The Resonant Cavity Study for Axion Dark Matter

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- 高昕, 康召丰, 李金勉, 孙铮, …

Outline

Introduction and Theoretical Motivation

The Peccei–Quinn Mechanism and Axion Models

The Overview of the Axion Experiments

The Resonant Cavity Study for the Axion Dark Matter

Summary

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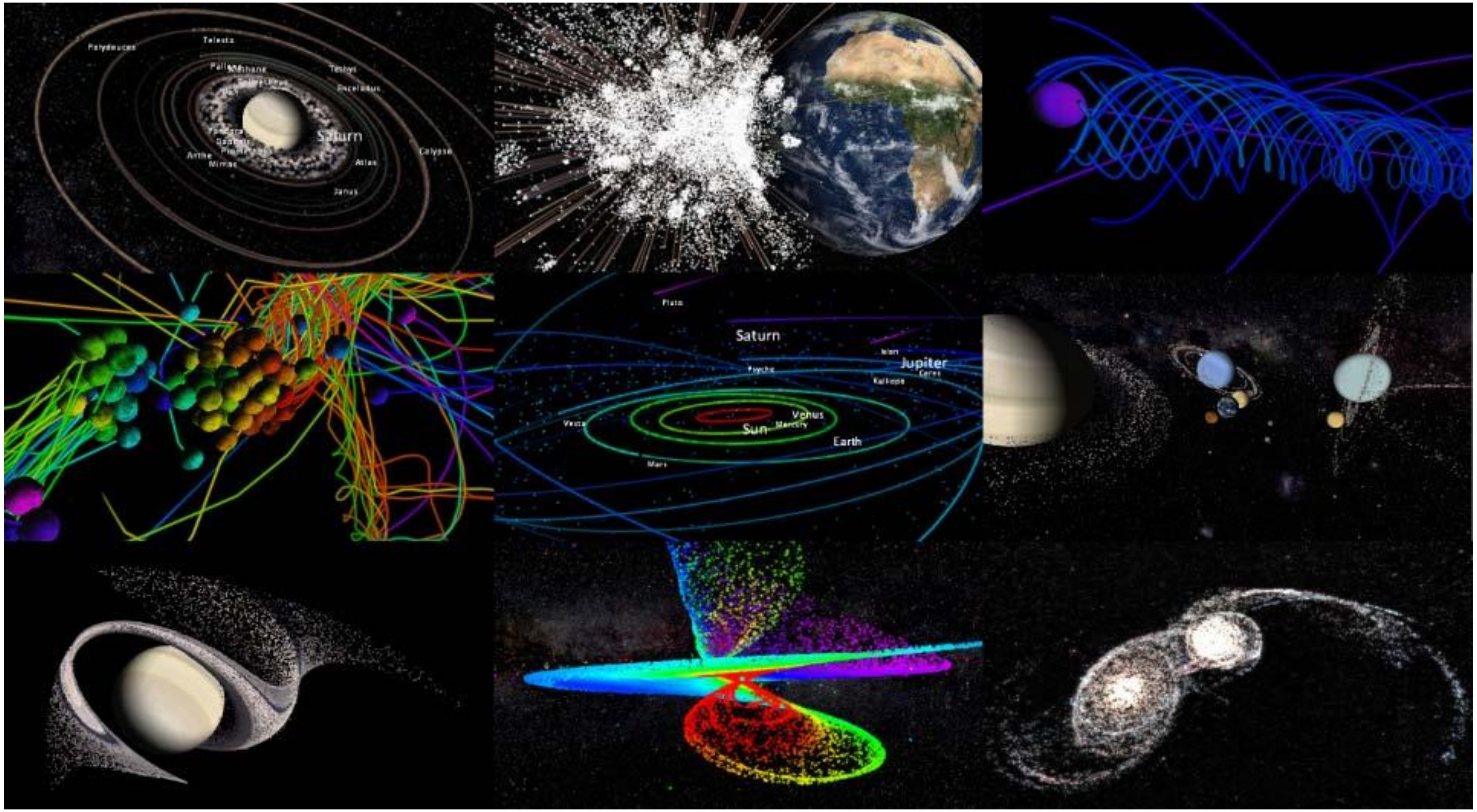


The Standard Model (SM)

- Gauge symmetry: $\mathrm{SU}(3)_C \times SU(2)_L \times \mathrm{U}(1)_Y$
- Fermions: Q_i, U_i^c, D_i^c, L_i, E_i^c
- Higgs: H

How to study the new physics beyond the SM?

The convincing evidence for physics beyond the SM:

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

The SM is incomplete!

Major Theoretical Problems in the SM

- Fine-tuning problems

- Aesthetic Problems

- The vacuum stability problem

  The stability problem can be solved easily in the new physics models.

Fine-Tuning Problems:

- Cosmological constant problem

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

- Gauge hierarchy problem

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

- Strong CP problem

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

- The SM fermion masses and mixings

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

Aesthetic Problems:

- Interaction unification
- Fermion unification
- Charge quantization
- Gauge coupling unification

The first three problems can be solved when we embed the SM into the Grand Unified Theories (GUTs) and string models.

New Physics Scenarios:

- Cosmological constant problem: string landscape with weak anthropic principle

Solution to the gauge hierarchy problem but not the strong CP problem.

- Gauge hierarchy problem: supersymmetry

Gauge coupling unification, dark matter, and radiative electroweak symmetry breaking, etc.

- Grand Unified Theory (GUT)

SU(5), and SO(10), etc.

- Superstring Theory and M-theory

Type I, Heterotic $E_8 \times E_8$, Heterotic SO(32), Type IIA, Type IIB.

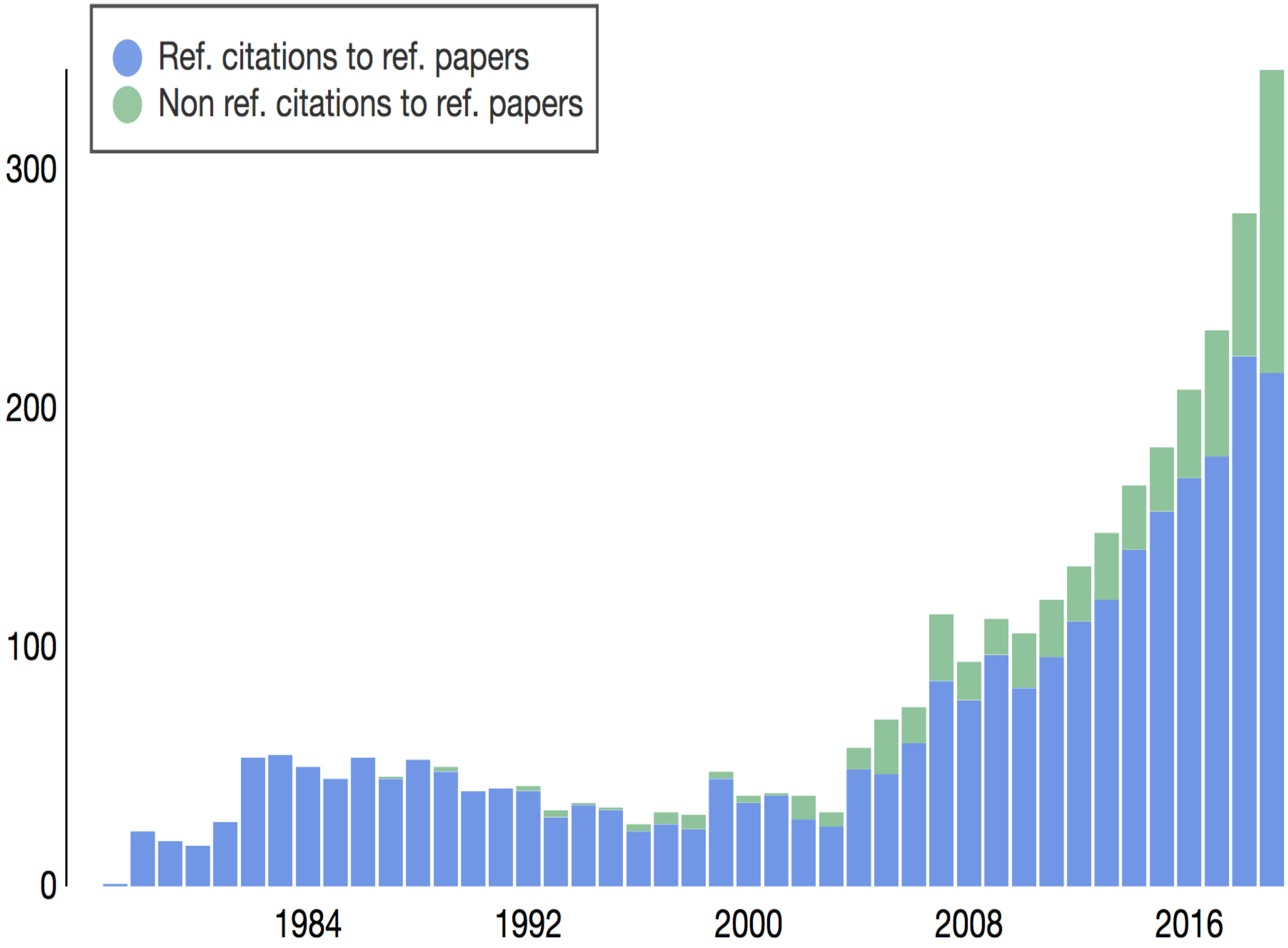
The Research Field

- 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 promising dark matter: WIMP, axion, asymmetric DM.

A. Tan et al. [PandaX-II Collaboration], Phys. Rev. Lett. 117, no. 12, 121303 (2016) [arXiv:1607.07400 [hep-ex]];
D. S. Akerib et al. [LUX Collaboration], Phys. Rev. Lett. 118, no. 2, 021303 (2017) [arXiv:1608.07648 [astro-ph.CO]].

- In the Summer 2016, assuming WIMP is not dark matter, which particle is the promising dark matter candidate?

Strong CP problem: Peccei-Quinn mechanism and axion models!!!


Ref. citations to ref. papers
Non ref. citations to ref. papers
300
200
100
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1984
1992
2000
2008
2016

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Strong CP Problem

- The topological term which violates the CP

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} Tr F_{\mu\nu}\tilde{F}^{\mu\nu} \text{ where } \tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$

- $\bar{\theta} = \theta + \theta_q$ parameter is a dimensionless coupling constant which is infinitely renormalized by radiative corrections.
- No theoretical reason for $\bar{\theta}$ as small as 1.3×10^{-10} required by the experimental bound on the EDM of the neutron.
- $\bar{\theta}$ may be a random variable with a roughly uniform distribution in the string landscape [1].

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

[1] Donoghue.

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 is the best solution to the Strong CP Problem.

Peccei–Quinn Mechanism

- An anomalous global $U(1)_{PQ}$ symmetry.
- If there are two Higgs doublets in the SM, we can have the $U(1)_{PQ}$ symmetry [2]

$$
\begin{aligned}
-\mathcal{L} &= y^u_{ij} Q_i U^c_i H_u + y^d_{ij} Q_i D^c_i H_d + y^e_{ij} L_i E^c_i H_d \\
&\quad + V\left(H_u^\dagger H_u,\ H_d^\dagger H_d,\ (H_d^\dagger H_u)(H_u^\dagger H_d)\right) .
\end{aligned}
$$

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

$$
\begin{aligned}
Q_i / U^c_i / D^c_i / L_i / E^c_i &\longrightarrow e^{i\alpha} Q_i / U^c_i / D^c_i / L_i / E^c_i \ , \\
H_d / H_u &\longrightarrow e^{-i2\alpha} H_d / H_u \ .
\end{aligned}
$$

[2] Weinberg; Wilczek.

Peccei–Quinn-Weinberg-Wilczek Axion

- Peccei–Quinn-Weinberg-Wilczek Axion is

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

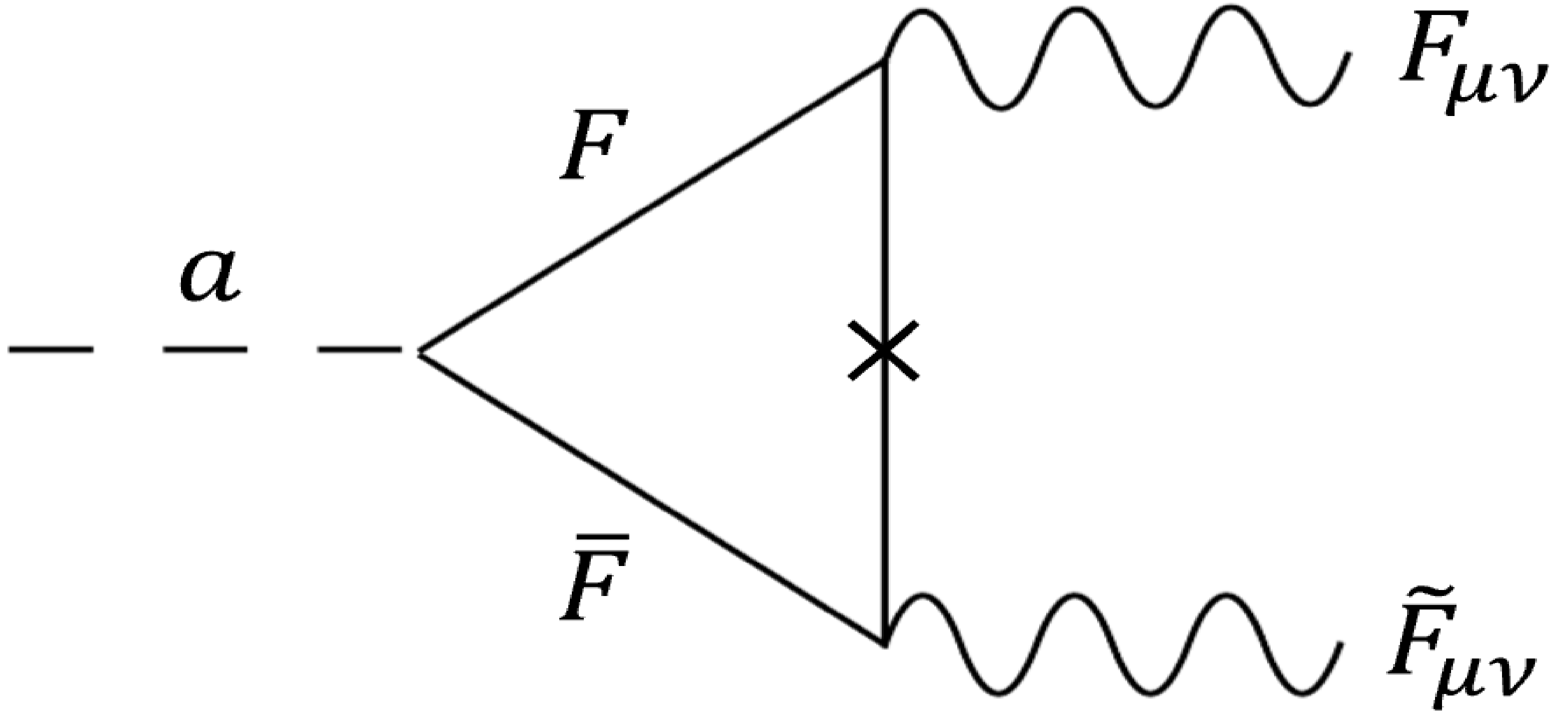
- The solution to the strong CP problem: $\bar{\theta} = 0$.

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

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

- The axion mass

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



- The PQWW /Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) Models:
  F and $\bar{F}$ are the SM fermions
- The Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model:
  F and $\bar{F}$ are the vector-like fermions

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 Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) Axion

- One 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 Kim-Shifman-Vainshtein-Zakharov (KSVZ) Model

- 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 $f_a = |\langle S \rangle|$.

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 [5]

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

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

Axion Mass

- The axion mass is [6]

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

- The more previse calculations give $m_a = 60 - 150\ \mu\text{eV}$ [7], and $m_a = 26.5 \pm 3.4\ \mu\text{eV}$ [8].
- The axion mass is around 50 μeV.

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

[7] 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).

[8] 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

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

where

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

The Connections between Axion/ALP and New Physics

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

There exists the possibility: no coupling between axion and photons at one loop?

- The superstring models: many Axion-Like Particles (ALPs).

Witten, “Axions may be intrinsic to the structure of string theory”.

- Axion inflation.
- The neutrino masses and mixing: $U(1)_{B-L} = U(1)_{PQ}$, and the baryon asymmetry can be explained via the leptogenesis.
- Relaxation mechanism.

Solution to the gauge hierarchy problem.

- Dark energy particles are similar to axion/ALPs.

Quintessence Field, Chameleons, Galileons, and Symmetrons, etc.

- Dark matter.

The Connections between Axion/ALP and New Physics

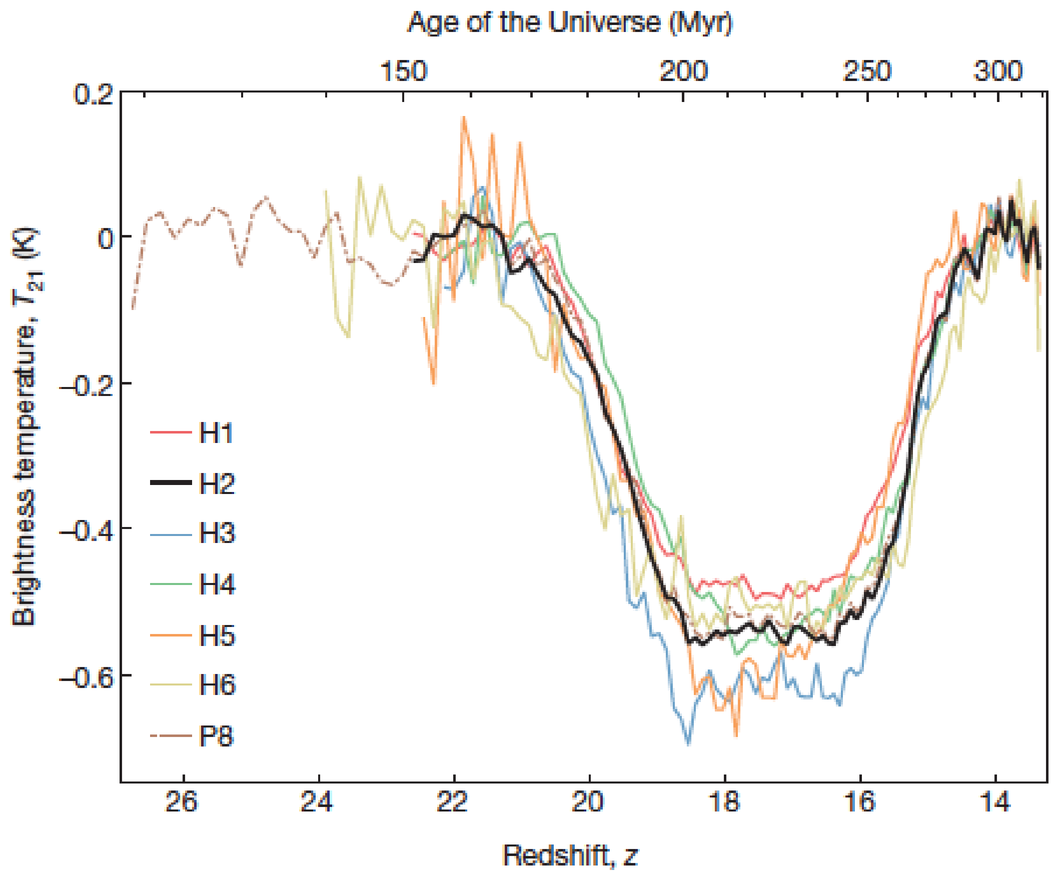
- The Froggatt-Nielsen (FN) mechanism is the solution to the fermion mass hierarchy problem: $U(1)_{FN} = U(1)_{PQ}$.
- Baryon asymmetry via axion quark nugget (AGN).
- Gravitation wave

$$\frac{\alpha_g}{4} a R^{\beta}{}_{\alpha\gamma\delta} \tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta} \text{ with } \tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta} \equiv \frac{1}{2}\epsilon^{\gamma\delta\mu\nu} R^{\alpha}{}_{\beta\mu\nu}.$$

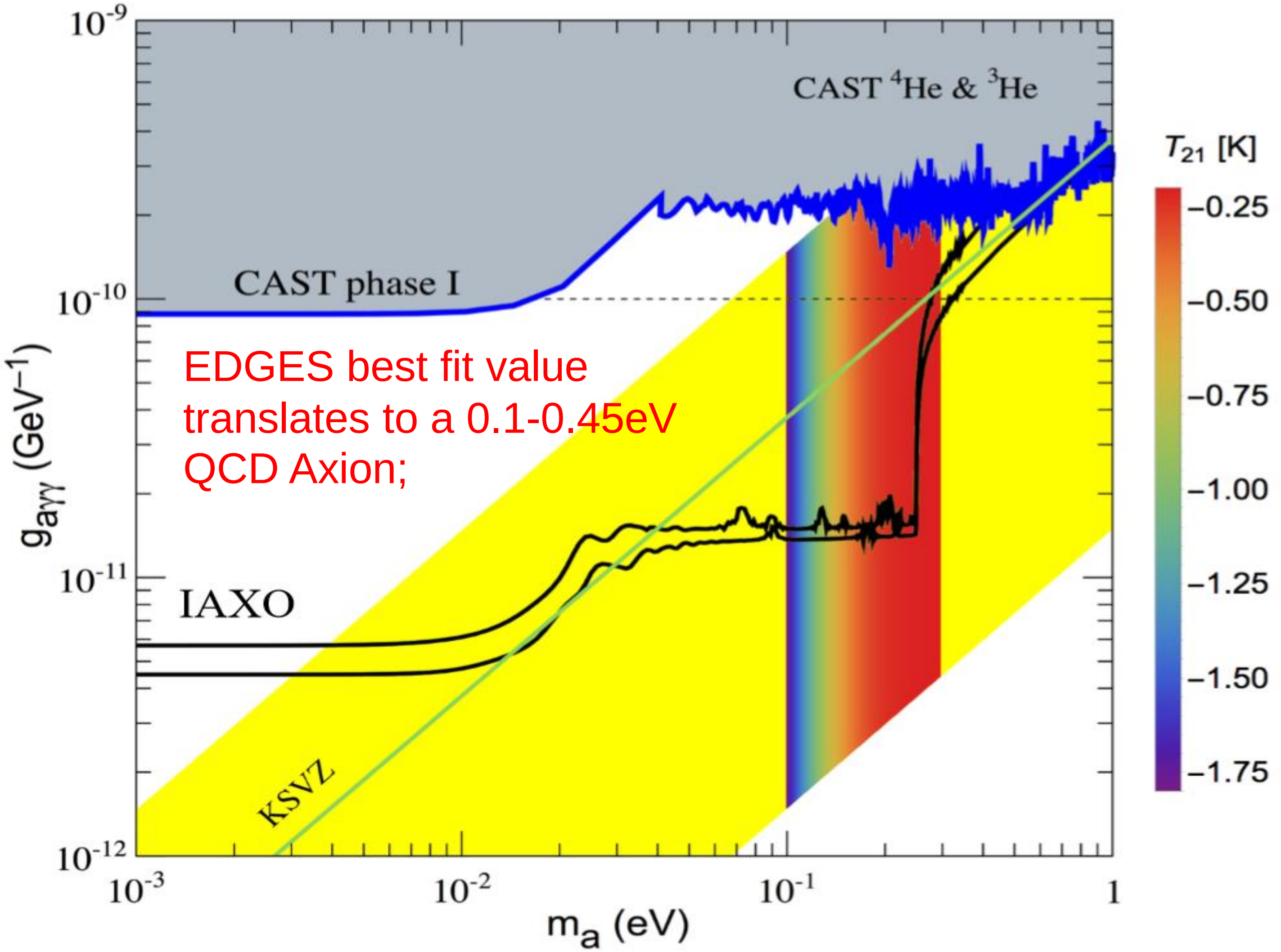
- The EDGES results and XENON1T results.
- The scale coincidence: the $U(1)_{PQ}$ symmetry breaking scale,

right-handed neutrino mass, and supersymmetry breaking scale, messenger scale in gauge mediation, axion quality problem, and string-scale gauge coupling unification, etc.

EDGES Experiment's Result and the QCD Axion



(EDGES collaboration, 2018)



ΛCDM predictsT_{21} depth to be at most -0.2K (3.8 sigma discrepancy!)

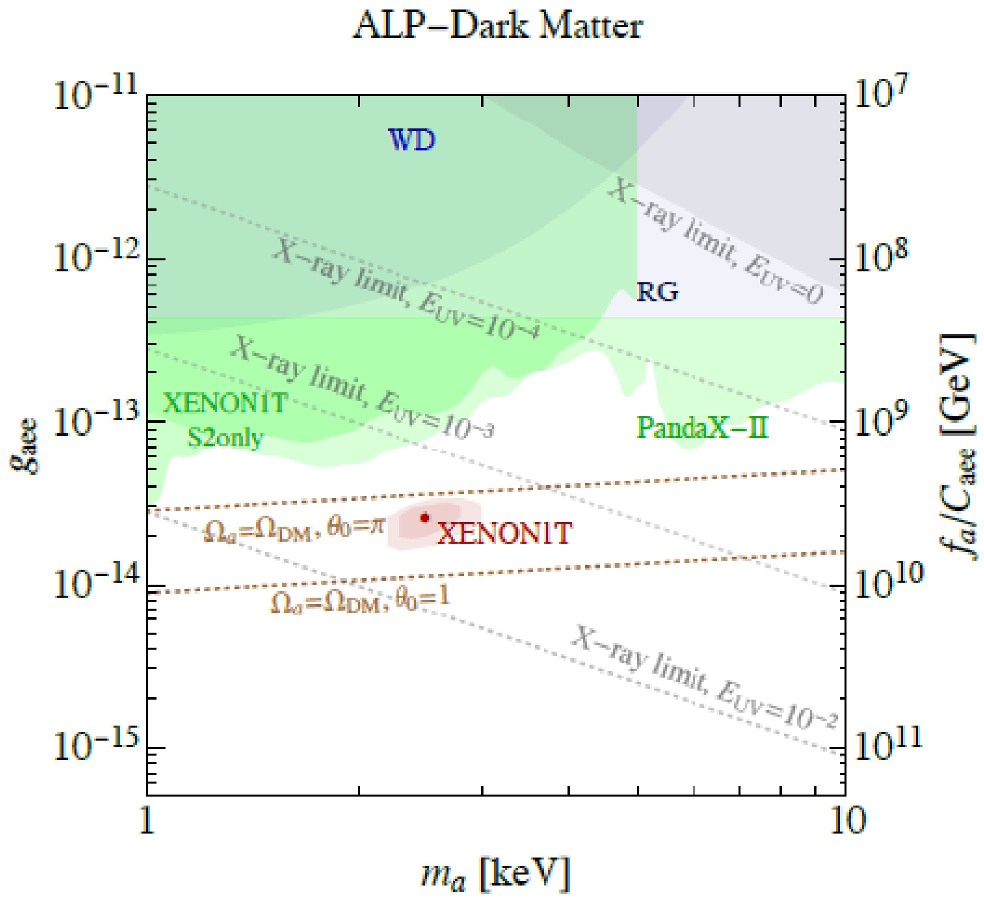
"This may deserve two Nobel prizes"

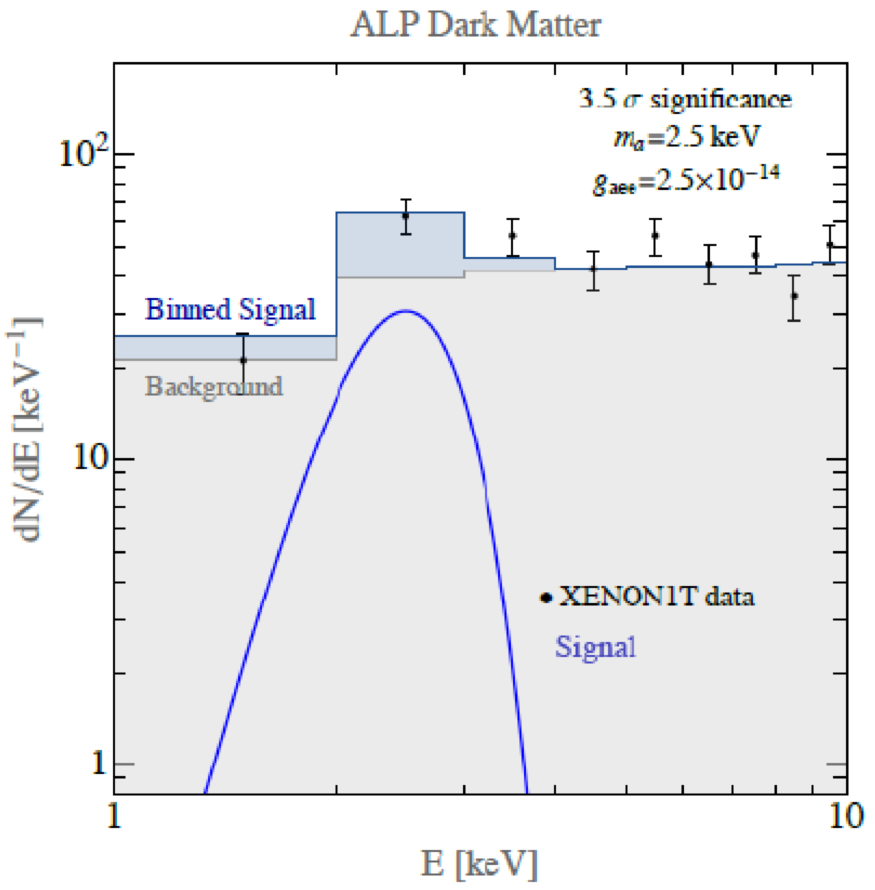
A. Loeb ,Chair of Harvard Astrophysics Department

Nick Houston, Chuang Li, Tianjun Li, Qiaoli Yang, and Xin Zhang, Phys. Rev. Lett. **121**, 111301

Future experiments and large scale surveys such as IAXO and EUCLID should have the capability to directly probe the relevant parameter region and thereby test this scenario.

The ALP Dark Matter Interpretation for the XENON1T Excess





Probing the GUT and String Theory

- How to probe the GUT scale, string scale, and Planck scale?

- The cosmological constant SUSY breaking:

$$M^2_{SUSY} \sim \Lambda^{1/4} \times M_{\rm Pl}.$$

- The Type I seesaw mechanism: $M_\nu M_N \sim \langle H \rangle^2.$

- Probing the GUT and string theory: $f_a \sim M_{GUT}$ and $f_a \sim M_{String}$.

Probing the UV scale via the IR scale!

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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 $V_{\mathrm{DM}} \sim 10^{-3}$)

Overview of the Axion Experiments

- Search for ALPs in the laboratory (Dark Matter Independent Searches)

Light-shining-through wall experiments (ALPS-II)

Polarization experiments (PVLAS)

The 5th force experiments(ARIADNE)

…

- Solar axions (Dark Matter Independent Searches)

Helioscopes(CAST, IAXO)

Underground detectors (CDEX, LUX PANDAX, XENON1T)

…

- Direct detection of dark matter axions (Axion Dark Matter Searches)

Haloscopes(ADMX, HAYSTAC, CAPP-CULTASK)

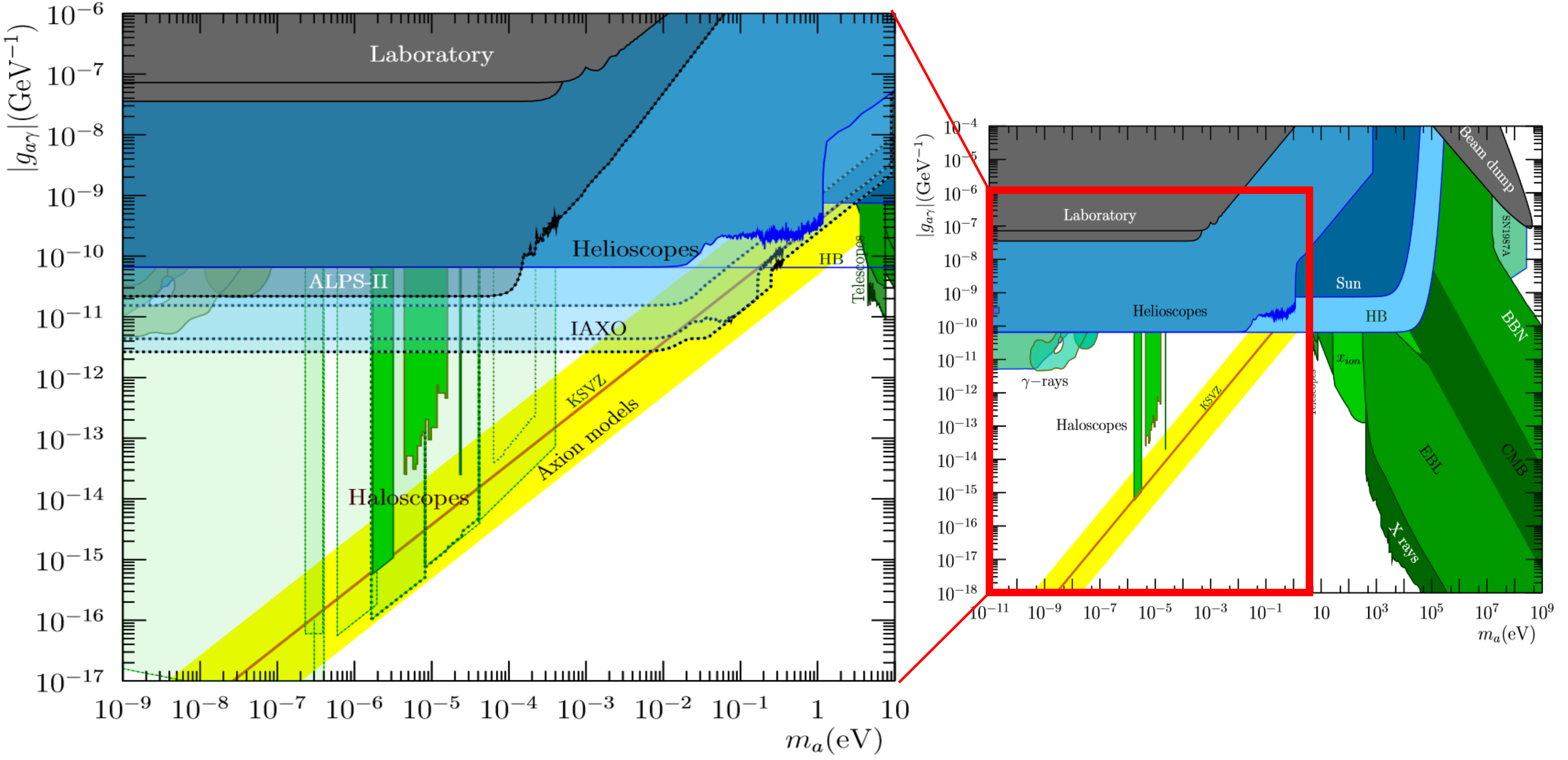
Dish antenna and Dielectric Haloscopes(MADMAX)

Low frequency resonators with LC circuits(ABRACADABRA)

NMR techniques(CASPEr)

…

Constraints and Future constraints



Axion Nobel Olympics

ADMX(Washington, Florida, Lawrence Livemore National Laboratory, Fermi Laboratory, Berkeley Microwave cavity)

HAYSTAC(Yale ADMX-HF collaboration Microwave cavity)

ABRACADABRA(MIT, Princeton, Toroidal)

ARIADNE(UNR, Perimeter Institute, Stanford Axion-mediated long-range forces)

CAST and IAXO(CERN)

CAST-CAPP(CERN Rectangular cavities-TE modes)

MADMAX(DESY, Germany, Dielectric interfaces)

ALPs(DESY, Germany, Coupled FP resonators)

KLASH(KLOE magnet in Frasctric, Italy, Microwave cavity)

QUAX(National Laboratories of Legnaro, Italy, Magnetized media)

Axion Nobel Olympics

IBS/CAPP(CULTASK, Microwave cavity)

ORGAN(UWA, Axion-Bragg Resonators)

Nature V 534, 2 June 2016

SHIN WOONG-JAE

South Korea's Nobel dream

The Asian nation spends more of its economic output on research than anywhere else in the world. But it will need more than cash to realize its ambitions.

BY MARK ZASTROW

Behind the doors of a drab brick building in Daejeon, South Korea, a major experiment is slowly taking shape. Much of the first-floor lab space is under construction, and one glass door, taped shut, leads directly to a pit in the ground. But at the end of the hall, in a pristine lab, sits a gleaming cylindrical apparatus of copper and gold. It's a prototype of a device that might one day answer a major mystery about the Universe by detecting a particle called the axion — a possible component of dark matter.

If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. "It will transform Korea, there's no question about it," says physicist Yannis Semertzidis, who leads the US$7.6-million-per-year centre at South Korea's premier technical university, KAIST. But there's a catch: no one knows whether axions even exist. It's the kind of high-risk, high-reward project

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Experimental Plan

- The resonant cavity experiment for the QCD axion with mass around 50 μeV, which can be a viable cold dark matter candidate .
- The current upper limit on the axion mass for the cavity experiment to probe is around 40 μeV.
- Plan: the QCD axion with mass range [32 μeV, 40 μeV] or

  [23 μeV, 40 μeV].
- Future Plan: the single photon detector, and probing

  the QCD axion with mass range [40 μeV, 150 μeV]

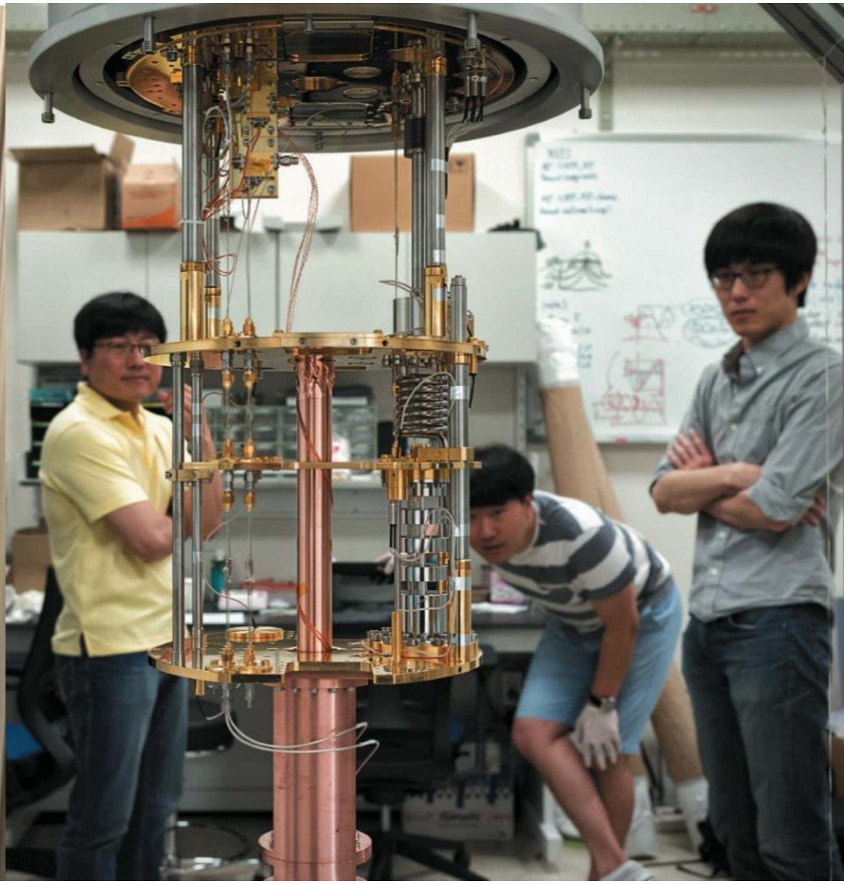
  and [150 μeV, 400 μeV]
- Future Plan: the GUT and string scale axions.

当前轴子暗物质的共振腔探测实验都是质量从小到大的方式扫描，并且已有技术能探测的轴子质量上限是 40 μeV. 我们独辟蹊径，采用弯道超车策略，拟直接扫描轴子的质量范围约为 32-40 μeV. 特别是我们的目标轴子质量比将来同期的其它国际实验的更大、更接近暗物质轴子质量的理论预言值，故我们更有希望首先发现轴子，率先取得突破性、开拓性成果。

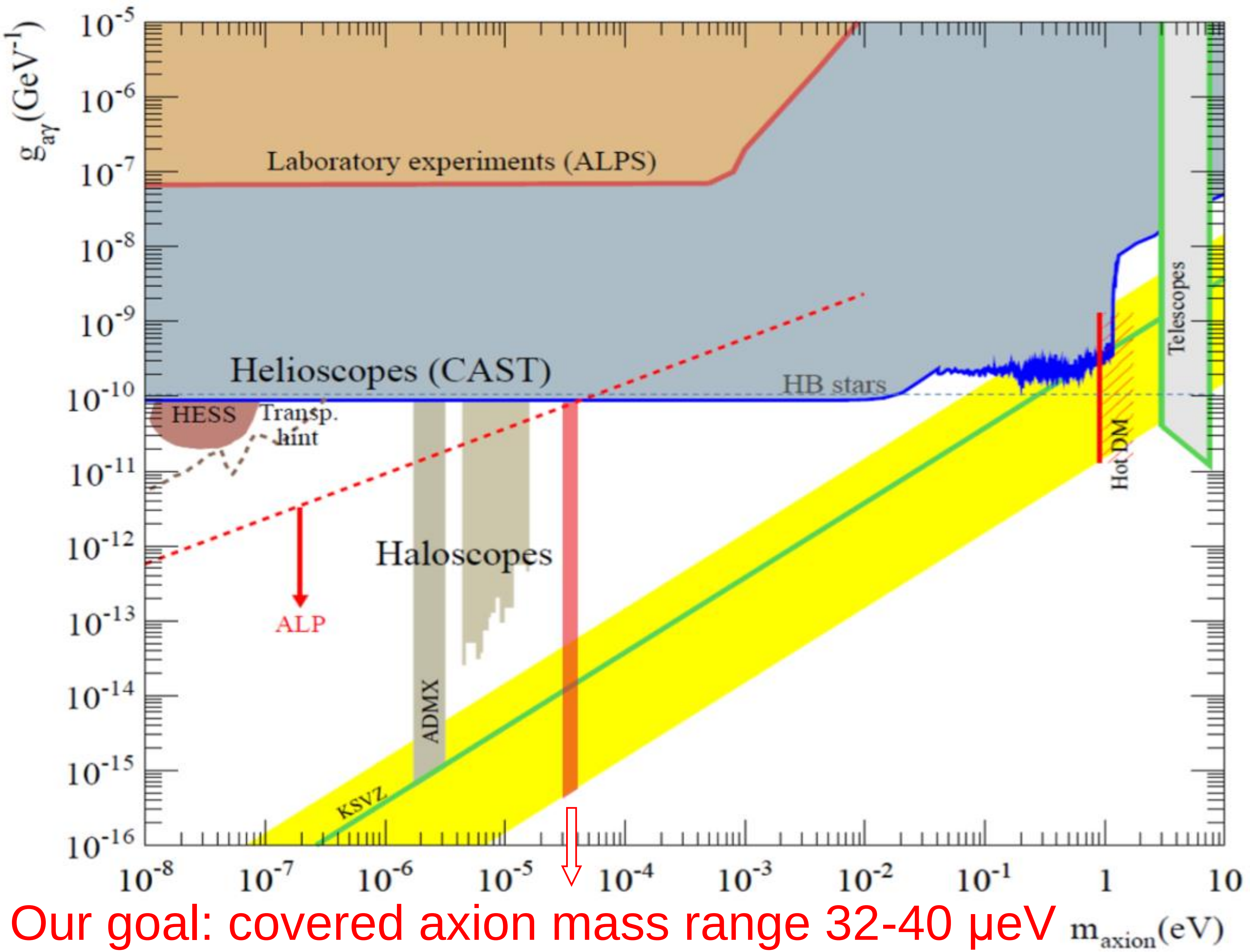
At present, resonant cavity detection is one of prevalent and mature scheme

ADMX G2

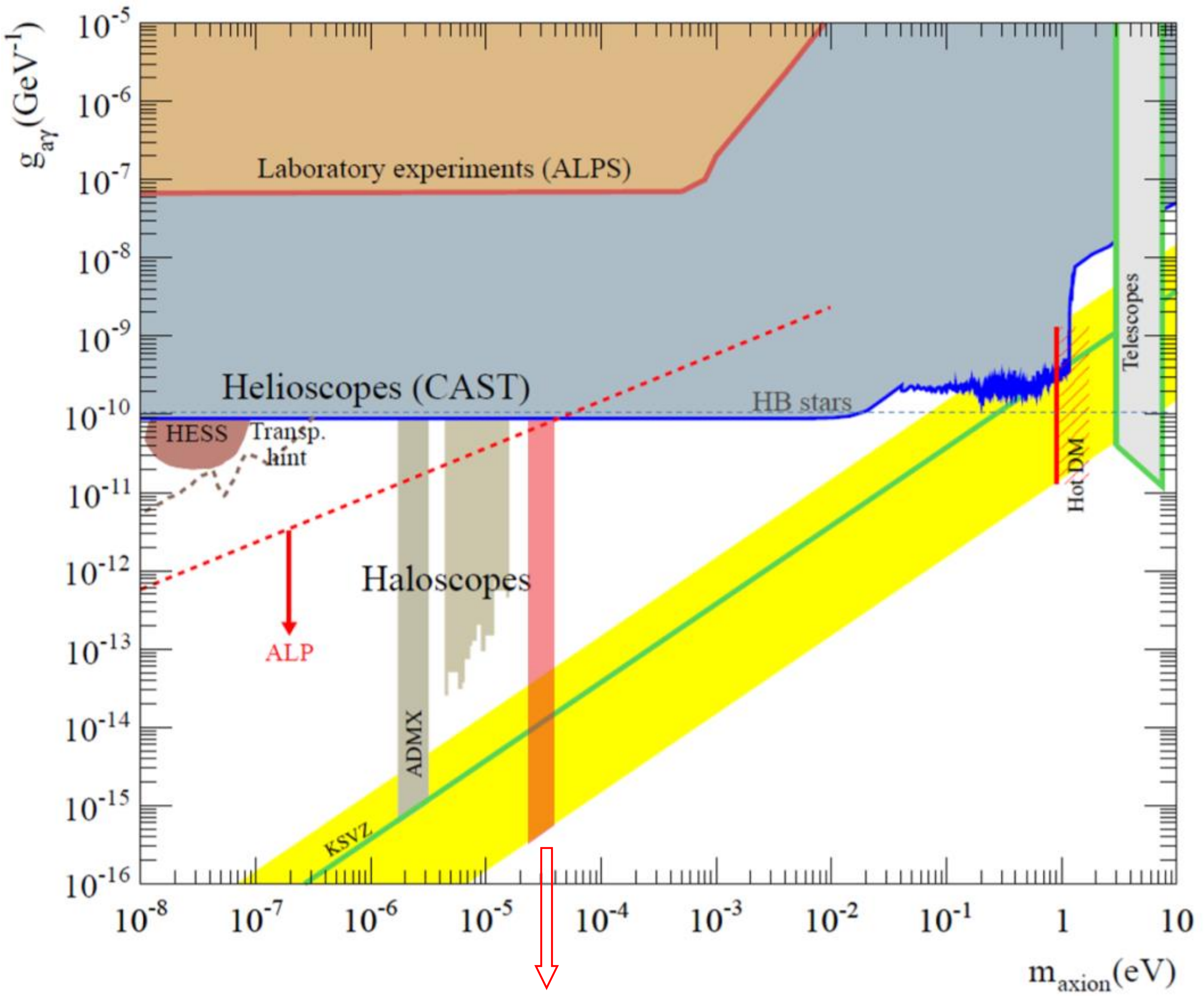
HAYSTAC



CAPP-CULTASK



Our goal: covered axion mass range 32-40 μeV



Our goal: covered axion mass range 23-40 μeV

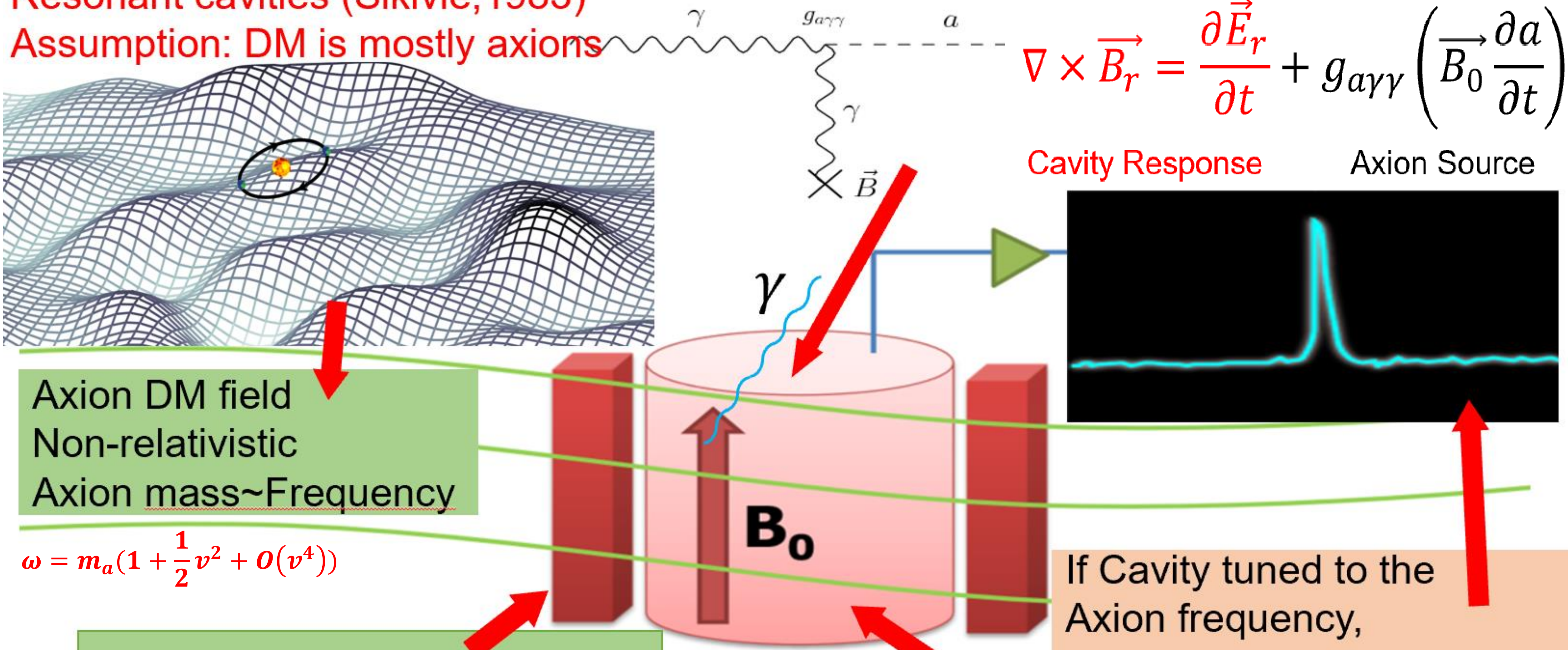
Resonant Cavity Detection (Haloscope) Basic principles

Resonant cavities (Sikivie,1983)

Assumption: DM is mostly axions

$$\nabla \times \overrightarrow{B_r} = \frac{\partial \vec{E}_r}{\partial t} + g_{a\gamma\gamma}\left(\overrightarrow{B_0}\frac{\partial a}{\partial t}\right)$$

Cavity Response — Axion Source



Axion DM field

Non-relativistic

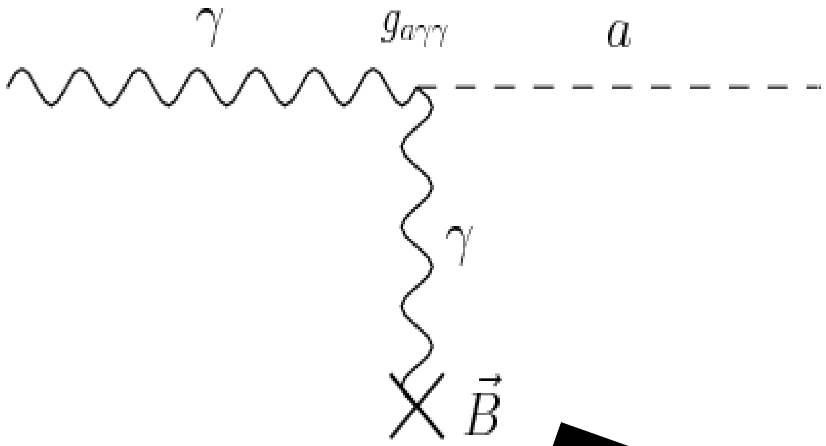
Axion mass~Frequency

$$\omega = m_a\left(1 + \frac{1}{2}v^2 + O(v^4)\right)$$

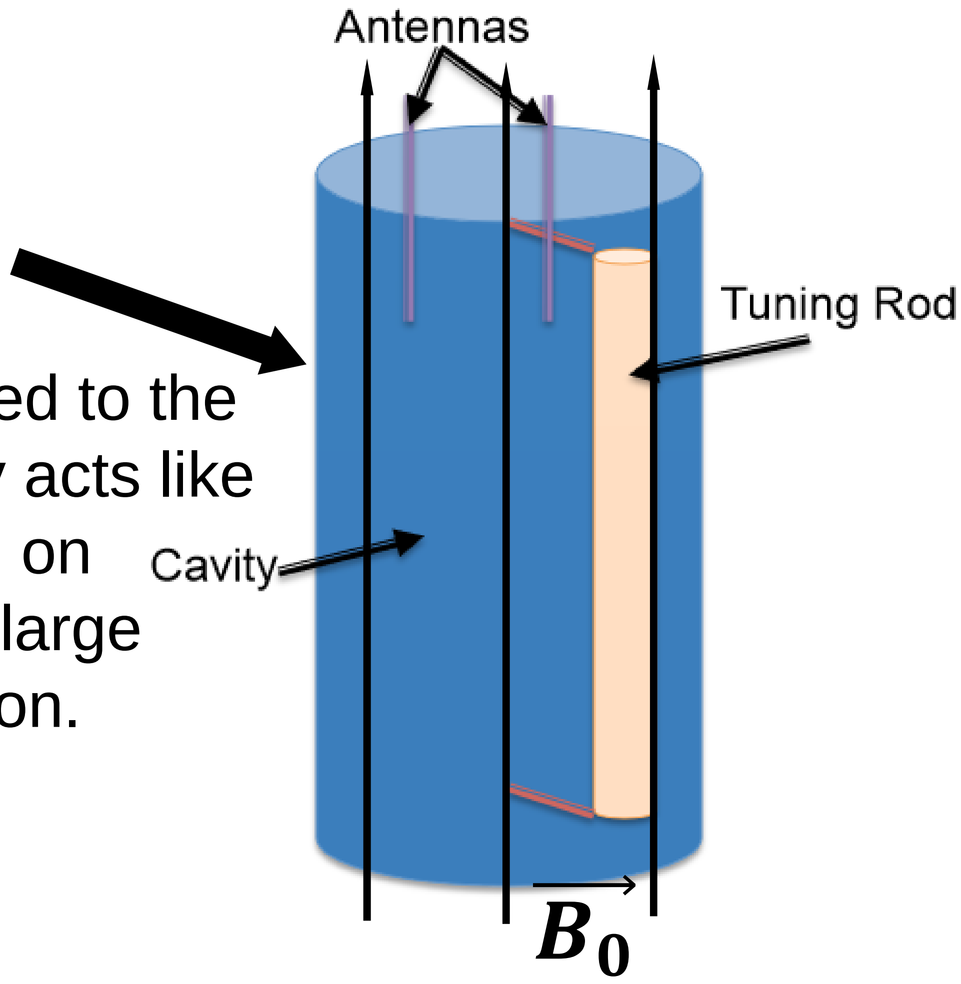
Cavity's size smaller than De Broglie wavelength of Axion

If Cavity tuned to the Axion frequency, Conversion is boosted By resonant factor Q (Quality factor)

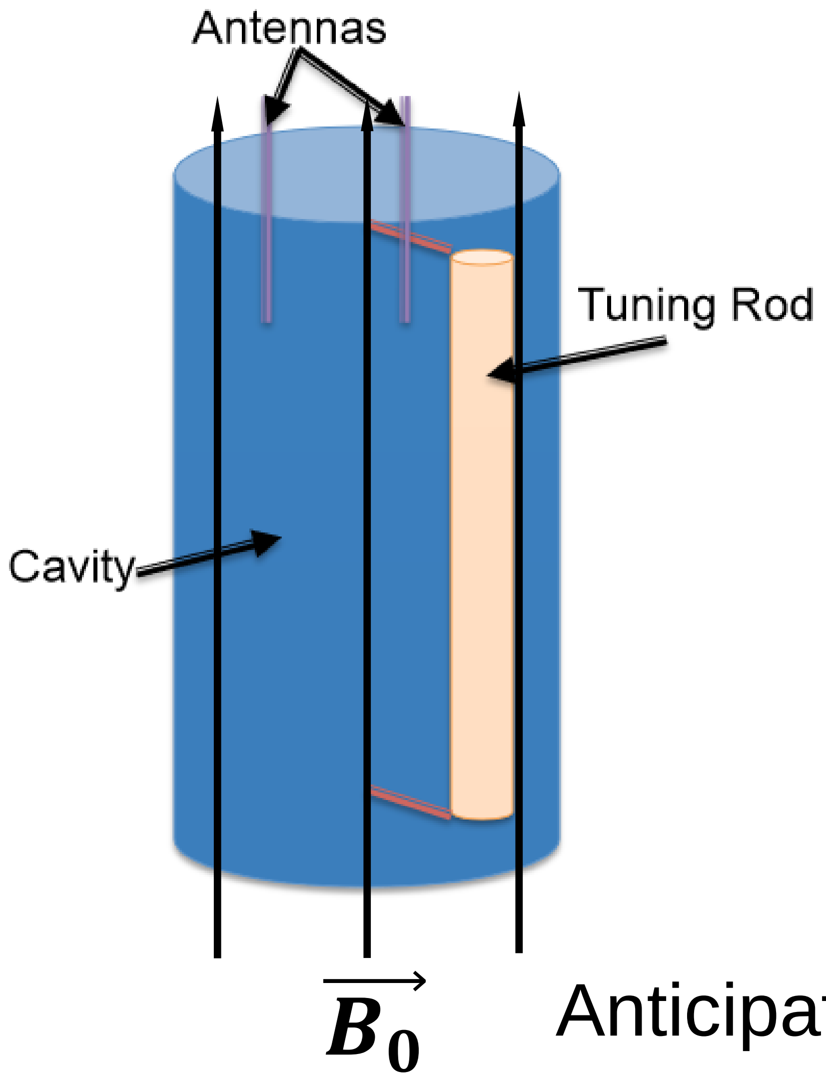
Why We Need Resonant Cavity?



If the resonance is tuned to the axion mass, the cavity acts like a forced oscillator and on resonance achieves a large axion-induced excitation.



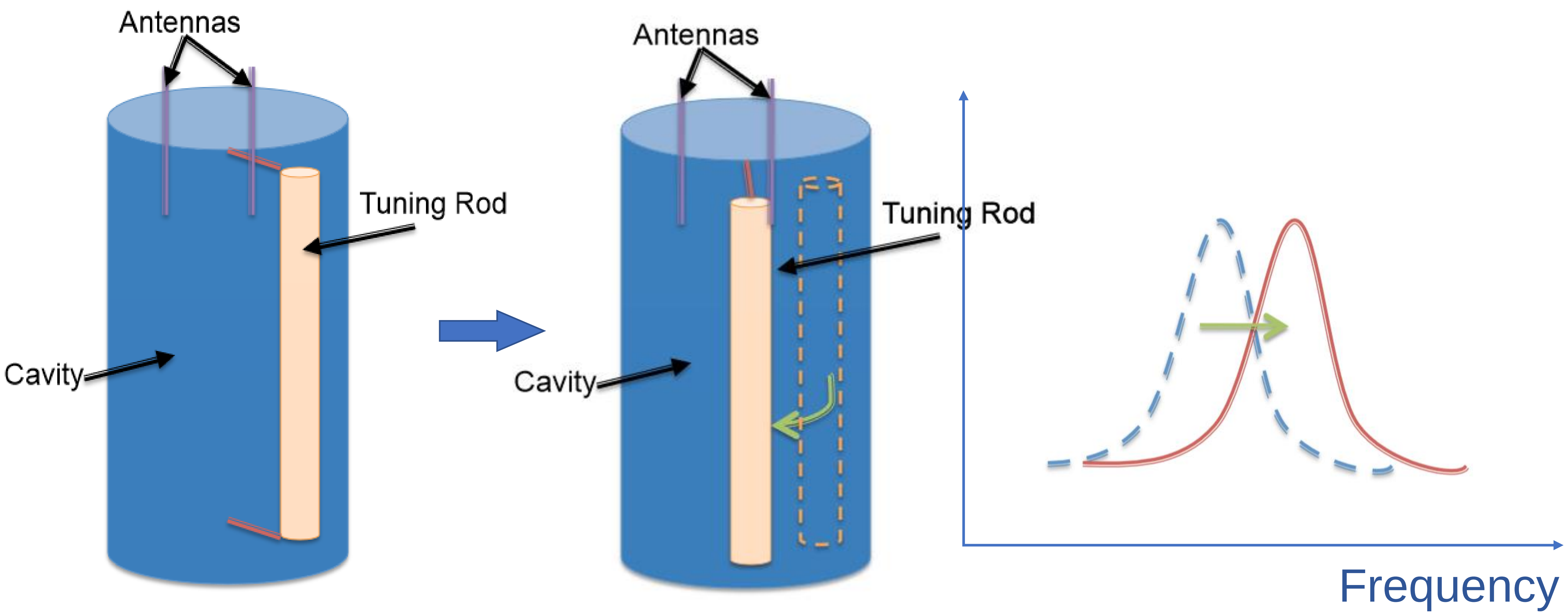
Detect Axion Dark Matter: Haloscope



- Incoming axions convert into quanta of excitation of TM modes of the cavity.
- Equilibrium between axion-stimulated excitation of the mode and spontaneous de-excitation due to thermal relaxation.
- Equilibrium population controlled by axion conversion rate and cavity Q
- Power transfer increased by coherence between cavity E-field and axion field

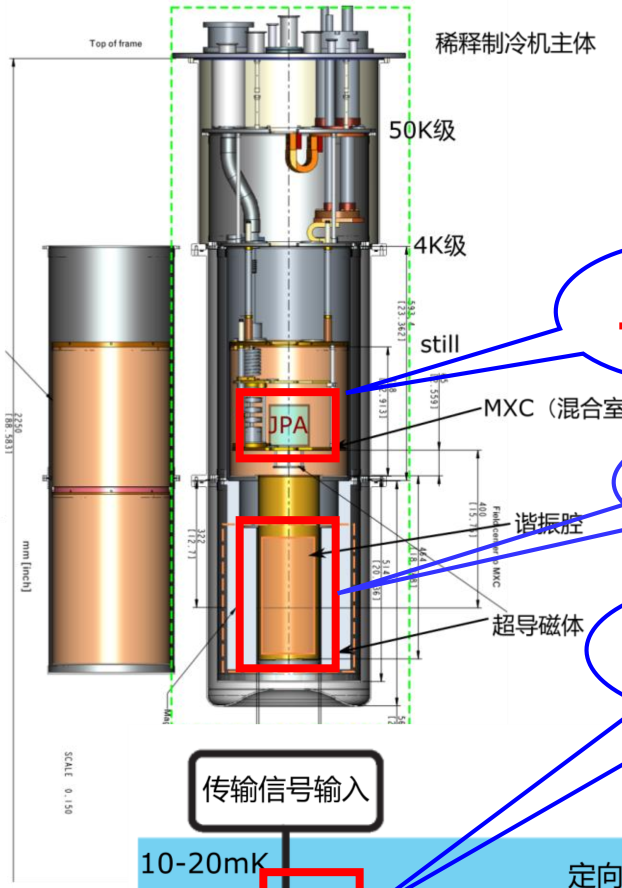
Anticipated Signal Strength: $A_s \propto g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C_{mnl} Q$

Microwave Cavity needs tunable resonance

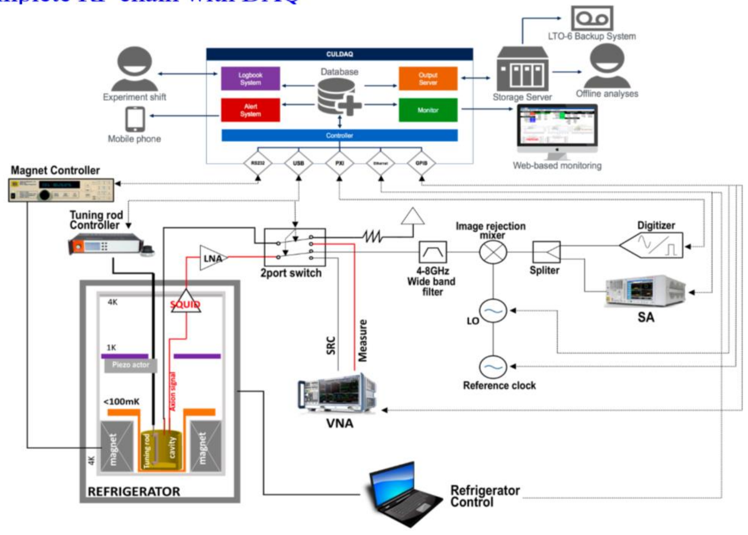


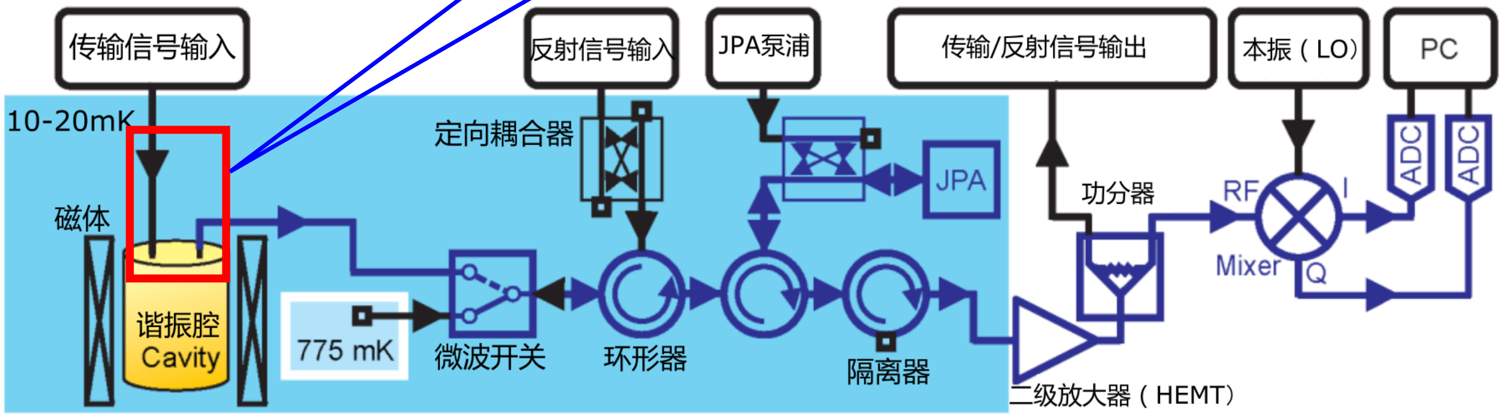
整体实验方案

JPA：约瑟夫森参量放大器
TWPA：行波参量放大器

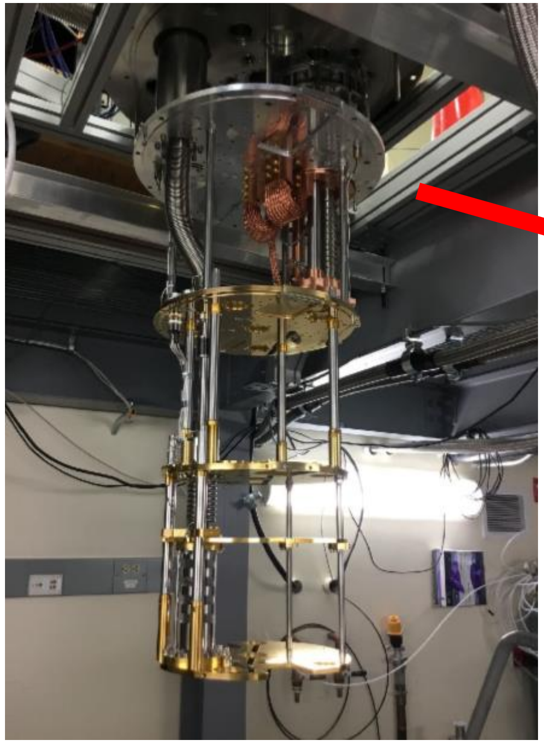


Complete RF chain with DAQ

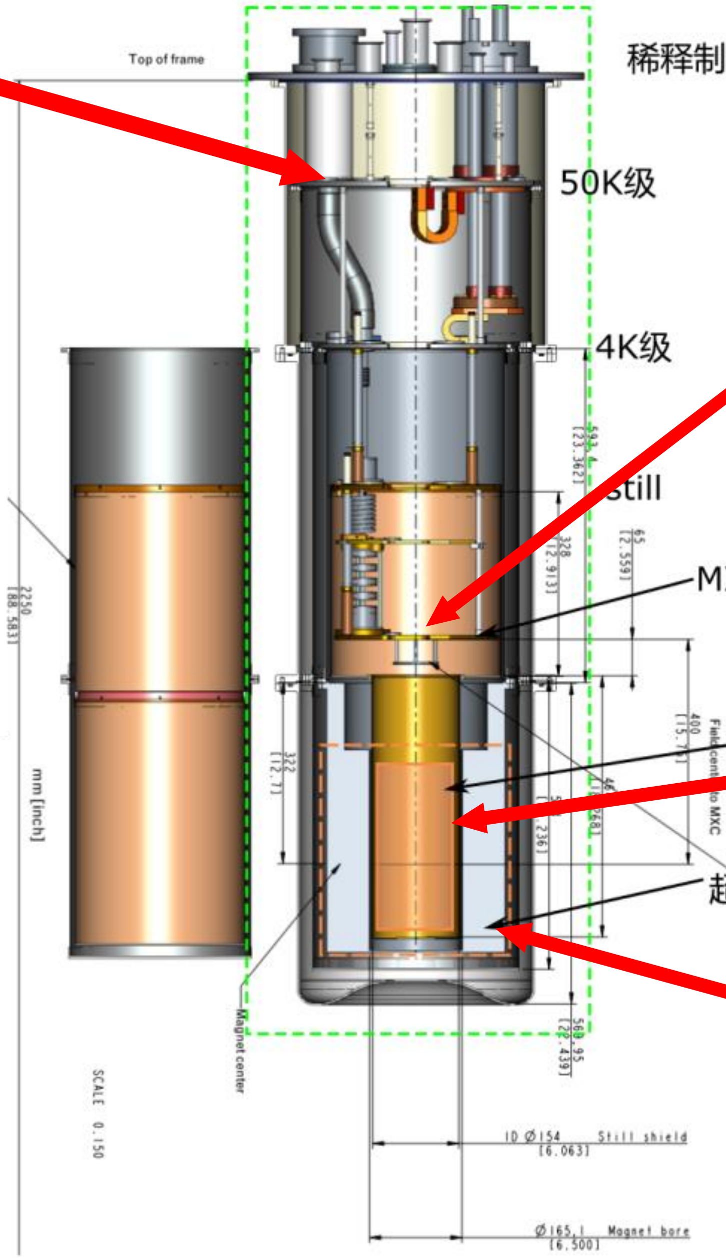


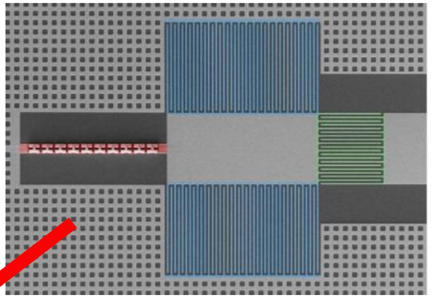


Resonant Cavity Haloscope Structure

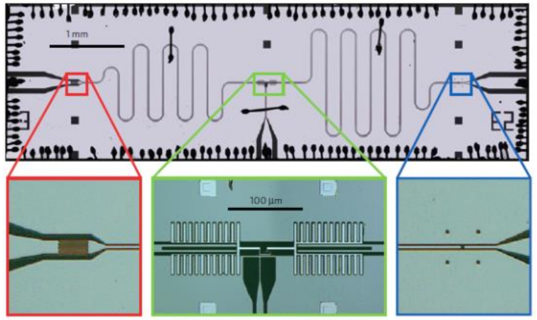


Dilution Refrigerator

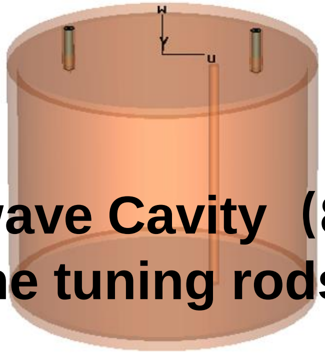




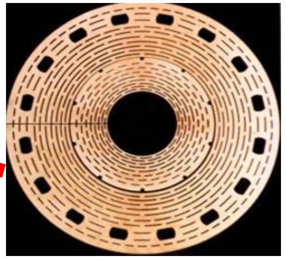
Amplifier Package
(JPA or TWPA)



Superconducting Qubits
And Circuit QED(Future)



Microwave Cavity （8-10GHz)
(with the tuning rods)



Superconducting Magnet 14T

Main performance index of Resonant Cavity Haloscope

- We want :

 1.High sensitivity

 2. Proper time to scan the parameter space

- These requires:

1.Reduced system noise

2.Faster scan

- Conditions:

Lower temperatures

Higher magnetic field

Larger effective volume

Improved Cavity Quality factor

Signal Noise Ratio: $\frac{S}{N} = \frac{P_{signal}}{k_B T_S}\sqrt{\frac{\delta t}{\delta \nu_a}}$

Signal Power: P_{signal}

$$= \frac{Q\beta}{(1+\beta)^2} g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 V C_{010}$$

$$\propto Q$$

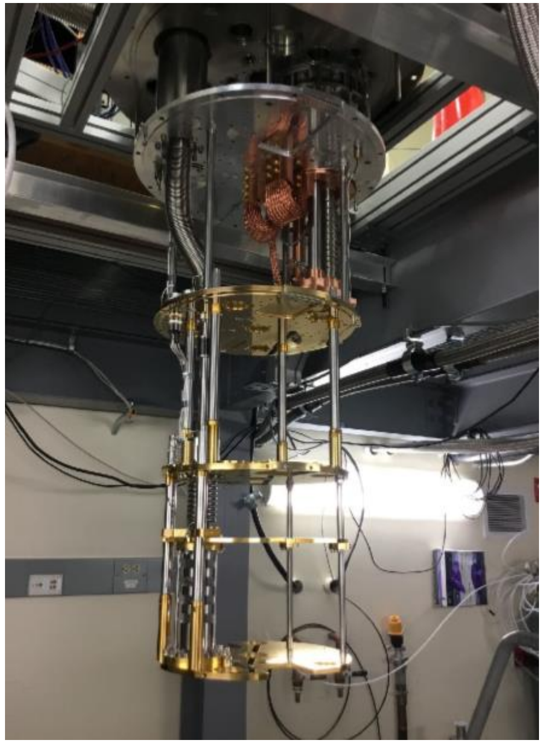
Scan Rate:

$$\frac{df}{dt} = \left(\frac{S}{N}\right)^{-2} \frac{Q_a}{Q_L} \left(\frac{P_{signal}}{k_B T_s}\right)^2$$

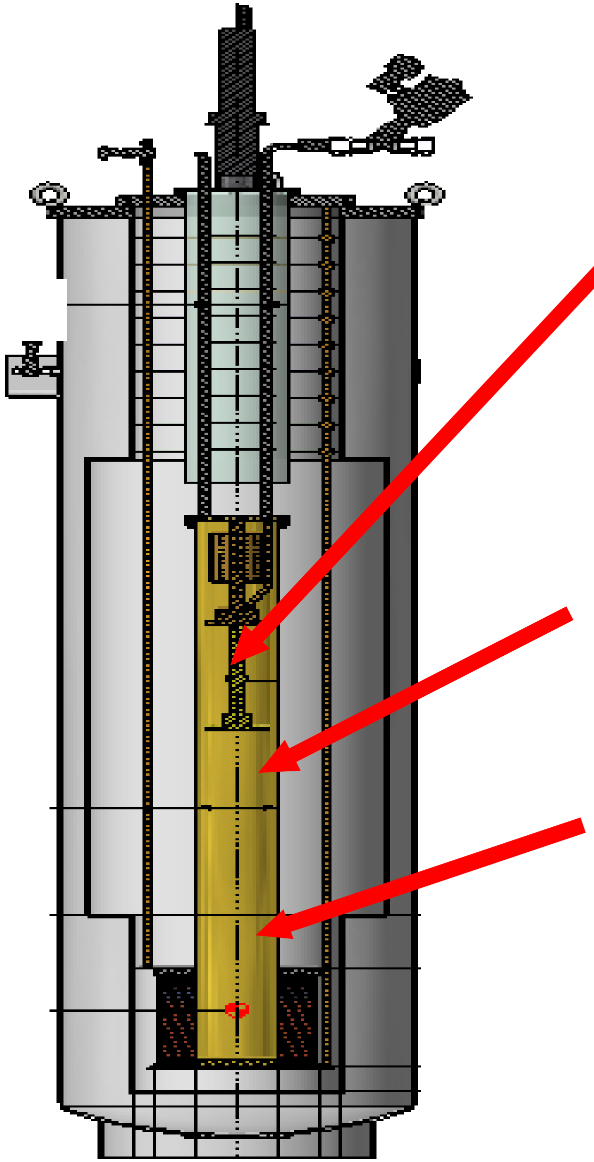
Design index of our experiment

Components	Parameters
Superconducting Magnet	Field strength: 14T Diameter: 65mm/50mm Long:20-30cm
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

Cryogenics System: Dilution Refrigerator(He-3,He-4 system)



Bluefors LD250



Three major components:

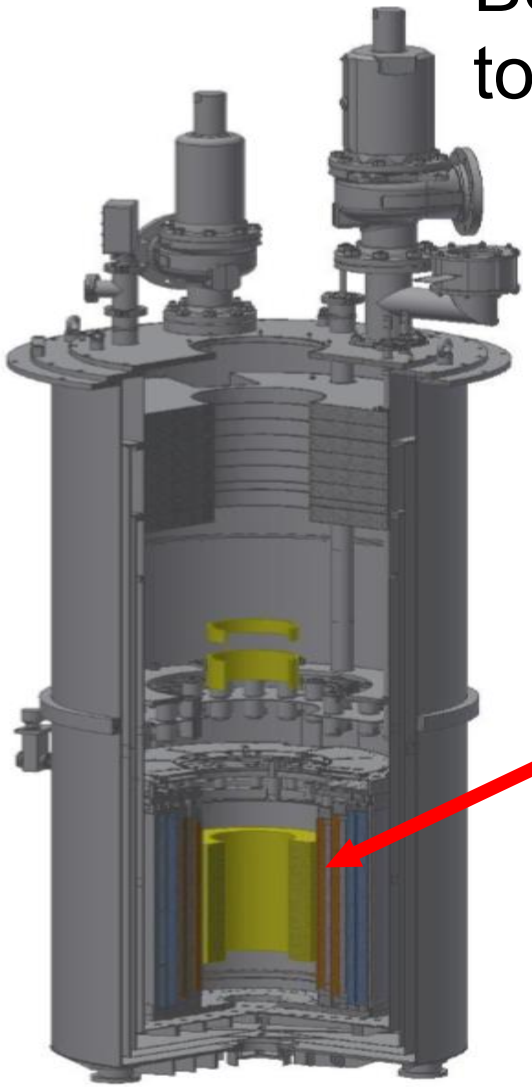
1. Sorption pump
Controls the temperature of He-3 liquid

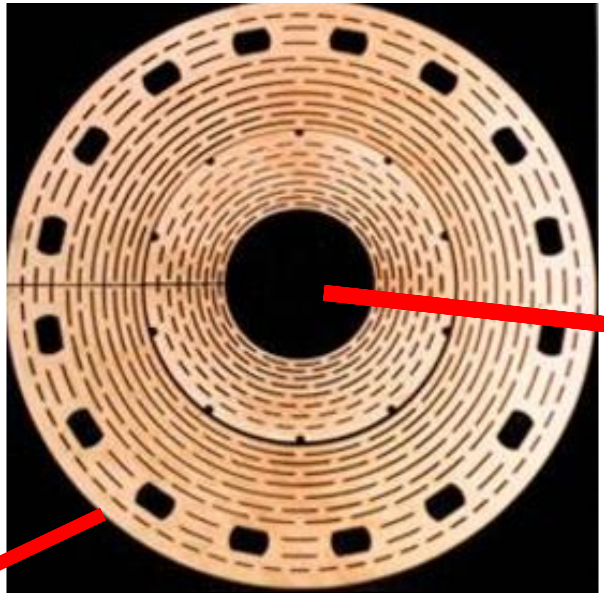
2. 1K pot (~2 K by an external pump)
Condenses He-3 gas

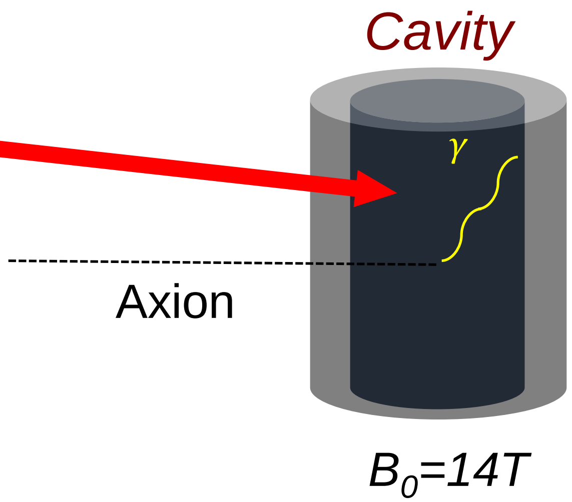
3. He-3 pot
Evaporative cooling by the charcoal pump

Superconducting Magnet: 14Tesla

Bore of 65mm in diameter and sensitivity to higher mass axions:14T static field.

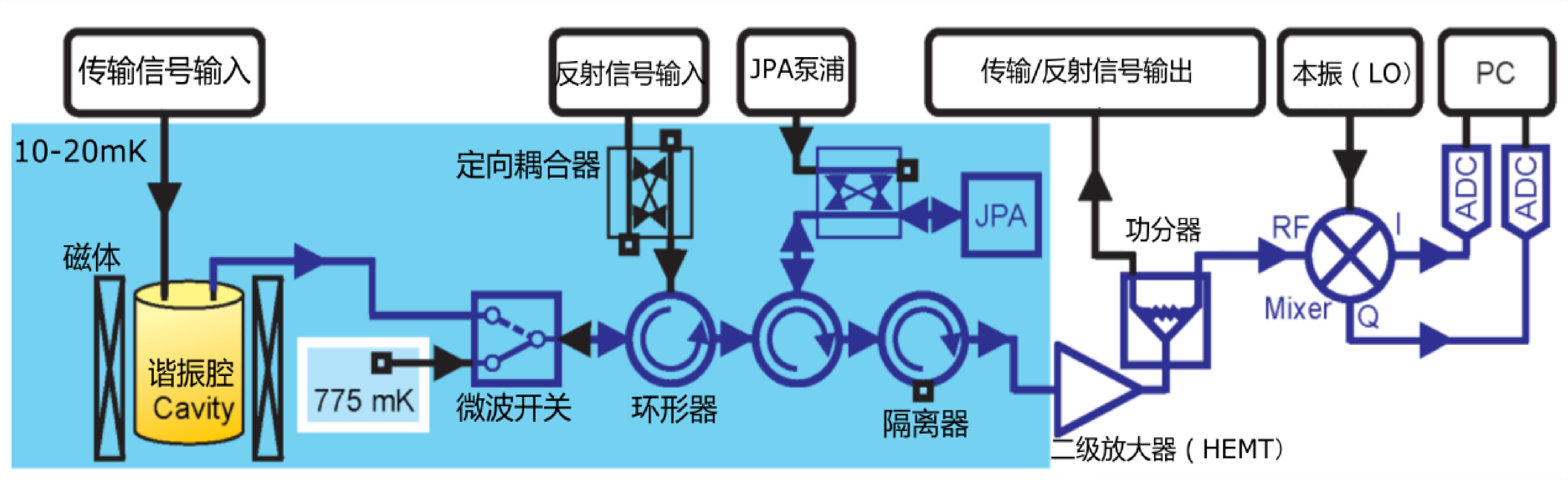






Considering that there are two layers of cold shield between the magnet and the cavity, the effective regime of the experiment is D=50mm

Receiver System

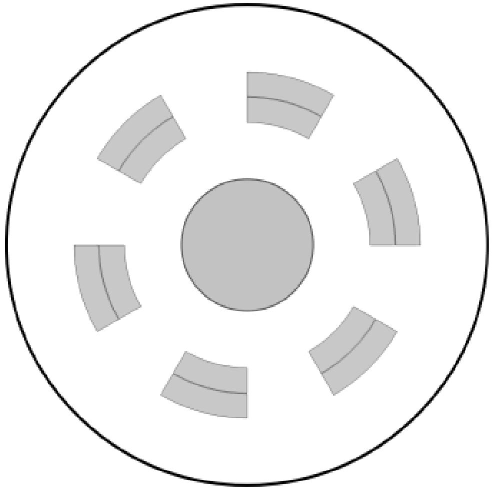
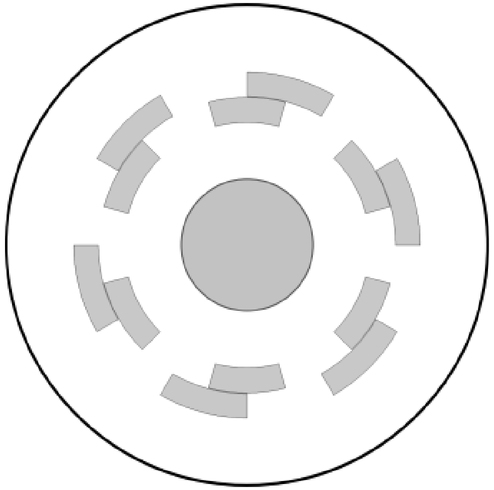
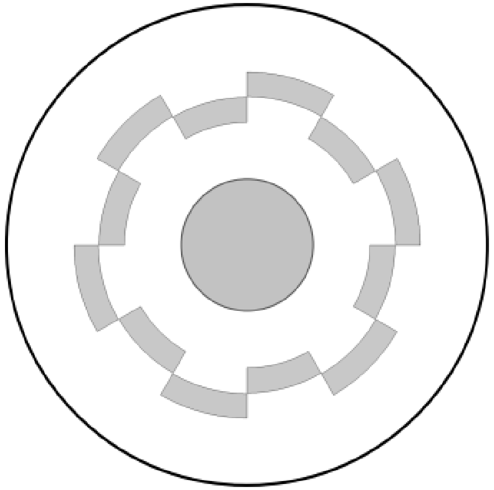


Switch toggles between cavity and hot source for calibration
Preamplifier = JPA amplifier circuit + directional coupler + circulator

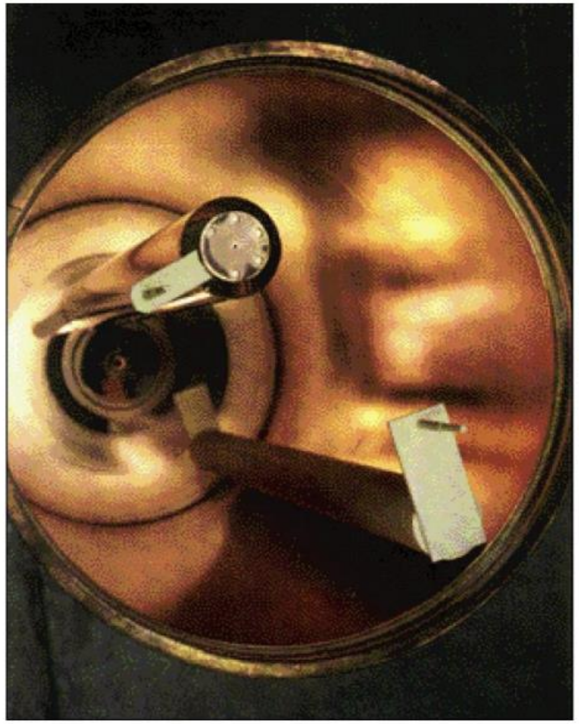
Signals from JPA amplified at 4K and room temperature
Signals down-converted to Intermediate Frequency (IF) band using IQ mixer; IF signals digitized and processed by Data Acquisition (DAQ) computer:

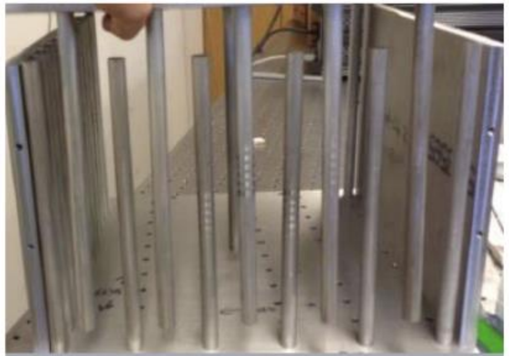
技术创新

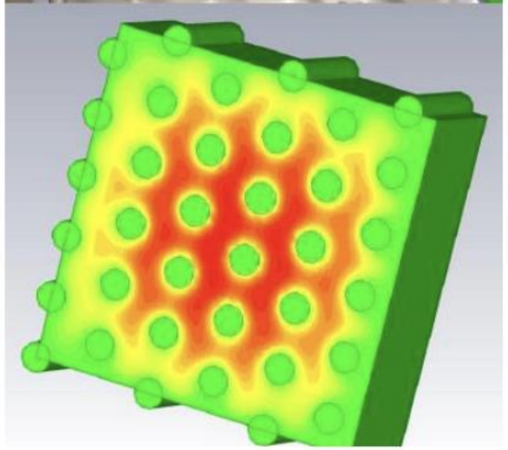
- JPA和光子探测技术已经基本具备。
- 谐振频率的升高，10GHz共振腔与目前国际上已测的1GHz附近的共振腔，其体积有近千倍的减小。如何提高共振腔的体积是一个非常大的技术难点和技术创新。
- 圆柱形谐振腔中间加粗金属棒和两层弧形模块的方式可有效的增大谐振腔的半径和体积，改变金属棒的位置和旋转内层弧形模块可改变谐振腔的频率。

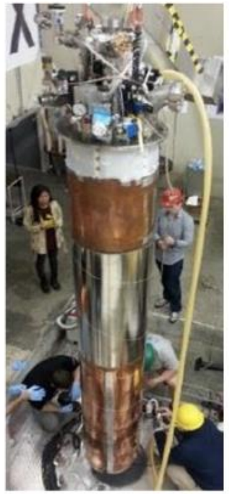




Resonant Cavity (ADMX)









1-2 GHz: 4 cavities
•R ≈ 8 cm

2-6 GHz: cavities
•R ≈ 4 cm

6-8 GHz: PBG cavity
•~14 cm X 14 cm

Magnet	Diam	TM_{010}	B	Cavities	Total V	Tnoise	P	Time for an octive
	cm	freq	T		liters	K	yW	months
ADMX	42	0.55	7.4	1	138	0.17	107	16
ADMX	17	1.3	7.4	4	95	0.19	240	14

Cavity (8-10GHz) Design and Simulation

The power of the Axion converted into photons in the resonant cavity is:

$$P_a = \left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right)^2 V B_0^2 \rho_a C_{mnp} \frac{1}{m_a} Q_L$$

V is the volume of the cavity filled with magnetic field and C_{mnp} is the form factor describing the coupling between the Axion field and the specific electromagnetic field mode TM_{mnp} in the cavity.
TM_{mnp} is defined as:

$$C_{mnp} = \frac{\left|\int d^3x \boldsymbol{B}_0 \cdot \boldsymbol{E}_{mnp}(\boldsymbol{x})\right|^2}{B_0^2 V \int d^3x \varepsilon(\boldsymbol{x}) \left|\boldsymbol{E}_{mnp}(\boldsymbol{x})\right|^2}$$

The parameters related to the resonator are as follows: V, C_{mnp}, Q_L

The form factor is related to the selected resonant mode:

Mode	C
TM010	0. 69
TM020	0. 13
TM030	0. 05

Numerical results:
0.6922
0.1312
0.0534

Operate at 8-10 GHz:

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

Scan Rate:

$$\frac{df}{dt} \approx 1009 MHz/year - 1198 MHz/year \text{(KSVZ)}$$
$$\frac{df}{dt} \approx 18 MHz/year - 22 MHz/year \text{(DFSZ)}$$

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: $\delta \nu_a = \frac{\nu}{Q_a} = 8000 Hz - 10000 Hz$

$\delta t \approx 1.4 hours - 2.2 hours$ (KSVZ) $\delta t \approx 3 days - 6 days$(DFSZ)

To 10 GHz, we need to improve our device

- We want :

  1.High sensitivity

  2.Proper time to scan the parameter space

  These requires:

1.Reduced system noise

2.Faster scan

- Conditions:

Lower temperatures

Higher magnetic field

Larger effective volume

Improved Cavity Quality factor

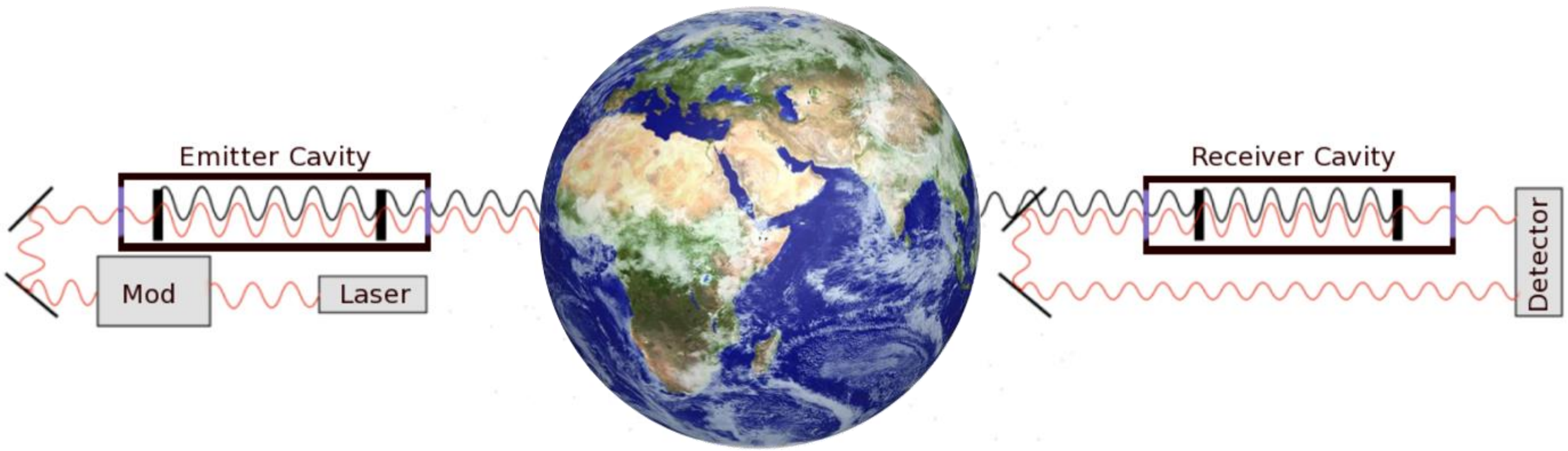
$$\frac{df}{dt} = \left(\frac{S}{N}\right)^{-2} \frac{Q_a}{Q_L} \left(\frac{P_{signal}}{k_B T_s}\right)^2$$

$$P_{signal} = \frac{Q\beta}{(1+\beta)^2} g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B_0^2 V C_{010}$$

$$\frac{S}{N} = \frac{P_{signal}}{k_B T_s} \sqrt{\frac{\delta t}{\delta \nu_a}}$$

轴子被证实后对科技影响

- 大力促进物理学、宇宙学和天文学的发展，一门新学科轴子天文学。
- 特别是了解星系的演化与暗物质结构和分布。
- 为探索普朗克和超弦能标的新物理打开了一扇窗口。
- 创新科技应用：轴子通讯，如提供潜水艇间的信息传递方案等。



轴子通讯

潜水艇间信息传递：

当前困难：VLF 非常低频， 3-30 kHz，可穿透海水约20米。

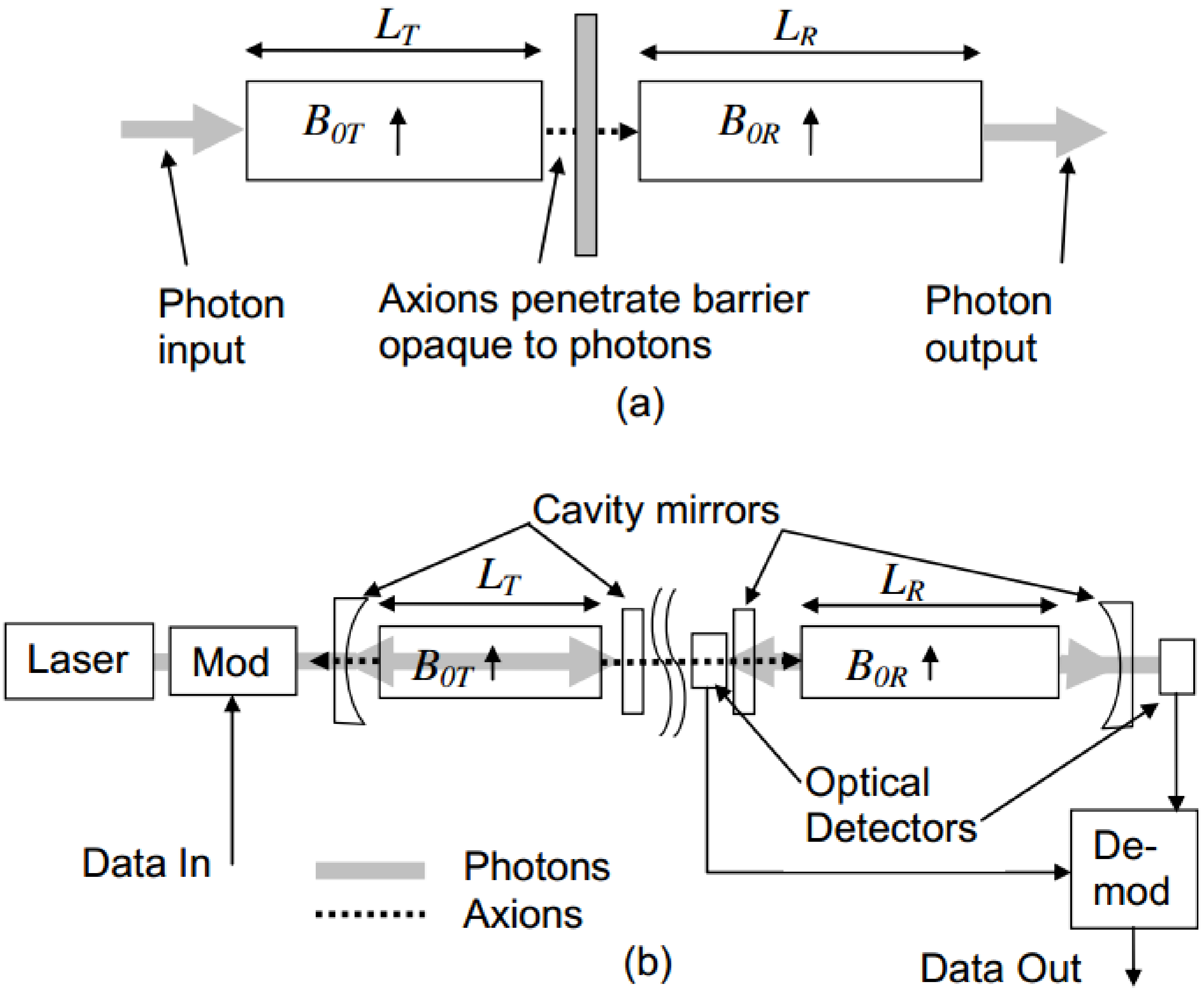
ELF 极端低频， 3-300 Hz，可穿透海水几百米。

发射装置体型巨大，只能陆地发射信号，潜水艇水下接收信号，单向传递信息。

轴子通讯：

- 携带信息的轴子能穿越大气，海洋与星体传播，且基本没有损耗。
- 轴子是玻色子，波束密度可以很高，中微子做不到这点。
- 所需能量少，易聚焦，装置小，易操作。

轴子通讯



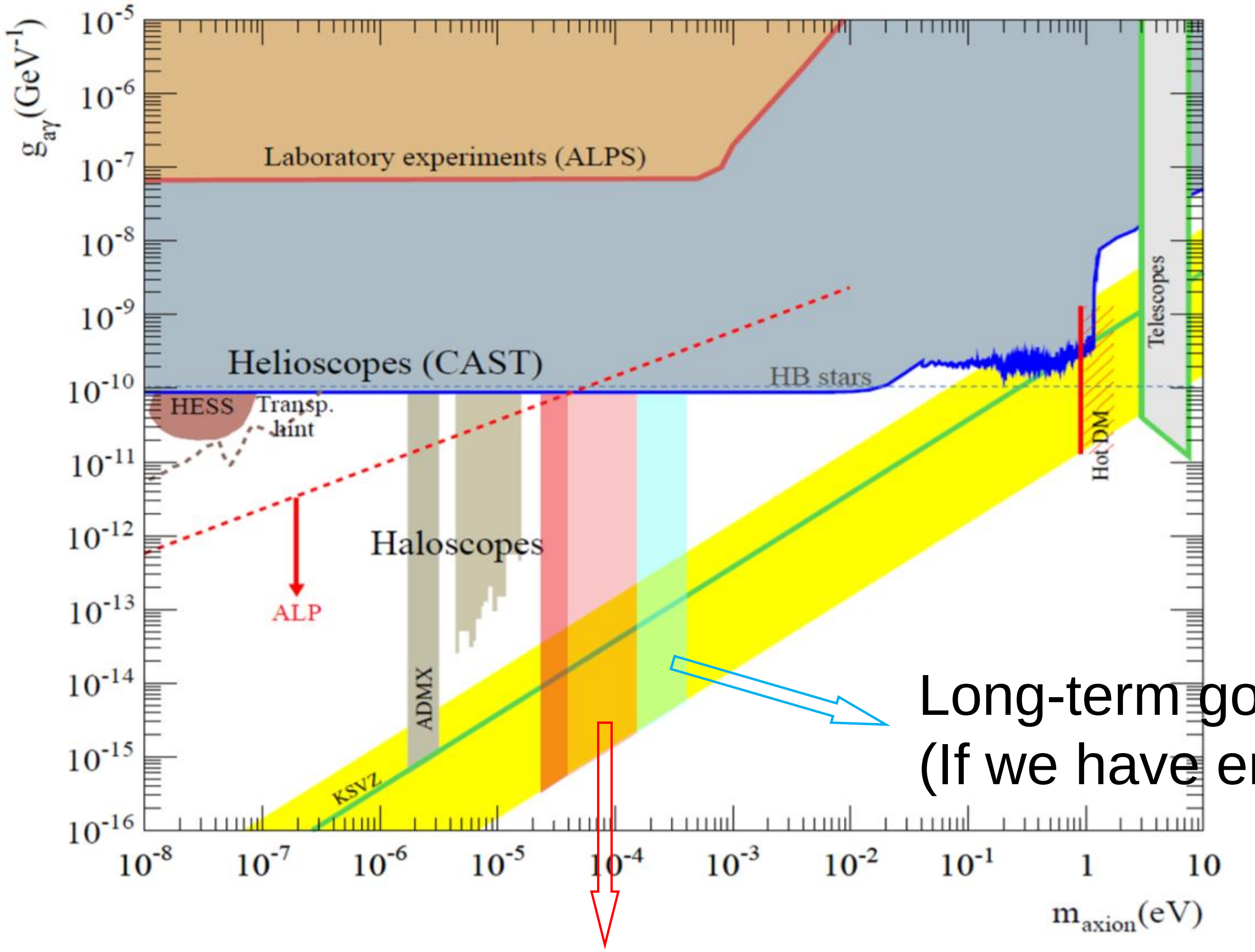
L_T
L_R
B_{0T}
B_{0R}
Photon input
Axions penetrate barrier opaque to photons
Photon output
(a)
Cavity mirrors
L_T
L_R
Laser
Mod
B_{0T}
B_{0R}
Optical Detectors
Data In
Photons
Axions
De-mod
Data Out
(b)

轴子能源

- 轴子暗物质能量转化为光能
- 特别是能量守恒定律自动满足
- 问题：如何储存能量?
- 既要脚踏实地，也要仰望星空!

In the Future (Two goals)

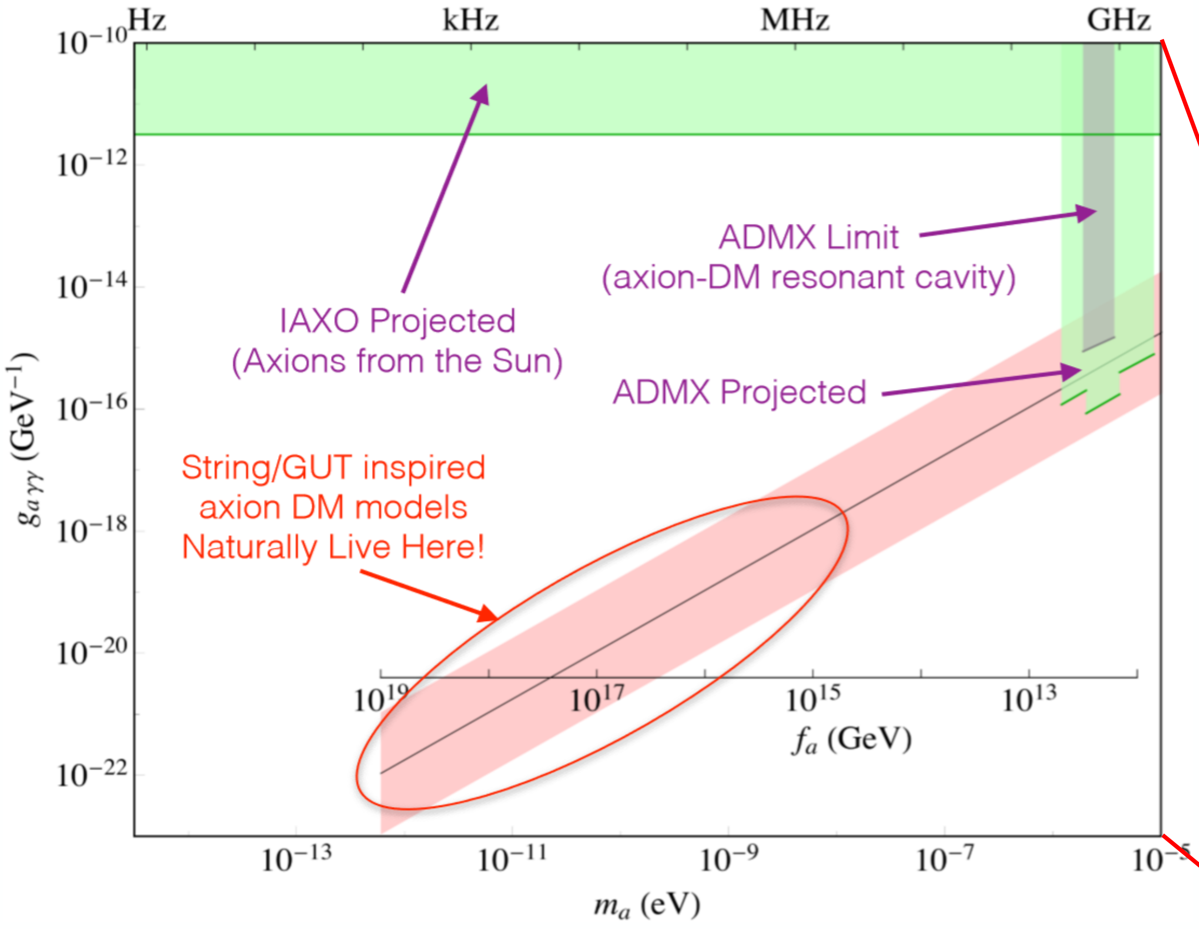
1.Beyond 10GHz (QCD Axion for m_a>40μeV)

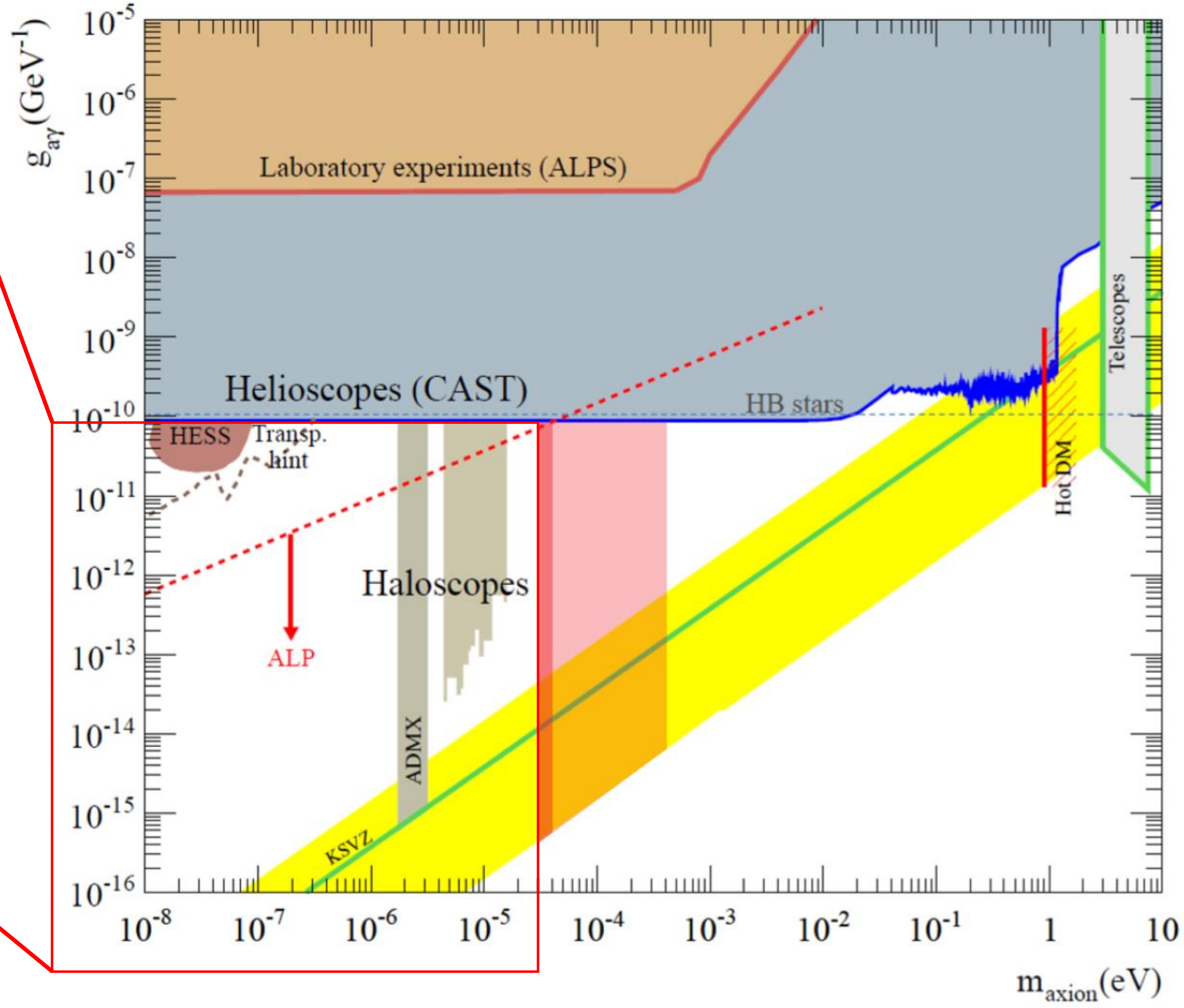


Long-term goal:150-400μeV
(If we have enough budget)

Beyond 10GHz expected goal: Covered axion mass range:40-150 μeV

II. GUT/String inspired Axion





Outline

Introduction and Theoretical

The Peccei–Quinn Mechanism and Axion Models

The Overview of the Axion Experiments

The Resonant Cavity Study for the Axion Dark Matter

Summary

Summary

- The Peccei-Quinn mechanism provides the best solution to the strong CP problem.
- It predicts axion, which can be a cold dark matter candidate.
- Axion and ALPs have deep connections to supersymmetry, grand unified theory, string theory, inflation, as well as dark energy, dark matter, the SM fermion masses and mixings, gravitational wave, baryon asymmetry, relaxation mechanism, etc, and provide explanations to the EDGES results and XENON1T excess, etc. Thus, axion and ALPs are the promising new physics beyond the SM.
- How to probe axion and ALPs at the current and future experiments?

Summary

- We propose an experiment to probe the QCD axion with mass range [32, 40] μeV or [23, 40] μeV.
- We plan to probe the QCD axion with mass range [40,150] μeV or [40, 400] μeV, and GUT/string-scale axions.

Thank You Very Much
for Your Attention!


谢 谢