PRESENTATION

Search for Axion Dark Matter

with New Approaches

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(Kyoto & Geneva)

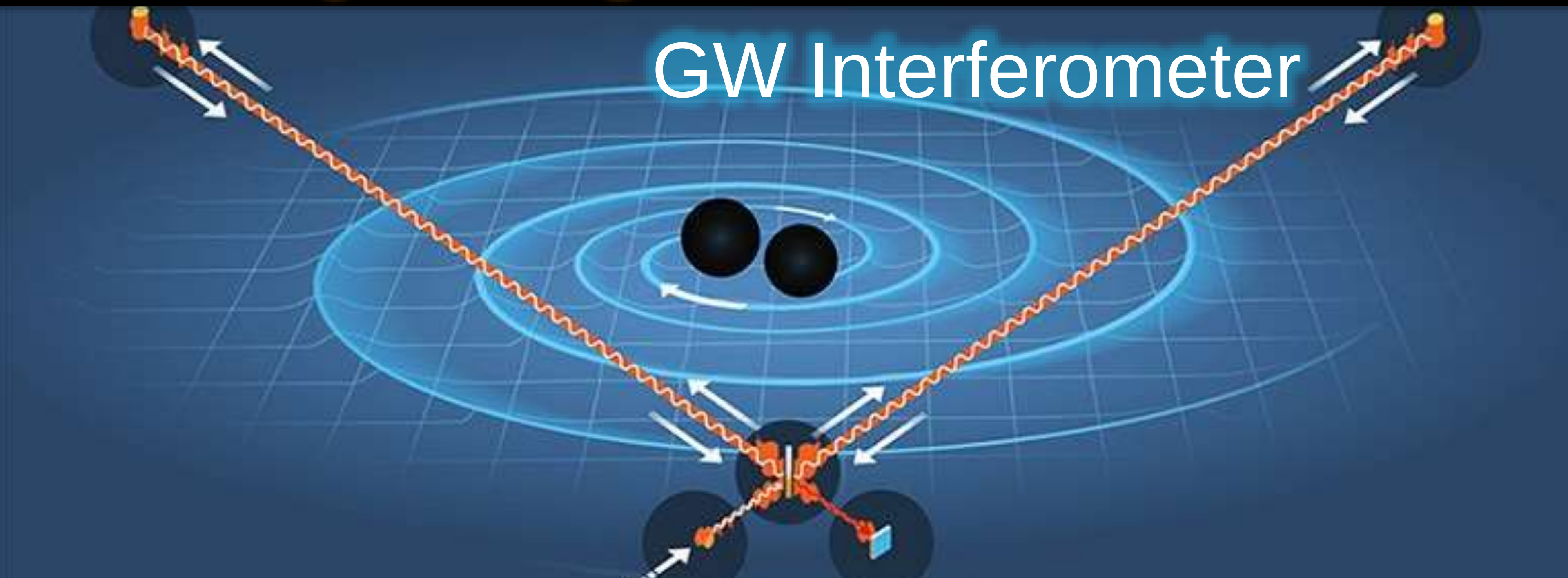
TF, Tazaki & Toma arXiv: 1811.03525
Nagano, TF, Obata & Michimura(in prep)

20th. Feb. 2019@USP

UNIVERSITÉ DE GENÈVE

京都大学 KYOTO UNIVERSITY

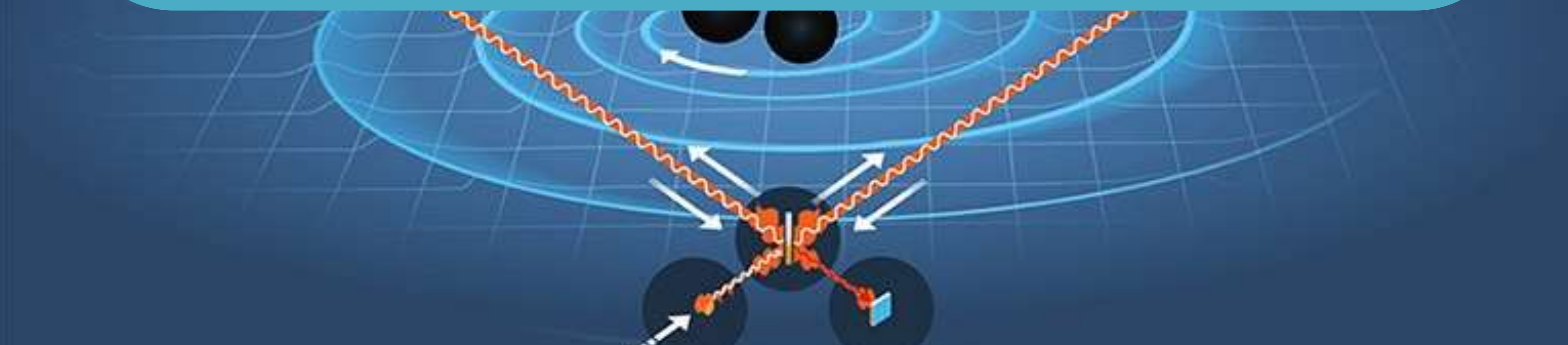
introduction



Main Message

PPD and GW detector provide new and best methods to search for axion dark matter.

PPD observation improves limit on Fuzzy DM.
GW interferometer can be ADM detector for free.



Plan of Talk

1. Introduction — What's axion DM?
2. Protoplanetary Disk — New obs. limit ($m \sim 10^{-22}\mathrm{eV}$)
3. GW Interferometer — New Exp. limit ($m \sim 10^{-12}\mathrm{eV}$)
4. Summary

Who is Dark Matter?

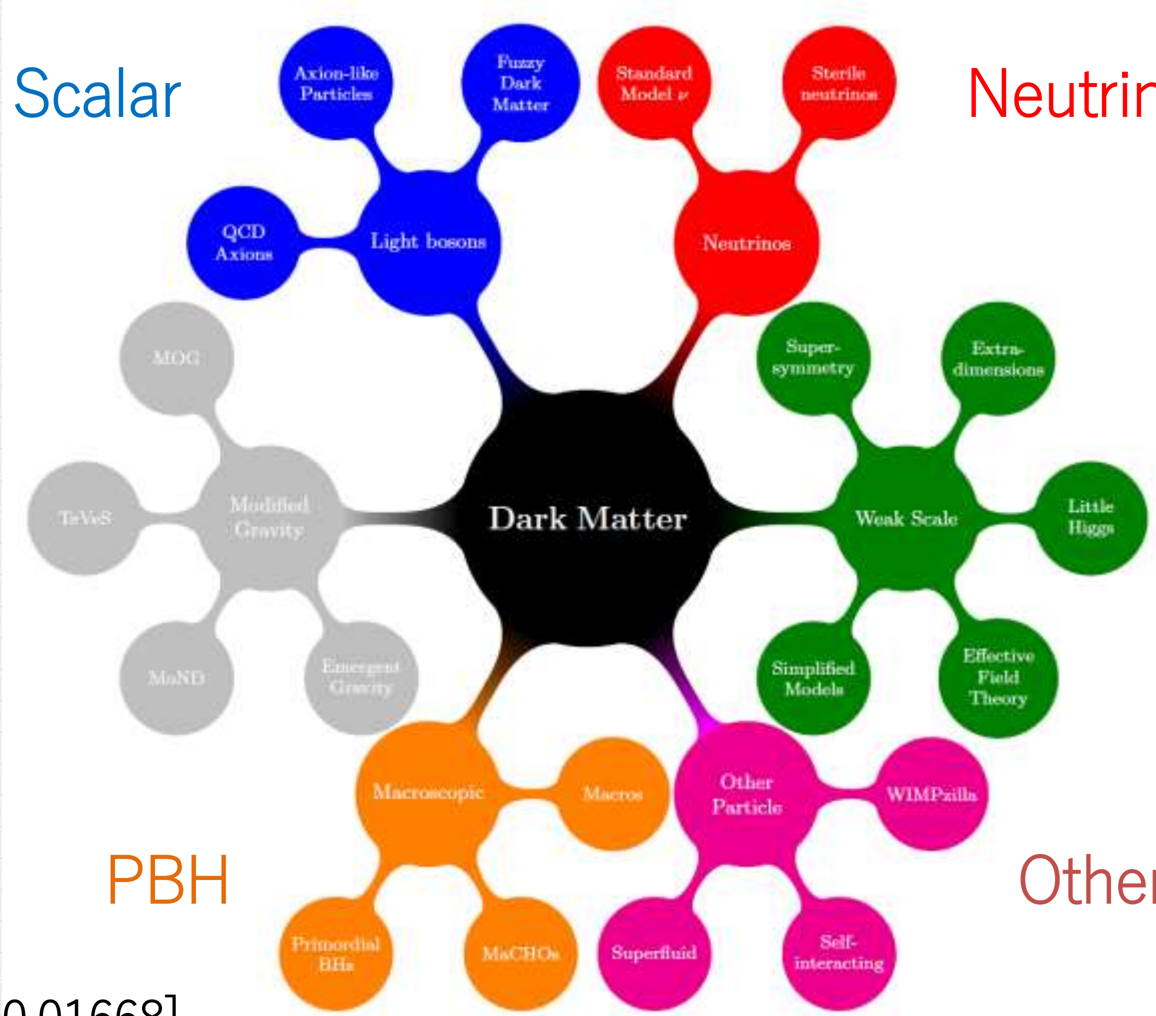
DM candidates

Scalar

Neutrino

M-Gravity

WIMP



PBH

Other

Berton&Tait[1810.01668]

DM candidates

Scalar DM

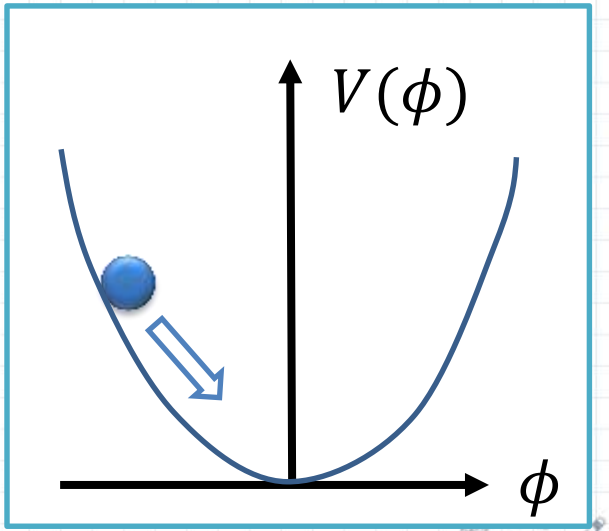
Berton&Tait[1810.01668]

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. ($10^{-22}\mathrm{eV} \lesssim m \lesssim 10^{3}\mathrm{eV}$)

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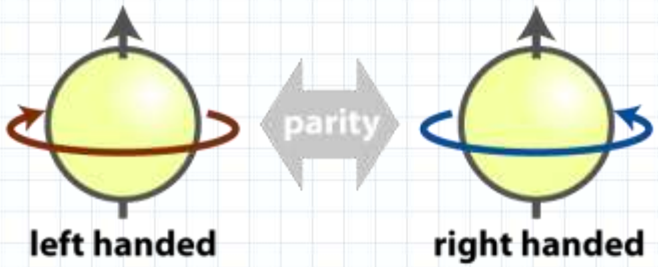
Fuzzy DM
(cf. Lyman-α limit)

Decay into γ
(hopeless to detect)

What characterizes ADM?

- ADM can be very light. ($10^{-22}\mathrm{eV} \lesssim m \lesssim 10^{3}\mathrm{eV}$)

- ADM breaks parity



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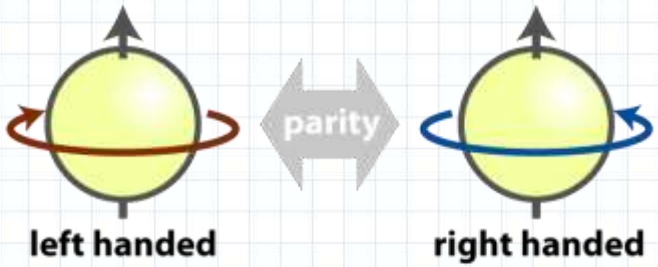

- ADM may be coupled to photon!!

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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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Non-linear

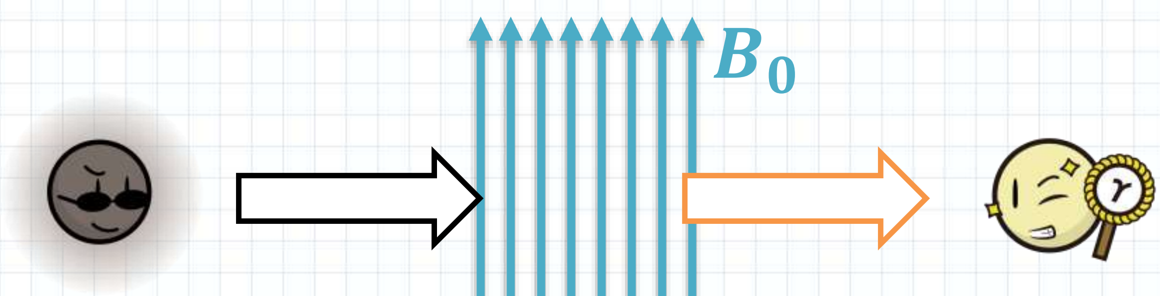
Conventionally constant magnetic field is introduced

Axion-Photon Conversion

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

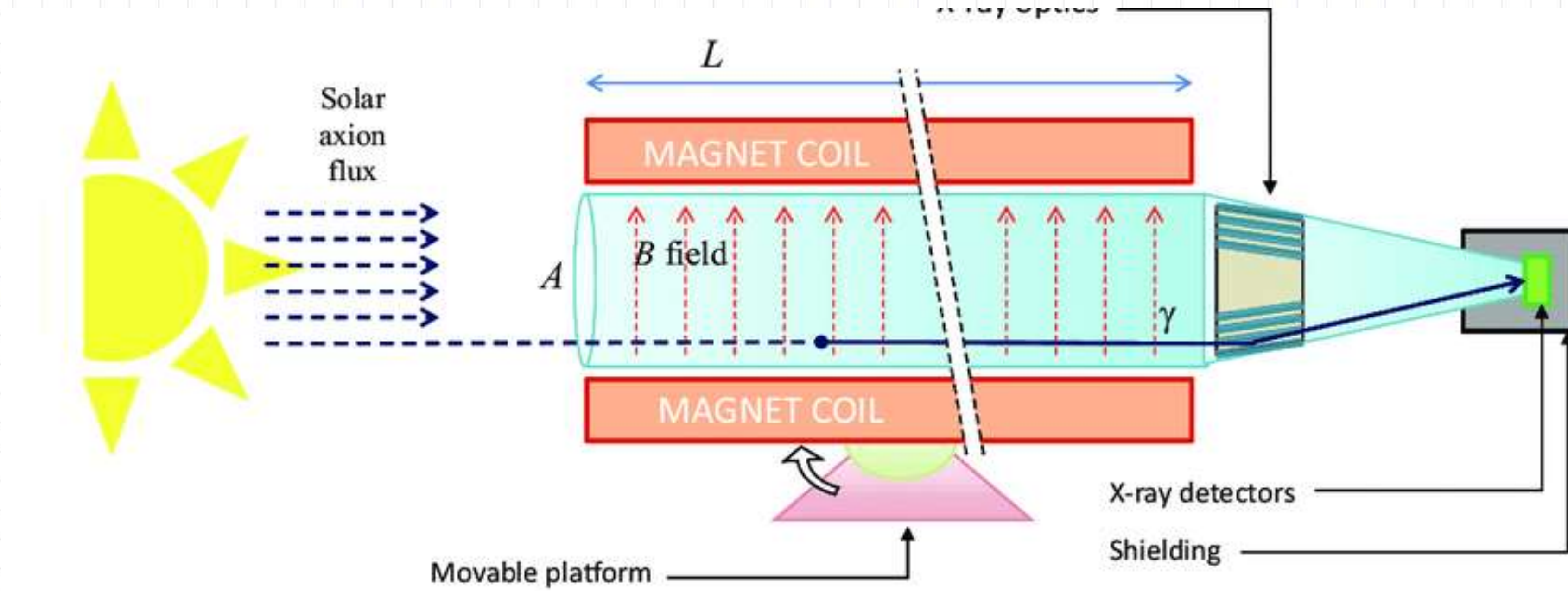
Photon: $$\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\boldsymbol{B_0}\dot{\phi}$$

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



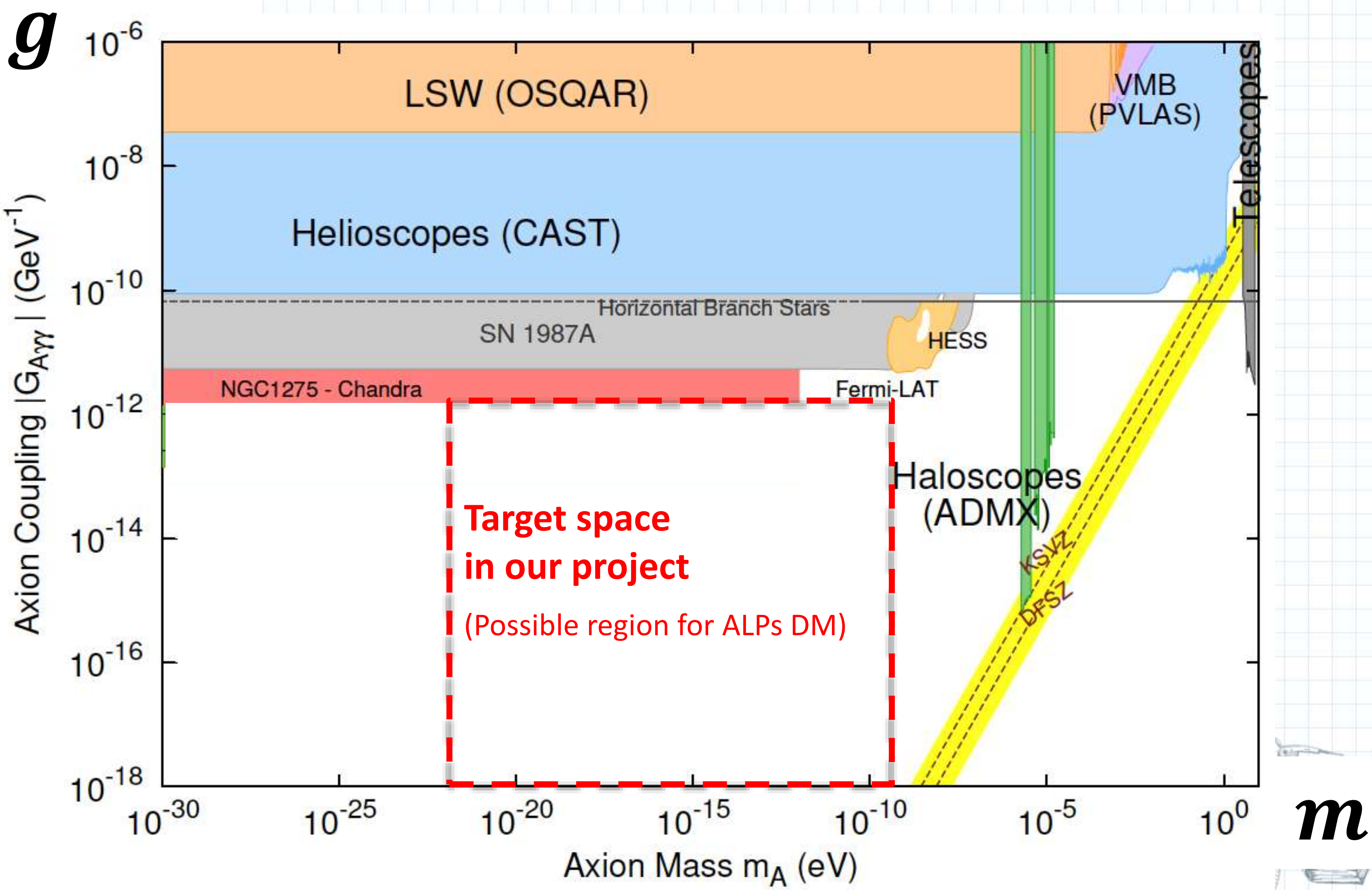
Experiments with AP conversion

- Axion Helioscope



introduction

Current constraint



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Non-linear

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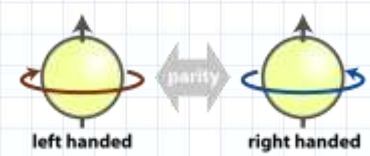
Photon EoM: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}$

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

⇨ 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!

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

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

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

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

Birefringence

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

- 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

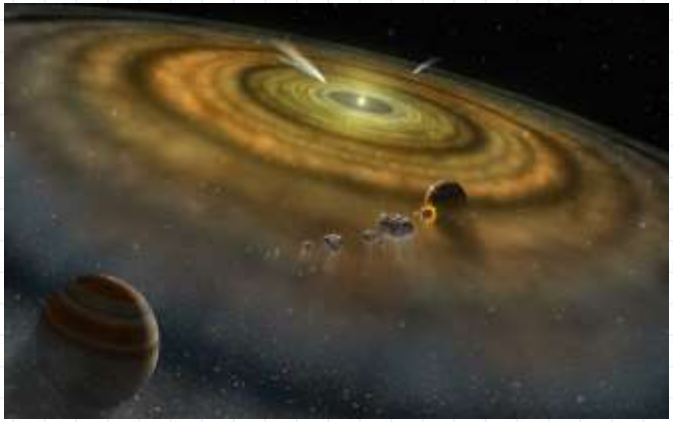
- Observations of PPD can be used!

PPD is a flattened gaseous object surrounding a young star.

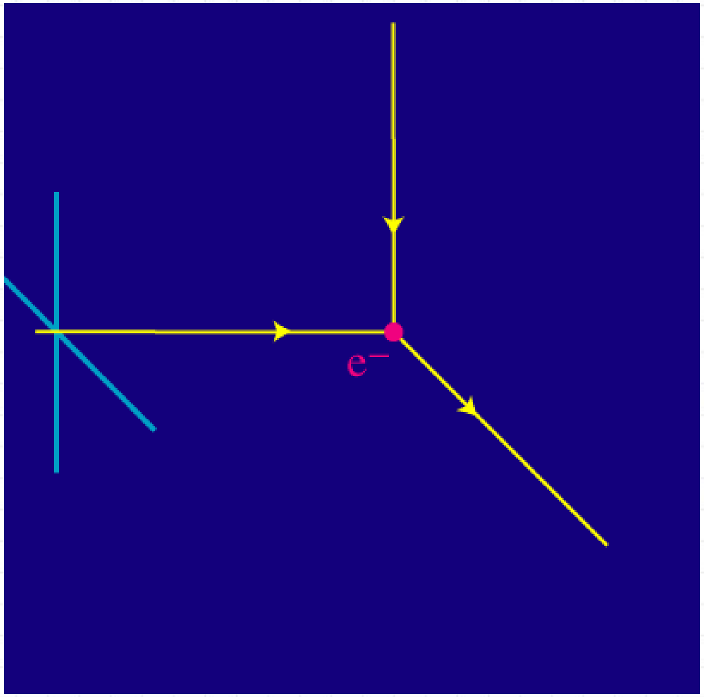
PPDs are bright simply by scattering the central star's light.

Real data

Artist's image



Polarization of scattered light

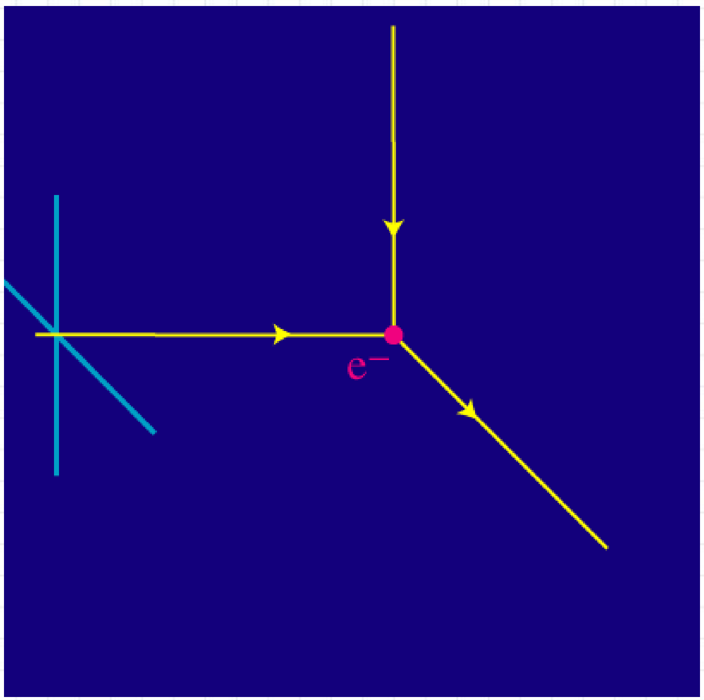


Consider incoming radiation from the left being scattered by 90 degrees out of the screen:

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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along its
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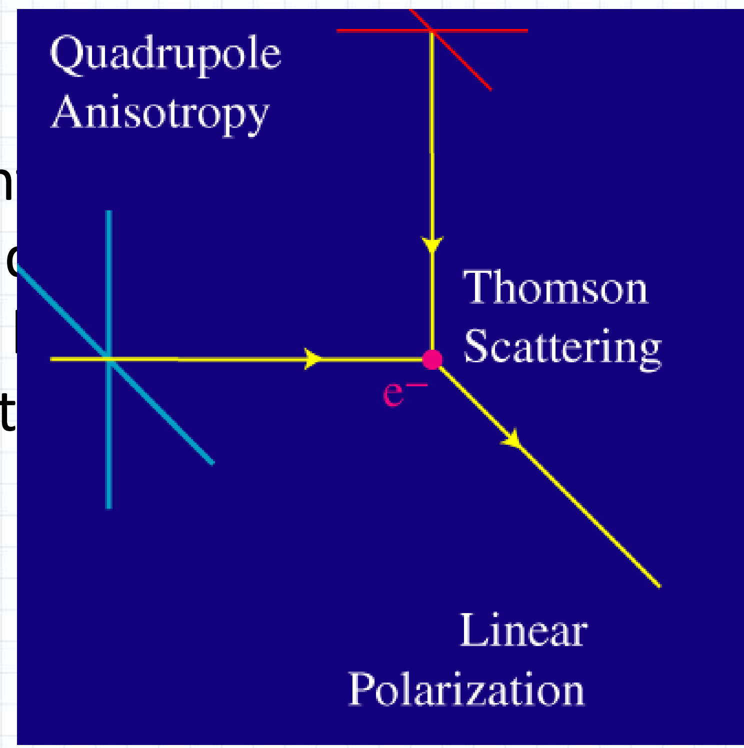
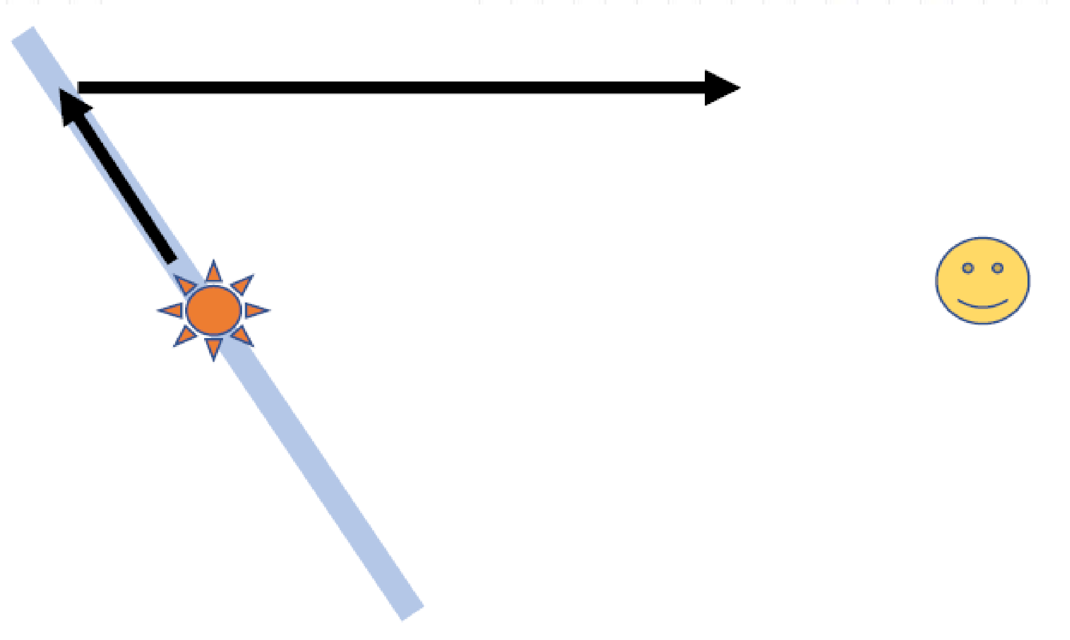
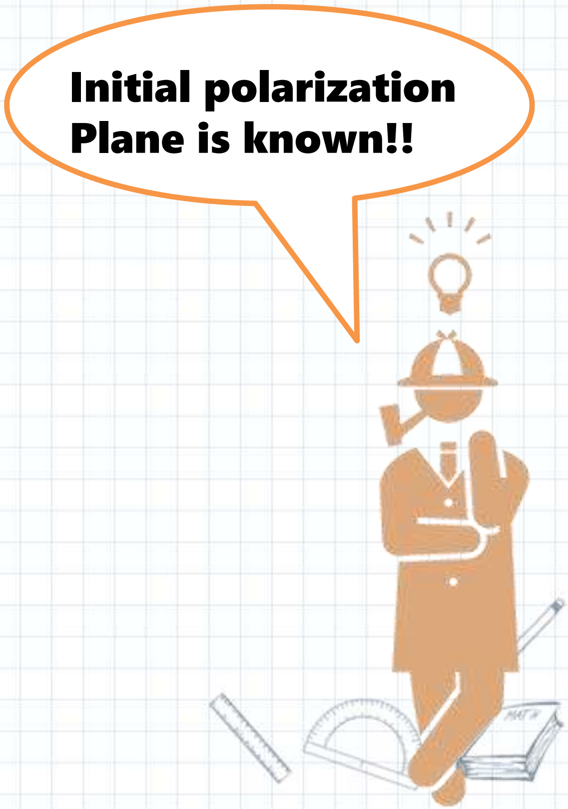


[Credit: Weyne Hu's homepage]

Polarization of PPD

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



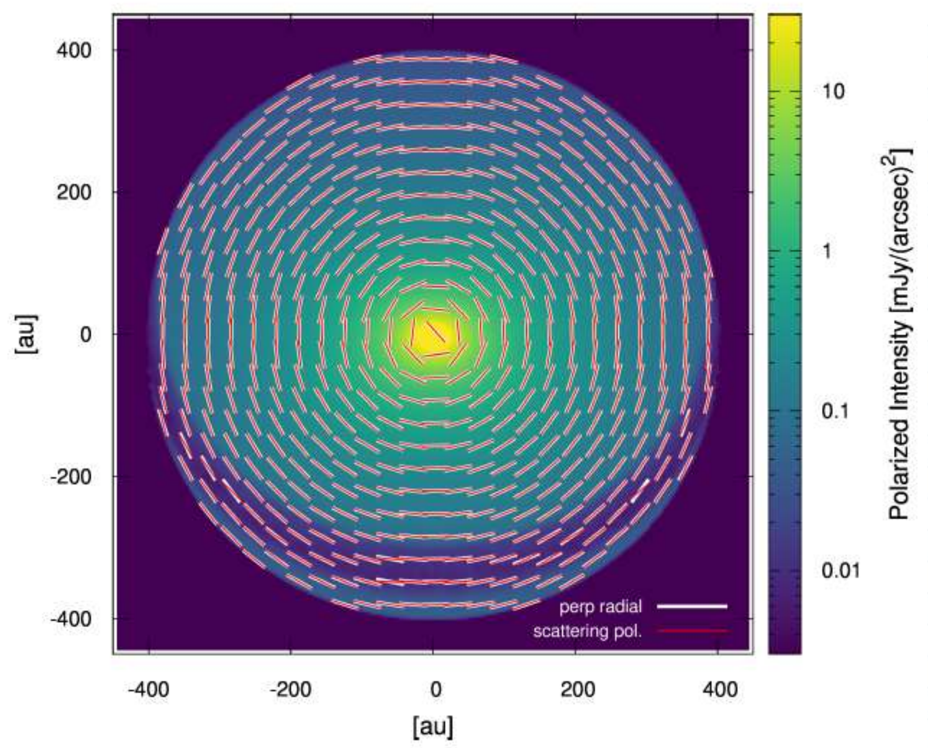


Obsevation of PPD

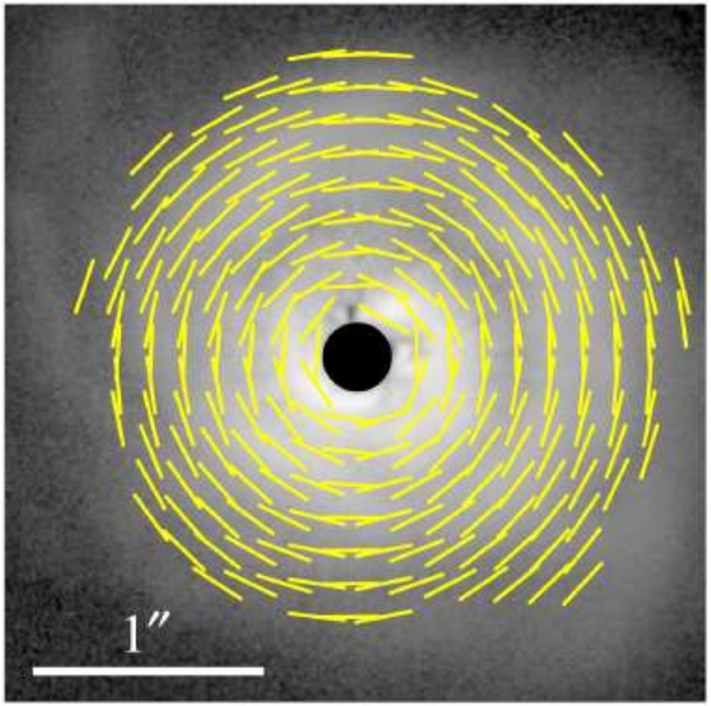
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM

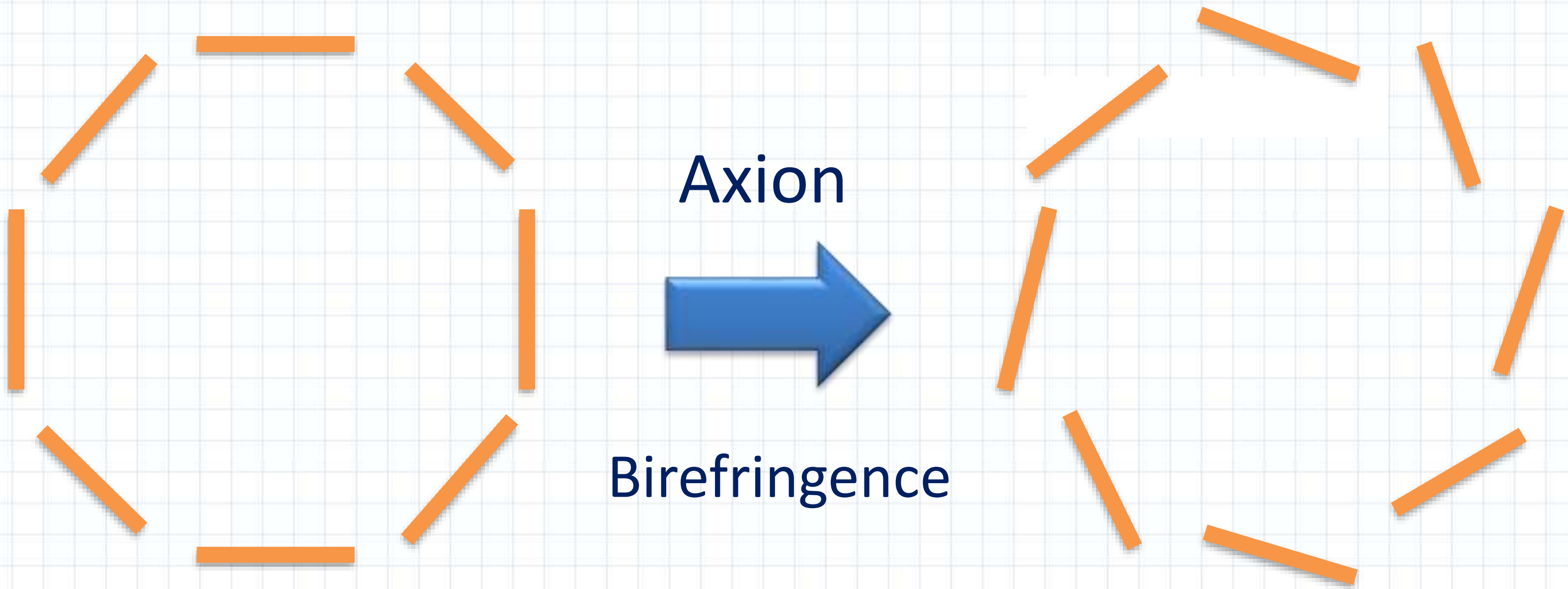


Observation by SUBARU



AB Aurigae (160pc away)

Axion DM rotates pol. plane?



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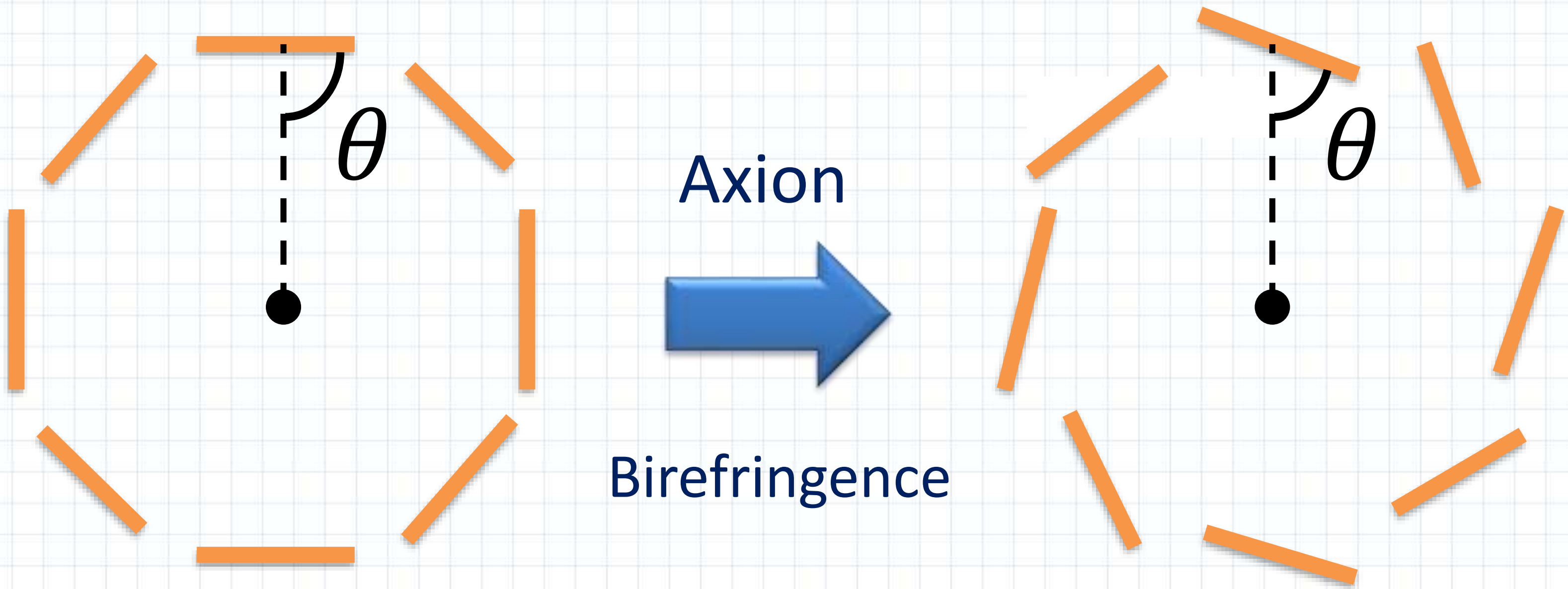


Is this angle 90° or not?

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

Obsevation of PPD

The observation data reveals

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

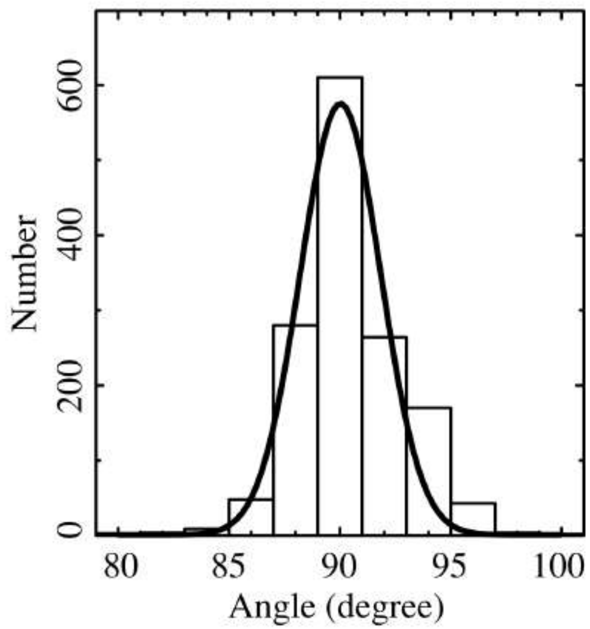


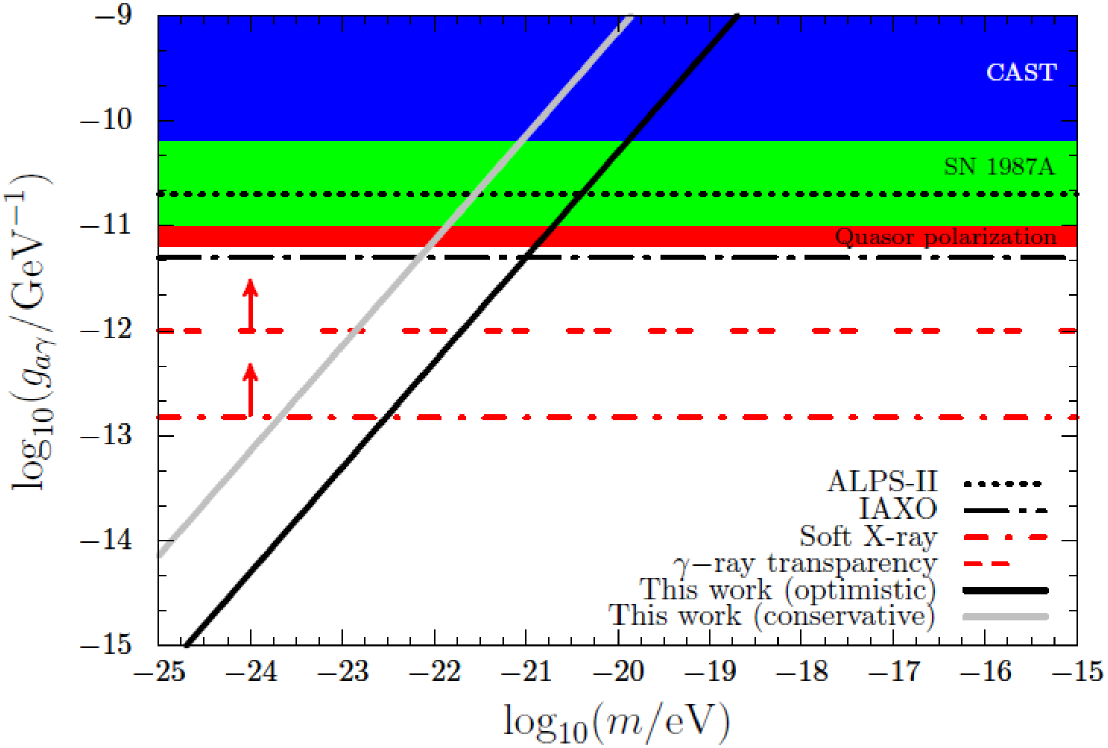
Figure 3 shows the observed polarization vector (the position angle as 0.5 arctan(U/Q)) image of AB Aur (see the caption of Figure 3 about the construction of the vector image) and a histogram of the angles between the polarization vectors and lines from the stellar position to the vector position. The polarization vector pattern is a good indicator of whether the Stokes Q and U are affected by residual speckle noise of the bright central star. This is because when the Stokes Q and U contain such noise, the polarization vectors show either random or parallel alignment. As a result of Gaussian fitting in the histogram, we found that the central position and FWHM are $90^\circ\!.1 \pm 0^\circ\!.2$ and $4^\circ\!.3 \pm 0^\circ\!.4$, respectively. Since the polarization vectors are clearly centrosymmetric, we conclude that the residual speckle noise of AB Aur is quite low and any features identified in our PI images (the ring gap, dips, and peaks) are real.

[TF. Tazaki & Toma (2018)]

New constraint

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

g



m[eV]

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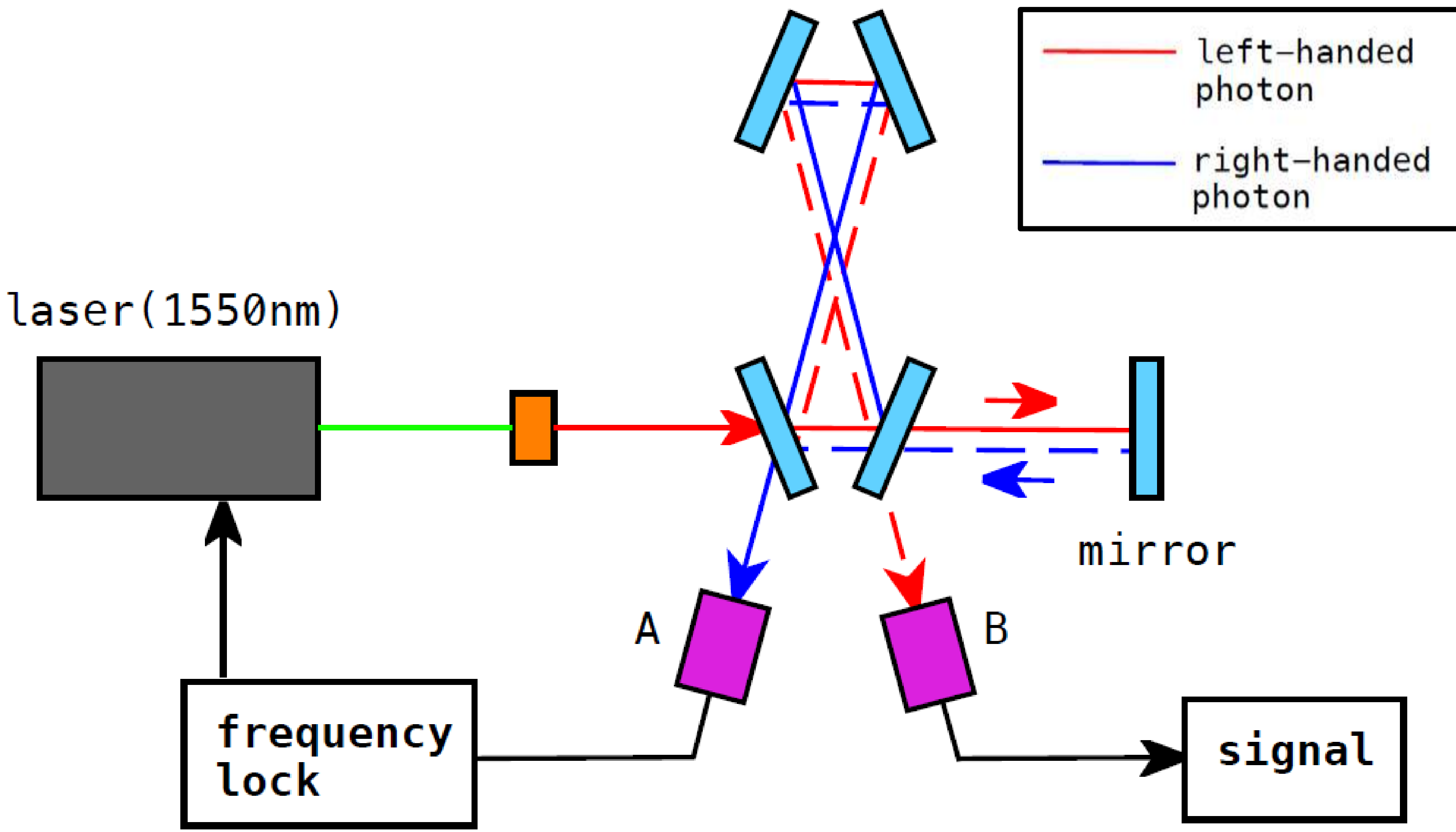
New experiment

[Obata, TF, Michimura(2018)]



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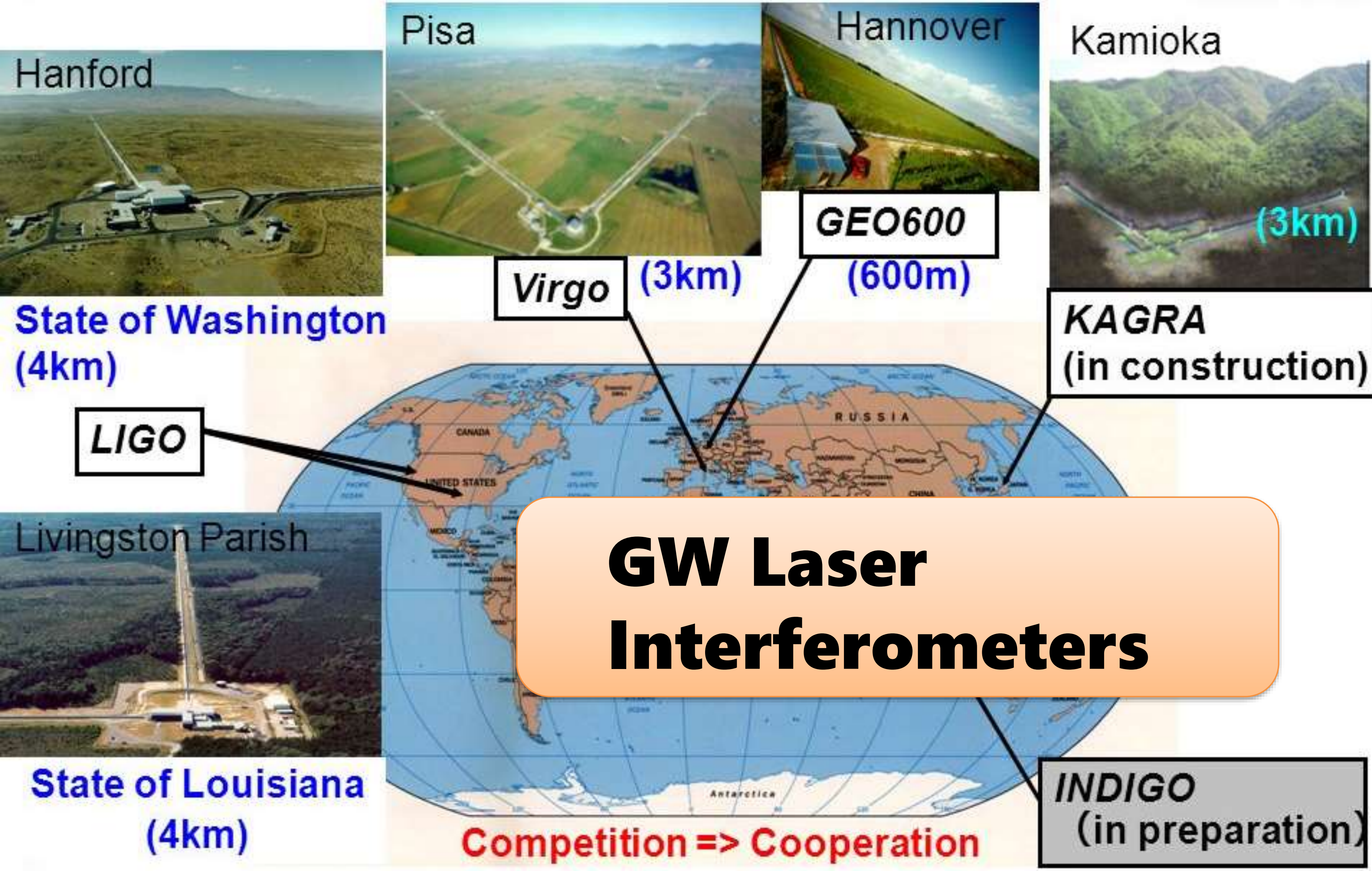


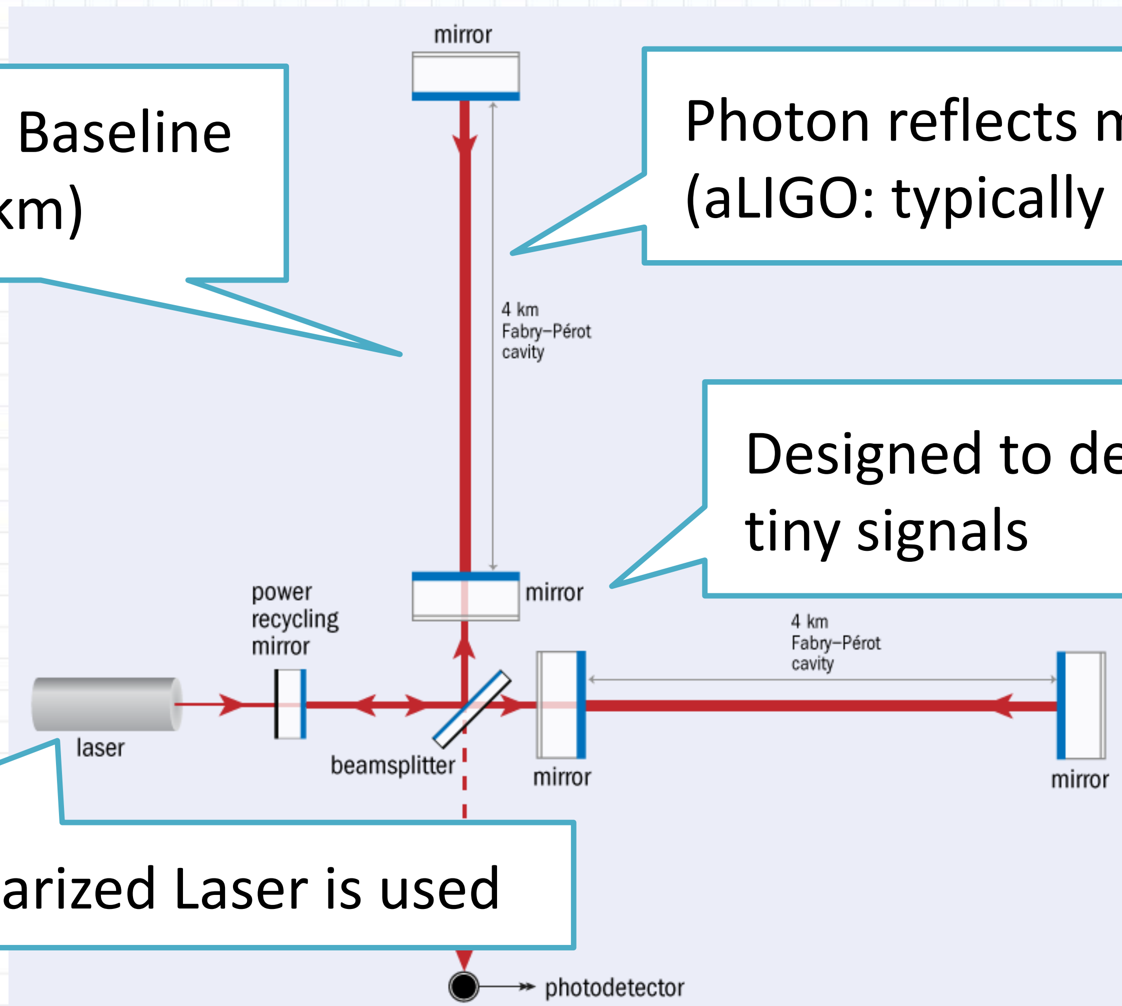
New experiment

Can we play the same game

with GW interferometers?

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

Target mass is changed

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

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

$$\Xi \equiv mT/2 \approx (m/10^{-22}\mathrm{eV})(T/1\mathrm{kpc})$$

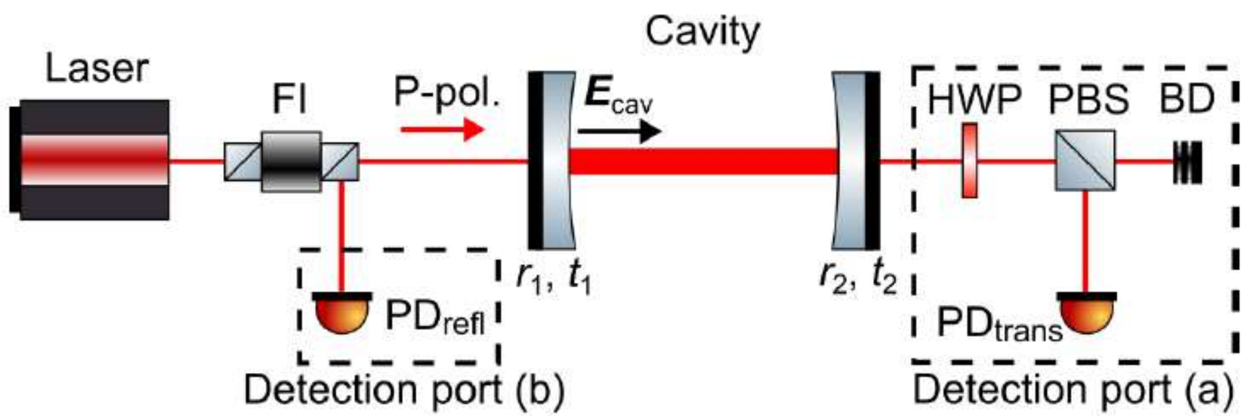
- Rotation angle becomes tiny…

$$\theta(t,T) \approx 10^{-12} \left(\frac{m}{10^{-12}\mathrm{eV}}\right)^{-1} \sin \Xi \sin(mt + c) g_{12}$$

$$\Xi \equiv mT/2 \approx (m/10^{-12}\mathrm{eV})(T/10\mathrm{ms})$$

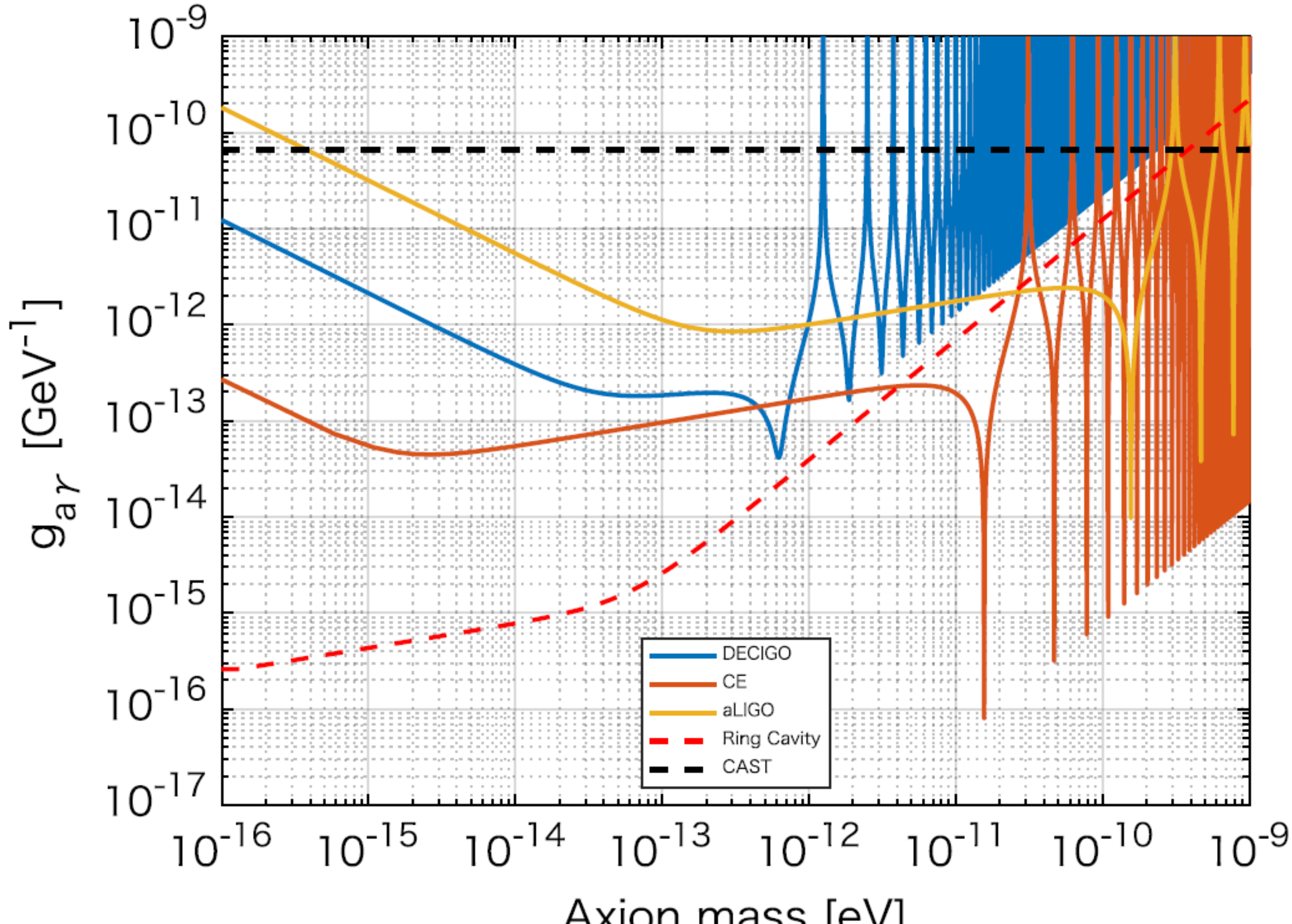
Coexist with GW observation

- 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



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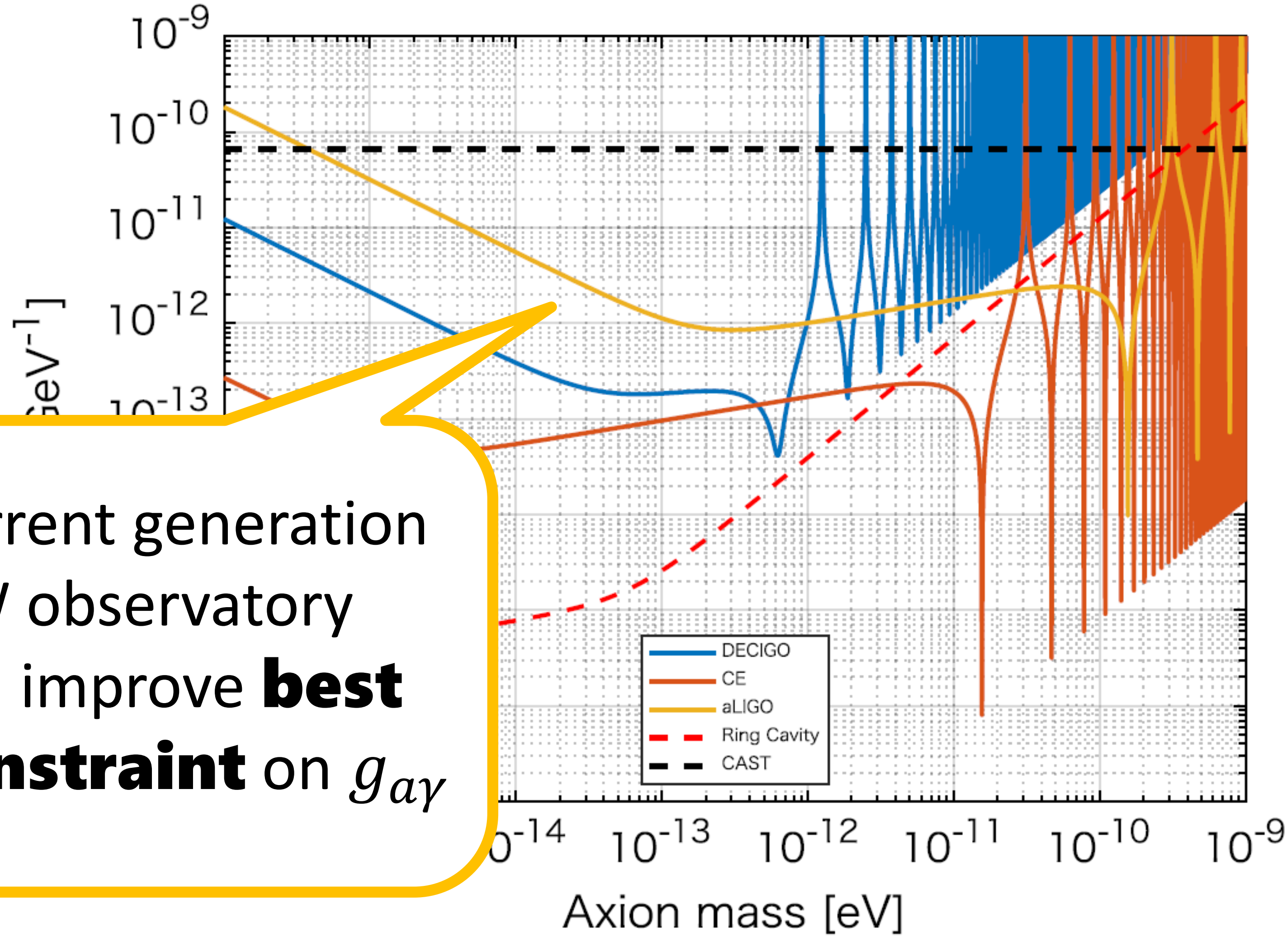

Current generation GW observatory can improve **best constraint** on $g_{a\gamma}$

New experiment

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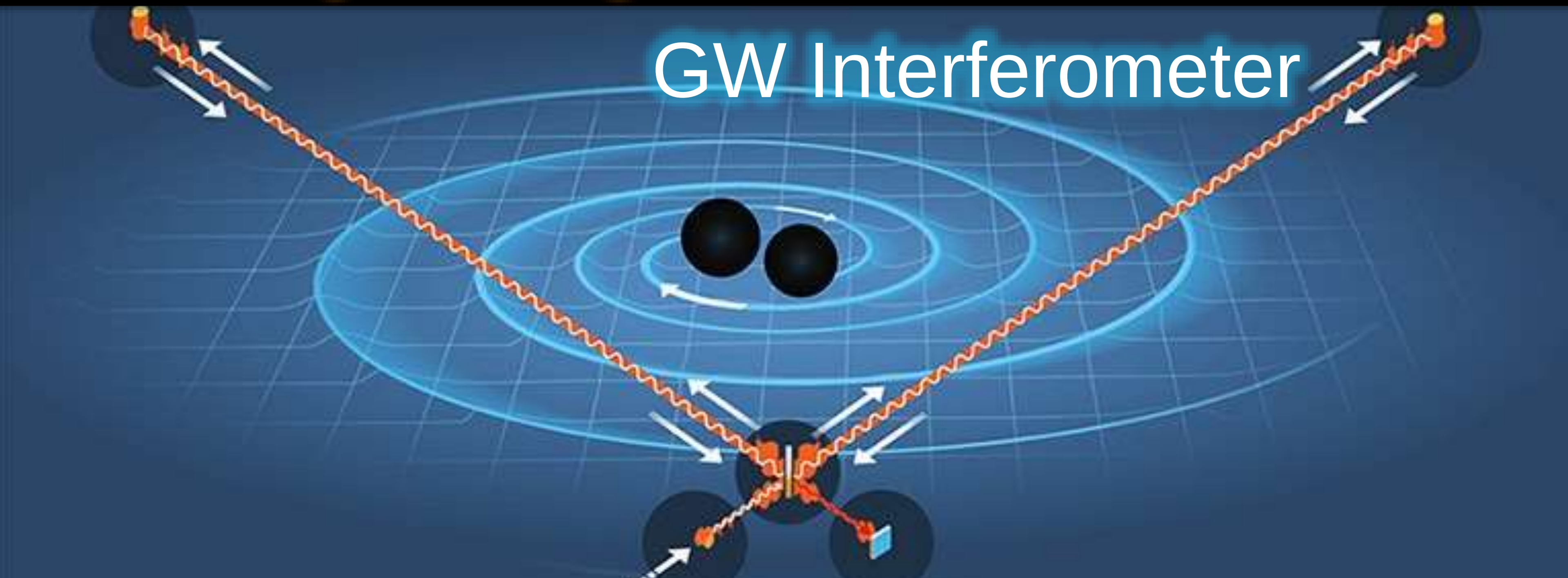
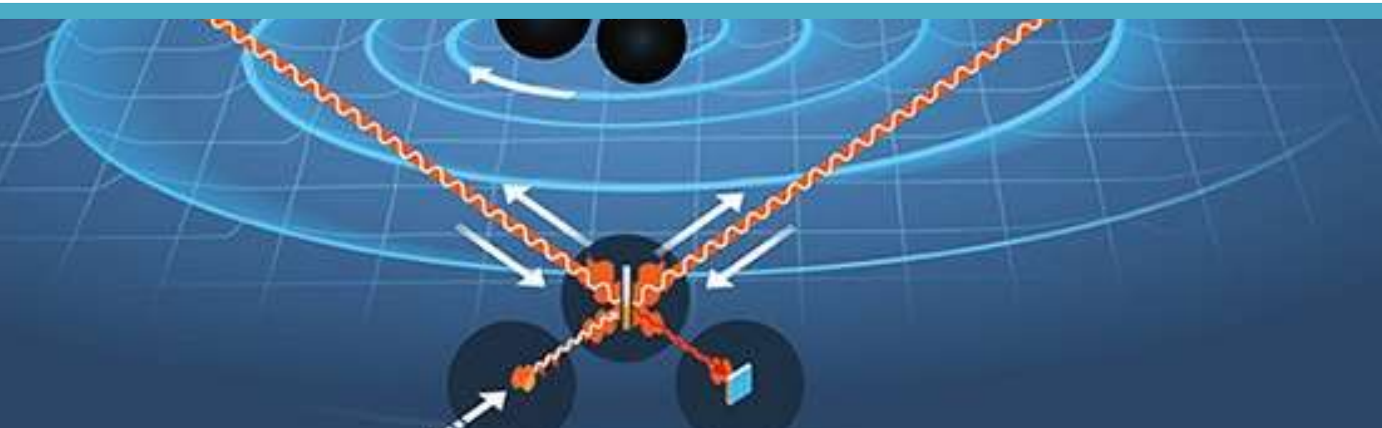
introduction
Protoplanetary Disk


GW Interferometer

Main Message

PPD and GW detector provide new and best methods to search for axion dark matter.

PPD observation improves limit on Fuzzy DM.
GW interferometer can be ADM detector for free.



Summary

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

THE THEME
OF CHAPTER IS...

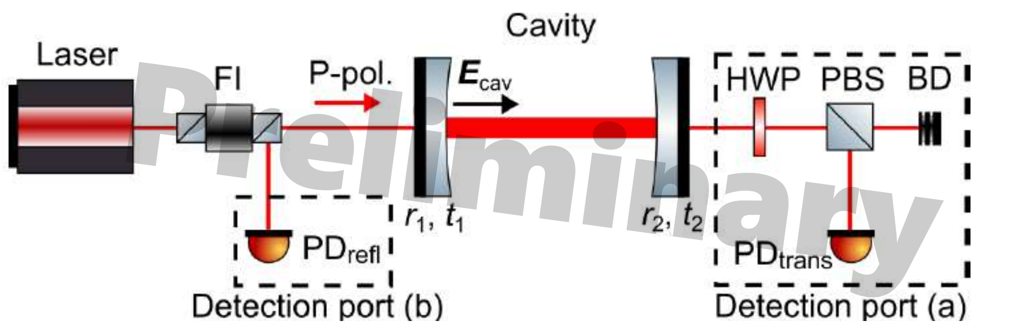
Thank you！

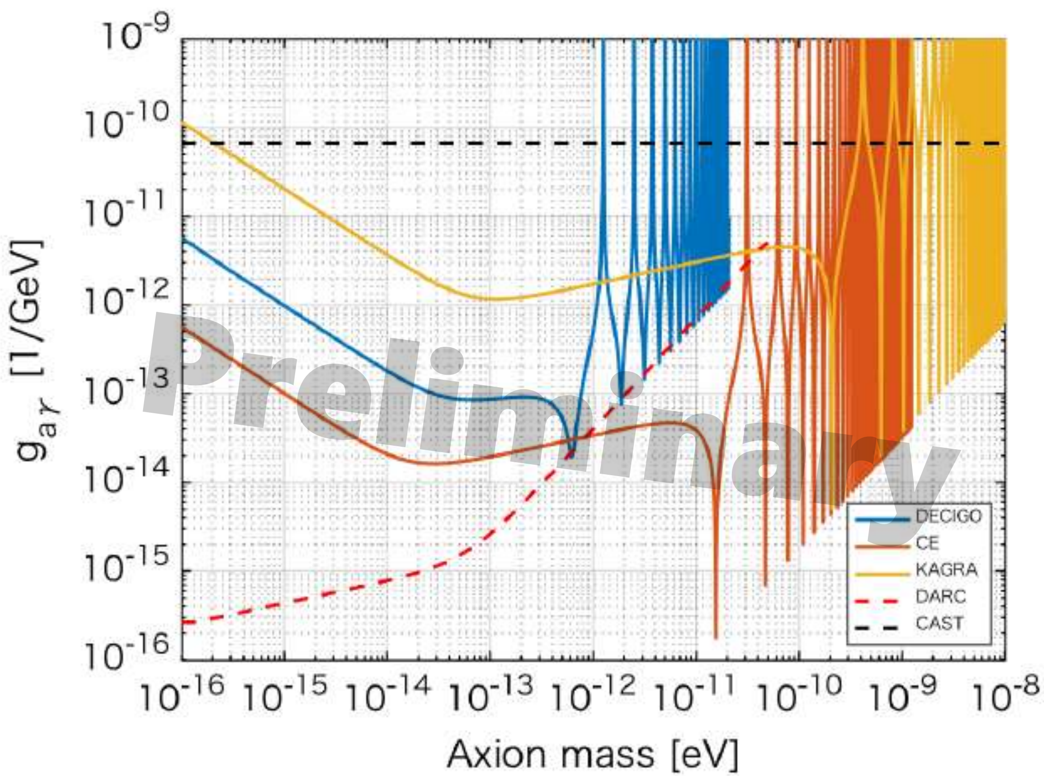
New experiment

[Nagano, Obata, Michimura & TF (in prep)]

- GW laser interferometer can be converted into ADM search experiment by adding detector at tail

- KAGRA may be reborn as the best ADM detector while keeping its ability to observe GWs.





New experiment

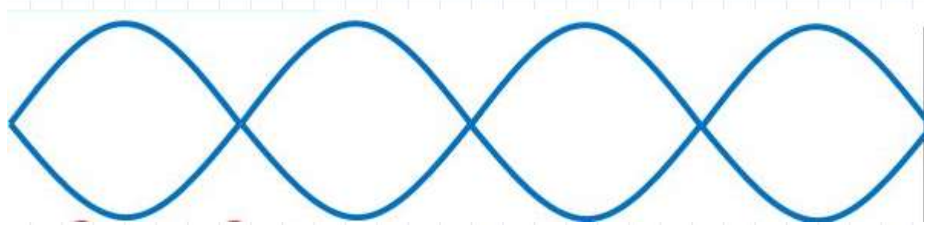
[Obata, TF, Michimura(2018)]

- Dispersion relations for Left/Right pol. are different

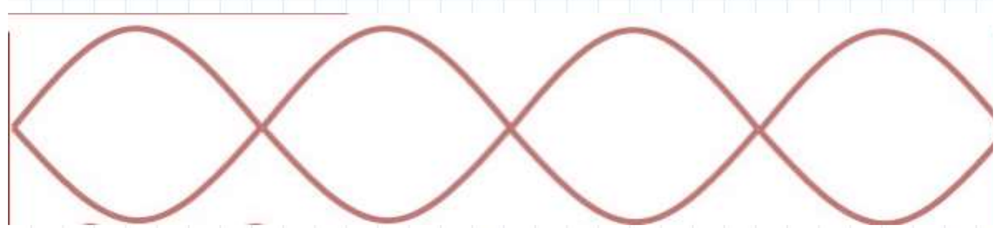
  Travel distance (kx) ⇔ # of oscillation $(\omega_{\pm} t)$

- How can we experimentally measure it?

Right



Left



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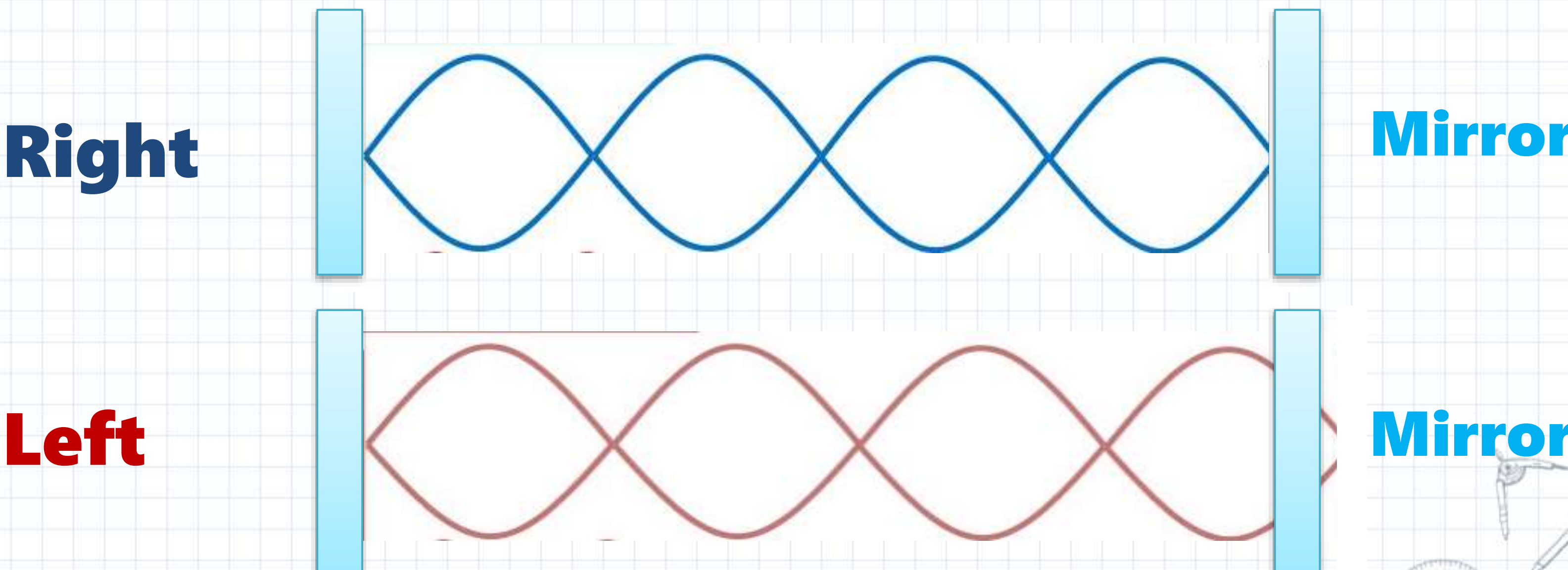

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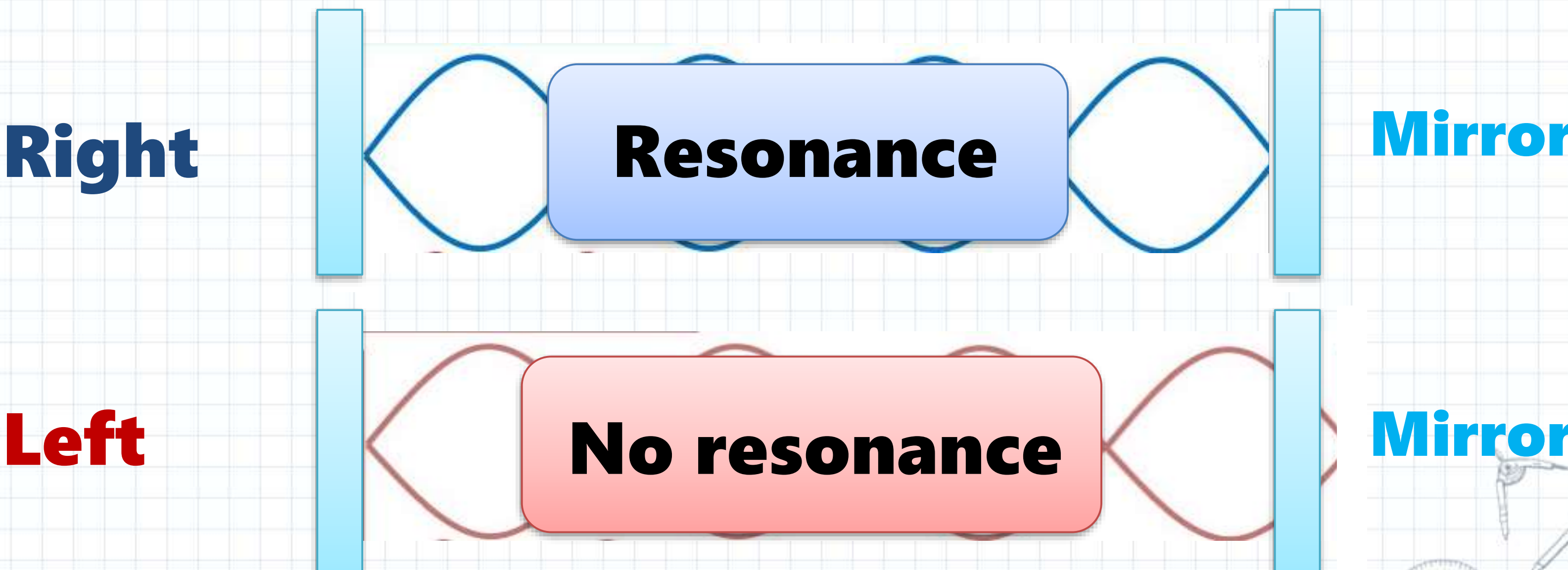


New experiment

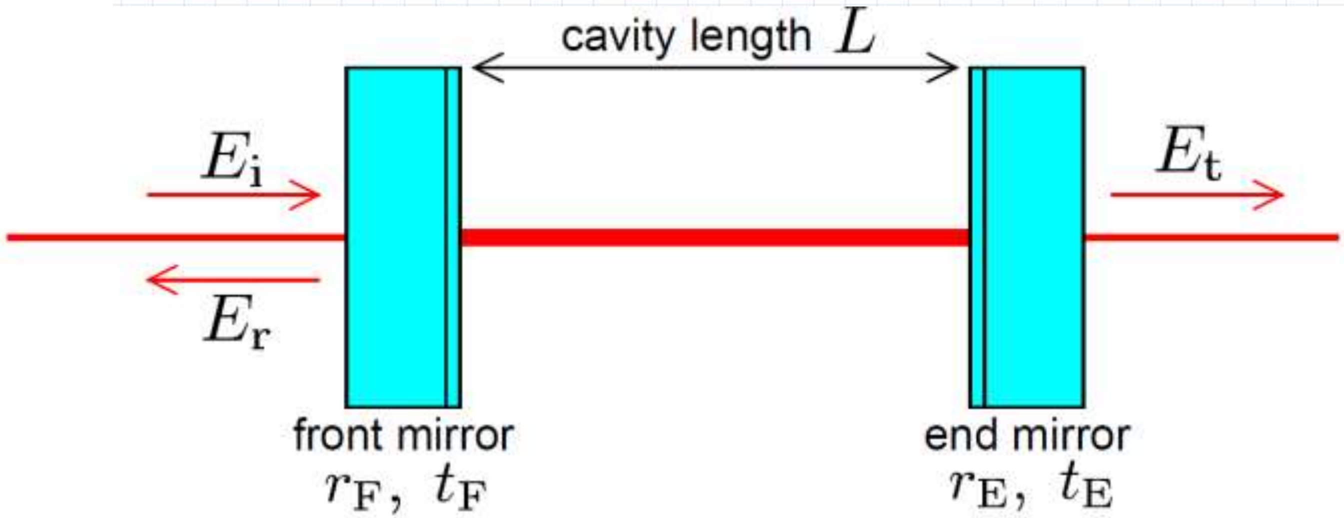
[Obata, TF, Michimura(2018)]

- 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

Fabry-Perot Resonator

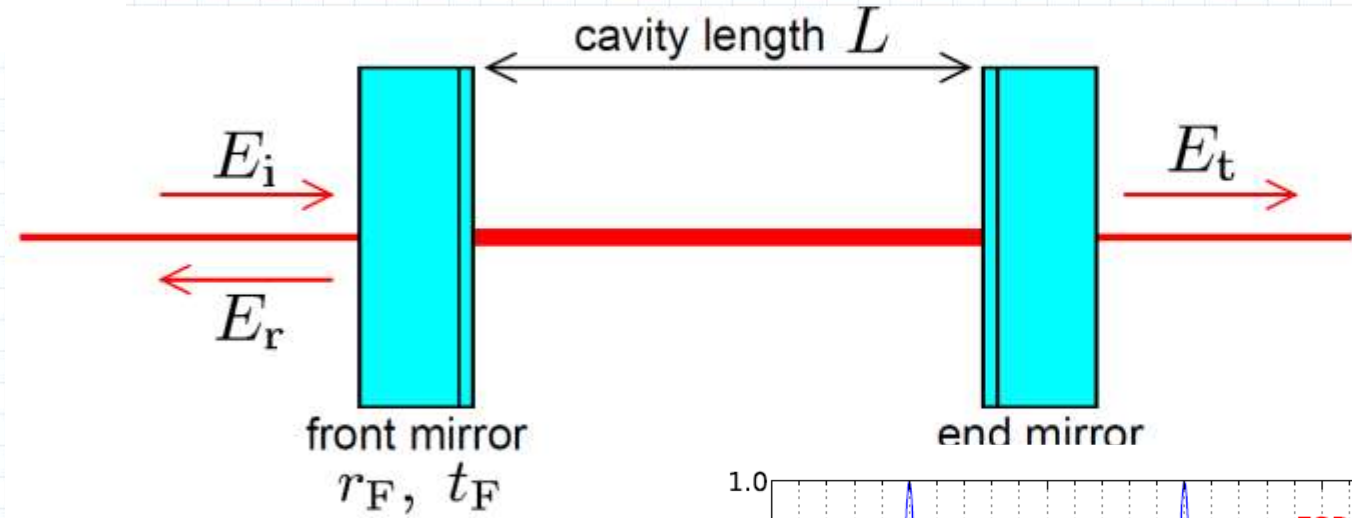


E changes its phase by $\phi = 2L\omega$ for one round trip.

$$E_\mathrm{t} = E_\mathrm{i} t_\mathrm{F} t_\mathrm{E} e^{-i\phi/2} + E_\mathrm{i} t_\mathrm{F} r_\mathrm{E} r_\mathrm{F} t_\mathrm{E} e^{-3i\phi/2} + E_\mathrm{i} t_\mathrm{F} r_\mathrm{E}^2 r_\mathrm{E}^2 t_\mathrm{E} e^{-5i\phi/2} + \cdots$$

$$P_\mathrm{t} = |E_\mathrm{t}|^2 = \frac{(t_\mathrm{F} t_\mathrm{E})^2}{(1 - r_\mathrm{F} r_\mathrm{E})^2 + 4 r_\mathrm{F} r_\mathrm{E} \sin^2(\phi/2)} |E_\mathrm{i}|^2$$

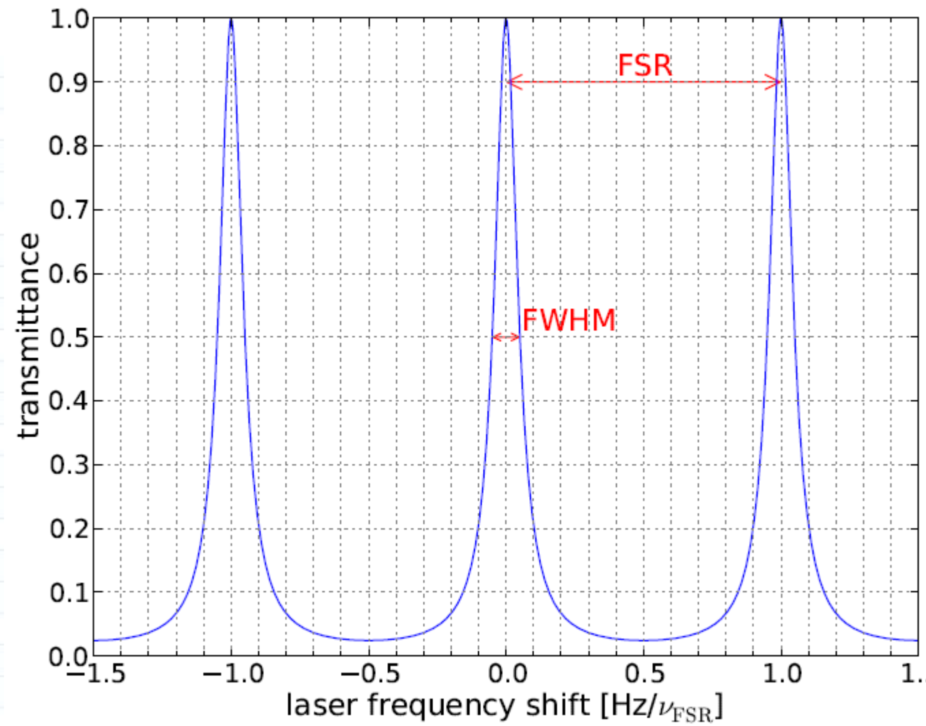
Fabry-Perot Resonator



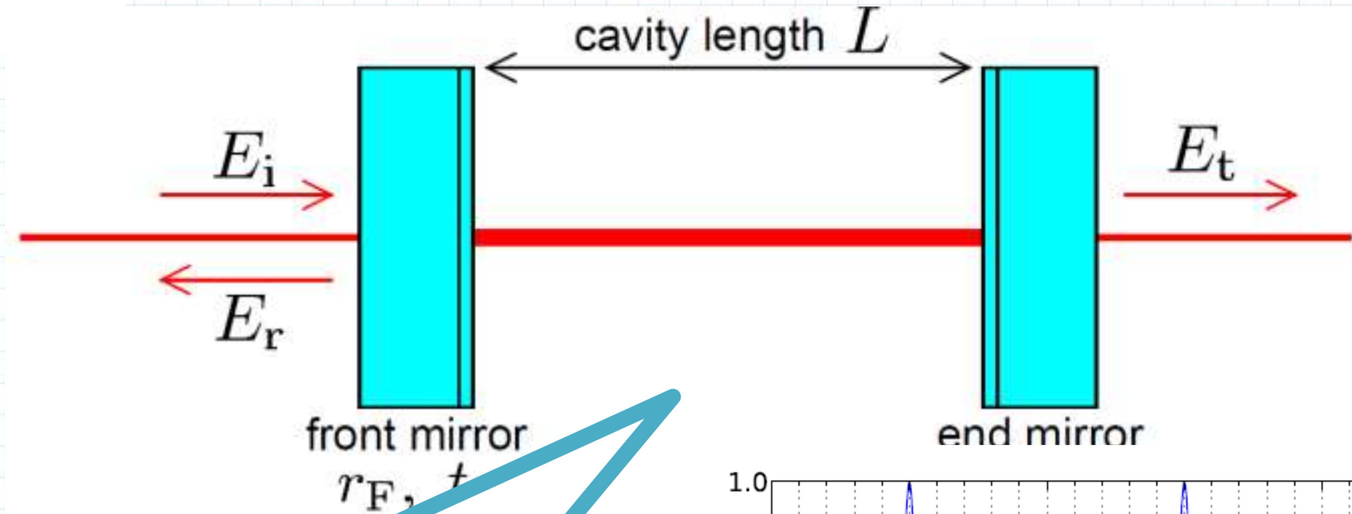
Sharp Resonance at $\phi = 2\pi\mathbb{N}$

Transmittance is almost unity

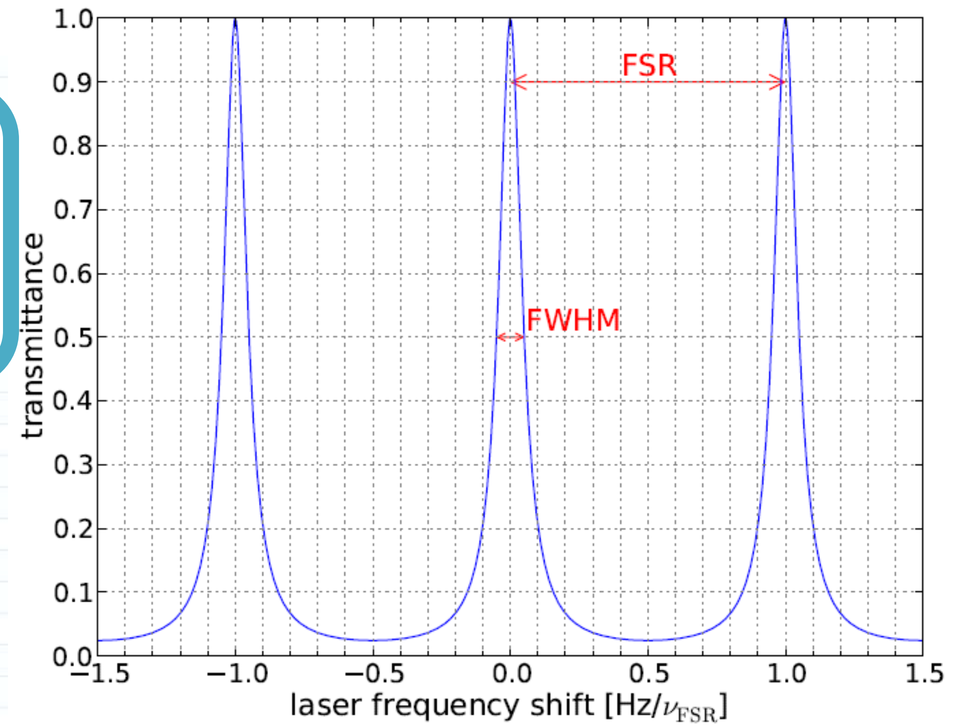
$|E_t|^2 \simeq |E_i|^2$ for $r_F = r_E$



Fabry-Perot Resonator



Cavity virtually vanishes at the resonance!

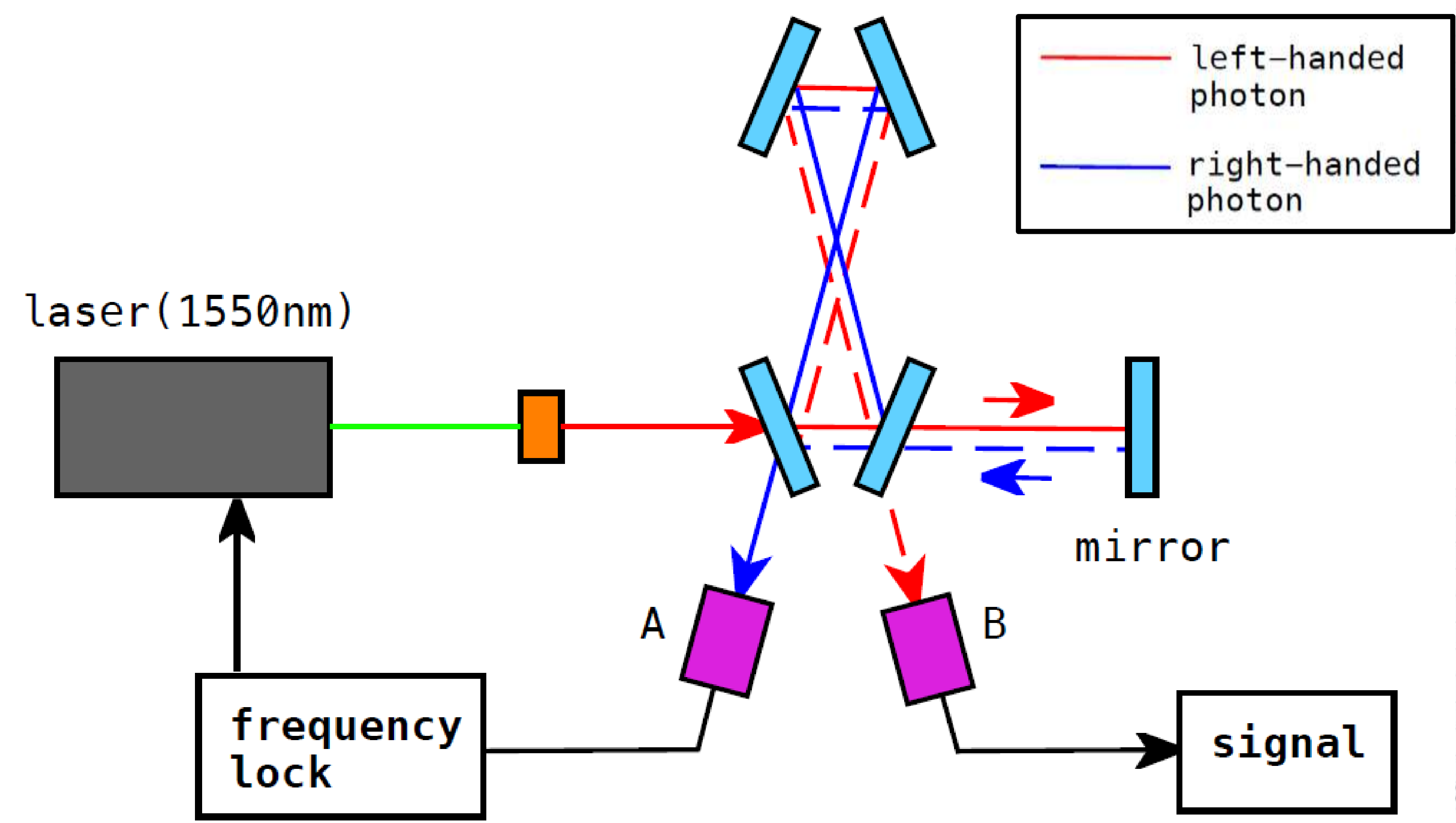


Transmittance is almost unity

$|E_t|^2 \simeq |E_i|^2$ for $r_F = r_E$

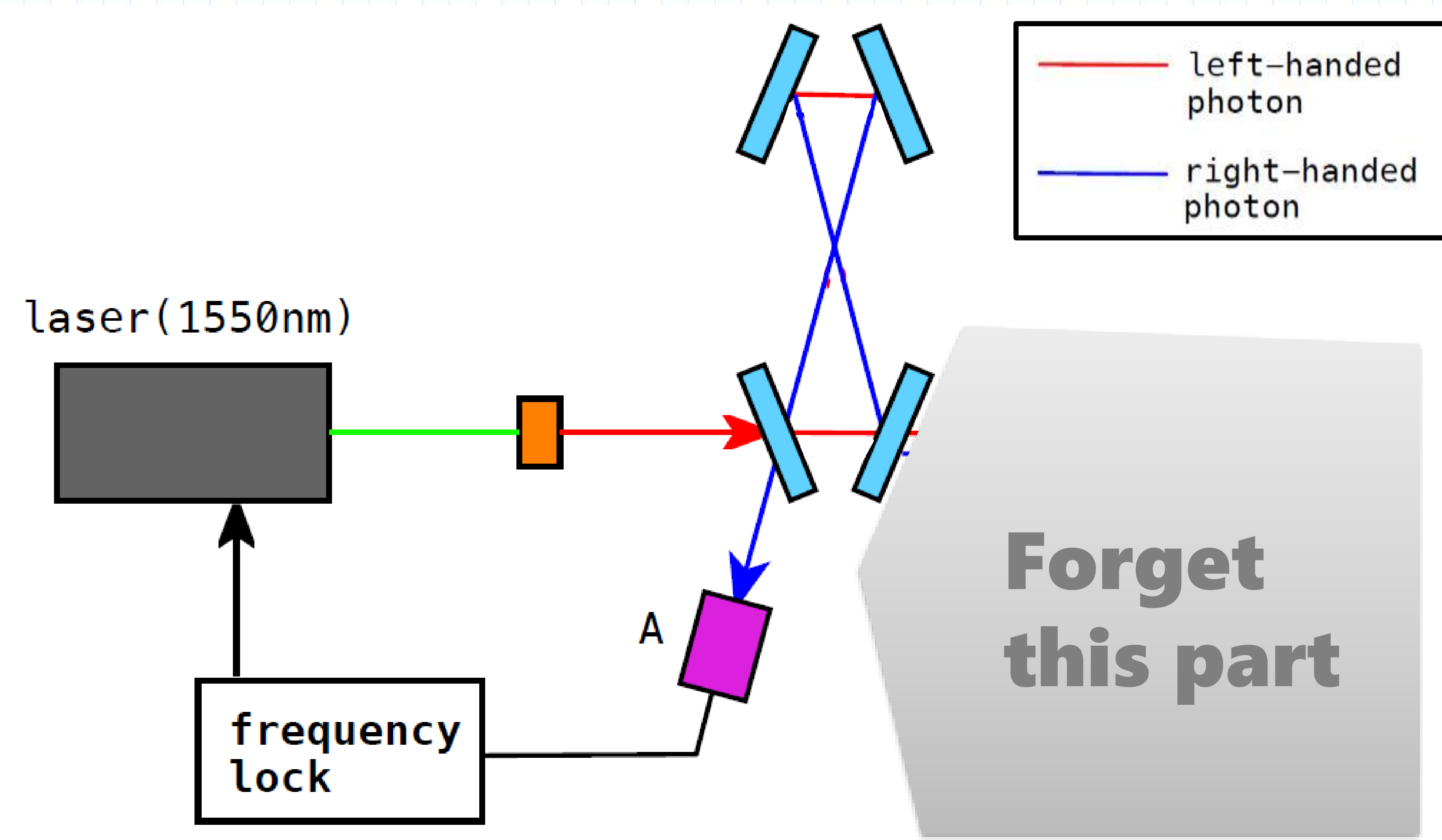
New experiment

[Obata, TF, Michimura(2018)]



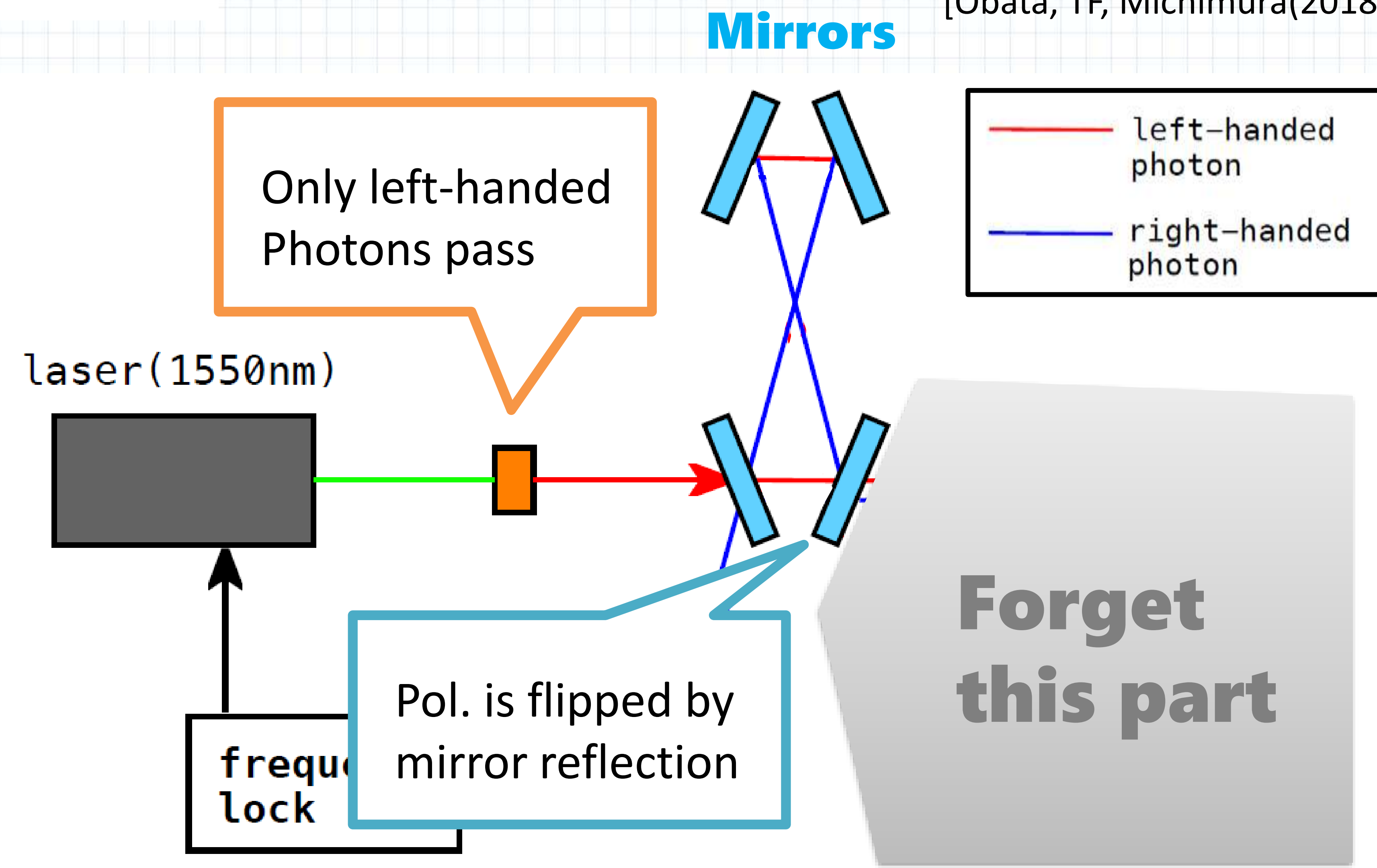
New experiment

[Obata, TF, Michimura(2018)]



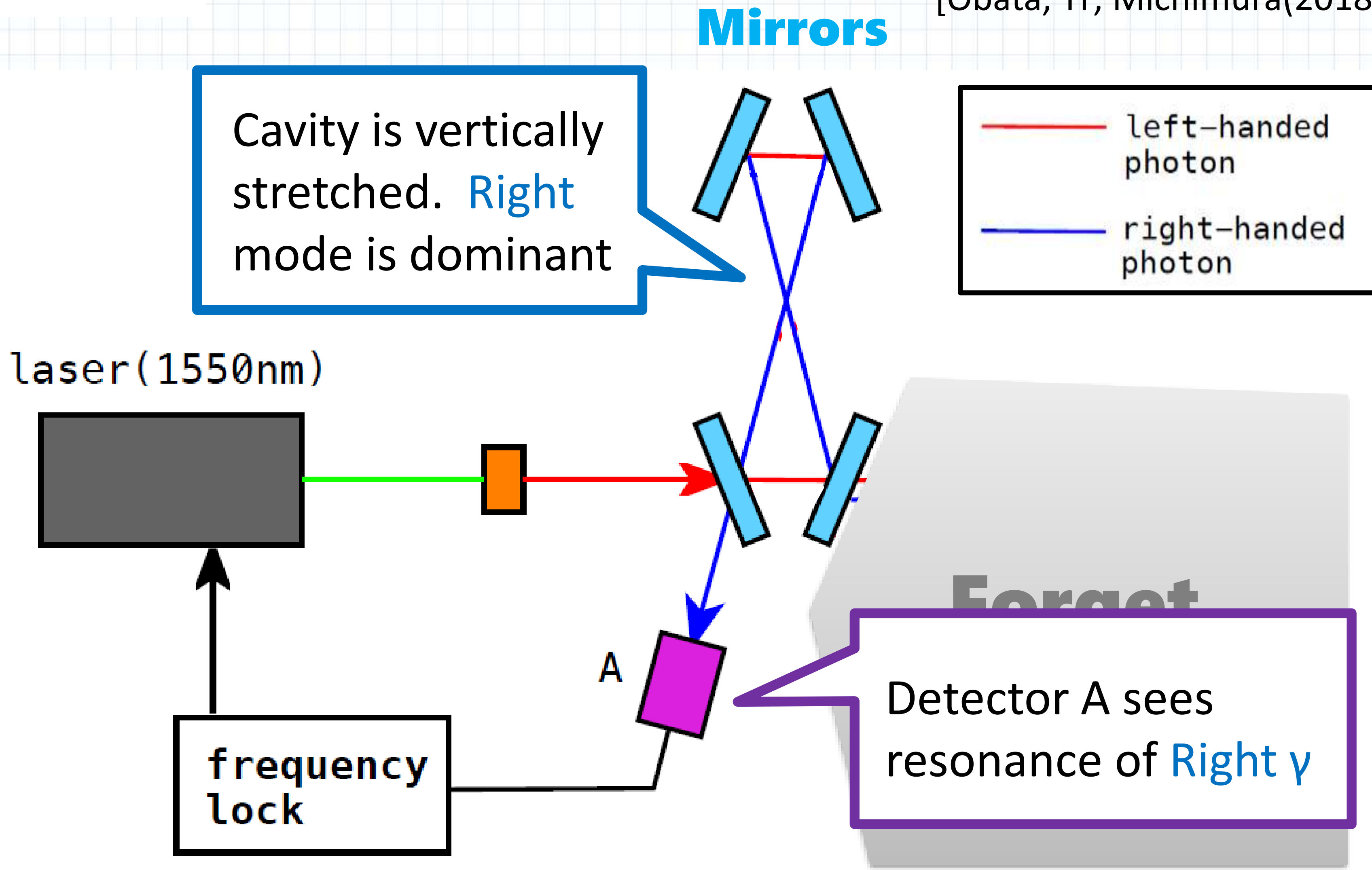
New experiment

[Obata, TF, Michimura(2018)]



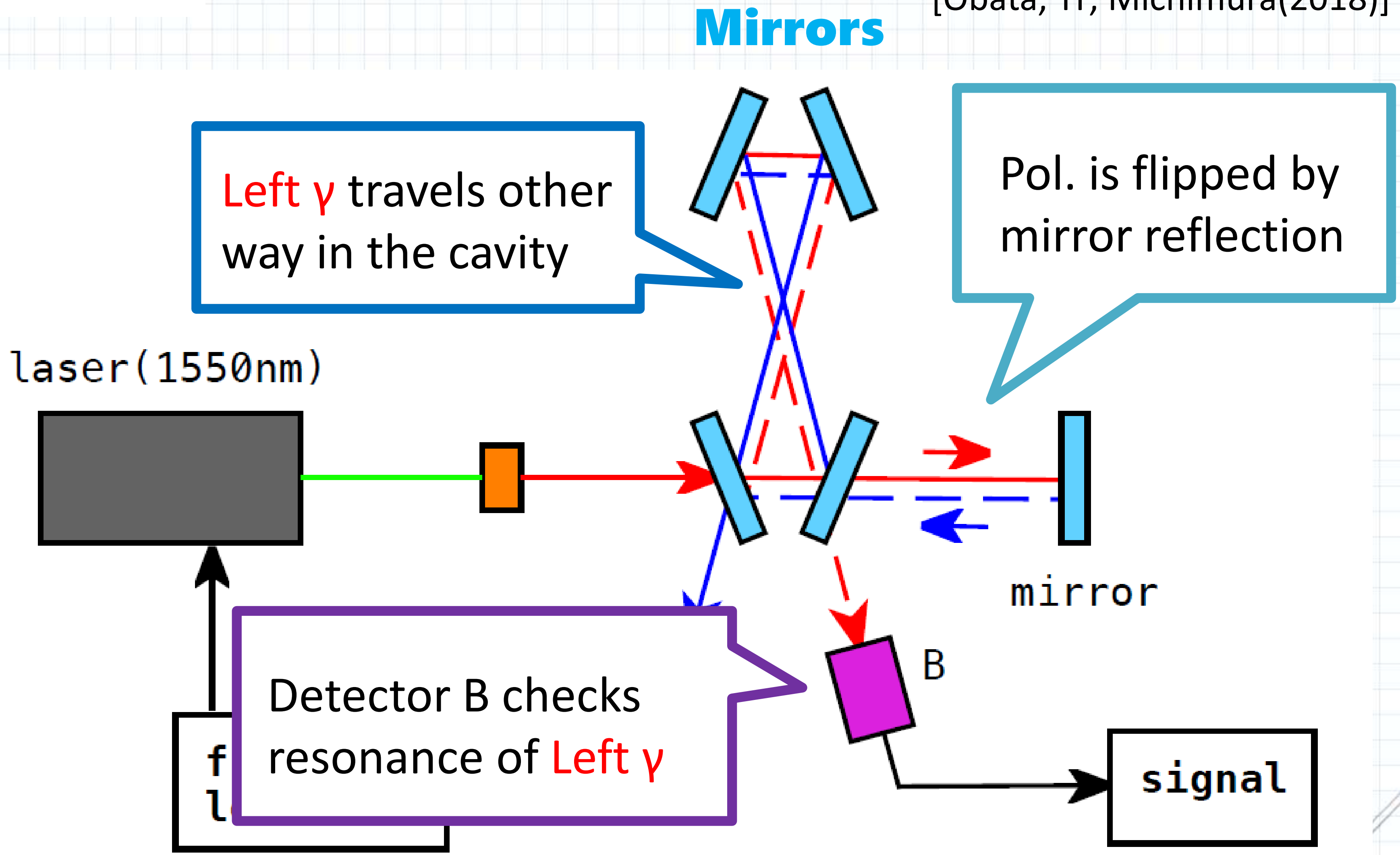
New experiment

[Obata, TF, Michimura(2018)]



New experiment

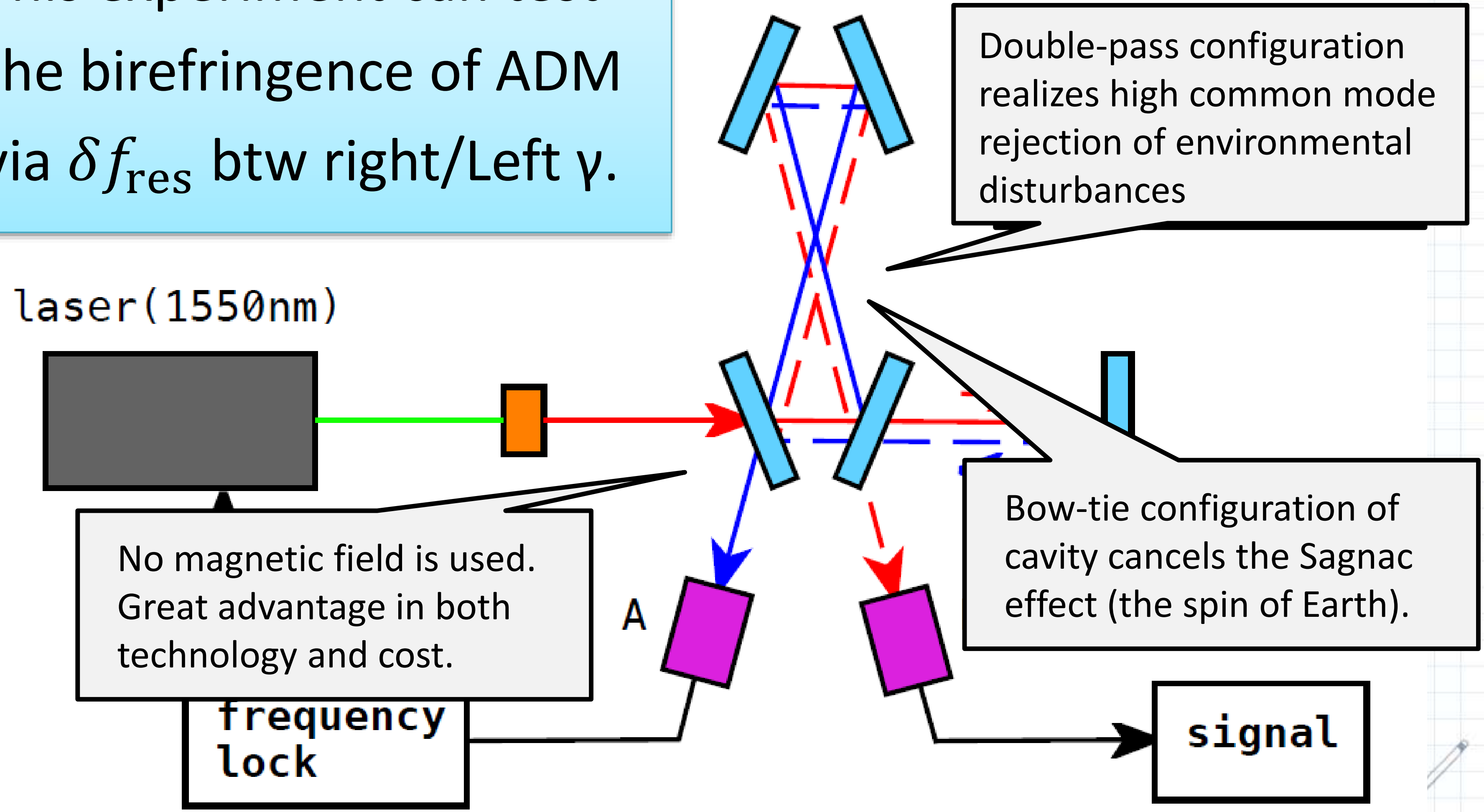
[Obata, TF, Michimura(2018)]



New experiment

[Obata, TF, Michimura(2018)]

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



Double-pass configuration realizes high common mode rejection of environmental disturbances

Bow-tie configuration of cavity cancels the Sagnac effect (the spin of Earth).

No magnetic field is used. Great advantage in both technology and cost.