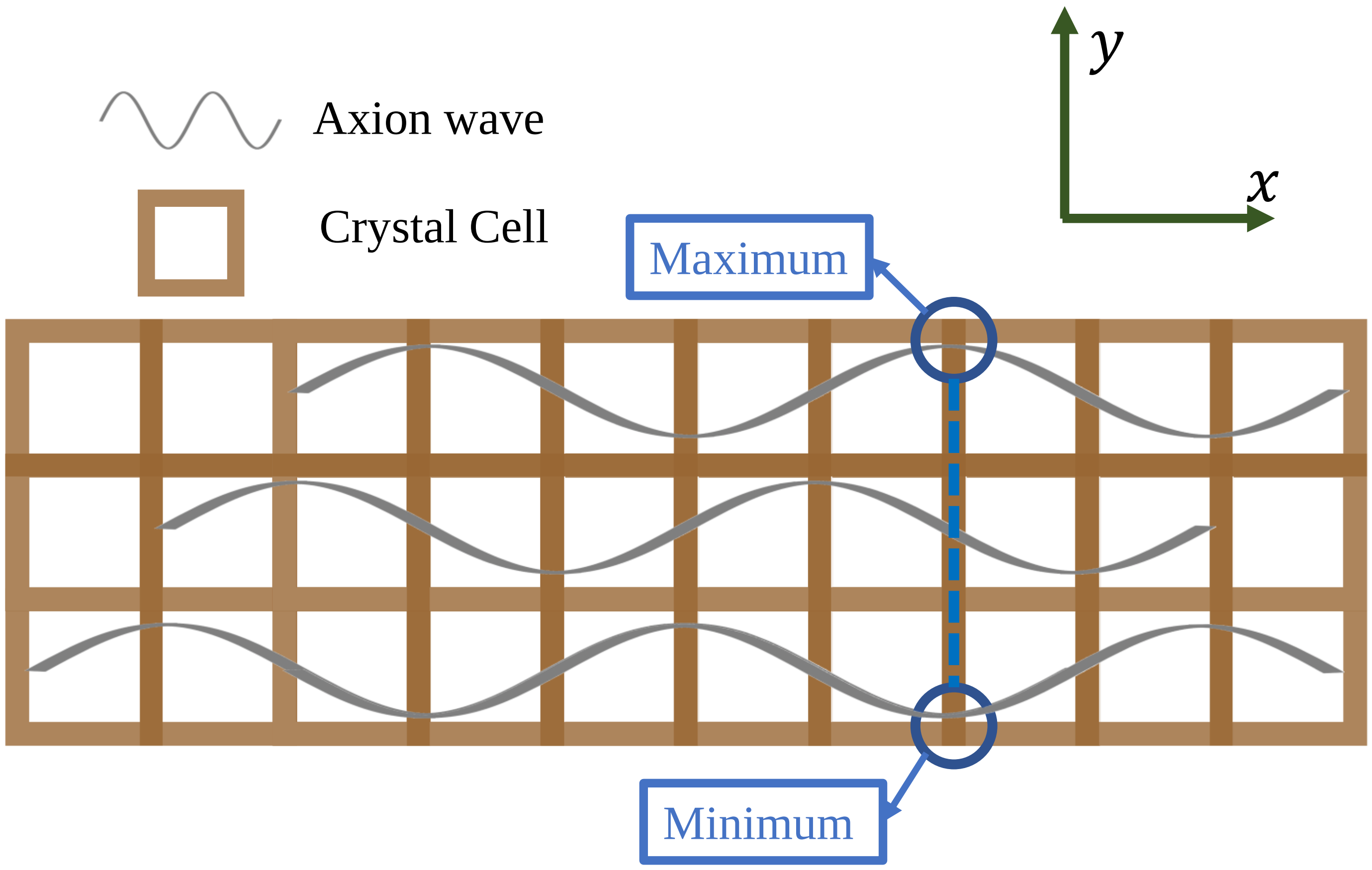


Fig: Schematic figure for coherent destruction on transverse direction.

3.2 Thin Film Stacking

- Stacking films along y-axis. The thickness of each layer is π, and the phase difference between two layers is 2π。

- The laser keep reflecting while propagating along x-axis. This is equivalent to rectangular waveguide in TE mode. The transition probability scales as $P \propto L_x^2$。

- If there are thousands of layers, and if $L_x = 1\text{m}$, $P^{1\text{m}}_{\text{laser}\to a} = 7.14 \times 10^{-11}$。
If $L_x = 10\text{m}$, $P^{10\text{m}}_{\text{laser}\to a} = 7.10 \times 10^{-9}$.

- For comparison, in LSW experiment[2], $B = 9\text{T}, L = 14.3\text{m}$, and $P^{\text{LSW}} = 4.06 \times 10^{-11}$

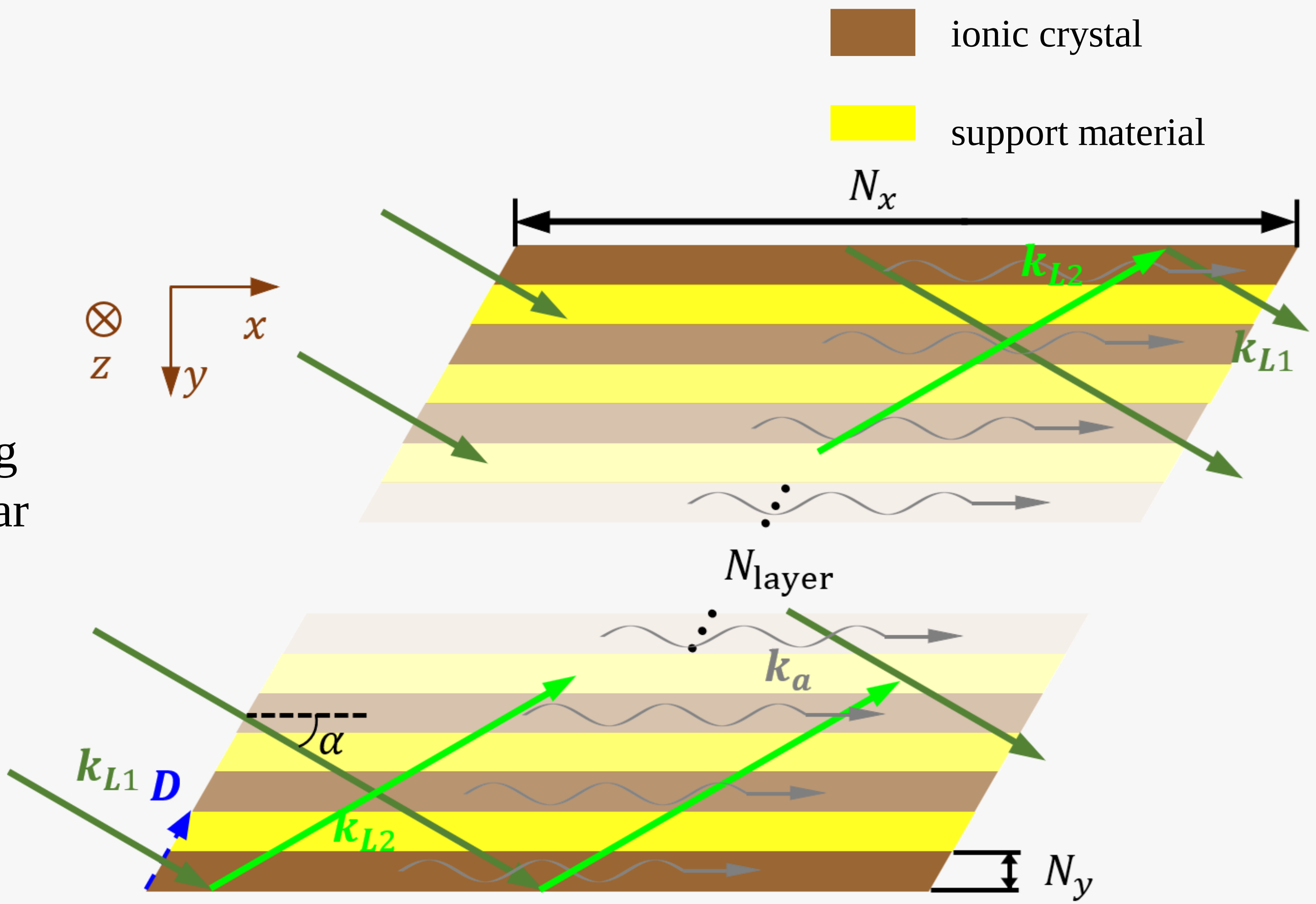


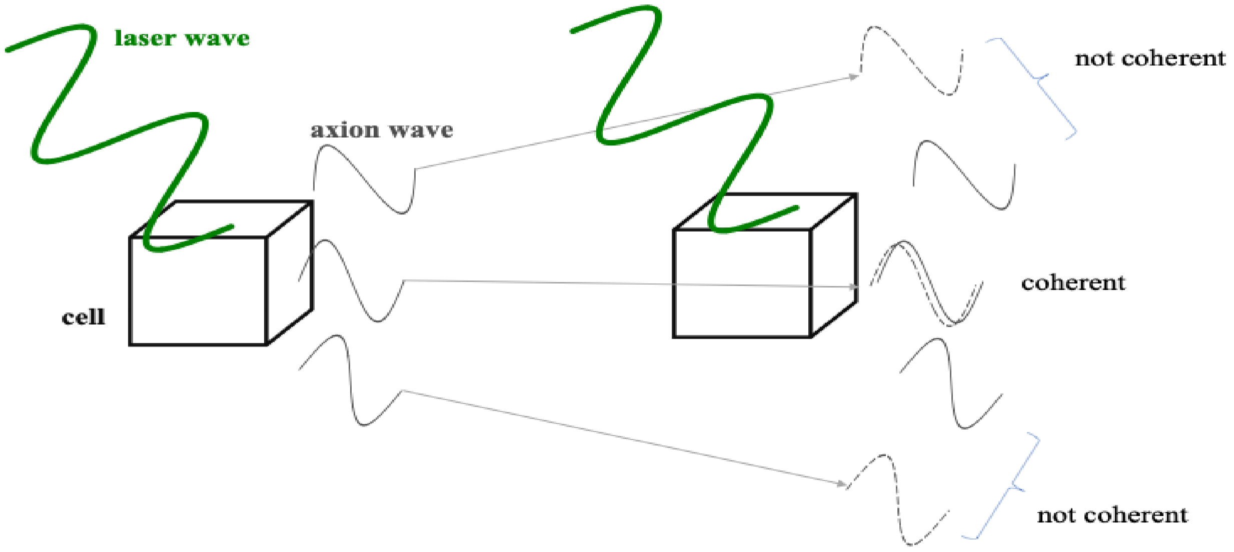
Fig: Schematic figure for thin film stacking. The brown areas are the ionic crystal, while the yellow areas are supporting materials.

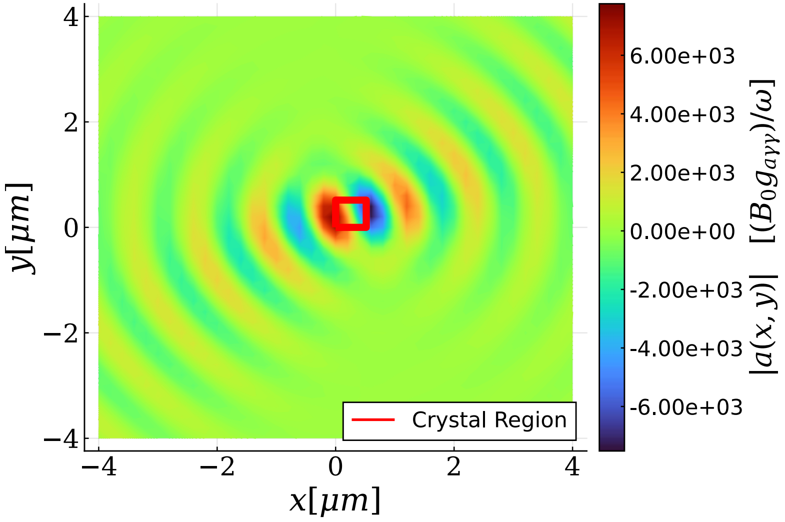
[2] R. Ballou, et al., PRD 92, 092002(2015)

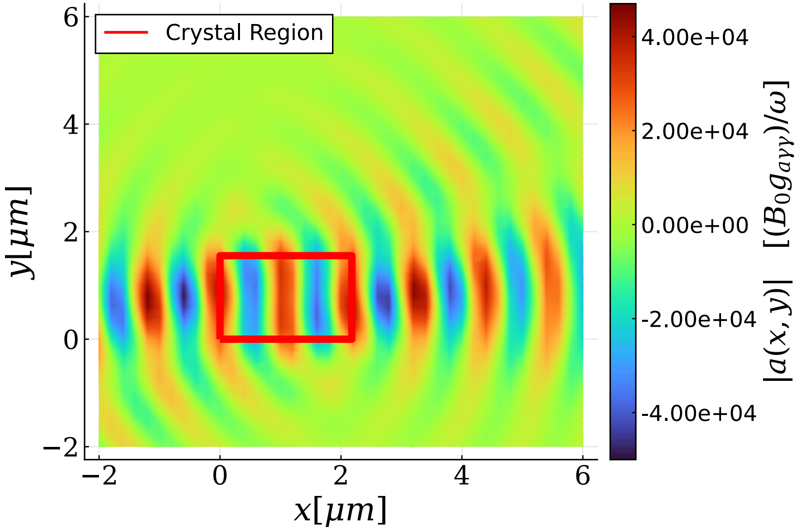
3.3*Longitudinal Coherent

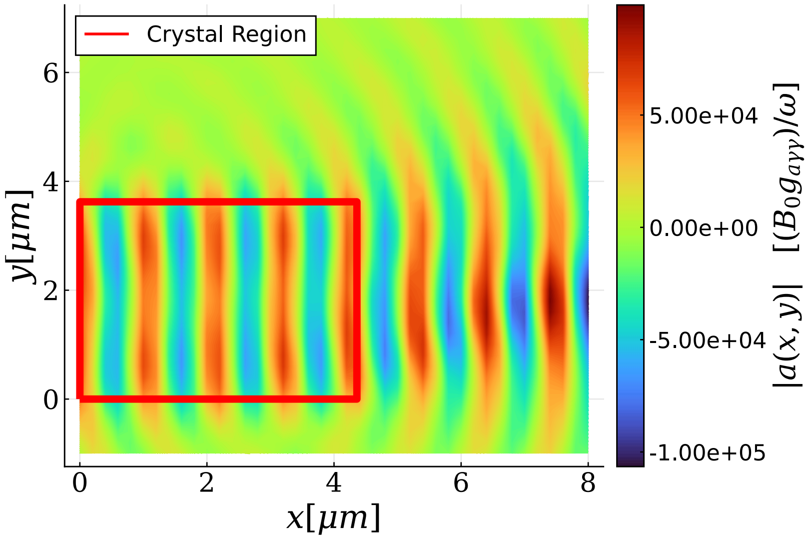
- With the increase of transverse size of crystal, the axion wave approaches plane wave.

- The axion wave produced at one cell, when propagating to the next cell, if the phase matches, will coherently superposed with axion produced at next cell.









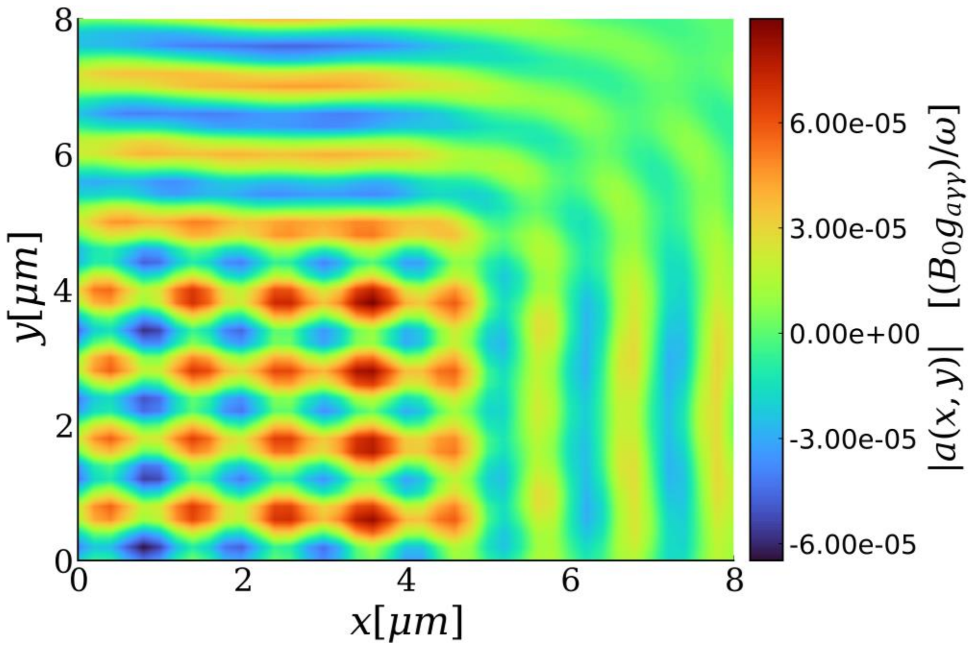
$N_x = N_y = N_z = 950$

$N_x = N_z = 4000, N_{\text{layer}} = 2$

$N_x = N_z = 8000, N_{\text{layer}} = 4$

3.4* Random Distributed Charge

- In crystal, the charges are regularly distributed, while in plasma, the charges are randomly distributed.
- The phase of random charge is undetermined, and the axion wave cannot coherently superposed.



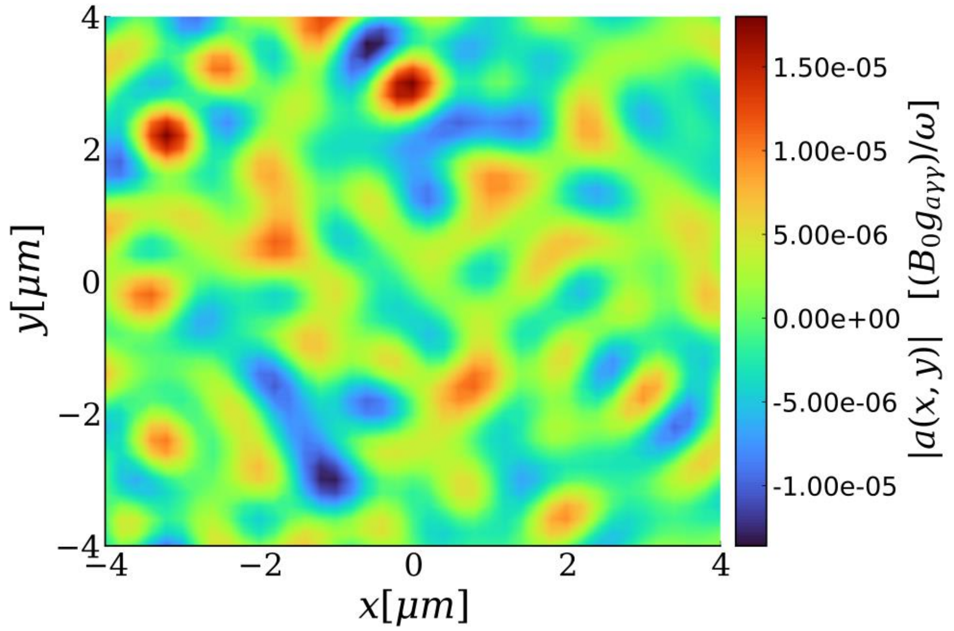


Fig: Axion wave function generated by laser and charge. Left: regularly positioned charge; Right: randomly distributed charge.

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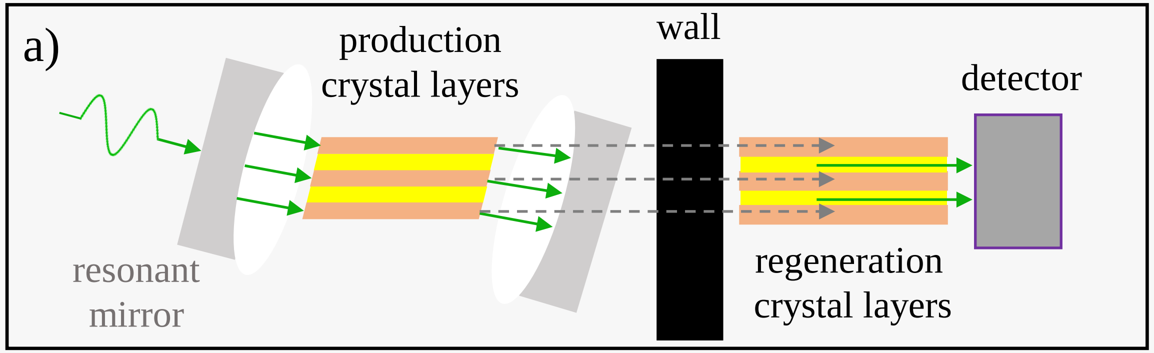
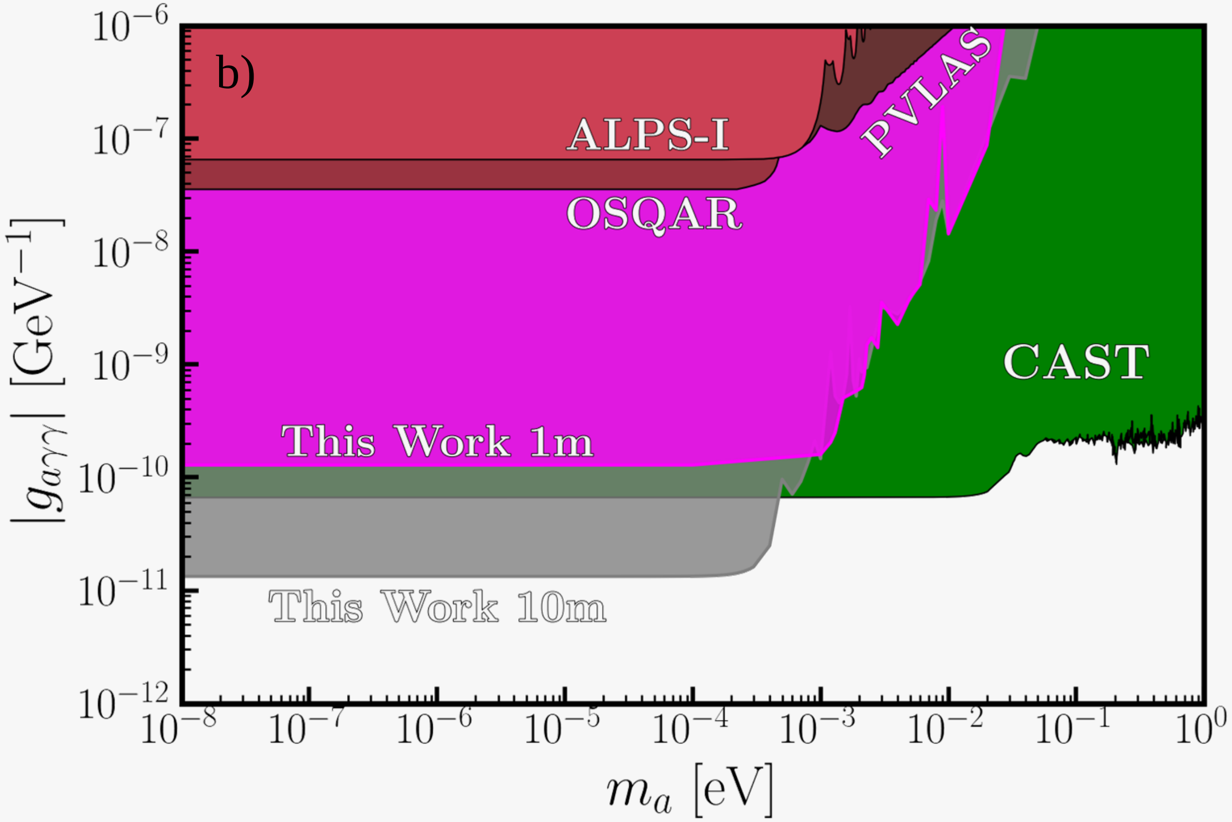
4. Experimental Design

- Our design is similar to LSW: generate axion → using wall to block light → regenerate light and detect.
- Laser wavelength 1064nm, power 150kW, running for one year 3×10^7s.
- If the crystal length is 10m， we can constraint the coupling constant to $g_{a\gamma\gamma} \gtrsim 1.32 \times 10^{-11}\text{GeV}^{-1}$, better than CAST.





Left: Experimental design. Right: Estimated exclusion line based on parameters.

5. Summary

- We propose a novel way to generate axion using optical light and ionic crystal.

- We find that, if the laser is injected into the crystal at some specific angle, their can be a coherent enhancement for axion production.

- By stacking thin film layers with specific distance, the coherence can be further enhanced.

- In this way, if the size of the crystal is as large as the magnetic field in LSW experiments, the conversion probability can be 2-order-of-magnitude larger.

- For crystal of 10 meters long, and after one year of data collection, we can obtain an exclusion line better than all current terrestrial experiments.

Appendix. Coherent Enhancement

- The transition probability is:

$$P_{\text{laser}\to a} \propto \frac{g_{a\gamma\gamma}^2}{S} \int_0^{\pi} \mathrm{d}\theta \int_0^{2\pi} \mathrm{d}\phi P_{\text{single}}$$

$$\times \left|\mathcal{T}_{\text{lat}}\left(\Delta \boldsymbol{k}; \{\boldsymbol{r}_s\}\right)\right|^2,$$

Single cell contribution

Multiple cell superposition☆

$$\mathcal{T}_{\text{lat}} = \sum_l \exp\left(-i\Delta\boldsymbol{k}\cdot\boldsymbol{r}_l\right)$$

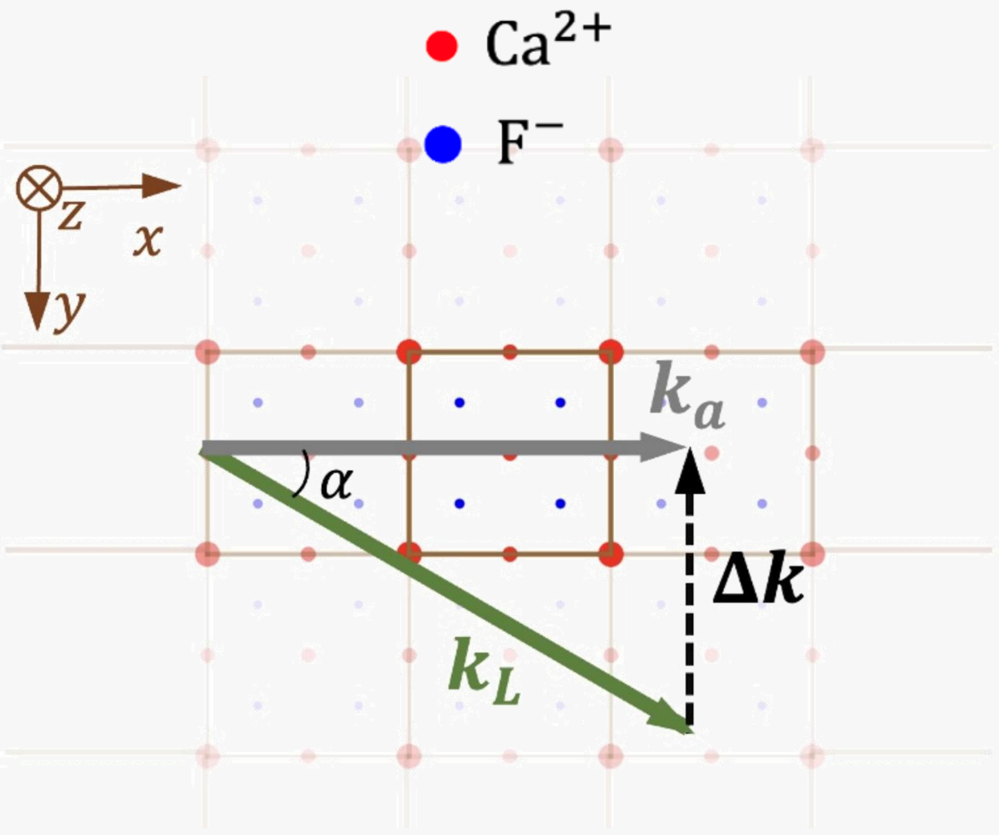


Fig: Schematic figure for coherent condition.

- When $\boldsymbol{\Delta k} \parallel \boldsymbol{y}$, there are coherent enhancement.
- At the peak of the coherence:

$$\mathcal{T}_{\text{lat}}^{\max} = \frac{1-\exp\left[\mathrm{i}N_y \omega d \cot\alpha\right]}{1-\exp\left[\mathrm{i}\omega d \cot\alpha\right]} N_x N_z$$

- when $N_y \omega d \cot\alpha = \pi$, the coherence is maximum. For CaF_2, this corresponds to $L_y = N_y d =$ 518nm. This is a very thin layer.