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光共振器を用いた アクシオン暗黒物質の探索

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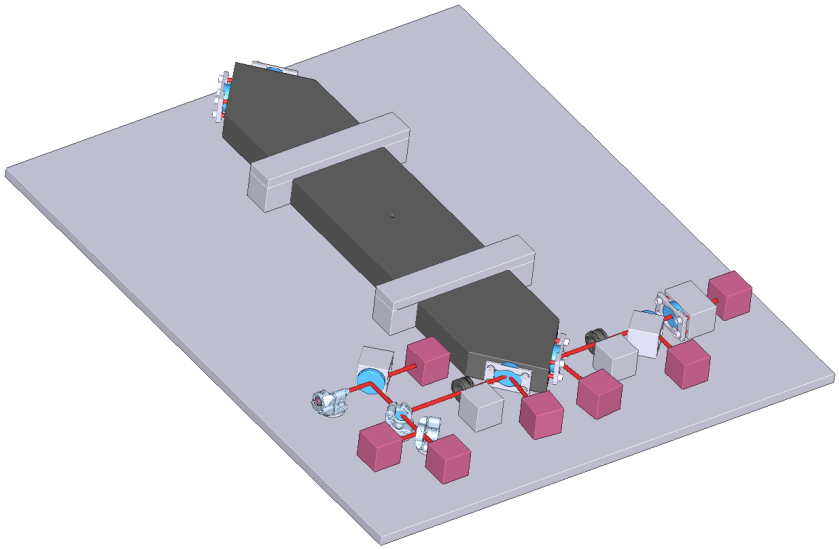
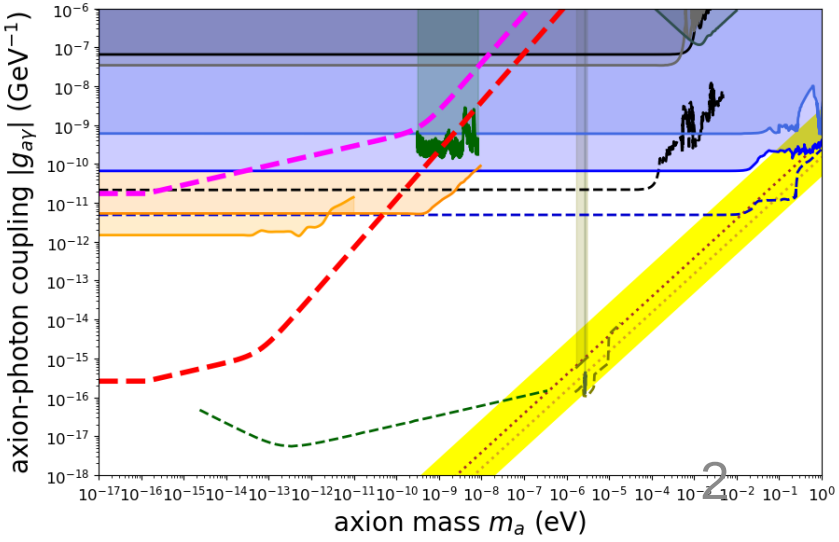
概要

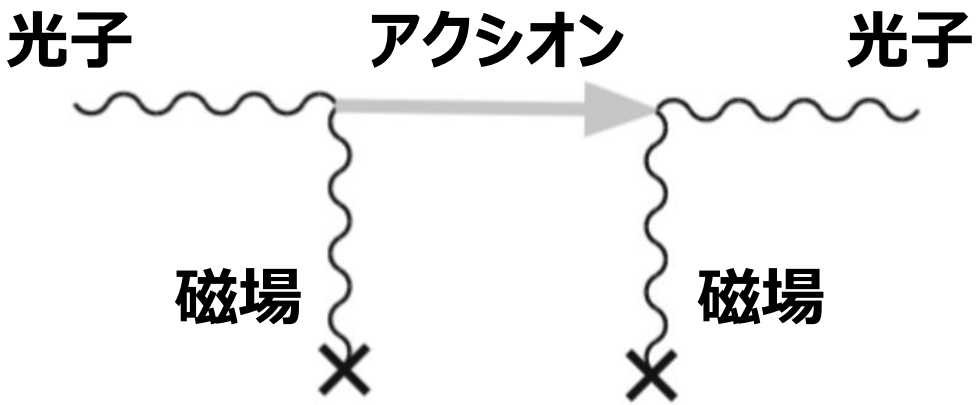
- 光リング共振器を用いてアクシオン暗黒物質を探査する新手法を提案
  I. Obata, T. Fujita, YM, PRL 121, 161301 (2018)
- 円偏光の光速差を測定する
- アクシオン質量 $m_a \lesssim 10^{-10}\,\mathrm{eV}$ で既存の上限値を数桁超える探査が可能
- プロトタイプ実験が進行中





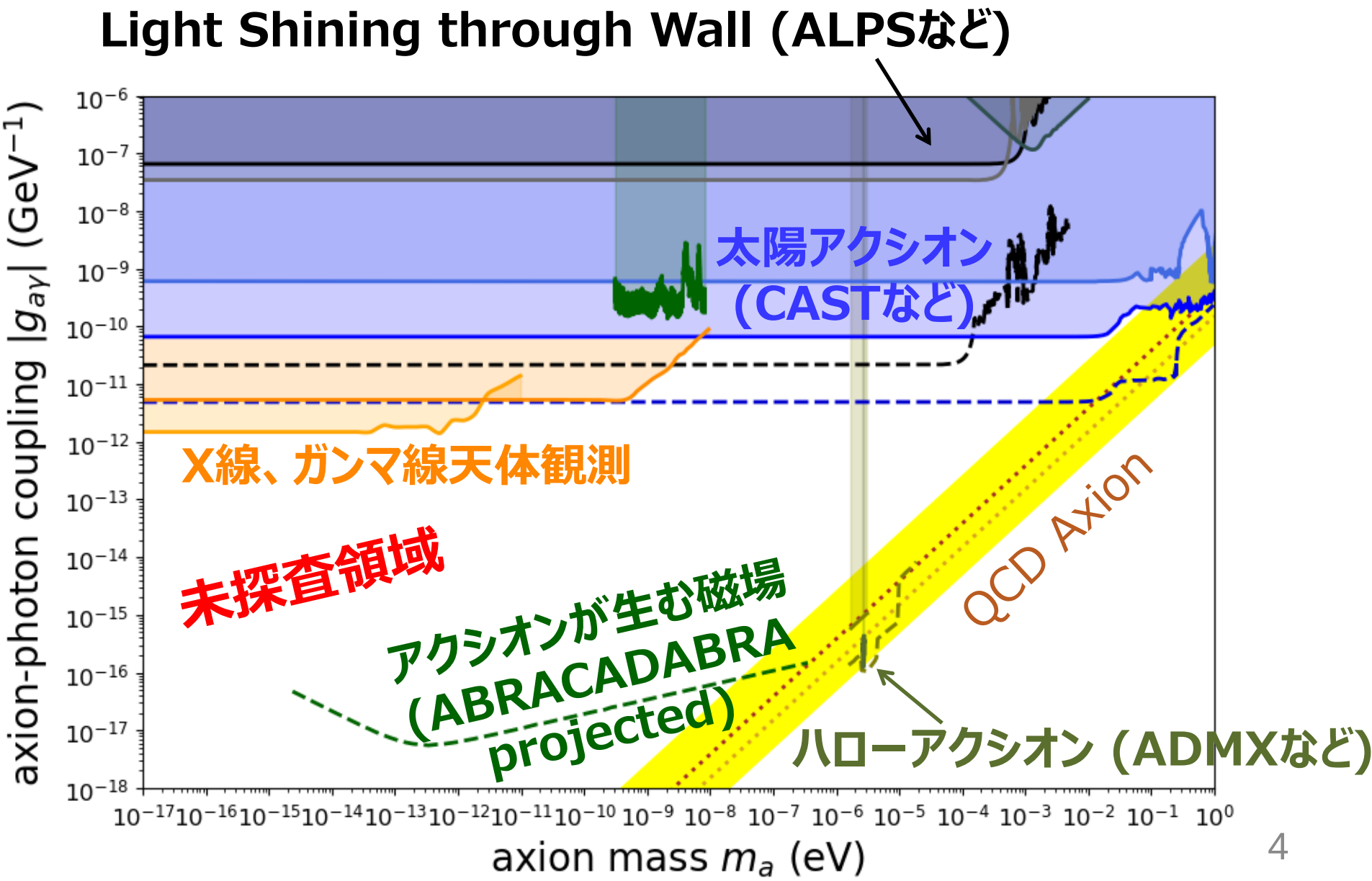
アクシオン

- 量子色力学の強いCP問題を解決するために導入された擬スカラー粒子
- ひも理論など高次元理論からも様々な axion like particles (ALPs)が予言されている
- 暗黒物質の候補(m<<keV、物質と微小な相互作用)
- アクシオンの探査方法
  アクシオン-光子相互作用を探査する方法が主流
  特に磁場を用いる手法が盛ん



Primakoff効果

これまでの上限値や提案実験



円偏光の速度差に着目

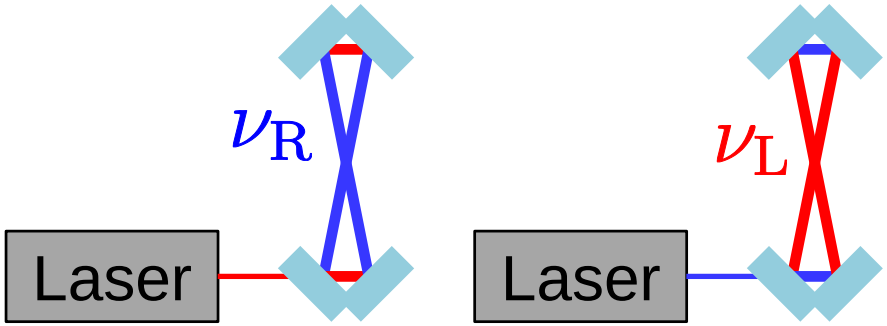
- アクシオン-光子相互作用($\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$)により
  左円偏光と右円偏光に速度差が生じる

$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

coupling constant　axion field　axion mass

- 円偏光の速度差を光共振器の共振周波数差として測定

$$\frac{\delta c}{c} = \frac{\nu_{\mathrm{L}} - \nu_{\mathrm{R}}}{\nu}$$

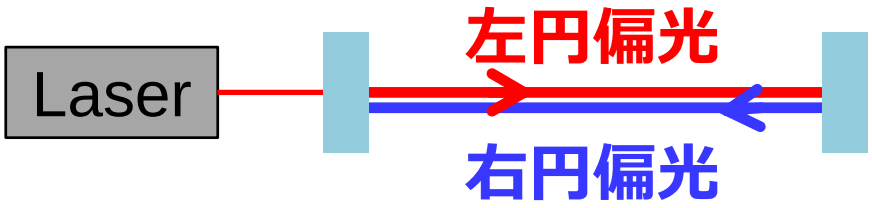


- 振動源となりうる強磁場を用いずに探査することが可能

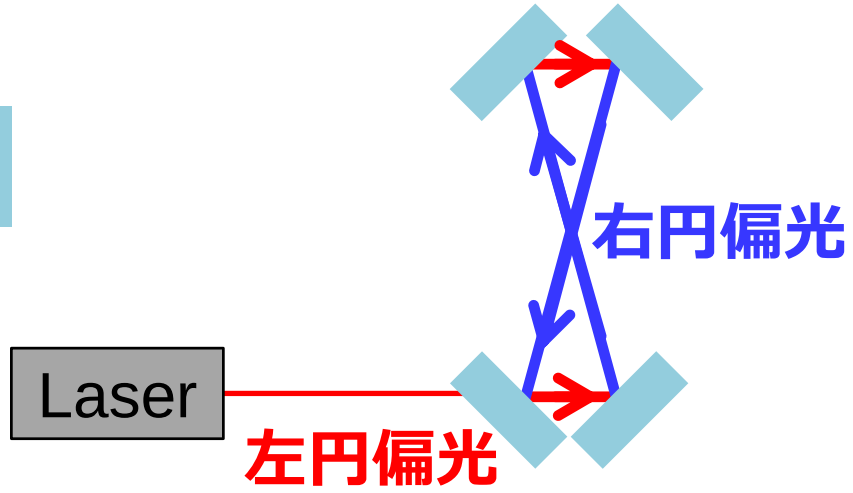
我々のアイディア

- ボウタイ共振器を用いる

線形共振器では光速の差の影響がキャンセル



ボウタイ共振器なら大丈夫

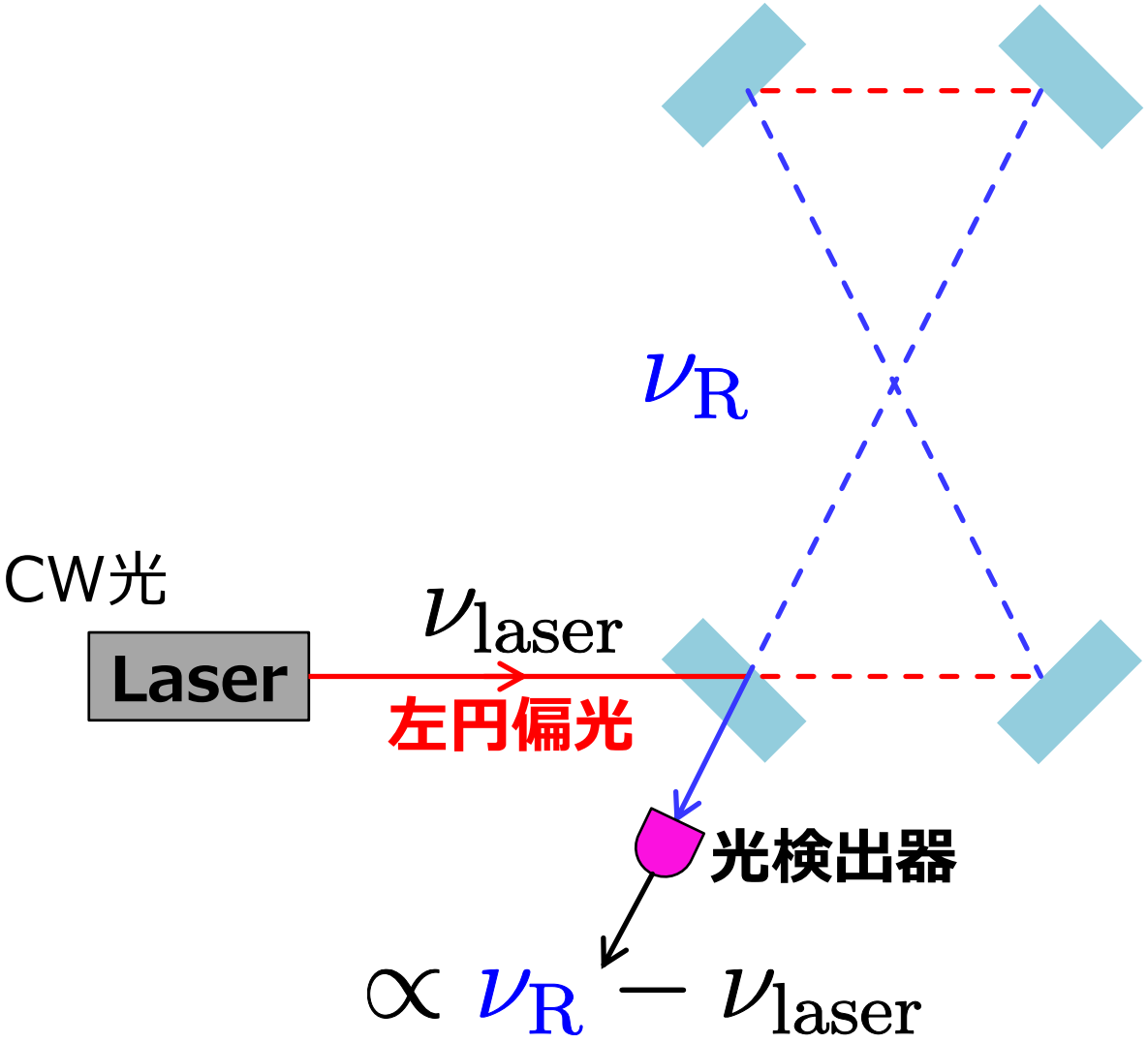


- ダブルパス構成を用いる
  透過光を打ち返すことで同じ共振器を逆回りに使って円偏光の間の共振周波数差をヌル測定

YM+, PRL 110, 200401 (2013)

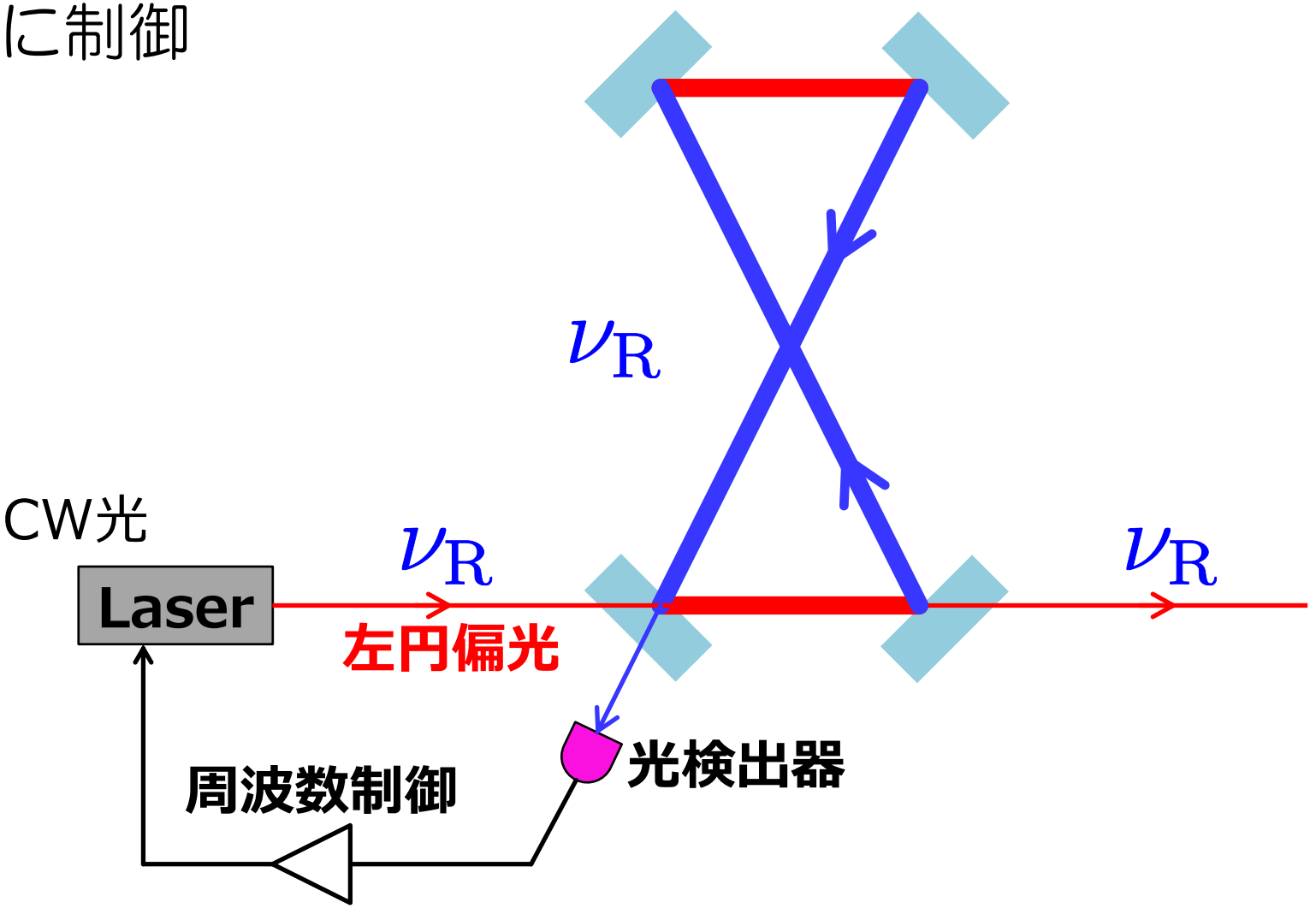
ボウタイ共振器とダブルパス構成

- 左円偏光を共振器に入射



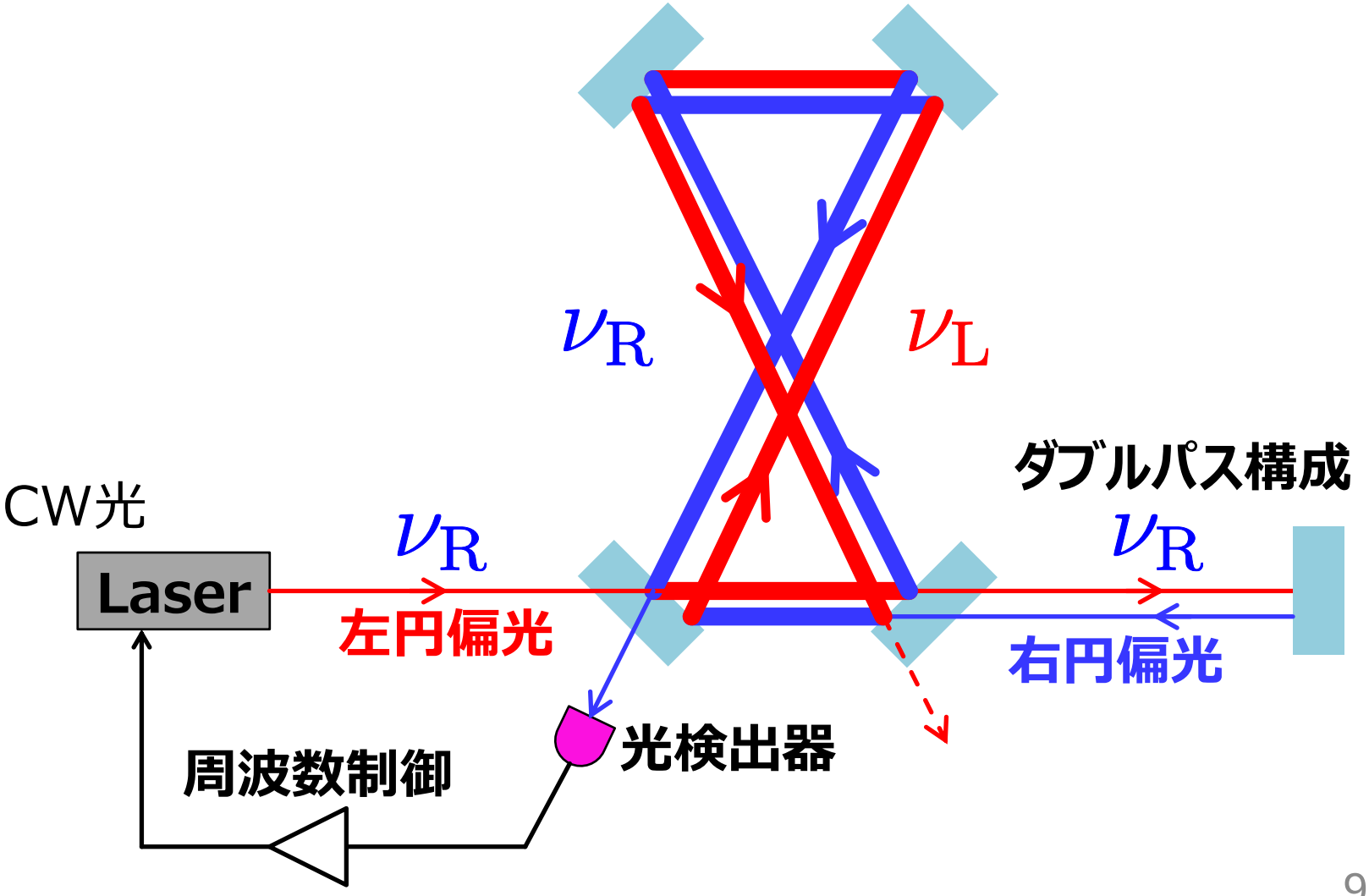
ボウタイ共振器とダブルパス構成

- レーザーの周波数を右円偏光の共振周波数(ν_R)に制御



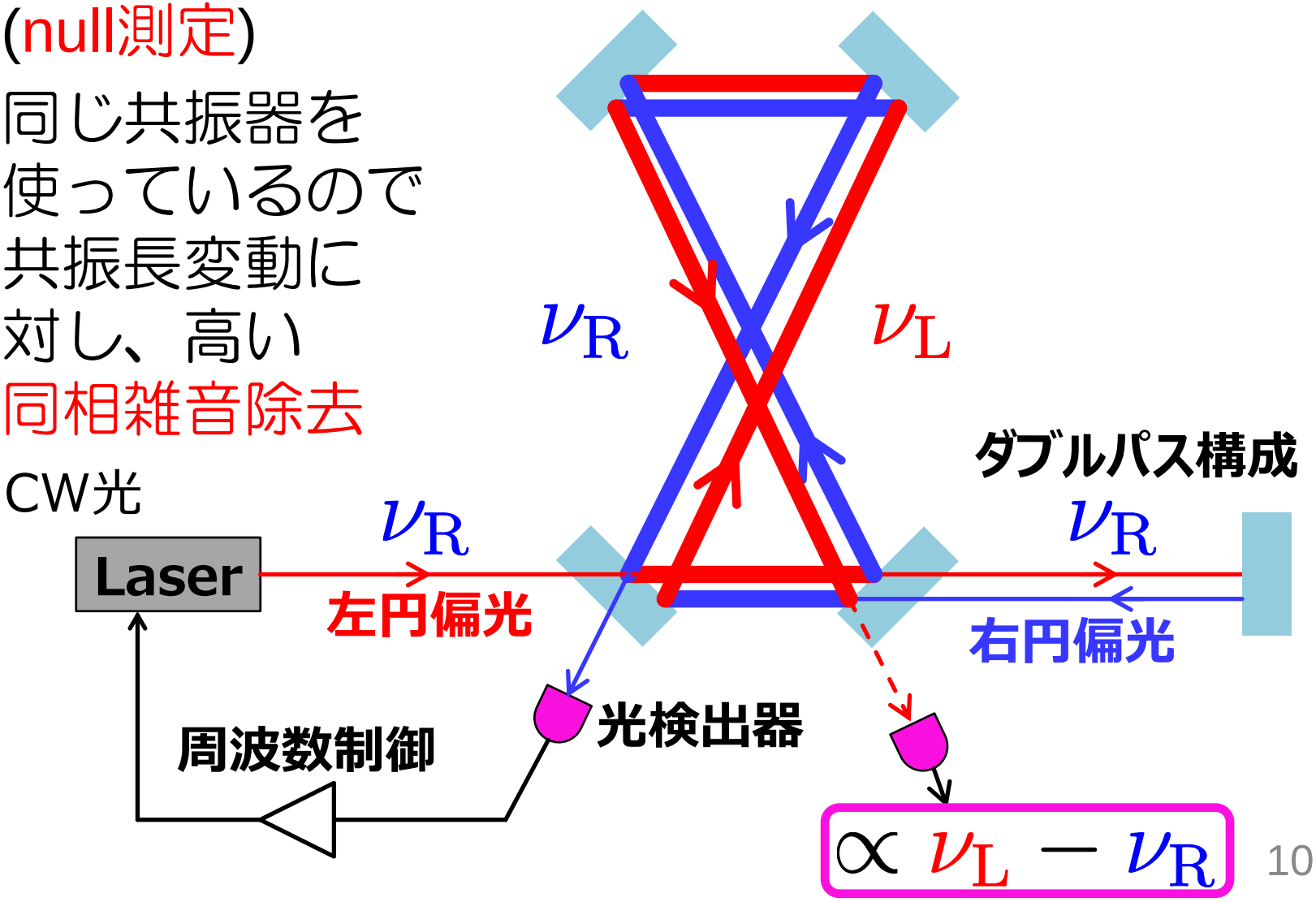
ボウタイ共振器とダブルパス構成

- 透過光を打ち返す(右円偏光を逆回りに入射)



ボウタイ共振器とダブルパス構成

- 共振器の反射光からアクシオン信号が取り出せる(null測定)
- 同じ共振器を使っているので共振長変動に対し、高い同相雑音除去



この構成の感度

- **DANCE**
  Dark matter **A**xion search with ri**N**g **C**avity **E**xperiment
- 共振器長変動(変位雑音)は同相雑音除去により原理的には雑音にならない
- 光検出器の散射雑音で決まる

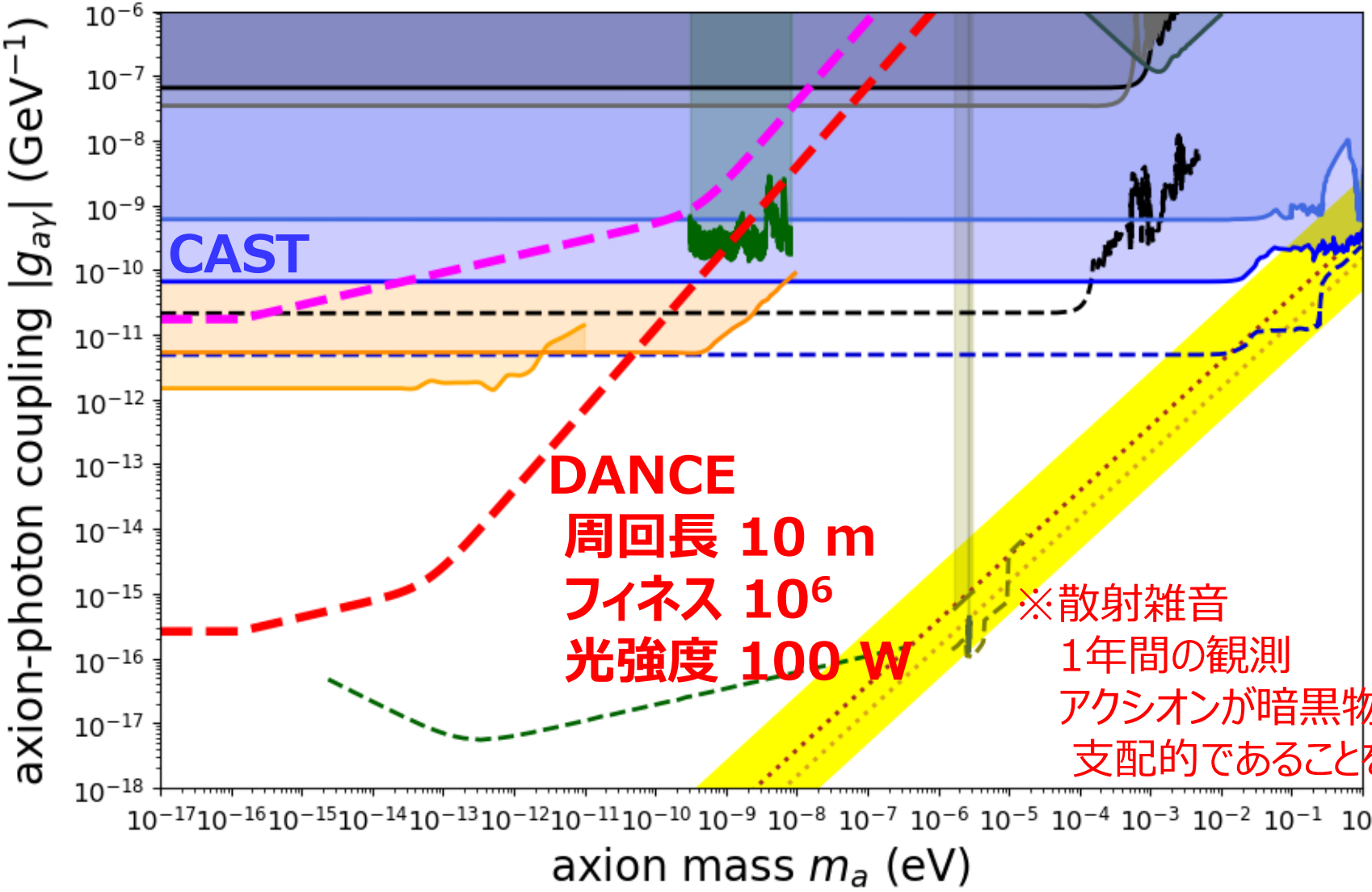
$$\sqrt{S_{\mathrm{shot}}} = \sqrt{\frac{\lambda}{4\pi P}\left(\frac{\pi^2}{L^2\mathcal{F}^2} + m_a^2\right)}$$

input laser power
cavity length
finesse
axion mass

- アクシオンの密度 = 暗黒物質の密度 と仮定すれば感度が計算できる

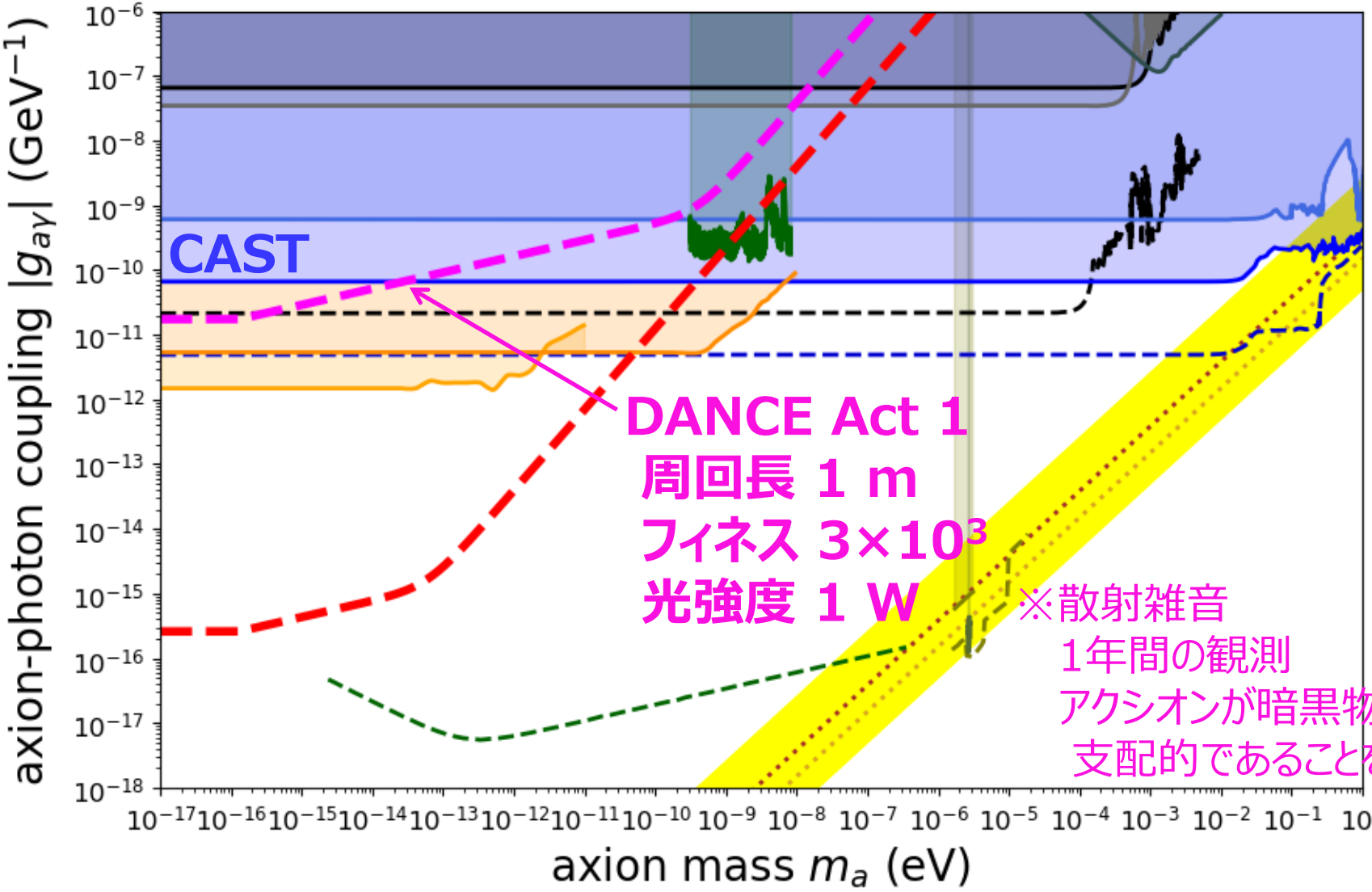
未探査領域を探査可能

Dark matter Axion search with riNg Cavity Experiment

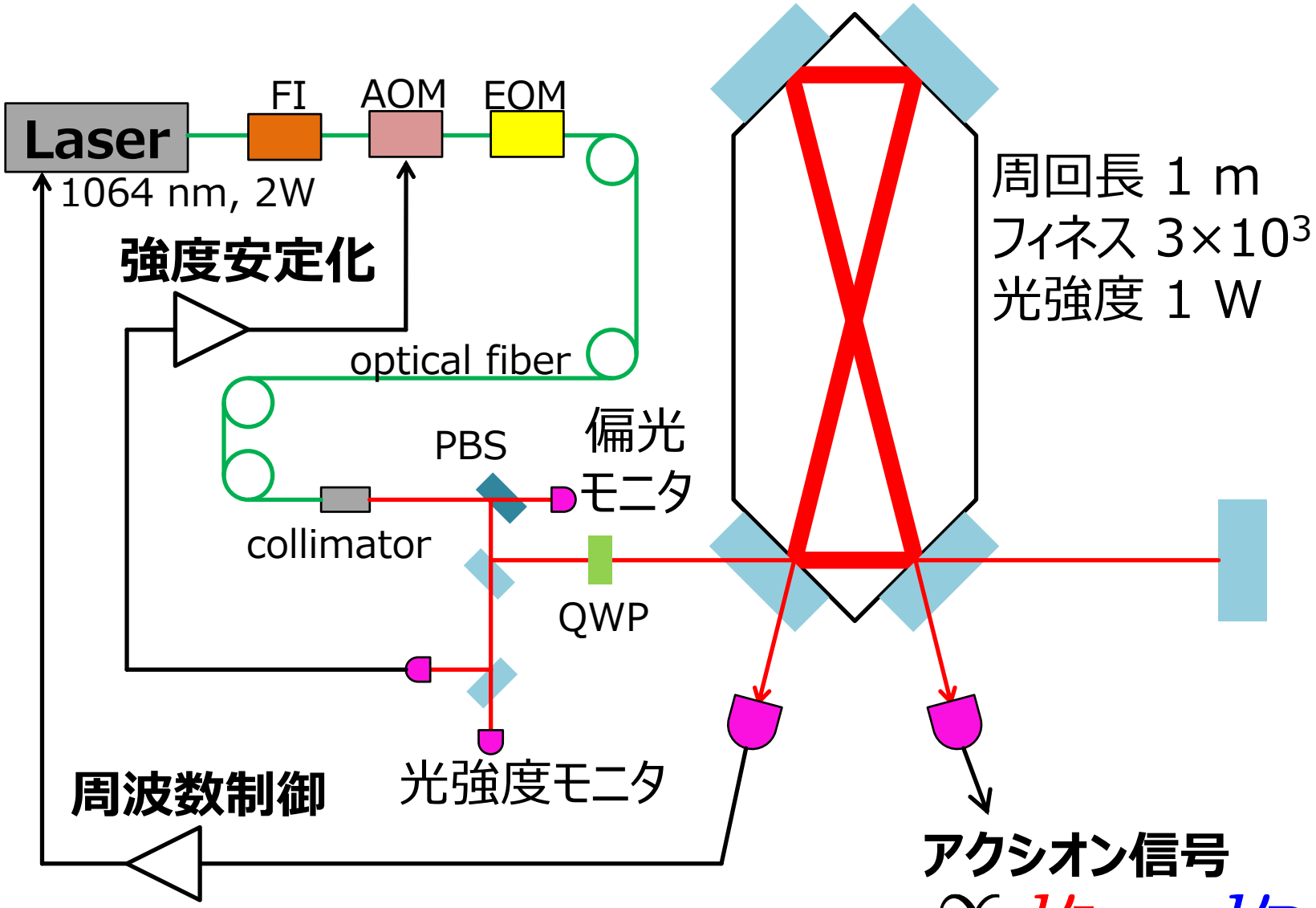


プロトタイプ実験でもCAST超え

Dark matter Axion search with riNg Cavity Experiment

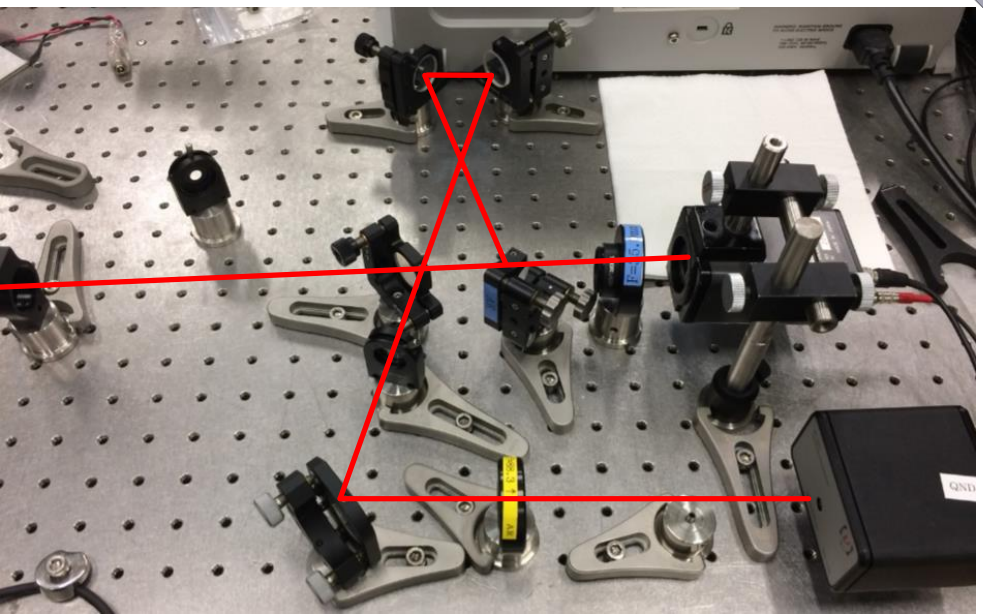


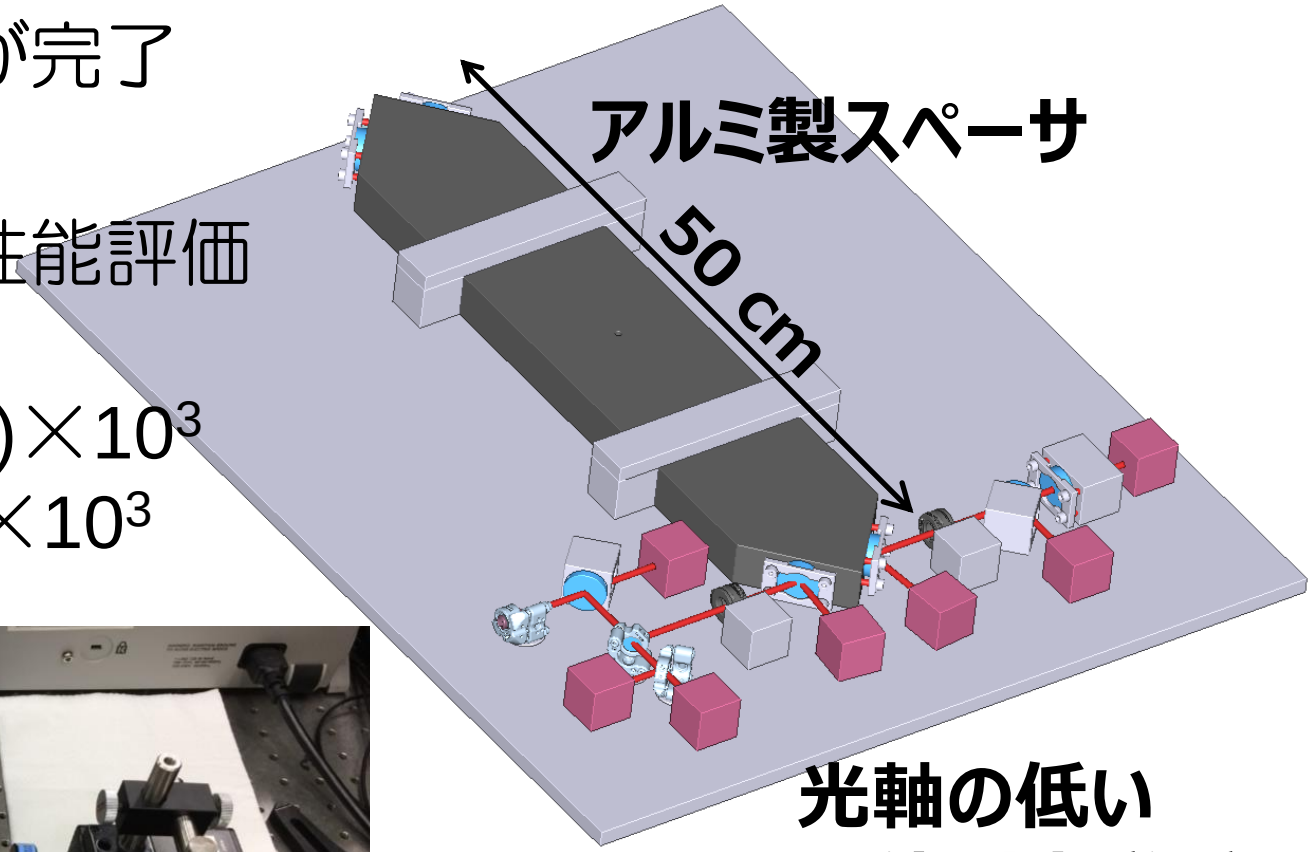
DANCE Act 1の構成



DANCE Act 1の準備状況

- 光学系設計が完了
- 光共振器の性能評価
  - フィネス
    (1.9±0.5)×10^3
    設計値3×10^3





光軸の低い
一体型光学系

今後の展望

- 光共振器とモノリシック光学系を製作し、性能評価
- 2019年中に最初の探査開始予定

- 光共振器を用いた別の手法でのアクシオン探査の可能性
  - 光リング共振器と直線偏光を用いる
    H. Liu+, arXiv:1809.01656
  - 重力波望遠鏡のFabry-Pérot共振器を用いる
    K. Nagano+, arXiv: 1903.02017
    → 14pK203-12 小幡さんの講演

まとめ

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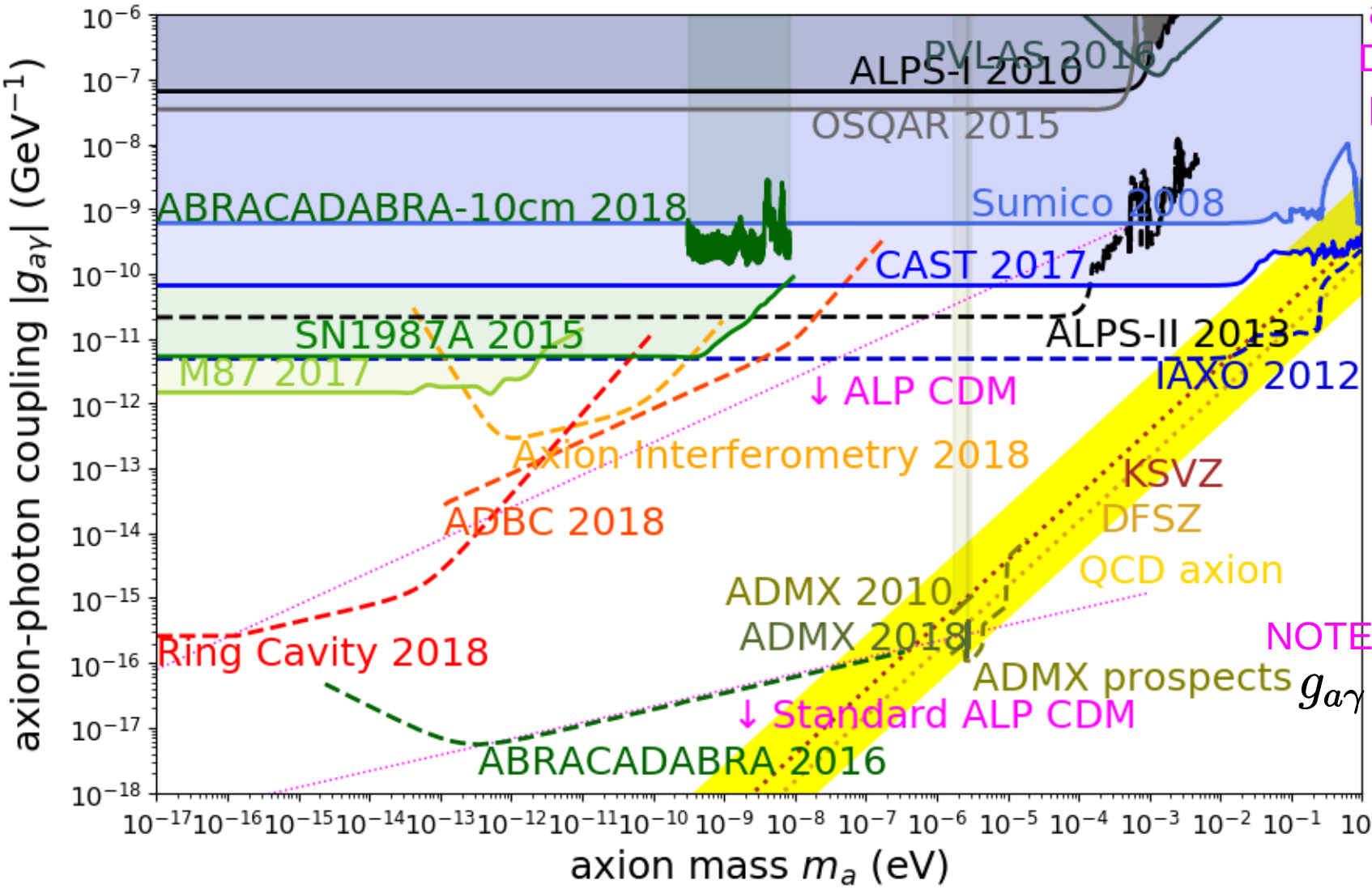
- アクシオン質量 $m_a \lesssim 10^{-10}\,\mathrm{eV}$ で既存の上限値を数桁超える探査が可能

- プロトタイプ実験が進行中
  DANCE Act 1
  CASTの上限値を数倍超える探査
  光学系設計が完了、製作へ
  2019年中に最初の探査開始予定

補助スライド

Bounds on Axion-Photon Coupling

- Extracted experiments to be reviewed here



Comparison of LSW Experiments

- ALPS at DESY
  uses HERA magnets
- OSQAR at CERN
  uses LHC magnets without a cavity
- CROWS and STAX are microwave experiments and can achieve high Q and high power, but L is small

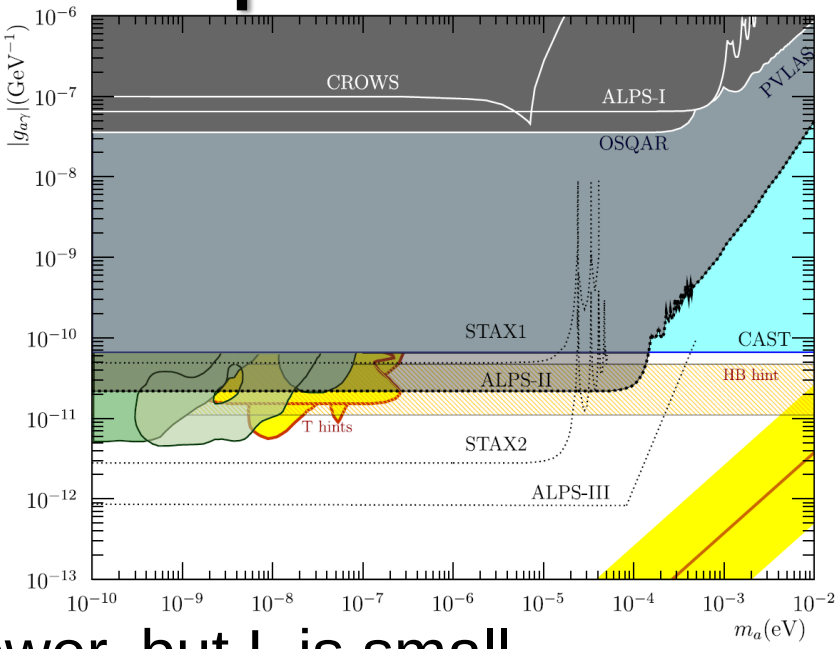


Table 4
List of the most competitive recent LSW results, as well as the prospects for ALPS-II, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a. For microwave LSW (CROWS and STAX) the quality factors Q are listed.

Experiment	Status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$ [GeV^{-1}]
ALPS-I [433]	Completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	Completed	3	0.15	50	10^4	10^4	9.9×10^{-8} [a]
OSQAR [434]	Ongoing	9	14.3	18.5	–	-	3.5×10^{-8}
ALPS-II [436]	In preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	Concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	Concept	15	0.5	10^5	10^4	–	5×10^{-11}
STAX2 [438]	Concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

[a] The limit is better for specific m_a values, see Fig. 6.

Comparison of Helioscopes

- 1G: Brookhaven
- 2G: Sumico at UTokyo
- 3G: CAST at CERN
- 4G (future): IAXO at CERN

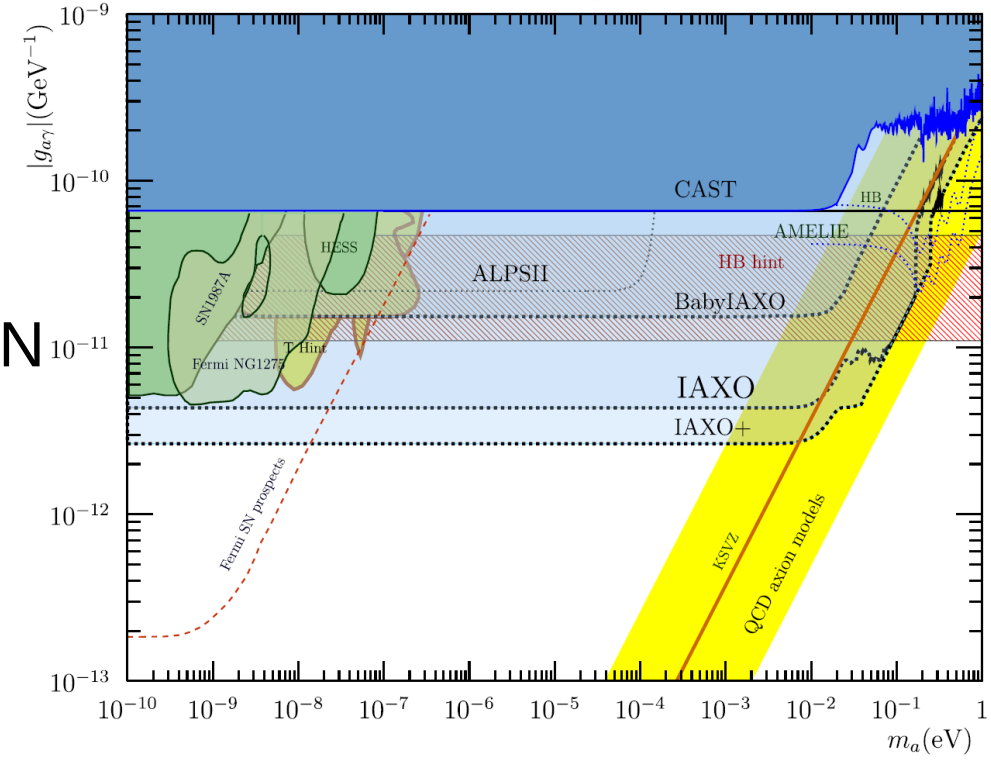


Table 5
List of past and future helioscopes with some key features. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{10} = g_{a\gamma} \times 10^{10}$ GeV for low m_a. The numbers for the TASTE, BabyIAXO and IAXO helioscopes correspond to the design parameters considered in the quoted references.

Experiment	References	Status	B (T)	L (m)	$\mathcal{A}$ (cm^2)	Focusing	g_{10}
Brookhaven	[38]	Past	2.2	1.8	130	No	36
SUMICO	[46,486]	Past	4	2.5	18	No	6
CAST	[481,483,488,491,492]	Ongoing	9	9.3	30	Partially	0.66
TASTE	[499]	Concept	3.5	12	2.8×10^3	Yes	0.2
BabyIAXO	[500]	In design	~2.5	10	2.8×10^3	Yes	0.15
IAXO	[487,501]	In design	~2.5	22	2.3×10^4	Yes	0.04

Haloscope Experiments

- Many experiments with different resonant frequency
- ADMX at UWash is leading experiment
- Lower frequency is tough since it requires larger cavity with larger magnet
- Higher frequency is tough since it requires smaller cavity with smaller signal

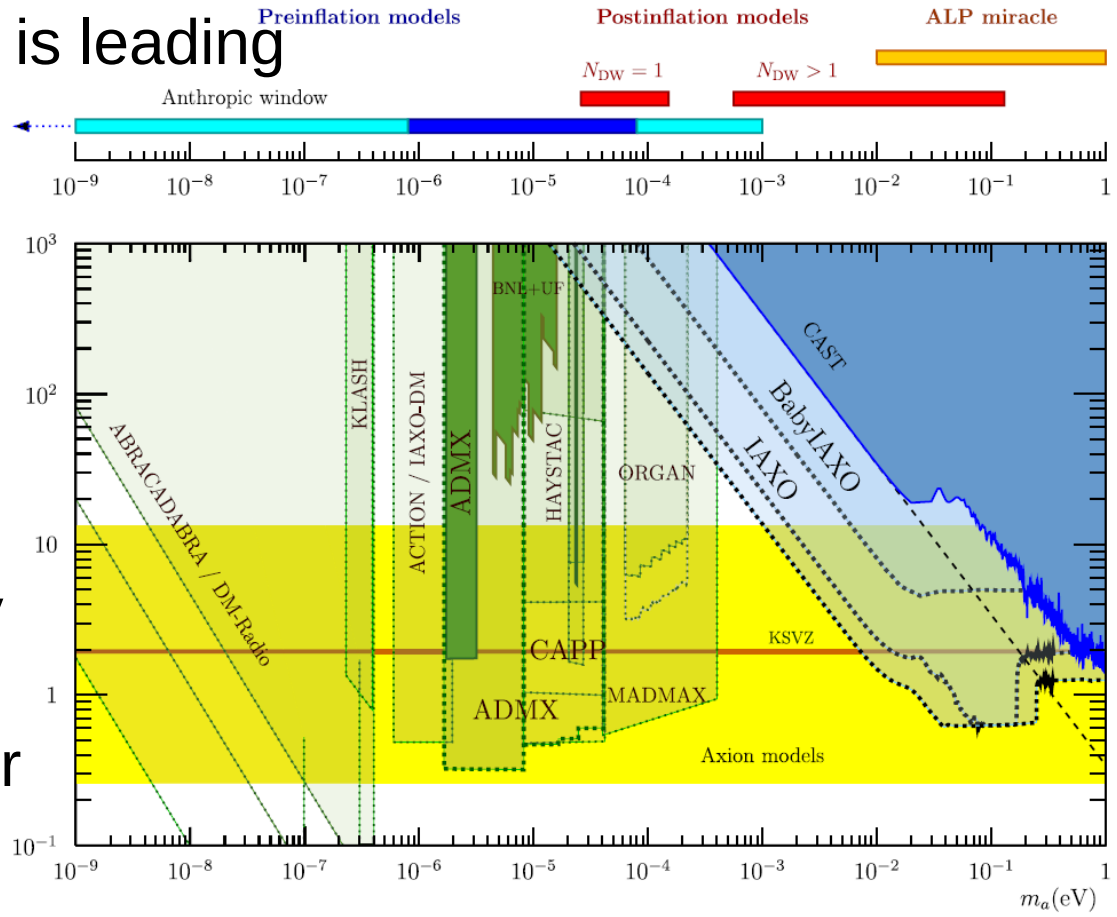


Fig. 18. Exclusion regions from haloscope searches (in green) expressed in terms of $|C_{a\gamma}|\sqrt{\tilde{\varrho}_a}$. We display $C_{a\gamma}$ in the sense of $C_{a\gamma} = g_{a\gamma} f_A (2\pi/\alpha)$ from (2.42) by rescaling sensitivities on $g_{a\gamma}$ by the known relation between f_A, m_A. Some of the regions tentatively within reach of future experiments are indicated as semi-transparent green areas. Some of those regions are dependent, to different extents, on successful completion of R&D on novel detection concepts, as explained in the text. Regions explored and projected by helioscopes are also shown (in blue). As usual the yellow band and orange line represent the QCD axion models and the benchmark KSVZ model respectively. The sketch on top shows the mass ranges for which total DM density can be obtained in different models, as explained in Section 3.1.1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Low Frequency Resonators with LC

- Detect oscillating magnetic field generated by dark matter axions in an external homogeneous magnetic field

$$\mathbf{B}_a = \frac{1}{i\omega}\nabla \times \mathbf{E}_a = -g_{a\gamma}\mathbf{v} \times \mathbf{B}_e a$$

axion DM velocity (10^{-3})

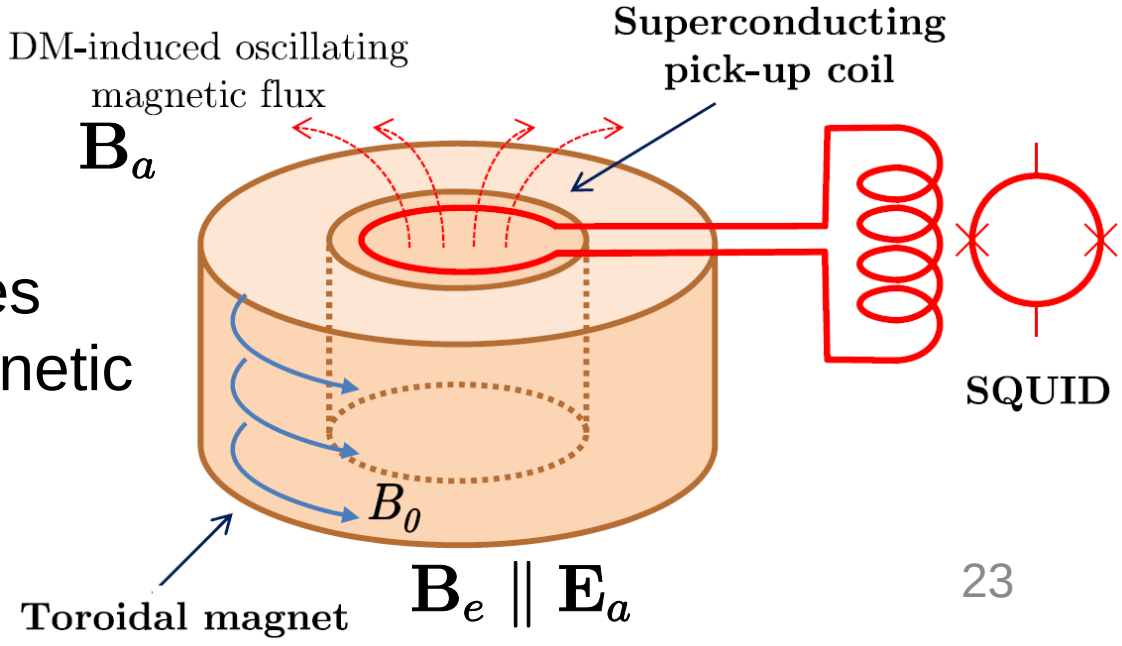
external magnetic field

axion field

$$a(t) = a_0 \cos\left(m_a t + \delta_\tau(t)\right)$$

- Also assumes ALP density = dark matter density

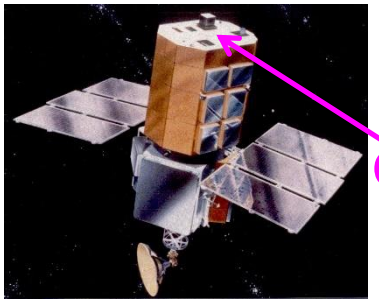
- ABRACADABRA experiment at MIT
  toroidal magnet gives no background magnetic field at the center



SN1987A (2015)

JCAP **02**, 006 (2015)

- Absence of gamma-ray signal from SN1987A
  - ALPs would be emitted from core-collapse supernova via Primakoff process
  - ALPs eventually convert into gamma-ray in the magnetic field of Milky Way (~ μG ~ 0.1 nT over ~ kpc)
- data from GRS (Gamma Ray Spectrometer) of SMM (Solar Maximum Mission) satellite coincidence with neutrino signal was used
- Better limit possible by Fermi-LAT observation
- Dependent on supernova models and Milky Way magnetic field



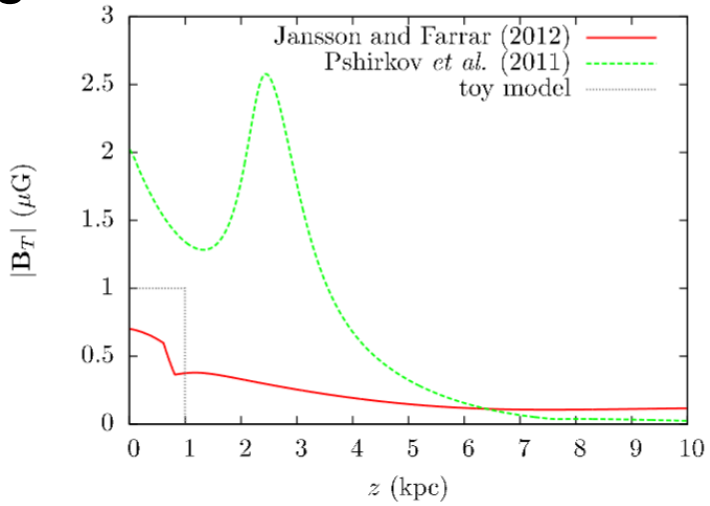


Figure 8. Norm of the transverse Galactic magnetic field as a function of the distance in the direction of SN1987A in various models.

M87 (2017)

JCAP **12**, 036 (2017)

- Absence of substantial irregularities in the X-ray power law spectrum from M87 galaxy in Virgo cluster
  - close (16.4 Mpc) and hosts SMBH bright in X-ray
  - X-ray photon to ALPs conversion under magnetic field
  - magnetic field in Virgo (~35-40 μG) modeled from Faraday rotation measurements
    (magnetized plasma is birefringent and induces wavelength-dependent rotation of polarization of photons)
  - photon-ALP conversion probability is energy dependent and thus X-ray spectrum would change
- data from Chandra was used
- Dependent on Virgo magnetic field

Many Other Astrophysical Limits

Hydra A (58.3 Mpc) with Chandra (X-ray)
ApJ **772**, 44 (2013)

PKS 2155-304 (z=0.116)
with H.E.S.S. (γ-ray)
PRD **88**, 102003 (2013)

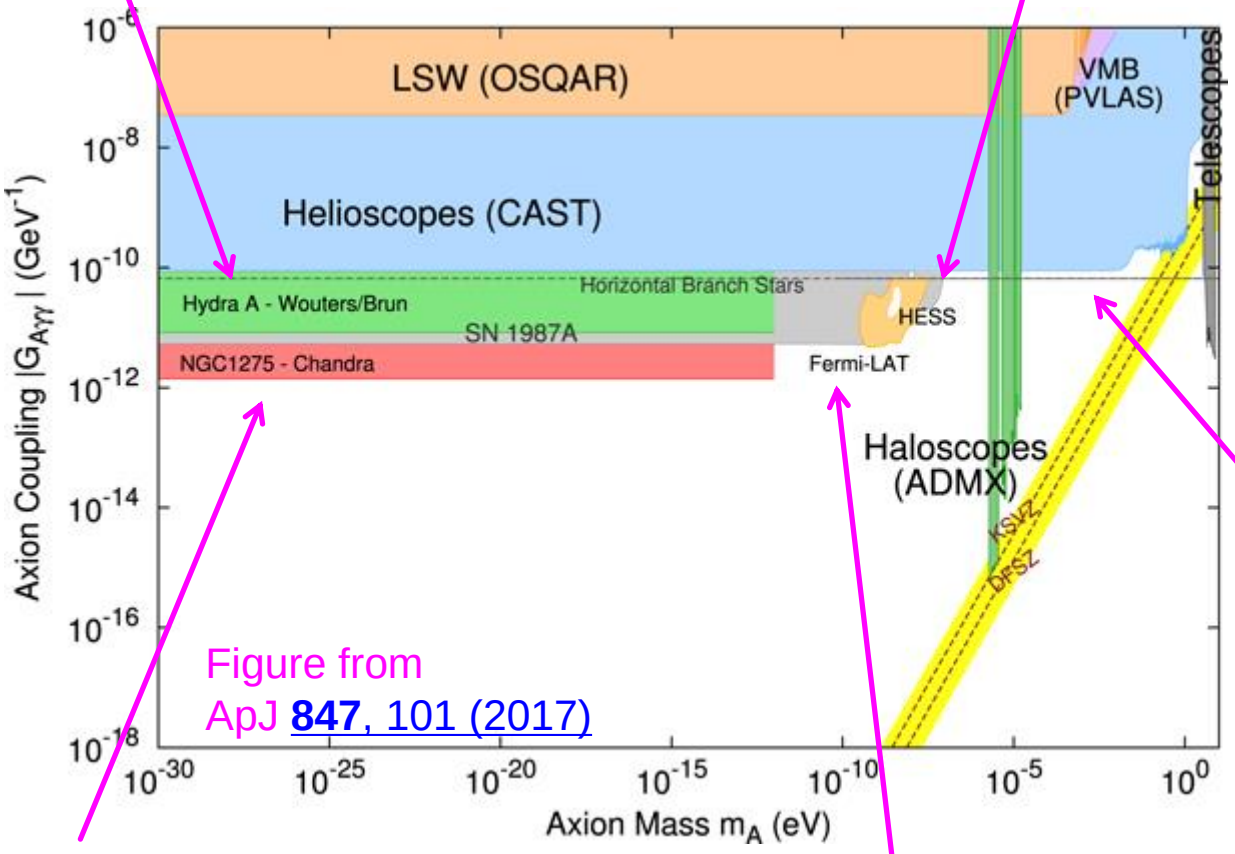
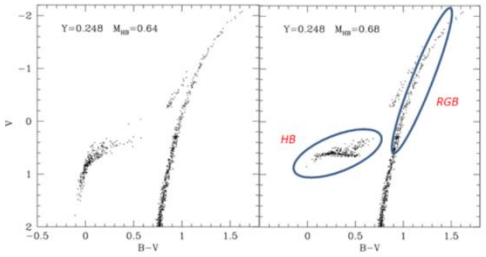


Figure from
ApJ **847**, 101 (2017)



Ratio of horizontal branch stars to red giants in globular clusters
(HB stars reduce with axion-photon coupling)
PRL **113**, 191302 (2014)

NGC1275 with Chandra (X-ray)
ApJ **847**, 101 (2017)

NGC1275 (68.2 Mpc) with Fermi-LAT (γ-ray)
PRL **116**, 161101 (2016)

Interferometric Searches

- Light speed difference between two circular polarizations

$$c_\pm = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

Can be derived from Maxwell-Axion equations

- If local ALP density = local DM density, $\varrho_a = \frac{m_a^2 a_0^2}{2} = \varrho$

$$\delta c \equiv |c_+ - c_-|$$

$$\simeq 3 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\,\mathrm{GeV}}\right) \sin(m_a t + \delta_\tau)$$

local DM density (0.3 GeV/cm^3)

phase which changes with time scale

- Can be measured with laser interferometers and cavities
- Can be measured without magnets!

$$\tau = \frac{\lambda}{v} = \frac{2\pi}{m_a v^2}$$

de Broglie wavelength

axion velocity (assume dark matter velocity 10^{-3})

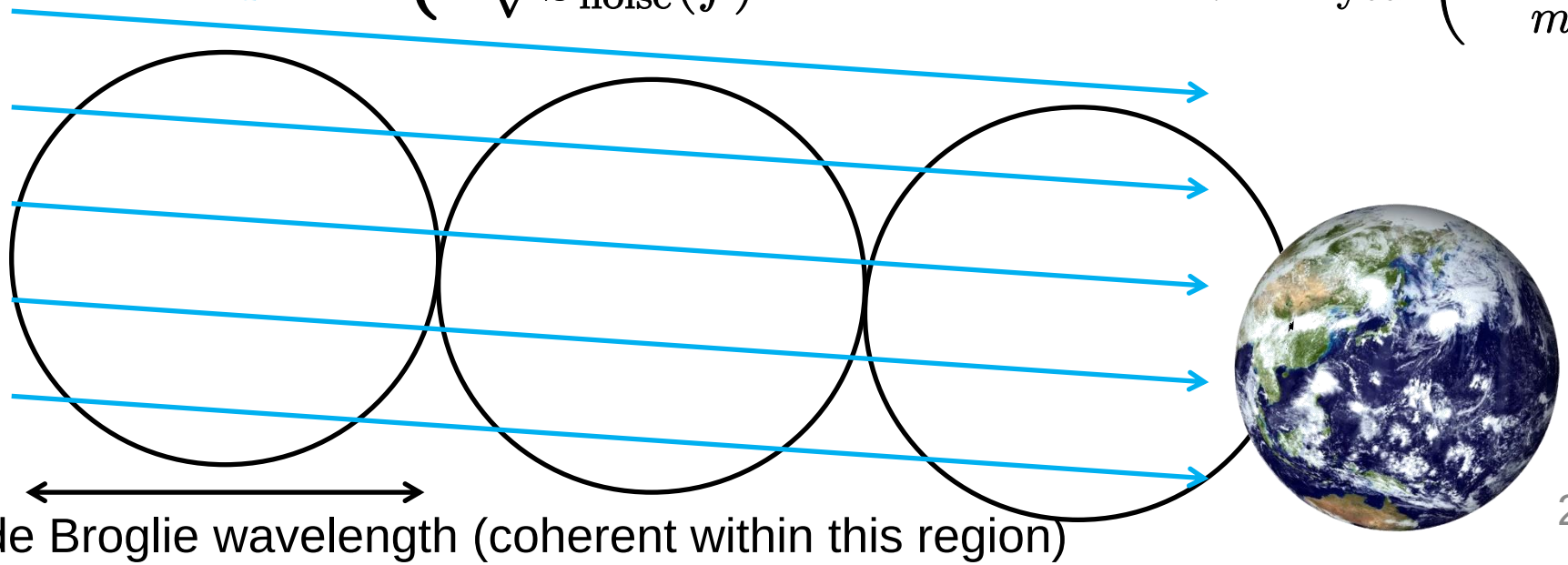
- Also assumes ALP = dark matter

Coherent Time Scale

- SNR grows with √Tobs if integration time is shorter than coherent time scale
- SNR grows with $(\mathrm{Tobs})^{1/4}$ if integration time is longer

$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \lesssim \tau) \\ \dfrac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

$$\tau \simeq 1\ \mathrm{year}\left(\frac{10^{-16}\ \mathrm{eV}}{m_a}\right)$$



DeRocco + Hook (2018)

PRD **98**, 035021 (2018)

- Linear cavity with quarter wave plates inside
  mirror reflection flips left-handed to right-handed
- 40 m, finesse 10^6, intra cavity power 1 MW, 30 days integration

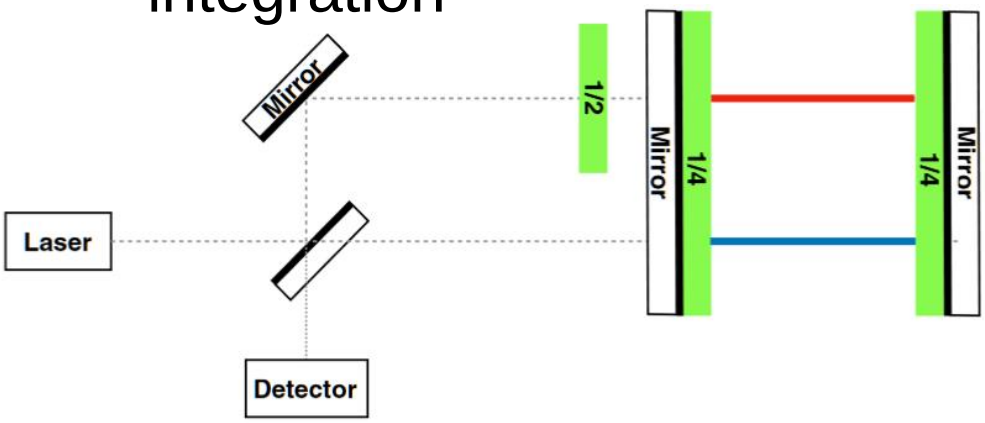


FIG. 3. A diagram of our proposed axion interferometer where the same mirrors are used to form both cavities. The dotted line is linearly polarized light, the red line is ↺ polarized light and the blue line is ↻ polarized light. Two quarter wave plates and a half wave plate are used to maintain the circular polarization of the light. This setup cancels the radiation pressure noise associated with the displacement of the mirror, leaving only noise due to radiation torque. Torque noise in this setup can be several orders of magnitude smaller than the radiation pressure noise experienced by the setup in Fig. 2.

radiation pressure torque noise at low freq.

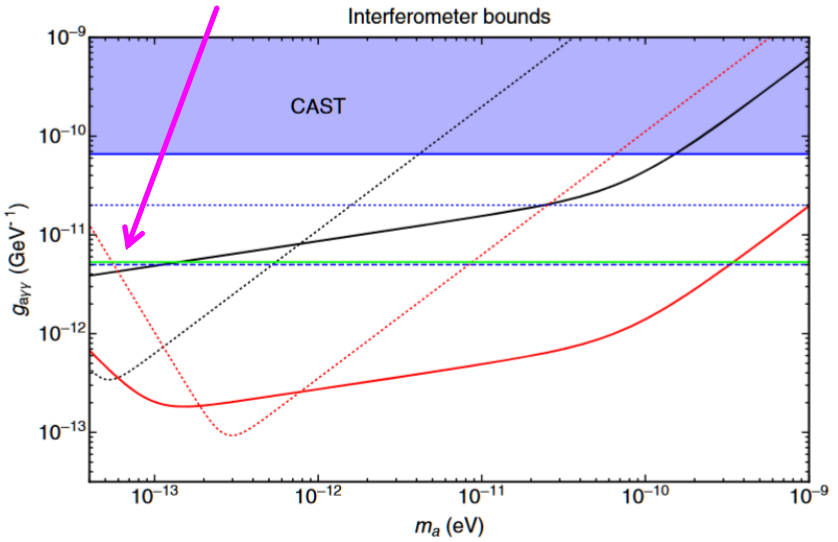
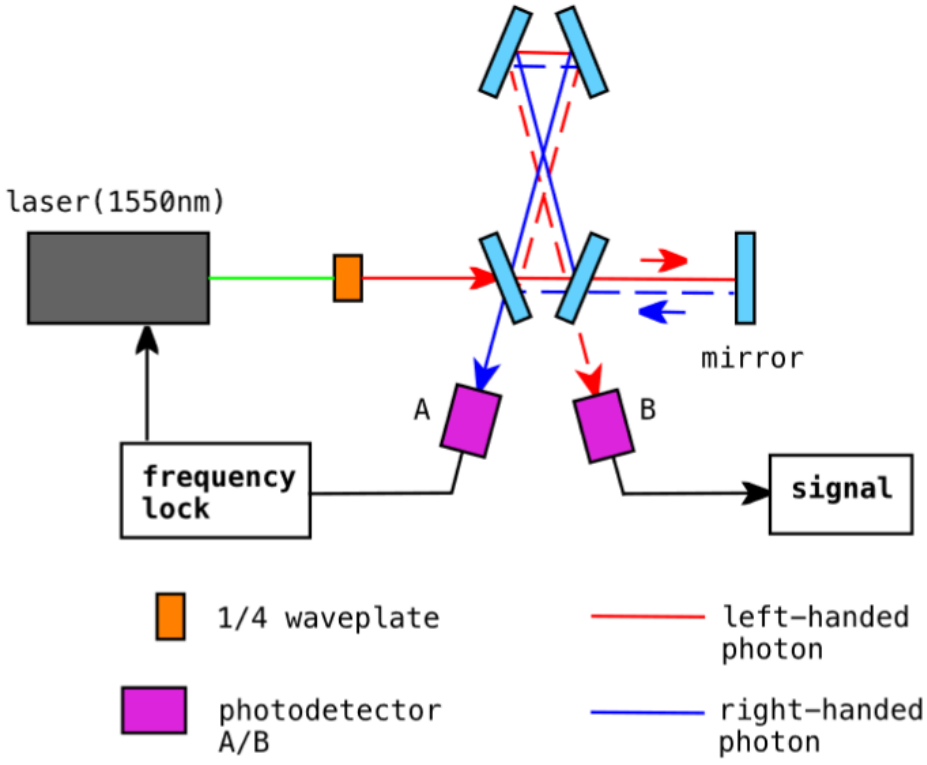


FIG. 5. Same as Fig. 4 but using the configuration shown in Fig. 3. Radiation pressure noise is cancelled leaving only radiation torque noise. We take the beams to be separated by 1 cm and the mirror to be circular and 10 cm in diameter.

Obata + Fujita + Michimura (2018)

PRL **121**, 161301 (2018)

- DARC: Dark matter Axion search with a Ring Cavity (tentative)
- Bow-tie configuration to keep polarization modes
- Double-pass for common mode rejection



research highlights

OPTICAL METROLOGY

Axion sensor

Phys. Rev. Lett. **121**, 161301 (2018)

A current challenge in modern physics is to design experiments for ascertaining the existence of the axion — a proposed dark matter particle found in theories beyond the standard model of particle physics. Now, Ippei Obata and co-workers from the University of Tokyo and Kyoto University, Japan, have investigated the use of an optical ring cavity that makes it possible to search for a tiny difference in the phase velocity of left- and right-handed circularly polarized photons that, in principle, is induced by coupling of photons to axion dark matter. The team used a double-pass bowtie cavity to realize a null experiment with strong rejection from environmental disturbances. Analysis of their set-up suggests that the sensitivity level of the photon–axion coupling constant was estimated to be 3×10^{-16} GeV^{-1} for a low-mass range below 10^{-16} eV, which is beyond the current bound by several orders of magnitude. *NH*

https://doi.org/10.1038/s41566-018-0321-2

Nature Photonics **12**, 719 (2018)

Obata + Fujita + Michimura (2018)

- 10 m, finesse 10^6,
  100 W input,
  1 year integration
  - this means 30 MW intra cavity power

- Note that mirror complex reflectivity difference between p and s polarizations from nonzero incident angle was not considered (incident angle tuning necessary)

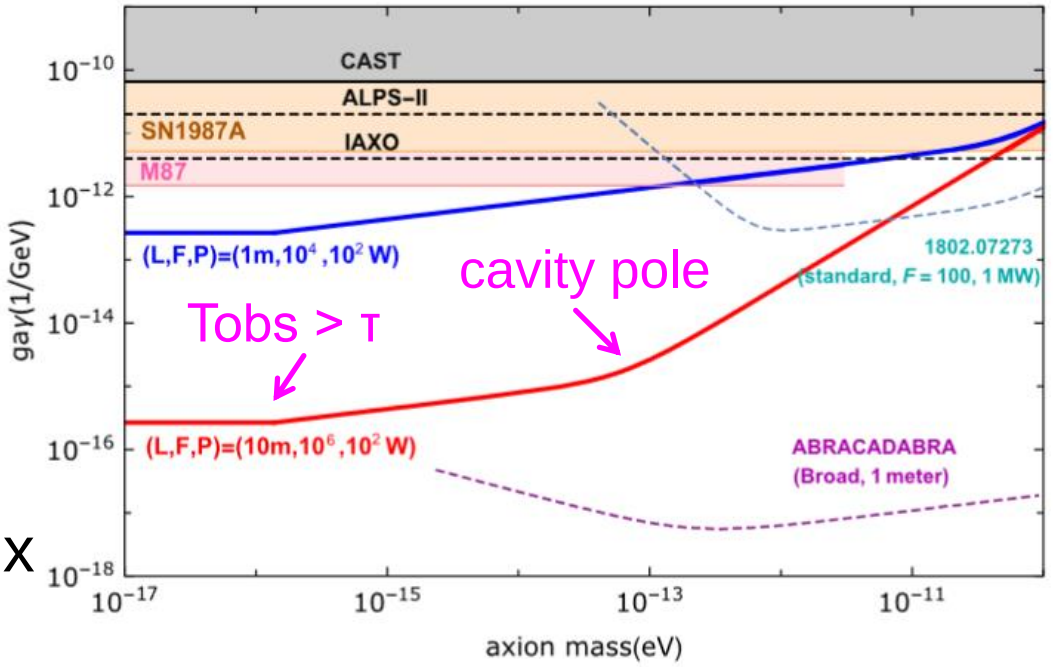
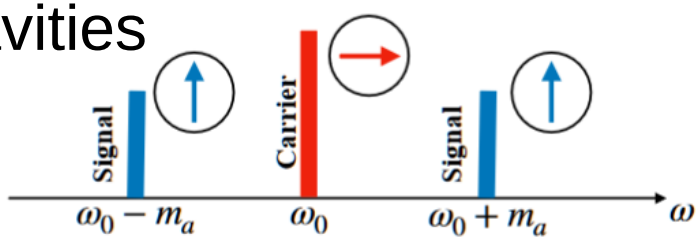


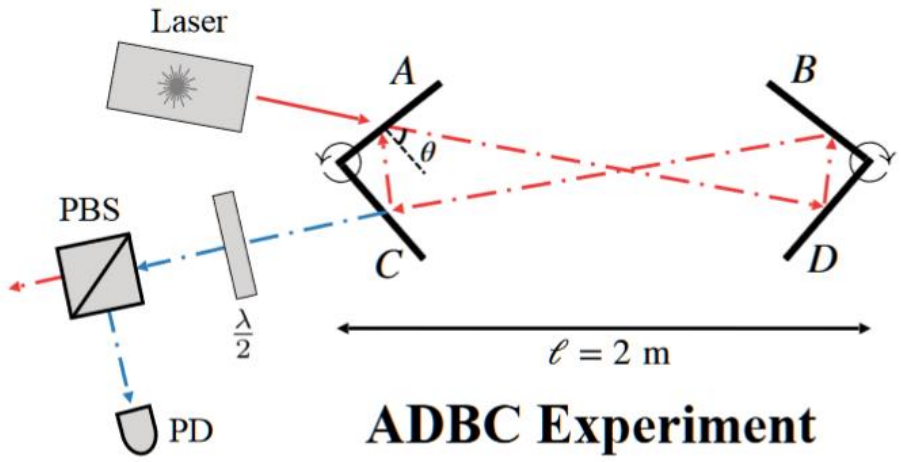
FIG. 2. The sensitivity curves for the axion-photon coupling constant $g_{a\gamma}$ with respect to the axion mass m. The solid blue (red) line shows the sensitivity of our experiment $(L, F, P) = (1(10)\ \mathrm{m}, 10^4(10^6), 10^2(10^2)\ \mathrm{W})$. The gray band represents the current limit from CAST [5]. The dashed black lines are the prospected limits of IAXO [6] and ALPS-II [7] missions. The dashed turquoise blue and purple lines show the proposed reaches of axion optical interferometer suggested in [10] and ABRACADABRA magnetometer [12]. The orange and pink bands denote the astrophysical constraints from the cosmic ray observations of SN1987A [15] and radio galaxy M87 [17].

ADBC by MIT Group (2018)

arXiv:1809.01656

- Axion Detection with Birefringent Cavities
- Use linear polarization and detect sidebands of other polarization
- Tune incident angle for resonant detection at high freqs.
- 40 m, finesse 2e5 for → (3e3 for ↑), intra cavity power 1 MW, 30 days integration in total





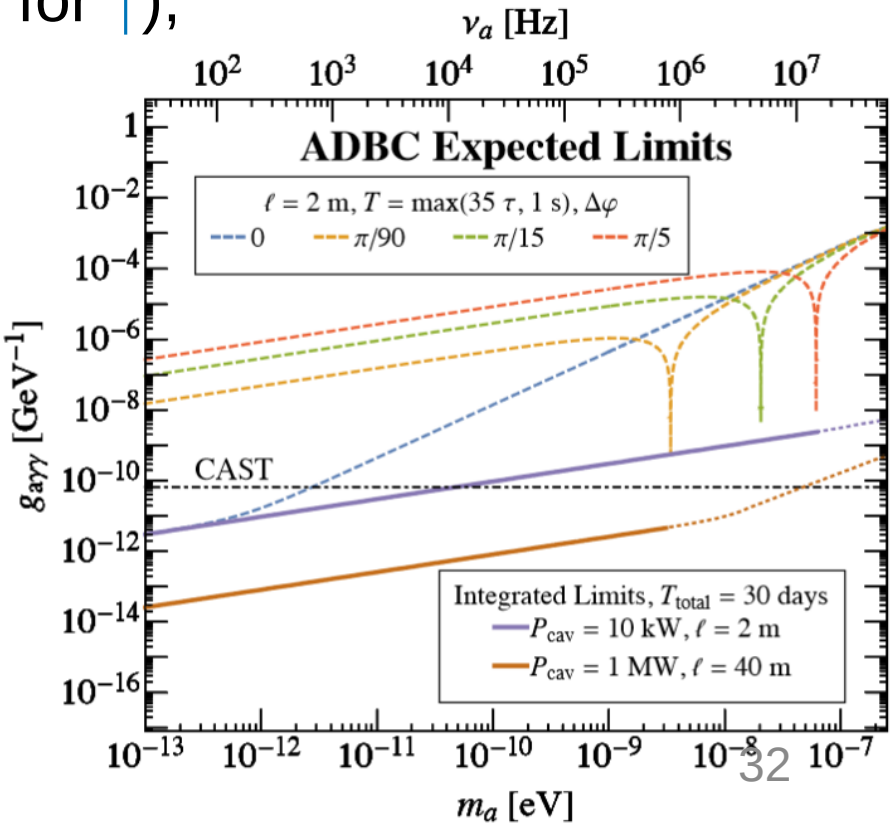
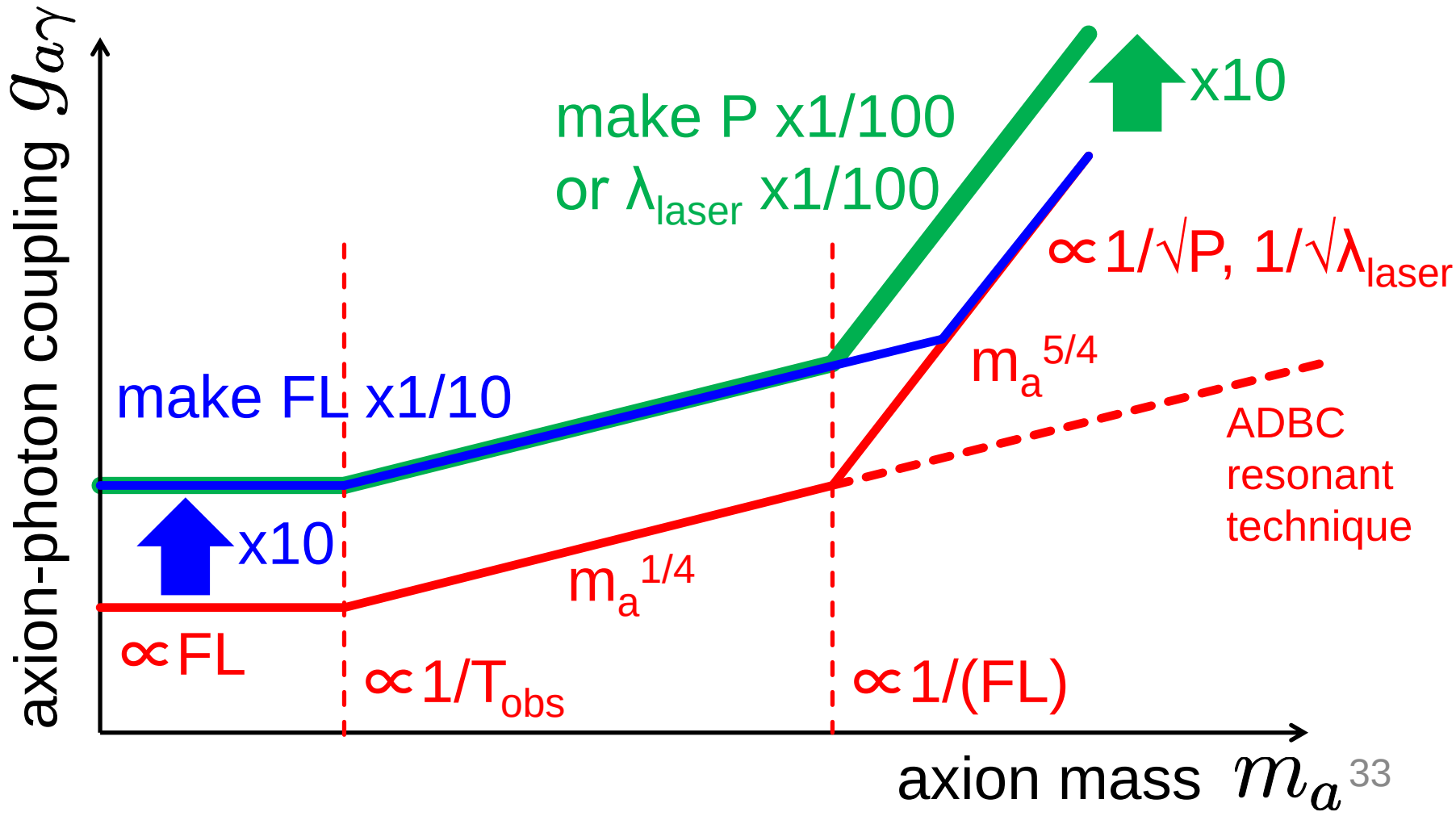


FIG. 2: Schematic of the ADBC experiment. The red optical

Sensitivity Design

- Brute force necessary, you cannot win for free