レーザー干渉計による アクシオン暗黒物質の探索

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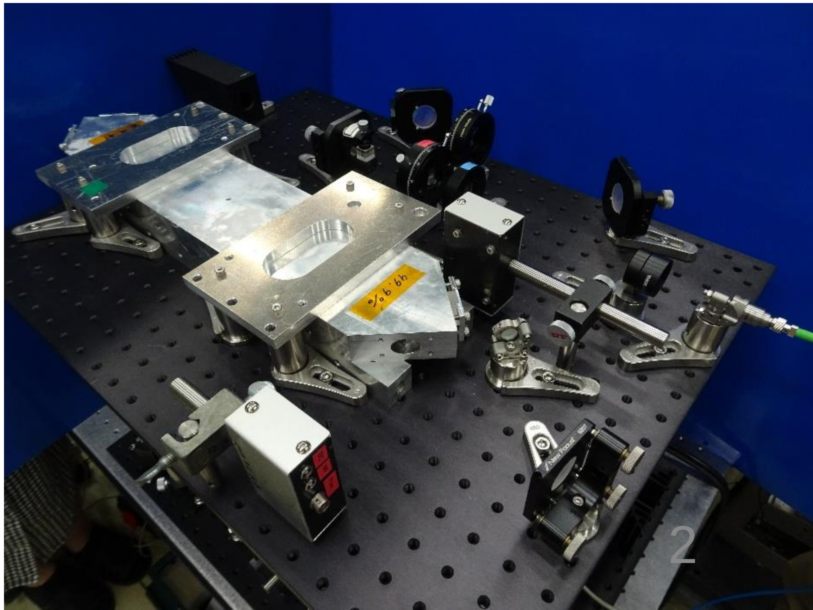
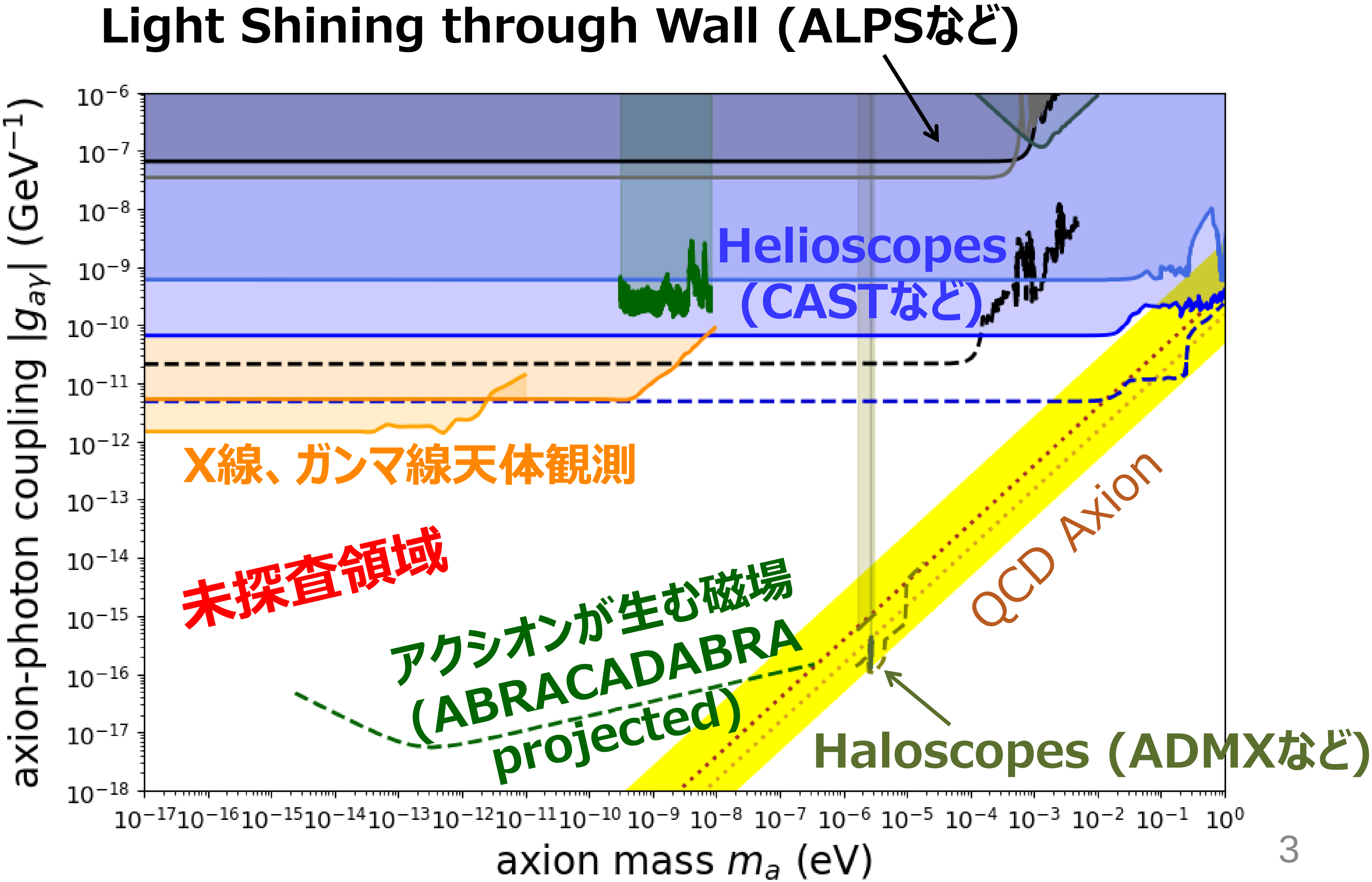
概要

- 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
- レーザー干渉計型重力波検出器でも探査可能
  K. Nagano+, arXiv:1903.02017



アクシオン-光子相互作用



円偏光の速度差に着目

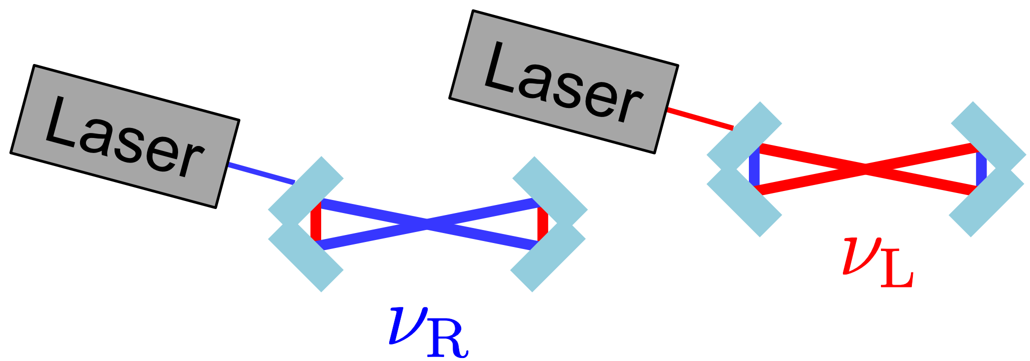
- アクシオン-光子相互作用($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$)により
  左円偏光と右円偏光に速度差が生じる

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

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

$$\frac{\delta c}{c} = \frac{\nu_L - \nu_R}{\nu}$$

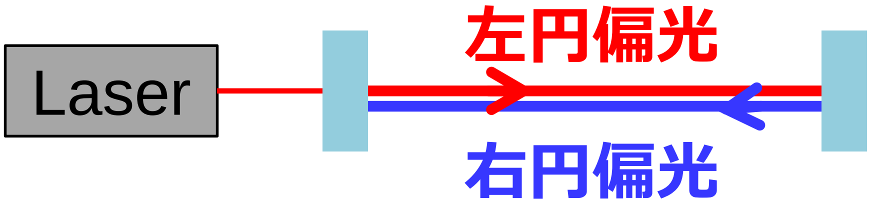


- 振動源となりうる強磁場を用いずに探査することが可能

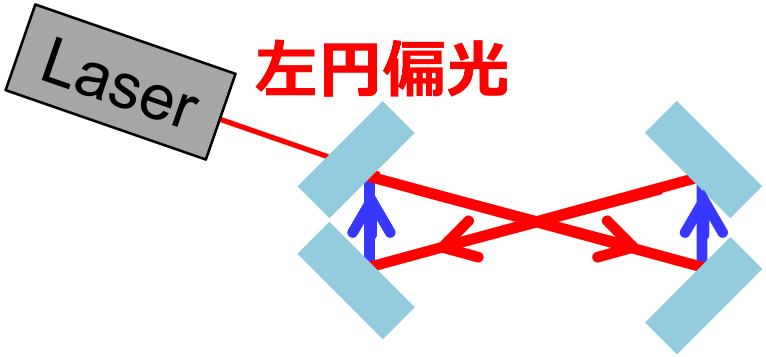
我々のアイディア

- 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

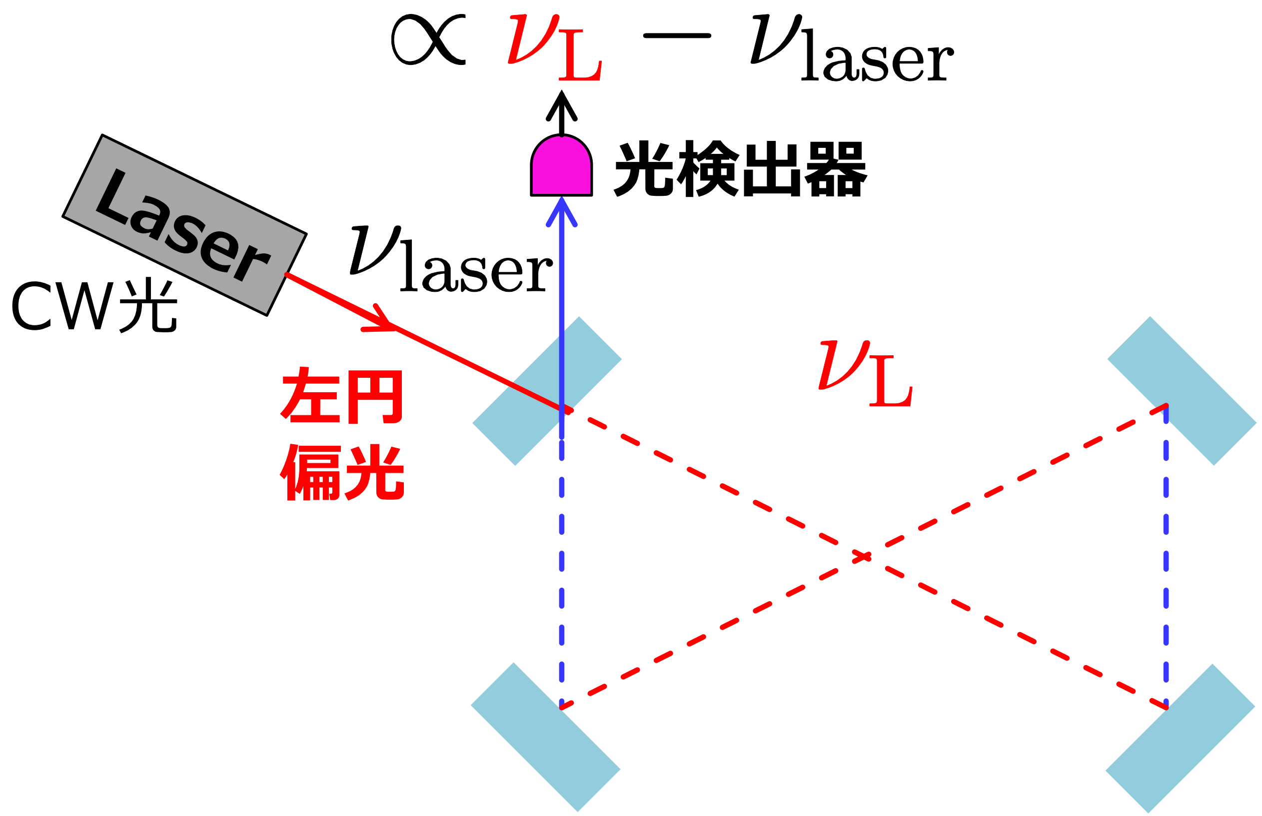


- ダブルパス構成を用いる
  透過光を打ち返すことで同じ共振器を逆回りに使って円偏光の間の共振周波数差をヌル測定

Y. Michimura+, PRL 110, 200401 (2013)

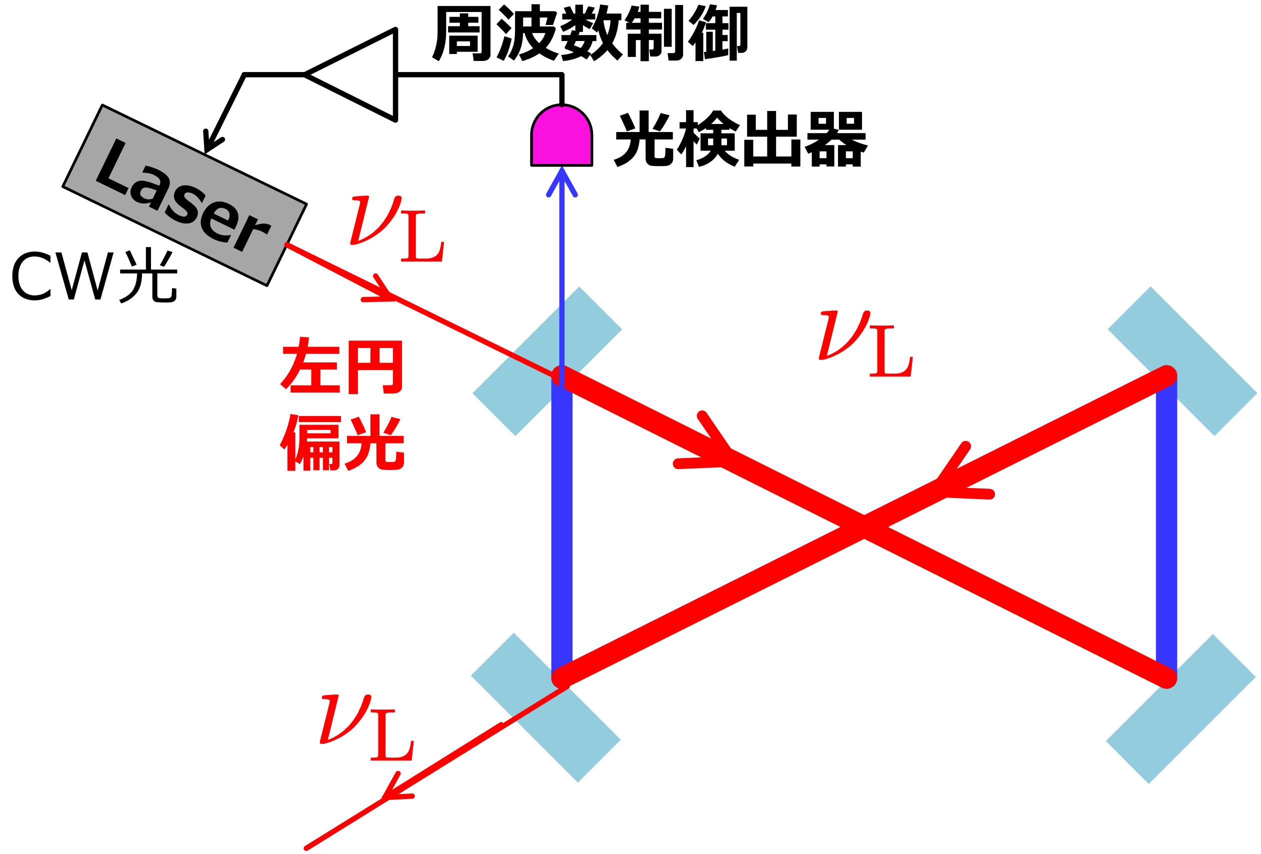
ボウタイ共振器とダブルパス構成

- 左円偏光を共振器に入射



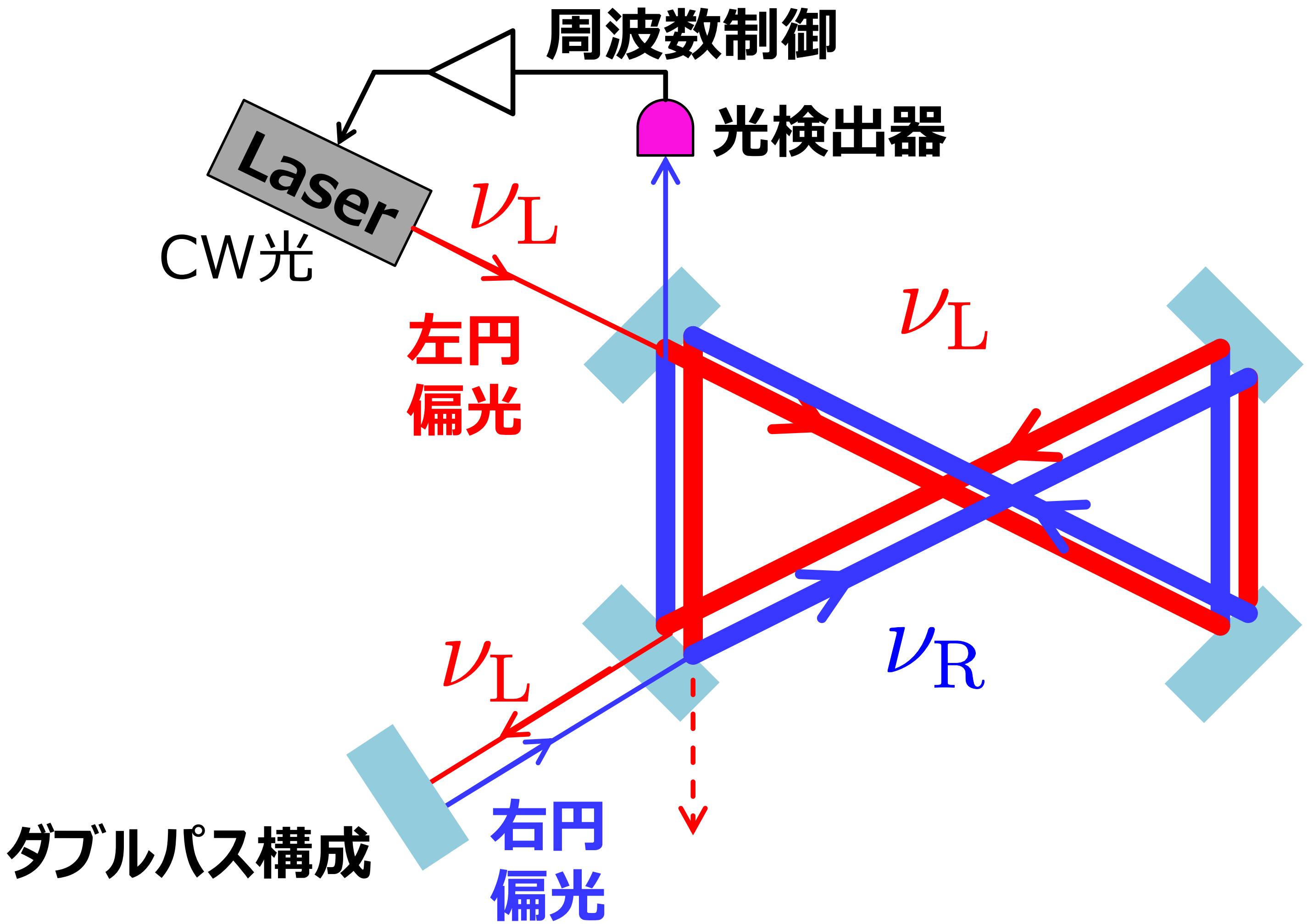
ボウタイ共振器とダブルパス構成

- レーザーの周波数を左円偏光の共振周波数(ν_L)に制御



ボウタイ共振器とダブルパス構成

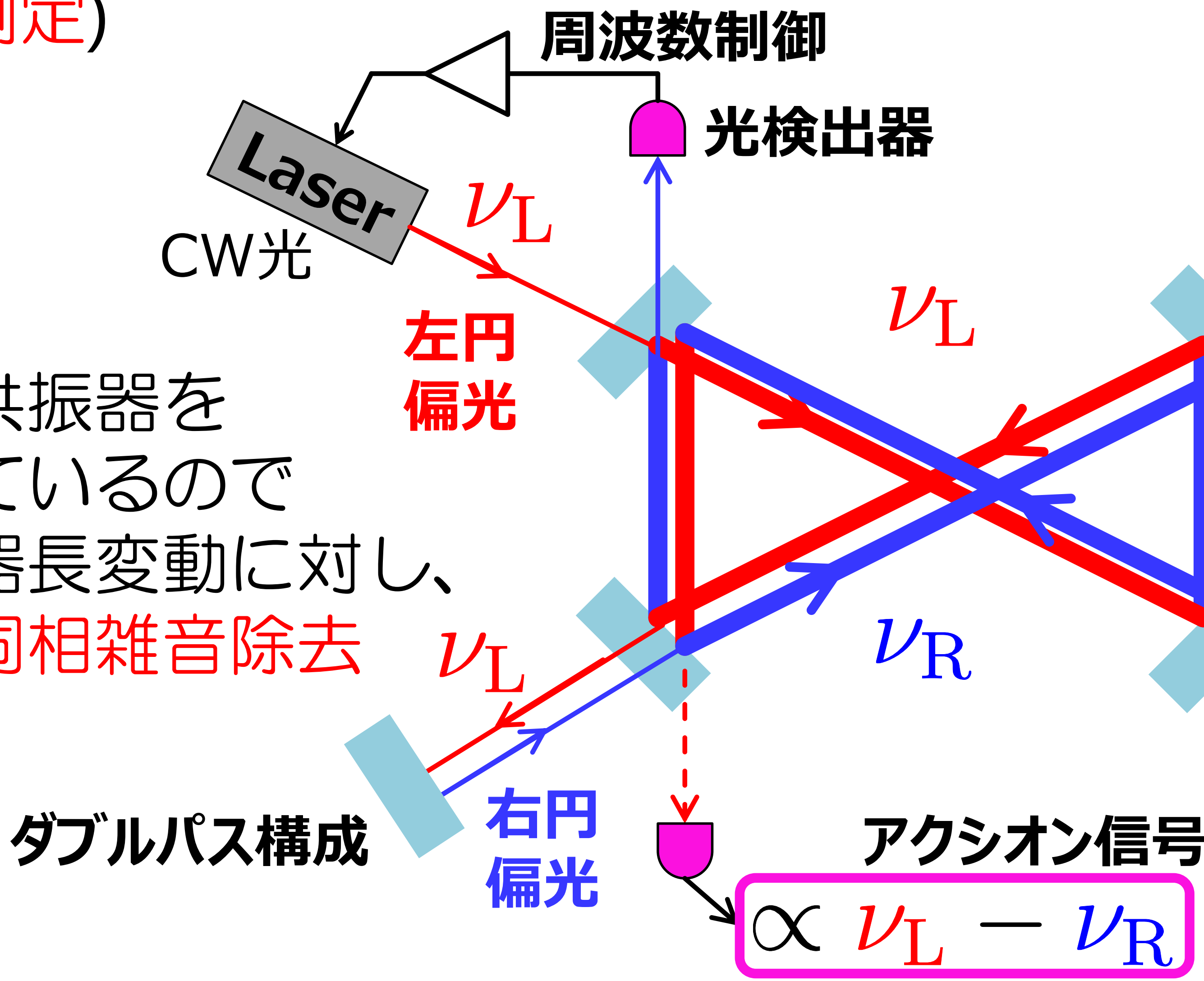
- 透過光を打ち返す(右円偏光を逆回りに入射)



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器長変動に対し、高い同相雑音除去



この構成の感度

- **DANCE**
  Dark matter Axion search with riNg Cavity Experiment
- 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

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

input laser power

cavity length

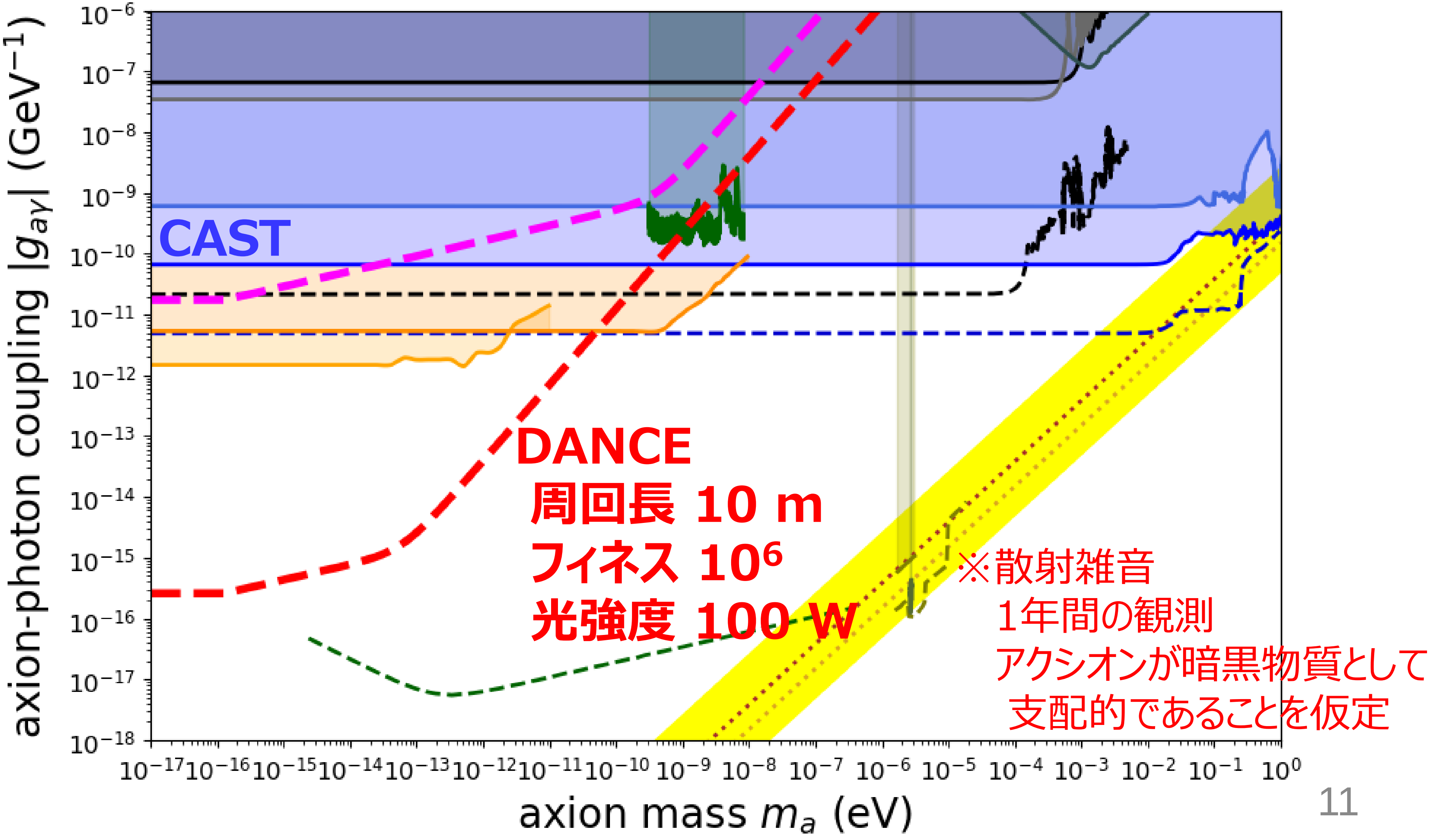
finesse

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

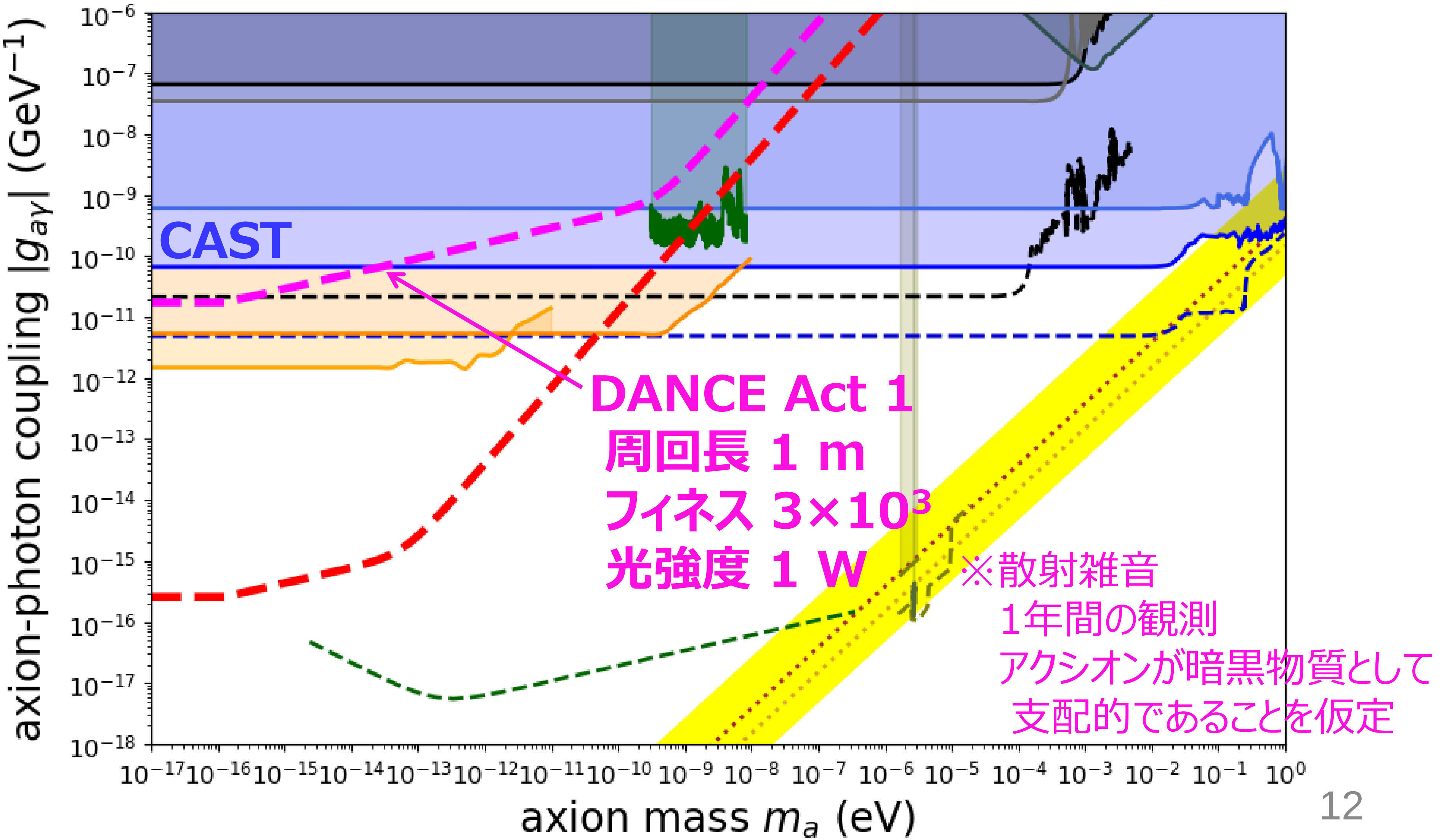
未探査領域を探査可能

Dark matter Axion search with riNg Cavity Experiment

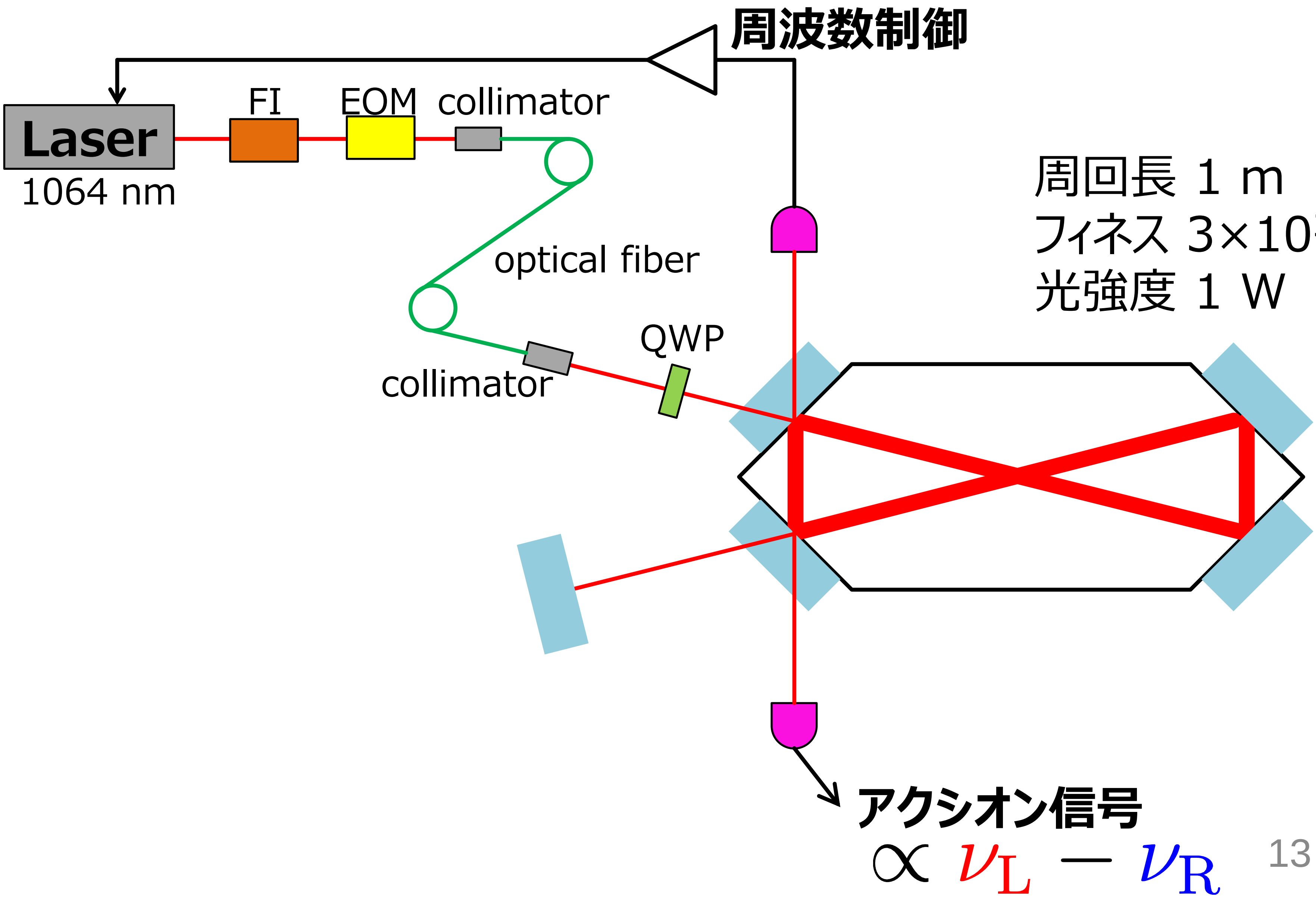


プロトタイプ実験でもCAST超え

Dark matter Axion search with riNg Cavity Experiment



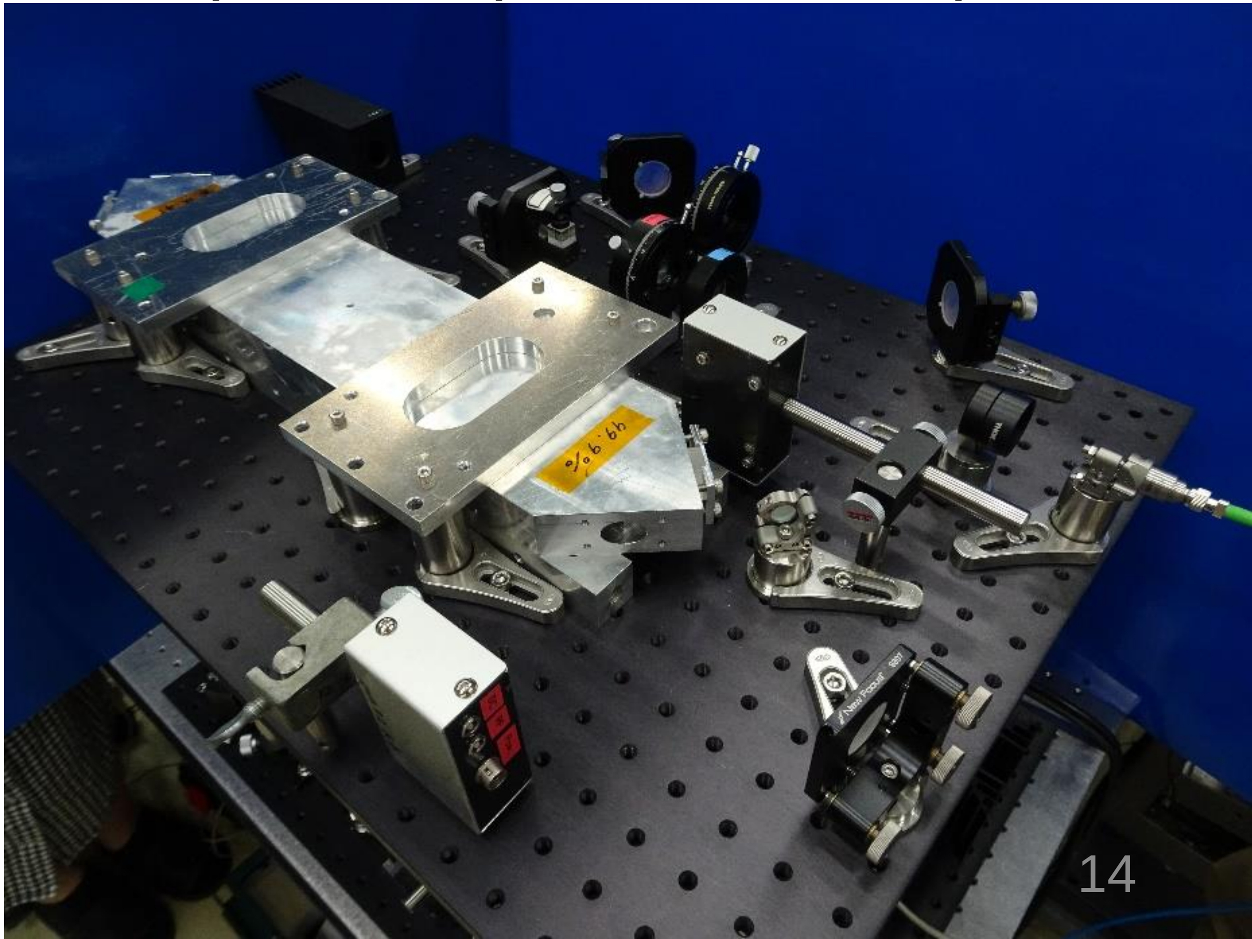
DANCE Act 1の構成



周回長 1 m
フィネス 3×10^3
光強度 1 W

DANCE Act 1の実施状況

- 光学系の組み立て完了
- 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)
- 2019年秋までに最初のデータ



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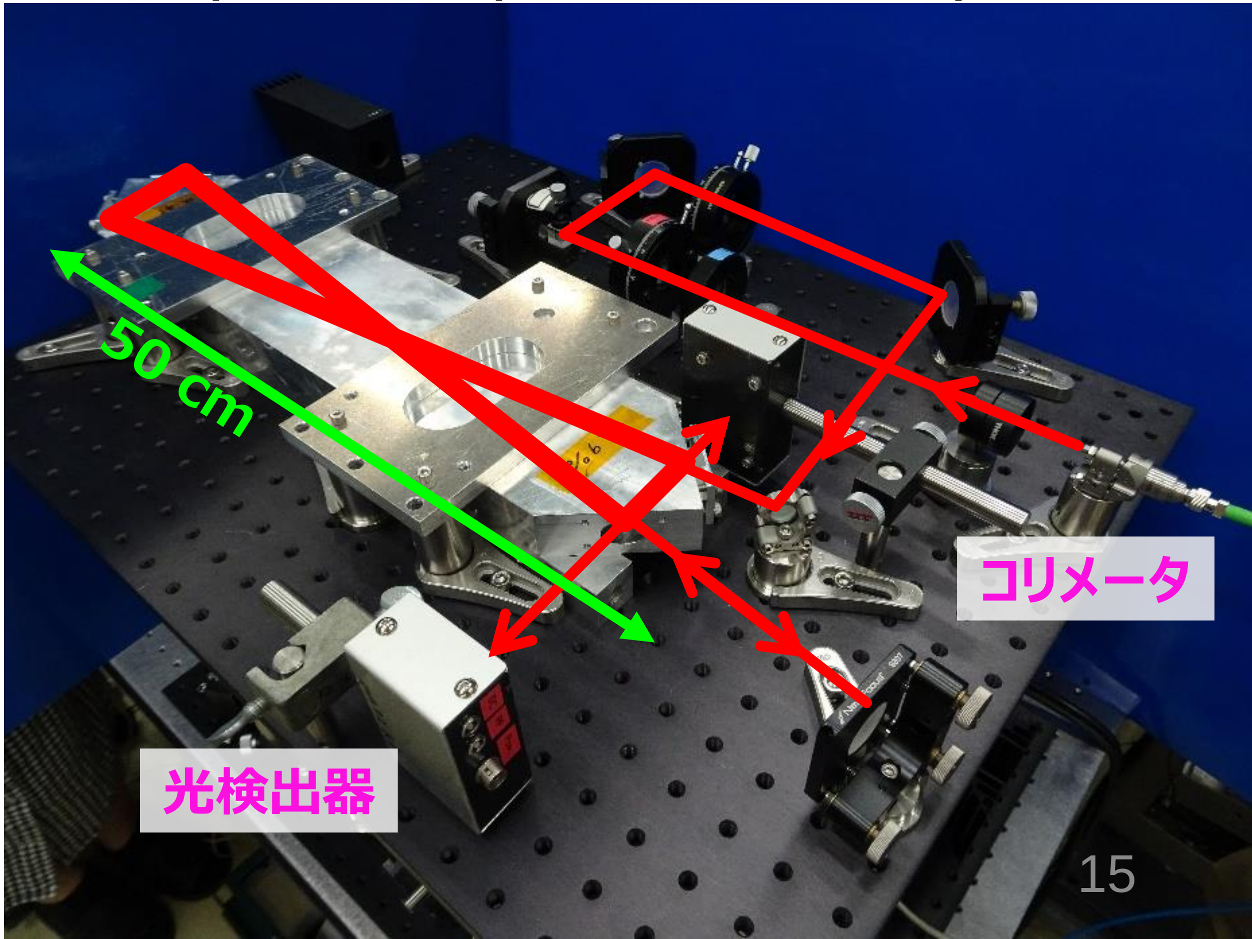
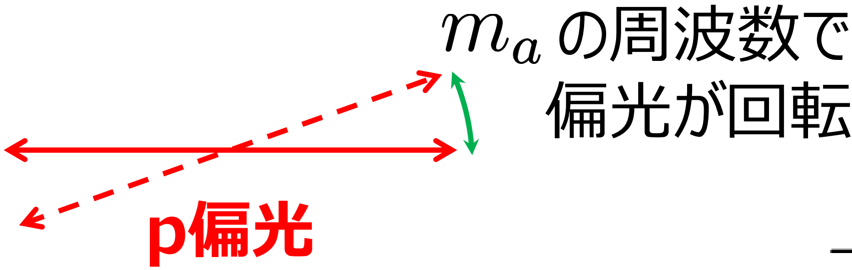
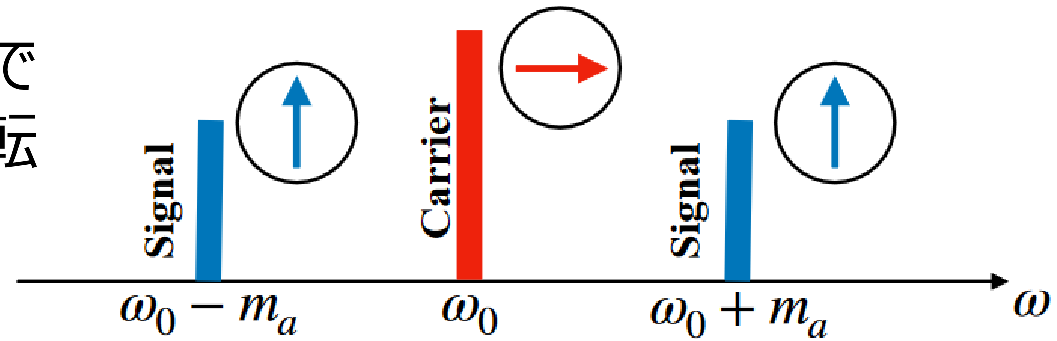


線形光共振器でもできる

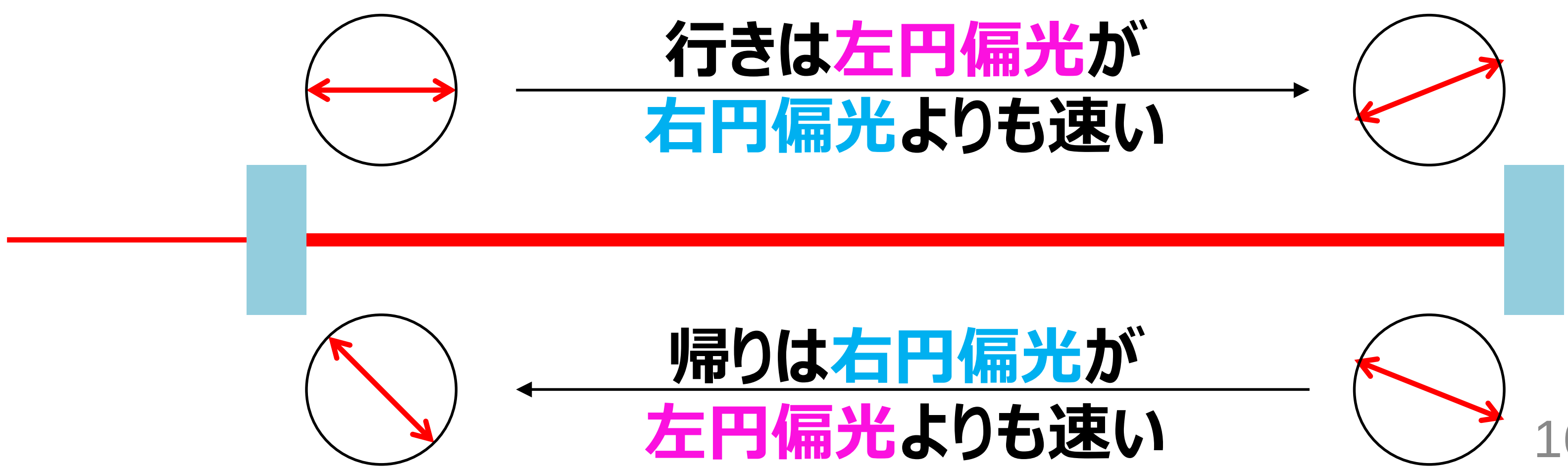
- 円偏光間の速度差は直線偏光の回転を生む





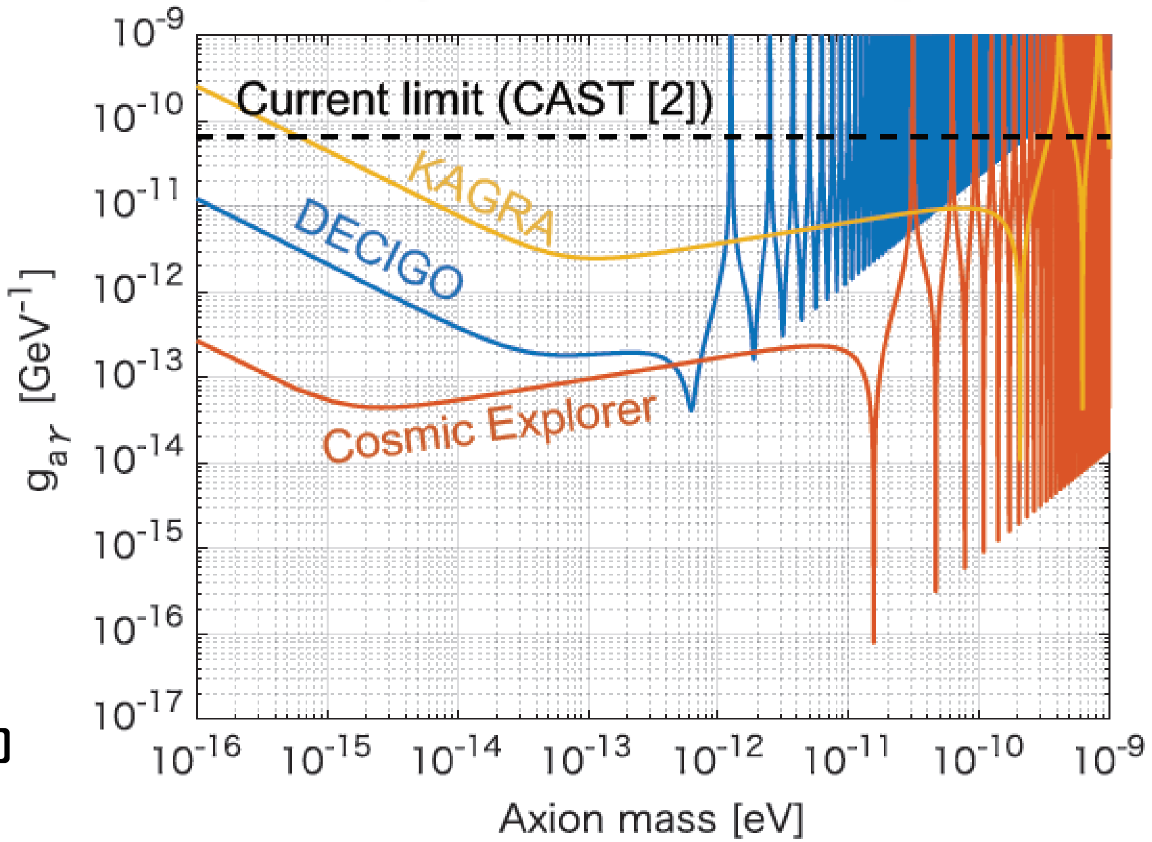
H. Liu+, arXiv:1809.01656

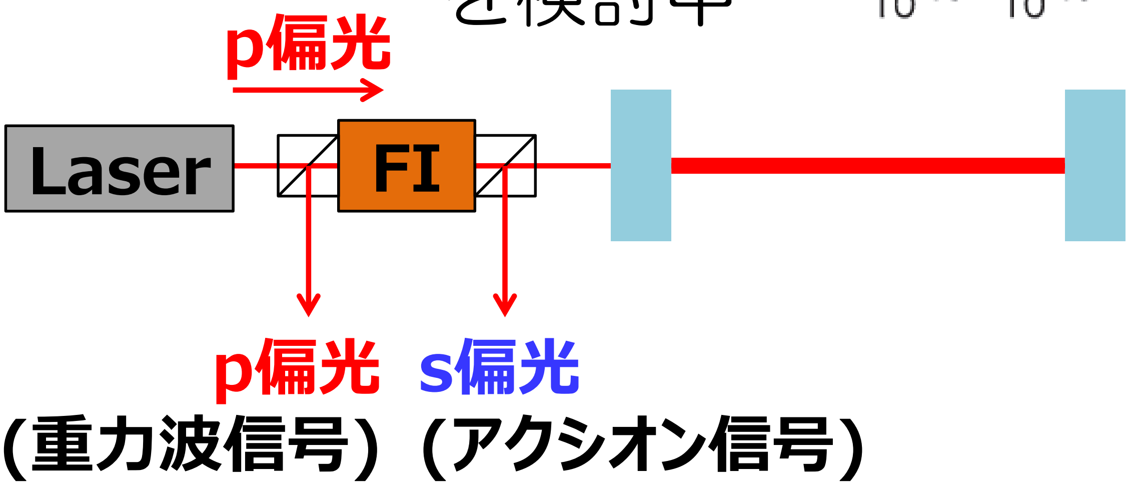
- 直線偏光の振動周期と光共振器の往復時間が一致すると高い感度を持つ



重力波検出器の光共振器でできる

- 長共振器長、
  高光強度が有利
- 重力波信号と
  区別可能
  重力波信号は
  p偏光に出る
- KAGRAへの導入
  を検討中





K. Nagano+,
arXiv: 1903.02017

まとめ

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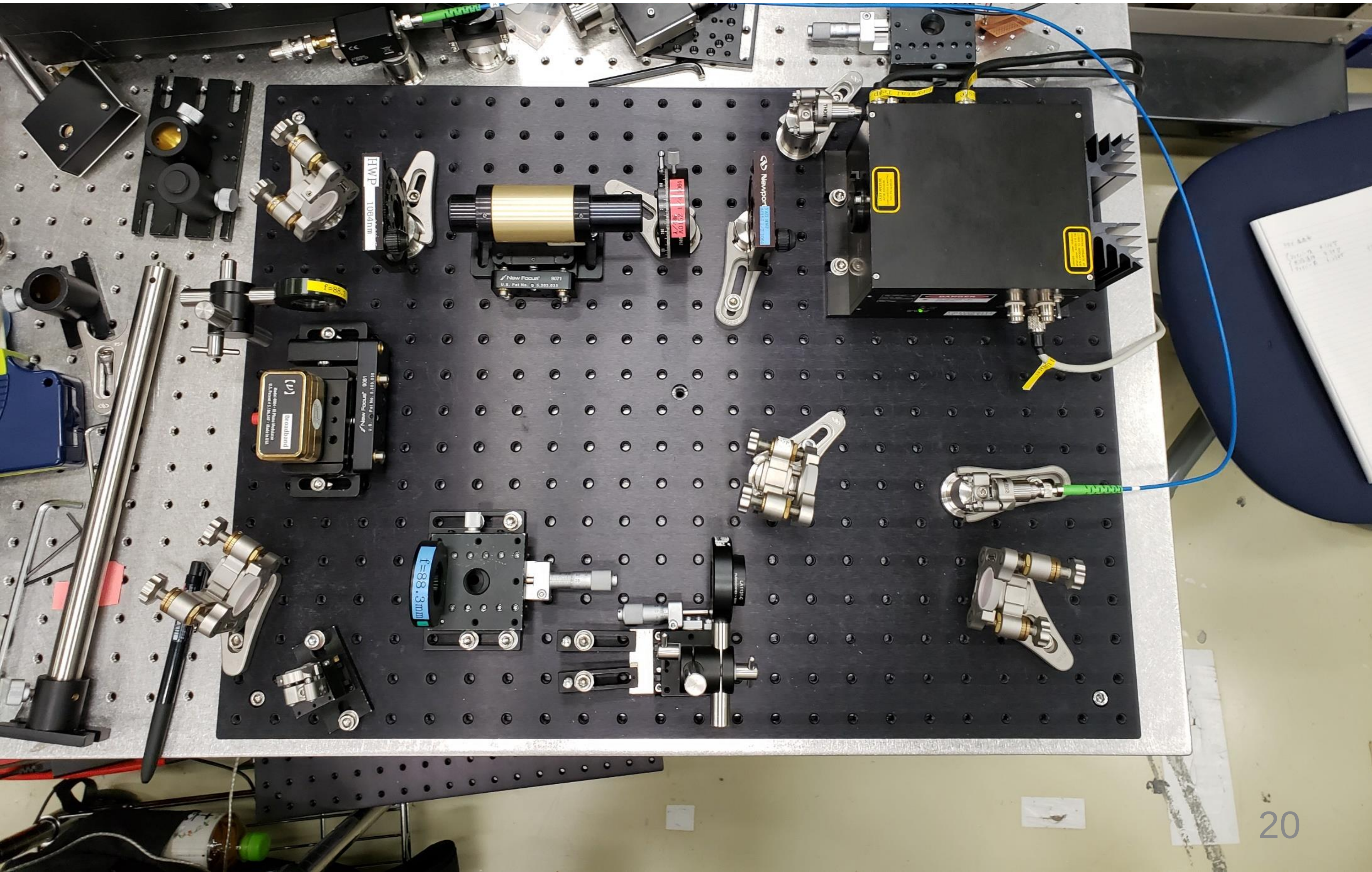
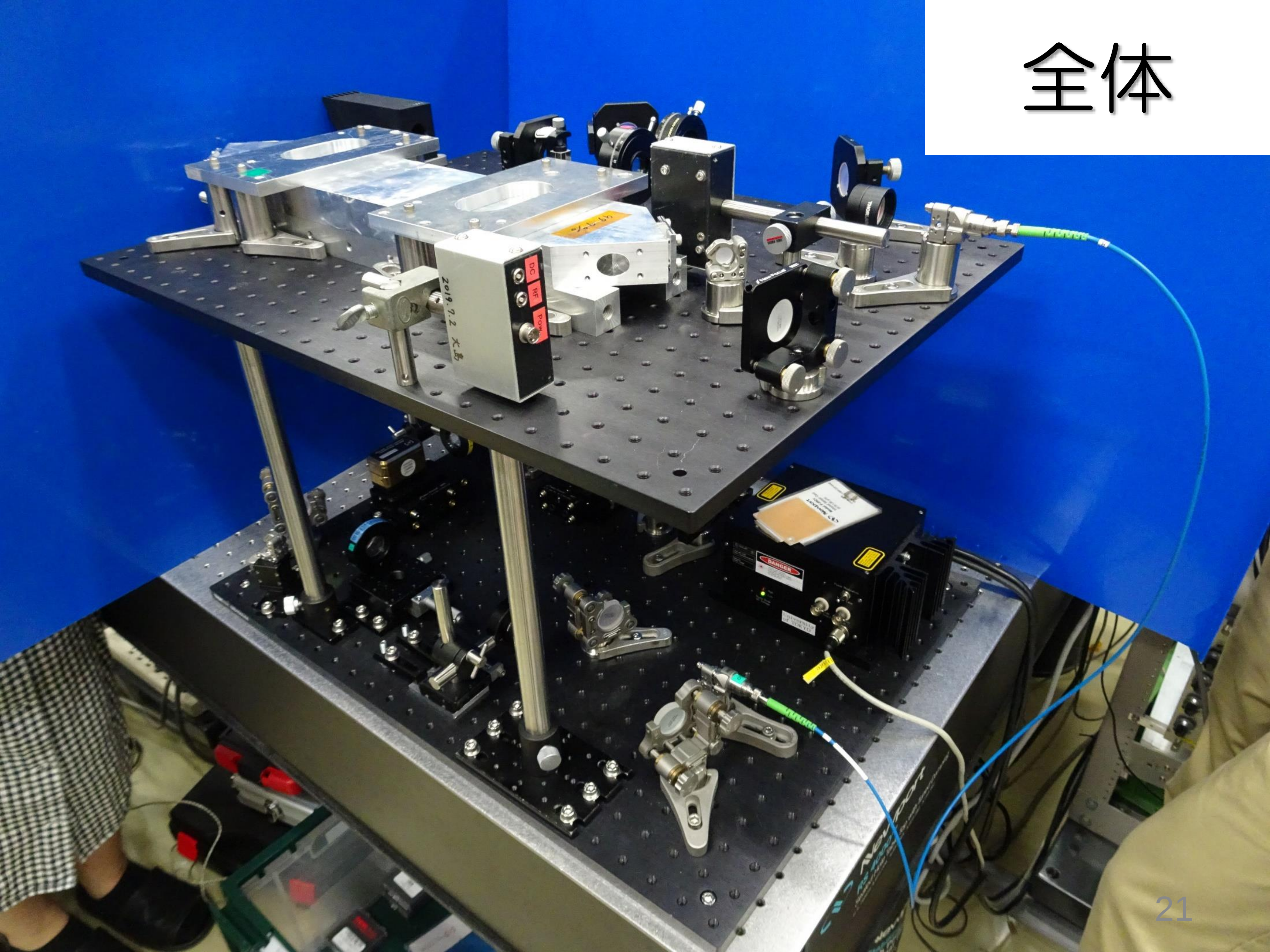
  ボウタイ共振器とダブルパス構成
- アクシオン質量 $m_a \lesssim 10^{-10}\,\mathrm{eV}$ で既存の上限値を数桁超える探査が可能
- プロトタイプ実験DANCE Act 1が進行中
  CASTの上限値を数倍超える探査
  2019年中に最初の探査開始予定
- レーザー干渉計型重力波検出器でも探査可能
  K. Nagano, T. Fujita, YM, I. Obata, arXiv: 1903.02017

補助スライド

入射光学系



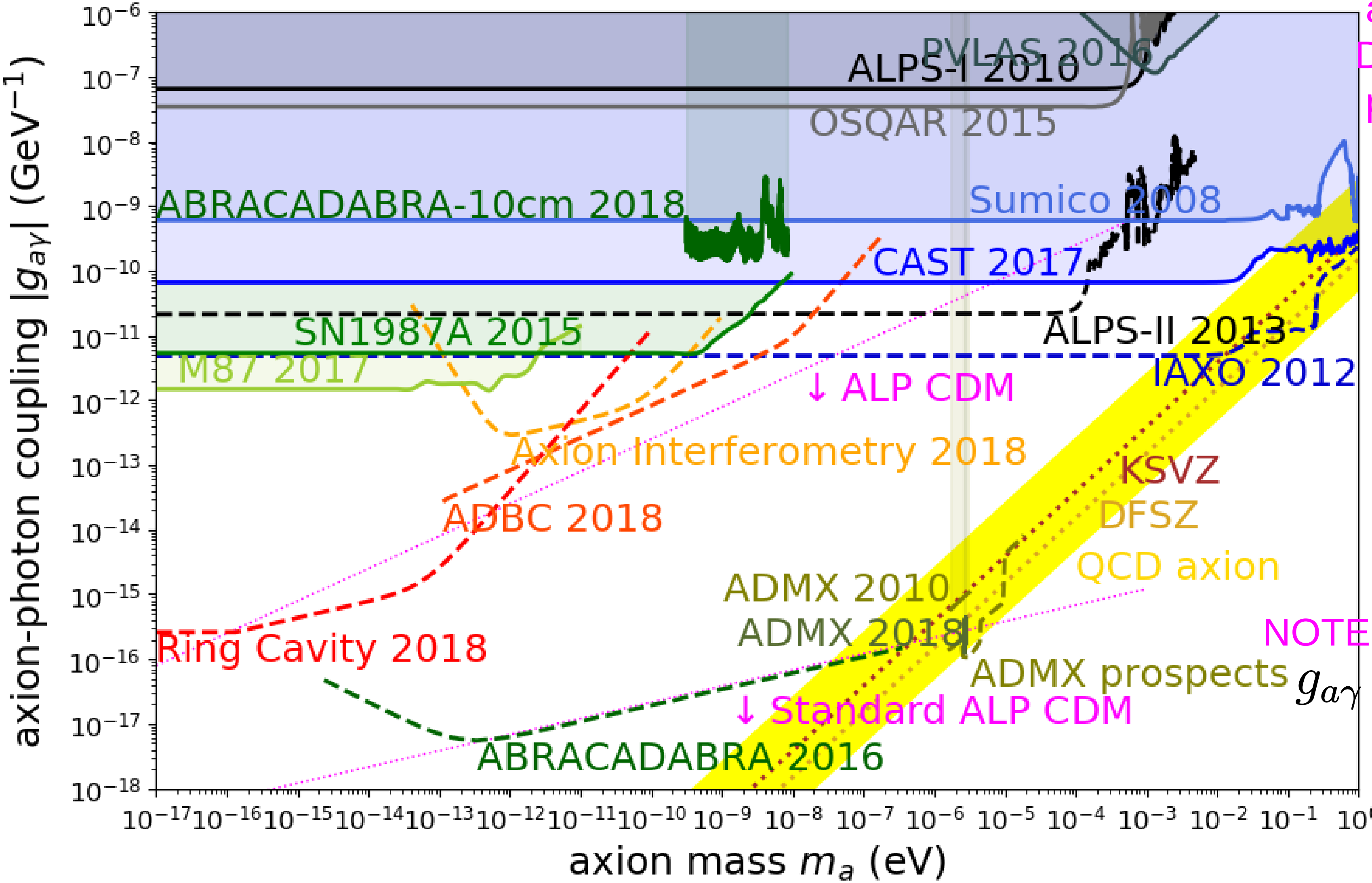
全体



Bounds on Axion-Photon Coupling

- Extracted some interesting experiments

Solid: achieved
Dashed: proposals



NOTE that $g_{a\gamma} \propto 1/f_a$

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

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

de Broglie wavelength

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

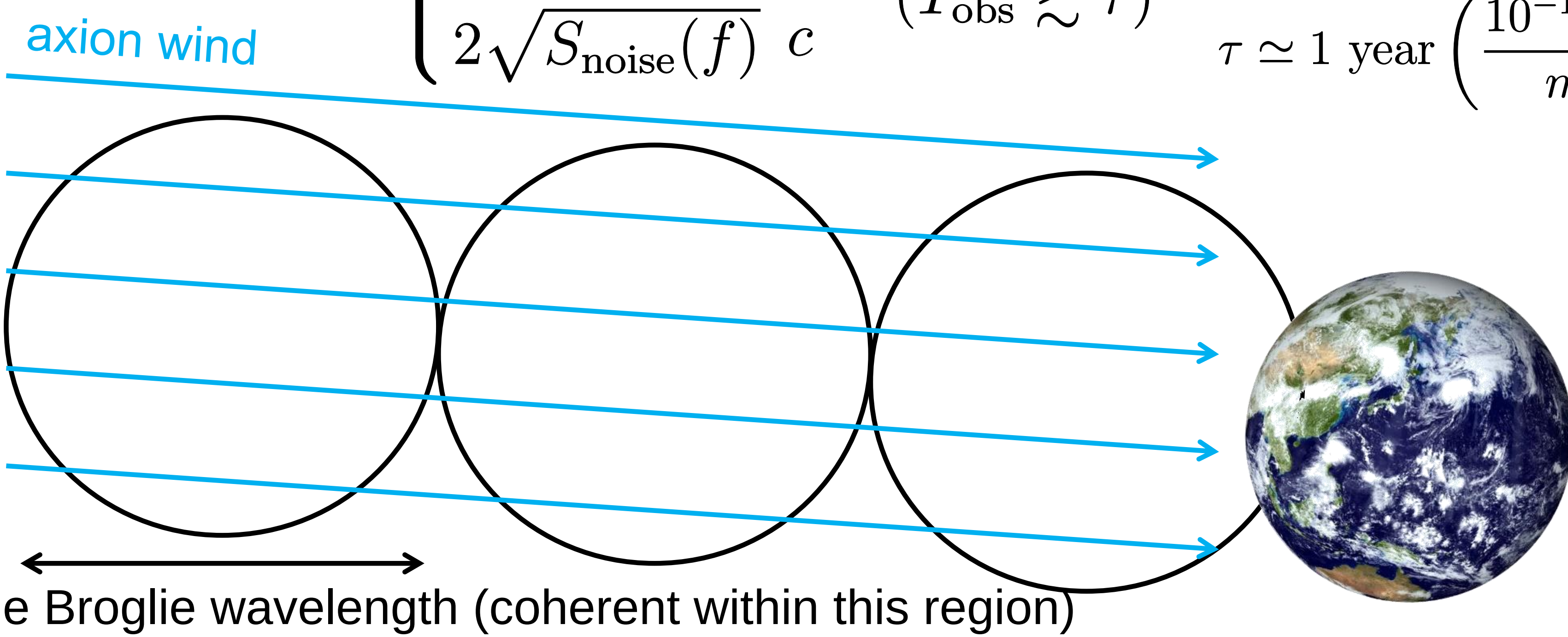
- Can be measured with laser interferometers and cavities
- Can be measured without magnets!
- Also assumes ALP = dark matter

Coherent Time Scale

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

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

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



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

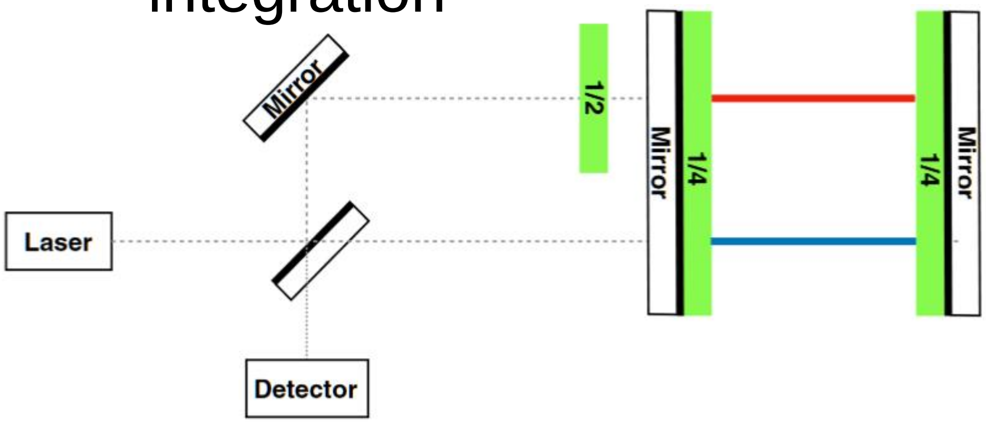


FIG. 3. A diagram of our proposed axion interferometer where the same mirrors are used to form both cavities. The dotted line is linearly polarized light, the red line is ↺ polarized light and the blue line is ↻ polarized light. Two quarter wave plates and a half wave plate are used to maintain the circular 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.

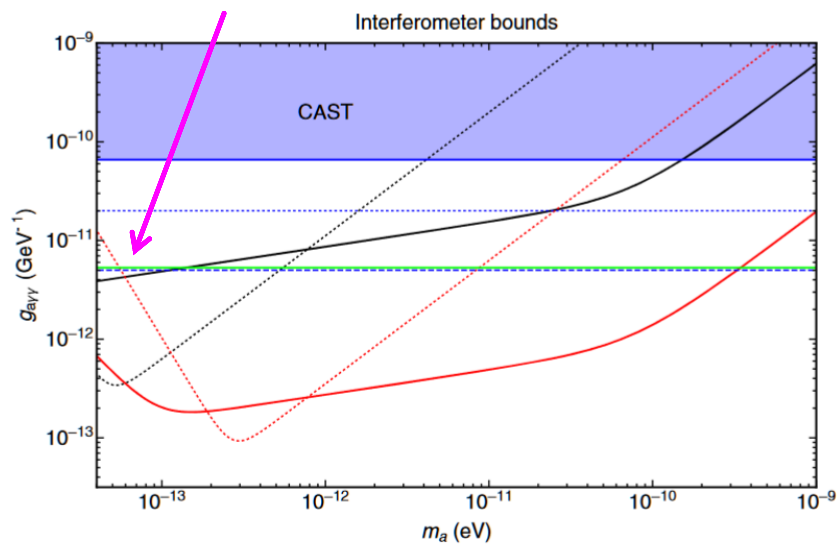
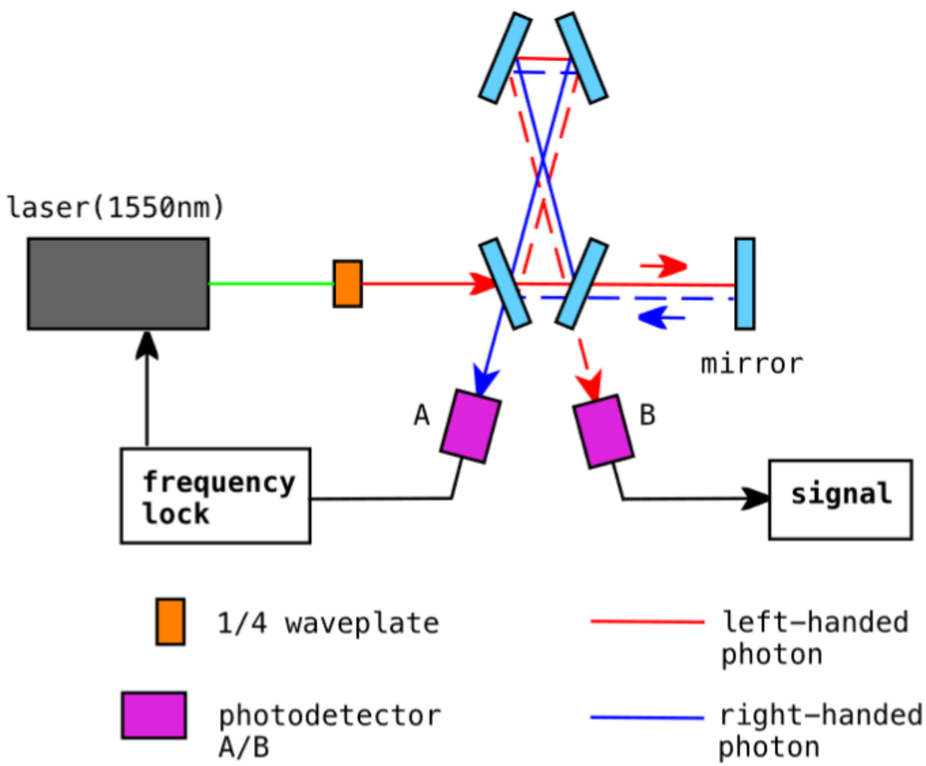


FIG. 5. Same as Fig. 4 but using the configuration shown in Fig. 3. Radiation pressure noise is cancelled leaving only radiation torque noise. We take the beams to be separated by 1 cm and the mirror to be circular and 10 cm in diameter.

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)

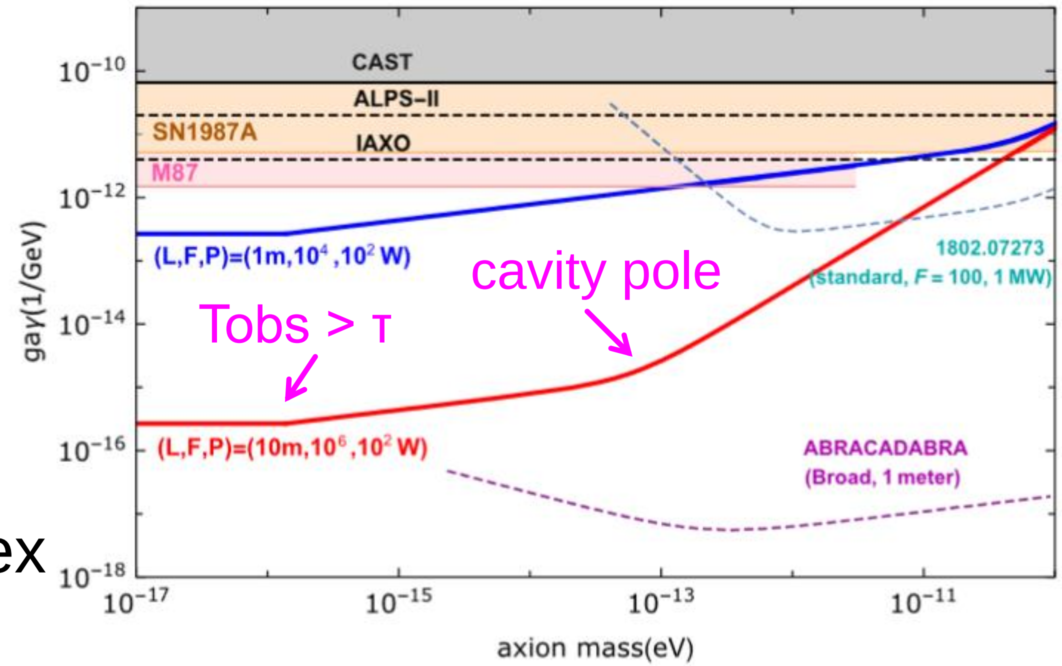
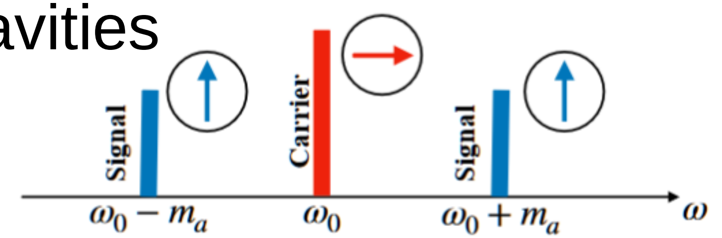


FIG. 2. The sensitivity curves for the axion-photon coupling constant $g_{a\gamma}$ with respect to the axion mass m. The solid blue (red) line shows the sensitivity of our experiment $(L, F, P) = (1(10)\ \mathrm{m}, 10^4(10^6), 10^2(10^2)\ \mathrm{W})$. The gray band represents the current limit from 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

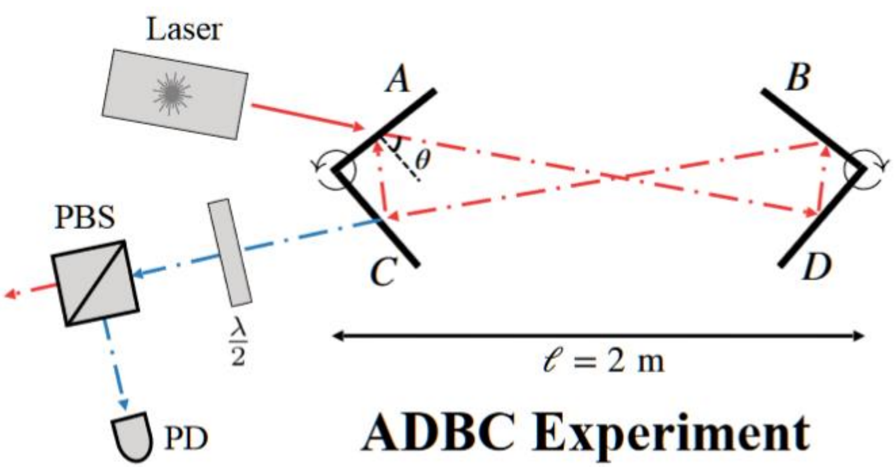
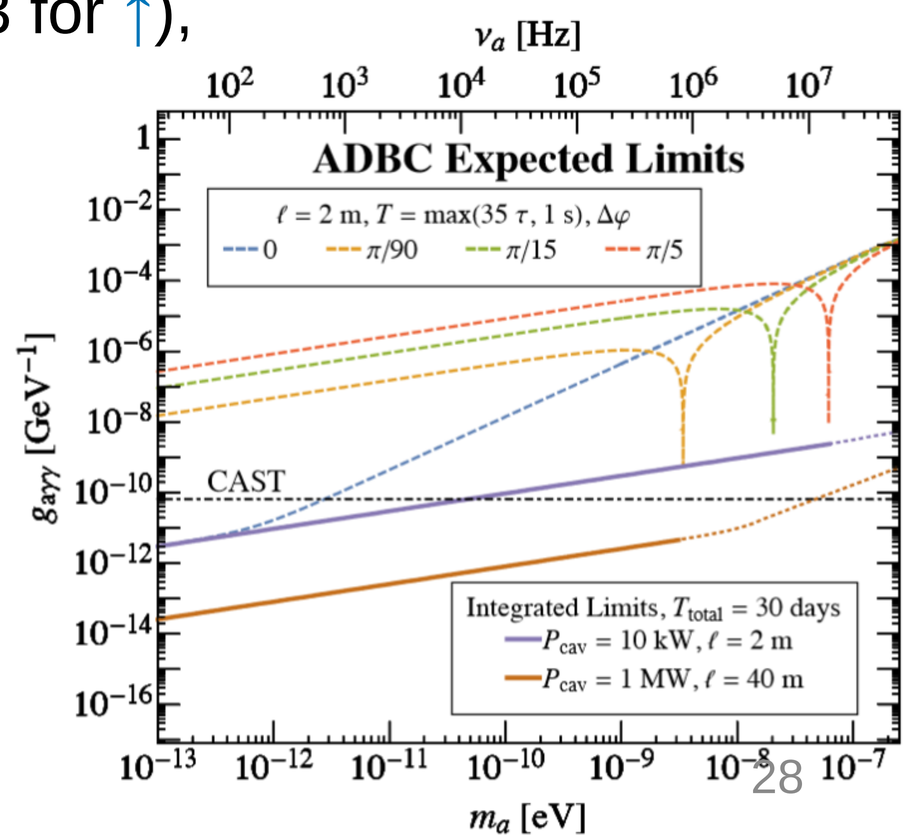


FIG. 2: Schematic of the ADBC experiment. The red optical



Sensitivity Design

- Brute force necessary, you cannot win for free

  NOTE that $\delta c \propto \lambda_{laser}$ and shot noise $\propto \sqrt{\lambda_{laser}}$