Axion Theories and Experiments

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Outline

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The convincing evidence for physics beyond the SM:

- Dark energy
- Dark matter
- Neutrino masses and mixings
- Baryon asymmetry
- Inflation

The SM is incomplete!

Major Problems in the SM

- Fine-tuning problems
- Aesthetic problems
- Electroweak vacuum stability problem

  It can be solved easily in the new physics models, for example, supersymmetry, etc.

Fine-tuning problems

- Cosmological constant problem

$$\Lambda_{\mathrm{CC}} \sim 10^{-122} M_{\mathrm{Pl}}^4 \ .$$

- Gauge hierarchy problem

$$M_{\mathrm{EW}} \sim 10^{-16} M_{\mathrm{Pl}} \ .$$

- Strong CP probelm

$$\theta < 1.3 \times 10^{-10} \ .$$

- The SM fermion masses and mixings

$$m_{\mathrm{electron}} \sim 10^{-5} m_{\mathrm{top}} \ .$$

Aesthetic Problems:

- Interaction unification
- Fermion unification
- Gauge coupling unification
- Charge quantization
- Too many parameters

These prolems might be solved when we embed the SM into the Grand Unified Theories (GUTs) and string models.

Fine-tuning Problems:

- Cosmological constant problem

  String landscape. Question: how to test it at the future colliders?

$$V = \Lambda^3\phi + \cos\left(\frac{\phi}{f} + c\right) ~,~~ \phi \to \phi + 2\pi f ~.$$

- Gauge Hierarchy problem

  Supersymmetry, large extra dimension(s), and strong dynamics, etc.

- Strong CP probelm

  Peccei-Quinn mechanism.

- The SM fermion masses and mixings

  The Froggat-Nielsen meschanism.

String Landscape

- An enormous "landscape" for long-lived metastable string/M theory vacua due to flux compactifications [1].
- Weak anthropic principle [2].
- The first concrete explanation of the very tiny value of the cosmological constant, which can take only discrete values.
- Solution to gauge hierarchy problem.

  Although the tiny cosmological constant and light Higgs mass are not technically natural in QFT, they can indeed be natural in the string landscape if the vacua with tiny cosmological constant and light Higgs mass are populated in the string landscape!

The string landscape cannot explain the strong CP problem!

[1] Giddings, Kachru and Polchinski; Kachru, Kallosh, Linde and Trivedi; Susskind; Denef and Douglas.
[2] Weinberg.

Supersymmetric KSVZ Axion Models with Universal Intermediate-Scale Supersymmetry Breaking [3]

- String landscape: cosmological constant problem, and gauge hierarchy problem.
- Peccei–Quinn mechanism: strong CP problem.
- Axion quality problem.

  The gauged discrete Z_N PQ symmetry with $N \geq 10$ inspired from the anomalous $U(1)_A$ gauge theory in string theory.
- Gauge coupling unification, and string-scale gauge coupling unification from F-theory model building.
- Dark matter: axion.
- The intermediate-scale (10^{11} GeV) coincidence:

  The PQ symmetry breaking scale, right-handed neutrino masses, and supersymmetry breaking scale, etc.

[3] V. Barger, C. W. Chiang, J. Jiang and TL, Nucl. Phys. B **705**, 71-91 (2005).

The Research Field

- The worst scenario around 2002: only Higgs particle was found at the LHC.
- In late April or early May 2016, assuming no new physics signal at the LHC, what shall we study?
- The string landscape might indeed solve the cosmological constant problem, and gauge hierarchy problem?
- The interesting problem might be the strong CP problem?

The supersymmetric axion models with universal intermediate-scale supersymmetry breaking!

Outline

The $U(1)_A$ Problem in the QCD

- The QCD Lagrangian

$$
\begin{aligned}
\mathcal{L}_{MSM} &= -\frac{1}{2g_s^2}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} + \bar{Q}_i i\not{D} Q_i + \bar{U^c}_i i\not{D} U_i^c + \bar{D^c}_i i\not{D} D_i^c \\
&\quad - \left(h_u^{ij} Q_i U_j^c \widetilde{H} + h_d^{ij} Q_i D_j^c H + \mathrm{H.C.} \right) \ .
\end{aligned}
$$

The $U(1)_A$ Problem in the QCD

- Because $m_u/m_d << \Lambda_{QCD}$, we have approximate $U(2)_V \times U(2)_A$ symmetry.
- $U(2)_V = SU(2)_I \times U(1)_B$ is a good approximate symmetry of nature.
- Quark condensations $\langle \bar{u}u \rangle / \langle \bar{d}d \rangle \neq 0$ break the $U(2)_A$ symmetry, so we have four Nambu-Goldstone bosons.
- Although pions are light, we do not have another light state due to $\left(m_{\eta'} \simeq 960 \text{ MeV}\right)^2 >> \left(m_{\pi}^2 \simeq 140 \text{ MeV}\right)^2$.

$U(1)_A$ **is not a symmetry in QCD.**

The Solution to the $U(1)_A$ Problem

- The topological term

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} \mathrm{Tr} F^{\mu\nu} \widetilde{F}^{\mu\nu} \ , \quad \widetilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \ .$$

- The topological term is a total derivative

$$F_{\mu\nu} \widetilde{F}^{\mu\nu} = \partial_\mu K_\mu, \ K_\mu = \frac{1}{16\pi^2} \epsilon^{\mu\nu\alpha\beta} \left(A^a_\nu \partial_\alpha A^a_\beta + \frac{1}{3} f_{abc} A^a_\nu A^b_\alpha A^c_\beta \right) .$$

- Being a total derivative, the θ term does not affect the equations of motion.

The Solution to the $U(1)_A$ Problem

- The field configurations with the instanton boundary conditions give rise to a nonvanishing

$$\int d^4x (\mathcal{L}_\theta)_{\text{one instanton}} \quad = \quad \theta \ .$$

- $\mathcal{L}_\theta$ is not $U(1)_A$ invariant, and then $U(1)_A$ is not a symmetry of QCD

Two Higgs doublets are needed for the $U(1)_A$ invariance for the Yukawa couplings

$$q_f \longrightarrow e^{i\gamma_5\alpha} q_f \ , \quad \theta \longrightarrow \theta - 2\alpha \ .$$

Strong CP Problem

- $\overline{\theta} = \theta + \theta_{\rm q}$ parameter is a dimensionless coupling constant and infinitely renormalized by radiative corrections.

$$\theta_{\rm q} \;=\; {\rm ArgDet}(Y_U Y_D) \; .$$

- The experimental bound on the neutron EDM is smaller than 3.0×10^{-26} e cm, while the contribution from the $\bar{\theta}$ is

$$d_n \;=\; 2.4(1.0)^{-16}\overline{\theta} \; {\rm e \; cm} \; .$$

- No theoretical reason for $\overline{\theta}$ as small as 10^{-10} required by the experimental bound on the EDM of the neutron.
- $\overline{\theta}$ may be a random variable with a roughly uniform distribution in the string landscape.

Strong CP problem: why $\overline{\theta}$ is so tiny?

The Possible Solutions to the Strong CP Problem

- Massless quark solution, but not consistent with Lattice QCD.

  If one of the quark fields (say the up quark) was massless, the QCD Lagrangian would have a global $U(1)_u$ axial symmetry, which could be used to rotate the $\overline{\theta}$ term to zero.

- RGE running of $\overline{\theta}$: $\overline{\theta}$ is chosen to be zero at some high scale.

  We can show that all 6-loop diagrams and below cannot generate any RG running.

- Parity: $\overline{\theta} = \theta + \mathrm{ArgDet}(Y_u) + \mathrm{ArgDet}(Y_d) = 0$

$$P : SU(2)_L \leftrightarrow SU(2)_R \,,\ Q_L \leftrightarrow Q_R^{\dagger} \,,\ H_L \leftrightarrow H_R^{\dagger} \,,\ L_L \leftrightarrow L_R^{\dagger} \,.$$

  θ is forbidden, and Y_u/Y_d are Hermitian. The problem arises after a bi-fundamental Higgs is added due to the one-loop contribution to $\overline{\theta}$.

- Soft P (CP) breaking typically called Nelson-Barr models.

  CP is a valid symmetry in the high-energy theory, and is spontaneously broken in such a way that θ naturally turns out to be small. The fine-tuning is still needed.

Peccei–Quinn Mechanism

- The $U(1)_A$ symmetry becomes $U(1)_{PQ}$ symmetry.
- If there are two Higgs doublets in the SM, we can have the $U(1)_{PQ}$ symmetry [4]

$$-\mathcal{L} = y_{ij}^u Q_i U_i^c H_u + y_{ij}^d Q_i D_i^c H_d + y_{ij}^e L_i E_i^c H_d + V\left(H_u^\dagger H_u,\ H_d^\dagger H_d,\ (H_d^\dagger H_u)(H_u^\dagger H_d)\right) .$$

- The $U(1)_{PQ}$ symmetry

$$Q_i/U_i^c/D_i^c/L_i/E_i^c \longrightarrow e^{i\alpha} Q_i/U_i^c/D_i^c/L_i/E_i^c ,$$
$$H_d/H_u \longrightarrow e^{-i2\alpha} H_d/H_u .$$

[4] Weinberg; Wilczek.

Peccei–Quinn-Weinberg-Wilczek Axion

- Peccei–Quinn-Weinberg-Wilczek Axion is

$$a \equiv \sin\beta \mathrm{Im} H_d^0 + \cos\beta \mathrm{Im} H_u^0 \ , \quad \mathrm{where} \tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle} \ .$$

- The solution to the strong CP problem: $\overline{\theta} = 0$.

$$V_{\mathrm{Instanton}} = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\overline{\theta}}{2}\right)} \ ,$$

$$\overline{\theta} = \theta + \theta_{\mathrm{q}} + a/f_a \ , \quad f_a = \sqrt{\langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2} \ .$$

- The axion mass

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim 5.7 \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right) \mu\mathrm{eV} \ .$$

Peccei–Quinn-Weinberg-Wilczek Axion

- Weak axion, which has $f_a \sim 246$ GeV and $m_a \sim 25$ keV, is ruled out by $K \to \pi a$ and $J/\Psi \to a\gamma$ experiments.
- Question: can we propose the axion models with the TeV-scale $U(1)_{PQ}$ symmetry breaking and very large f_a?
- Answer: No!
- Point: anomaly argument, and then the only relevant parameter is f_a.
- Solutions: invisible DFSZ and KSVZ Axions

Introducing a SM singlet S with intermediate-scale VEV, so $f_a \simeq \langle S \rangle \simeq 10^{10} - 10^{12}\mathrm{GeV}$.

The DFSZ Axion

- The PQWW model with an SM singlet S

$$S \longrightarrow e^{i2\alpha} S ~, \quad -\mathcal{L} = S^2 H_d H_u ~.$$

- In the supersymmetric SMs, we have

$$W = \frac{1}{M_{\rm Pl}} S^2 H_d H_u ~.$$

A natural solution to the μ problem.

- The DFSZ Axion

$$a \equiv \frac{1}{f_a} \left(\langle H_u^0 \rangle {\rm Im} H_d^0 + \langle H_d^0 \rangle {\rm Im} H_u^0 + \langle S \rangle {\rm Im} S \right) ~.$$

where $f_a = \sqrt{\langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2 + \langle S \rangle^2}$.

The KSVZ Axion

- A pair of vector-like quarks (XQ^c, XQ) and a SM singlet S

$$XQ^c/XQ \longrightarrow e^{i\alpha} XQ^c/XQ ~, \quad S \longrightarrow e^{-i2\alpha} S ~.$$

- The Lagrangian is

$$-\mathcal{L} = S XQ^c XQ ~.$$

- The KSVZ axion is the imaginary part of S, and $f_a = |\langle S \rangle|$.

The Minimal Invisible Axion Model [5]

- The SM with a SM singlet S, and the $U(1)_{PQ}$ charges are

$$Q_i,\ L_i,\ U_i^c,\ D_i^c, E_i^c : 1\ ,\quad H_u : 2\ ,\quad S : -4\ .$$

- The Lagrangian is

$$\mathcal{L} \;=\; -y_{ij}^u Q_i U_j^c H_u - y_{ij}^d \frac{S}{M_*} Q_i D_j^c \widetilde{H}_u, -y_{ij}^e \frac{S}{M_*} L_i E_j^c \widetilde{H}_u\ .$$

- For M_* to be the reduced Planck scale, the effective axion PQ scale will be $f_a \sim 10^{15-16}$ GeV.

[5] Y. Gao, T. Li and Q. Yang, [arXiv:1912.12963 [hep-ph]].

Axion Dark Matter Relic Density

- Axion dark matter density is

$$\Omega_a h^2 = 0.15X \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} .$$

- Pre-inflationary scenario: misalignment mechanism, and $X \sim \sin^2 \theta_{\rm miss}/2$.
- Post-inflationary scenario: misalignment mechanism and topological defect decays, and $X \subset (2, 10)$.

Topological defects are mainly strings and domain walls associated with the axion field.

- Axion dark matter density is [6]

$$\Omega_a h^2 \simeq 0.12 \left(\frac{28\,\mu\mathrm{eV}}{m_a} \right)^{7/6} = 0.12 \left(\frac{f_a}{2.0 \times 10^{11}\,\mathrm{GeV}} \right)^{7/6} .$$

[6] L. Di Luzio, M. Giannotti, E. Nardi and L. Visinelli, [arXiv:2003.01100 [hep-ph]].

Axion Mass

- The axion mass is [7]

$$m_a \simeq 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right) .$$

- The more previse calculations give $m_a = 60 - 150\ \mu\text{eV}$ [8], and $m_a = 26.5 \pm 3.4\ \mu\text{eV}$ [9].
- The axion mass is around 50 μeV.

[7] G. Grilli di Cortona, E. Hardy, J. Pardo Vega and G. Villadoro, JHEP **01**, 034 (2016).

[8] T. Hiramatsu, M. Kawasaki, K. Saikawa and T. Sekiguchi, Phys. Rev. D **85**, 105020 (2012); M. Kawasaki, K. Saikawa and T. Sekiguchi, Phys. Rev. D **91**, no.6, 065014 (2015).

[9] V. B. Klaer and G. D. Moore, JCAP **11**, 049 (2017).

The Axion Lagrangian

$$\mathcal{L}_a^{\rm int} \supset \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}aF\tilde{F} + C_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f + \frac{C_{a\pi}}{f_a f_\pi}\partial_\mu a[\partial\pi\pi\pi]^\mu - \frac{i}{2}\frac{C_{an\gamma}}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}\,,$$

where $[\partial\pi\pi\pi]^\mu = 2\partial^\mu\pi^0\pi^+\pi^- - \pi_0\partial^\mu\pi^+\pi^- - \pi_0\pi^+\partial^\mu\pi^-$,

The Axion Lagrangian

$$
\begin{aligned}
C_{a\gamma} &= \frac{E}{N} - 1.92(4)\,, \\
C_{ap} &= -0.47(3) + 0.88(3)\, c_u^0 - 0.39(2)\, c_d^0 - C_{a,\,\mathrm{sea}}\,, \\
C_{an} &= -0.02(3) + 0.88(3)\, c_d^0 - 0.39(2)\, c_u^0 - C_{a,\,\mathrm{sea}}\,, \\
C_{a,\,\mathrm{sea}} &= 0.038(5)\, c_s^0 + 0.012(5)\, c_c^0 + 0.009(2)\, c_b^0 + 0.0035(4)\, c_t^0\,, \\
C_{ae} &= c_e^0 + \frac{3\alpha^2}{4\pi^2}\left[\frac{E}{N}\log\left(\frac{f_a}{m_e}\right) - 1.92(4)\log\left(\frac{\mathrm{GeV}}{m_e}\right)\right]\,, \\
C_{a\pi} &= 0.12(1) + \frac{1}{3}\left(c_d^0 - c_u^0\right)\,, \\
C_{an\gamma} &= 0.011(5)\, e\,.
\end{aligned}
$$

The Axion Lagrangian

$$\mathcal{L}_a^{\rm int} \supset \frac{1}{4} g_{a\gamma} a F \tilde{F} - i g_{af} a \bar{f} \gamma_5 f - \frac{i}{2} g_d \, a \, \bar{n} \sigma_{\mu\nu} \gamma_5 n F^{\mu\nu} \, , .$$

where

$$g_{a\gamma} = \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a} \, , \qquad g_{af} = C_{af} \frac{m_f}{f_a} \, , \qquad g_d = \frac{C_{an\gamma}}{m_n f_a} \, .$$

Axion Electrodynamics:

- Generic coupling to electromagnet field:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$

Modified Maxwell's Equations:

- $\nabla \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{j} + g_{a\gamma\gamma}(\vec{B}\frac{\partial a}{\partial t} - \vec{E} \times \nabla a)$
- $\nabla \cdot \vec{E} = \rho - g_{a\gamma\gamma}\vec{B} \cdot \nabla a$
- $\nabla \cdot \vec{B} = 0$
- $\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$

$$\partial_\mu F^{\mu\nu} = j^\nu - g_{a\gamma\gamma}\tilde{F}^{\mu\nu}\partial_\mu a$$

Axion current: $J_a^\nu \equiv -g_{a\gamma\gamma}\tilde{F}^{\mu\nu}\partial_\mu a$

Bianchi identity: $\partial_\mu \tilde{F}^{\mu\nu} = 0$

$\nabla a \sim 0$ (Gradients suppressed by $V_{\rm DM} \sim 10^{-3}$)

The Axion Quality Problem

- Because $U(1)_{PQ}$ symmetry is an anomalous symmetry, we cannot forbid the terms such as MXQ^cXQ and $M_S^2S^2$, etc, w hich breaks the $U(1)_{PQ}$ symmetry, for the EFT point of view.
- The global symmetries will be broken by quantum gravity effect. Let us consider the following set of effective operators of dimension $d = 2m + n$ that violate the PQ symmetry by n units

The Axion Quality Problem

$$
\begin{aligned}
V^{n}_{\mathrm{PQ-break}} &= \frac{\lambda_n |\Phi|^{2m} \left(e^{-i\delta_n}\Phi^n + e^{i\delta_n}{\Phi^\dagger}^n \right)}{{\mathrm{M_{Pl}}}^{d-4}} \\
&\supset \frac{\lambda_n f_a^4}{2} \left(\frac{f_a}{\sqrt{2}\mathrm{M_{Pl}}} \right)^{d-4} \cos\left(\frac{na}{f_a} - \delta_n \right) \\
&\approx m_*^2 f_a^2 \left(\frac{\theta^2}{2} - \frac{\theta}{n} \tan\delta_n \right) ,
\end{aligned}
$$

where $m_*^2 = \frac{\lambda_n f_a^2}{2} \left(f_a/(\sqrt{2}\mathrm{M_{Pl}}) \right)^{d-4} \cos\delta_n$.

The Axion Quality Problem

- The CP conserving minimum $\theta = 0$ of the QCD induced potential is shifted to

$$\langle\theta\rangle = \frac{m_*^2 \tan\delta_n}{n(m_a^2 + m_*^2)} .$$

- To satisfy the neutron EDM constraint, we require $d \geq 8, 10, 21$ respectively for $f_a \sim 10^8, 10^{10}, 10^{15}$ GeV.
- Solution: the anomalous $U(1)_X$ gauge symmetry in string models which is broken down to the discrete Z_N symmetry, etc.

The Connections between Axion/ALP and New Physics

- The supersymmetric SMs: μ problem, dark matter density problem, etc.
- The Grand Unified Theories.

  There exists the possibility: no coupling between axion and photons.
- The superstring models: many Axion-Like Particles (ALPs).

  Witten, Axions may be intrinsic to the structure of string theory.
- Axion inflation.
- The intermediate-scale coincidence: the $U(1)_{PQ}$ symmetry breaking scale, right-handed neutrino masses, supersymmetry breaking scale, messenger scale in gauge mediation, axion quality problem, and string-scale gauge coupling unification, etc.
- Relaxation mechanism

  Solutions to the gauge hiearchy problem, etc.

The Connections between Axion/ALP and New Physics

- Dark matter.
- Dark energy particles are similar to axion/ALPs.

  Quintessence Field, Chameleons, Galileons, and Symmetrons, etc.
- Baryon asymmetry via axion quark nugget (AGN).
- The Froggatt-Nielsen (FN) mechanism is the solution to the fermion mass hierarchy problem: $U(1)_{FN} = U(1)_{PQ}$.
- Gravitational wave:

  $\frac{\alpha_g}{4} a R^{\beta}{}_{\alpha\gamma\delta} \tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}$ with $\tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta} \equiv \frac{1}{2}\epsilon^{\gamma\delta\mu\nu} R^{\alpha}{}_{\beta\mu\nu}$.
- The neutrino masses and mixings: $U(1)_{BL} = U(1)_{PQ}$, and the baryon asymmetry can be explained via the leptogenesis.
- The EDGES results and XENON1T results, etc.

Outline

Introduction and Motivation

Strong CP Problem and Peccei–Quinn Mechanism

Axion Experiments

The Resonant Cavity Search for Axion Dark Matter

Detection of axion/ALP

The various axion searches can be categorized by if the axion is dark matter.

1.Dark Matter independent searches

Axion from natural sources:

Axion helioscopes(CAST,IAXO)

Underground Detectors(XENON,PANDAX,LUX)

Cherenkov Telescopes(AS-γ,LHAASO,HESS)

Producing axion/ALPs in the lab:

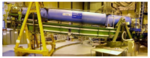
Light shining through walls (ALPS(I-III))

Fifth force experiments(ARIADNE,QUAX)

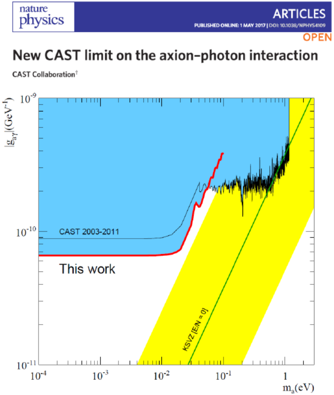
Polarization experiments(PVLAS)

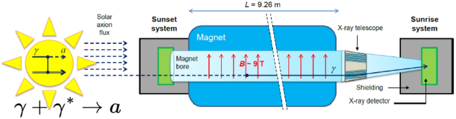
Solar Axion (CAST,IAXO)

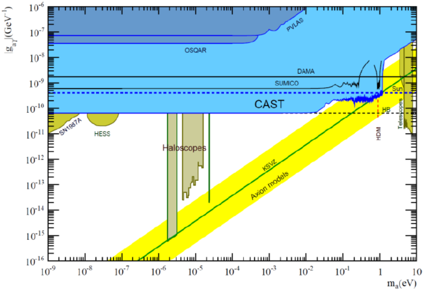
Latest CAST limit: $g_{a\gamma} < 0.66 \times 10^{-10}\mathrm{GeV}^{-1}$at 95%CL



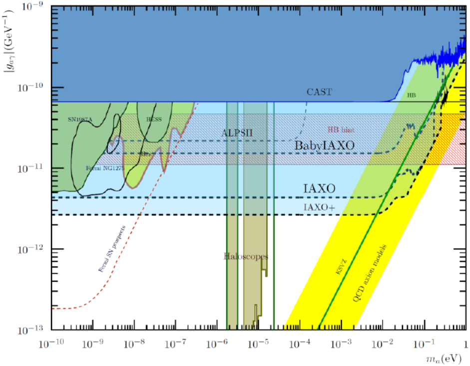
CAST at CERN

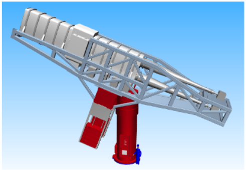




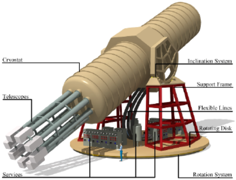


In the future, IAXO





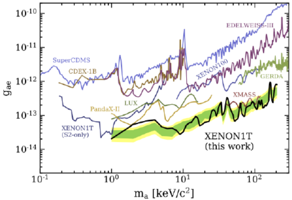
Baby IAXO
(Intermediate experimental stage before IAXO)



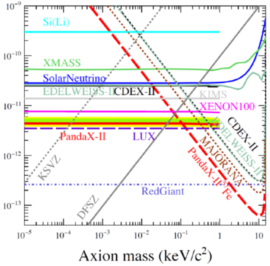
IAXO

Solar Axion: direct detection experiment
Underground Detectors(XENON,PANDAX,LUX)

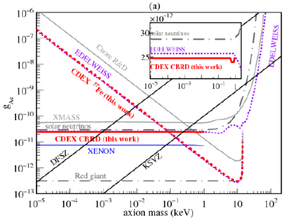
Due to the coupling of Axion to electron and nucleon, the solar Axion with high energy can generate recoil signal in low temperature dark matter detector.



XENON Collaboration
arXiv:2006.0972



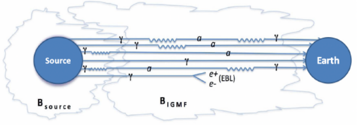
PANDAX, Collaboration
PRL 119 (2017)



CDEX, Collaboration
Phys.Rev. D95
(2017) no.5, 052006

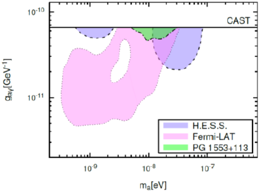
HE photon energy spectrum:

High Energy photons traversing in stellar or interstellar magnetic fields could convert into axion, resulting in the distortion of photon energy spectrum:

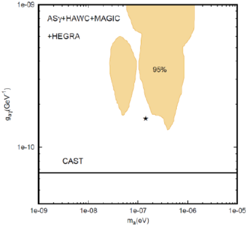


$$P_{\gamma\to a}(E_\gamma) = \left(1+\frac{E_c^2}{E_\gamma^2}\right)^{-1} \sin^2\left(\frac{g_{a\gamma\gamma}B_{\rm T}L}{2}\sqrt{1+\frac{E_c^2}{E_\gamma^2}}\right)$$

Gama ray telescopes like AS-γ,LHAASO,HESS can observe HE photons from very distant sources:

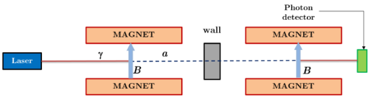


J.Guo, H.-J. Li, X.-J. Bi,
S.-J. Lin, P.-F. Yin 2002.07571

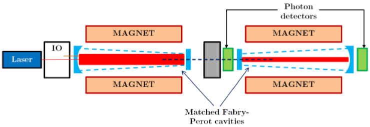


AS-γ轴子限制：X.-J.Bi, Y.Gao, J.Guo,
N.Houston, T. Li, F.Xu, X.Zhang, 2002.01796

Light-shining-through-wall(LSW) (ALPS,OSQAR)



Standard LSW experiment configuration



Enhanced LSW configuration (future)

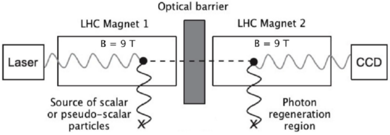
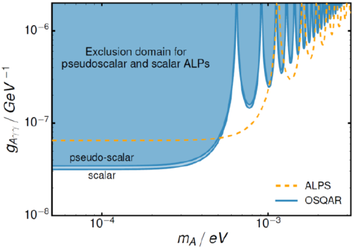


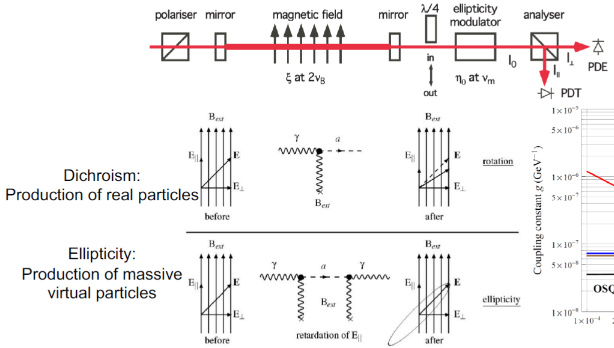
FIG. 1. Principle of the OSQAR LSW experiment.

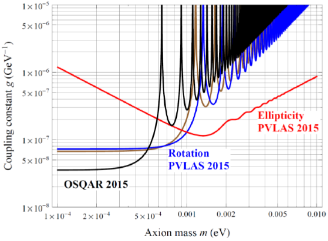


OSQAR: Phys.Rev.Lett. 113 (2014) no.16, 161801
ALPS: Phys.Lett. B689 (2010) 149-155

Polarization experiments(PVLAS)

PVLAS experiment: study QED vacuum birrefringence and sensitivty to ALPs:





PVLAS , EPJC 76 (2016) no.1, 24

Axion-mediated macroscopic forces

If $\bar{\theta} \neq 0$, the axion has a coupling: $\bar{\theta}\psi\bar{\psi}am_\psi/f$. It will mediate a $\bar{\theta}^2/f^2r^2$ force.

If the axion has spin couplings: $\bar{\psi}\gamma^\mu\gamma^5\psi\partial_\mu a/f$ .It will mediate a $1/f^2r^4$ force between spins.

If it has both of these couplings, then there is also a $\bar{\theta}/f^2r^3$ force between the two objects.

The concomitant interactions between fermions mediated by ALP exchange are of three types:

1.Monopole-Monopole $\propto \bar{g}_{a\psi}\bar{g}_{a\psi'}$

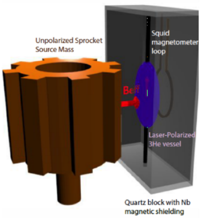
2.Monopole-Dipole $\propto \bar{g}_{a\psi}g_{a\psi'}$

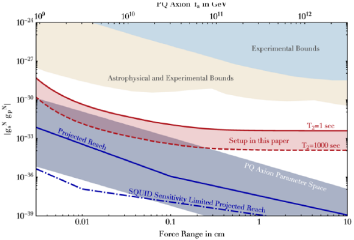
3.Dipole-Dipole $\propto g_{a\psi}g_{a\psi'}$

ARIADNE experiment

Search the short-range force by NMR technique, the experiment is sensitive to products of fermion couplings: $\propto \bar{g}_{a\psi} g_{a\psi'}$

Arvanitaki, Geraci
Phys. Rev. Lett. 113, 161801 (2014)

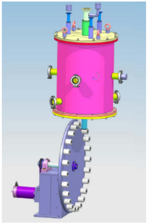


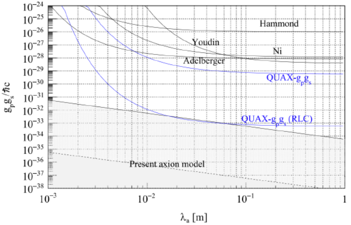


QUAX experiment

Search the monopole-dipole force coupled to electron-spins $\propto \bar{g}_{aN} g_{ae}$ by detecting the magnetization induced by a extra magnet field(created by the axion field gradient) in a paramagnetic material

N. Crescini, C. Braggio, et al
, Nucl. Instrum. Meth. A842 (2017) 109–113





2.Axion Dark Matter searches
(Searches for axions/ALPs that rely on them being dark matter)

DM-photon conversions in the lab:

Conventional Haloscopes(ADMX, HAYSTAC, ORGAN,CAPP-CULTASK,CAST-CAPP)

Dielectric Haloscopes(MADMAX)

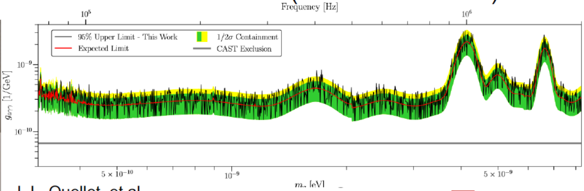
Low frequency resonators with LC circuits (ABRACADABRA)

DM induced Oscillating EDMs:

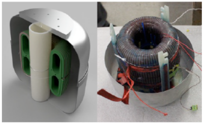
NMR techniques(CASPER)

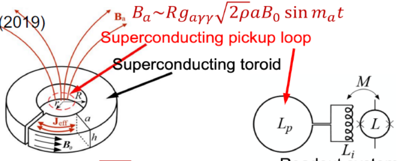
Low frequency resonators with LC circuits (ABRACADABRA)

ABRACADABRA at MIT



J. L. Ouellet, et.al.
Phys. Rev. Lett. **122**, 121802(2019)



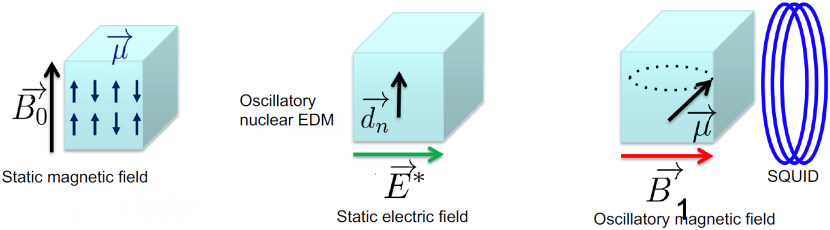


$J_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_a} B_0 \sin m_a t$

$\Phi_a(t) = g_{a\gamma\gamma}\sqrt{2\rho_a} B_0 \sin m_a t \times B_0 V G_{toroid}$

$f_a = 10^{16} GeV, B_0 \sim 5T$, R$\sim$4m: $B_a \sim 10^{-22} T (KSVZ)$

DM induced Oscillating EDMs: NMR techniques(CASPER)



The applied magnetic field is colinear with the sample magnetization.

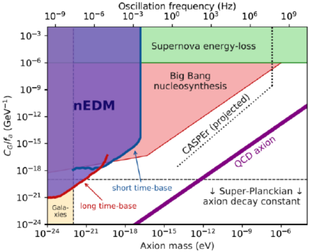
The effective electric field in the crystal is perpendicular to the applied magnetic field.

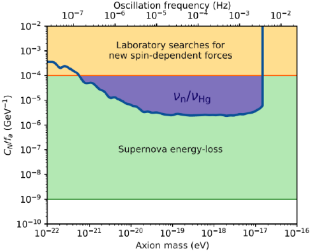
The SQUID pickup loop is arranged to measure the transverse magnetization of the sample.

PRD 88 (2013) arXiv:1306.6088, PRX (2014) arxXiv:1306.6089, PRD 84 (2011) arXiv:1101.2691

Nuclear Spin Precession in Electric and Magnetic Fields (nEDM)

Due to the periodic oscillation of the Axion field, the neutrons (nuclei) obtain periodic EDM





C. Abel,et al. PRX7 (2017) no.4, 041034

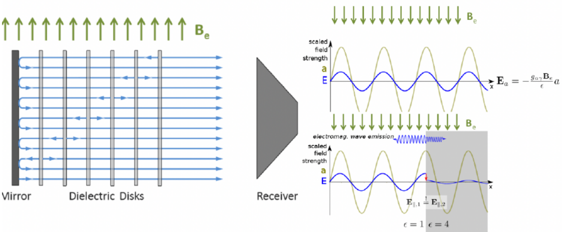
$$d_n(t) \approx +2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\ e \cdot \mathrm{cm}$$

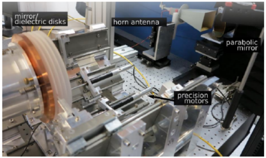
$$H_{\rm int}(t) = \frac{C_N a_0}{2 f_a} \sin(m_a t)\ \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$$

$$d_{\rm Hg}(t) \approx +1.3 \times 10^{-19} \frac{C_G a_0}{f_a} \cos(m_a t)\ e \cdot \mathrm{cm}$$

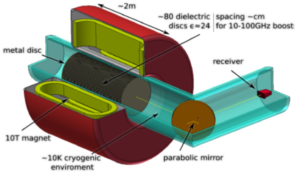
Dielectric Haloscopes(MADMAX)

DM field + Magnet field + Boundary condition in the dish
Theory predicts that there will be photon emission normal to surface





MADMAX at DESY



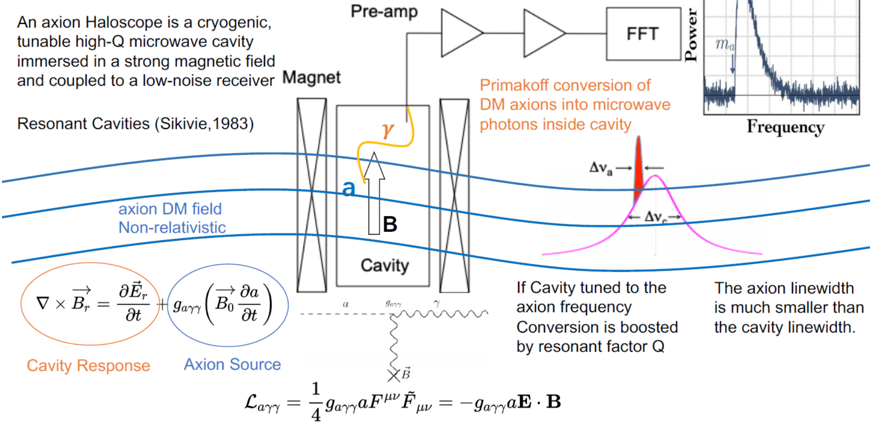
To satisfy the usual continuity requirements:
$\boldsymbol{E}_{\parallel,1} = \boldsymbol{E}_{\parallel,2}$ and $\boldsymbol{B}_{\parallel,1} = \boldsymbol{B}_{\parallel,2}$,EM waves of frequency:$\nu_a = m_a/2\pi$ must be present to compensate for the discontinuity

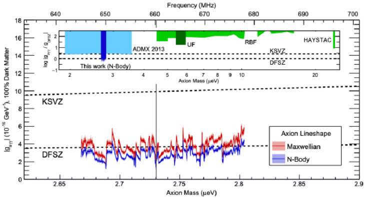
Haloscopes(Resonant Cavity experiment)

ADMX HAYSTAC CAPP-CULTASK

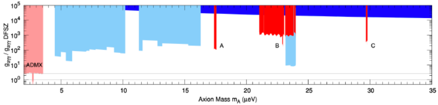
Resonant cavity detection is one of prevalent and mature scheme

Resonant Cavity Detection (Haloscope) Basic principles

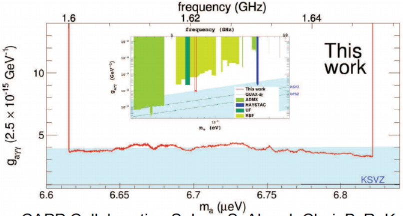




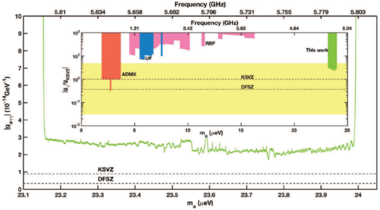
ADMX Collaboration Phys. Rev. Lett. 120, 151301(2018)



ADMX sidecar experiment(Higher-m_a experiment)
ADMX Collaboration Phys. Rev. Lett. 121, 261302(2019)



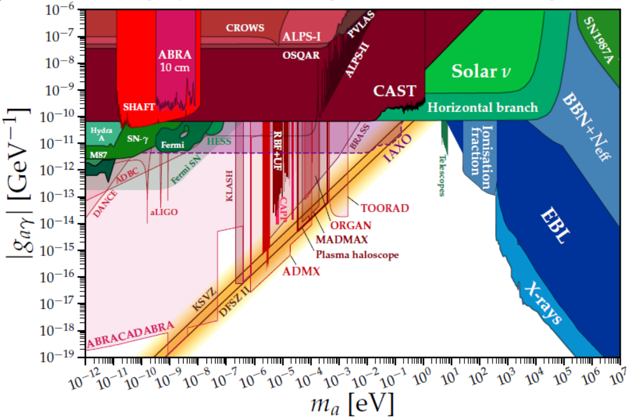
CAPP Collaboration S. Lee, S. Ahn, J. Choi, B. R. Ko, and Y. K. Semertzidis Phys. Rev. Lett. **124**, 101802 (2020)



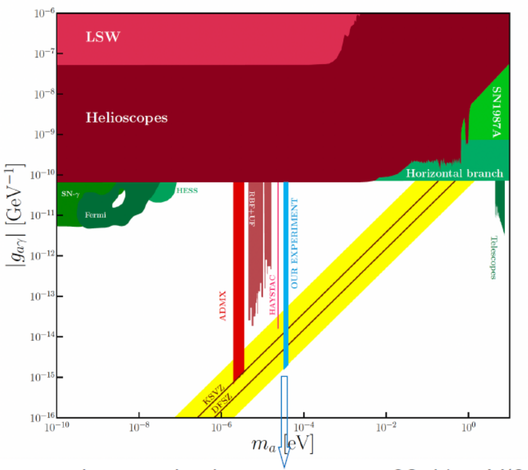
L. Zhong et al., Phys. Rev. D 97, 092001 (2018)

Overall picture(Constraints and Future constraints for $g_{a\gamma}$)

There are already many constraints on axion physics, and many experiments planning to search even further
At present, only the resonant cavity experiment can directly test the theoretical accuracy of QCD axion

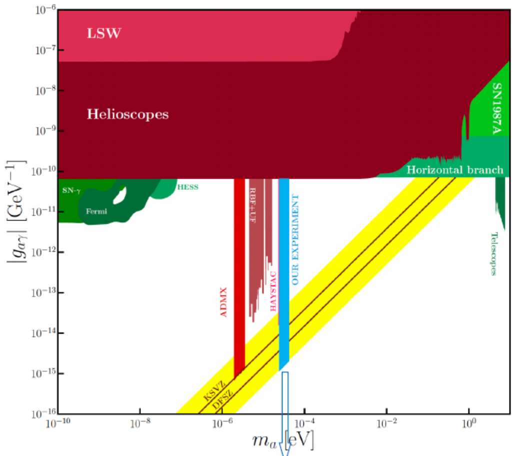


Our proposal:



Oure goal covered axion mass range~32-41 μeV(8-10GHz)

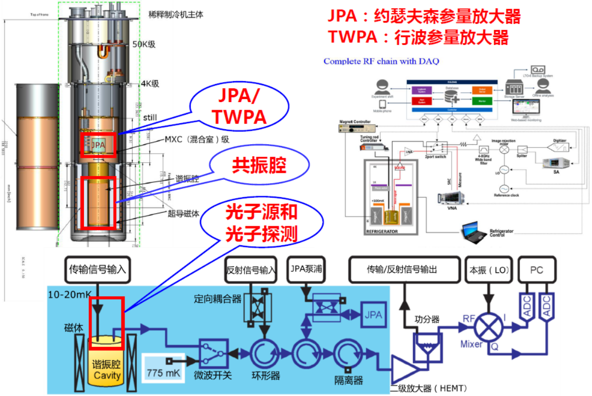
Our proposal:



Oure goal covered axion mass range~24-41 μeV(5.8-10GHz)

整体实验方案

JPA：约瑟夫森参量放大器
TWPA：行波参量放大器



Bounds on Axion Couplings

Star	Hint ($1\,\sigma$)	Bound ($2\,\sigma$)
Sun	–	$g_{a\gamma} \le 2.7 \times 10^{-10}\,\mathrm{GeV}^{-1}$
WDLF	$g_{ae} = 1.5^{+0.3}_{-0.5} \times 10^{-13}$	$g_{ae} \le 2.1 \times 10^{-13}$
WDV	$g_{ae} = 2.9^{+0.6}_{-0.9} \times 10^{-13}$	$g_{ae} \le 4.1 \times 10^{-13}$
RGB Tip	$g_{ae} = 1.4^{+0.9}_{-1.3} \times 10^{-13}$ (M3+M5)	$g_{ae} \le 3.1 \times 10^{-13}$ (M3+M5)
	–	$g^S_{ae} \le 0.7 \times 10^{-15}$; $g^S_{aN} \le 1.1 \times 10^{-12}$
HB	$g_{a\gamma} = (0.3 \pm 0.2) \times 10^{-10}\,\mathrm{GeV}^{-1}$	$g_{a\gamma} \le 0.65 \times 10^{-10}\,\mathrm{GeV}^{-1}$
	–	$g^S_{ae} \le 3 \times 10^{-15}$; $g^S_{aN} \le 6 \times 10^{-12}$
SN 1987A	–	$g^2_{an} + 0.29\, g^2_{ap} + 0.27\, g_{an}\, g_{ap} \lesssim 3.25 \times 10^{-18}$
	–	$g_d \lesssim 4 \times 10^{-9}\,\mathrm{GeV}^{-2}$ ($\Rightarrow f_a \gtrsim 9 \times 10^5$ GeV)
NS in CAS A	–	$g^2_{ap} + 1.6\, g^2_{an} \lesssim 1.1 \times 10^{-18}$
NS in HESS J1731-347	–	$g_{an} \le 2.8 \times 10^{-10}$
Black Holes	–	$f_a \le 6 \times 10^{17}$ GeV or $f_a \ge 10^{19}$ GeV

Table 3: Summary of stellar hints and bounds on axions. The hints are all at 1σ and the bounds at 2σ, except for the case of SN 1987A and NS in CAS A, for which a confidence level was not provided. We have not reported the hint from the NS in CAS A [432] since it is in tension with the more recent bound in [429].

Coupling	Source	Probes	Notes
$g_{a\gamma}$	Astro	Sun	$g_{a\gamma} \leq 2.7 \times 10^{-10}\text{GeV}^{-1}$ for m_a up to a few keV
		HB-stars	$g_{a\gamma} \leq 0.65 \times 10^{-10}\text{GeV}^{-1}$ for m_a up to a few 10 keV
		SN 1987A	$g_{a\gamma} \lesssim 6 \times 10^{-9}\text{GeV}^{-1}$ for $m_a \lesssim 100$ MeV
			$g_{a\gamma} \lesssim 5.3 \times 10^{-12}\text{GeV}^{-1}$ for $m_a \lesssim 4.4 \times 10^{-10}$ eV
	Cosmo	ADMX	$m_a \sim 2 - 3.5\mu$eV. DFSZ for $m_a \sim 3\mu$eV
		HAYSTACK	$g_{a\gamma} \sim (2-3) \times 10^{-10}\text{GeV}^{-1}$ for $m_a \sim (23-24)\mu$eV
		MADMAX	DFSZ for $m_a \sim 0.04 - 0.4$meV (*expected*)
		CULTASK	DFSZ for $m_a \sim 3 - 12\mu$eV (*expected*, CAPP 12-TB)
			KSVZ ($E/N = 0$) for $m_a \sim 3 - 40\mu$eV (*expected*, CAPP 25-T)
		KLASH	$g_{a\gamma} \sim 3 \times 10^{-16}\text{GeV}^{-1}$ for $m_a \sim 0.3 - 1\mu$eV (*expected*, *Ph. 3*)
		ABRACADABRA	$m_a \sim 2.5 \times 10^{-15} - 4 \times 10^{-7}$eV (*expected*).
			DFSZ for $m_a \sim 40 - 400$neV (*expected*, ABRA res, *Ph. 1*)
		Radio astronomy	DFSZ for $m_a \sim 0.2 - 20\mu$eV (*expected*)
	Sun	CAST	$g_{a\gamma} = 0.66 \times 10^{-10}\text{GeV}^{-1}$ for $m_a \lesssim 20$meV
		BabyIAXO	$g_{a\gamma} = 0.15 \times 10^{-10}\text{GeV}^{-1}$ for $m_a \lesssim 10$meV (*expected*)
			DFSZ for $m_a \sim 60 - 200$meV (*expected*)
		IAXO	$g_{a\gamma} = 4.35 \times 10^{-12}\text{GeV}^{-1}$ for $m_a \lesssim 10$meV (*expected*)
			DFSZ for $m_a \gtrsim 8$meV (*expected*)
	Lab	PVLAS	$10^{-7}\text{GeV}^{-1} \lesssim g_{a\gamma} \lesssim 10^{-6}\text{GeV}^{-1}$ for $m_a \sim 0.5 - 10$meV
		OSQAR	$g_{a\gamma} \simeq 4 \times 10^{-8}\text{GeV}^{-1}$ for $m_a \lesssim 0.4$meV
		ALPS II	$g_{a\gamma} \simeq 2 \times 10^{-11}\text{GeV}^{-1}$ for $m_a \lesssim 60\mu$eV (*expected*)

g_{ae}	Astro	RGB-stars WDs	$g_{ae} \leq 3.1 \times 10^{-13}$ for m_a up to a few 10 keV $g_{ae} \leq 2.1 \times 10^{-13}$ for m_a up to a few keV
	Sun	LUX XENON100 PandaX-II LZ DARWIN	$g_{ae} \leq 3.5 \times 10^{-12}$ $g_{ae} \leq 7.7 \times 10^{-12}$ $g_{ae} \leq 4 \times 10^{-12}$ $g_{ae} \leq 1.5 \times 10^{-12}$ $g_{ae} \leq 1 \times 10^{-12}$
$g_{a\gamma}g_{ae}$	Sun	helioscopes (CAST, LUX,...)	Depends on explicit values of $g_{a\gamma}$ and g_{ae}. Can be extracted from Eq. (244) and Eq. (247)
g_{an}	Astro	SN 1987A, NS	$g_{an} \leq 2.8 \times 10^{-10}$ (from NS in HESS J1731-347)
	Lab	ARIADNE CASPEr wind	measures $g^S_{aN} g_{an}$ down to DFSZ for $m_a \sim 0.25 - 4$meV (*expected for most optimistic choice* $g^S_{aN} = 10^{-12}\text{GeV}/f_a$ [482]). From $m_a \simeq 3.6 \times 10^{-12}$eV ($g_{an} \simeq 1.1 \times 10^{-14}$) and $m_a \simeq 9.5 \times 10^{-7}$eV ($g_{an} \simeq 5.1 \times 10^{-12}$) (*expected, Ph. 2*).
g_{ap}	Astro	SN 1987A	$g_{ap} \lesssim 3.3 \times 10^{-9}$ for $g_{an} = 0$ (hadronic axions).
g_d	Astro	SN 1987A	$g_d \leq 3 \times 10^{-9}$ GeV^{-2}
	Lab	CASPEr electric	QCD axion for $\log\left(\frac{m_a}{\text{eV}}\right) \simeq -11^{+0.8}_{-0.9}$ (*expected, Ph. 2*)

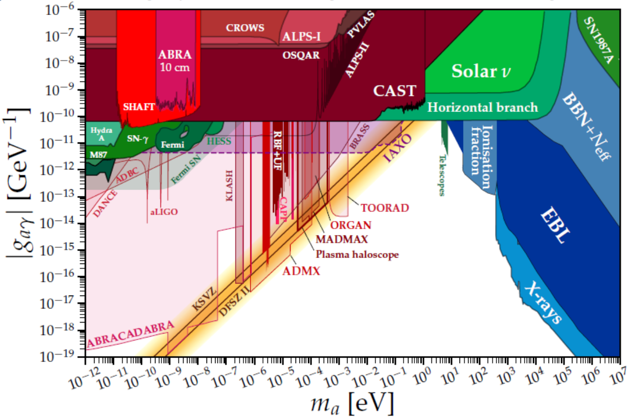
Haloscopes(Resonant Cavity experiment)

ADMX HAYSTAC CAPP-CULTASK

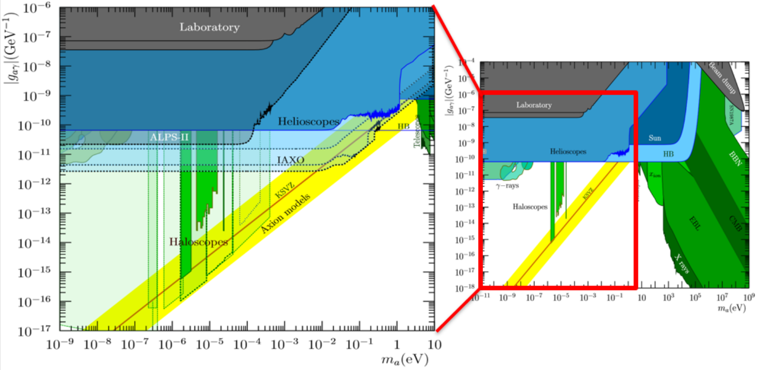
Resonant cavity detection is one of prevalent and mature scheme

Overall picture(Constraints and Future constraints for $g_{a\gamma}$)

There are already many constraints on axion physics, and many experiments planning to search even further
At present, only the resonant cavity experiment can directly test the theoretical accuracy of QCD axion



轴子暗物质的共振腔探测实验



Only the resonant cavity experiment has already been proved to be able to probe the QCD axion models!

国际轴子共振腔实验形成竞争之势

国际主要轴子暗物质共振腔实验：

ADMX, HAYSTAC(美国), MADMAX(德国), CULTASK(韩国), ORGAN(澳大利亚)

若能验证轴子暗物质，将是诺贝尔奖级别的工作，将大力促进物理学、宇宙学和天文学的发展。

Axion Nobel Olympics!

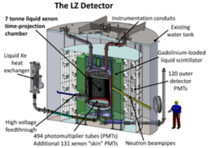
Axion Experiment

- We have gone through almost all the axion experiments and proposals in details, and thought it very carefully!!!
- The DOE Office of High Energy Physics and the NSF Physics Division have jointly selected a portfolio of projects for the second generation of direct detection dark matter experiments on July 11, 2014. The joint DOE/NSF second-generation program will include the LZ and SuperCDMS-SNOLAB experiments with their collective sensitivity to both low and high mass WIMPS, and ADMX-Gen2 to search for axions.
- In Summer 2016, we made the final decision to perform the resonant cavity experiment to search for QCD axion dark matter!

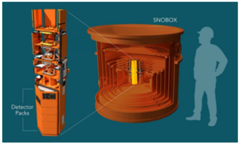
轴子暗物质实验的必要性

2014年7月11日，美国能源部（DOE）和美国国家自然科学基金（NSF）宣布支持3个第二代暗物质直接探测实验：

探测轴子暗物质的
ADMX-G2



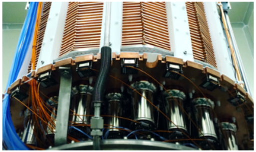
探测较重的WIMP暗物质的
LUX-ZEPLIN（LZ）



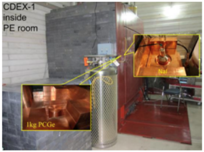
探测较轻的WIMP暗物质的
SuperCDMS

我国目前支持的暗物质实验直接探测实验主要有2个，均为探测WIMP暗物质，在轴子暗物质探测领域尚属空白：

暂无



PandaX（对应LZ）

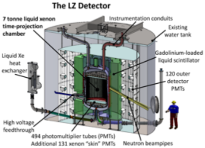


CDEX（对应SuperCDMS）

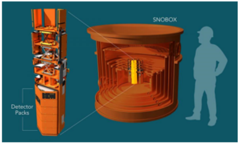
轴子暗物质实验的必要性

2014年7月11日，美国能源部（DOE）和美国国家自然科学基金（NSF）宣布支持3个第二代暗物质直接探测实验：

探测轴子暗物质的
ADMX-G2



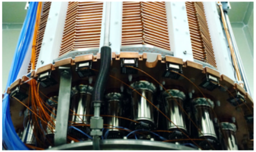
探测较重的WIMP暗物质的
LUX-ZEPLIN（LZ）



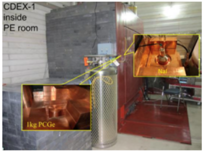
探测较轻的WIMP暗物质的
SuperCDMS

我国目前支持的暗物质实验直接探测实验主要有2个，均为探测WIMP暗物质，**在轴子暗物质探测领域尚属空白：**

2016年夏天，我们决定做轴子暗物质的共振腔探测实验。



PandaX（对应LZ）

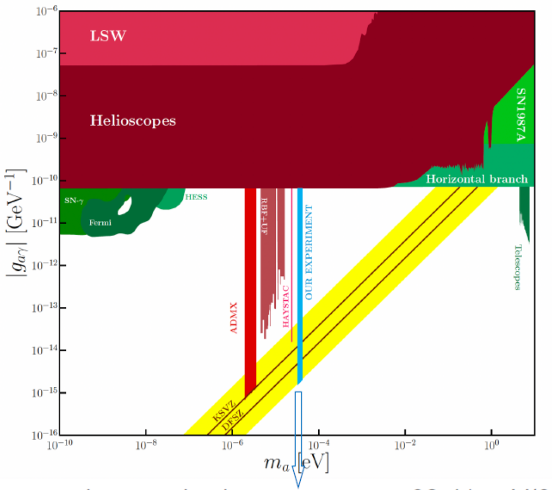


CDEX（对应SuperCDMS）

Experimental Goals

- The First Goal: the search for the QCD axion with mass around 50 μeV via resonant cavity experiment , which can be a viable cold dark matter candidate .
- The upper limit on the axion mass for the current resonant cavity experiment to probe is around 40 μeV.
- Plan: the QCD axion with mass range [32 μeV, 40 μeV] or [22 μeV, 40 μeV].
- Future Plan: the single photon detector, and probing the QCD axion with mass range [40 μeV, 150 μeV] and [150 μeV, 400 μeV]
- The Next Goal: the search for the GUT and string scale axions.

Our proposal:

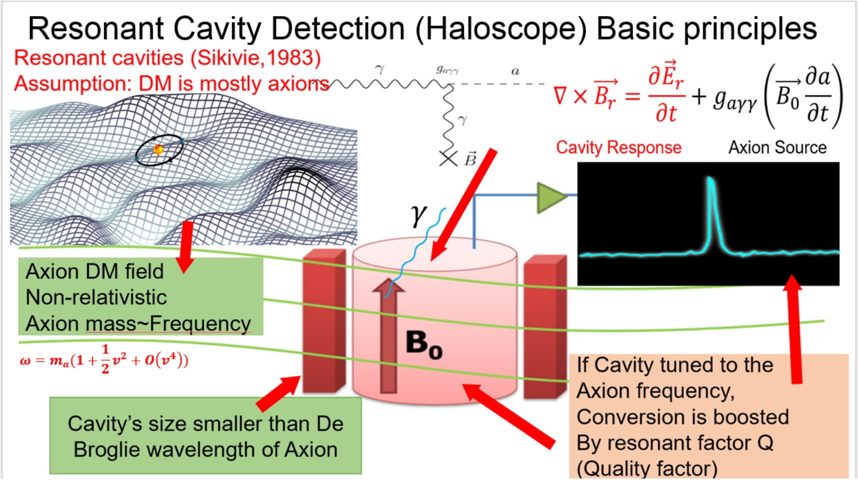


Oure goal covered axion mass range~32-41 μeV(8-10GHz)

Outline

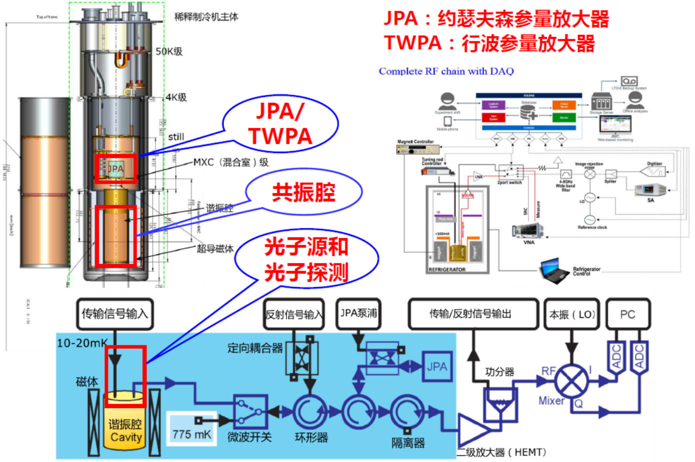
Collaboration Members:

Jie Fan (Institute of Physics, CAS),
Yu Gao (Institute of High Energy Physics, CAS),
Nick Houston (Beijing University of Technology),
Zhongqing Ji (Institute of Physics, CAS),
Yi-Rong Jin (Beijing Academy of Quantum Information Sciences),
Tianjun Li (Institute of Theoretical Physics, CAS),
Zhihui Peng (Hunan Normal University),
Liang Sun (Institute of Physics, CAS),
Jia Wang (Institute of Physics, CAS),
Xu Wang (Institute of Physics, CAS),
Qiaoli Yang (Jinan University),
Dongning Zheng (Institute of Physics, CAS).


Resonant Cavity Detection (Haloscope) Basic principles
Resonant cavities (Sikivie,1983)
Assumption: DM is mostly axions
γ
$g_{a\gamma\gamma}$
a
γ
$\vec{B}$
$\nabla \times \vec{B_r} = \frac{\partial \vec{E_r}}{\partial t} + g_{a\gamma\gamma}\left(\vec{B_0}\frac{\partial a}{\partial t}\right)$
Cavity Response
Axion Source
γ
B_0
Axion DM field
Non-relativistic
Axion mass~Frequency
$\omega = m_a(1 + \frac{1}{2}v^2 + O(v^4))$
Cavity's size smaller than De Broglie wavelength of Axion
If Cavity tuned to the Axion frequency,
Conversion is boosted
By resonant factor Q
(Quality factor)

整体实验方案

JPA：约瑟夫森参量放大器
TWPA：行波参量放大器




轴子实验团队
➢ 轴子理论与创新实验方案： 高宇，杨峤立, Nick Houston
➢ JPA/TWPA： 郑东宁，金贻荣, 相忠诚
➢ 共振腔： 孙亮，王佳，王旭
➢ 单光子源和探测： 彭智慧
➢ 稀释制冷机： 姬忠庆, 樊洁
➢ 总体协调负责： 李田军

实验进展

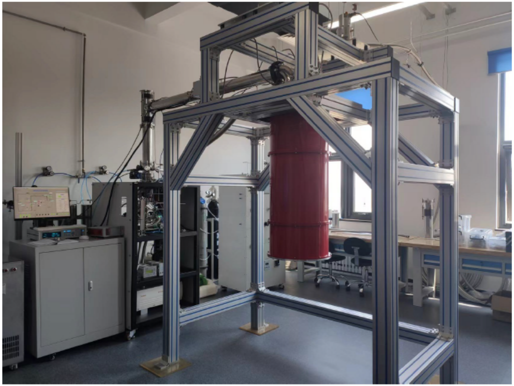
我们已获得了中国科学院科研仪器设备研制项目，“用于轴子探测的可调共振腔微波单光子探测系统”，**2020/1-2023/12**，**300**万元，并开展 **8-10 GHz** 的轴子可调共振腔微波单光子探测系统预研。

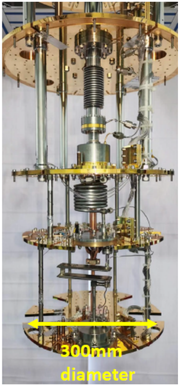
轴子实验相关预研已基本完成：

- 作为探测器工作在 **8-10GHz** 的可调频率共振腔；
- 在**8-10GHz**频率响应范围内的低噪声 **JPA**；
- 微波单光子源和探测。
- 并在湖南师范大学已经开展了 **8 GHz** 暗光子探测。

实验进展

- 轴子实验室：中国科学院物理研究所怀柔实验室；
- 极低温无液氦稀释制冷机，类似 Bluefors LD 400 或者 Oxford Triton 400.
- 预计2023年3月购买 9T超导磁体（冷孔90mm），超导磁体电源和电流引线.
- 预计2023年春季购买步进电机，用于共振腔调频。
- 预计2023年夏季实验集成并开始实验。

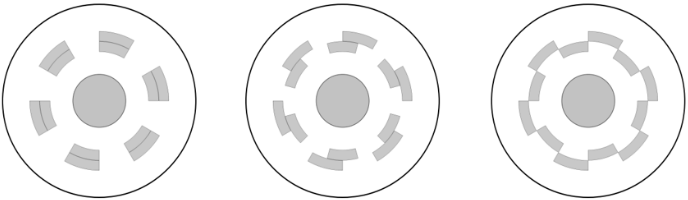




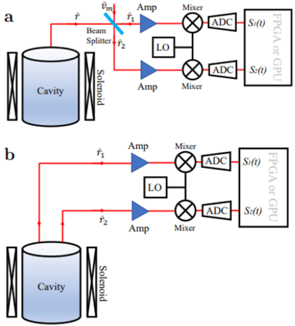
Specifications: Base T < 17mK, Cooling power 200uW. Similar size to Bluefors LD250/400 or Oxford Triton200/400.
Hope base T < 10mK, P>400uW@100mK by 2022/12

技术创新

- JPA和光子探测技术已经基本具备。
- 谐振频率的升高，10GHz共振腔与目前国际上已测的1GHz附近的共振腔，其体积有近千倍的减小。如何提高共振腔的体积是一个非常大的技术难点和技术创新。
- 圆柱形谐振腔中间加粗金属棒和两层弧形模块的方式可有效的增大谐振腔的半径和体积，改变金属棒的位置和旋转内层弧形模块可改变谐振腔的频率。



The dual-path scheme can enhance the signal-to noise ratio up to one-two order of magnitude compared with single-path scheme. Greatly increases scanning speed.



arxiv: 2201.08291

Design index of our experiment

Components	Parameters
Superconducting Magnet	Field strength: 9T Diameter: 90mm Long: 30cm
Resonant Cavity Design Frequency: 8-10GHz (Corresponding m_a:32-40μeV)	V=0.18L Q~100000 TM_{010} (C_{010}=0.69) (Test Running at 8GHz)
Cryogenics System	Physical Temperature:10mK~100mK
Receiver System(include JPA)	Noise temperature: Combining cryogenic system with receiver system, the system temperature is about 0.5K (Design target)

Operate at 8-10 GHz:

Signal Power: $P_{signal} \approx 10^{-23}W$(KSVZ) $P_{signal} \approx 10^{-24}W$(DFSZ)

Scan Rate:

$$\frac{df}{dt} \approx 172MHz/year - 205MHz/year\text{(KSVZ)}$$
$$\frac{df}{dt} \approx 3.1MHz/year - 3.8MHz/year\text{(DFSZ)}$$

At ν =8 GHz-10GHz, Scanning time of single frequency point:

Signal Noise Ratio: $\frac{S}{N} = \frac{P_{signal}}{k_B T_s}\sqrt{\frac{\delta t}{\delta \nu_a}} \sim 3$ Signal Band: $\delta \nu_a = \frac{\nu}{Q_a} = 8000Hz - 10000Hz$

⇩

$\delta t \approx 8.2hours - 12.9hours$ (KSVZ) $\delta t \approx 17.6\ days - 35.1days$(DFSZ)

实验进展

我们已获得了中国科学院全球共性挑战专项项目，“质量范围在 **50 μ eV** 左右的 **QCD** 轴子暗物质探测研究”，**2022/1-2024/12**，**260**万元，与日本理化学研究所（**RIKEN**）的蔡兆申教授团队合作，开展 **12.5 GHz** 左右的轴子暗物质探测预研。

相关预研包括：

- 作为探测器工作在 **12.5 GHz** 的可调频率共振腔；
- 在 **12.5 GHz**频率响应范围内的低噪声 **JPA**；
- 微波单光子源和探测。

Summary

- The Peccei-Quinn mechanism provides the natural solution to the strong CP problem.
- It predicts axion, which can be a cold dark matter candidate.
- Only the resonant cavity experiment has been proved to be able to probe the QCD axion models!
- We plan to perform the resonant cavity experiment in 2023, and hopefully have the results then!

Thank You Very Much for Your Attention!

Inflation: Standard Big Bang Cosmology Problems

- Horizon.
- Flatness.
- Initial conditions.
- Monopole.

The Cauchy Problem of the Universe: Initial Homogeneity and Initial Velocities.

Slow-Roll Parameters

For a generic inflaton potential $V(\phi)$, we have

$$\epsilon = \frac{M_{\rm Pl}^2 (V')^2}{2V^2} ~,~ \eta = \frac{M_{\rm Pl}^2 V''}{V} ~,~ \xi^2 = \frac{M_{\rm Pl}^4 V' V'''}{V^2} ~,$$

$$\sigma^3 = M_{\rm Pl}^6 (V')^2 V''''/V^3 ~,~ \delta^4(\phi) = M_{\rm Pl}^8 (V')^3 V'''''/V^4 ~,$$

$$\gamma^5 = M_{\rm Pl}^{10} (V')^4 V''''''/V^5 ~,~ \omega^6 = M_{\rm Pl}^{12} (V')^5 V'''''''/V^6 ~,$$

where $M_{\rm Pl}$ is the reduced Planck scale and $X' \equiv dX(\phi)/d\phi$.

Inflationary Observables

- The scalar spectral index

$$n_s = 1 + 2\eta - 6\epsilon \ .$$

- The running of the scalar spectral index

$$\alpha_s = 16\epsilon\eta - 24\epsilon^2 - 2\xi^2 \ .$$

- The tensor-to-scalar ratio

$$r = 16\epsilon \ .$$

- The power spectrum

$$P_s = \frac{V}{24\pi^2\epsilon} \ .$$

Inflation

- The number of e-folding

$$N(\phi) \;=\; \int_{t_i}^{t_e} H dt \approx \frac{1}{M_{\rm Pl}^2} \int_{\phi_e}^{\phi_i} \frac{V(\phi)}{V_\phi(\phi)} d\phi = \frac{1}{\sqrt{2}\, M_{\rm Pl}} \int_{\phi_e}^{\phi_i} \frac{d\phi}{\sqrt{\epsilon(\phi)}} \;.$$

- The Lyth bound

$$\Delta\phi \equiv |\phi_i - \phi_e| > \sqrt{2\epsilon_{\rm min}} N(\phi) M_{\rm Pl} \;.$$

For $r = 0.01$, 0.05, 0.1, 0.16, and 0.21, we obtain the large field inflation due to $\Delta\phi > 1.77\ M_{\rm Pl}$, $4.0\ M_{\rm Pl}$, $5.6\ M_{\rm Pl}$, $7.1\ M_{\rm Pl}$, and $8.1\ M_{\rm Pl}$ for $N(\phi) = 50$, respectively.

The Experimental Results

From the Planck, Baryon Acoustic Oscillations (BAO), and BICEP2/Keck Array data [10], we obtain

$$n_s = 0.968 \pm 0.006 \ , \ \ r = 0.028^{+0.026}_{-0.025} \ ,$$
$$\alpha_s = -0.003 \pm 0.007 \ , \ \ P_s = 2.20 \times 10^{-9} \ .$$

[10] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **594**, A20 (2016) [arXiv:1502.02114 [astro-ph.CO]]; P. A. R. Ade *et al.* [BICEP2 and Keck Array Collaborations], Phys. Rev. Lett. **116**, 031302 (2016) [arXiv:1510.09217 [astro-ph.CO]].

The Slow-Roll Inflation

- The problems: high dimensional operators ($\phi^n V(\phi)/M_{\rm Pl}^n$) and quantum corrections.
- Why these potentially dangerous corrections are suppressed or forbidden?
- Supersymmetry is not sufficient to protect slow-roll inflation from radiative corrections because it is broken by the inflationary background at the Hubble scale.
- The only symmetry that can forbid such corrections is a shift symmetry, *i.e.*, the action is invariant under a transformation $\phi \to \phi + c$. A field possessing this symmetry (at least to some approximate level) as an axion. But how about quantum gravity effects?

Peccei–Quinn Mechanism

- The axion solution can be stabilized by the gauged discrete PQ symmetry from the breaking of an anomalous gauged $U(1)$ symmetry in string models [11].

[11] Barger, Chiang, Jiang, and TL

The Natural Inflation

- The inflaton potential

$$V = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] .$$

- f can be larger than the reduced Planck scale.
- Question: how to realize it in string models?

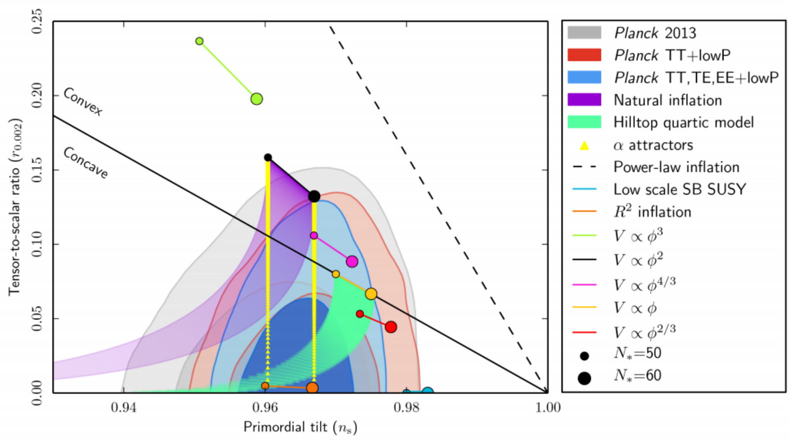


Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

The Kim-Nilles-Peloso (KNP) Alignment Mechanism [13]

- Two-field inflationary potential

$$V(\phi_1, \phi_2) = \sum_{i=1}^{2} \Lambda_i \left(1 - \cos\left[\frac{\phi_1}{f_i} + \frac{\phi_2}{g_i}\right]\right) .$$

- The determinant of the Hessian of this potential [12]

$$\mathrm{Det}\,(V_{ij}) = \frac{(f_2\, g_1 - f_1\, g_2)^2\, \prod_{i=1}^{2} \Lambda_i\, \cos\left[\frac{\phi_1}{f_i} + \frac{\phi_2}{g_i}\right]}{f_1^2\, f_2^2\, g_1^2\, g_2^2} .$$

[12] X. Gao, T. Li and P. Shukla, JCAP **1410**, 048 (2014) [arXiv:1406.0341 [hep-th]].

[13] J. E. Kim, H. P. Nilles and M. Peloso, JCAP **0501**, 005 (2005) [hep-ph/0409138].

The Kim-Nilles-Peloso (KNP) Alignment Mechanism

- It will have a flat direction if the following condition holds

$$\frac{f_1}{f_2} = \frac{g_1}{g_2} \ .$$

- A small enough deviation from this condition can create a mass hierarchy between the two axions rotated in a new basis.

- Rotation of axions

$$\psi_1 = \frac{g_1\,\phi_1 + f_1\,\phi_2}{\sqrt{f_1^2 + g_1^2}} \ , \quad \psi_2 = \frac{f_1\,\phi_1 - g_1\,\phi_2}{\sqrt{f_1^2 + g_1^2}} \ .$$

The Kim-Nilles-Peloso (KNP) Alignment Mechanism

- The potential becomes

$$V(\psi_1, \psi_2) = \Lambda_1 \left(1 - \cos\left[\frac{\psi_1}{f_1'}\right]\right) + \Lambda_2 \left(1 - \cos\left[\frac{\psi_1}{f_2'} + \frac{\psi_2}{f_{\rm eff}}\right]\right) ,$$

$$f_1' = \frac{f_1\, g_1}{\sqrt{f_1^2 + g_1^2}} , \quad f_2' = \frac{f_2\, g_2 \sqrt{f_1^2 + g_1^2}}{f_1\, f_2 + g_1\, g_2} , \quad f_{\rm eff} = \frac{f_2\, g_2 \sqrt{f_1^2 + g_1^2}}{|f_1\, g_2 - g_1\, f_2|} .$$

- If the deviation from the flatness condition is small enough, one can generate an 'effectively' large decay constant for ψ_2 combination.

The Kim-Nilles-Peloso (KNP) Alignment Mechanism

- With an appropriate hierarchy $\Lambda_2 \ll \Lambda_1$, we can make the field ψ_1 heavier than ψ_2 with the respective masses at the minimum given as

$$m^2_{\psi_1} \simeq \Lambda_1 \left(\frac{1}{f_1^2} + \frac{1}{g_1^2} \right), \quad m^2_{\psi_2} \simeq \frac{\Lambda_2 \left(f_2\, g_1 - f_1\, g_2 \right)^2}{g_2^2\, f_2^2\, \left(f_1^2 + g_1^2 \right)} \ .$$

- Stabilizing ψ_1 at one of its minimum $\overline{\psi_1} = 0$ would result in a single axion potential with large decay constant

$$V(\psi_2) = \Lambda_2 \left(1 - \cos\left[\frac{\psi_2}{f_{\rm eff}} \right] \right) \ .$$

The Kim-Nilles-Peloso (KNP) Alignment Mechanism

- We successfully embed the Kim-Nilles-Peloso (KNP) alignment mechanism for enhancing the axion decay constant in the context of large volume type IIB orientifolds [14].

[14] X. Gao, T. Li and P. Shukla, JCAP **1410**, 048 (2014) [arXiv:1406.0341 [hep-th]].

The Multi-Natural Inflation [15]

- The inflaton potential

$$V(\phi) = C - \Lambda_1^4 \cos\left(\frac{\phi}{f_1}\right) - \Lambda_2^4 \cos\left(\frac{\phi}{f_2} + \theta\right) \ .$$

- The parameters

$$f_1 \equiv f \ , \quad \Lambda_1 \equiv \Lambda \ , \quad f_2 = Af \ , \quad \Lambda_2^4 = B\Lambda^4 \ .$$

[15] M. Czerny and F. Takahashi, Phys. Lett. B **733**, 241 (2014) [arXiv:1401.5212 [hep-ph]]; M. Czerny, T. Higaki and F. Takahashi, JHEP **1405**, 144 (2014) [arXiv:1403.0410 [hep-ph]]; Phys. Lett. B **734**, 167 (2014) [arXiv:1403.5883 [hep-ph]].

The Multi-Natural Inflation

- The multi-natural inflation can be realized in the supergravity theory and string inspired models?
- The hilltop quartic inflation can be realized in some approximations

$$V \simeq \Lambda^4 \left(1 - \frac{\phi^p}{\mu^p} + ...\right) , \quad \text{where } p = 4 .$$

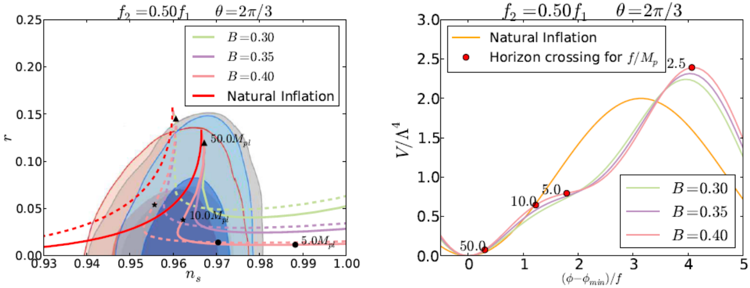


Figure 1: Left: the prediction of (n_s, r) of multi-natural inflation for three different values of Λ_2^4. Solid (dashed) lines correspond to the e-folding number $N = 60$ ($N = 50$). Right: the corresponding inflaton potentials. The red dots represent the position at horizon crossing at $N = 60$ for the case of $B = 0.40$.

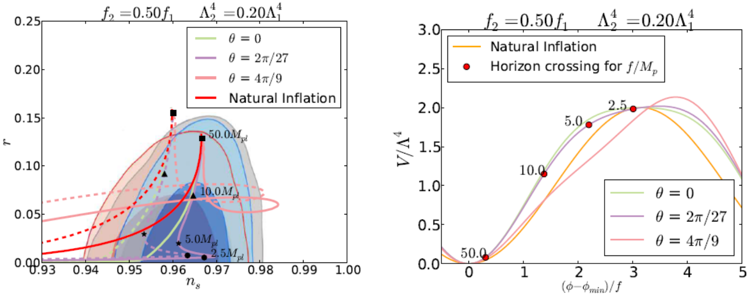


Figure 2: Same as Fig. 1 but for different values of the relative phase θ.

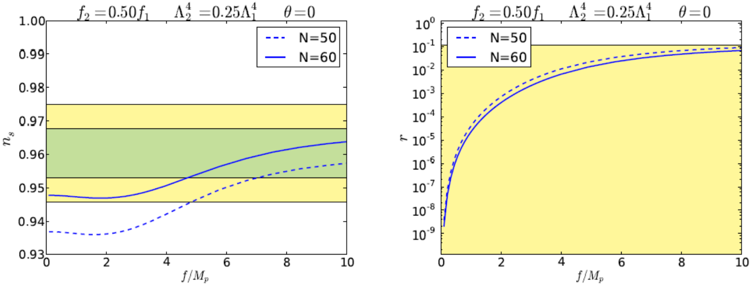


Figure 3: Behavior of n_s (left) and r (right) as a function of f. The shaded regions in the left figure correspond to 1 and 2σ allowed regions for n_s from Planck data. The shaded region on the right corresponds to the 95% CL for r ($r < 0.11$).

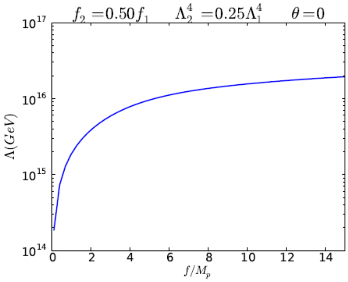


Figure 4: Planck normalized values for Λ (left) and m_ϕ (right) as a function of f.

The Axion Monodromy Inflation [16]

- The inflaton potential

$$V(\phi) = A_1\phi^p + \sum_{i=2}^{M} A_i \cos\left(\frac{\phi}{f_i} + \theta_i\right) + V_0 \ .$$

- p is a rational number such as $p = 1$, $p = 2/3$, $p = 2$, and $p = 4/3, 3$, while M depends on the number of hidden gauge sectors which non-perturbatively generate the potential of the axion inflaton.

[16] T. Kobayashi, A. Oikawa, N. Omoto, H. Otsuka and I. Saga, Phys. Rev. D **95**, no. 6, 063514 (2017) [arXiv:1609.05624 [hep-ph]]; and references therein.

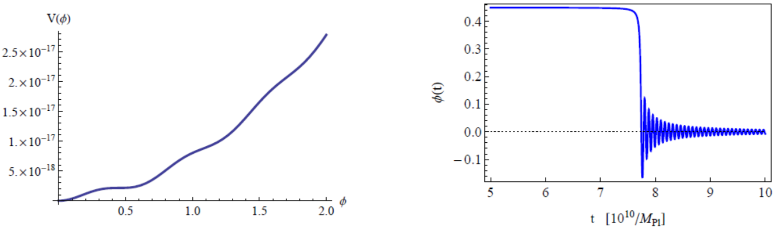


Figure 2: In the left panel, the inflaton potential is drawn by setting the parameters as $A_1/A_2 = 10.86169045$ and $A_2 = 6.30 \times 10^{-19}$, whereas the right panel shows the trajectory of the inflaton as a function of cosmic time t for the initial value of the inflaton, $\phi(0) = 0.4492824$ at $t = 0$.

N	n_s	r	m_ϕ^2	$H_{\rm inf}$	$V_{\rm inf}^{1/4}$	$\frac{dn_s}{d\ln k}$
60.0	0.9665	6.60×10^{-11}	7.67×10^{-17}	8.46×10^{-10}	3.83×10^{-5}	-2.52×10^{-3}
50.0	0.9665	1.55×10^{-10}	1.81×10^{-16}	1.30×10^{-9}	4.74×10^{-5}	-1.64×10^{-3}

Table 2: The cosmological observables such as spectral index n_s, its running $dn_s/d\ln k$, tensor-to-scalar ratio r, Hubble scale $H_{\rm inf}$, scalar potential $V_{\rm inf}^{1/4}$ at the pivot scale and the inflaton mass m_ϕ^2 at the vacuum. The parameters are set as $A_1/A_2 = 10.86169045$ and $A_2 = 6.30\times10^{-19}$ for the e-folding number $N = 60$, whereas those are set as $A_1/A_2 = 10.86169628$ and $A_2 = 6.30\times10^{-19}$ for the e-folding number $N = 50$. The initial value of inflaton field is also set as $\phi_{\rm ini} = 0.4492824$ in both cases.

The Pure Natural Inflation [17]

- The inflaton ϕ couples to the gauge field of a pure Yang-Mills theory

$$\mathcal{L} = \frac{1}{32\pi^2} \frac{\phi}{f} \epsilon^{\mu\nu\alpha\beta} \, \mathrm{Tr} \, F_{\mu\nu} F_{\alpha\beta} \ .$$

- The conventional potential from non-perturbative instantons is

$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f} \right) \right] \ .$$

[17] Y. Nomura, T. Watari and M. Yamazaki, arXiv:1706.08522 [hep-ph].

The Pure Natural Inflation

- The cosine potential is not correct in general, as argued by Witten [18] in the large N limit [19] with the 't Hooft coupling $\lambda \equiv g^2 N$ held fixed. In particular, while the physics is periodic in ϕ with the period of $2\pi f$ (because $\theta \equiv \phi/f$ is the θ angle of the Yang-Mills theory), the multi-valued nature of the potential allows for the potential of ϕ in a single branch

$$V(\phi) = N^2 \Lambda^4 \mathcal{V}(x) \ , \quad \text{where } x \equiv \frac{\lambda \phi}{8\pi^2 N f} \ .$$

- The potential does not to respect the periodicity under $\phi \rightarrow \phi + 2\pi f$.

[18] E. Witten, Nucl. Phys. B **156**, 269 (1979); Annals Phys. **128**, 363 (1980).
[19] G. 't Hooft, Nucl. Phys. B **72**, 461 (1974).

The Pure Natural Inflation

- The invariance under the CP transformation $\phi \to -\phi$ implies that $\mathcal{V}(x)$ is a function of x^2
- $\mathcal{V}(x)$ is expected to flatten as the potential energy approaches the point of the deconfining phase transition with increasing $|\phi|$ (since the dynamics generating the potential will become weaker).
- Assuming that the potential is given by a simple power law, we thus expect $\mathcal{V}(x) \sim 1/(x^2)^p$ $(p > 0)$. This potential is singular at $x \to 0$, and a simple way to regulate it is to replace x^2 with $x^2 + \mathrm{const.}$

The Pure Natural Inflation

- The axion potential is

$$V(x) = M^4 \left[1 - \frac{1}{(1+cx^2)^p}\right] \quad (p > 0) \ .$$

- The above potential for $p = 3$ can be obtained by a holographic calculation [20] in the limit of large N and 't Hooft coupling in the type IIA string theory with N stacks of D4-branes wrapping a circle:

$$V(\phi) = M^4 \left[1 - \frac{1}{\left(1 + \left(\frac{\phi}{F}\right)^2\right)^p}\right] \ , \quad \text{where } p = 3 \ .$$

[20] S. Dubovsky, A. Lawrence and M. M. Roberts, JHEP **02**, 053 (2012) [arXiv:1105.3740 [hep-th]].

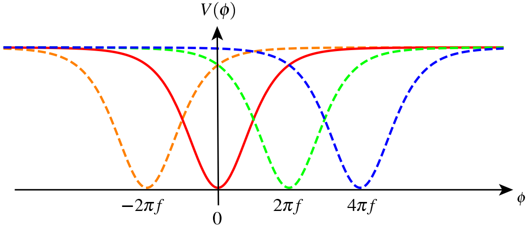


Figure : The potential of pure natural inflation (in the holographic limit $p = 3$). The potentials for other branches, which ensure the periodicity of physics under $\phi \to \phi + 2\pi f$, are also depicted by dashed lines.

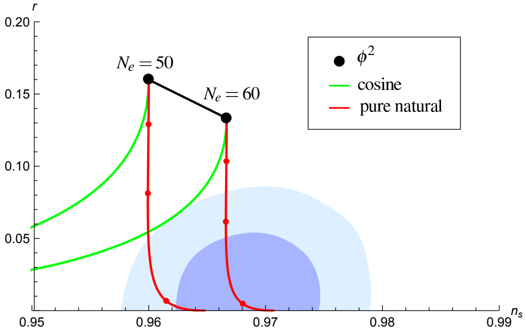


Figure : The predicted values of n_s and r superimposed with the 68% and 95% CL BICEP2/KECK Array contours. The black dots represent the predictions of the quadratic potential $V(\phi) = m^2\phi^2/2$, with e-folding $N_e = 50$ and 60. The green lines are the predictions of the cosine potential, and the red lines are those of the (holographic) pure natural inflation potential with $p = 3$. For the latter, one has varied $F/M_{\rm Pl} = 0.1 - 100$, with $F/M_{\rm Pl} = 10, 5, 1$ indicated by the red dots (from top to bottom).

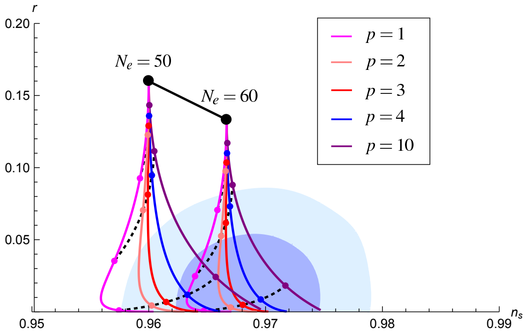


Figure : The pure natural inflation potentials with various values of $p = 1, 2, 3, 4, 10$.

The $E_8 \times E_8$ Heterotic String Theory

- The relevant Lagrangian for two form B_{MN} field

$$\begin{aligned} \mathcal{L} &= \frac{3}{4}\phi^{-3/2}F_{LMN}F^{LMN} , \\ H &= dB + \mathrm{tr}(AF - A^3/3) + \mathrm{tr}(\omega R - \omega^3/3) . \end{aligned}$$

- LMN are four-dimensional space-time coordinates

$$\mathcal{L} = \frac{3}{4}\phi^{-3/2}e^{6\sigma}F_{\mu\nu\rho}F^{\mu\nu\rho} .$$

- $F_{\mu\nu\rho}$ is dual to a CP-odd scalar

$$\phi^{-3/2}e^{6\sigma}F_{\mu\nu\rho} = \epsilon_{\mu\nu\rho\sigma}\partial^{\sigma}D .$$

The $E_8 \times E_8$ Heterotic String Theory

- So we have

$$dF = -\mathrm{Tr} F_{\mu\nu} \tilde{F}^{\mu\nu} + \mathrm{Tr} R_{\mu\nu} \tilde{R}^{\mu\nu} .$$

- Define dilaton field

$$S = e^{3\sigma} \phi^{-3/4} + 3i\sqrt{2} D .$$

- Thus, we have

$$\mathcal{L} = \frac{\mathrm{Im}(S)}{4} \mathrm{Tr} F_{\mu\nu} \tilde{F}^{\mu\nu} .$$

The $E_8 \times E_8$ Heterotic String Theory

- To cancel the Yang-Mills, one should introduce the Green-Schwarz term

$$\mathcal{L}_{\rm GS} ~=~ B \wedge F \wedge F \wedge F \wedge F ~.$$

- After compactification, we obtain

$$\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} B_{ij} \langle F_{kl} \rangle \langle F_{pq} \rangle \epsilon^{ijklpq} ~.$$

- Thus, we obtain

$$B ~=~ \frac{1}{2\pi} \sum_{i=1}^{n} \beta_i a_i ~, ~~~ \int_{C_j} \beta_i ~=~ \delta_{ij} ~.$$

- Axion inflation is still consistent with the current observations.
- Axions can arise from the string theory.

Thank You Very Much
for Your Attention!