Laser interferometric searches for ultralight dark matter

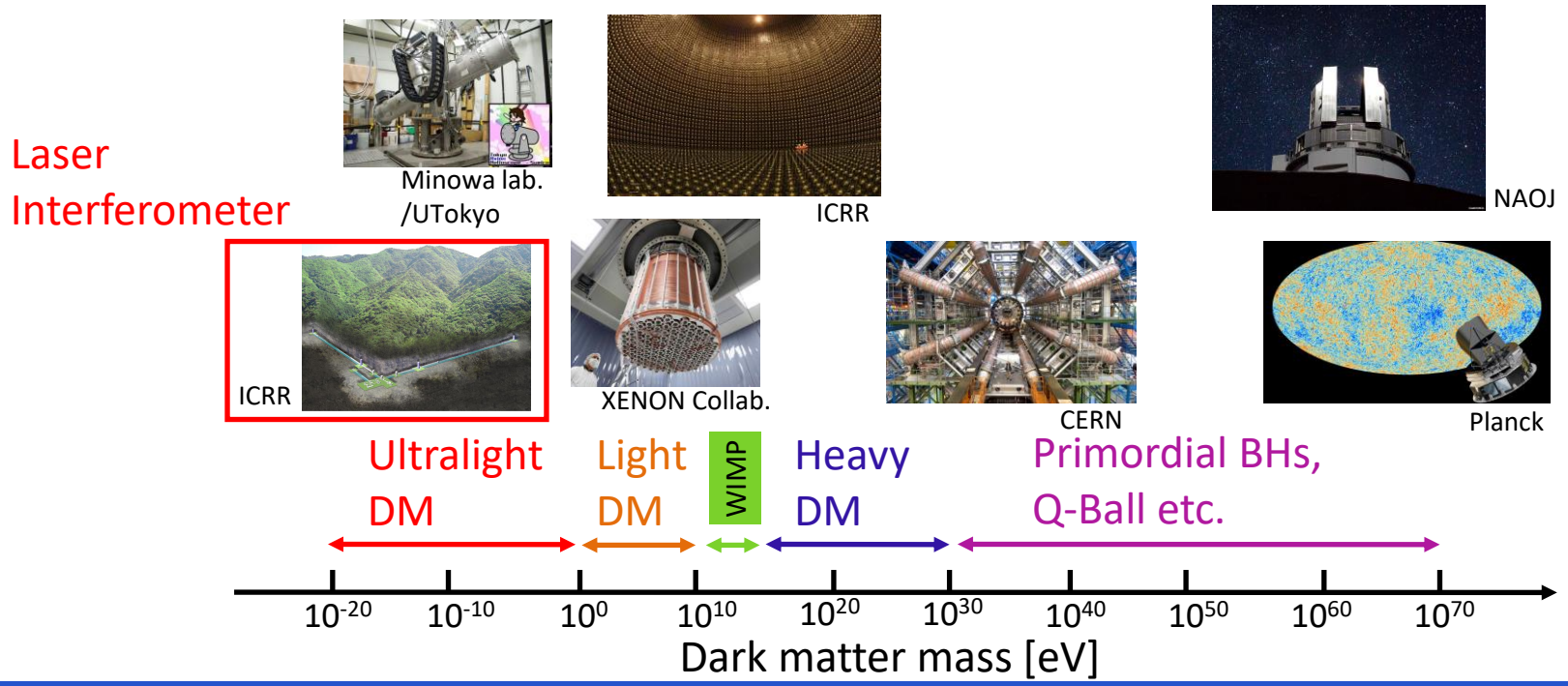
Koji Nagano on behalf of B01 group
(ISAS/JAXA)

Abstract

- Laser interferometer that is used for the precision measurement is one of the promising instruments for the cutting-edge ultra-light (UL) DM searches.
- We have two strategy:
  - Using the existing big instrument, e.g. KAGRA,
  - Development of the new table-top experiments.
- In this fiscal year,
  - We prepared instruments and analysis pipelines for the ULDM searches using KAGRA, (axion DM, vector DM)
  - We performed the first test axion DM observation using the 50-cm-long bow-tie cavity.
- Observation run will start in near future.

Dark matter search with interferometers

- Laser interferometers are widely used for the precision measurement, e.g. gravitational wave observatory.
- There are various proposals to use the interferometer for the ultralight dark matters (DMs) which behaves as classical waves.



Many studies!

- Axion-like particles (Pseudoscalar)
  - A. Melissinos, PRL 102, 202001 (2009)
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  - I. Obata+, PRL 121, 161301 (2018)
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  - S. M. Vermeulen+, Nature 600, 424 (2021)

Not exhaustive.
The ones that require magnetic field are not listed.

- U(1)B or U(1)B-L gauge bosons (vector)
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  - H-K Guo+, Commun. Phys 2, 155 (2019)
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  - LVK Collab., arXiv:2105.13085 (2021)
- Other candidate (not ULDM)
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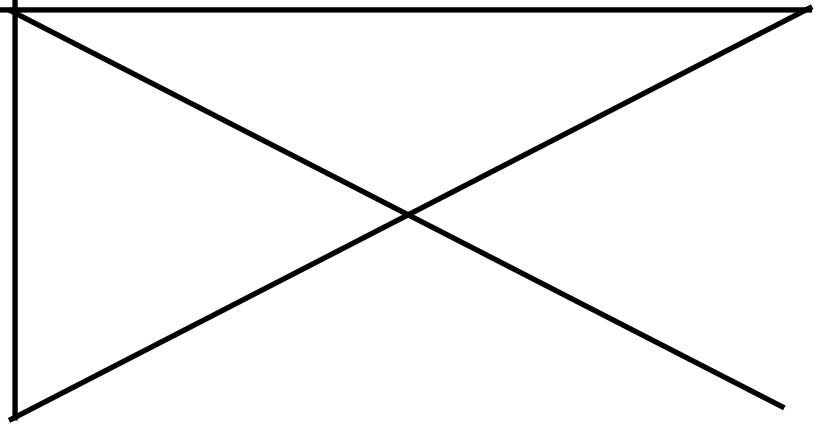
Researches in/around B01 group

	Existing instrument, KAGRA	Table-top experiments
Axion DM	- Installation of the optic for the next (GW) observation - Analysis pipeline development	- Development of the prototype experiment: DANCE - First test axion DM observation
Vector DM	- Ready for the observation (No additional installation is necessary.) - Analysis pipeline development	

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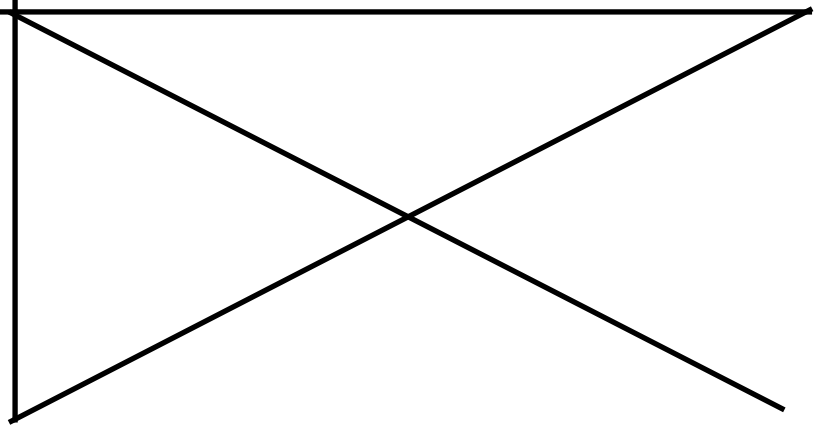
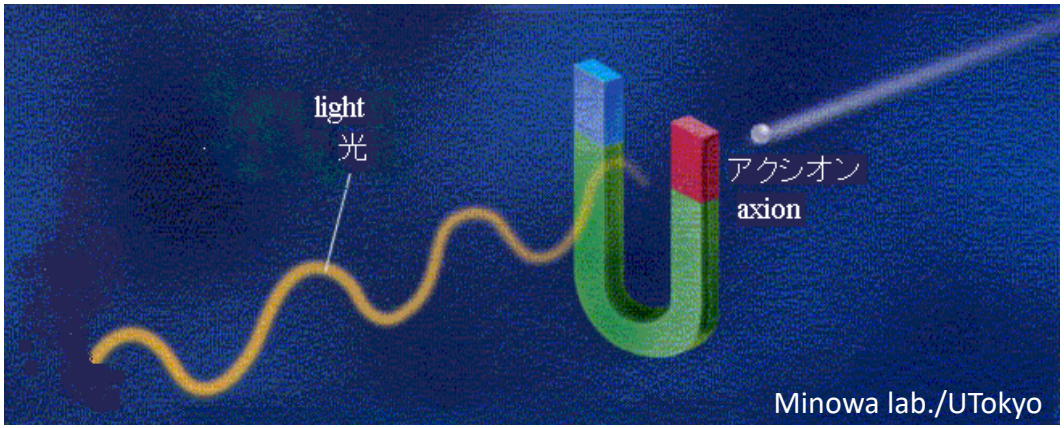
Vector DM	- Ready for the observation (No additional installation is necessary.) - Analysis pipeline development	

Axion and axion-like particle (ALP)

- Axion was originally proposed in 1970s to solve the strong CP problem in QCD physics.
- Recently, string theory suggested a plentitude of ALPs.
- Feature

(In this talk, ALPs are also called axions.)

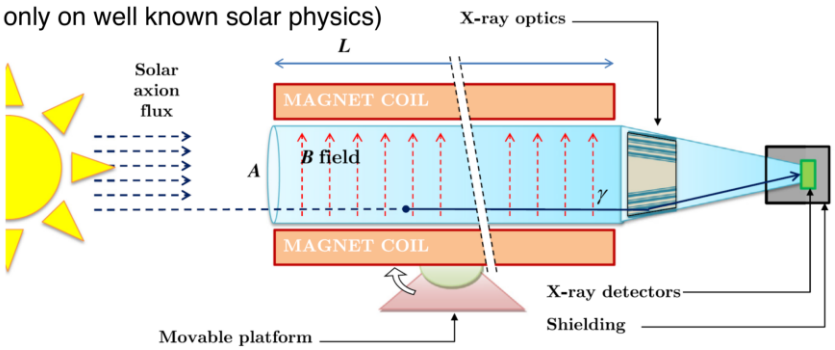
  - Typically have a small mass (<< eV).
  - Weakly couple with gauge bosons. In particular photon.
    - E.g.: Primakoff effect (axion-photon conversion).



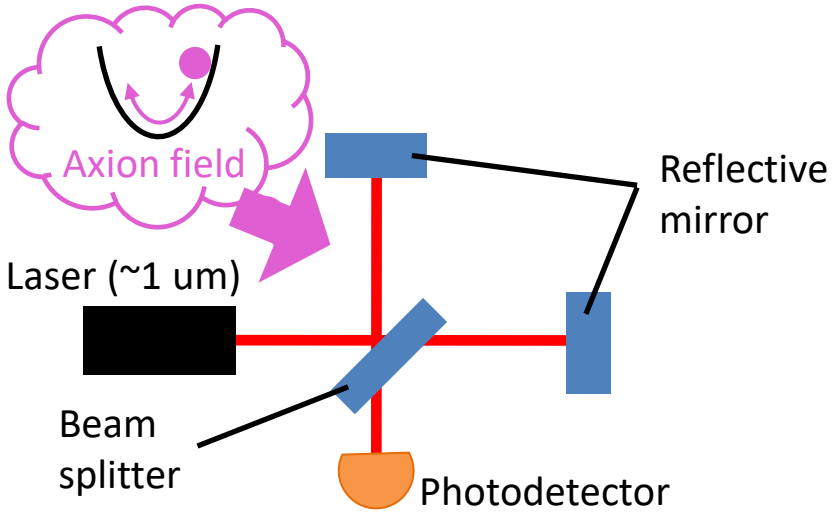
Schematic of the Primakoff effect.

Axion dark matter search

- The conventional way to probe axion is to use strong magnets, i.e. the Primakoff effect.
  - –However, the magnet could cause noises (vibration/electric noise) and increase cost.
- Recently, new approaches to search for axion were proposed that do not need any magnets but use interferometer.



Conventional way with the Primakoff effect.
(J. K. Vogel+, arXiv1302:3273)



Schematic of interferometric search.

Axion interaction with photons

- Axion varies phase velocity between two circular-polarized photons.

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

Axion-photon coupling (This will be measured)

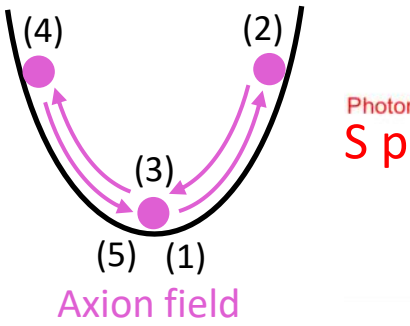
Axion field amplitude

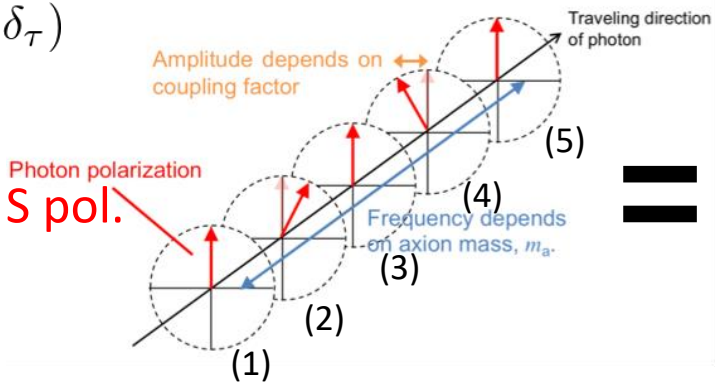
Photon wave number

Axion mass

- This leads to the polarization modulation of the linearly polarized light.

$a(t) = a_0 \sin(m_a t + \delta_\tau)$





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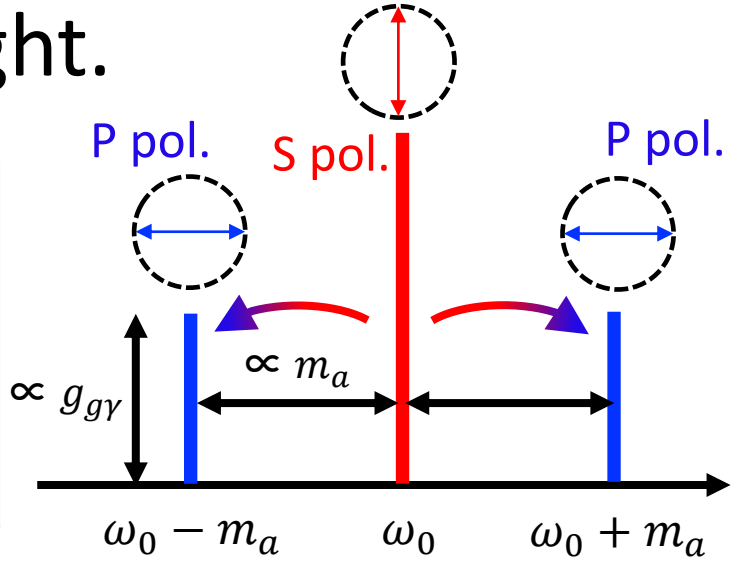
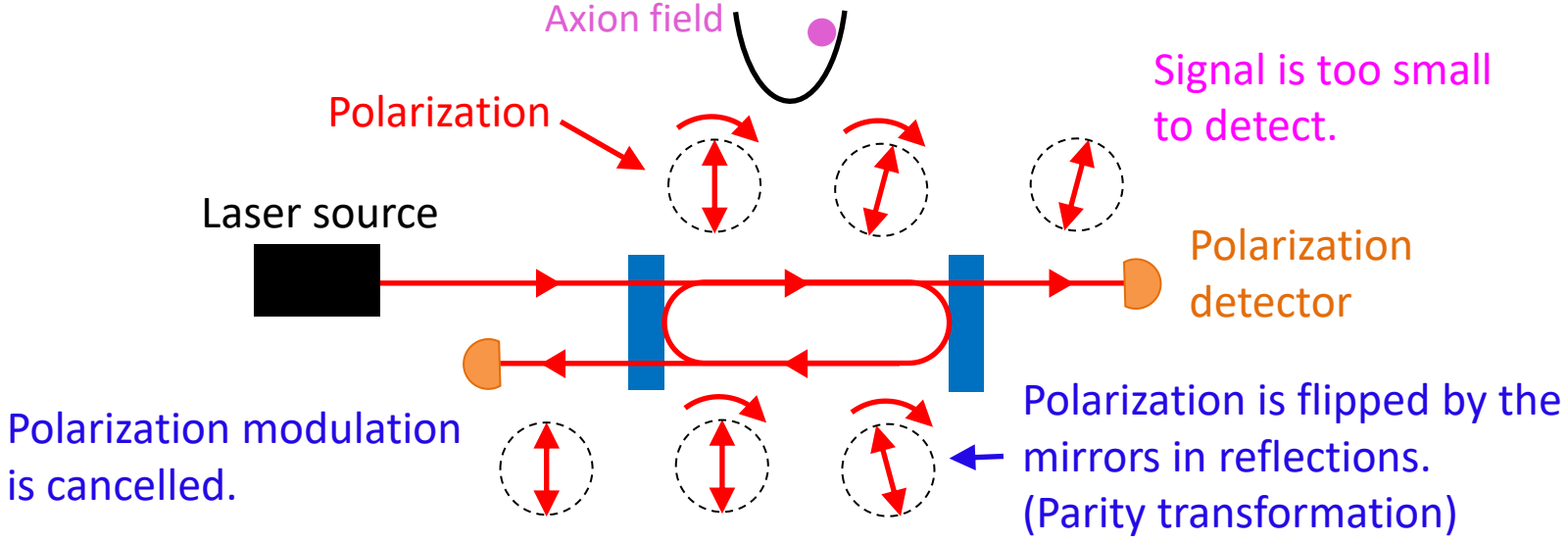


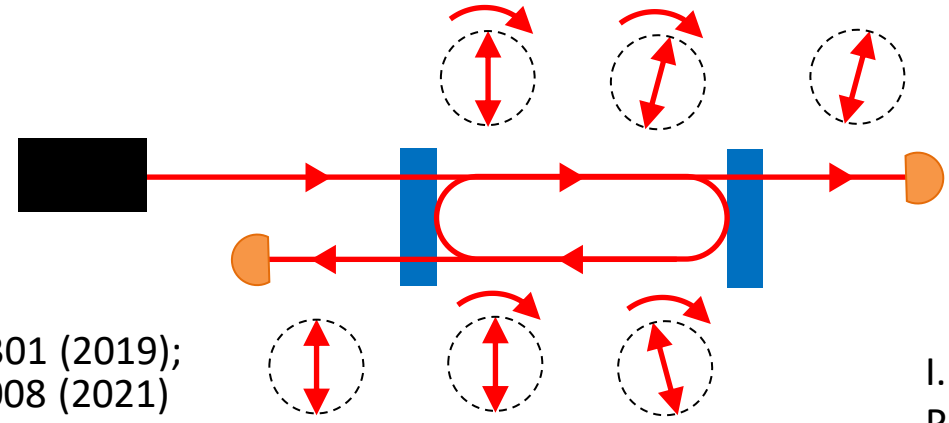
Polarization modulation caused by axion-photon coupling.

How to measure?

- However, the polarization rotation is small for the short interferometer since the interaction duration is short.
- In addition, the liner optical cavity is not so effective, unlike the gravitational wave detector, due to the parity transformation of the mirror.



Then, do you have solutions? -- Yes!

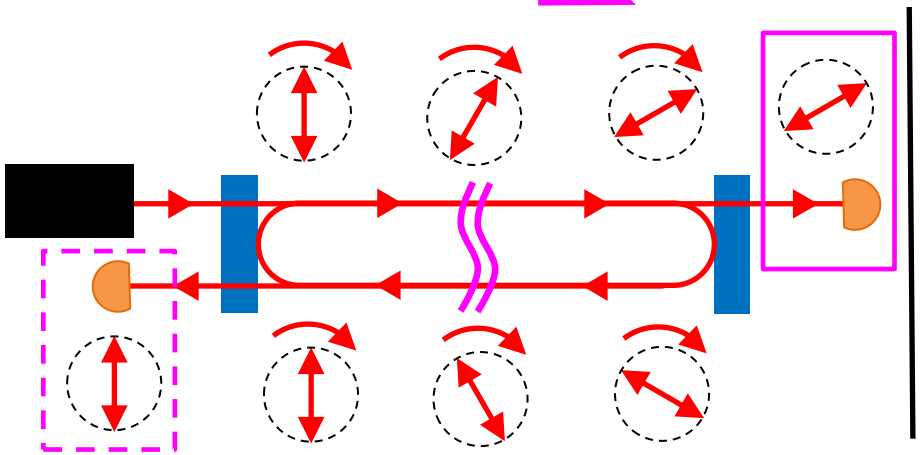


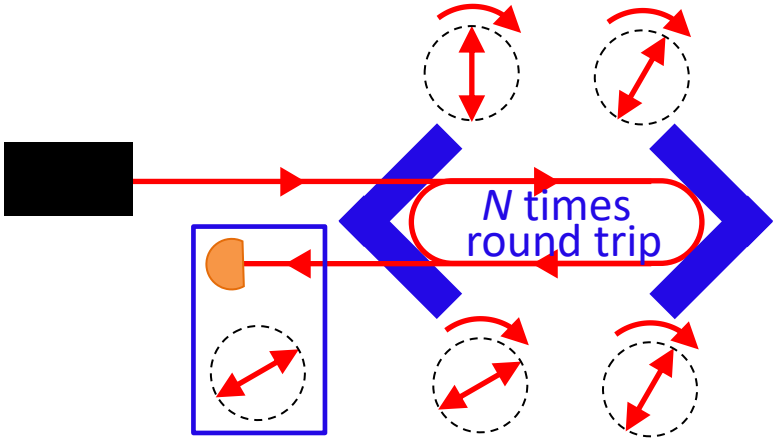
KN+, PRL 123 , 111301 (2019);
KN+, PRD 104, 062008 (2021)

Longer interferometer (m → km)

I. Obata,T. Fujita, Y. Michimura, PRL 121, 161301 (2018)

Use of pair mirrors (to keep parity and enhance the signal)





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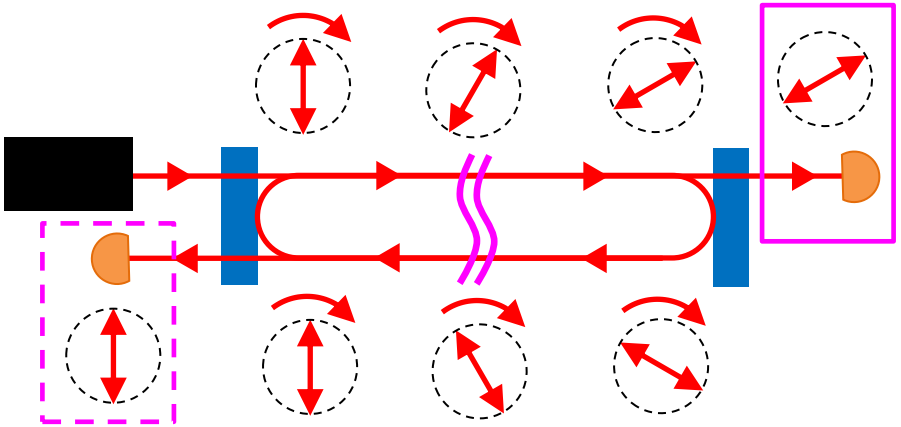
Gravitational wave observatory, such as KAGRA



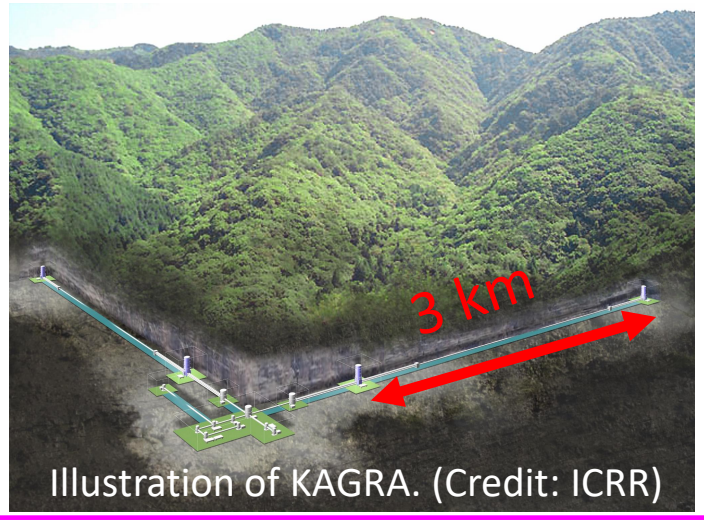
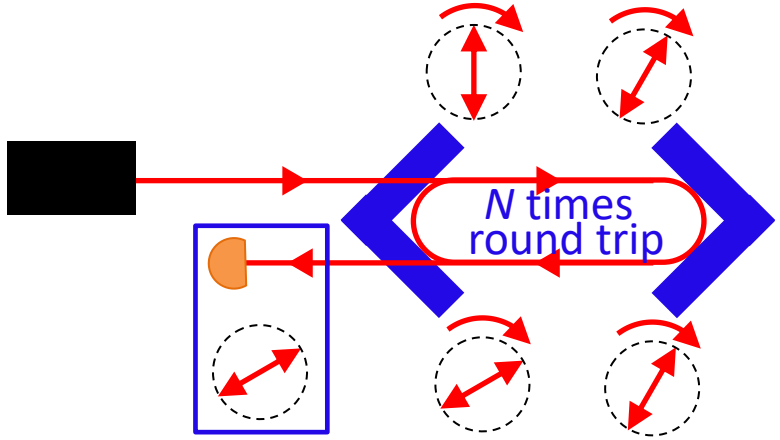
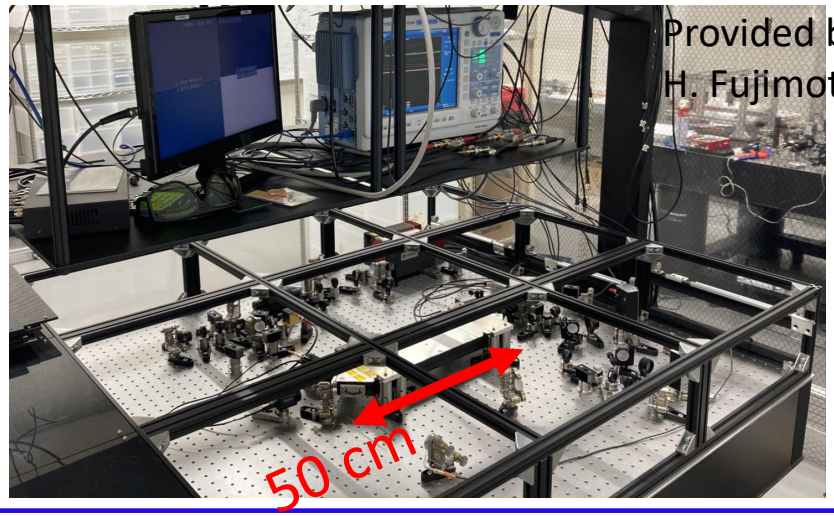


Illustration of KAGRA. (Credit: ICRR)

KN+, PRL 123 , 111301 (2019); KN+, PRD 104, 062008 (2021)

Table-top experiment (DANCE at UTokyo)





Provided by H. Fujimoto

I. Obata,T. Fujita, Y. Michimura, PRL 121, 161301 (2018)

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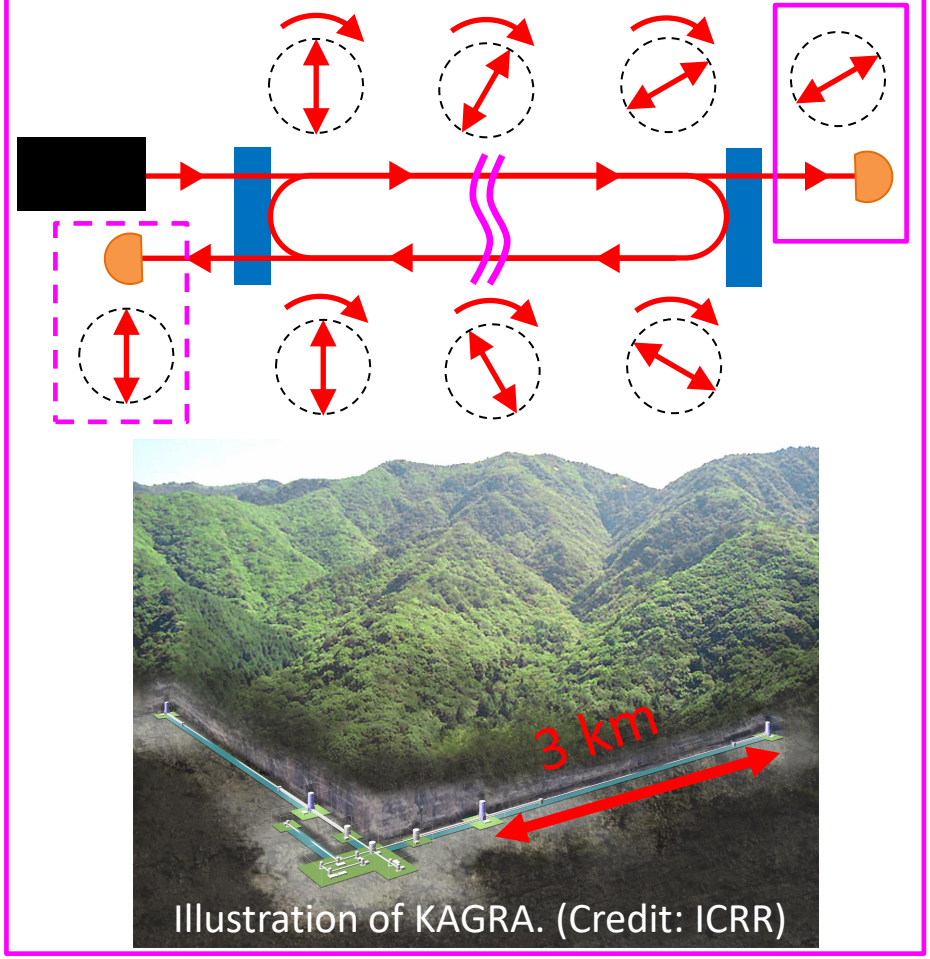

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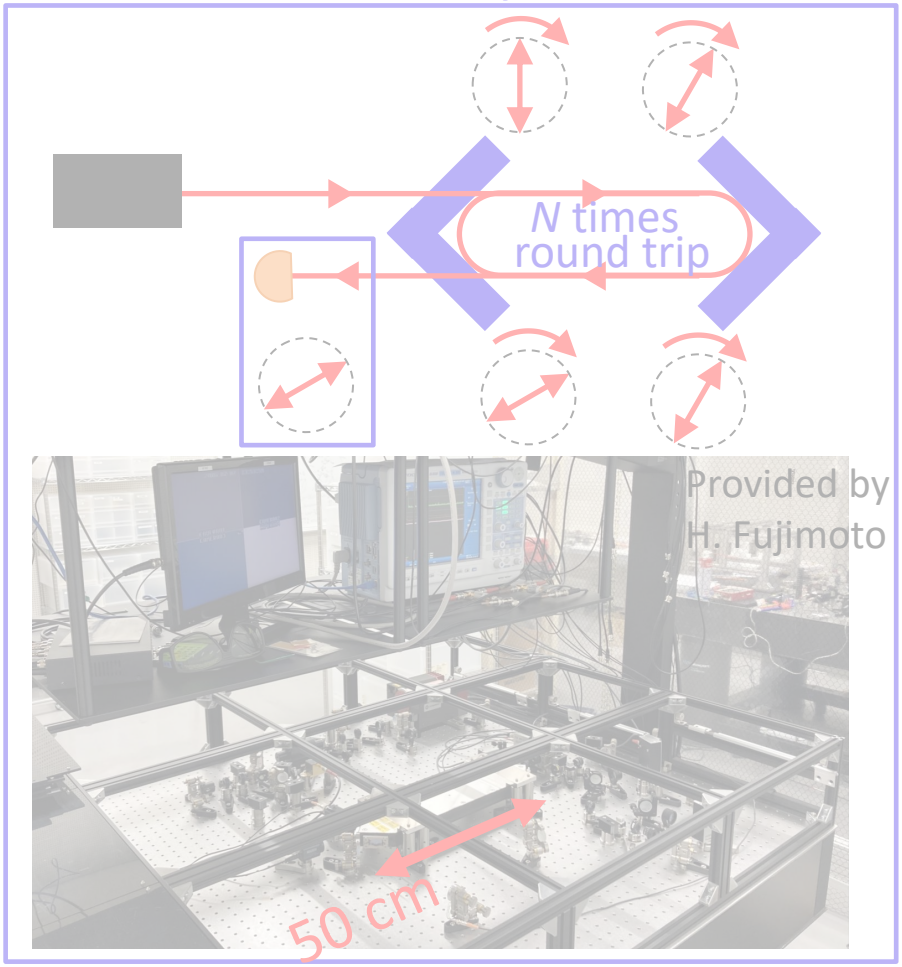

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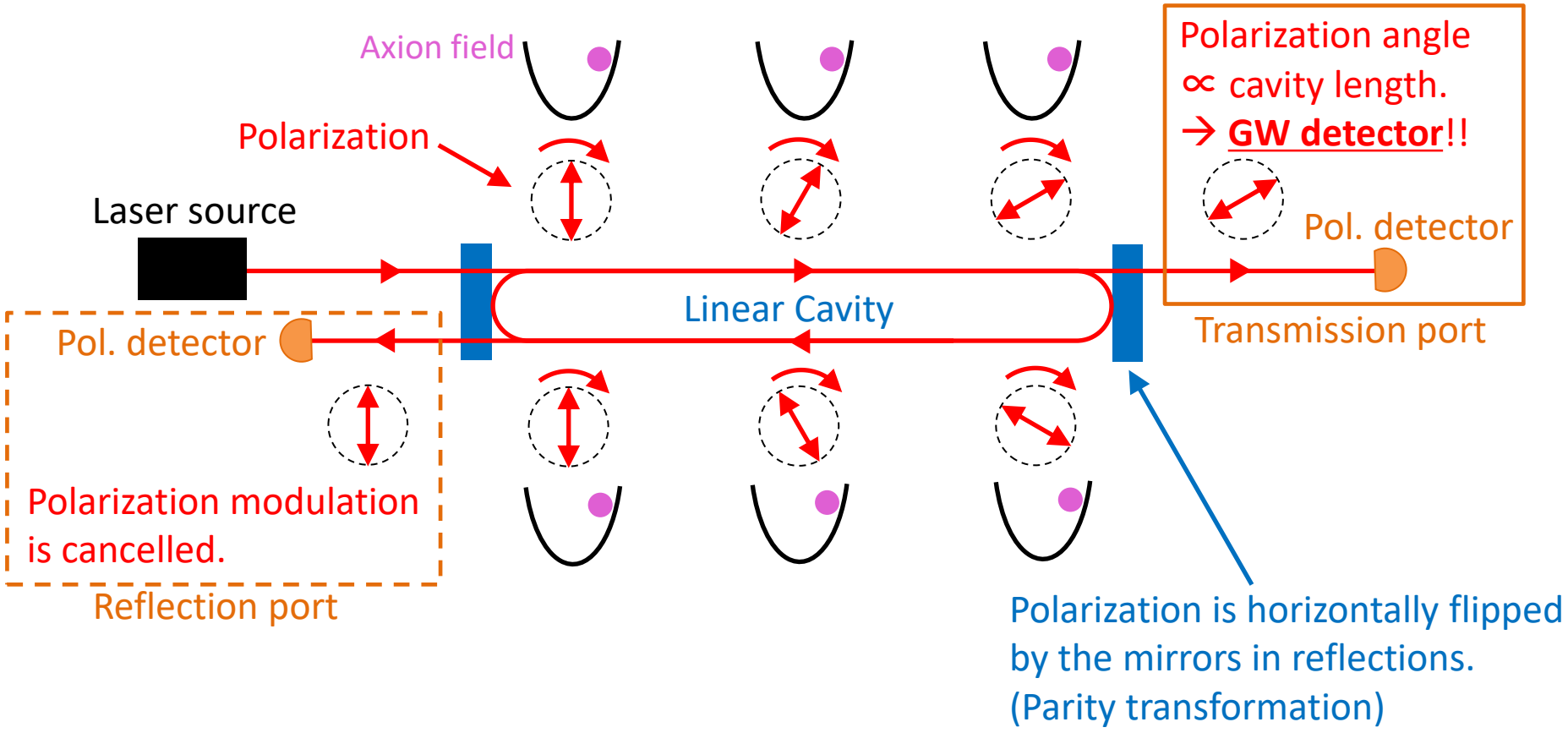
KAGRA

Illustration of KAGRA. (Credit: ICRR KAGRA Observatory)

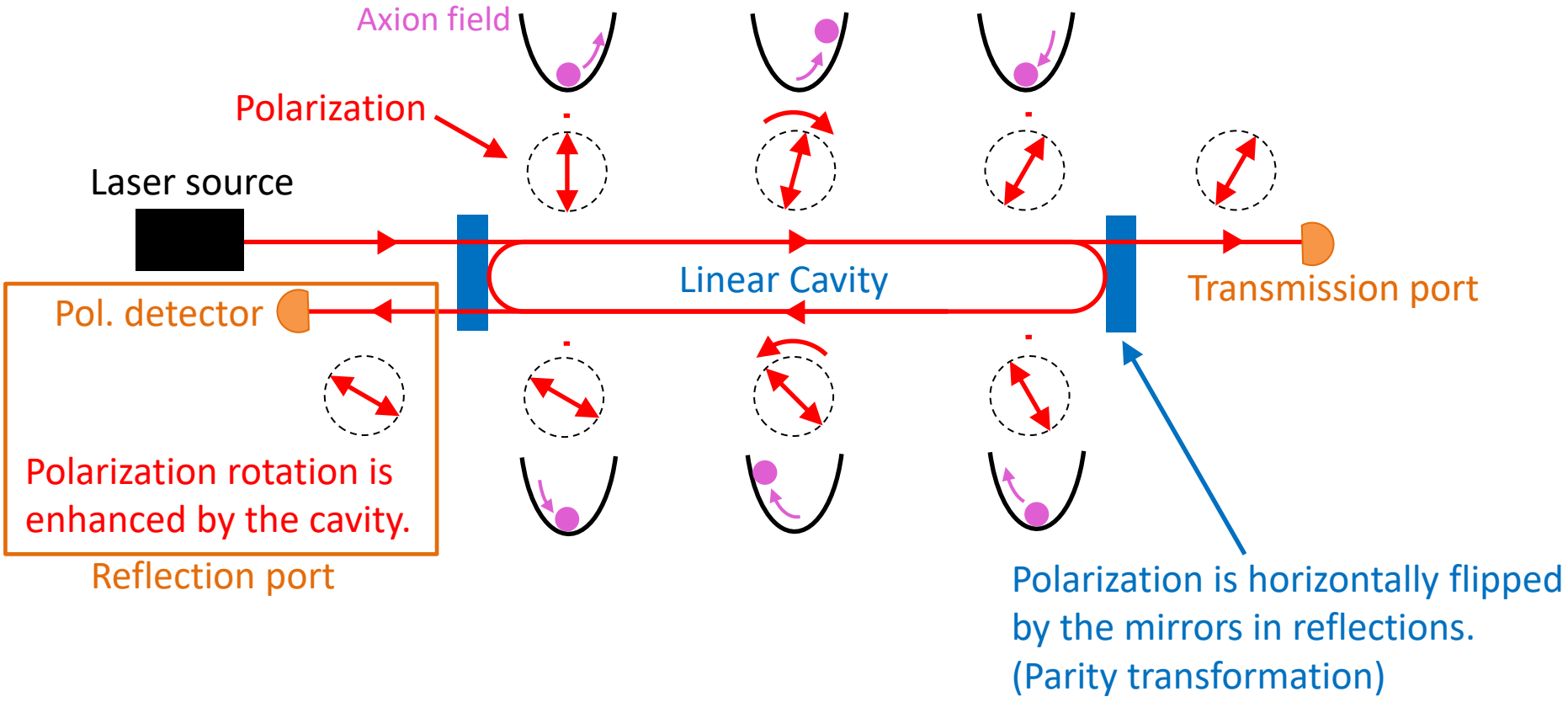
How to search for axions with KAGRA

(Case1) Axion is very light
[= Polarization modulation is very slow]

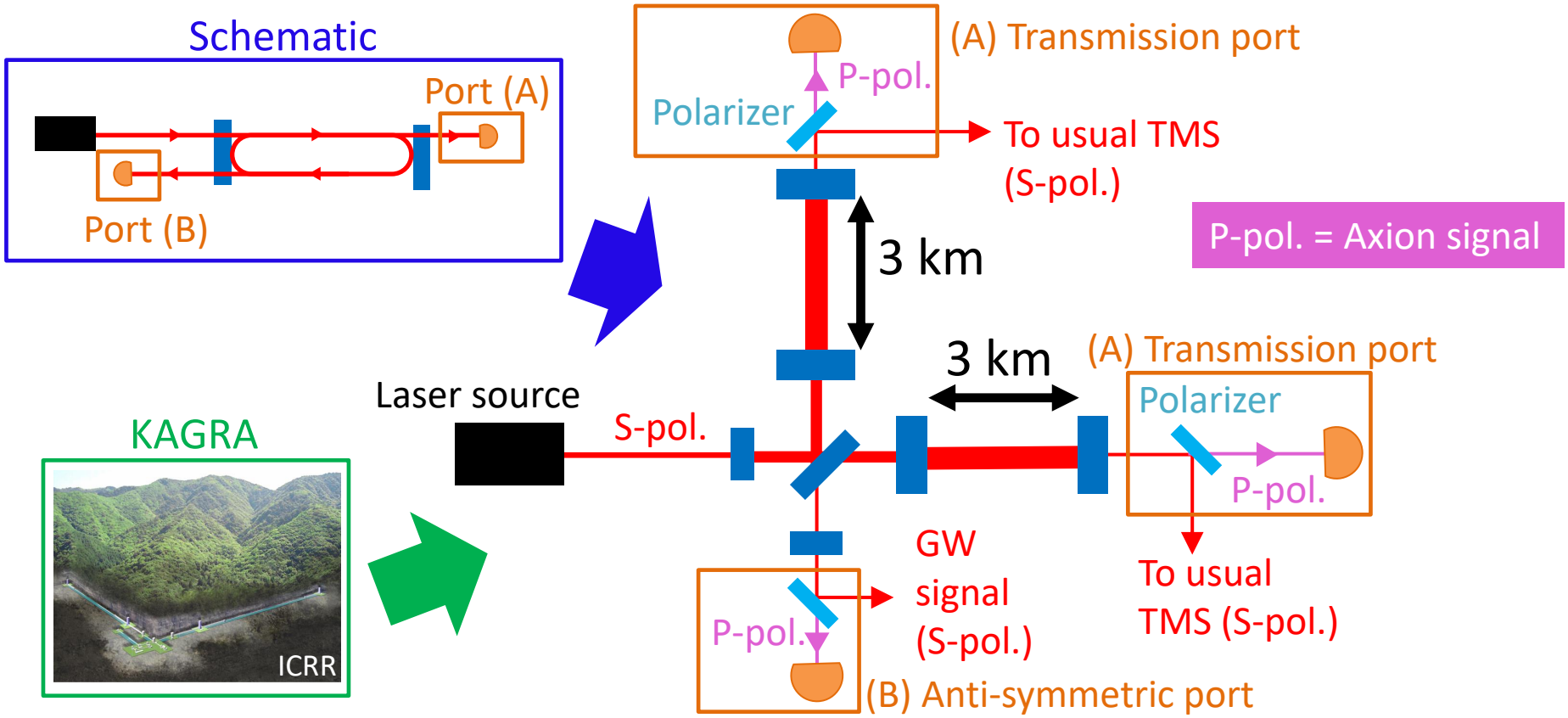


How to search for axions with KAGRA

(Case2) Axion is relatively heavy
[= Polarization modulation is relativity fast]

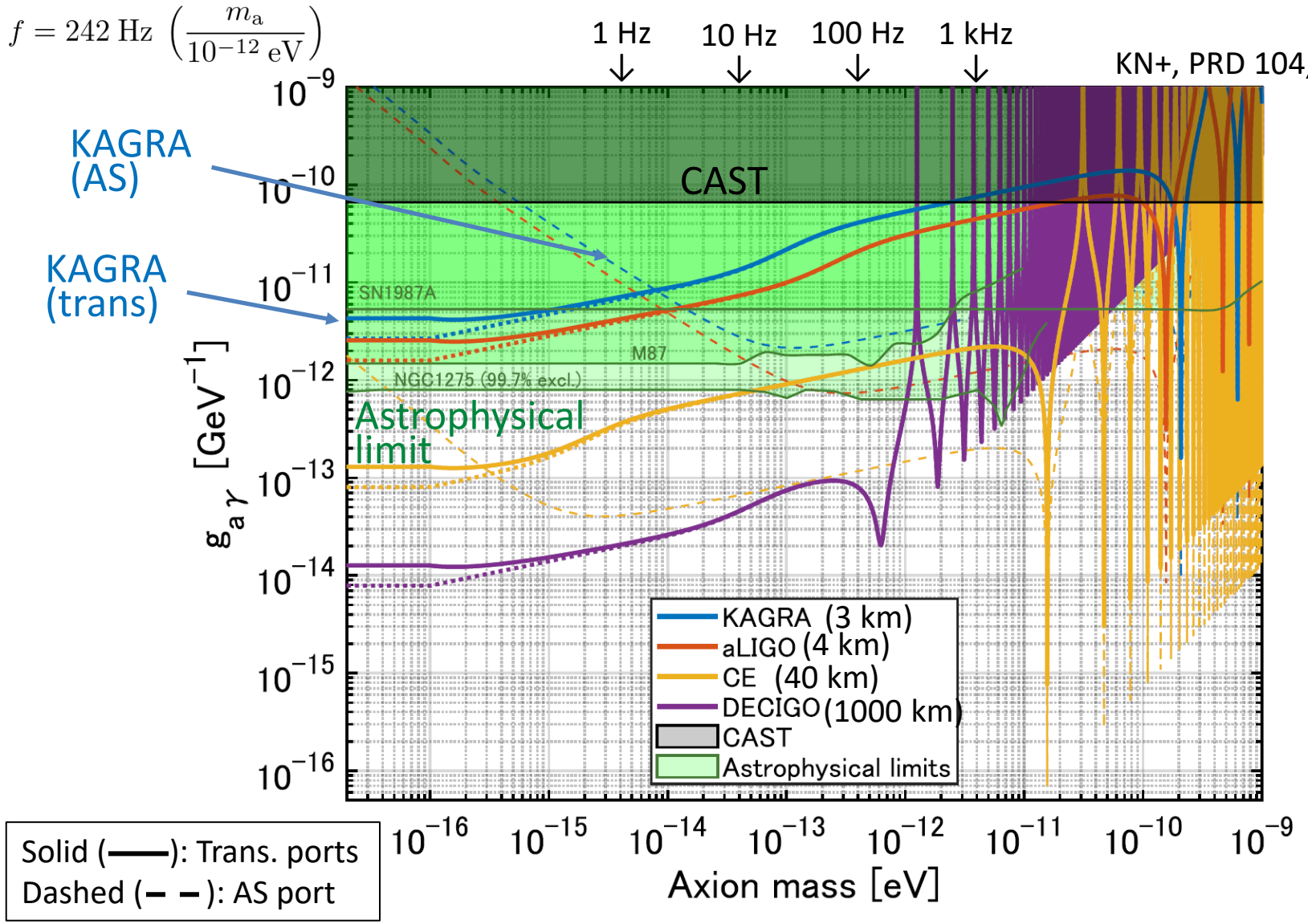


Axion dark matter search with gravitational wave detectors (ADAM-GD)



- This scheme can be applied to GW detectors just by putting polarizer and photodetectors.
- Axion dark matter search can be performed even during the GW observation.

Sensitivity estimation



1-year observation is assumed.

Solid (——): Trans. ports
Dashed (– –): AS port

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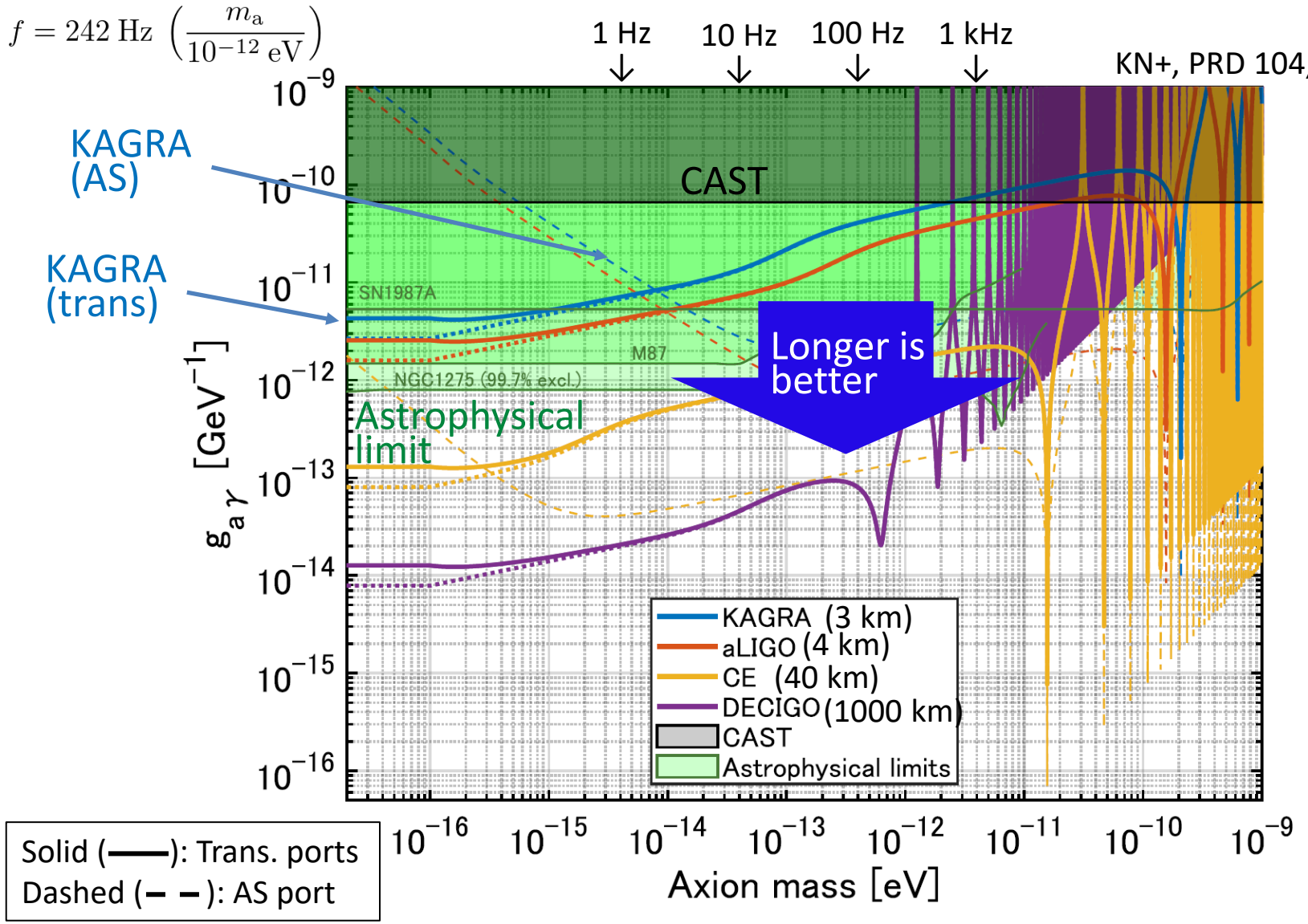

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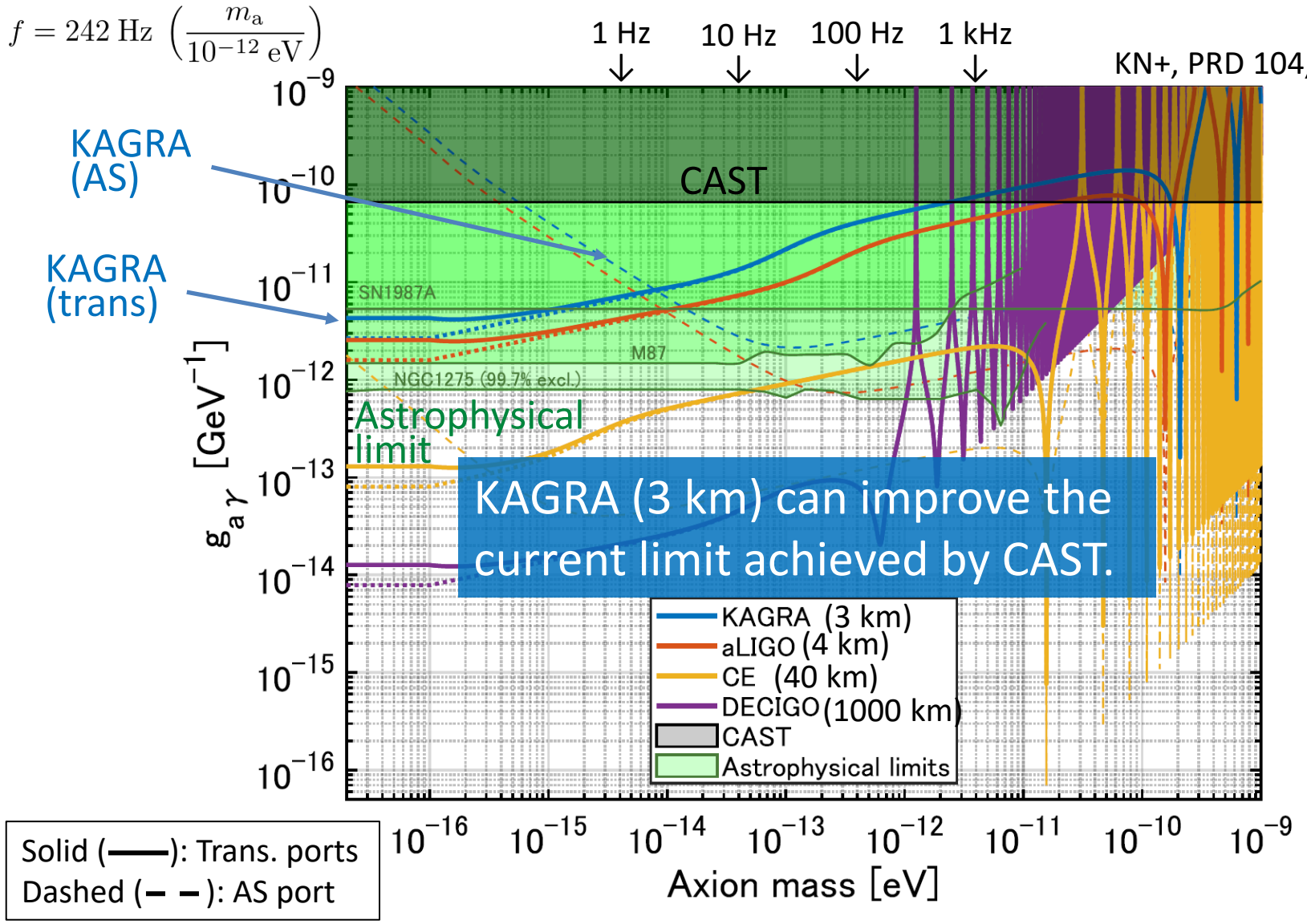

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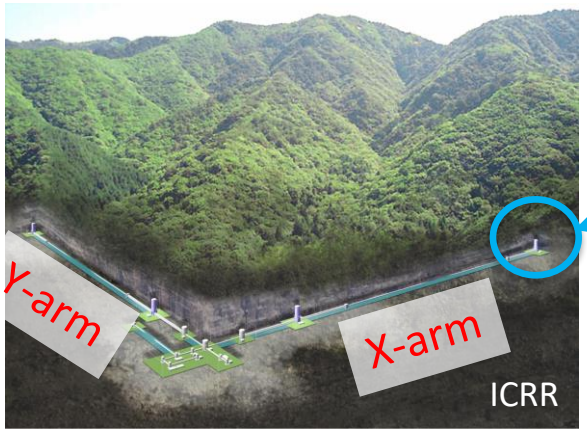
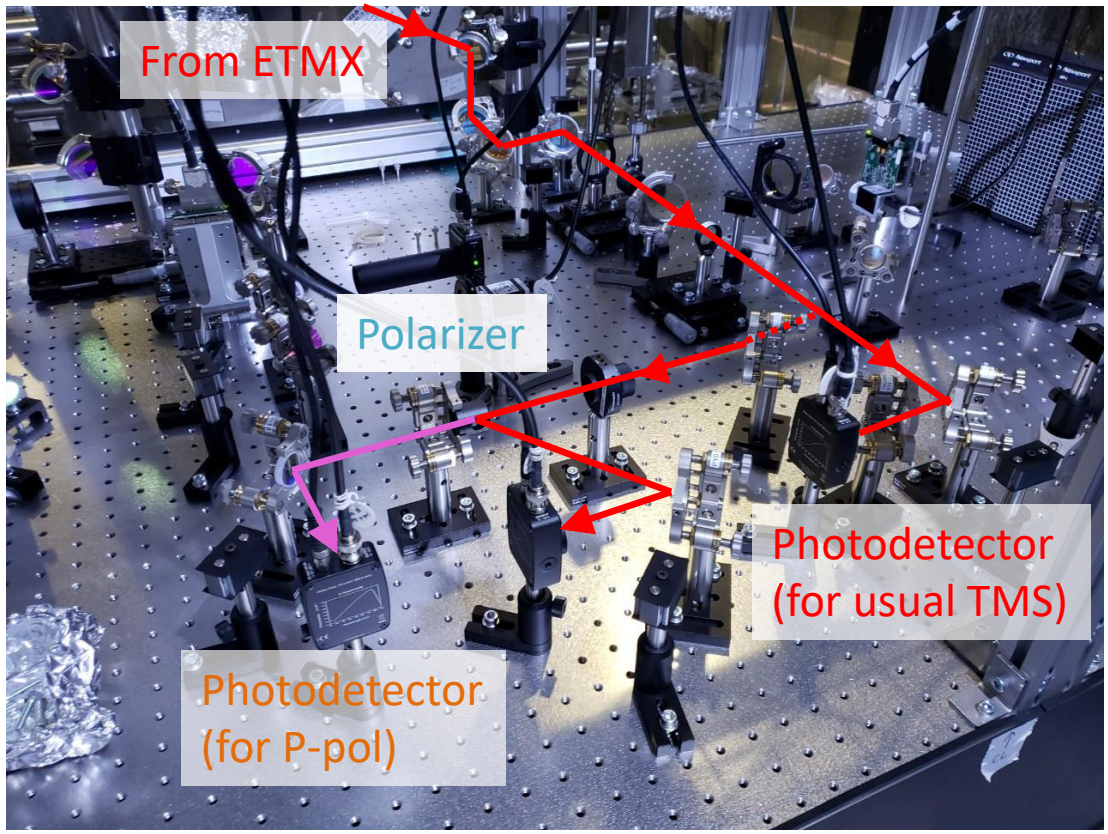
Polarization monitor at TMS in KAGRA

- Polarization monitor has been mostly installed at X-arm transmission monitor system (TMS).
  - This is used for polarization monitor during commissioning.

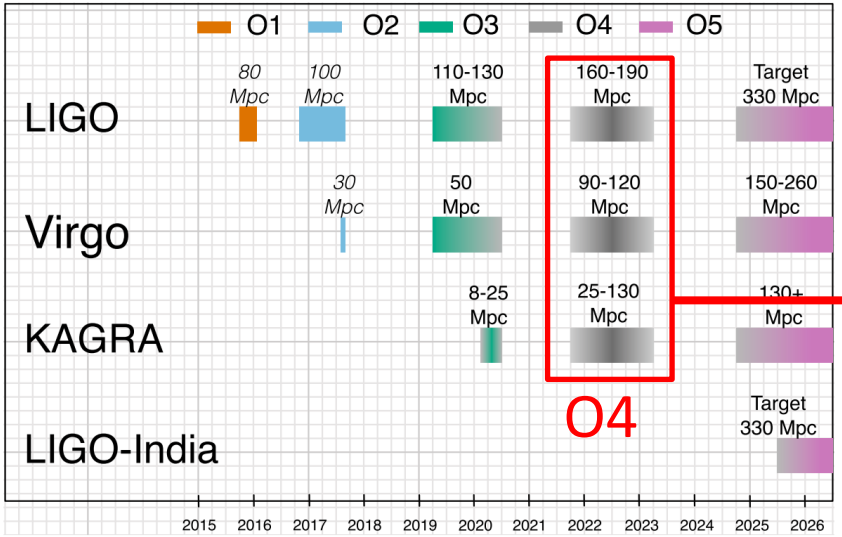




Picture of TMS at X-end. [klog #17692]

Upcoming schedule

- Up to FY2021, instrumental installations are (almost) done for the ADAM-GD.
- In the next fiscal year (FY2022),
  - We will prepare the analysis pipeline, which can be an application of (or the same to) the vector dark matter search or the continuous GW waves.
  - KAGRA will join the international GW observation run (called *O4*) in which the axion DM is also searched.



Planed GW observation runs. (LVK Collab., Living Reviews in Relativity 21, 3 (2020)

Delayed but will start in mid-December 2022 [1].

[1] https://www.ligo.caltech.edu/news/ligo20211115

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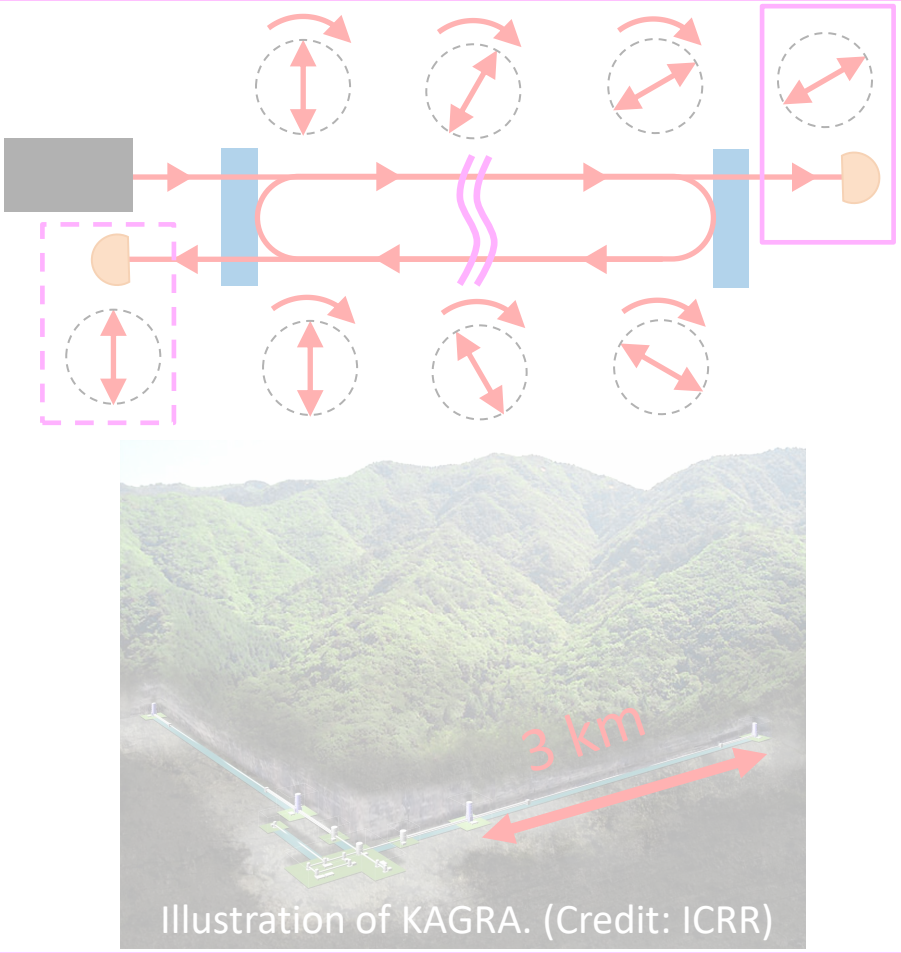
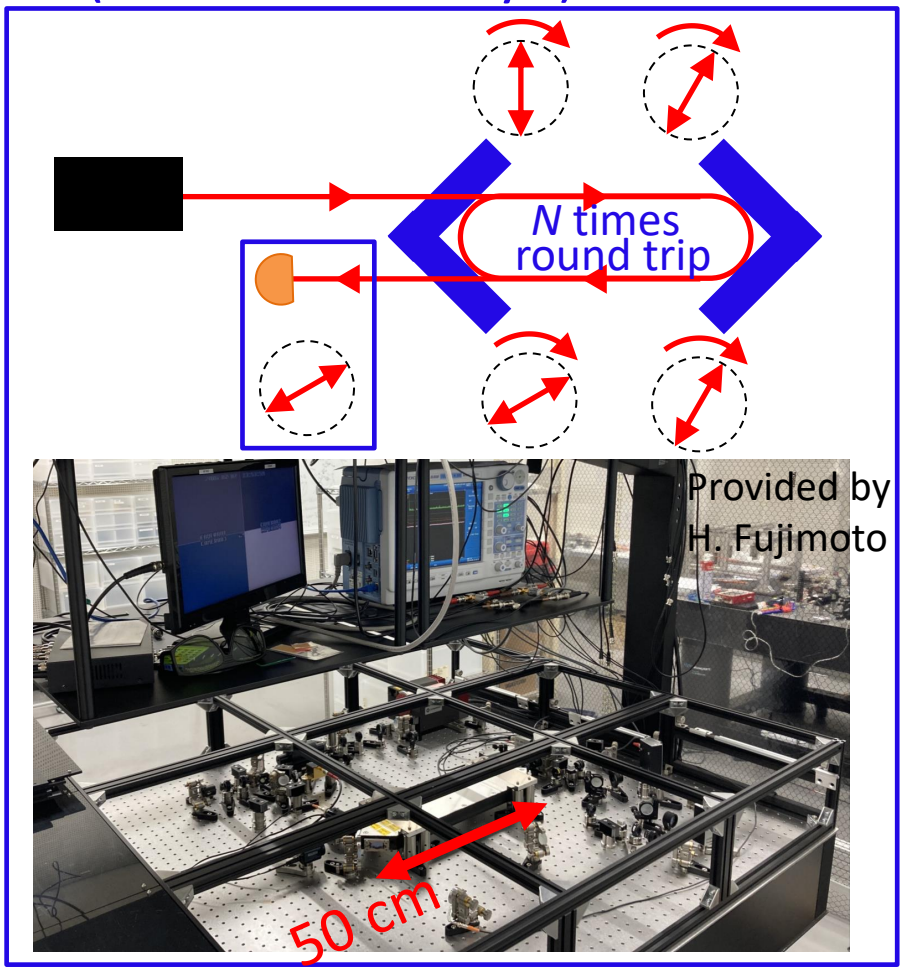


KN+, PRL 123 , 111301 (2019); KN+, PRD 104, 062008 (2021)

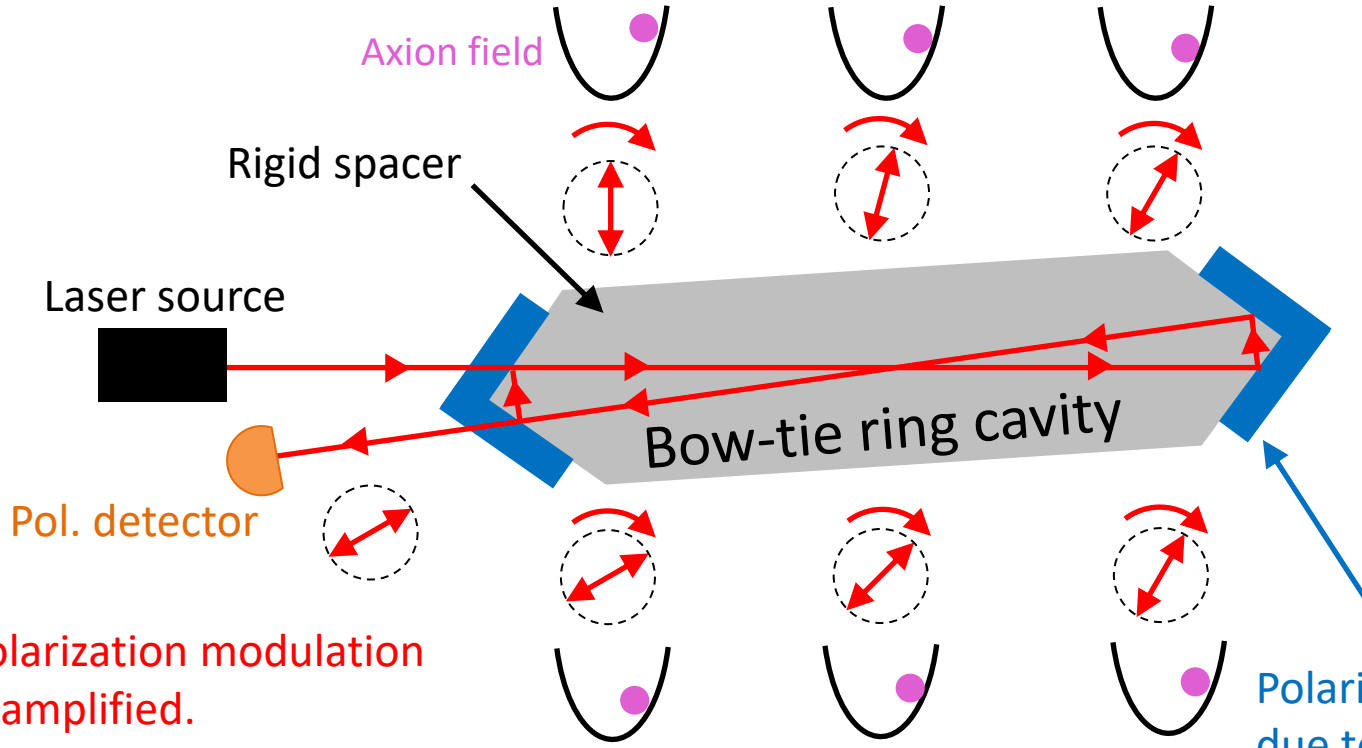
Table-top experiment (DANCE at UTokyo)



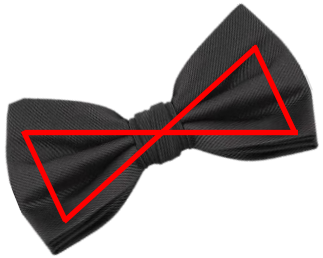
I. Obata,T. Fujita, Y. Michimura, PRL 121, 161301 (2018)

Search for axions with pair mirrors

- Polarization modulation can be enhanced.
- Table-top experiments can achieve as high sensitivity as the large instrument.



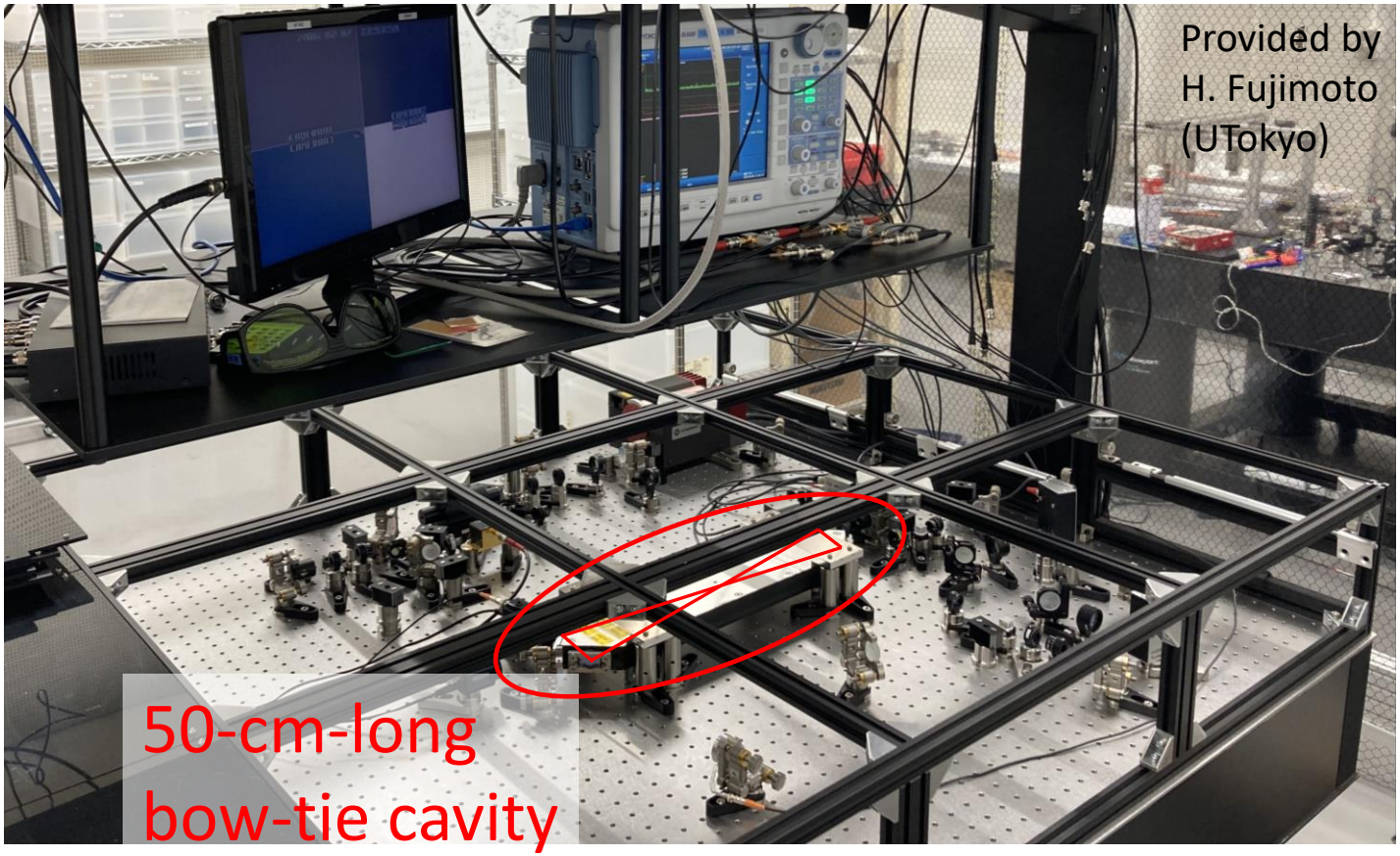
(Note) We use a bow-tie ring cavity to reduce the Sagnac effect.



I. Obata,T. Fujita, Y. Michimura, PRL 121, 161301 (2018)

DANCE experiment

- DANCE: Dark matter Axion search with riNg Cavity Experiment



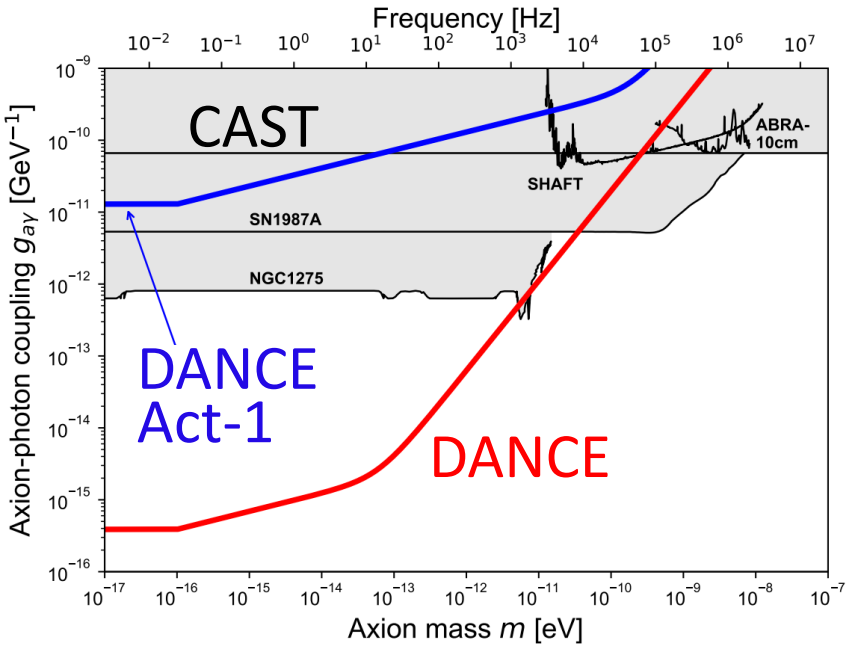
@UTokyo

DANCE overview

- DANCE aims to reach beyond CAST limit by 5 orders of magnitude, at most.
- DANCE Act-1 is the prototype experiment with moderate parameters to impose the comparable limit to CAST independently.

	DANCE	DANCE Act-1
Optical path length	10 m	1 m
Input laser power	100 W	1 W
Finesse (~ # of round trip)	1×10^{6}	3×10^{3}

Y. Oshima+, arXiv:2110.10607 (Modified)

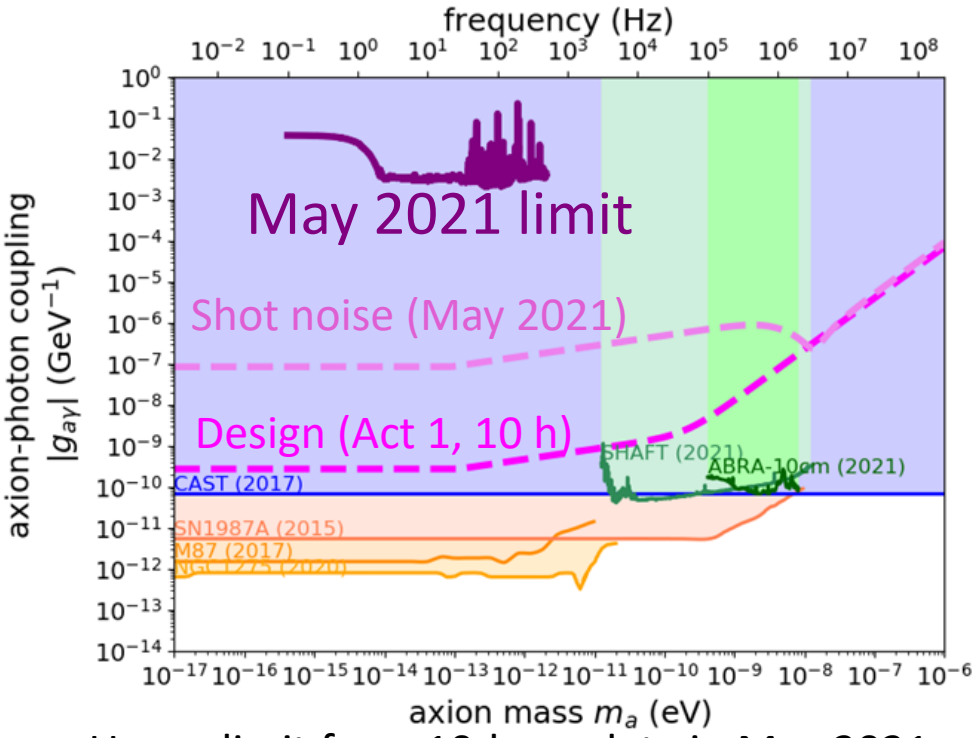


Design sensitivity. (only shot noise)

DANCE act-1 test observation

- In May 2021, the 12-days first test observing run was performed.
- Design sensitivity (= shot noise limit) was far.
  → Some practical issues.
- Non-simultaneous resonance of the p- and s-polarized light.
  - Reflection phases of the two polarizations are different.

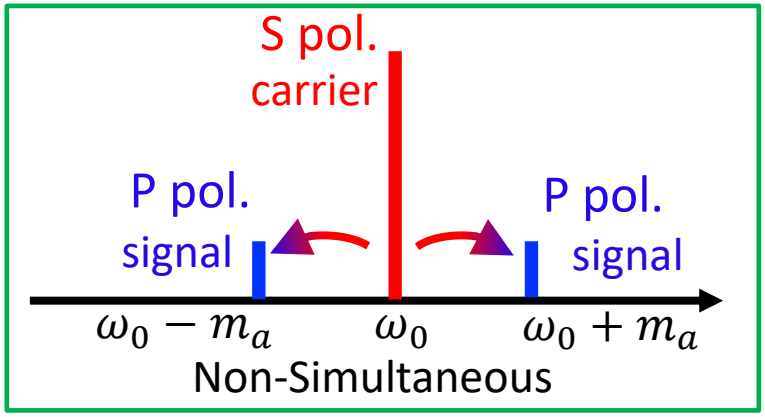
Analysis by Y. Oshima and H. Fujimoto.
Provided by Y. Michimura.

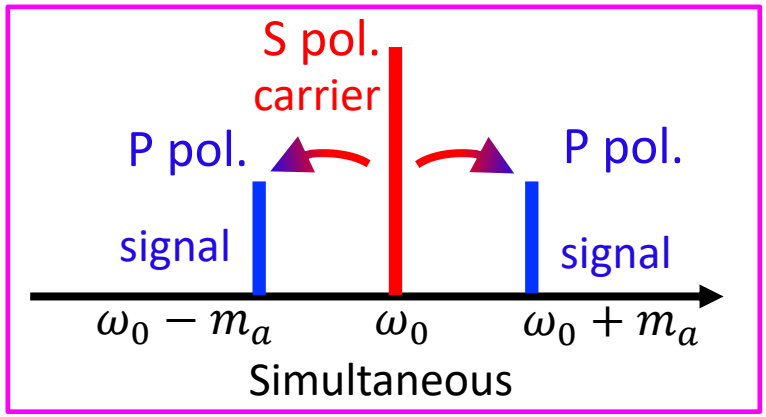


Upper limit from 10-hour data in May 2021.

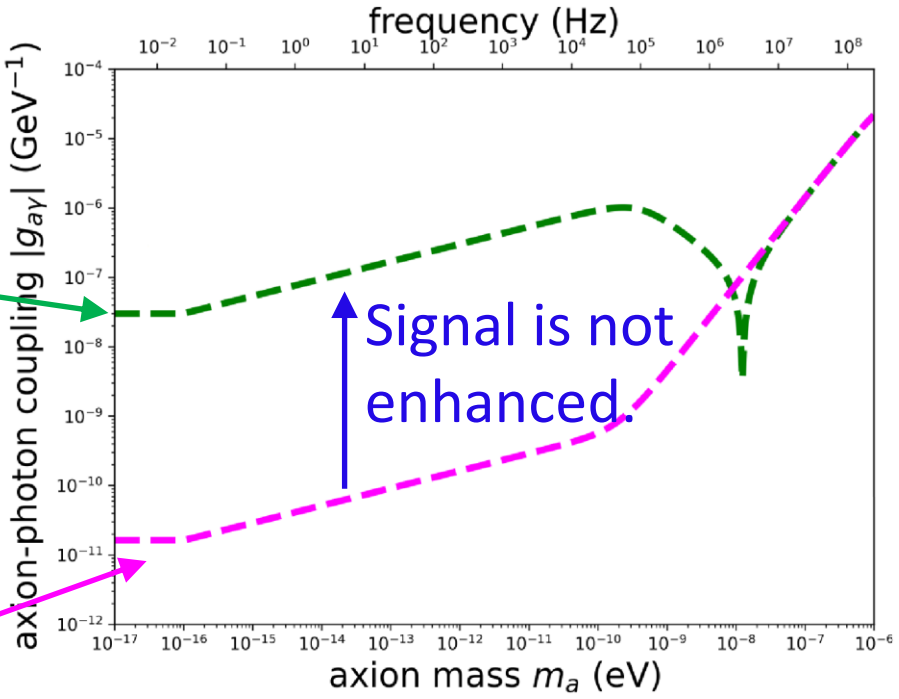
Simultaneous resonance is required

- To enhance the sensitivity, the s-pol. (carrier) and p-pol. (signal) lights should simultaneously resonate in the cavity.





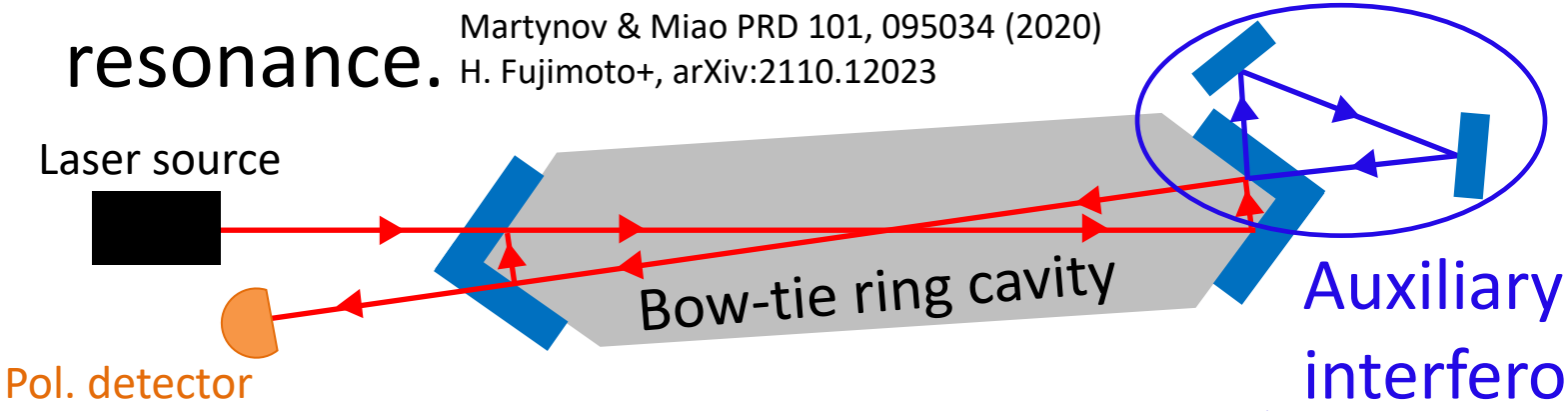
Provided by H. Fujimoto.



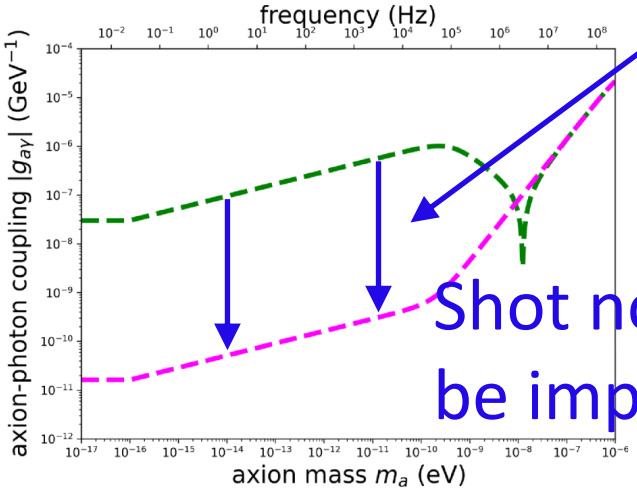
Phase compensation of p-polarization

- Auxiliary interferometer to compensate the phase difference can lead to the simultaneous resonance.

Martynov & Miao PRD 101, 095034 (2020)
H. Fujimoto+, arXiv:2110.12023



Auxiliary interferometer

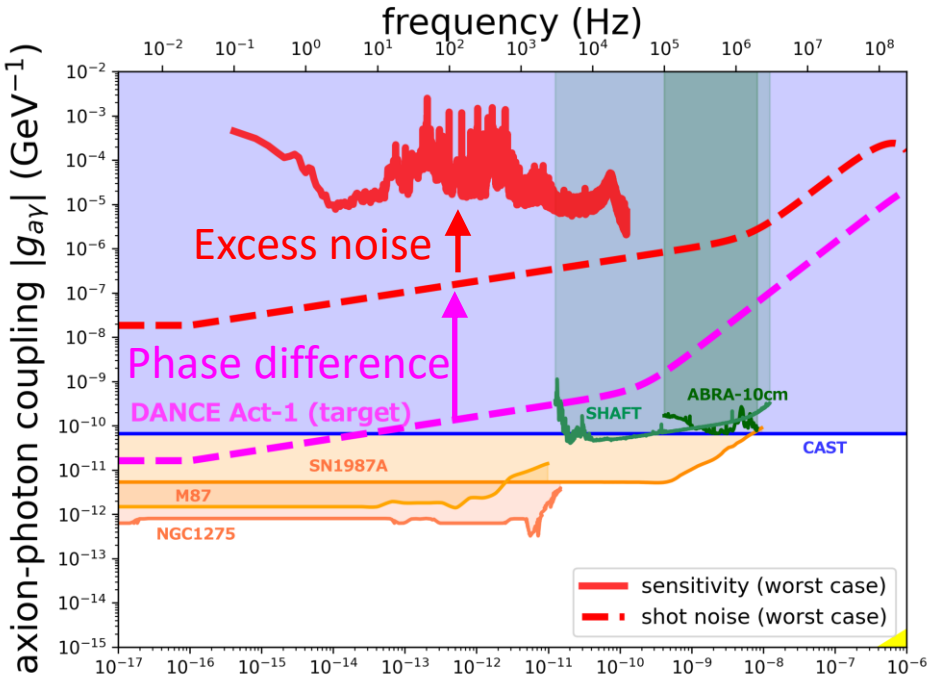


Shot noise can be improved.

Simultaneous resonance demonstration

- (Partial) simultaneous resonance by the auxiliary cavity has been demonstrated.
- However, there are still phase difference and excess noises.
- Further investigation is on going.

H. Fujimoto, Master Thesis, UTokyo (2022)



Provided by H. Fujimoto.

Current sensitivity estimation.
(1 year observation is assumed.)

Researches in/around B01 group

	Existing instrument, KAGRA	Table-top experiments
Axion DM	- Installation of the optic for the next (GW) observation - Analysis pipeline development	- Development of the prototype experiment: DANCE - First test axion DM observation
Vector DM	- Ready for the observation (No additional installation is necessary.) - Analysis pipeline development	

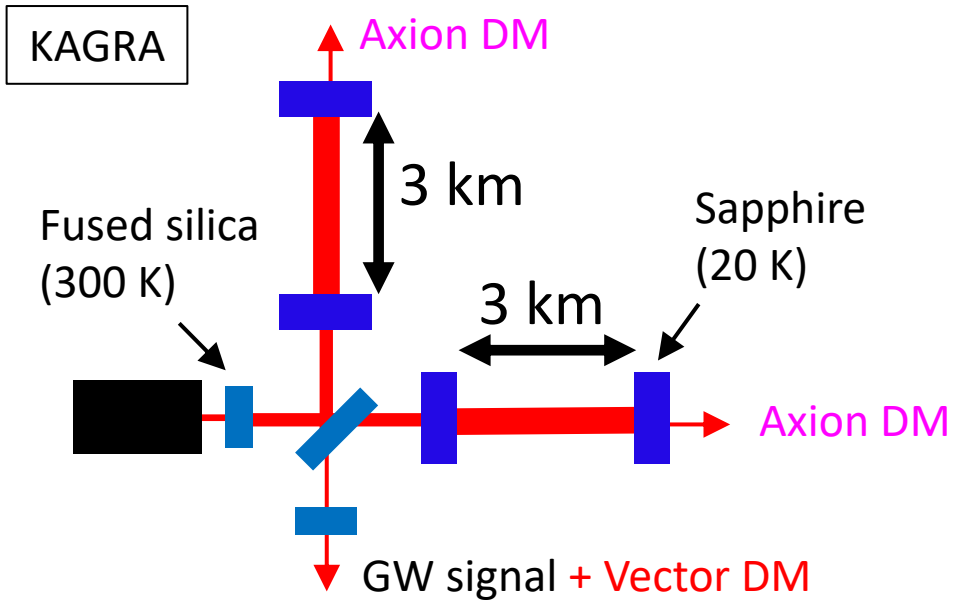
A few words on vector DM searches

- Vector DM behaves as force applied to the mirror in GW observatory.
  = GW observatory can intrinsically search for the vector DM.
- New upper limit has been put using the actual data of the GW detectors.

H-K Guo+, Communications Physics 2, 155 (2019)
LIGO, Virgo, KAGRA Collaboration, arXiv:2105.13085

- KAGRA, which has different material mirrors (sapphire and fused silica), can contribute in another way.

Y. Michimura+, PRD 102, 102001 (2020)
S. Morisaki+, PRD 103, L051702 (2021)



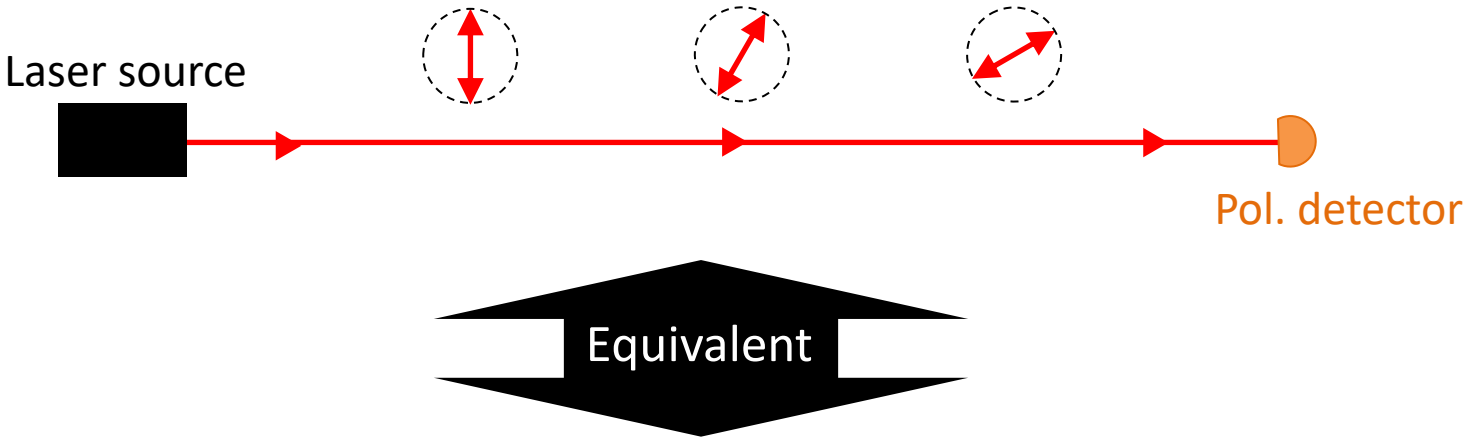
Summary

- Axion makes phase velocity modulation (or polarization-modulation) of the light.
- New schemes to search for the axion dark matter with laser interferometers are proposed and have been demonstrated.
  - –Axion DM search with GW detector (ADAM-GD)
  - –DANCE experiment
- Observation run will start in near future.

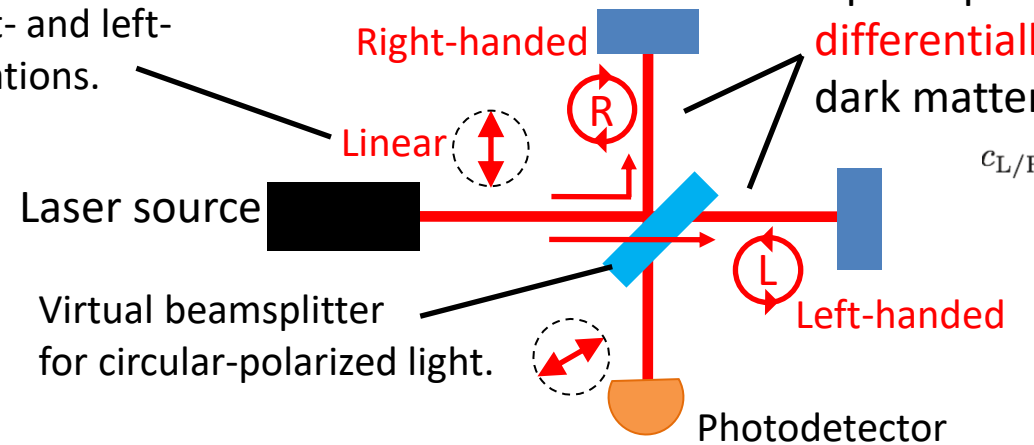
Appendix

Bonus slide

Basic idea how to prove polarization rotation



Note: Linear polarization is expressed as a super position of right- and left-handed polarizations.



Optical path lengths are differentially varied by axion dark matter.

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