PRESENTATION

Hunting Axion Dark Matter with New Techniques

Tomohiro Fujita
(Kyoto & Geneva)

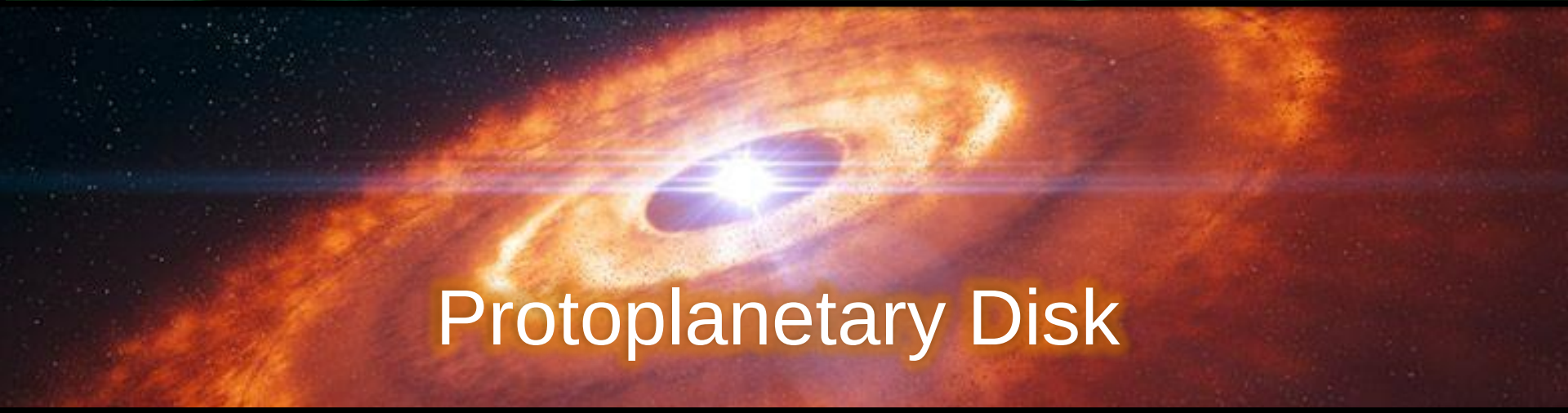
京都大学 KYOTO UNIVERSITY

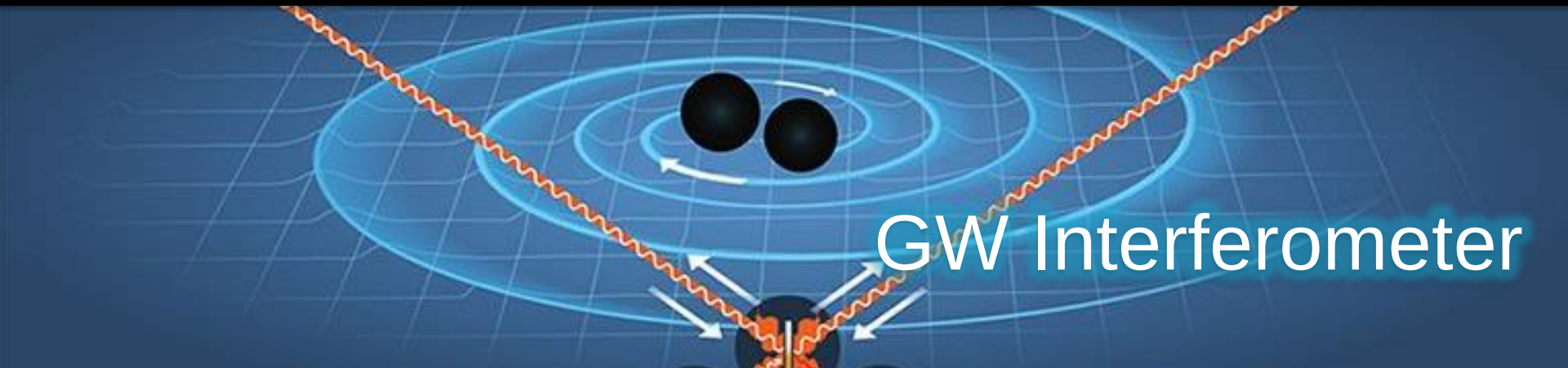
UNIVERSITÉ DE GENÈVE

Obata, TF & Michimura PRL**121,**161301(2018)
TF, Tazaki & Toma PRL**122,**191101(2019)
Nagano, TF, Obata & Michimura [1903.02017]

2nd. Jul. 2019@Warsaw U


Optical Ring Cavity


Protoplanetary Disk


GW Interferometer

Main Message

① Optical ring cavity ② Protoplanetary Disk and ③ GW interferometer provide new and best methods to search for axion dark matter!

Plan of Talk

1. Introduction
2. Optical Ring Cavity
3. Protoplanetary Disk
4. GW Interferometer
5. Summary

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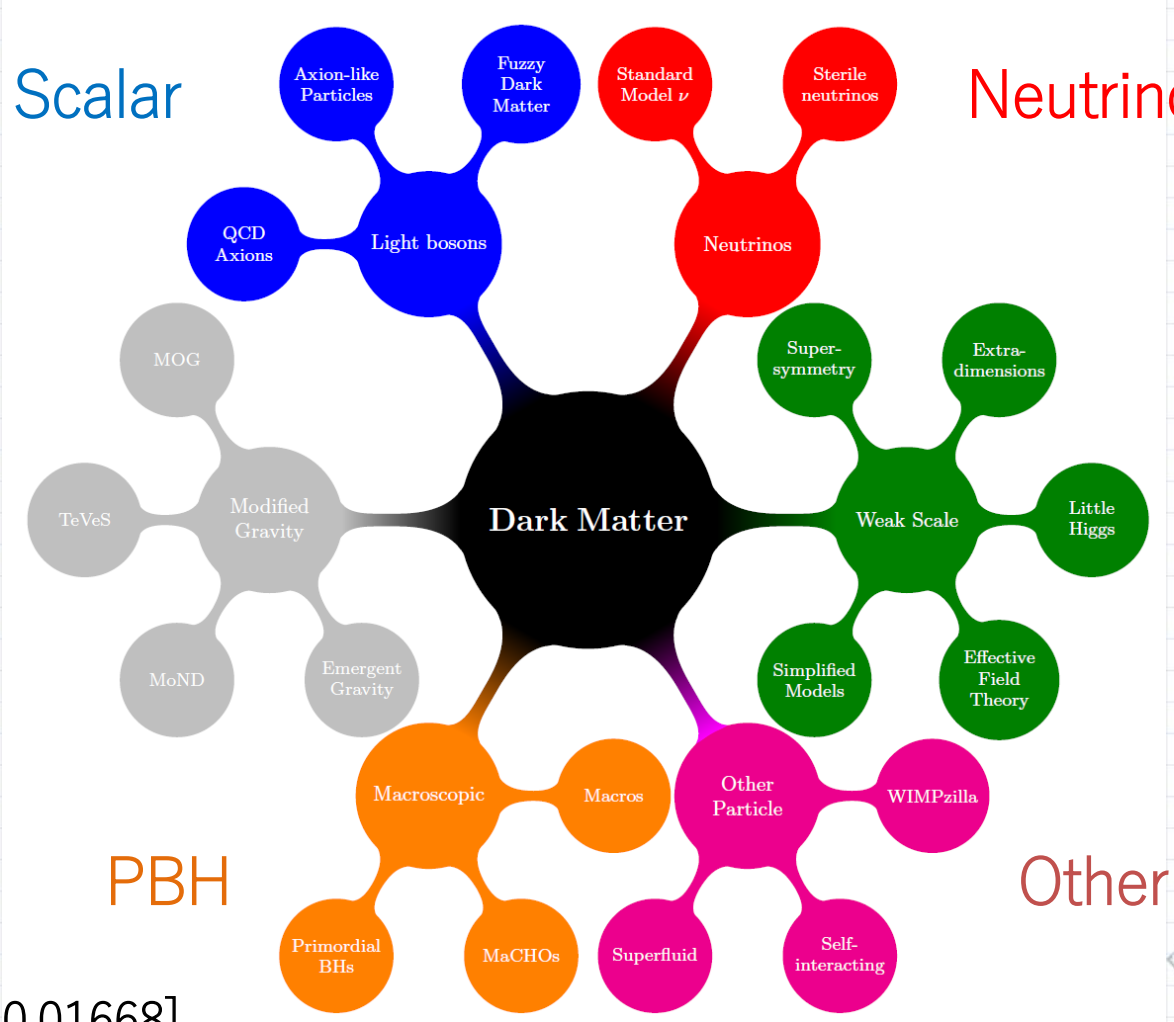
Who is Dark Matter?

PRESENTATION

DM candidates

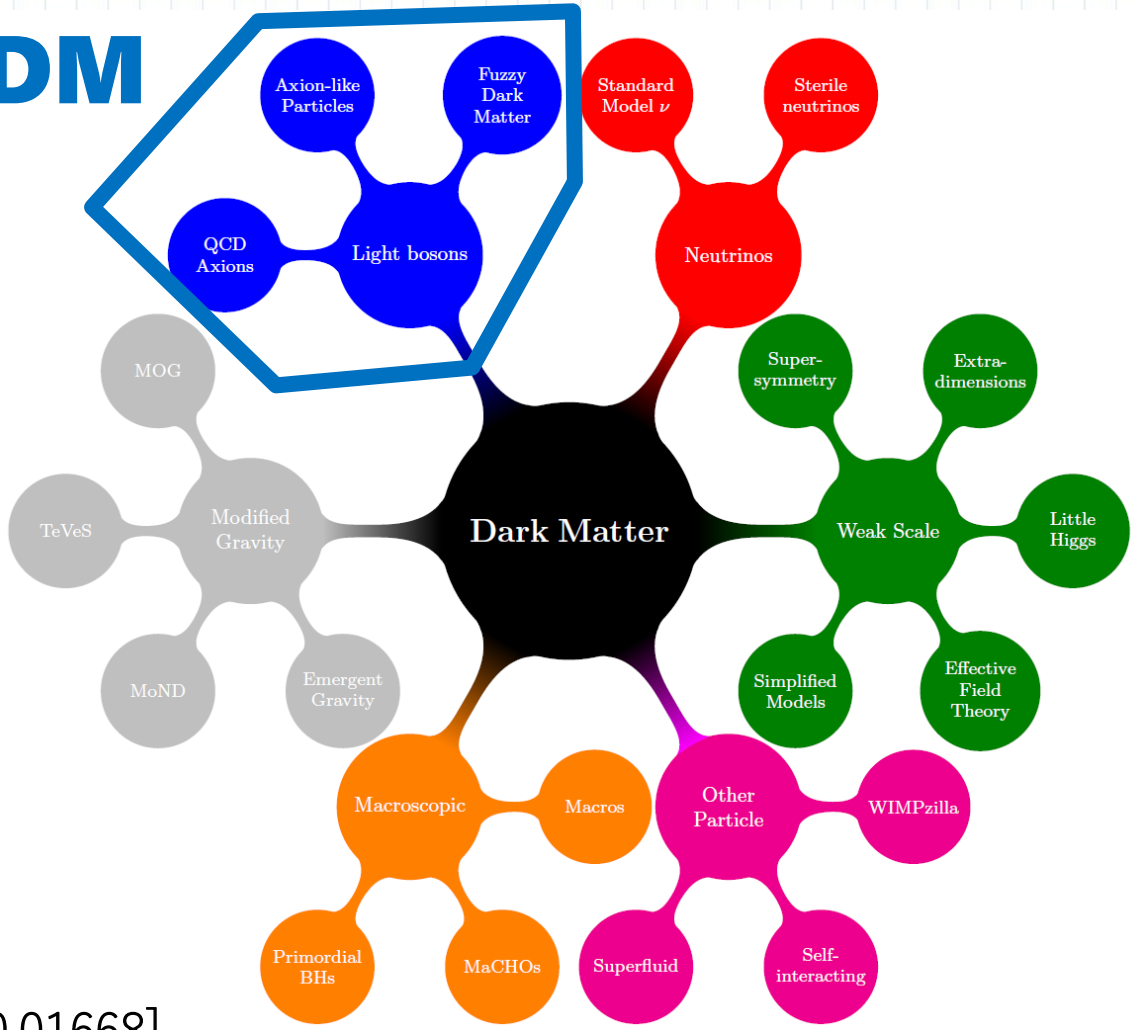


Berton&Tait[1810.01668]

PRESENTATION

DM candidates

Scalar DM



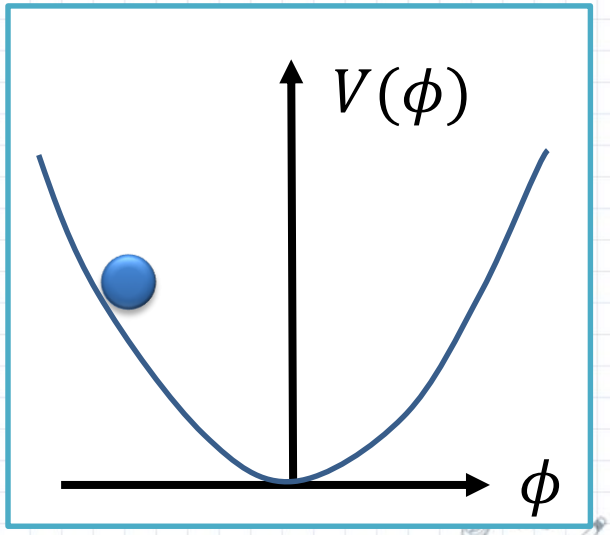
Berton&Tait[1810.01668]

Scalar Dark Matter (∋Axion & ALPs)

- Different from particle DMs: production & evolution

In this talk, we make no assumption on its production & evolution.

- Oscillating Scalar Field: $m \gg H$

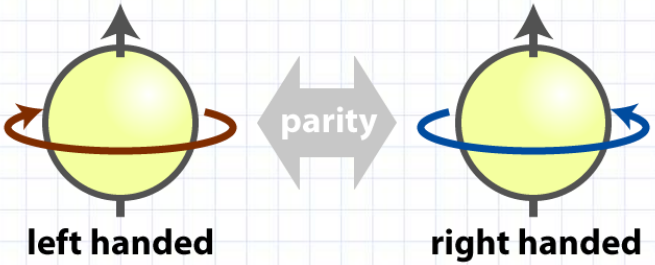


$$\phi = (a/a_0)^{-\frac{3}{2}} \phi_0 \cos(mt + \delta)$$

$$\rho_\phi \propto a^{-3}, \ \delta_m \propto \text{amplitude pert. } \delta\phi(t, \boldsymbol{x})$$

What characterizes ADM?

- ADM can be very light. ($10^{-22}\mathrm{eV} \lesssim m$)
- ADM breaks parity



- ADM may be coupled to photon!!

Useful to Search for DM

Axion-Photon Coupling

- Interaction term: $\mathcal{L}_{\phi\gamma} = \frac{1}{4} g \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$

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Photon: $$\left[\partial_t^2 - \partial_i^2\right] \boldsymbol{A} = -g\dot{\phi} \boldsymbol{\nabla} \times \boldsymbol{A}$$

Axion: $$\left[\partial_t^2 - \partial_i^2 + m^2\right] \phi = -g \dot{\boldsymbol{A}} \cdot \boldsymbol{\nabla} \times \boldsymbol{A}$$

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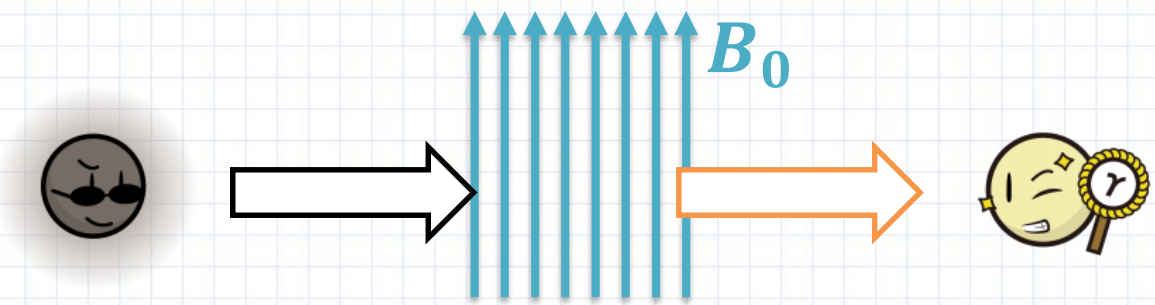
Conventionally constant magnetic field is introduced

Axion-Photon Conversion

- Assume constant Magnetic Field $\boldsymbol{B_0}$

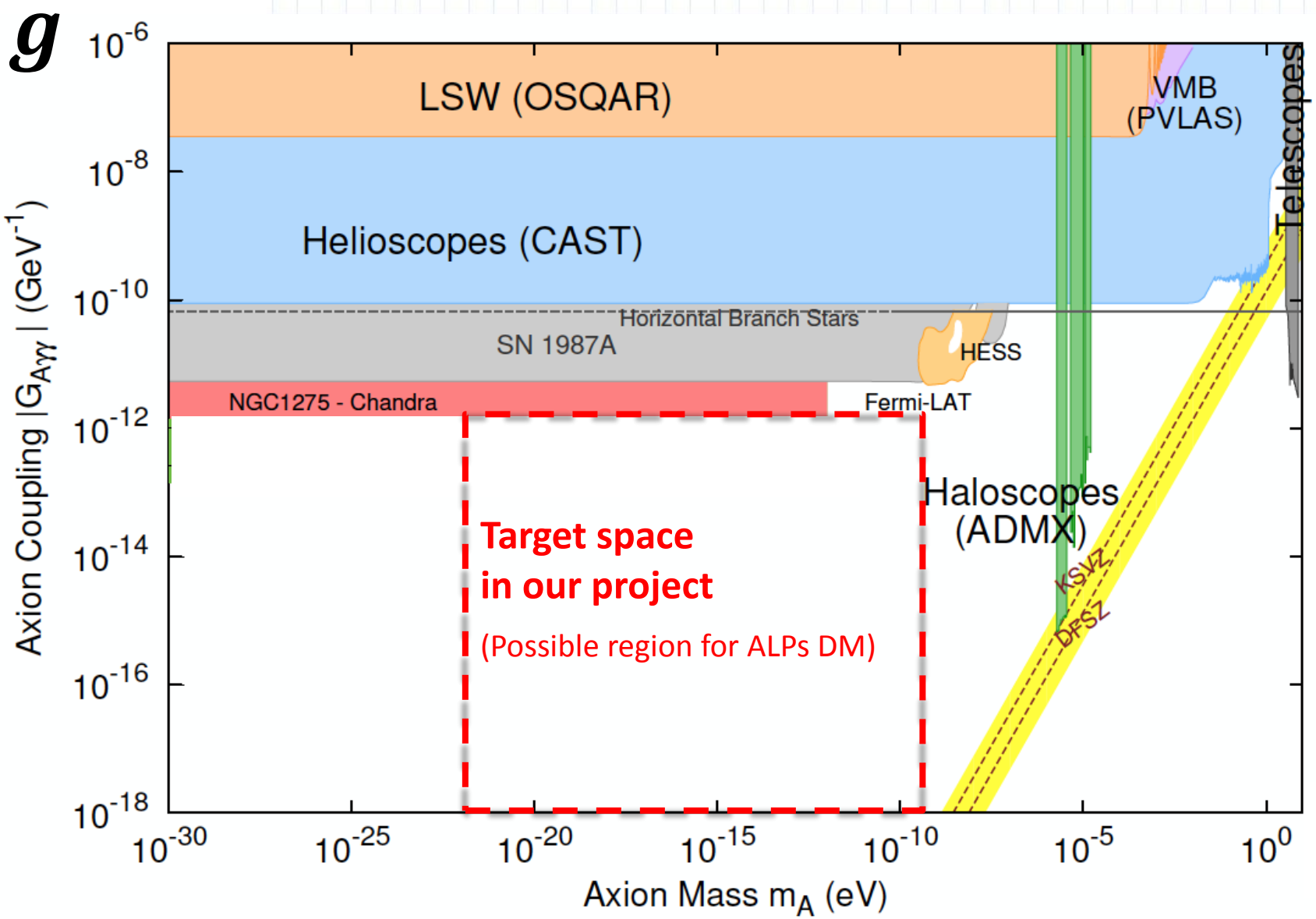
Photon: $$\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\boldsymbol{B_0}\dot{\phi}$$

Axion: $$\left[\partial_t^2 - \partial_i^2 + m^2\right]\phi = -g\boldsymbol{B_0}\cdot\dot{\boldsymbol{A}}$$



introduction

Current constraint



Axion-Photon Coupling

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Anything other than magnetic fields?

New experiment

What if Axion is Dark Matter?

Birefringence

- Assume background DM axion: $\phi(t) = \phi_0 \cos(mt)$

$-m\phi_0 \sin(mt)$

Photon EoM: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}$

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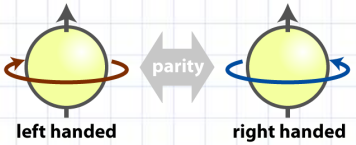
$i\hat{\boldsymbol{k}} \times \boldsymbol{e}_{L,R} = \pm\, \boldsymbol{e}_{L,R}$

Dispersion relations of Left/Right Pol. are modified

$$\omega_{L,R}^2 = k^2\left[1 \pm g\phi_0 \frac{m}{k}\sin(mt)\right]$$



Speed of light changes depending on polarization!

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New experiment

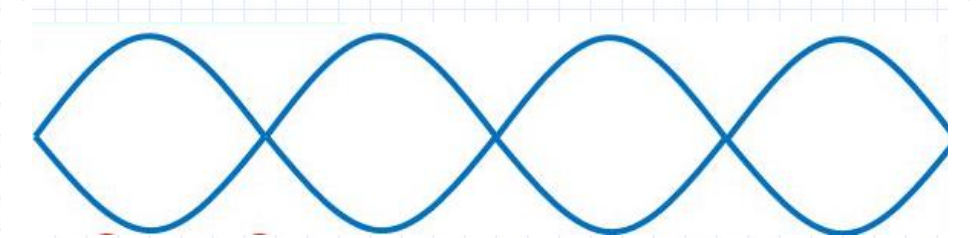
[DeRocco &Hook (2018),
Obata, TF, Michimura(2018)]

- Dispersion relations for Left/Right pol. are different

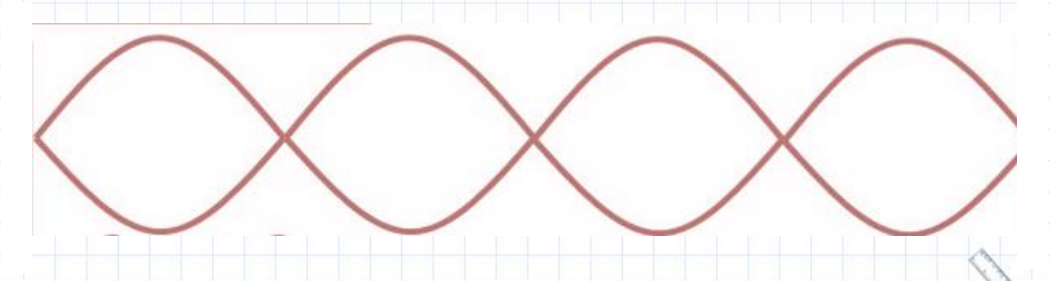
  Travel distance $(kx) \Leftrightarrow$ # of oscillation $(\omega_{\pm} t)$

- How can we experimentally measure it?

Right



Left



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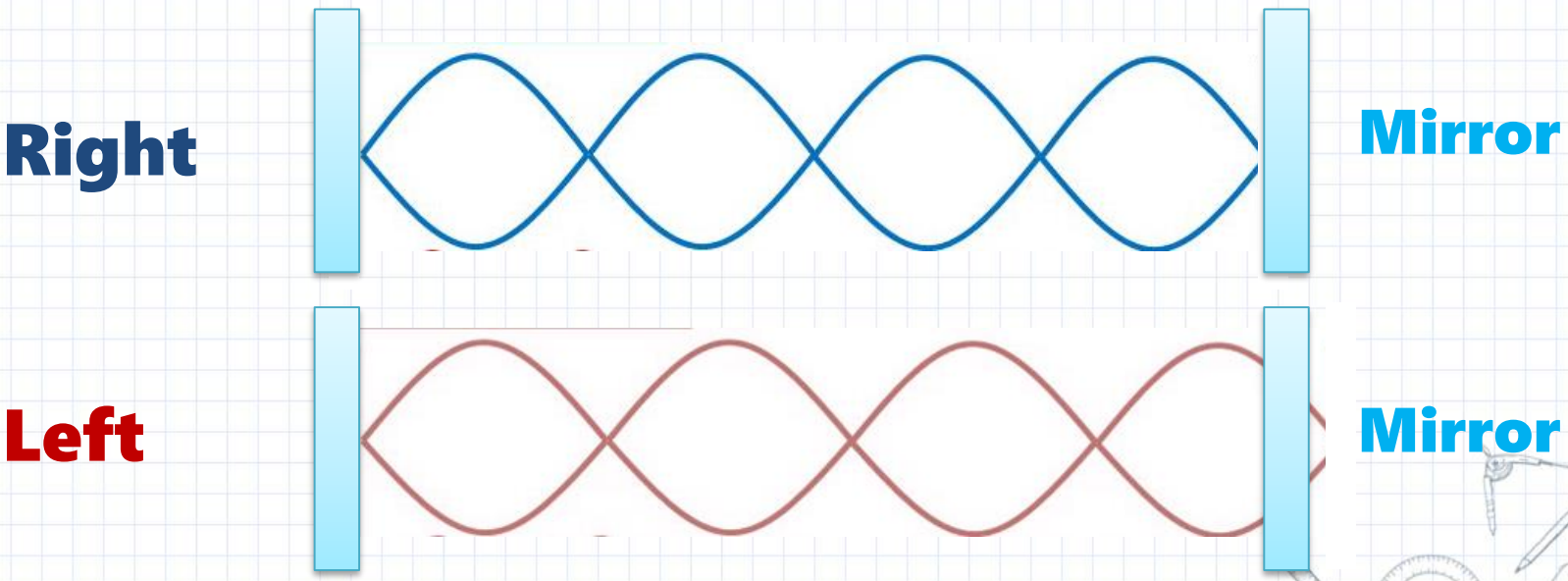

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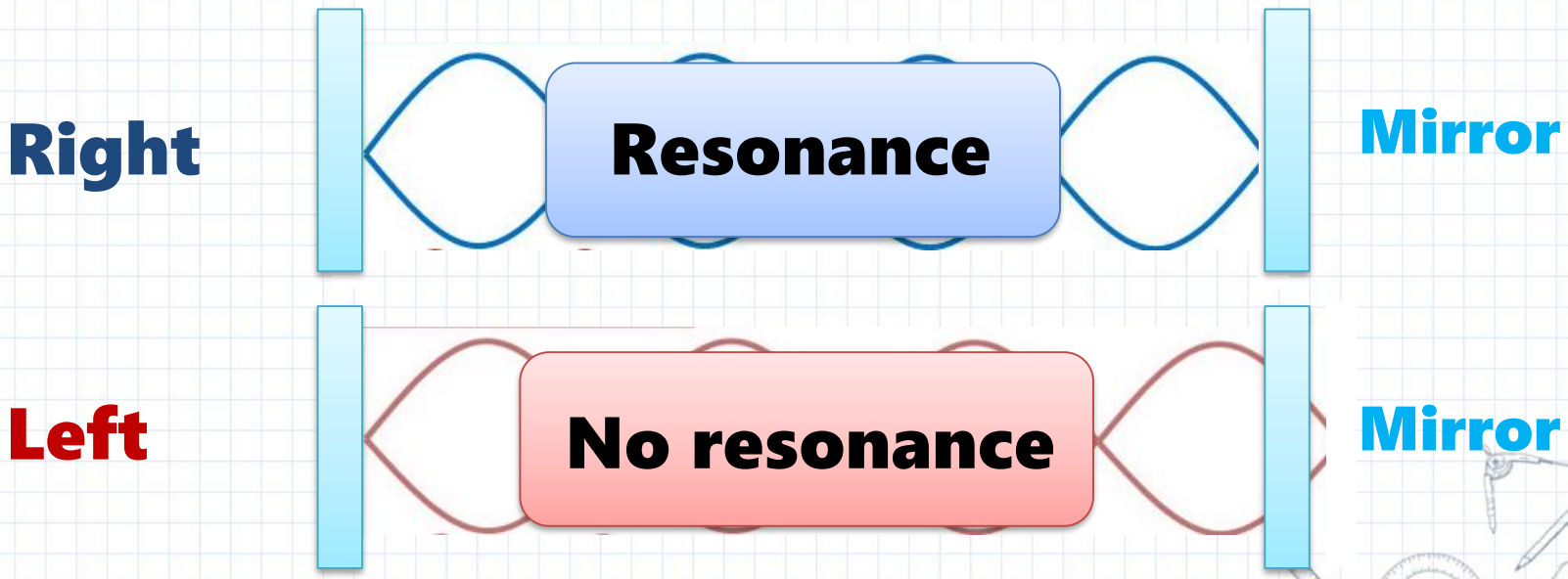

New experiment

[DeRocco &Hook (2018),
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- Dispersion relations for Left/Right pol. are different
- How can we experimentally measure it?

↓

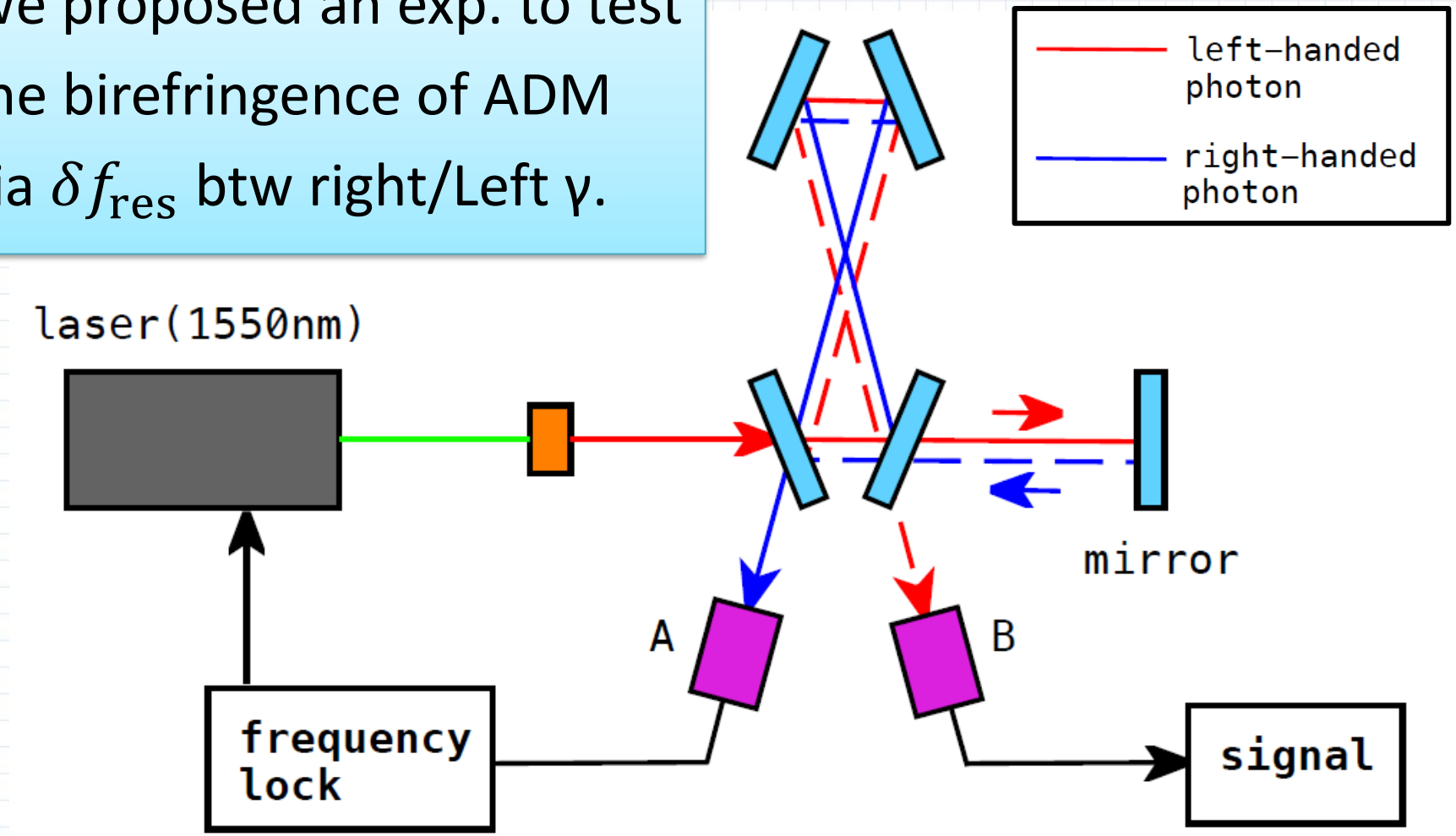
- Optical length changes for left/right pol.
- Resonant Frequency changes in optical cavity

DANCE experiment

Dark matter **A**xion search with ri**N**g **C**avity **E**xperiment

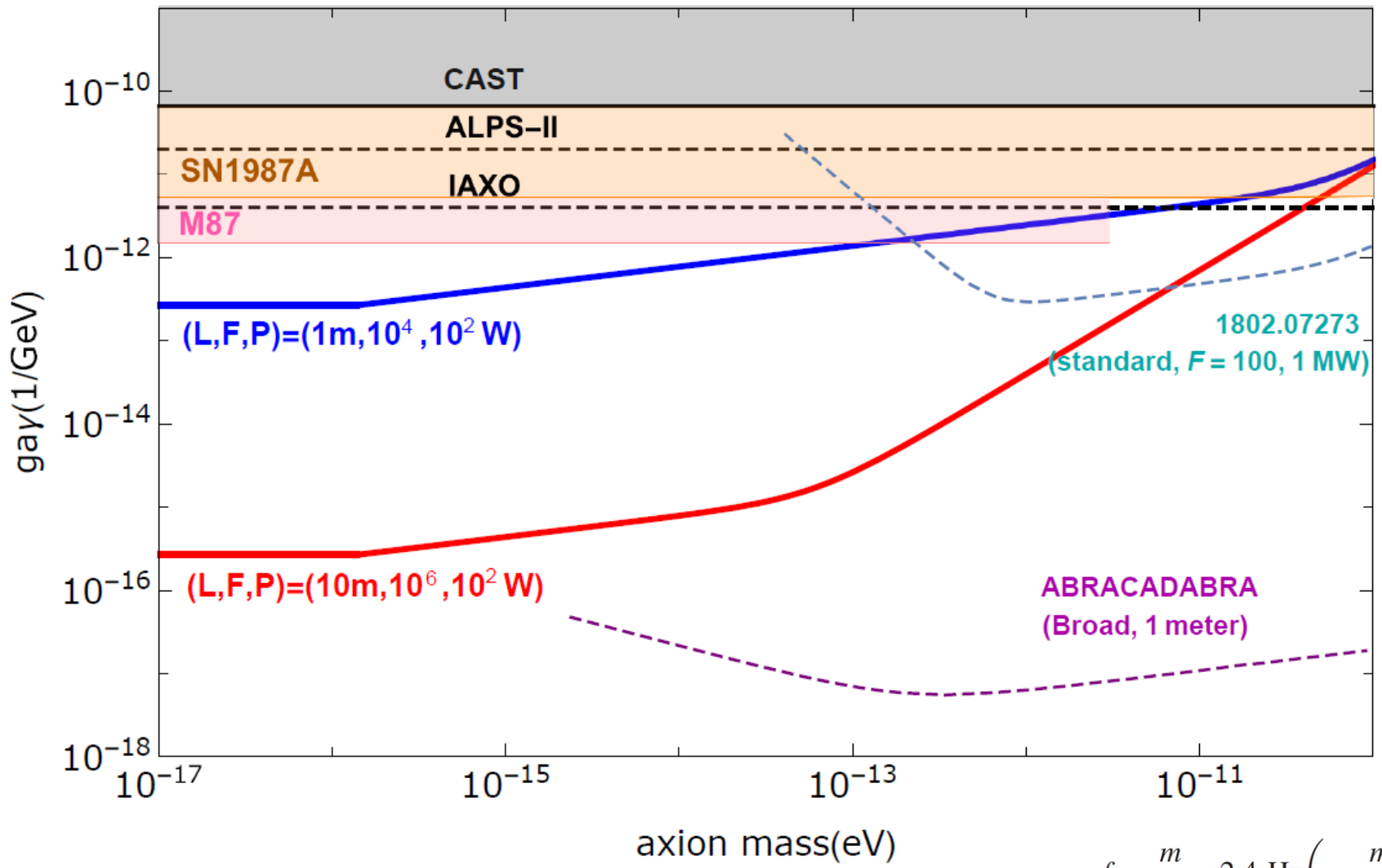
[Obata, TF, Michimura(2018)]

We proposed an exp. to test the birefringence of ADM via δf_{res} btw right/Left γ.



DANCE Sensitivity

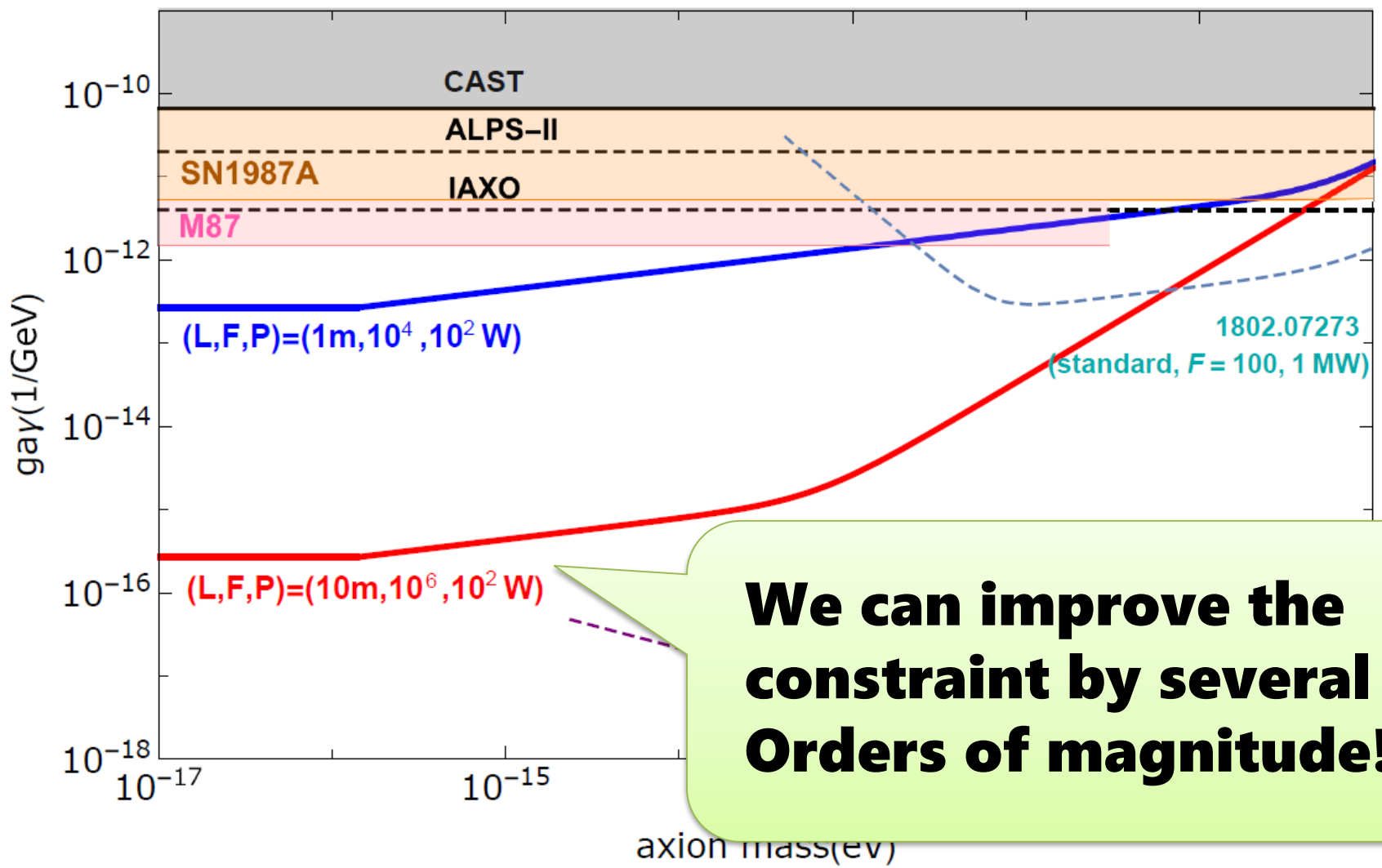
[Obata, TF, Michimura(2018)]



$$f = \frac{m}{2\pi} \simeq 2.4\ \mathrm{Hz}\left(\frac{m}{10^{-14}\ \mathrm{eV}}\right)$$

DANCE Sensitivity

[Obata, TF, Michimura(2018)]

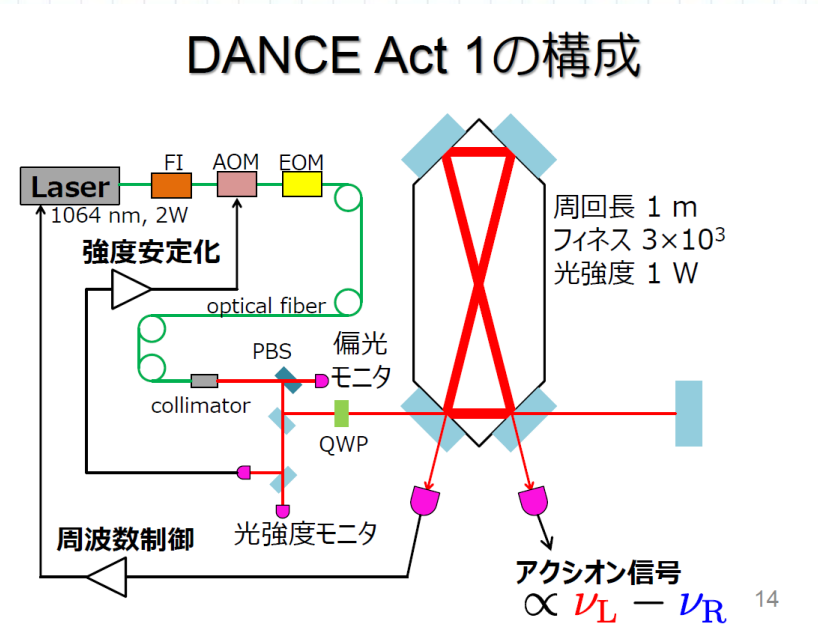


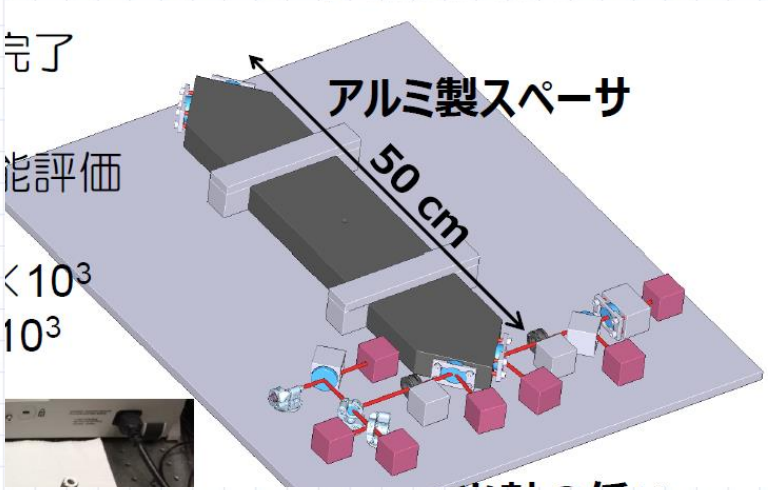
We can improve the constraint by several Orders of magnitude!

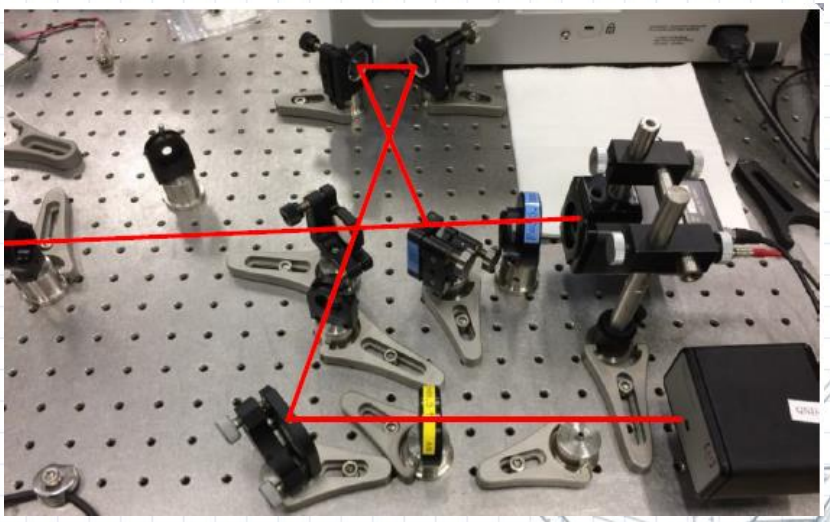
DANCE Act.1 has started!

PRESENTATION

- Prototype exp. (Act.1) is being constructed in U. Tokyo. (Ando lab.)
- The first result (1m, 3months) will be obtained within a year







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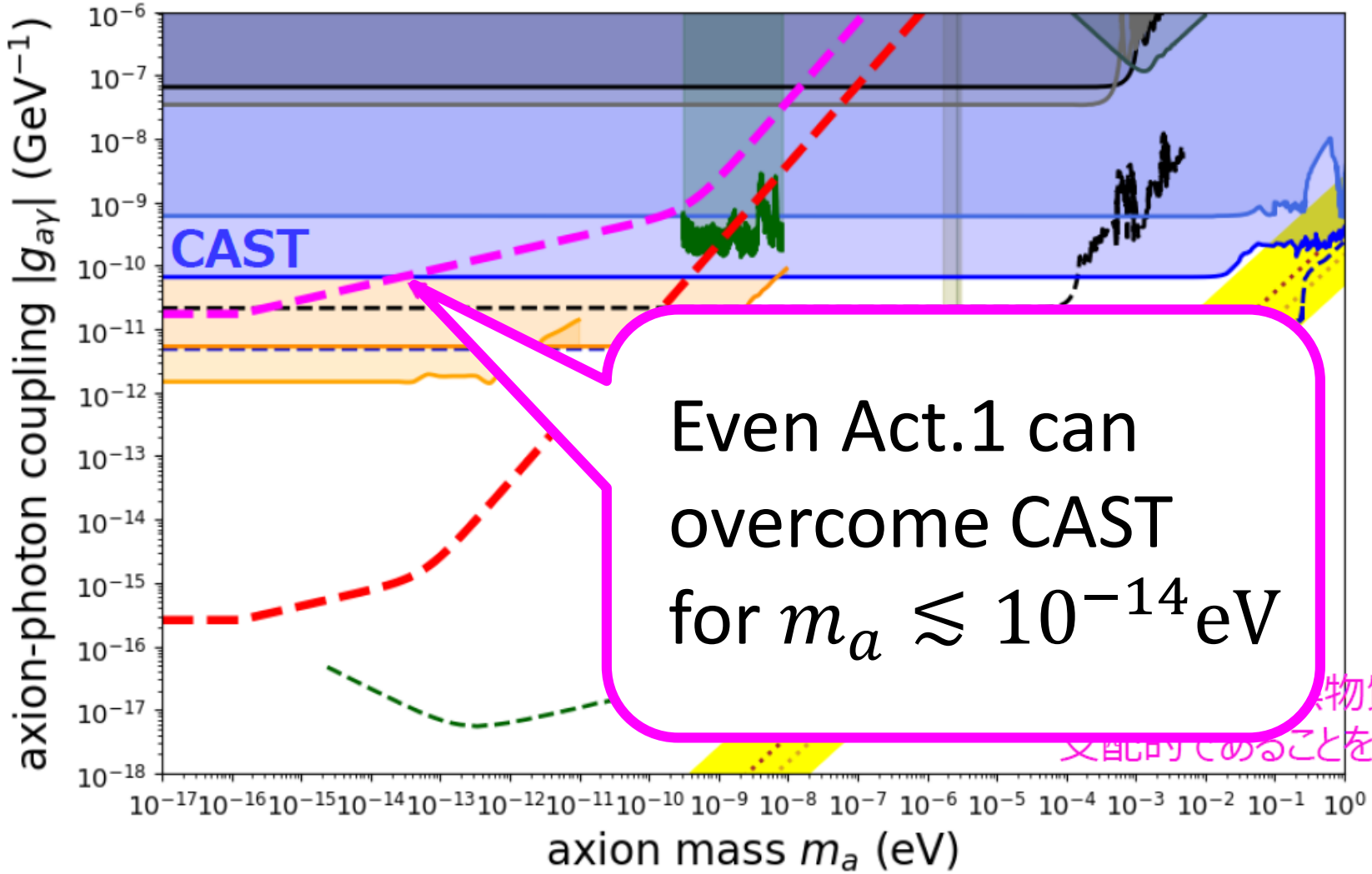
PRESENTATION



Even Act.1 can overcome CAST for $m_a \lesssim 10^{-14}$eV

物質として
支配的であることを仮定

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[No superluminality: 1201.4935]

Birefringence

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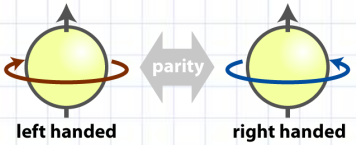


Speed of light changes depending on polarization!

Birefringence

- Another consequence: Rotation of liner pol. Plane

Linear pol. Photon can be decomposed into circular pol.

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 \\ i \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 1 \\ -i \end{pmatrix},$$

$$t \longrightarrow t+T$$

With ADM BG phase velocity are different,

⇨ polarization plane rotates

$$\frac{e^{ikT}}{2}\left[e^{i\int_t^{t+T}\delta\omega \mathrm{d}t}\begin{pmatrix} 1 \\ i \end{pmatrix} + e^{-i\int_t^{t+T}\delta\omega \mathrm{d}t}\begin{pmatrix} 1 \\ -i \end{pmatrix}\right]$$

$$= e^{ikT}\begin{pmatrix} \cos(\int_t^{t+T}\delta\omega\,\mathrm{d}t) \\ -\sin(\int_t^{t+T}\delta\omega\,\mathrm{d}t) \end{pmatrix}.$$

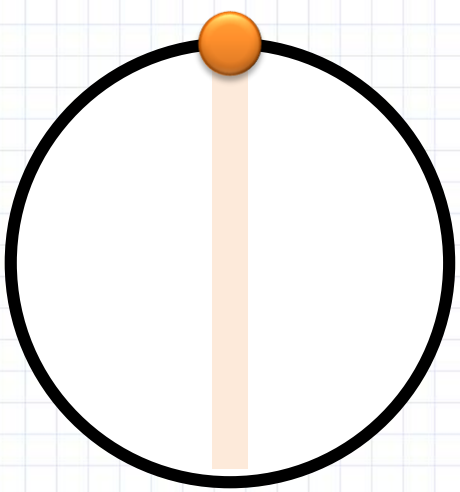
Birefringence

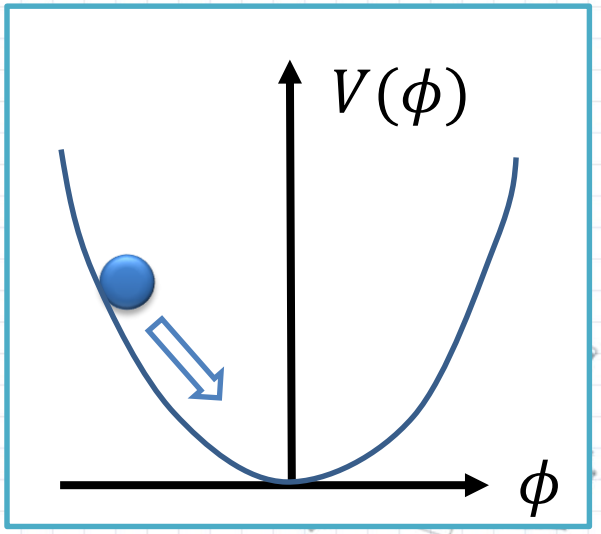
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- Rotation angle synchronizes with Axion

$$\theta(t,T) = \int_t^{t+T} \delta\omega(t)\,\mathrm{d}t = -\frac{g_{a\gamma}}{2}\left[\phi(t+T) - \phi(t)\right],$$

- Motion of the linear polarization plane





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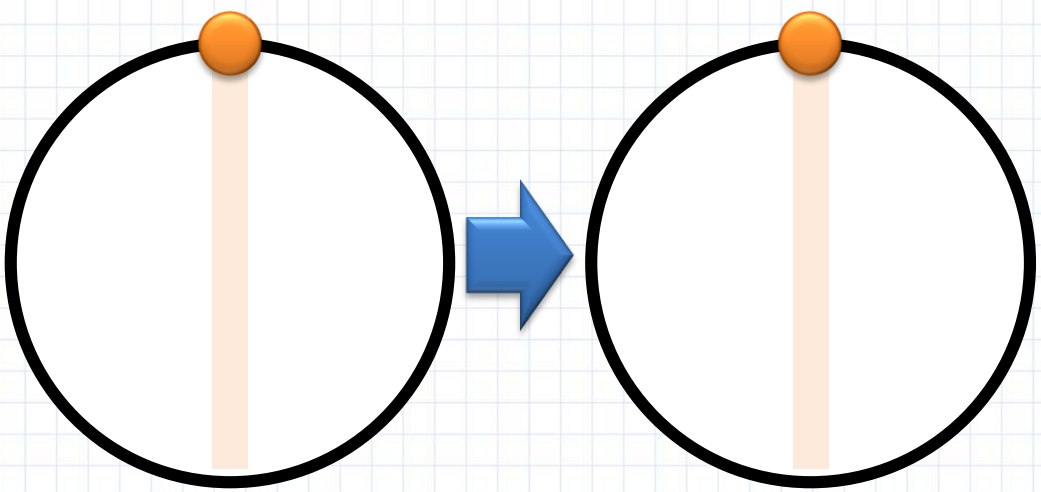

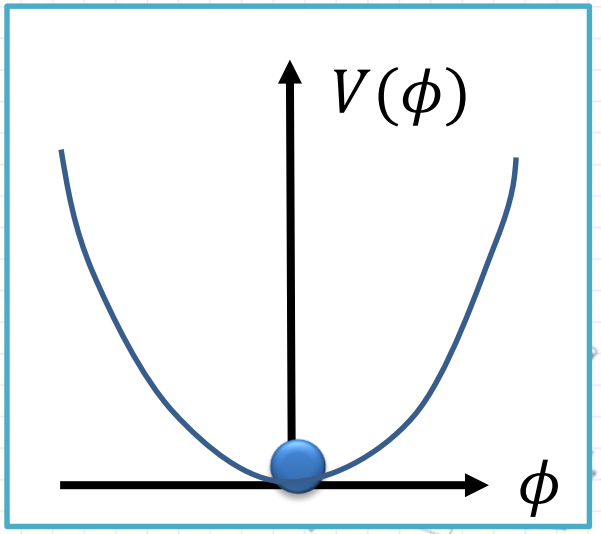

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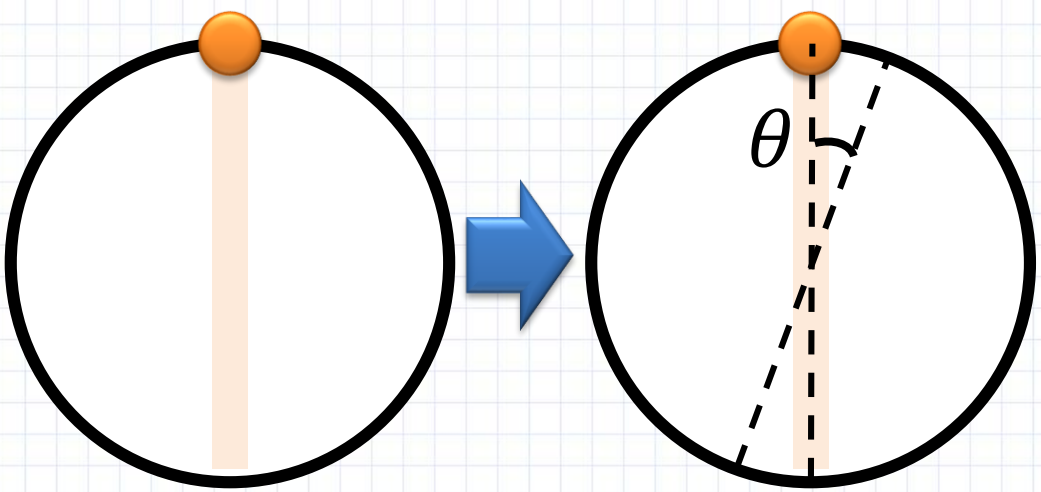
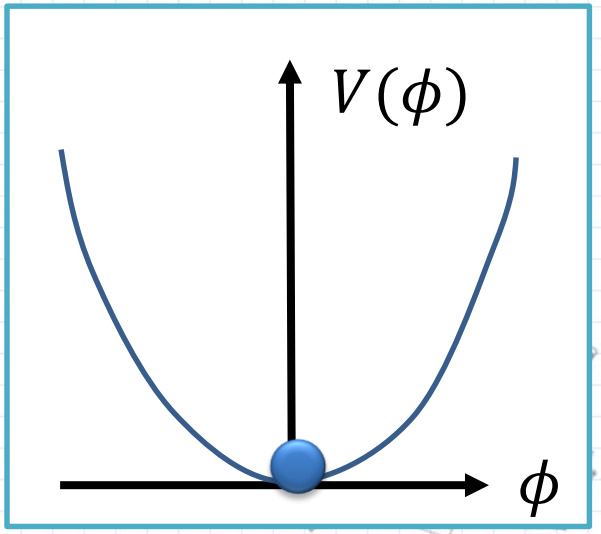




$$\rho_{\rm DM} = m^2\phi_0^2/2 \approx 0.3\ {\rm GeV/cm^3}$$

Birefringence

- Rotation angle is $\sim 10^{-2}$ for largest coupling g

$$\theta(t,T) \approx 2\times 10^{-2} \sin\Xi\, \sin(mt+\Xi+\delta)\, g_{12}\, m_{22}^{-1}$$

$$\Xi \equiv mT/2 \approx 10^2 (T/10{\rm pc}) m_{22}$$

$$g_{12} \equiv g_{a\gamma}/(10^{-12}{\rm GeV}^{-1}),$$
$$m_{22} \equiv m/(10^{-22}{\rm eV})$$

- How can we observe this?

In astro, we don't know the initial polarization plane. Can't measure θ …

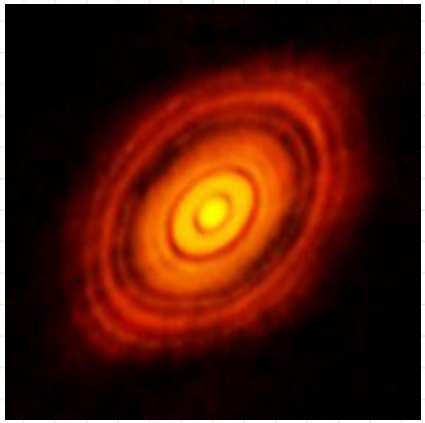
ProtoPlanetary Disk

- Observations of PPD can be used!

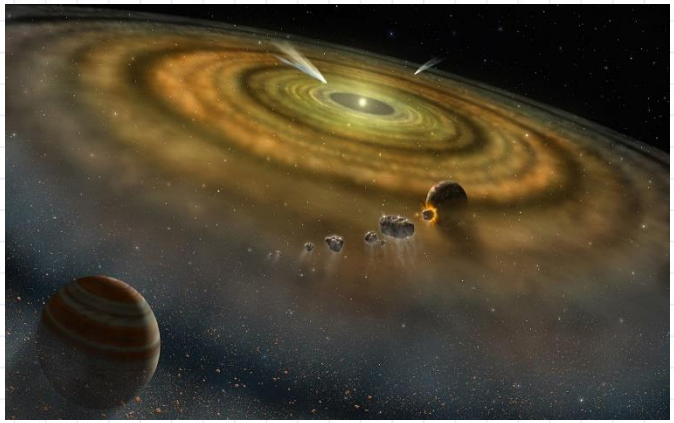
PPD is a flattened gaseous object surrounding a young star.

PPDs are bright simply by scattering the central star's light.

Real data

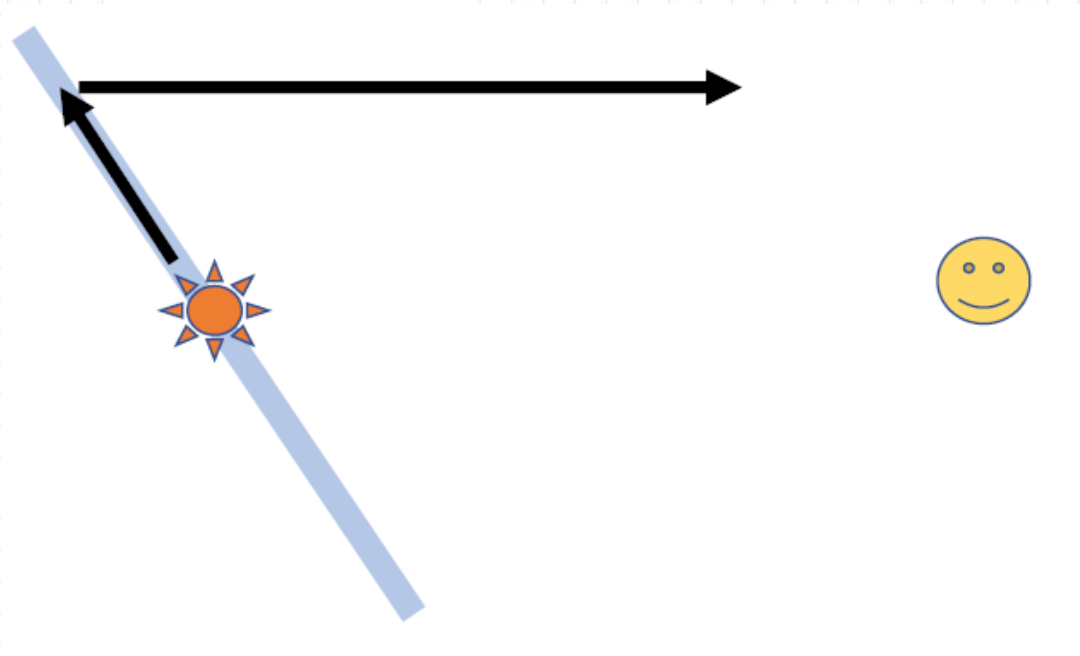


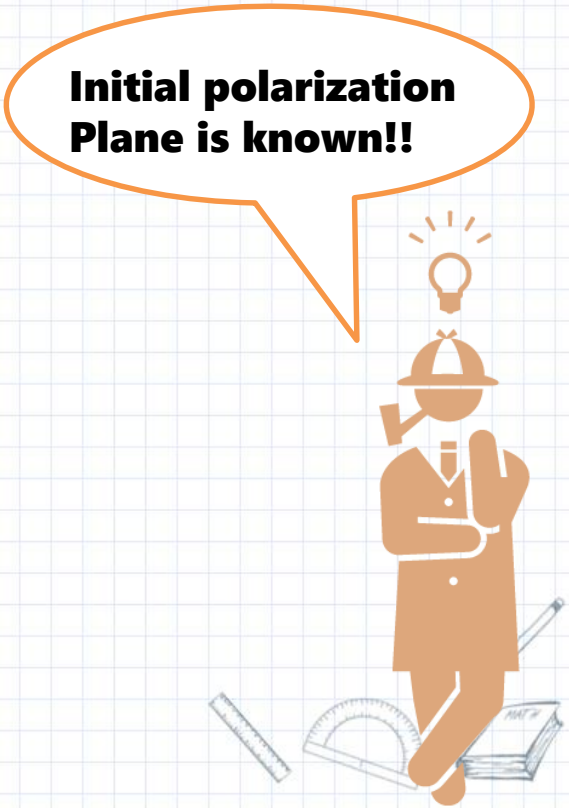
Artist's image



Polarization of PPD

- Scattered light should be polarized perpendicular to the scattering plane (=this monitor).



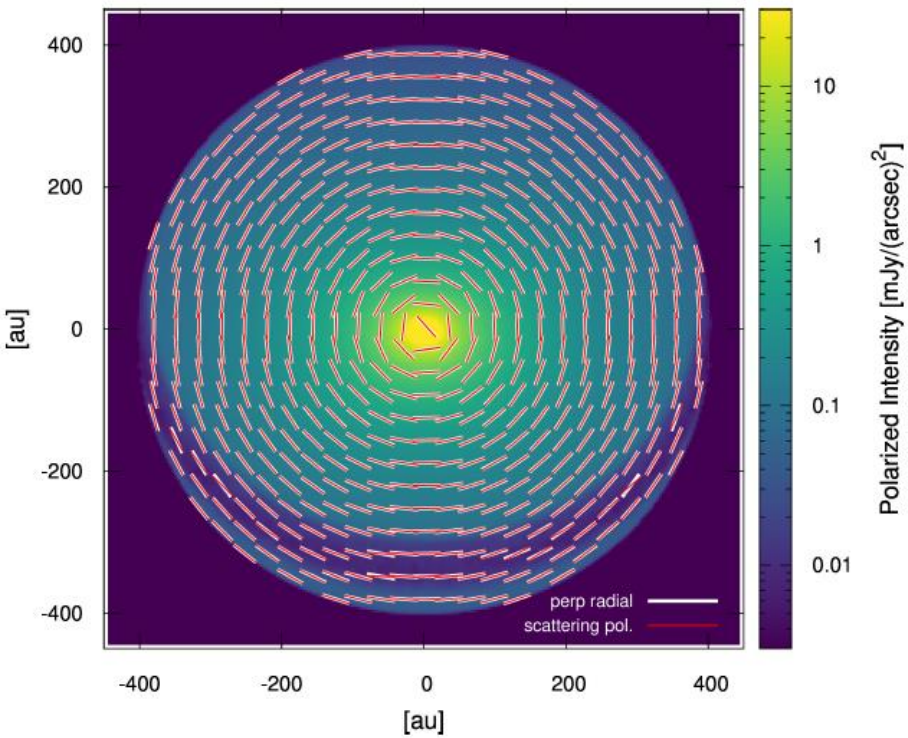


Obsevation of PPD

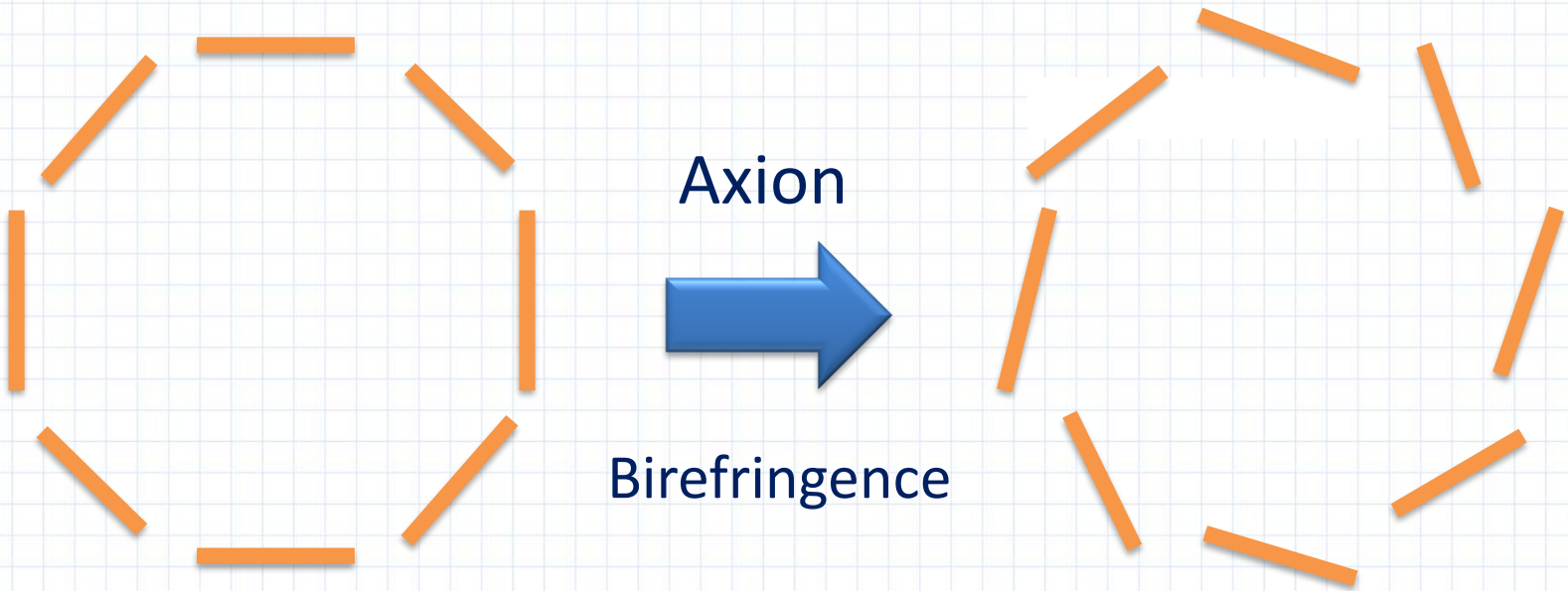
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM



Axion DM rotates pol. plane?



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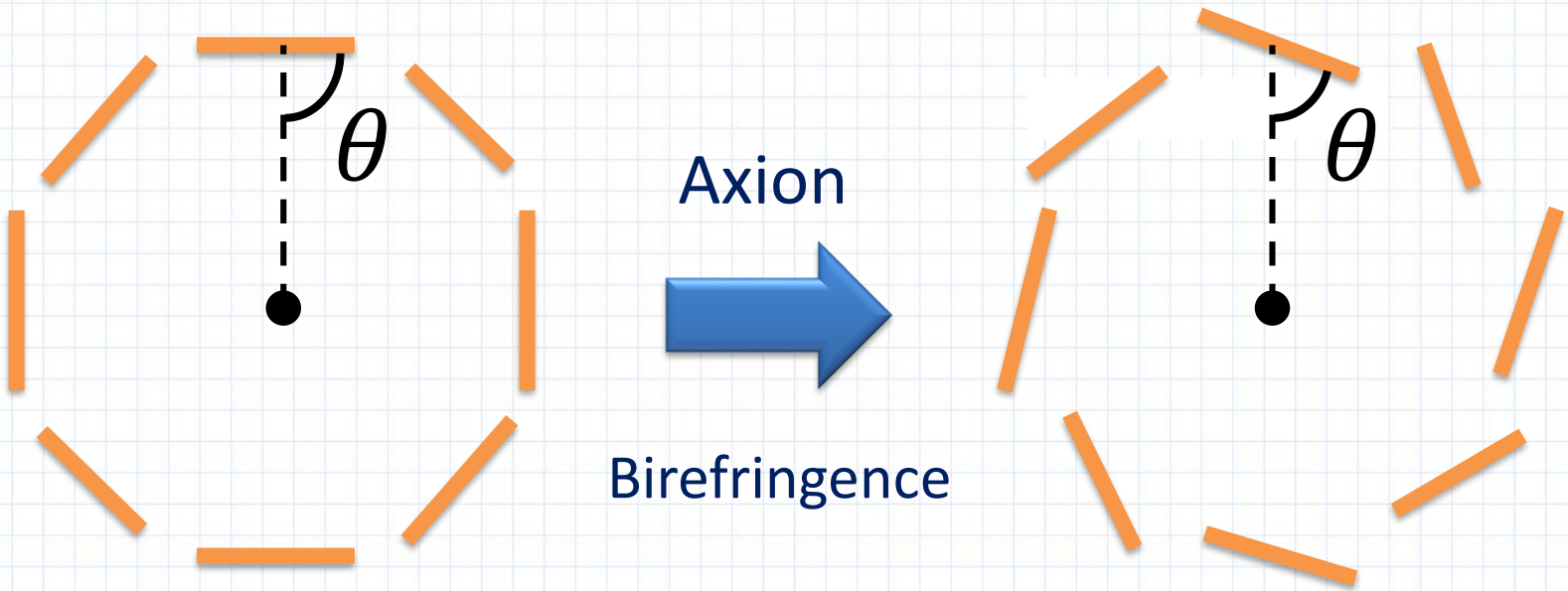

Is this angle 90° or not?

Obsevation of PPD

[Hashimoto et al. APJL729:L17(2011)]

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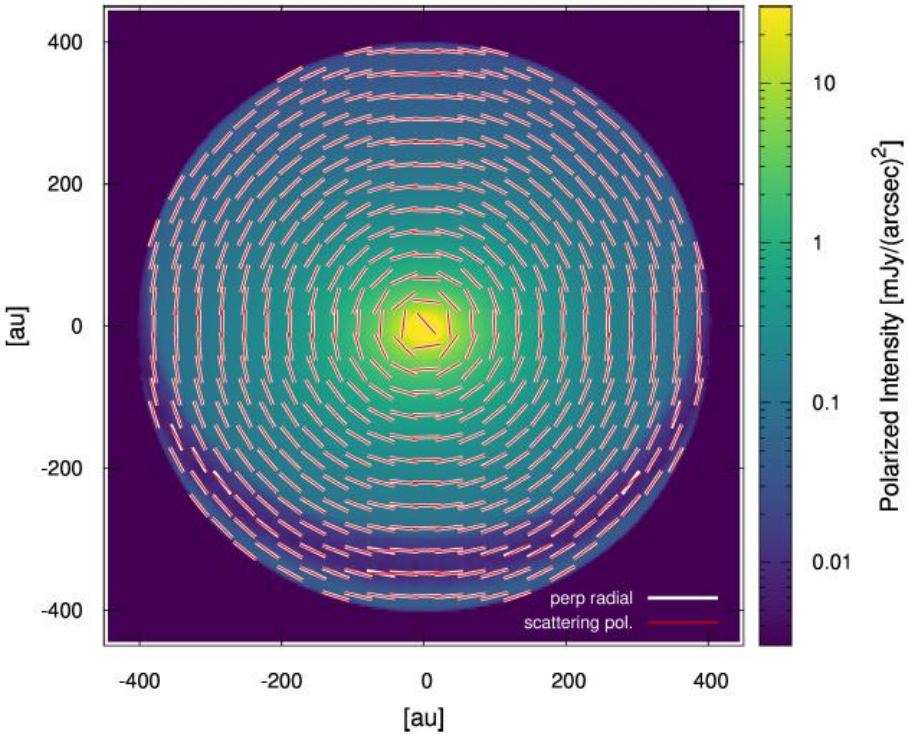
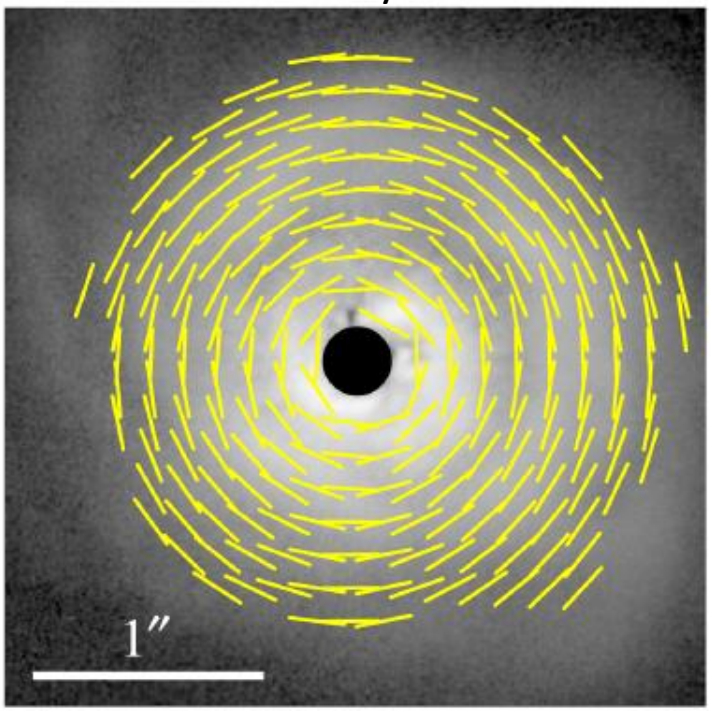


Observation by SUBARU



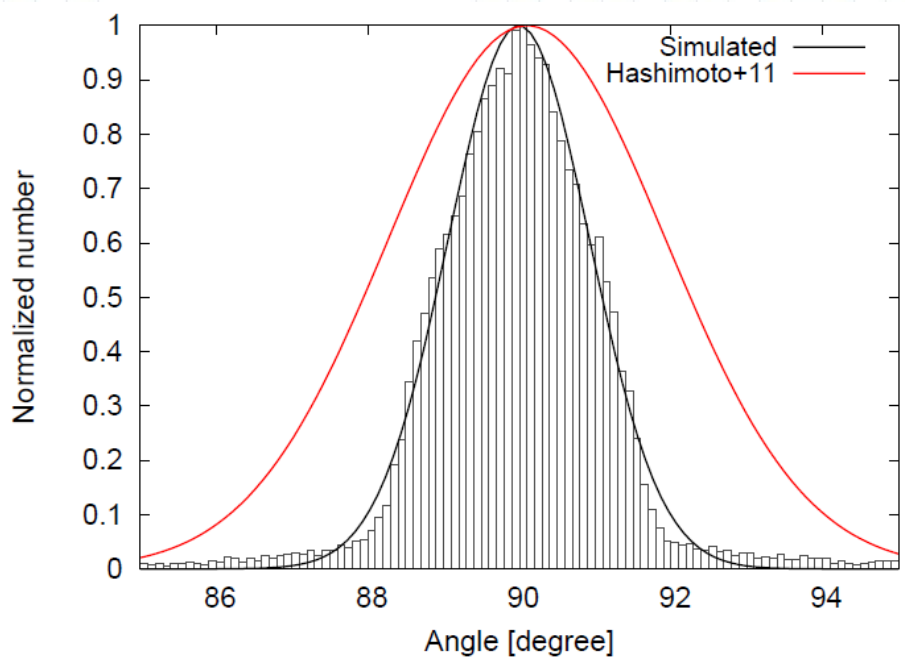
AB Aurigae (160pc away)

Obsevation of PPD

[Hashimoto et al. APJL729:L17(2011)]

The observation data reveals

$$\theta = 90°.1 \pm 0°.2 \quad \Rightarrow \quad |\Delta\theta| < 5 \times 10^{-3}$$

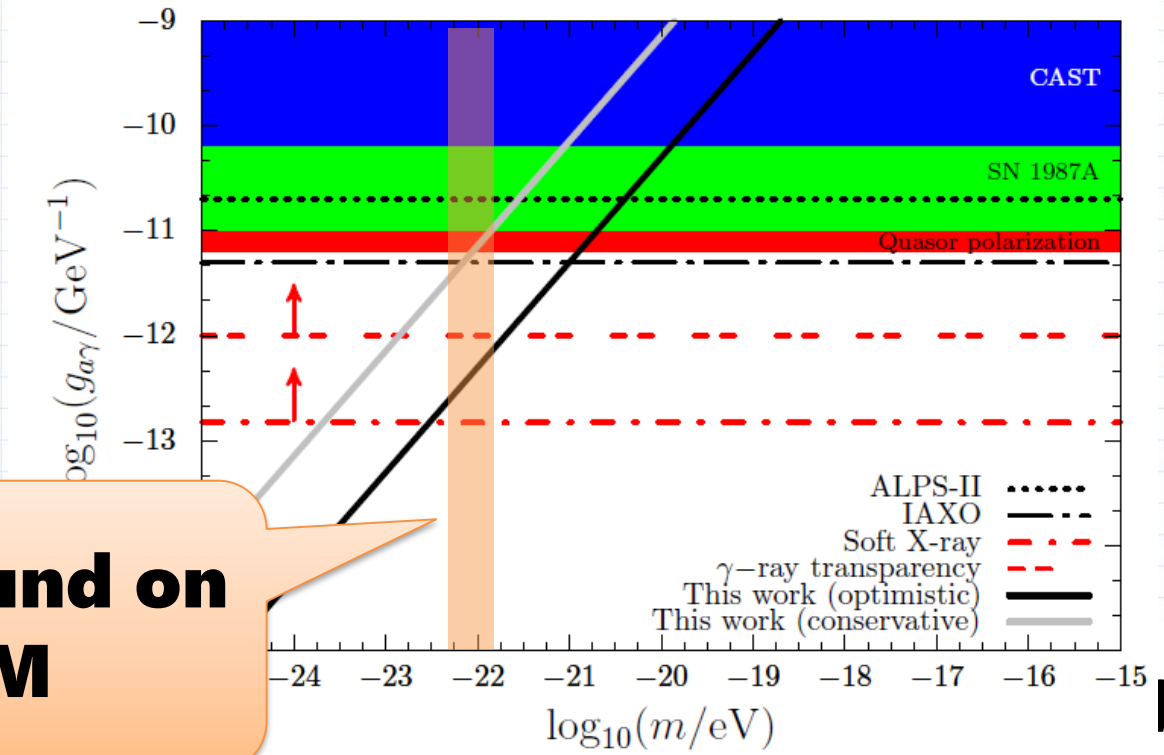


Our simulation confirms the effect of multiple Scatterings is negligible.

New constraint

[TF. Tazaki & Toma (2018)]
See also 1903.02666 for CMB

- Compared to the prediction, we obtain the best constraint on g of ultralight ADM ($m \sim 10^{-22}$eV)



g

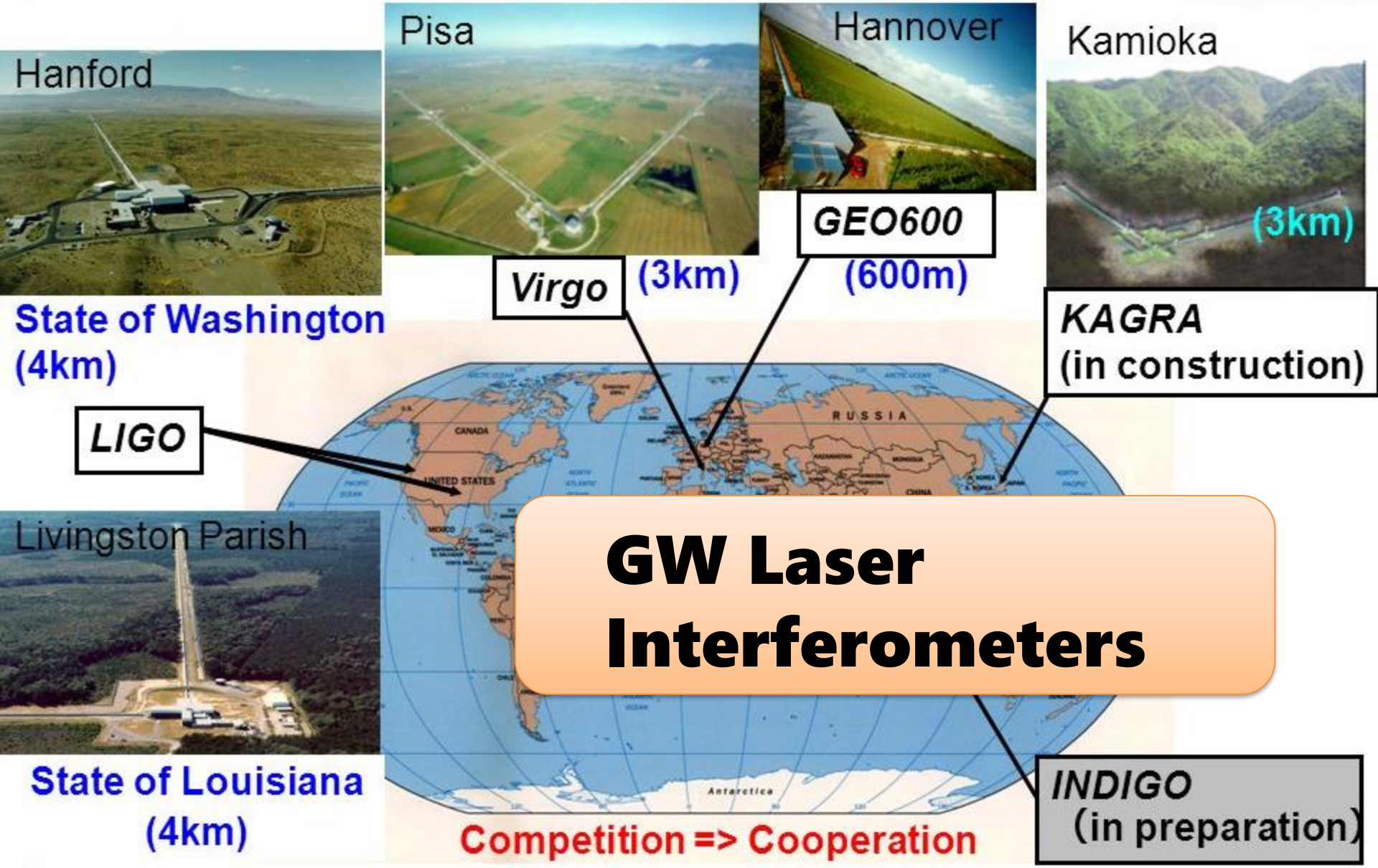
$m[\mathrm{eV}]$

Best bound on Fuzzy DM

Plan of Talk

1. Introduction
2. Optical Ring Cavity
3. Protoplanetary Disk
4. GW Interferometer
5. Summary

New experiment



GW Laser Interferometers

New experiment

Can we use GW interferometers

to search for Axion DM?

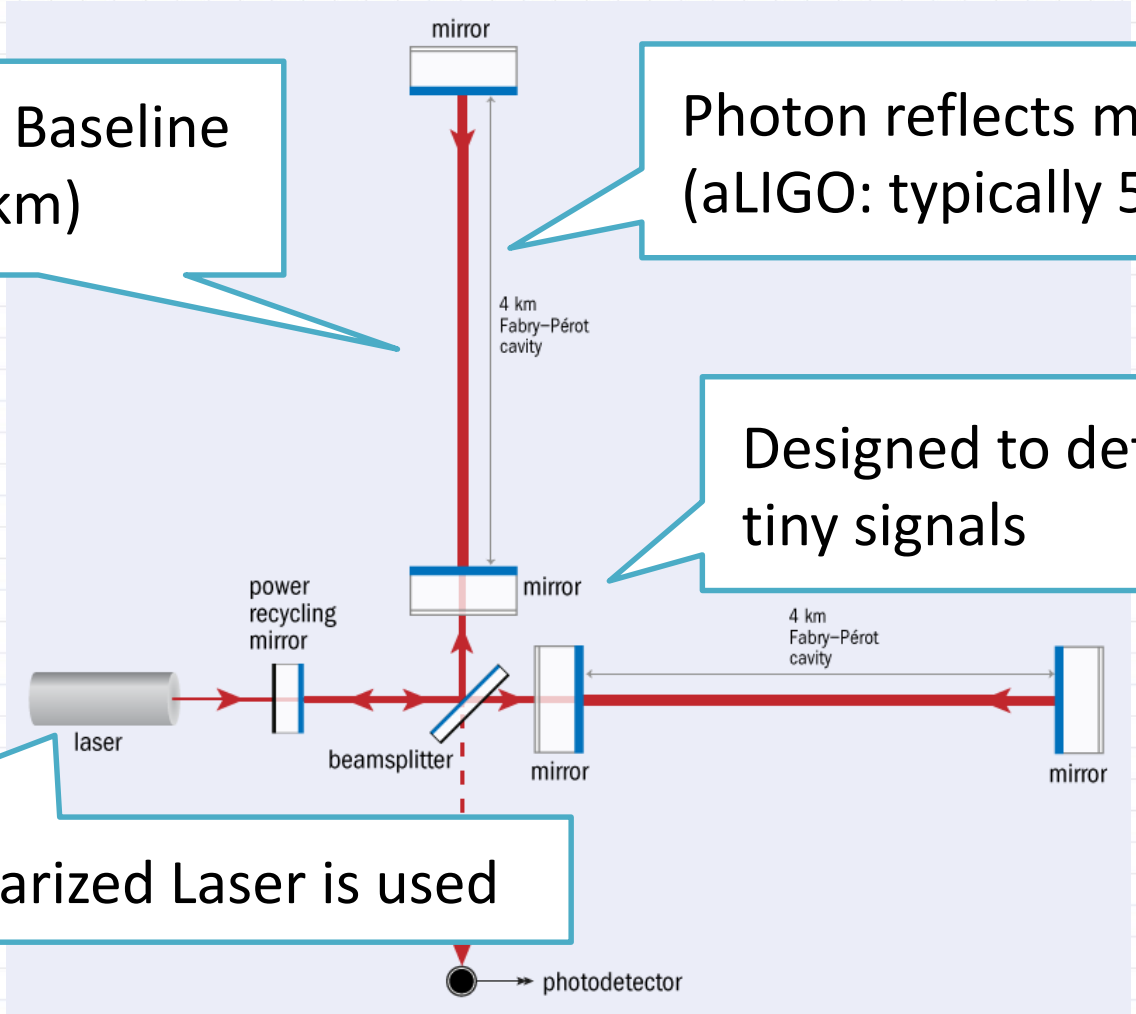
New experiment

Yes!! Because GW interferometer is

Very Long Baseline
(aLIGO: 4km)

Photon reflects many times
(aLIGO: typically 500 times)

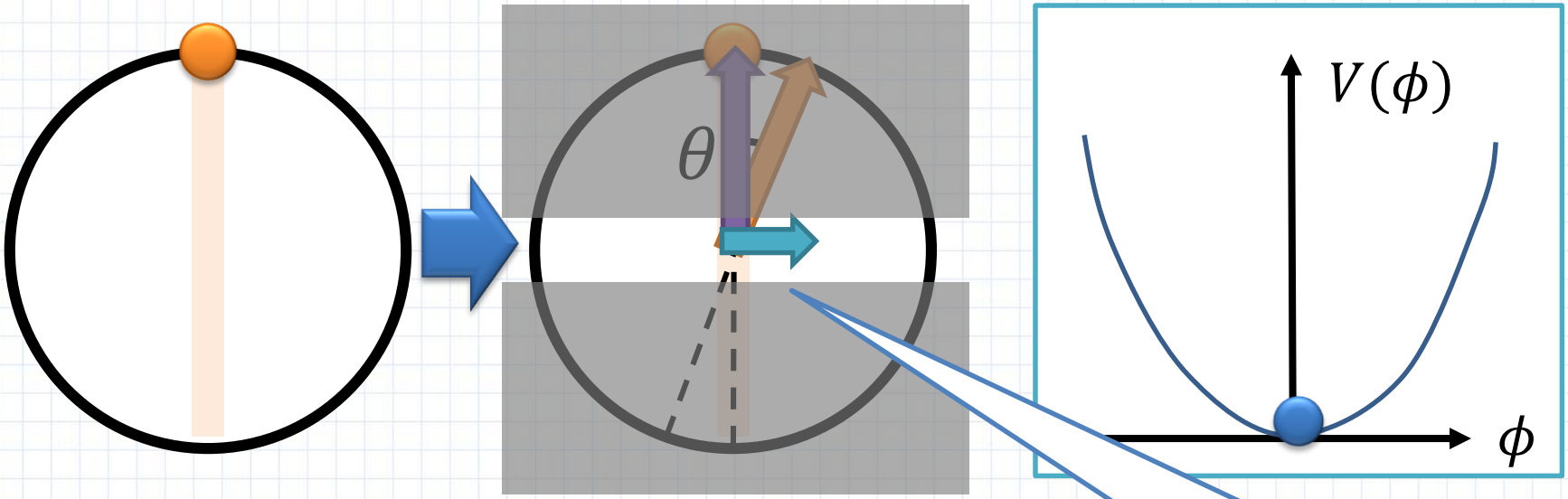
Designed to detect
tiny signals

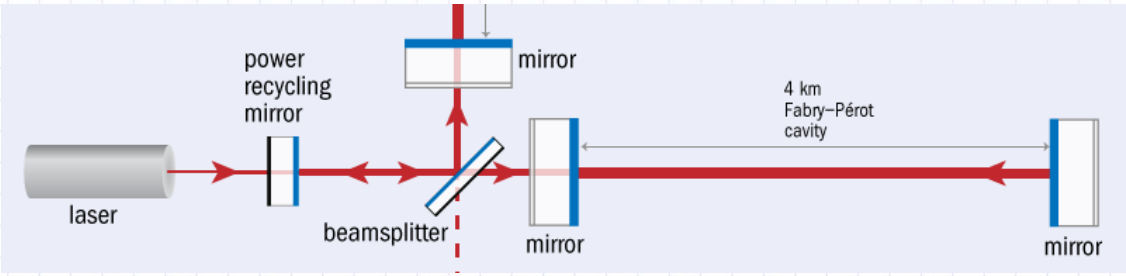


Linear Polarized Laser is used

New Observation

- Measure the other polarization component (horizontal) by filtering the original pol. component (vertical)

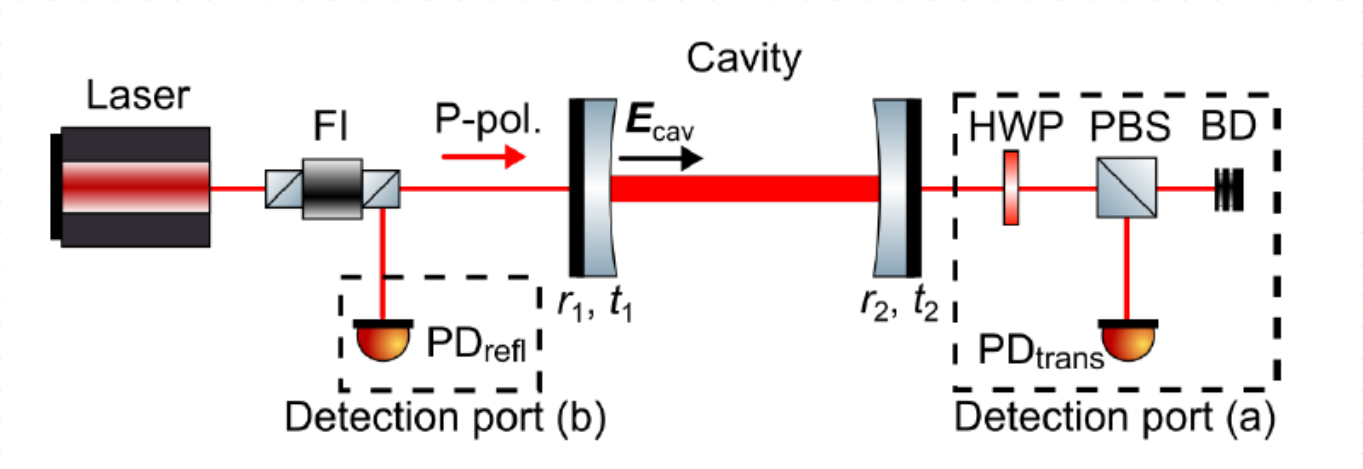




Only if $\theta \neq 0$ by ADM, we detect signal

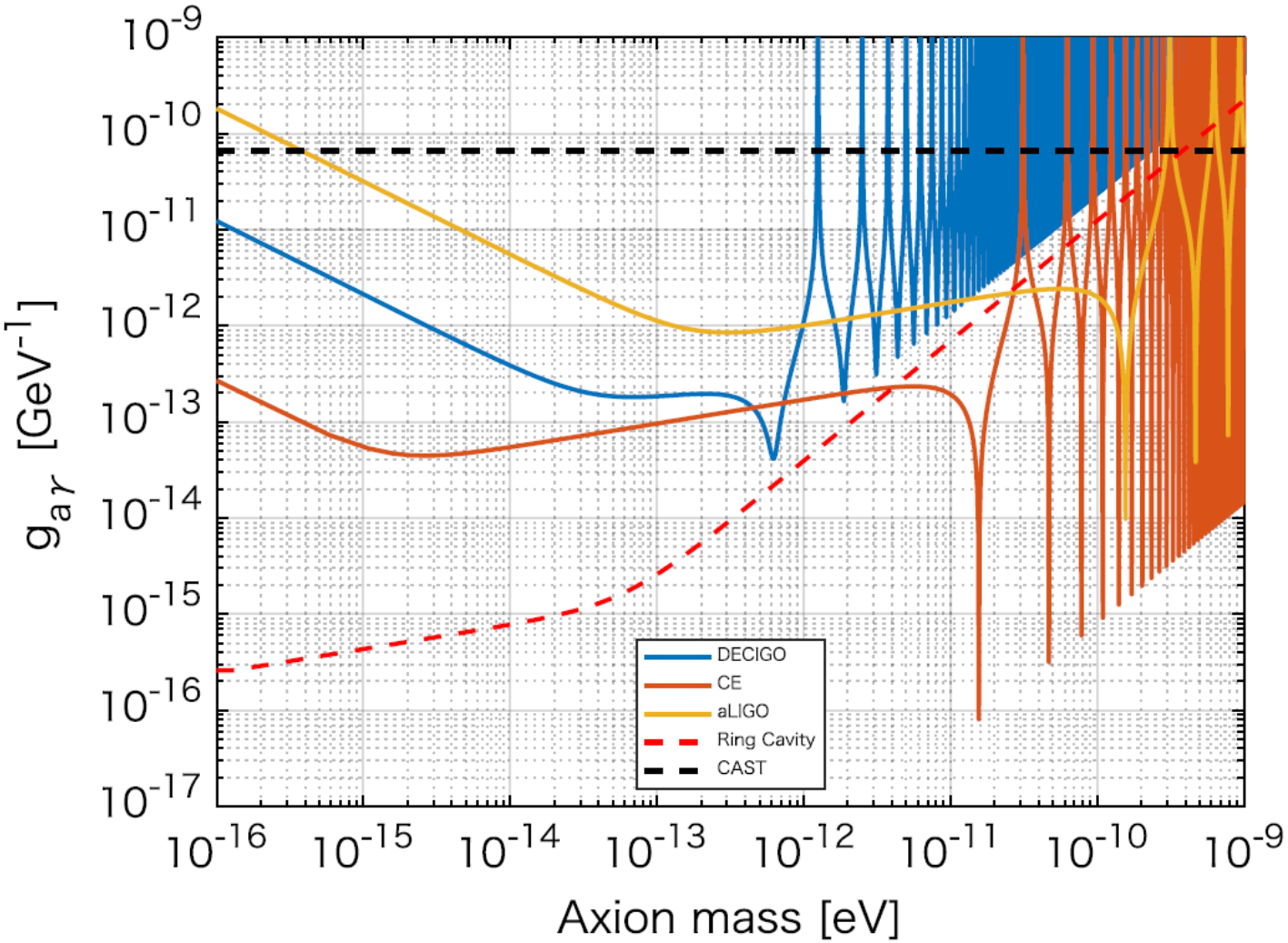
Coexist with GW observation

- Tiny signal compensated by long operation time

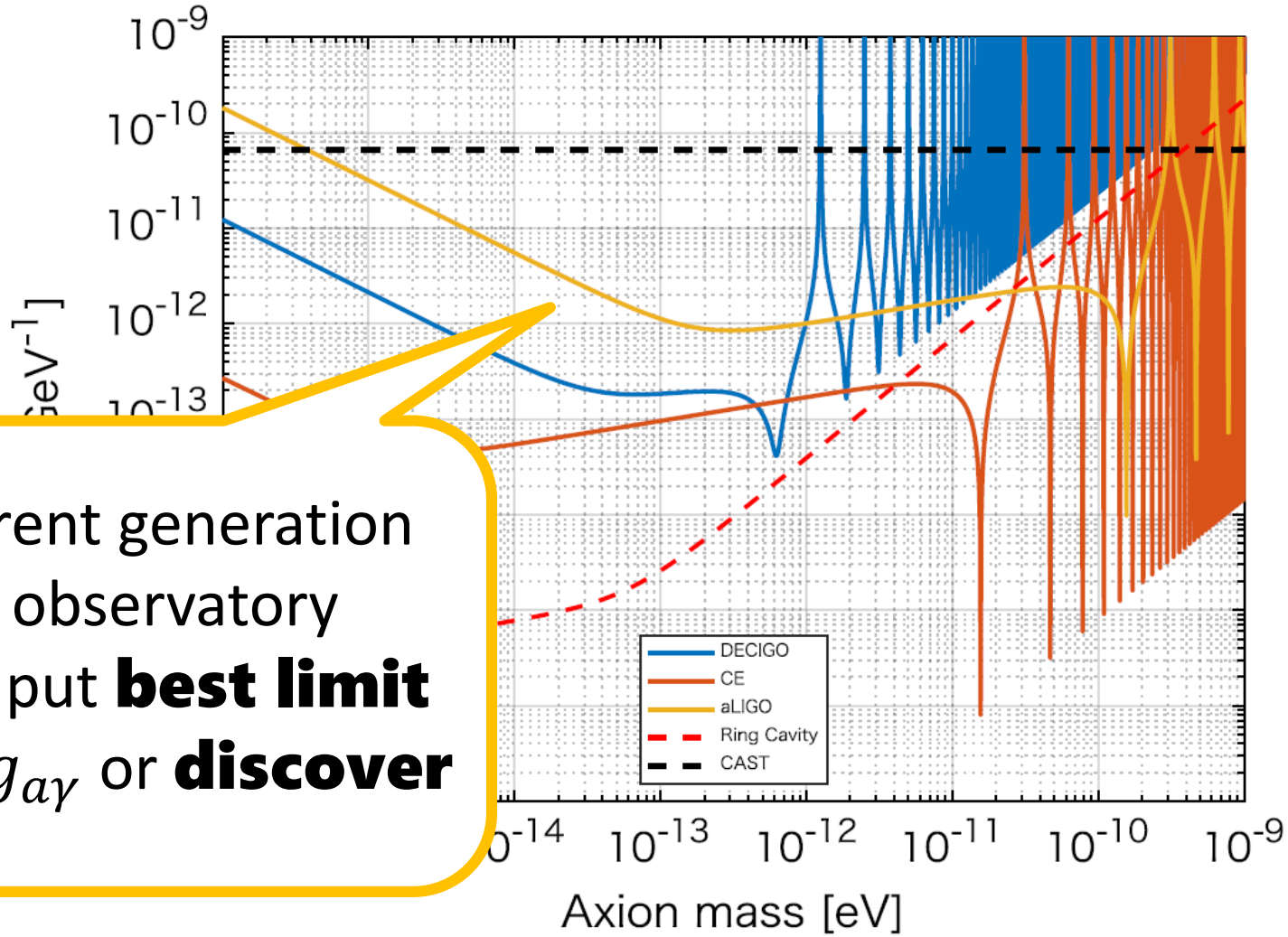


Additional instruments at the tail enable interferometers to probe ADM during the GW observation run **without loosing any sensitivity to GWs** ⇨ **Long Run!**

Sensitivity Curve for 1 year run

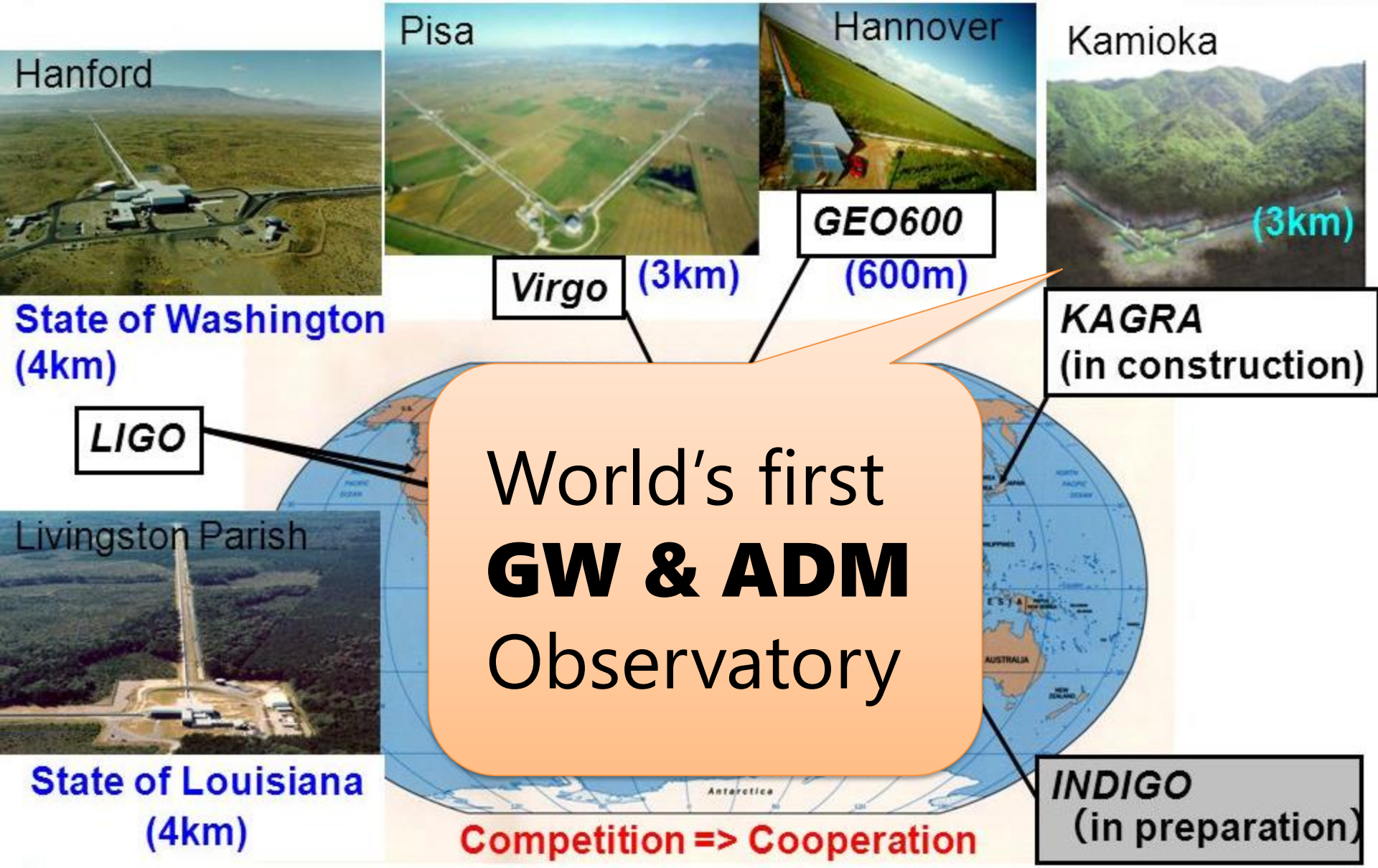


Sensitivity Curve for 1 year run



Current generation GW observatory can put **best limit** on $g_{a\gamma}$ or **discover**

New experiment



World's first
GW & ADM
Observatory

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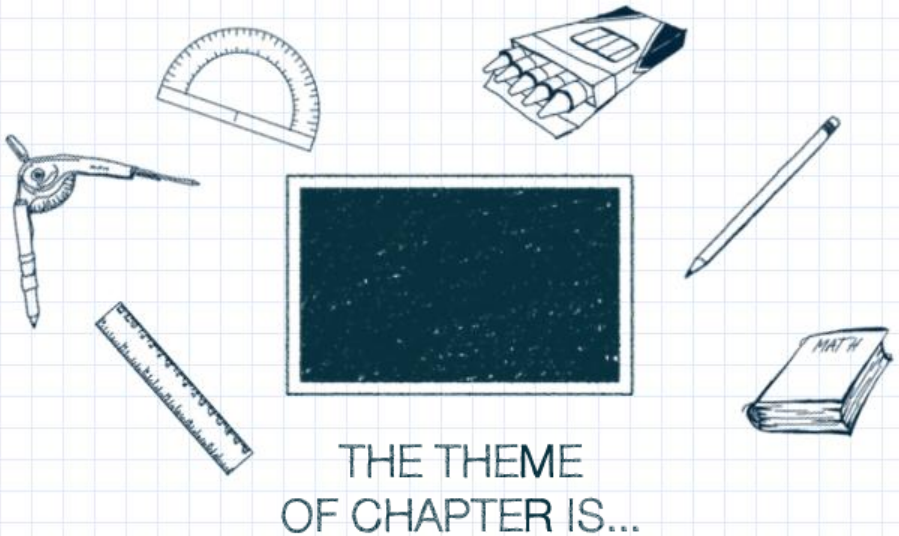
Summary

- Axion has been constrained by $a \leftrightarrow \gamma$ conversion
- The same coupling causes Birefringence w/ ADM
- Optical ring cavity and GW interferometer are sensitive to ADM with $\mathbf{10^{-16} < m < 10^{-12}}$
- Observations of protoplanetary disks are useful to search for ultralight ADM ($\mathbf{m \sim 10^{-22}}$)
- Just beginning. Let's think new one together!

Thank you !

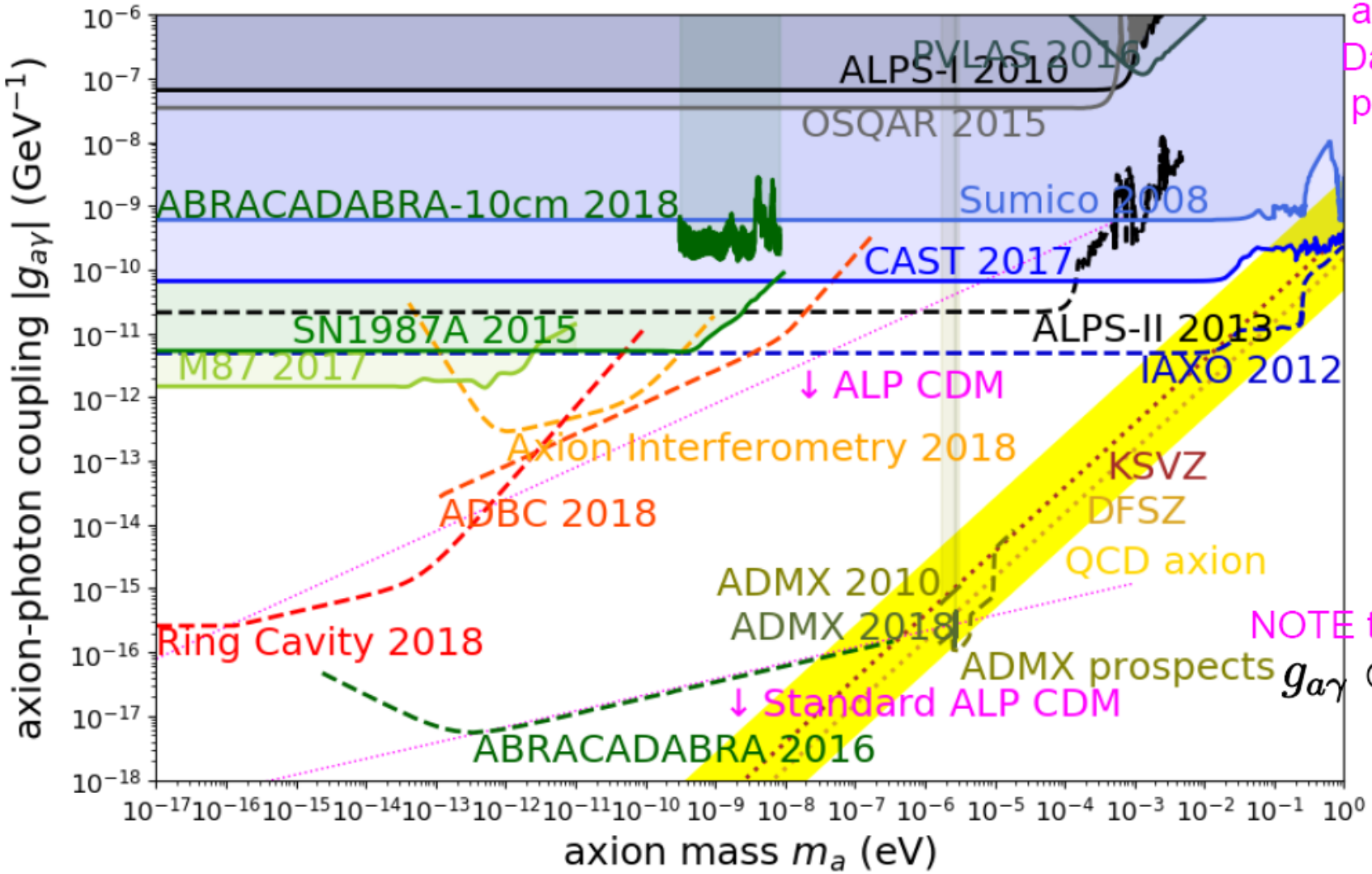


Backup Slides

Bounds on Axion-Photon Coupling

- Extracted experiments to be reviewed here

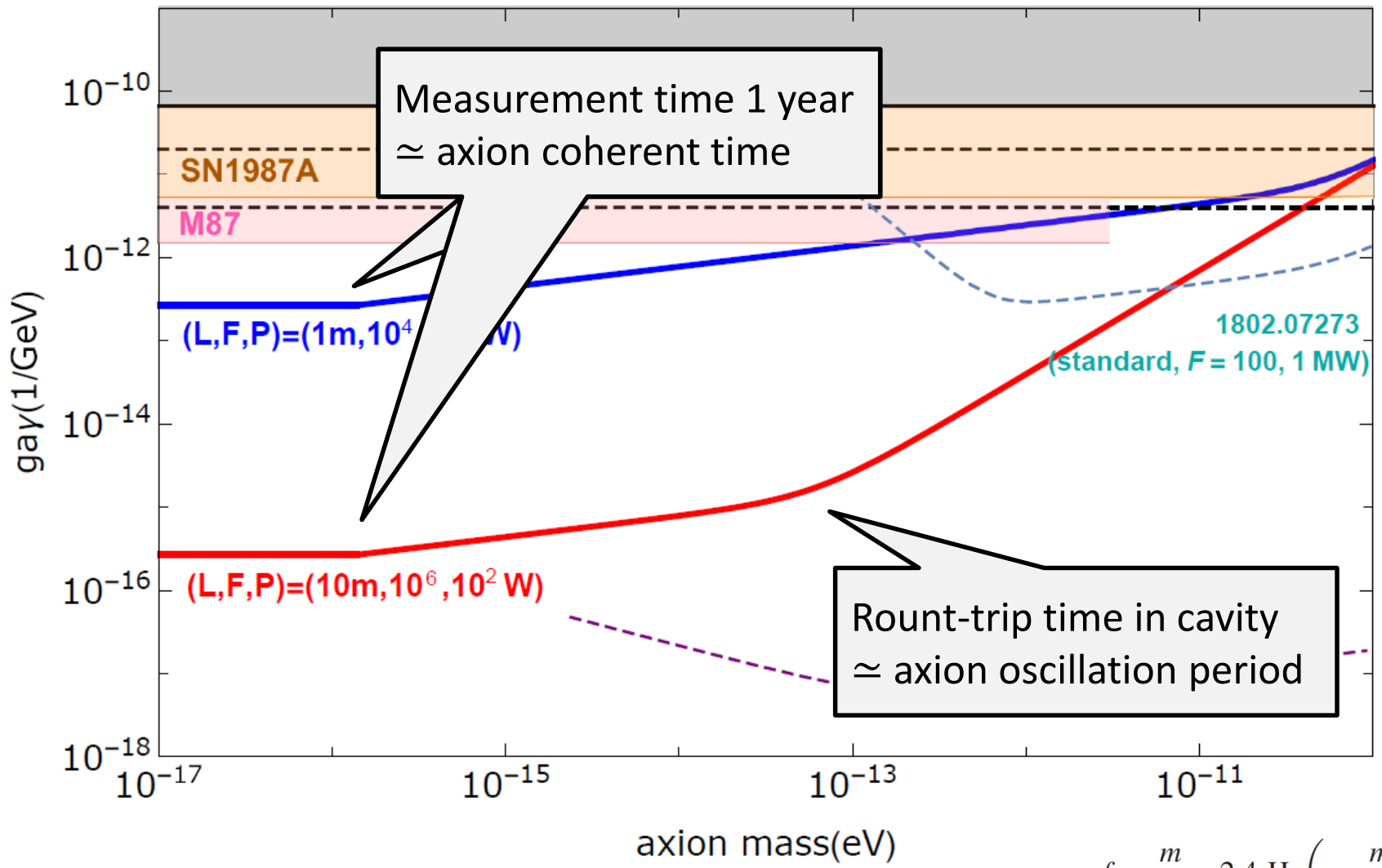
Solid: achieved
Dashed: proposals



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

New experiment

[Obata, TF, Michimura(2018)]



$$f = \frac{m}{2\pi} \simeq 2.4\ \mathrm{Hz}\left(\frac{m}{10^{-14}\ \mathrm{eV}}\right)$$

Axion coherent time

If measurement time T is longer than axion coherent time
the sensitivity improves only slowly

$$\text{SNR} \propto \sqrt{T} \xrightarrow{\tau_a < T} (\tau_a T)^{1/4}$$

People often discuss τ_a is (de Broglie wave length)/(relative velocity)

$$\tau_a = \frac{2\pi}{mv^2} \approx 1\text{yr}\left(\frac{10^{-16}\text{eV}}{m}\right)$$

Therefore, for $m > 10^{-16}\text{eV}$, the sensitivity highly depends on τ_a

MENU
nature photonics
research highlights

NANOPHOTONICS

Steering second-harmonics

Nano Lett. **18**, 6750–6755 (2018)

Credit: American Chemical Society

The phase control and shaping of the second-harmonic radiation generated from an AlGaAs nanodisk antenna has now been accomplished by a team of researchers from Italy, France and Australia. I
workers u
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to, for example, single-photon sources and nonlinear imaging. *DFPP*

https://doi.org/10.1038/s41566-018-0318-x

OPTICAL MANIPULATION

Virtual potential

Appl. Phys. Lett. **113**, 183702 (2018)

Optical tweezers are a popular tool for manipulating and sorting individual nanoparticles. Now, Avinash Kumar and John Bechhoefer from Simon Fraser University, Canada have shown that when equipped with a suitable feedback scheme tweezers can be used to create a more complicated force field, such as single- or double-well harmonic potentials, for controlling particle dynamics. In the experiments, a polarized 532-nm
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Our proposal was featured in Nature Photonics.

OPTICAL METROLOGY

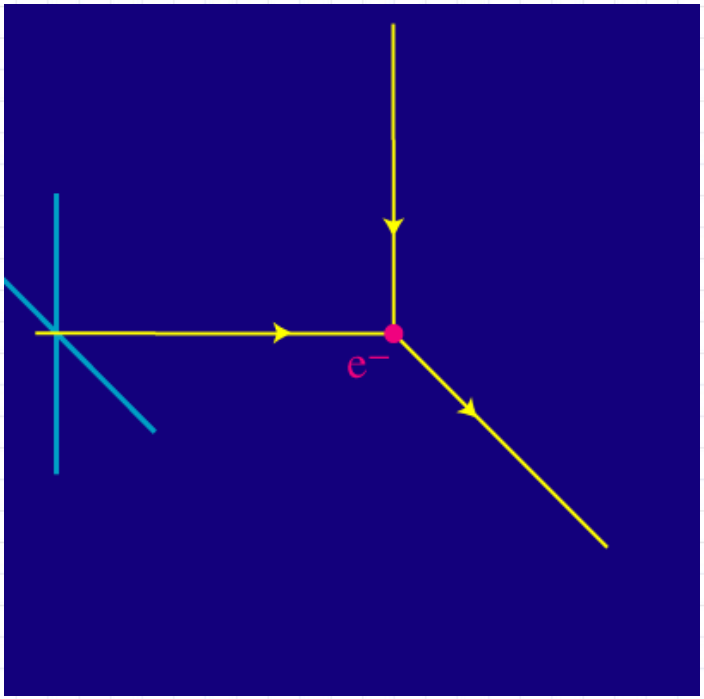
Axion sensor

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

Polarization of scattered light

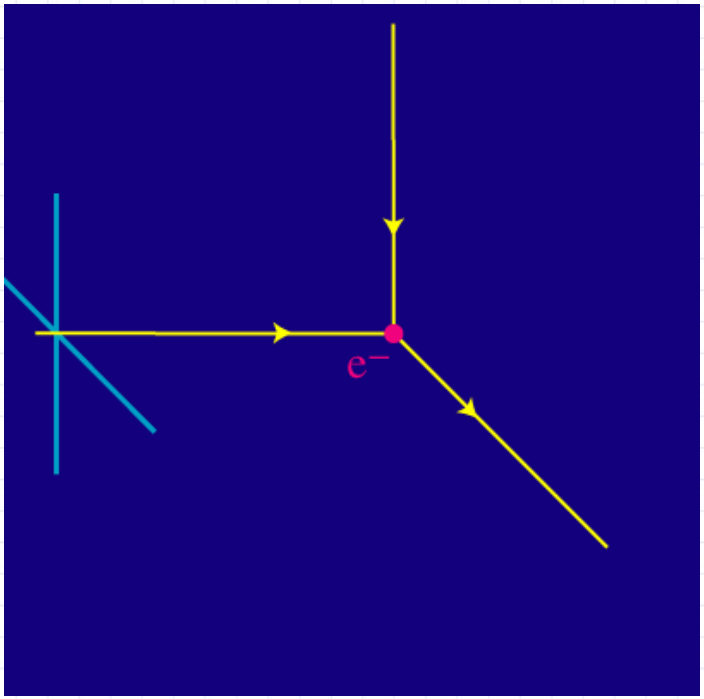


Consider incoming radiation from the left being scattered by 90 degrees out of the screen:

Since light cannot be polarized along its direction of motion, only one linear polarization state gets scattered.

[Credit: Weyne Hu's homepage]

Polarization of scattered light



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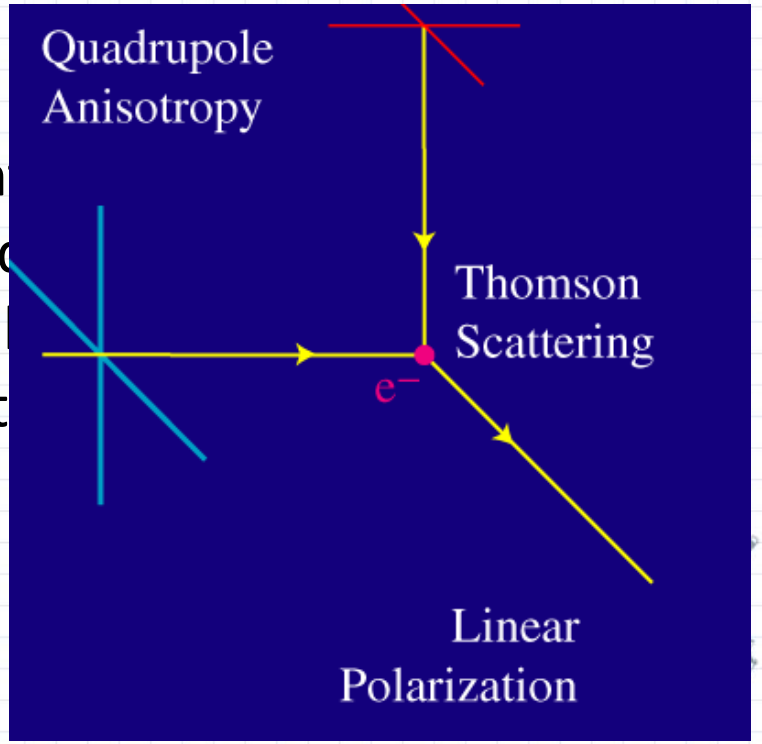
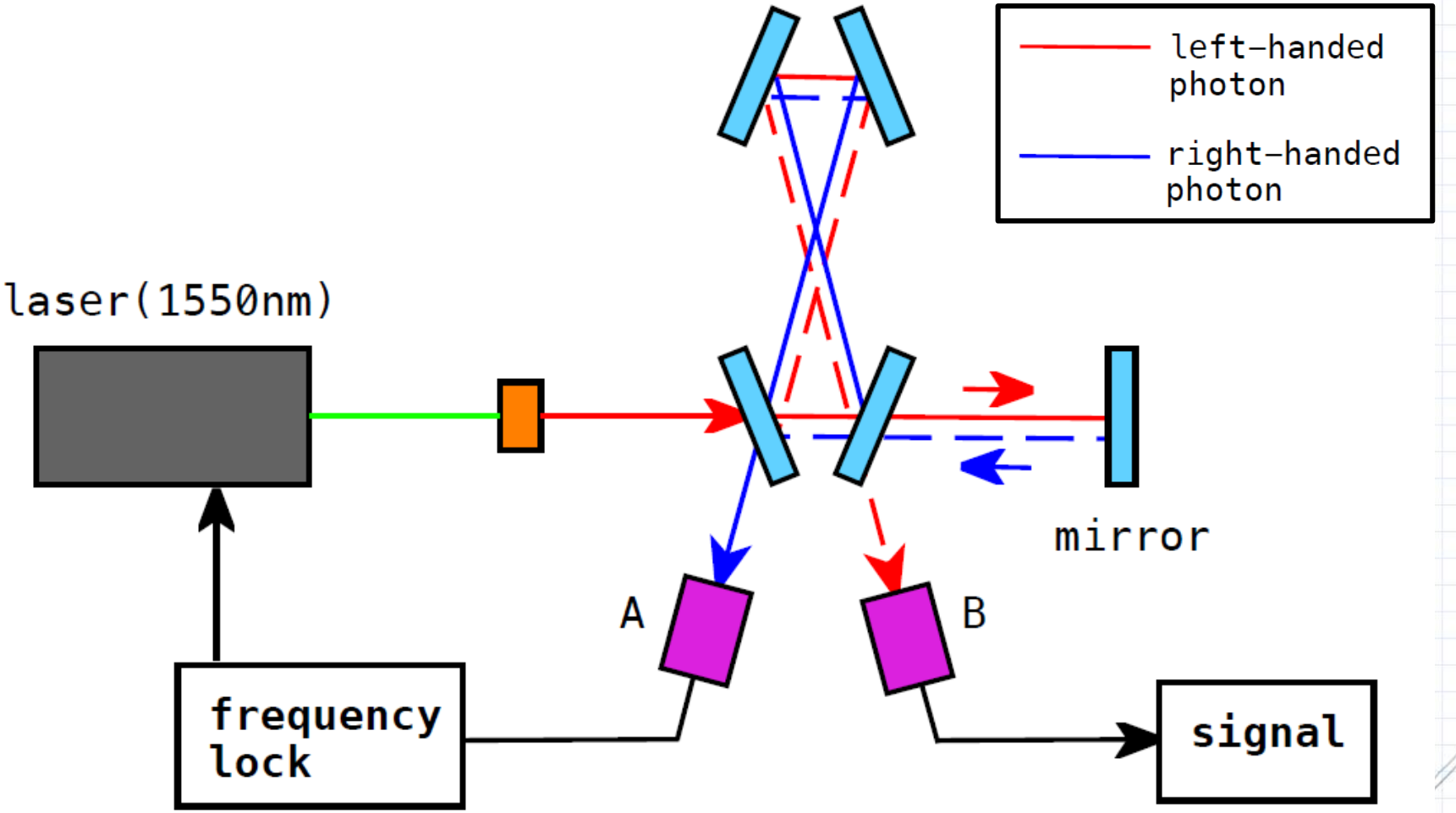


[Credit: Weyne Hu's homepage]

DANCE experiment

Dark matter **A**xion search with ri**N**g **C**avity **E**xperiment

[Obata, TF, Michimura(2018)]



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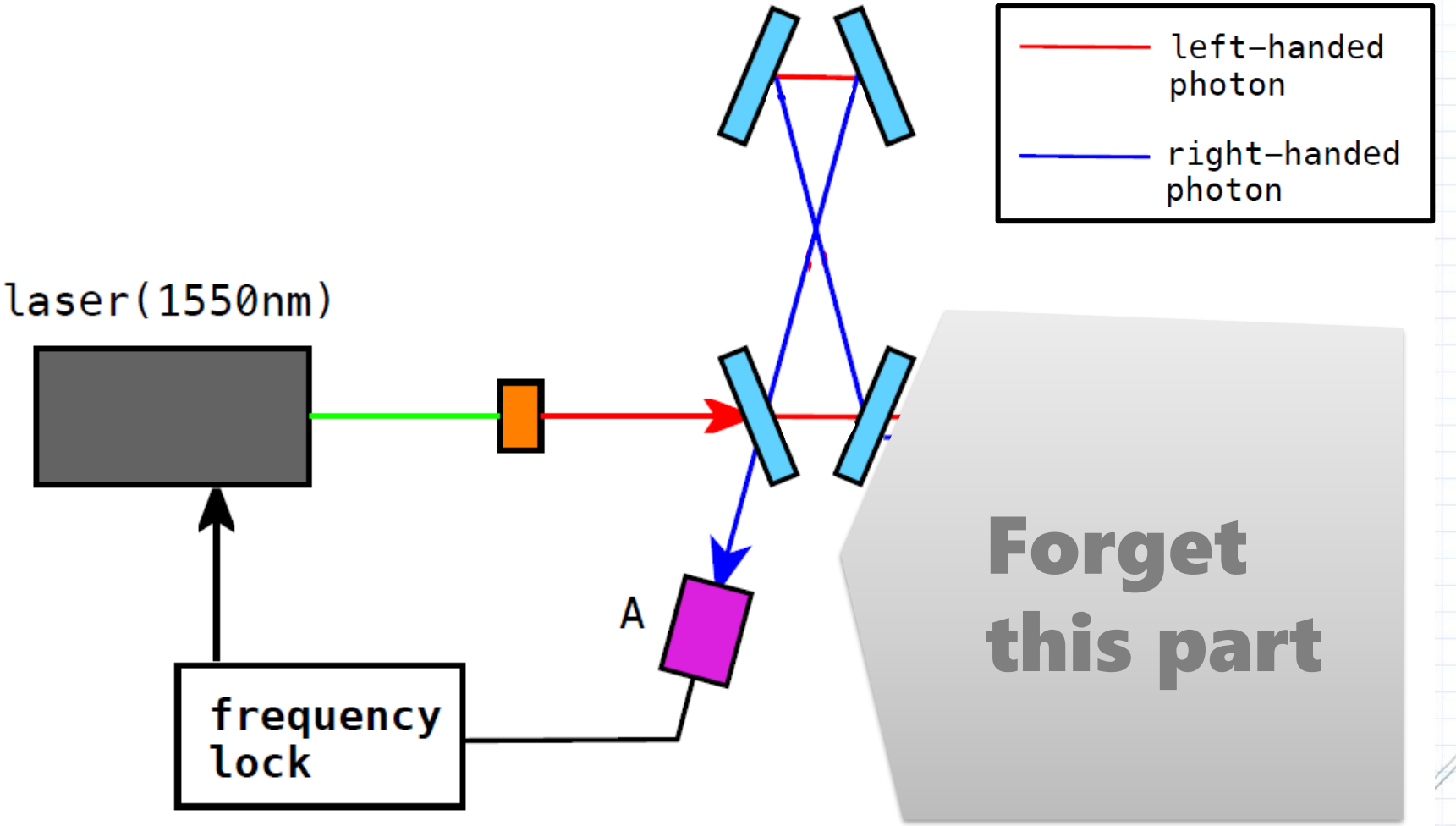

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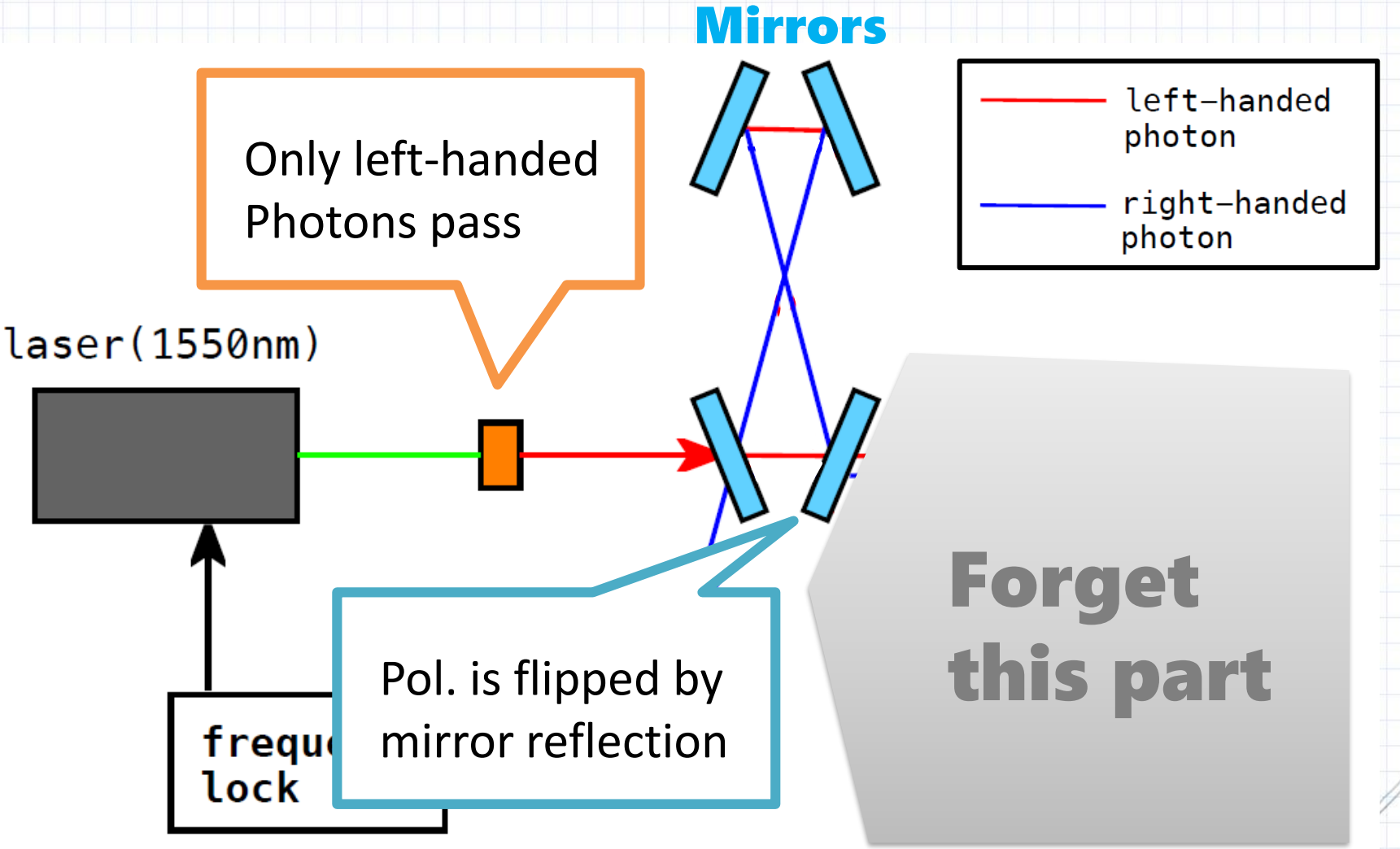

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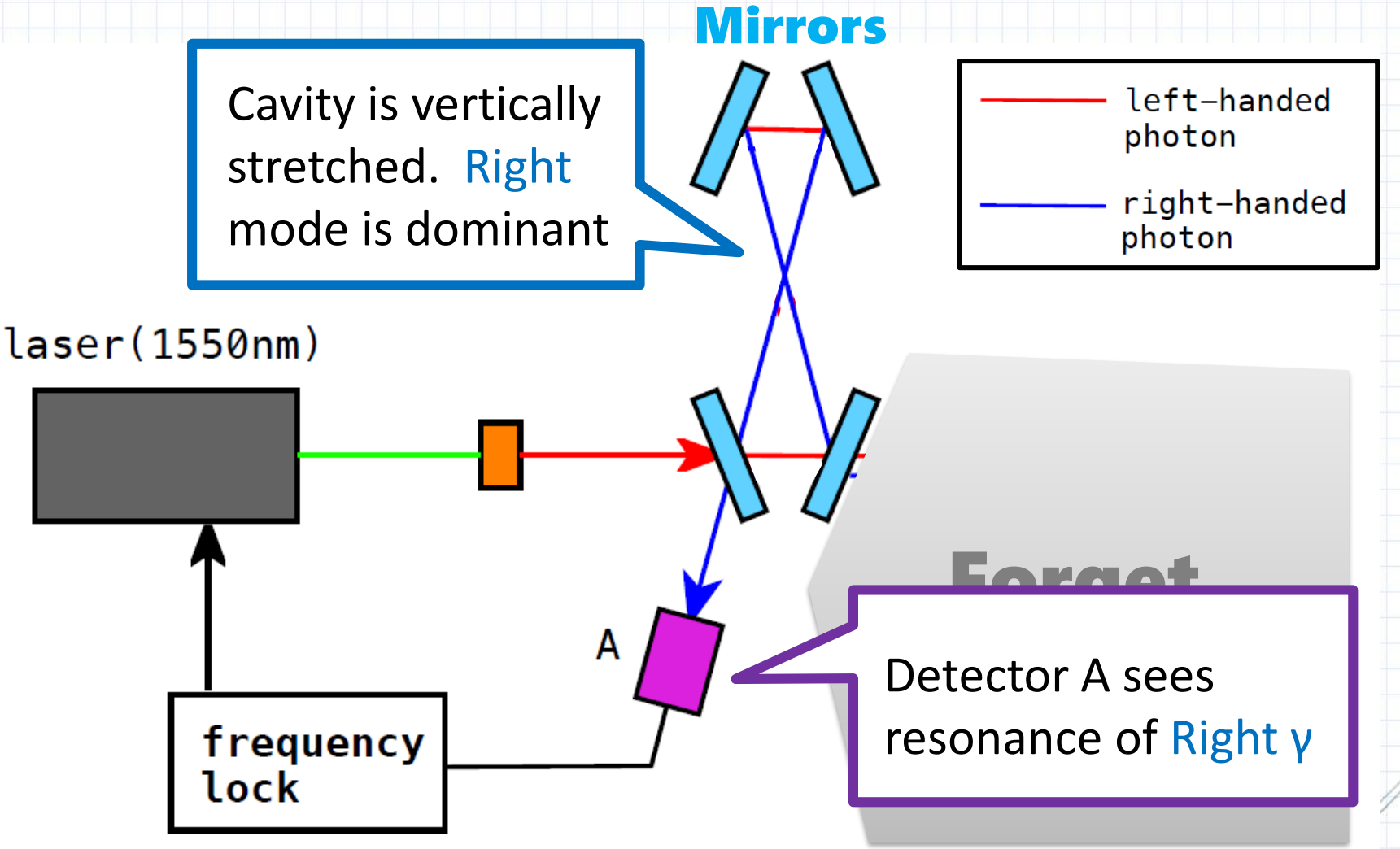

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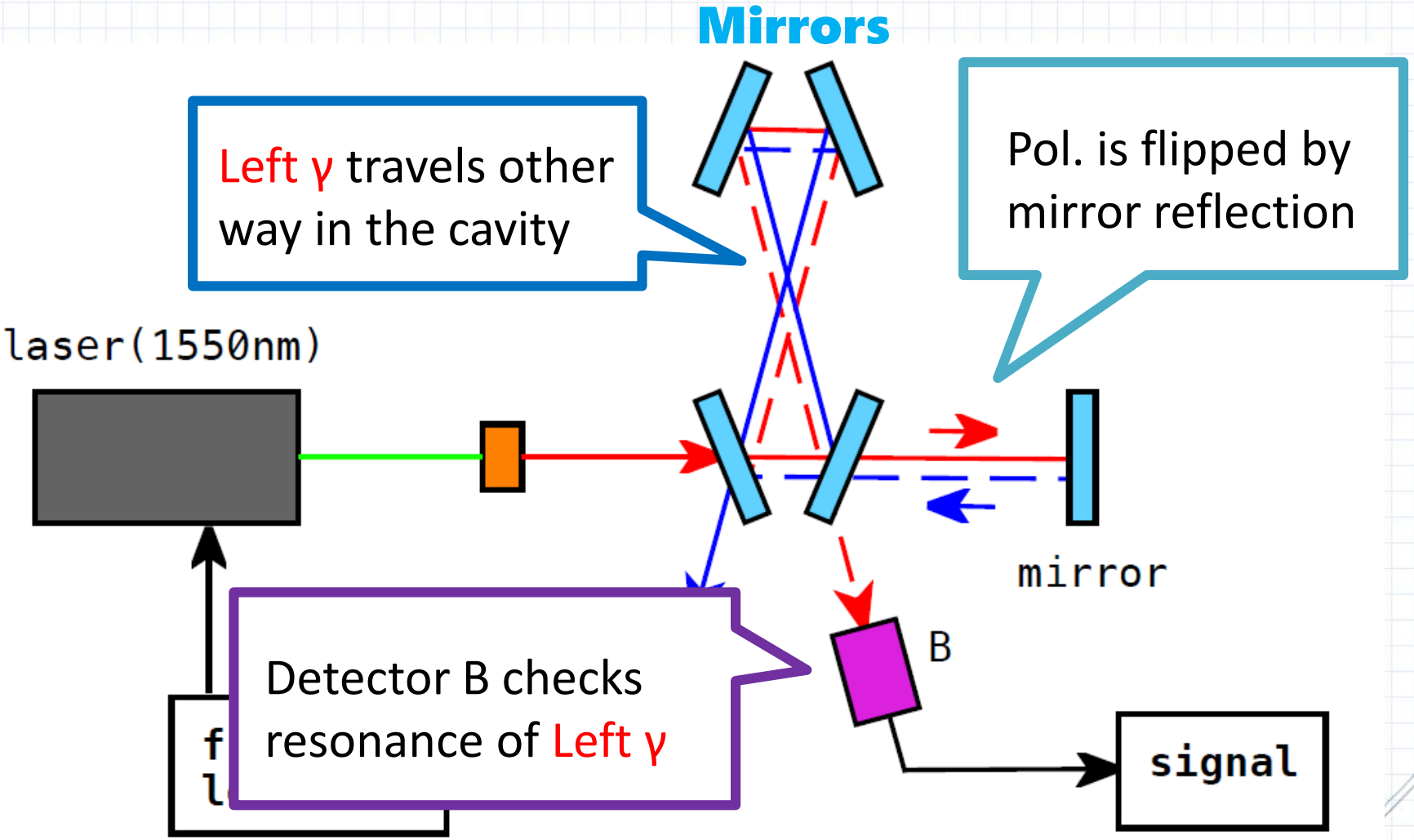

DANCE experiment

[Obata, TF, Michimura(2018)]

This experiment can test the birefringence of ADM via δf_{res} btw right/Left γ.