PRESENTATION

Hunting ALP dark matter

with laser experiments and protoplanetary disks

Tomohiro Fujita

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Obata, TF & Michimura PRL**121,**161301(2018)

TF, Tazaki & Toma PRL**122,**191101(2019)

Nagano, TF, Obata & Michimura PRL**123,**111301(2019)

22nd. Oct. 2020@IBS-ICTP

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Plan of Talk

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

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Who is Dark Matter?

DM candidates

Scalar

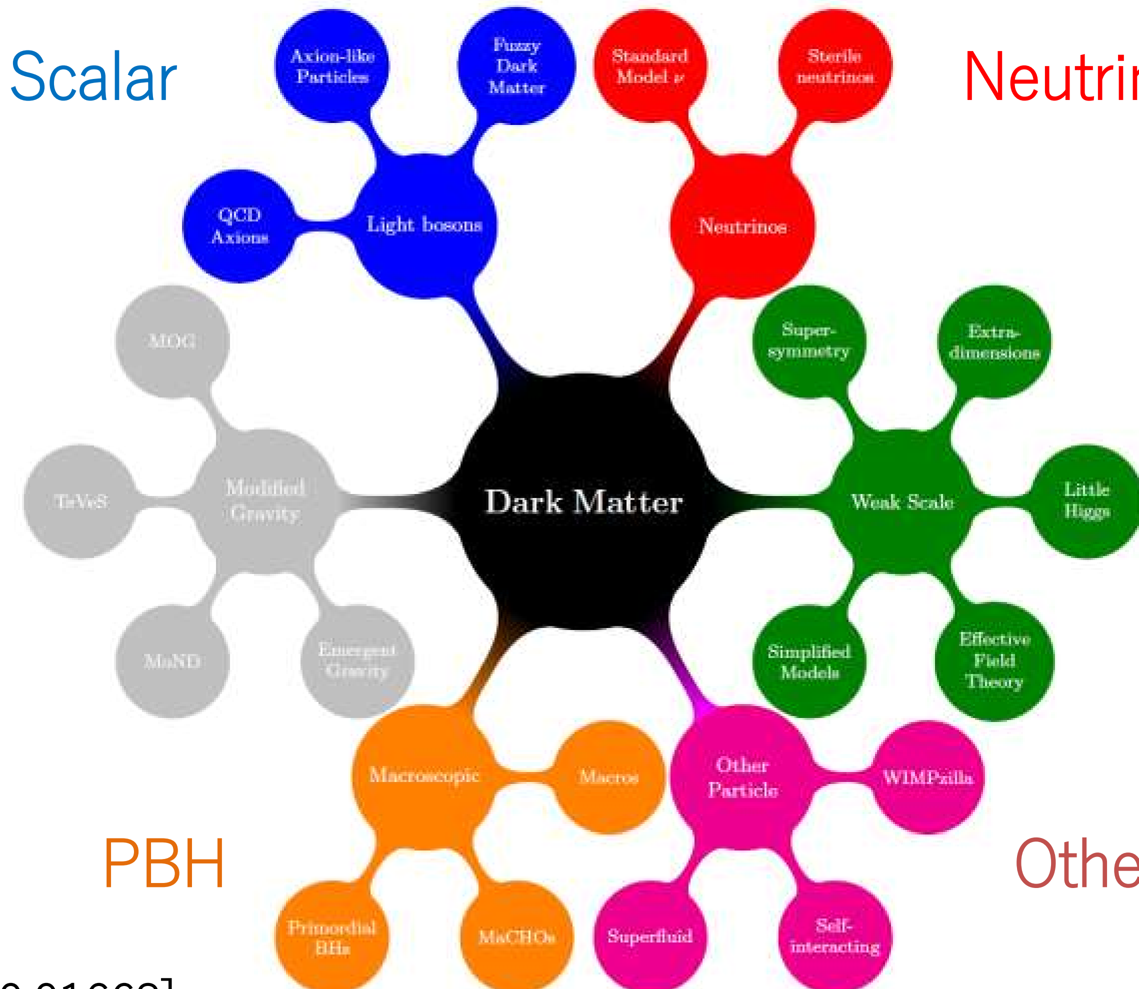
Neutrino

M-Gravity

WIMP

PBH

Other



Berton&Tait[1810.01668]

DM candidates

Scalar DM

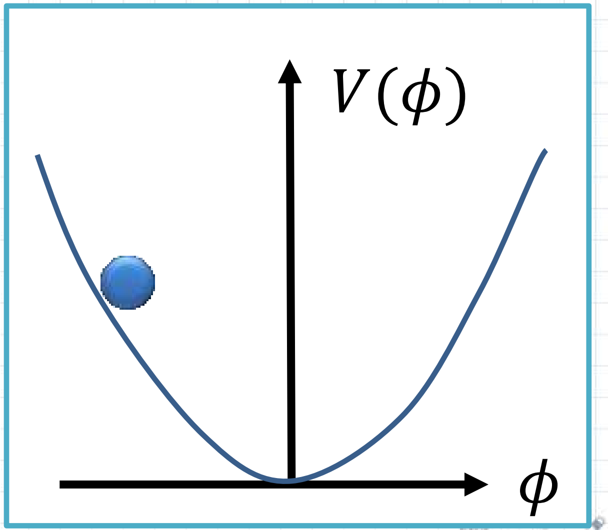
Berton&Tait[1810.01668]

Scalar Dark Matter ($\ni$Axion & ALPs)

- Different from particle DMs: production & evolution

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

- Oscillating Scalar Field: $m \gg H$



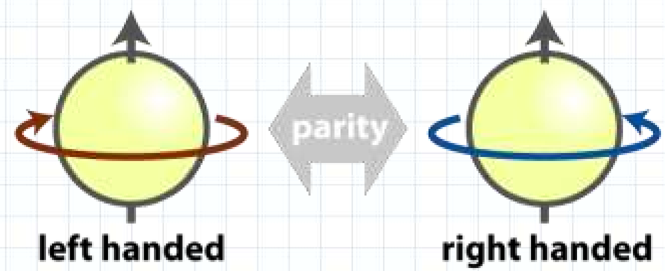
$$\phi = (a/a_0)^{-\frac{3}{2}}\, \phi_0 \cos(mt + \delta)$$

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

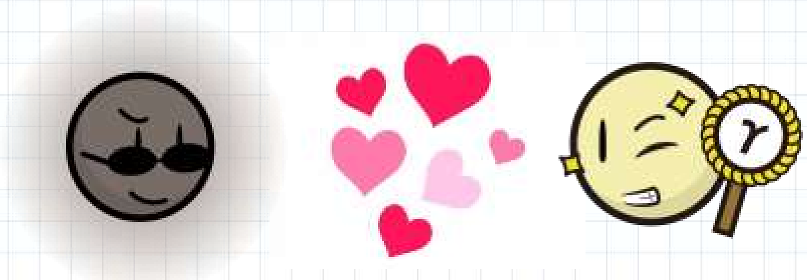
What characterizes ADM?

- 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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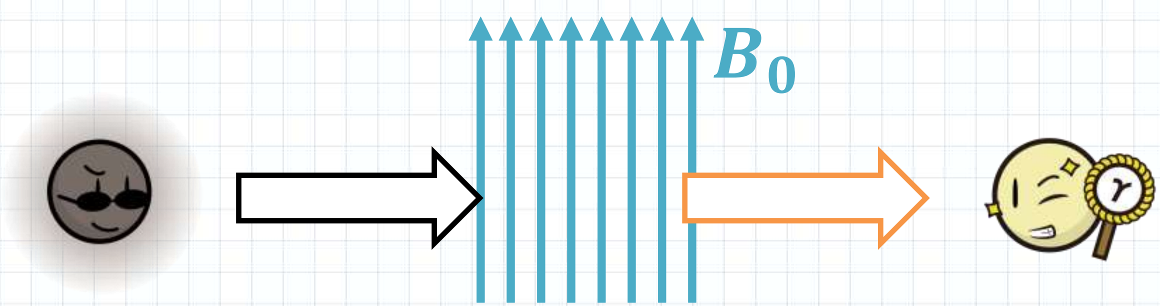
Conventionally constant magnetic field is introduced

Axion-Photon Conversion

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

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

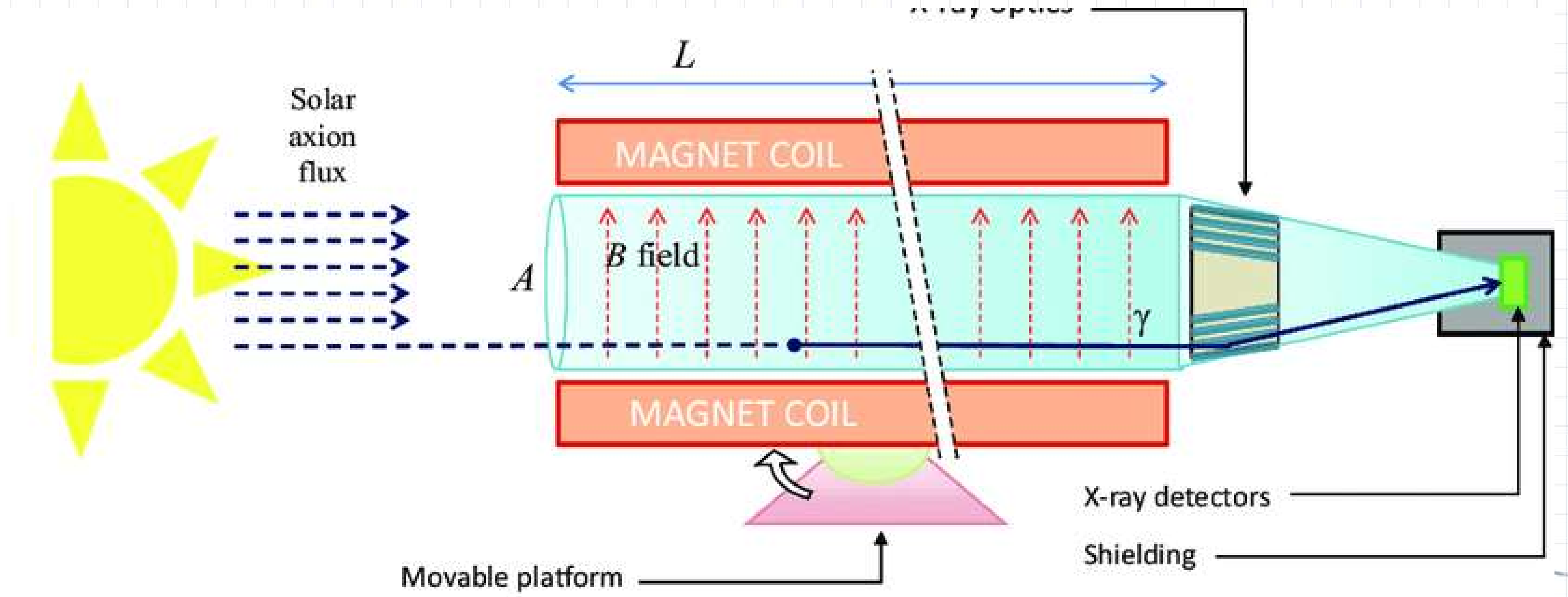
Axion: $$[\partial_t^2 - \partial_i^2 + m^2]\phi = -g\boldsymbol{B_0}\cdot\dot{\boldsymbol{A}}$$



introduction

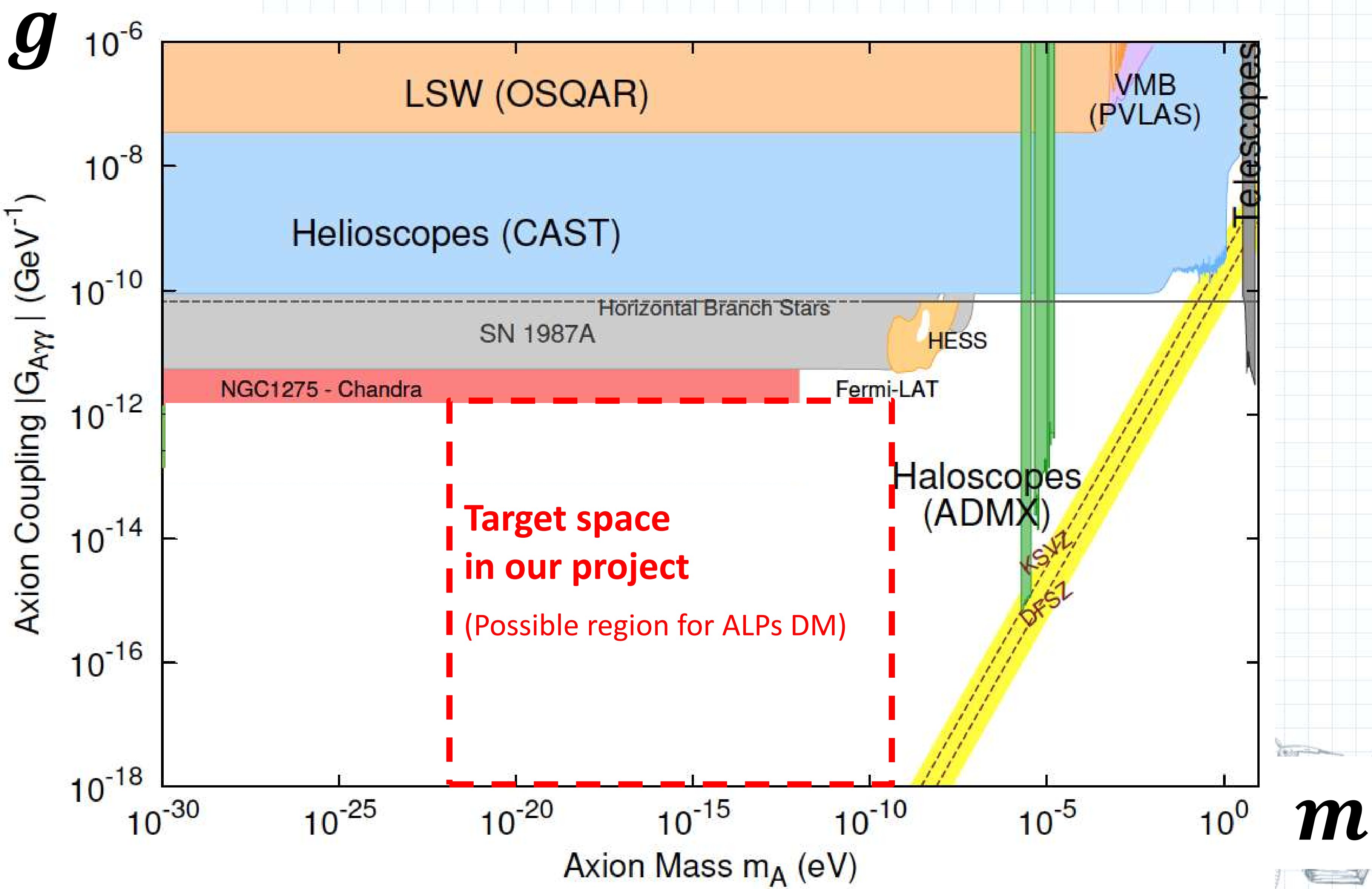
Experiments with AP conversion

- Axion Helioscope



[Irastorza&Redondo(2018)]

Current constraint



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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Anything other than magnetic fields?

New experiment

What if Axion is Dark Matter?

[Harari & Sikivie, Phys. Lett. B 289, 67 (1992)]

Birefringence

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

$-m\phi_0 \sin(mt)$

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

[Harari & Sikivie, Phys. Lett. B 289, 67 (1992)]

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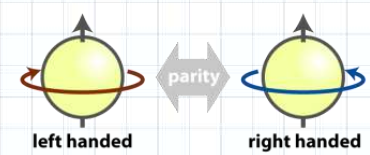
$i\hat{\boldsymbol{k}} \times \boldsymbol{e}_{L,R} = \pm\, \boldsymbol{e}_{L,R}$

⇨ 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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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

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

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

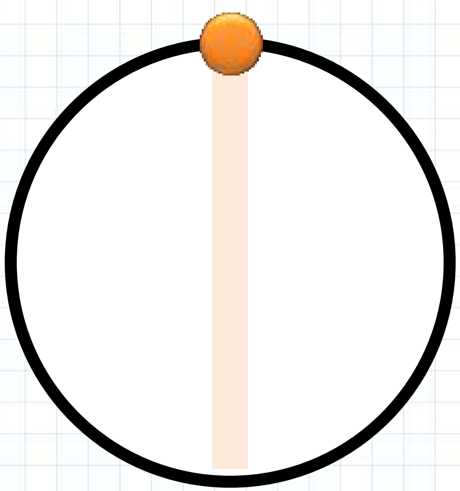
Birefringence

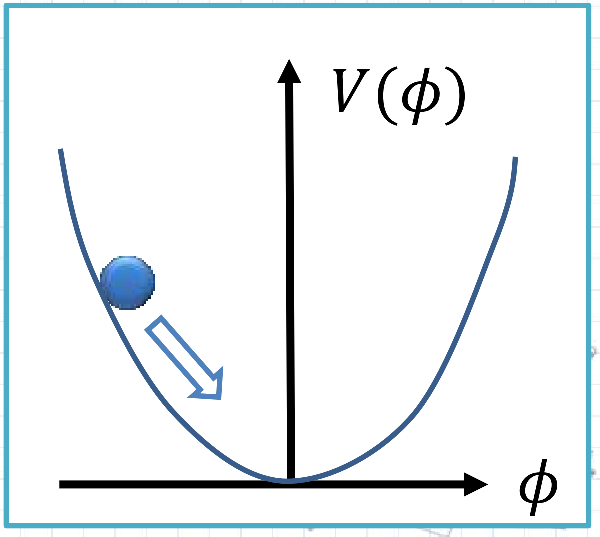
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- 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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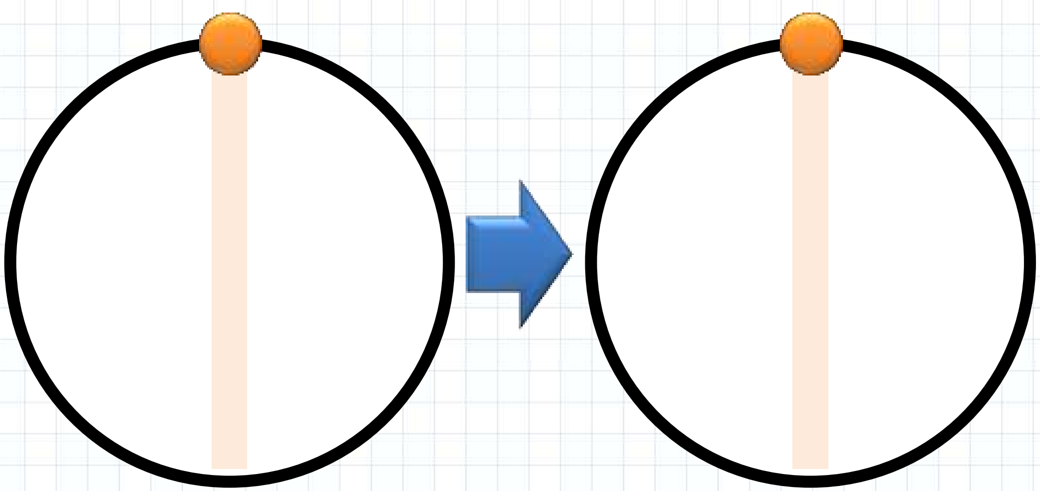

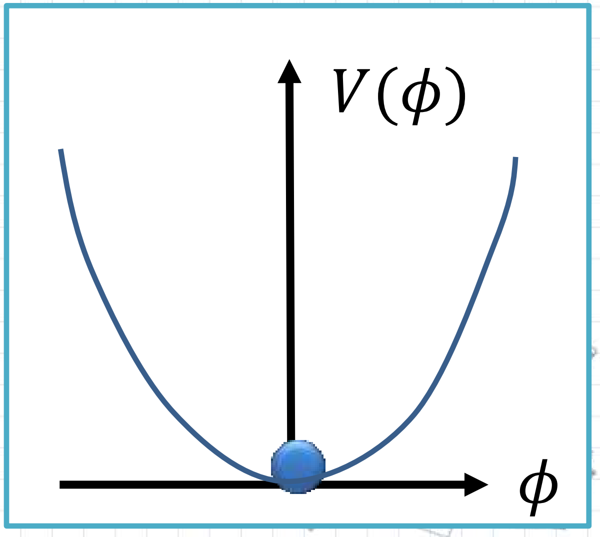

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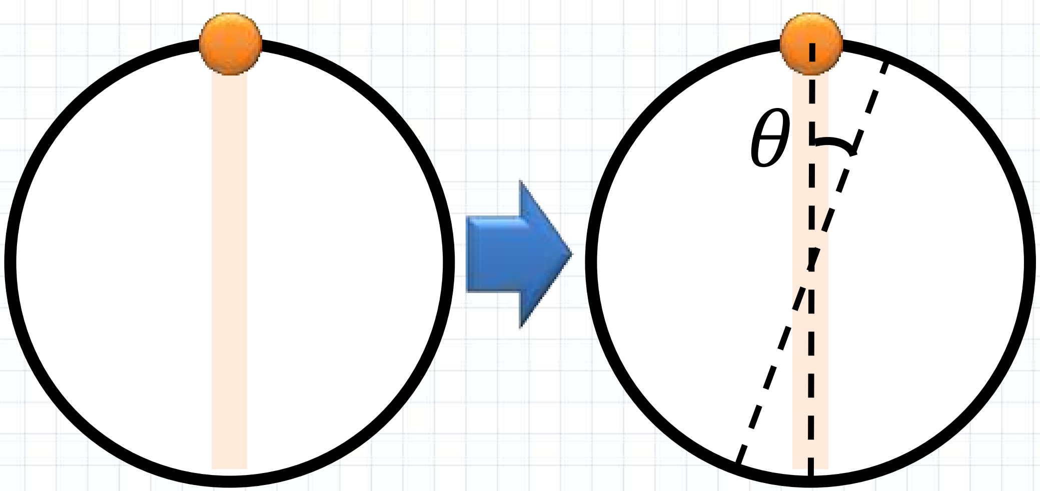
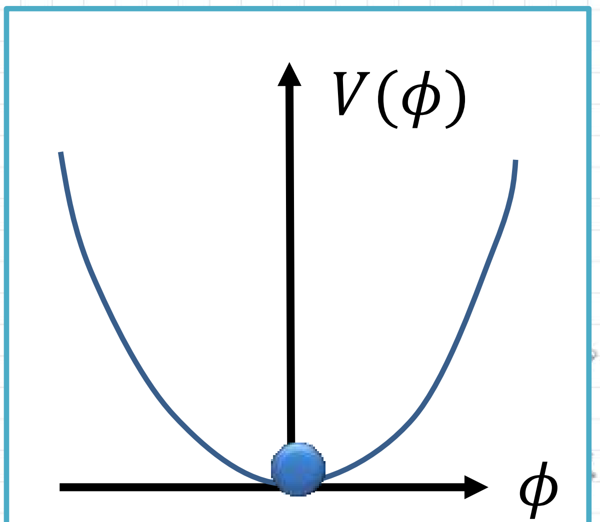




$\rho_{\rm DM} = m^2\phi_0^2/2 \approx 0.3\ {\rm GeV/cm^3}$

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

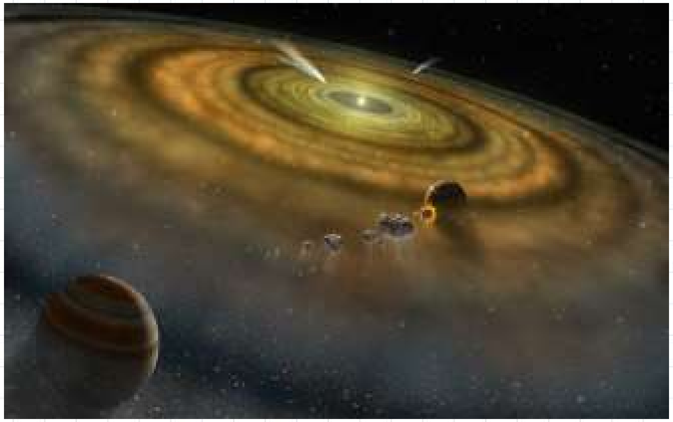
- Observations of PPD can be used!

PPD is a flattened gaseous object surrounding a young star.

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

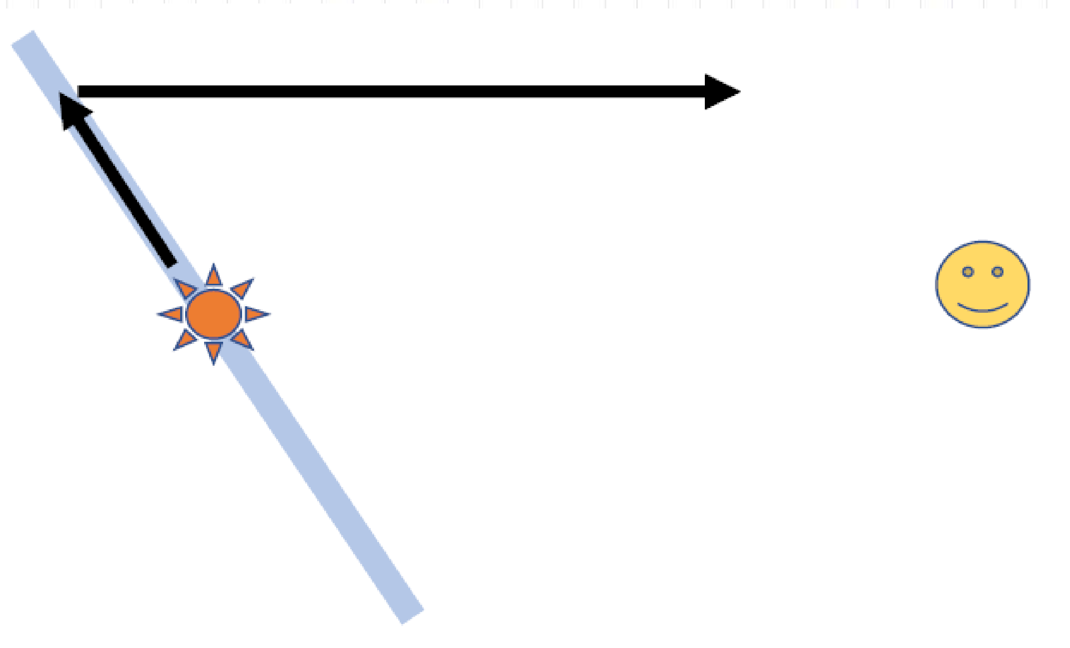
Real data

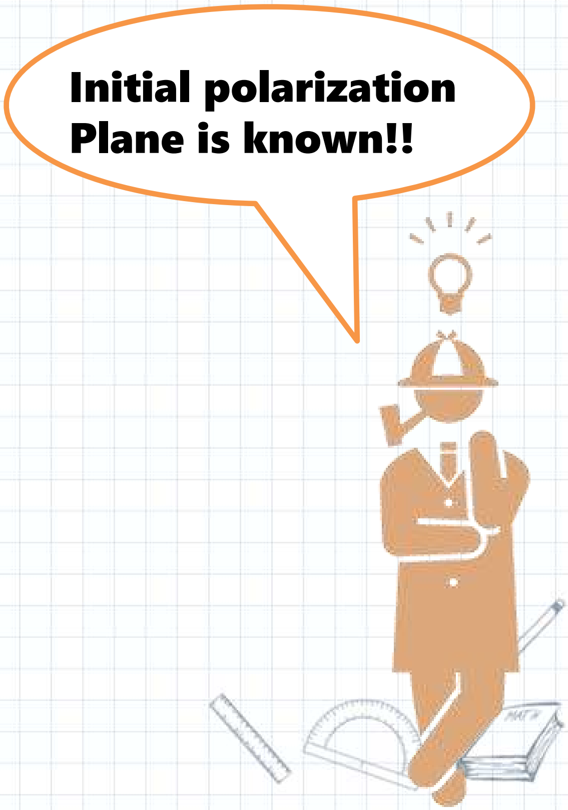
Artist's image



Polarization of PPD

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



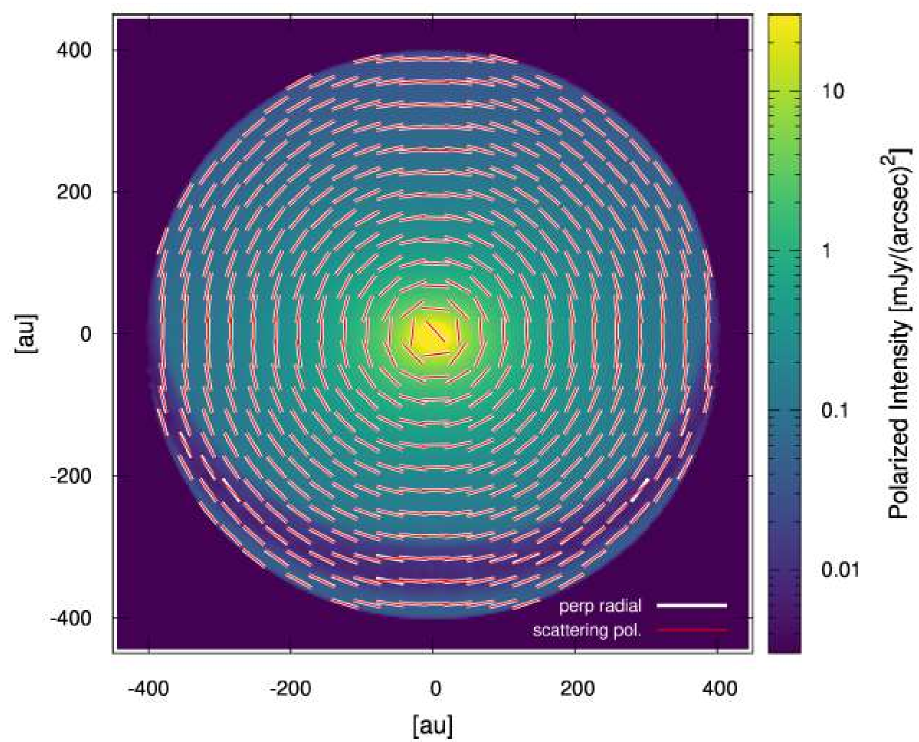


Obsevation of PPD

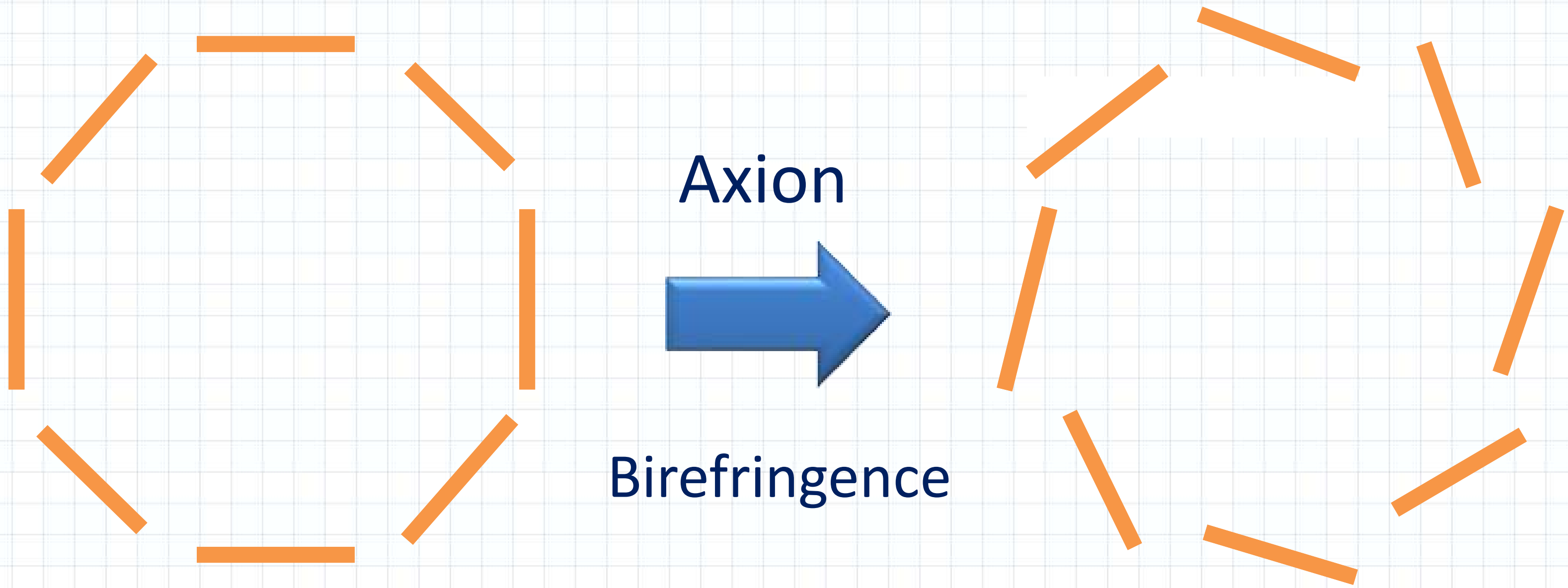
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM



Axion DM rotates pol. plane?



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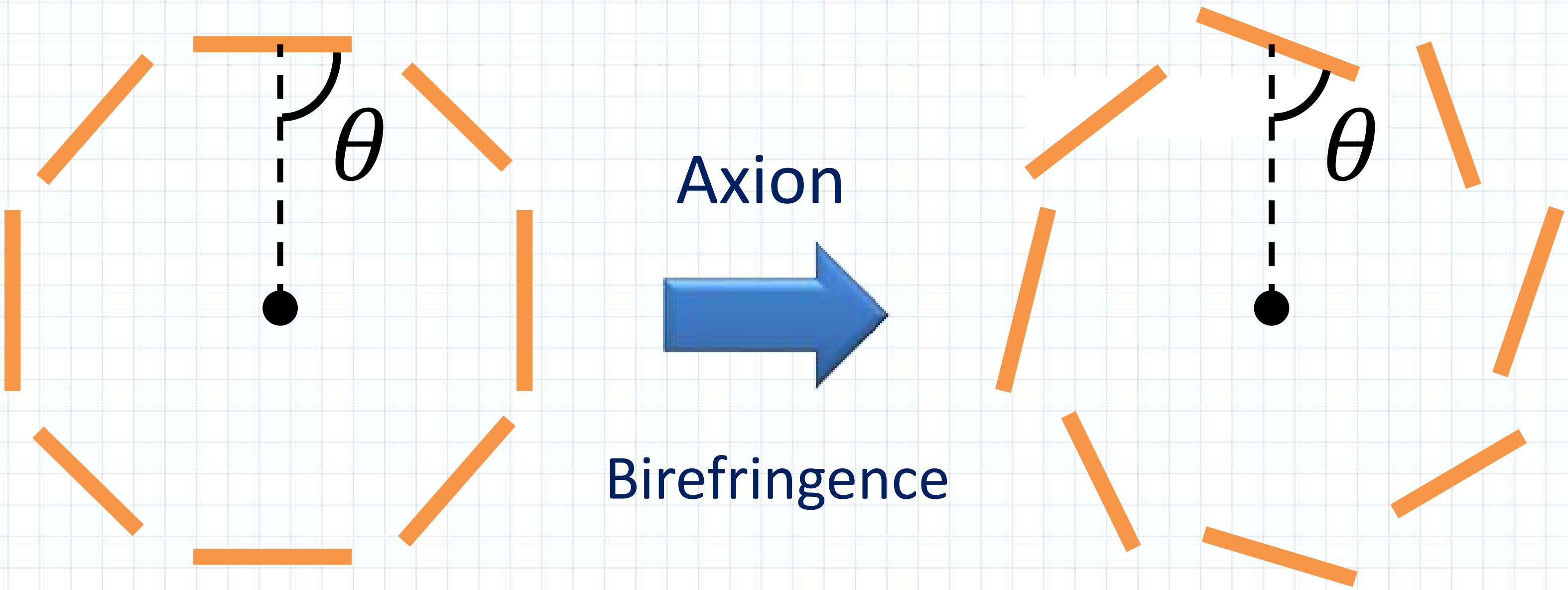

Is this angle 90° or not?

Obsevation of PPD

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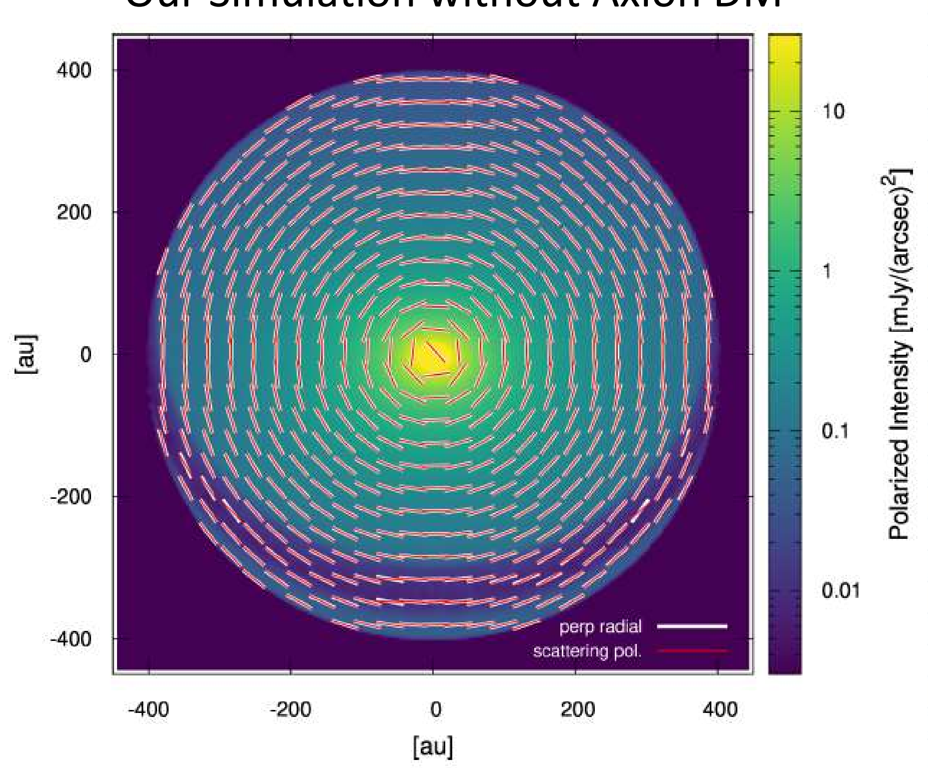
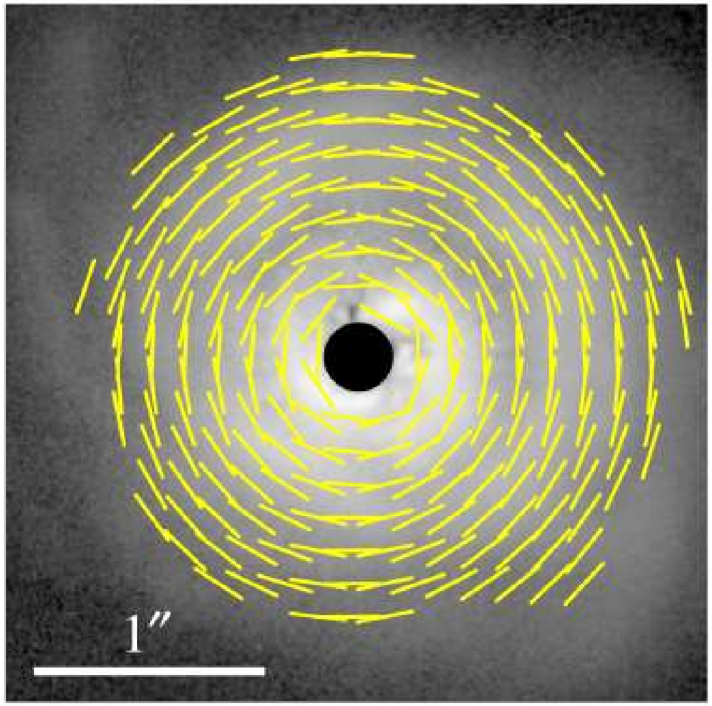
Our Simulation without Axion DM



Observation by SUBARU



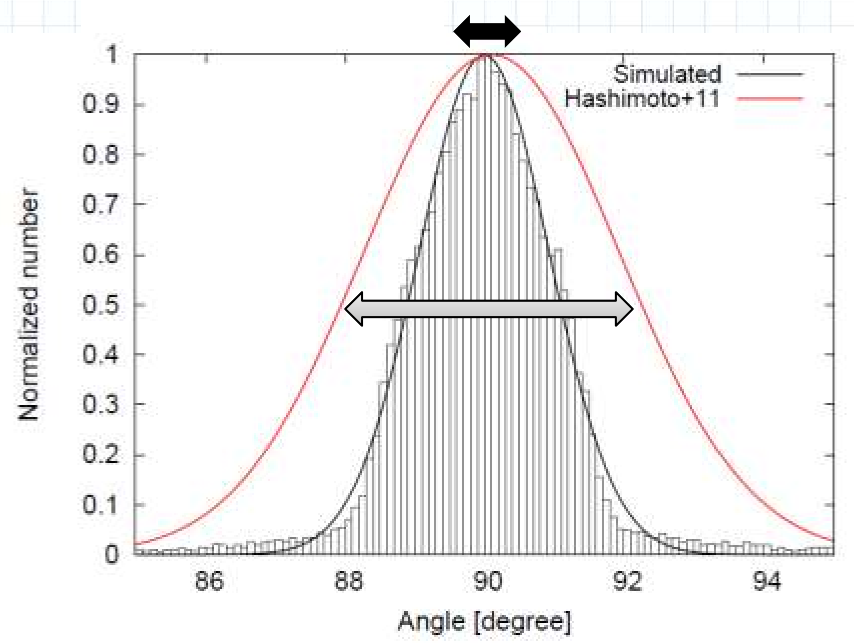
AB Aurigae (160pc away)

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

Obsevation of PPD

The observation data reveals

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



The width of the observed angle histogram is not fully explained….

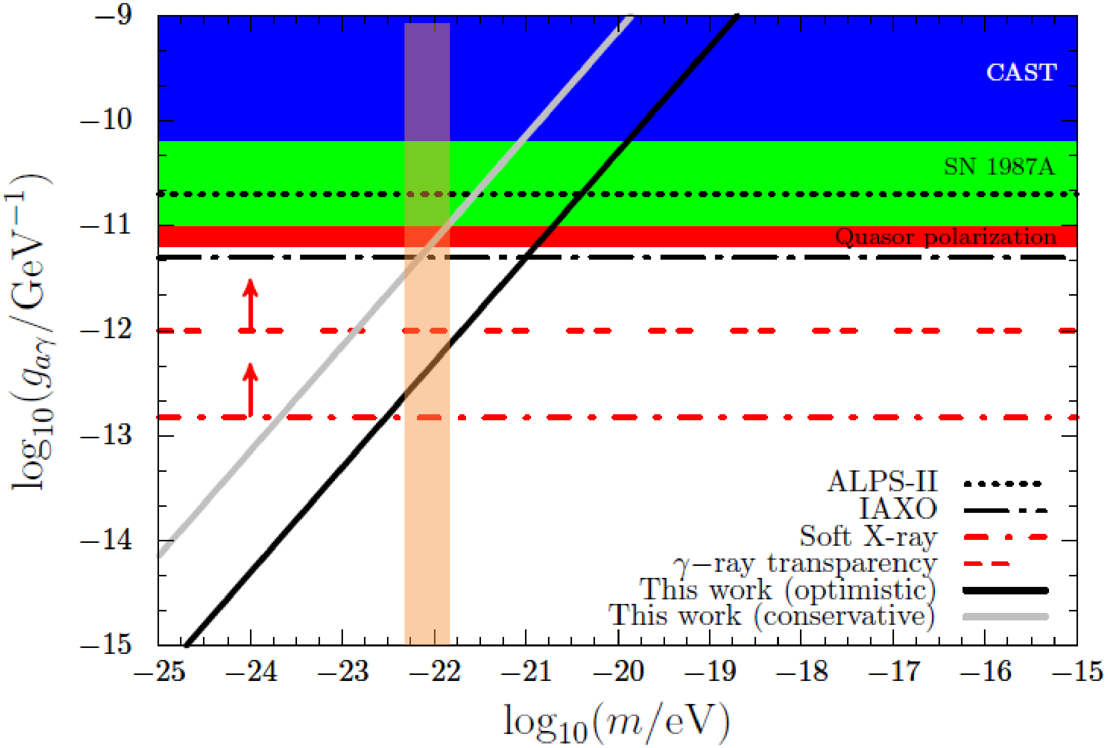
Our simulation confirms the effect of multiple Scatterings is negligible.

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[eV]

[TF. Tazaki & Toma (2018)]
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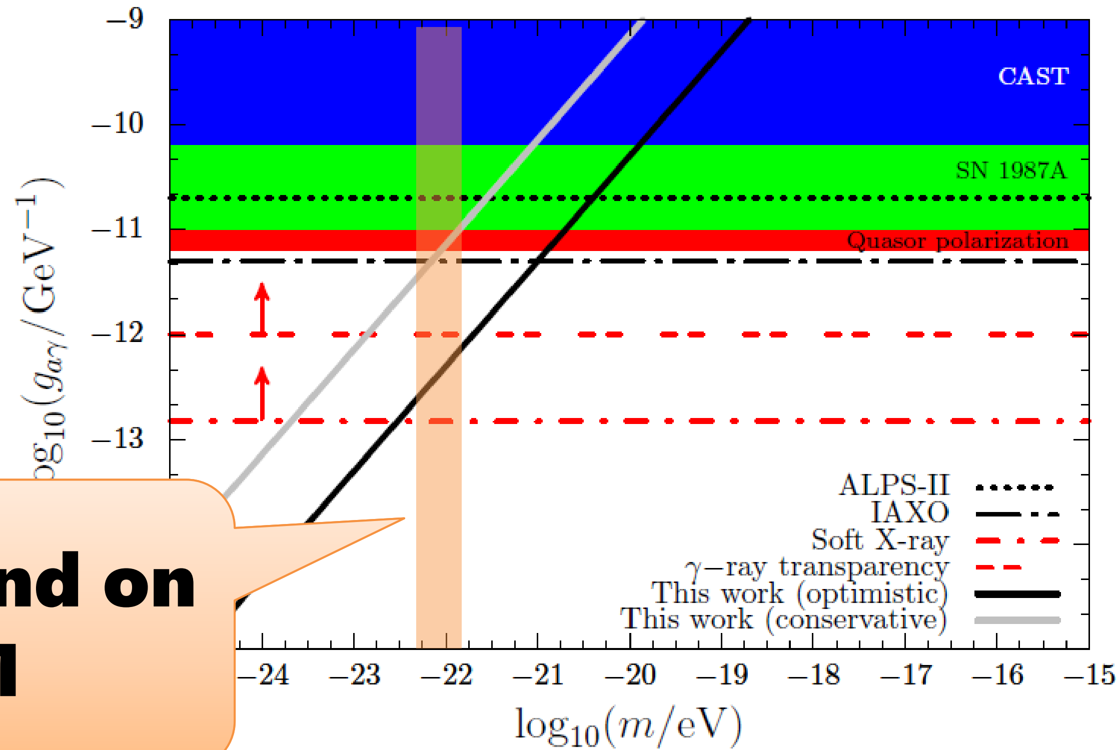
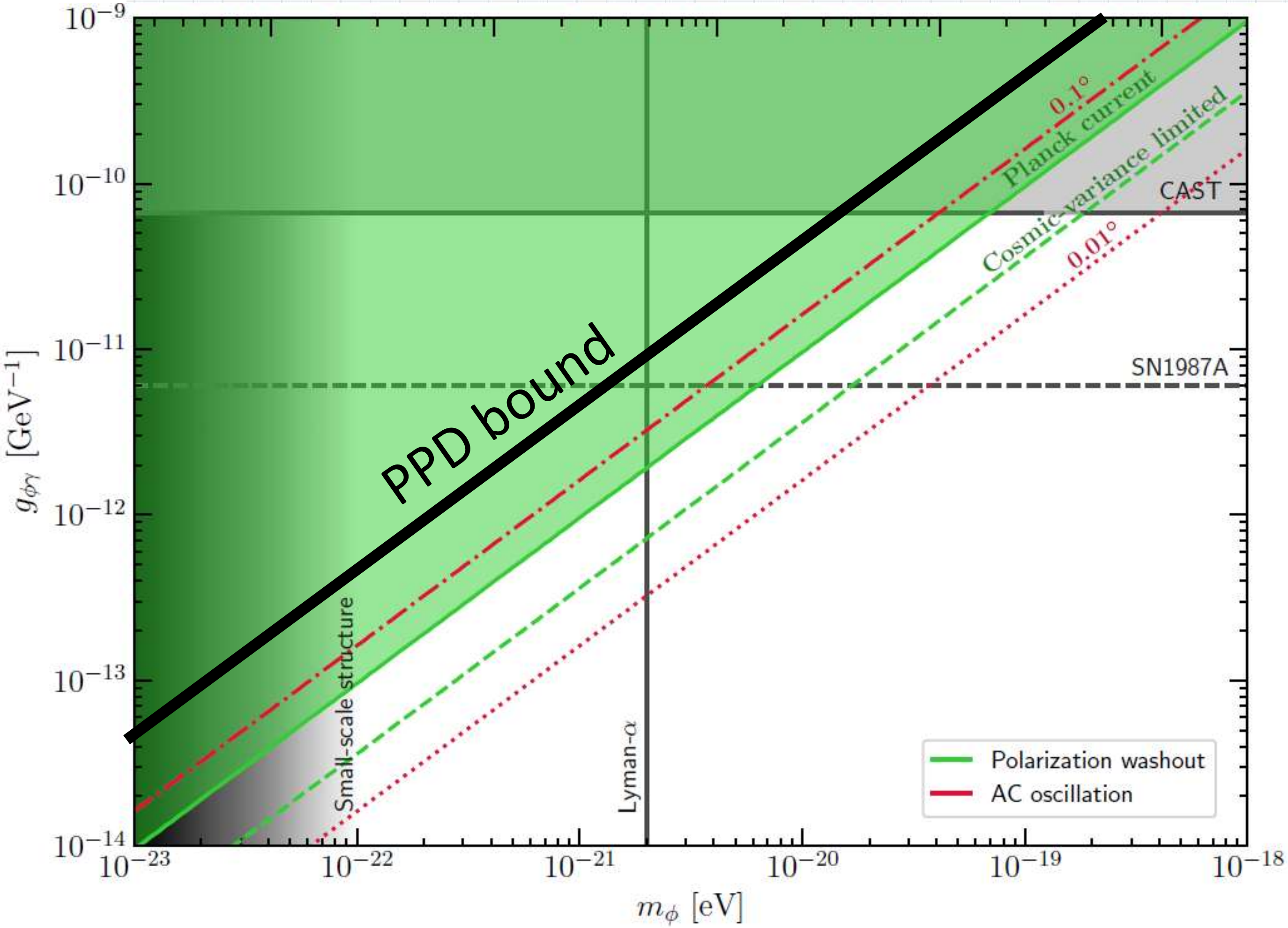


m[eV]

Best bound on Fuzzy DM

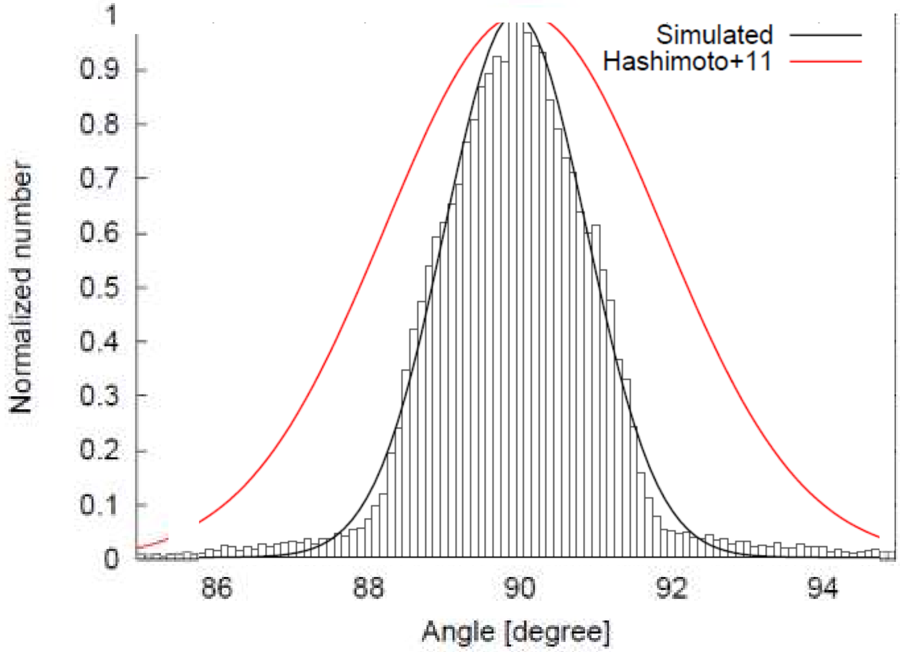
Fedderke+ PRD**100**,015040(2019)



After our paper, the “first” paper on
ADM constraint from CMB appeared!

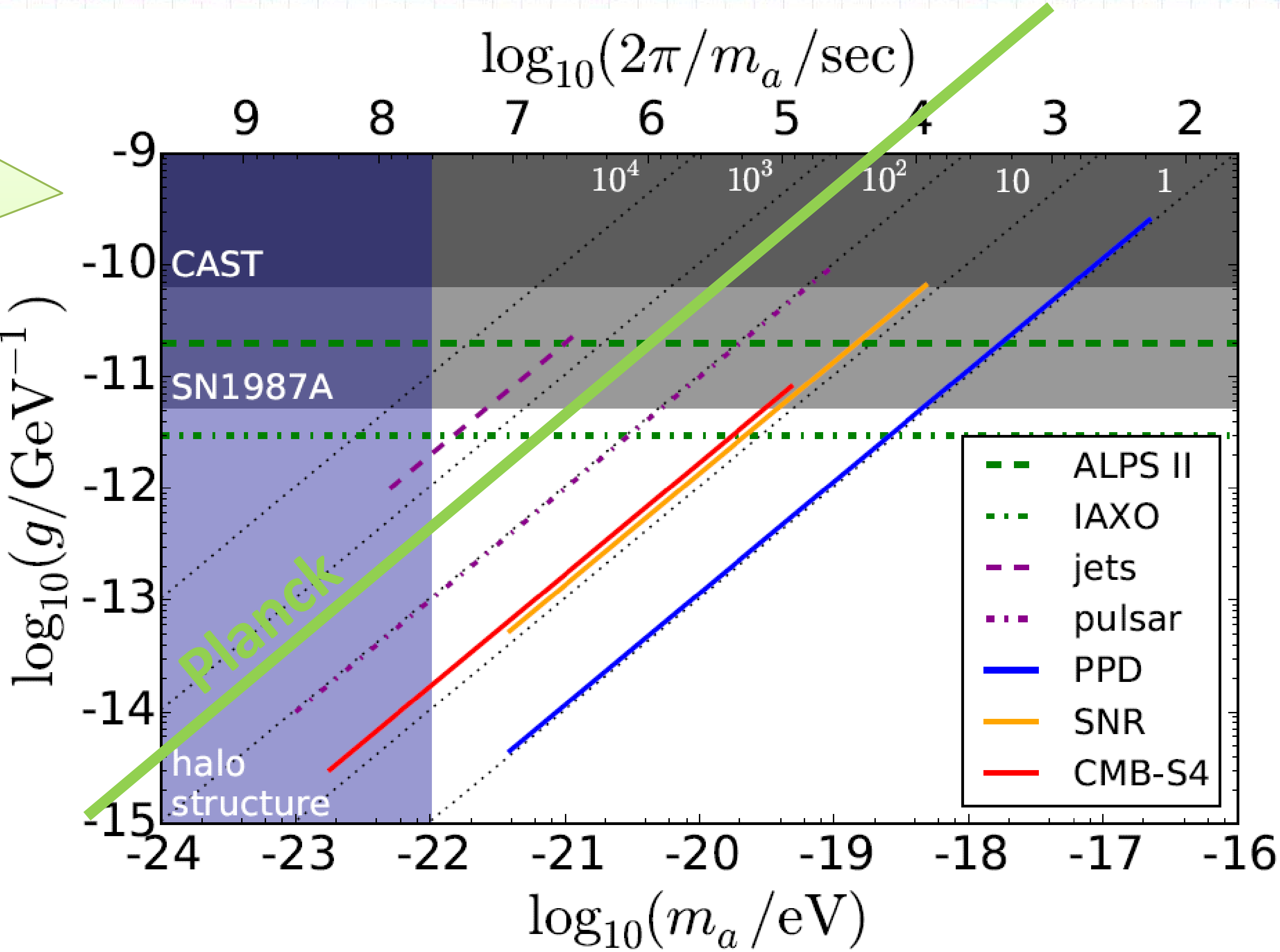
Long-term Obs of PPD

If we observe a PPD for longer time than m^{-1},
the periodic shift of θ should be detected.



Chigusa, Moroi & Nakayama: PLB**803**,135288(2020)

Forecast of future ADM Search



PPD has the biggest potential

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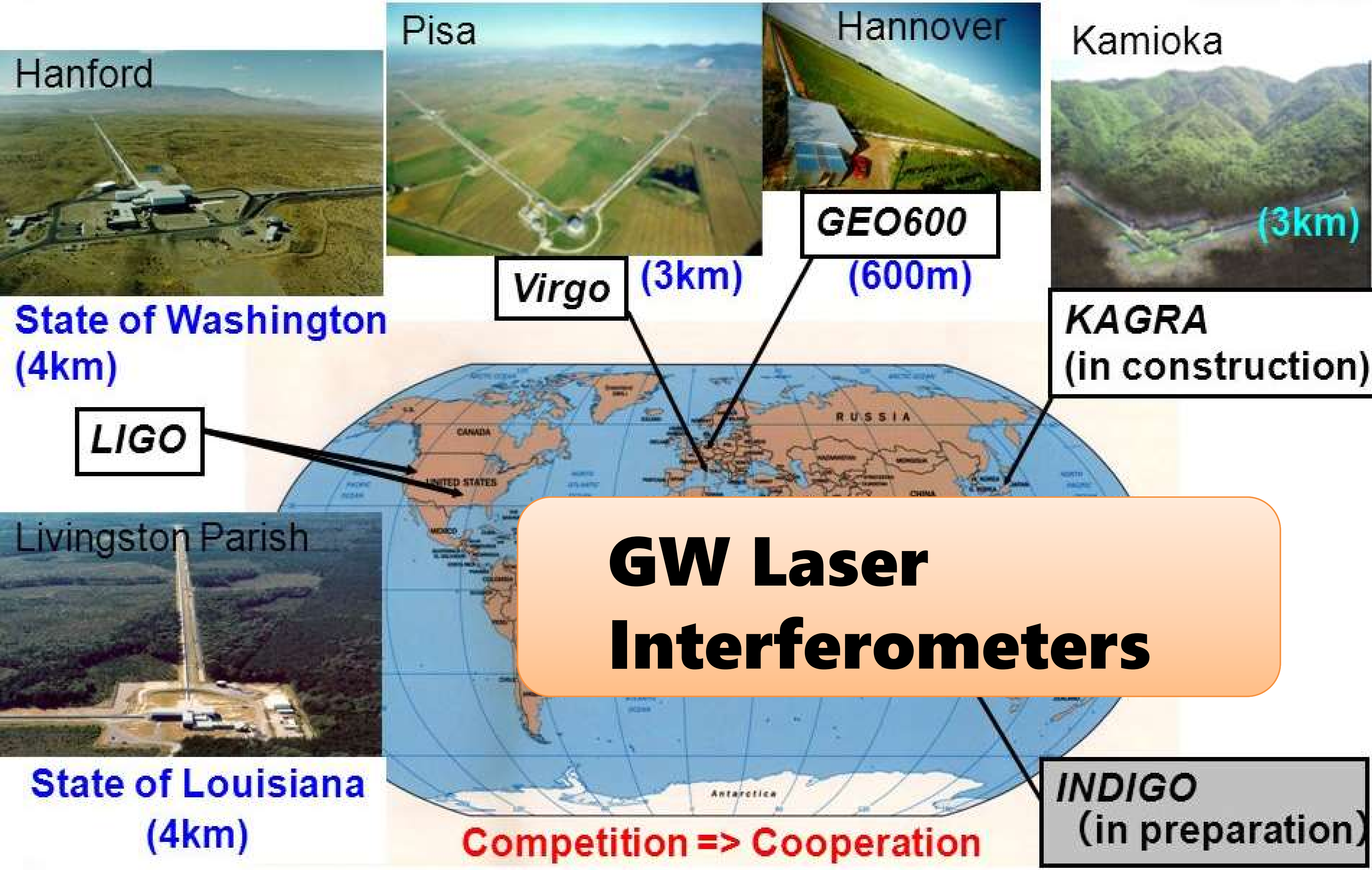
New experiment



New experiment

Can we use GW interferometers to search for Axion DM?

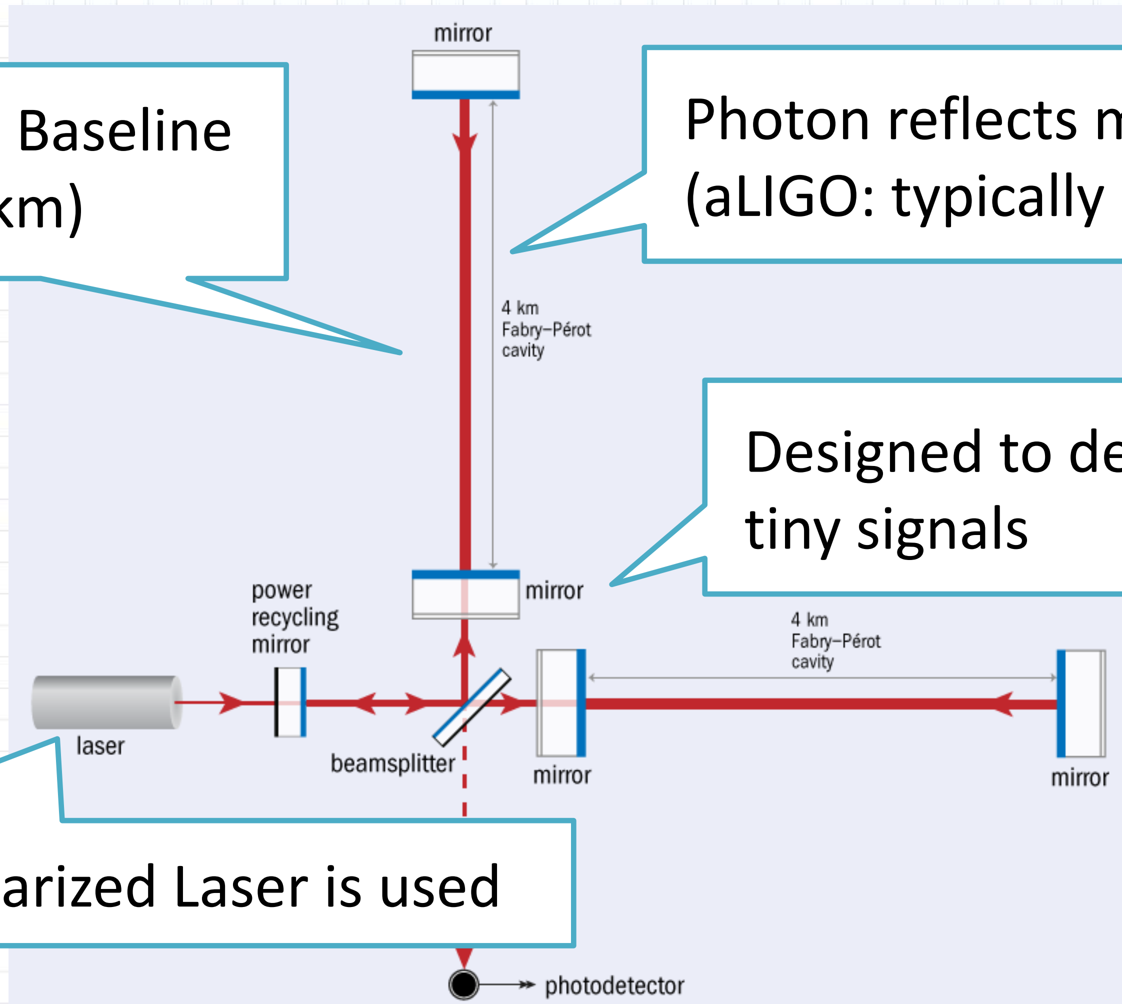
New experiment

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

Yes!! Because GW interferometer is

Very Long Baseline (aLIGO: 4km)

Photon reflects many times (aLIGO: typically 500 times)

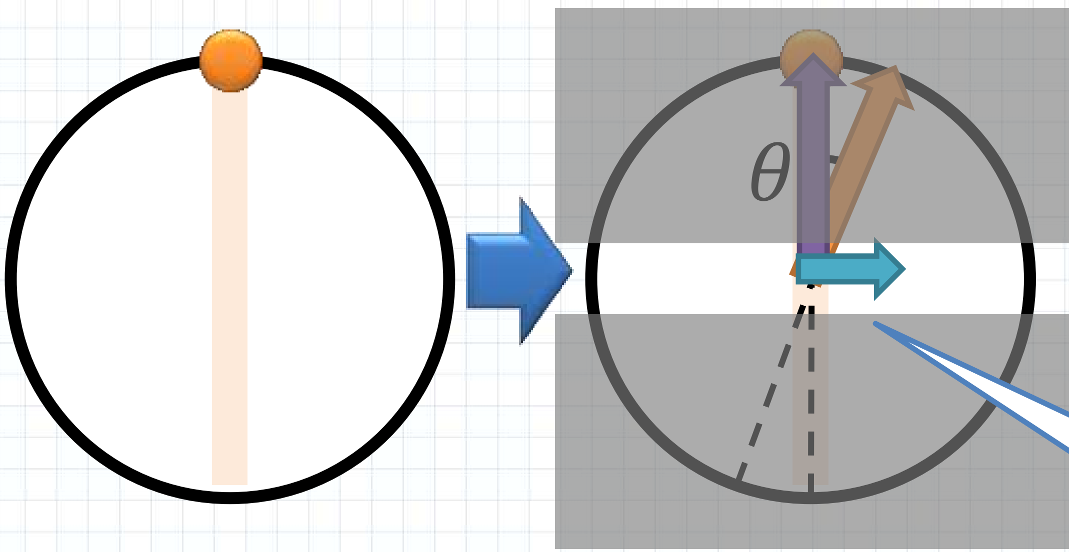


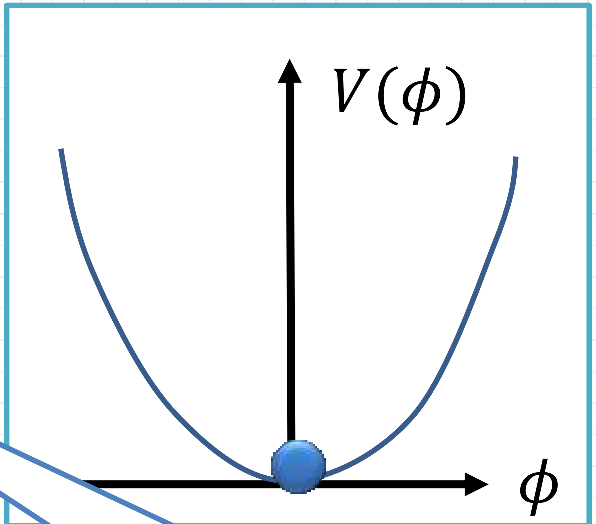
Designed to detect tiny signals

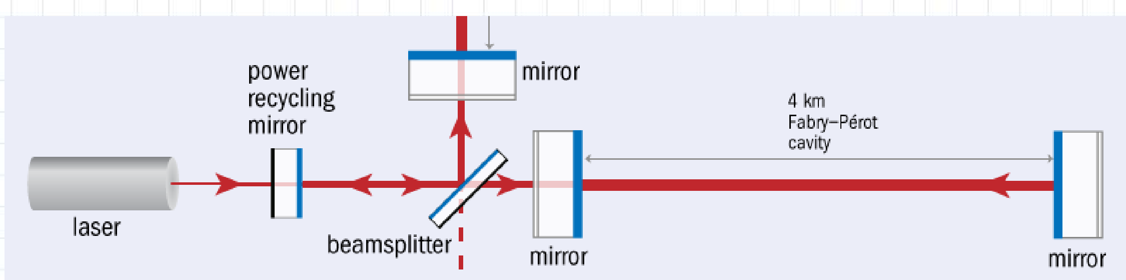
Linear Polarized Laser is used

New Observation

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



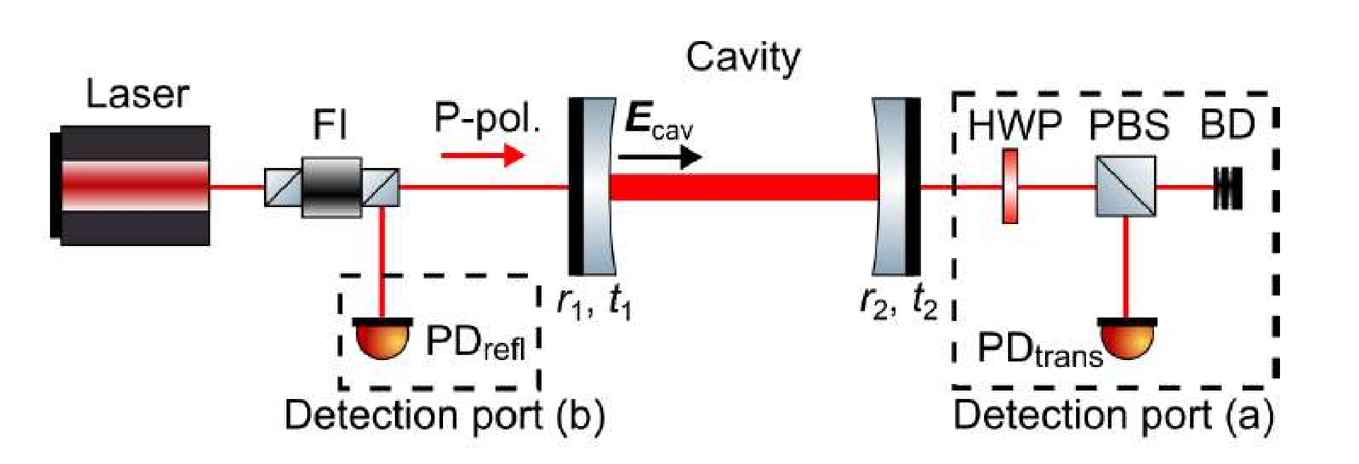




Only if $\theta \neq 0$ by ADM, we detect signal

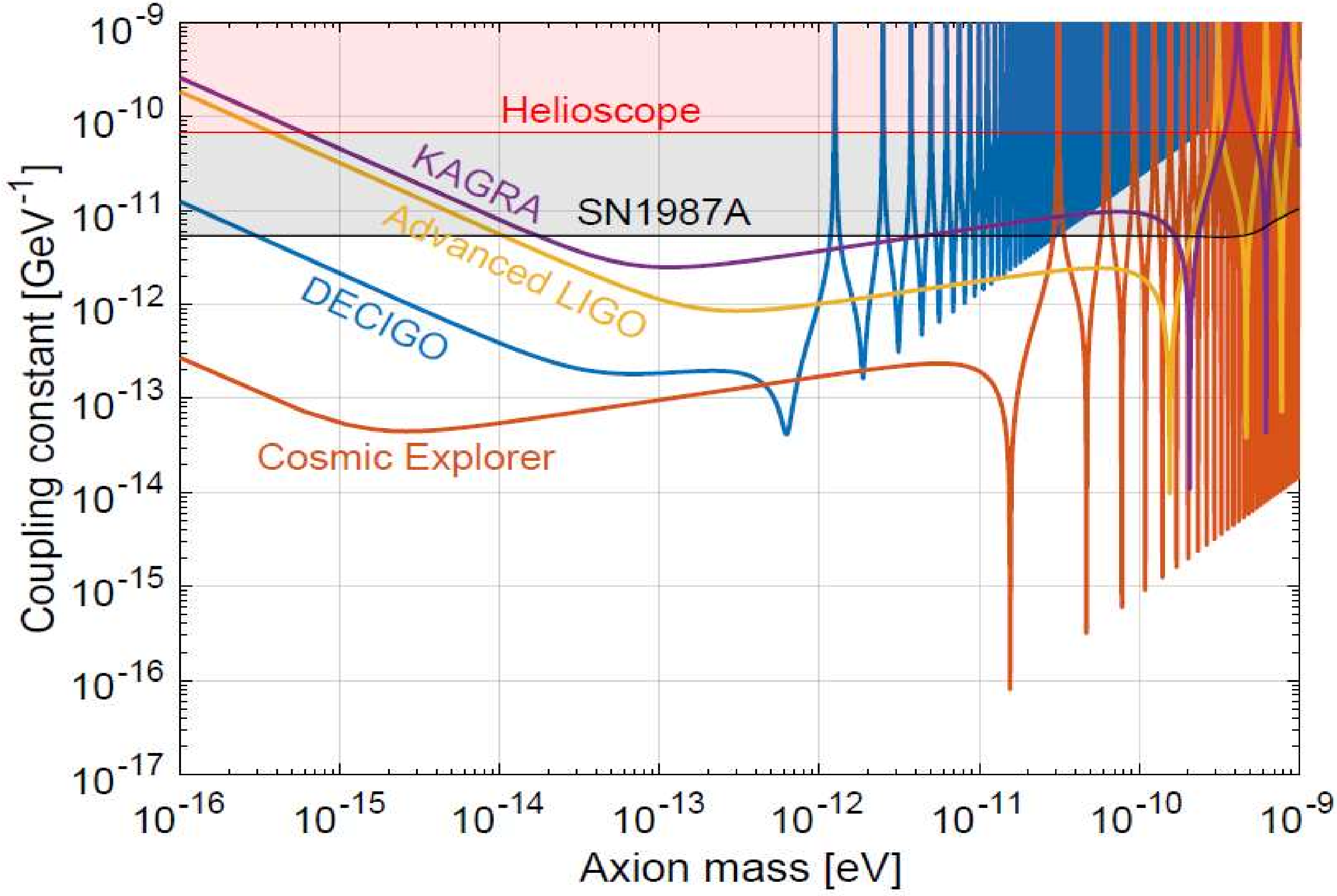
Coexist with GW observation

- Tiny signal compensated by long operation time

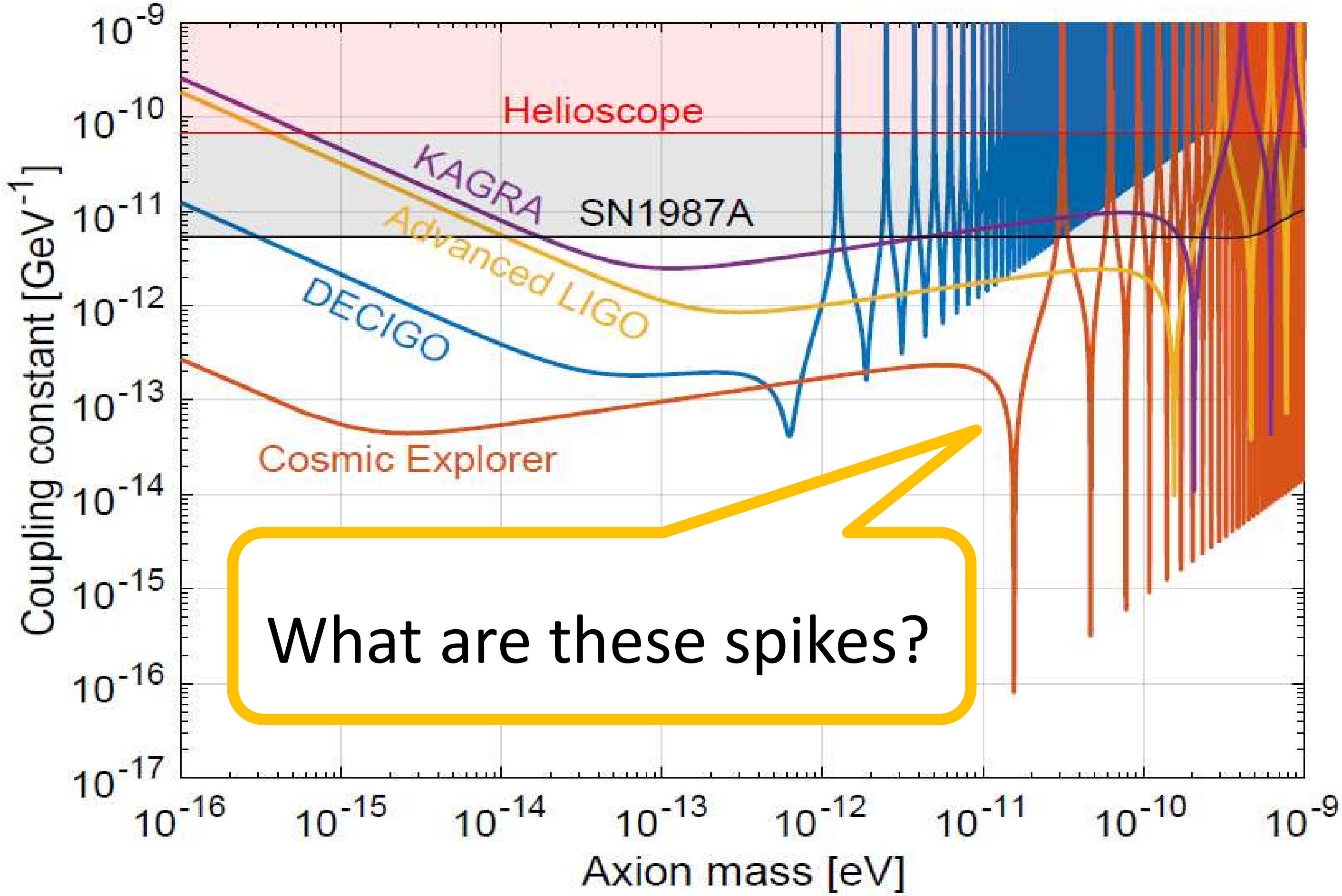


Additional instruments at the tail enable interferometers to probe ADM during the GW observation run **without loosing any sensitivity to GWs** ⇒ **Long Run!**

Sensitivity Curve for 1 year run



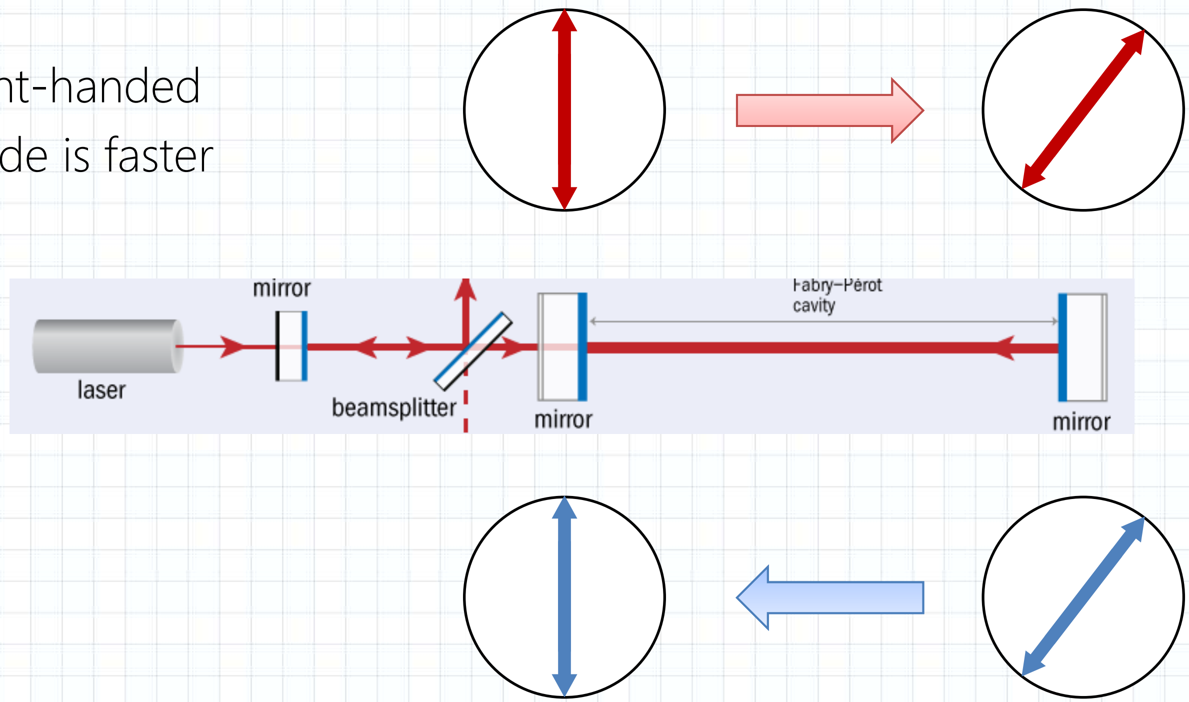
Sensitivity Curve for 1 year run



Lost sensitivity

If axion oscillation period is longer than 4km/c
rotation is cancelled and isn't accumulated

e.g. Right-handed
mode is faster

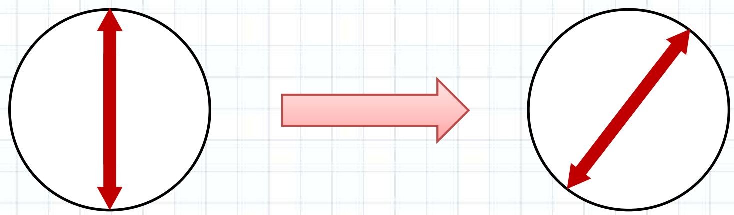


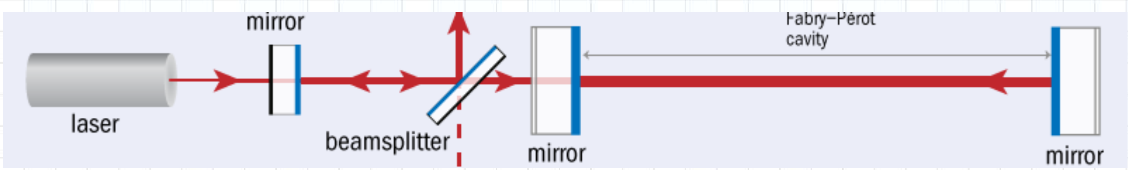
Resonant point

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

If axion oscillation period/2 = 4km/c,
rotation is accumulated.

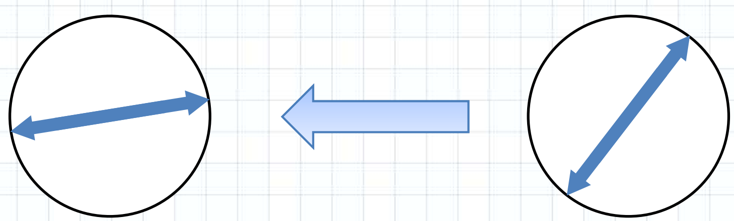
Right-handed
mode is faster



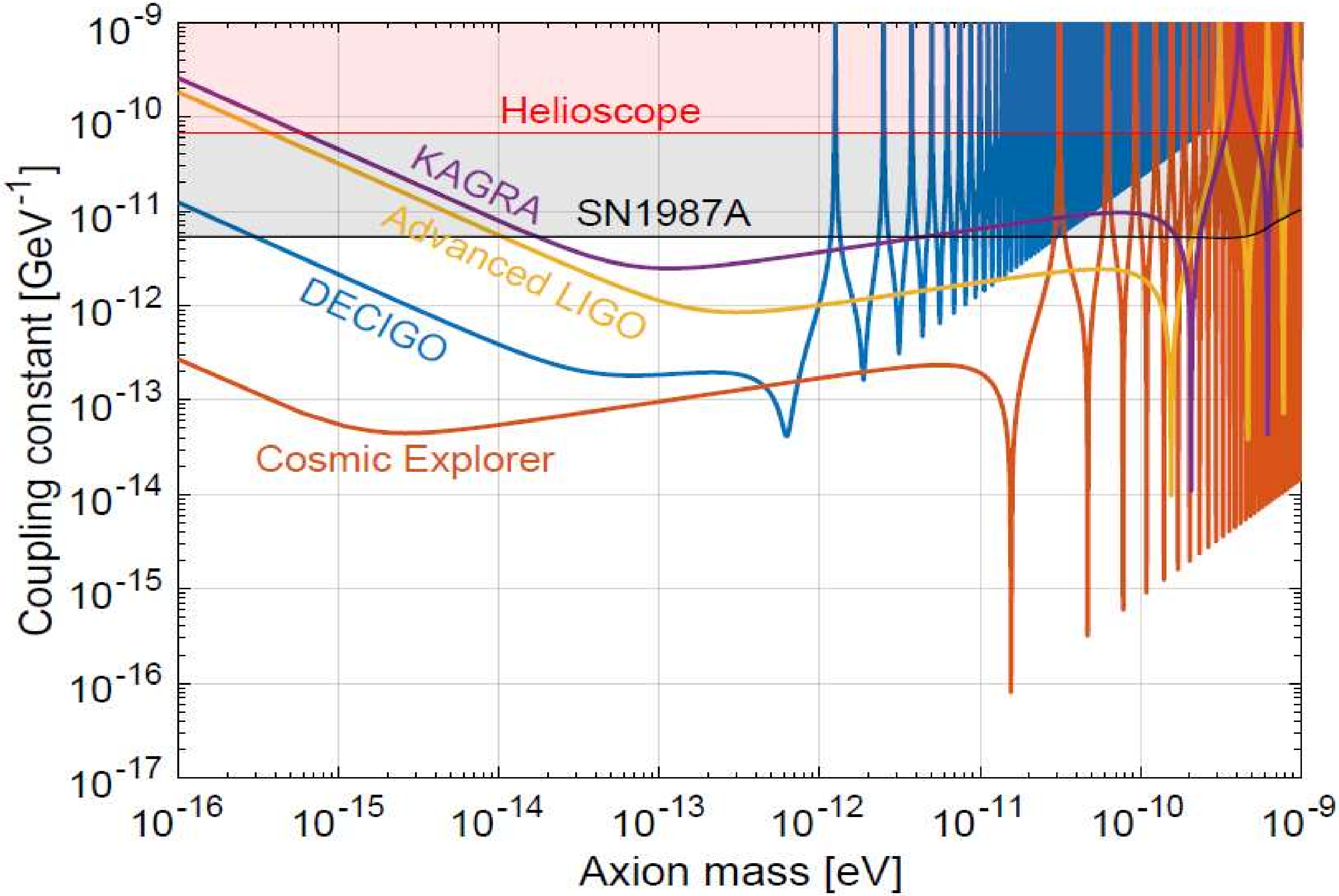


Then left-handed
mode gets faster

Rotation is addd!



Sensitivity Curve for 1 year run



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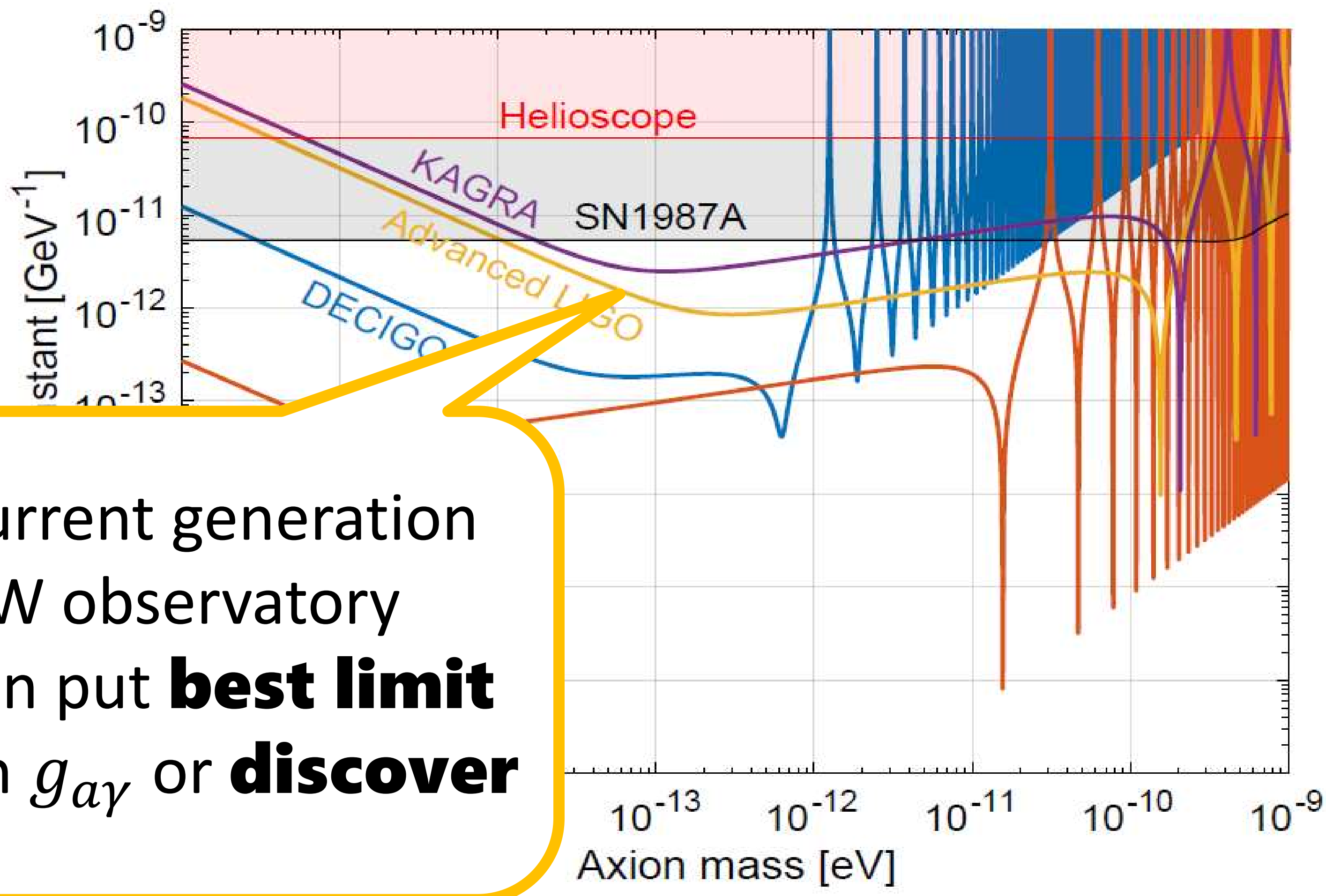
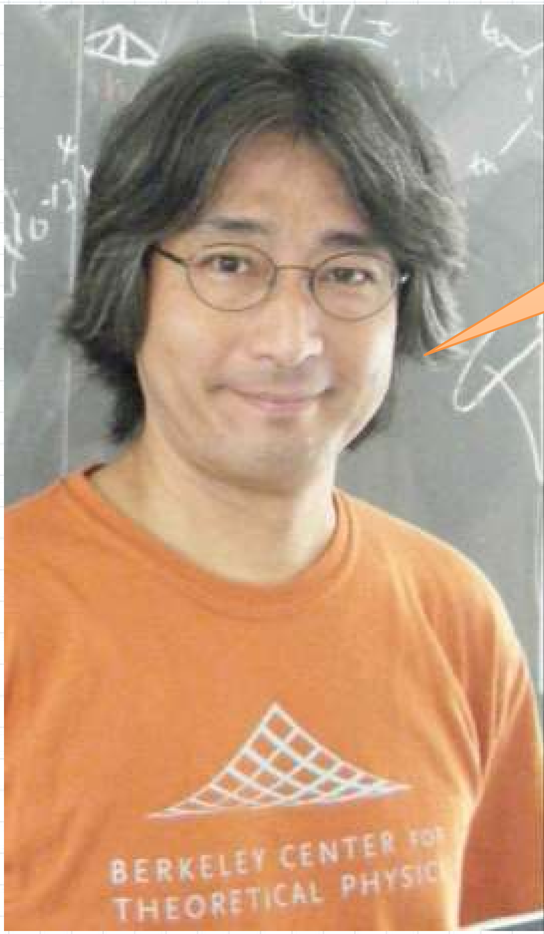


Current generation GW observatory can put **best limit** on $g_{a\gamma}$ or **discover**

New experiment

New grant



Prof. Hitoshi Murayama

Era of **non-WIMP** DM!

We applied for a big grant (Comprehensive study of the huge discovery space in dark matter).

- 14M USD/ 4yr in total
- 1.5M USD/ 4yr for our proposal!

Will be announced in this fall…

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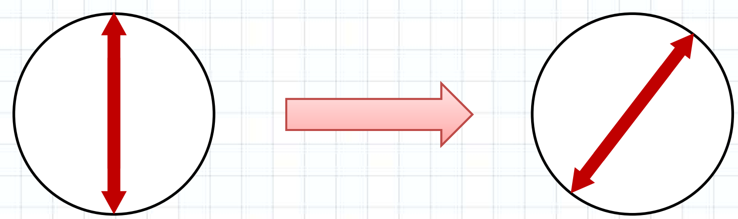
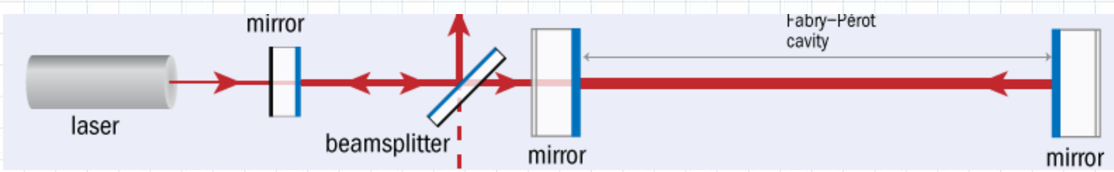
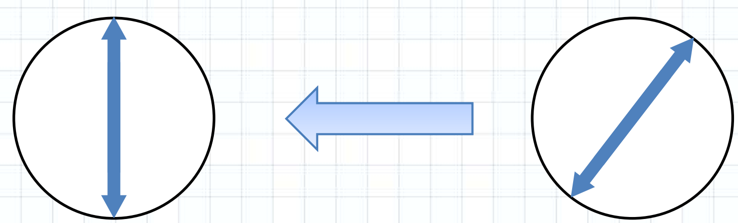
e.g. Right-handed
mode is faster



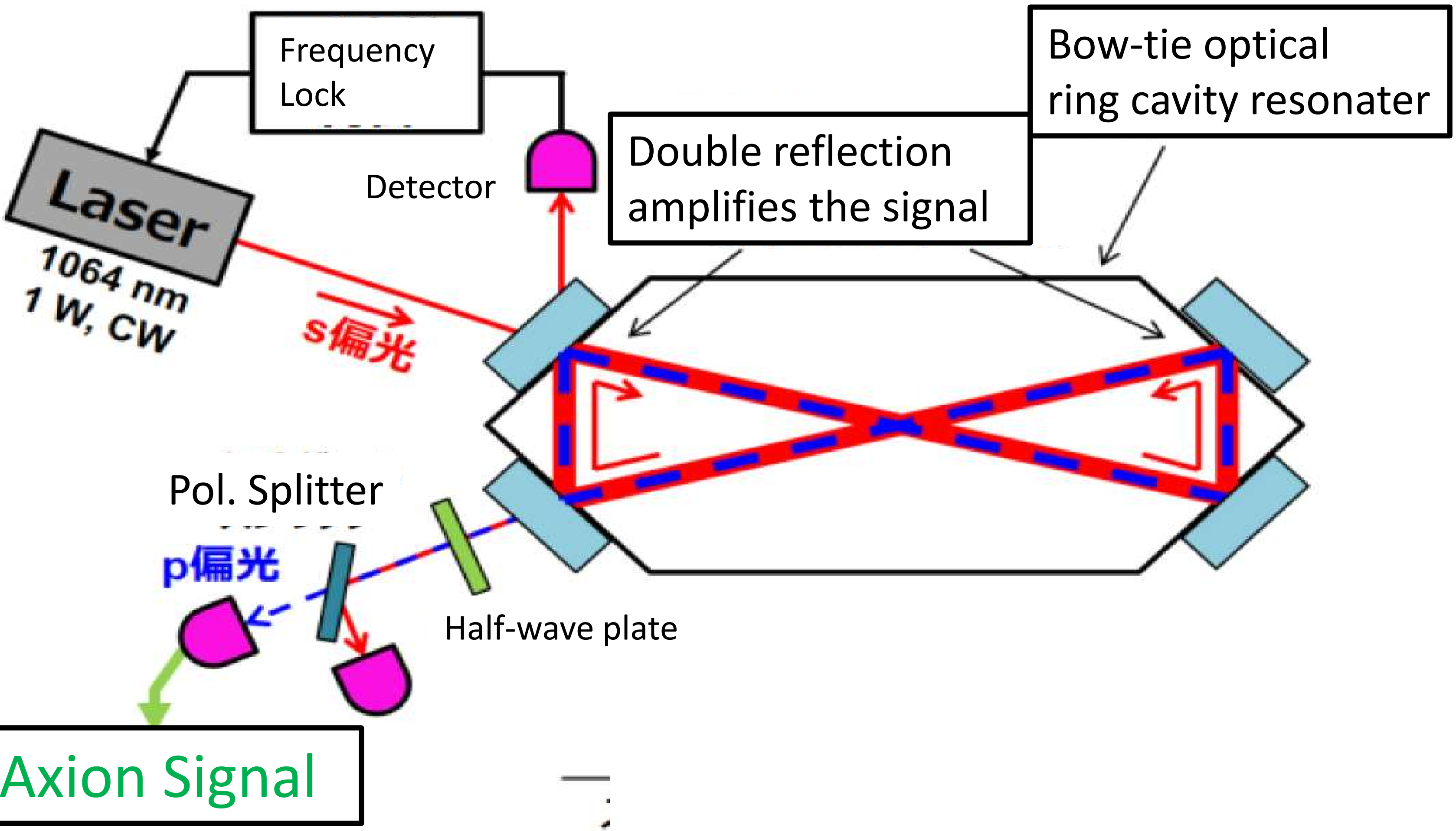




New experiment : DANCE

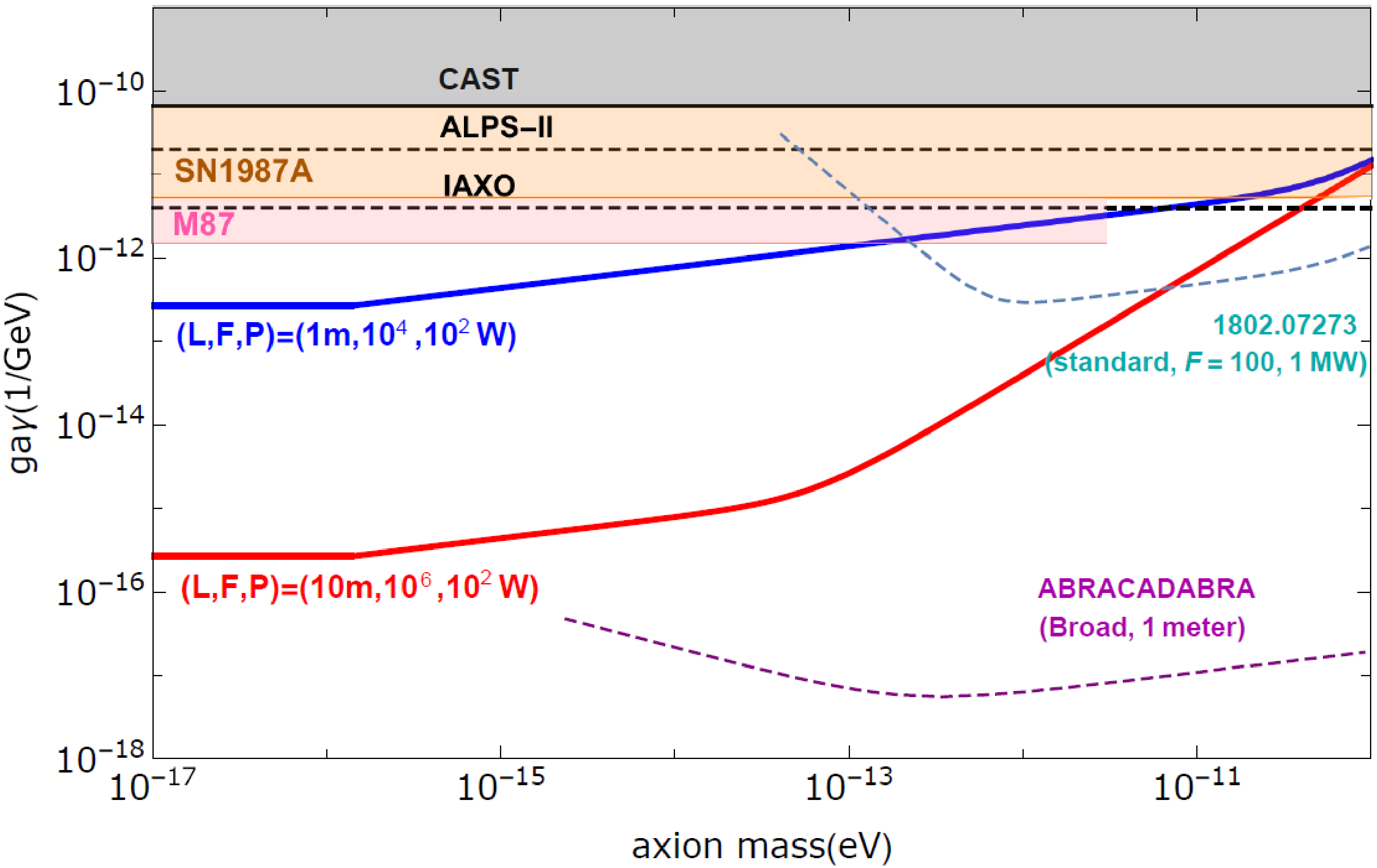
Dark matter Axion search with riNg Cavity Experiment

[Obata, TF, Michimura(2018)]
[Liu+(2018), ADBC experiment]



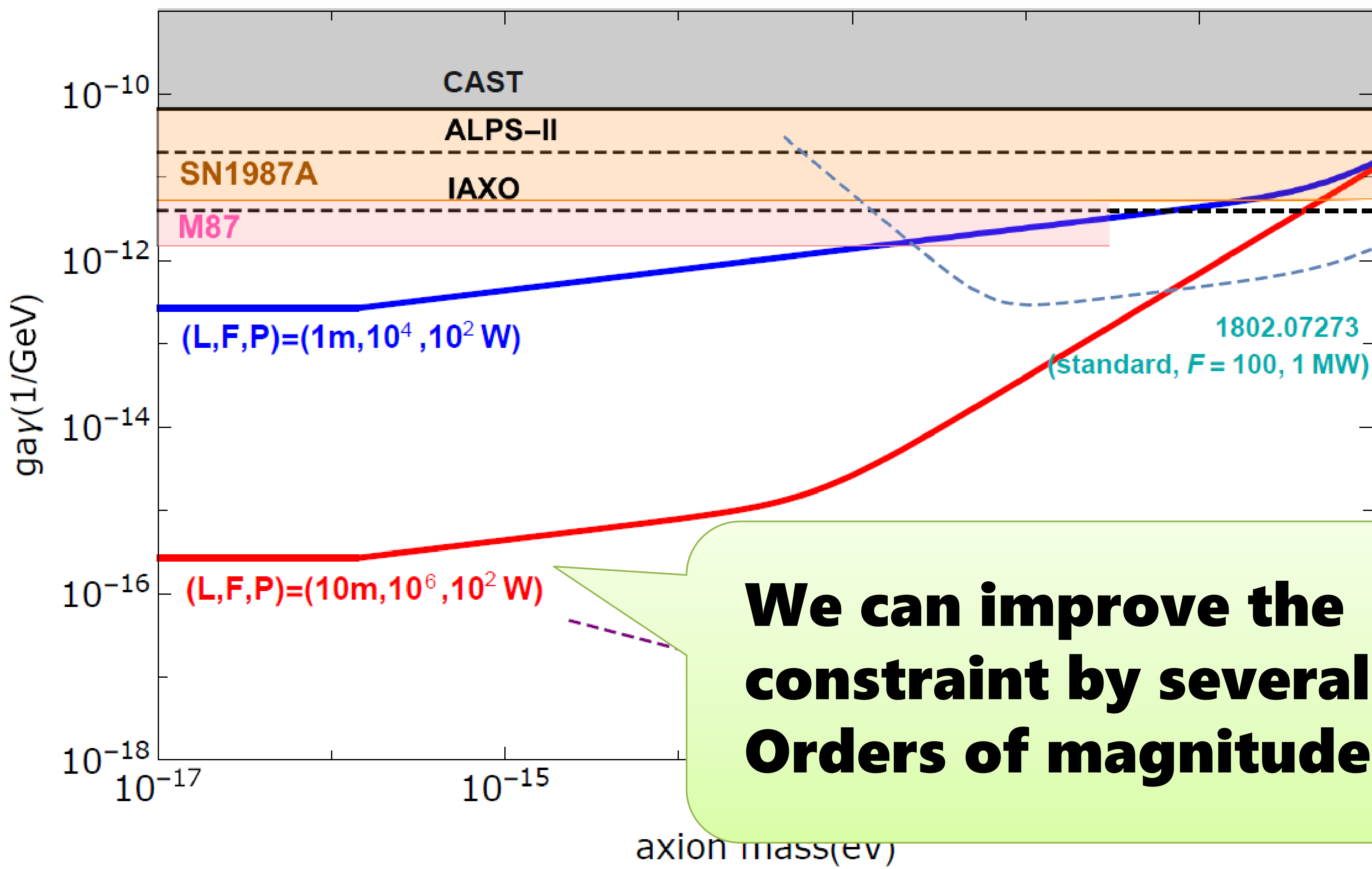
New experiment : DANCE

[Obata, TF, Michimura(2018)]



New experiment : DANCE

[Obata, TF, Michimura(2018)]



We can improve the constraint by several Orders of magnitude!

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. L
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Phase eng
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angle of s
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The preci
engineere

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
detection.
was
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OPTICAL METROLOGY

Axion sensor

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

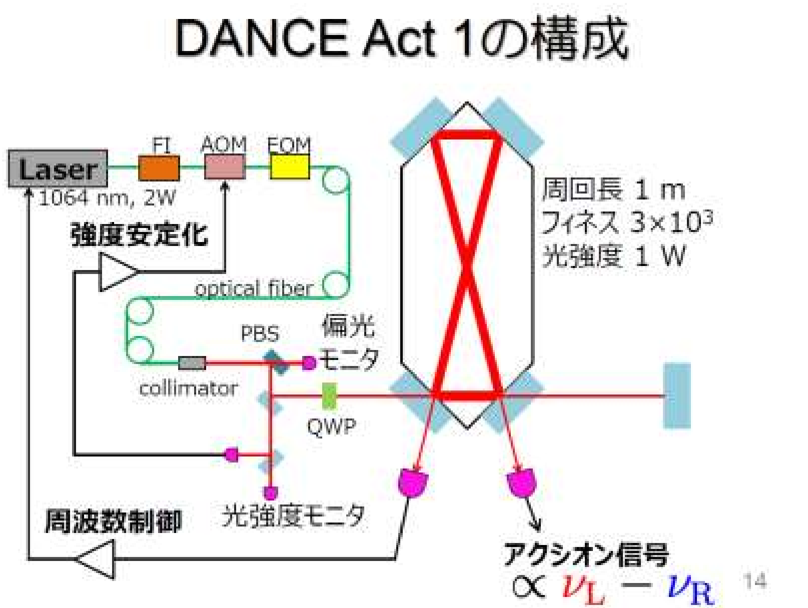
A current challenge in modern physics is to design experiments for ascertaining the existence of the axion — a proposed dark matter particle found in theories beyond the standard model of particle physics. Now, Ippei Obata and co-workers from the University of Tokyo and Kyoto University, Japan, have 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*

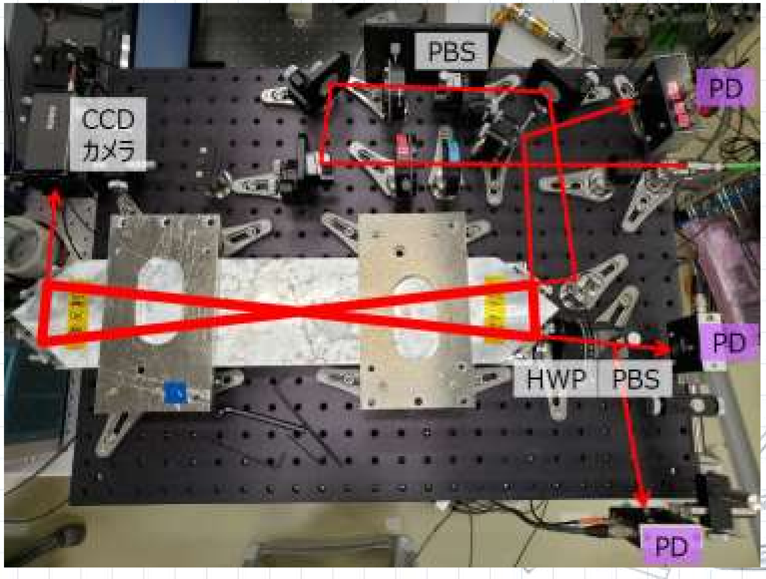
https://doi.org/10.1038/s41566-018-0321-2

Our proposal was featured in Nature Photonics.

DANCE Act.1 has started!

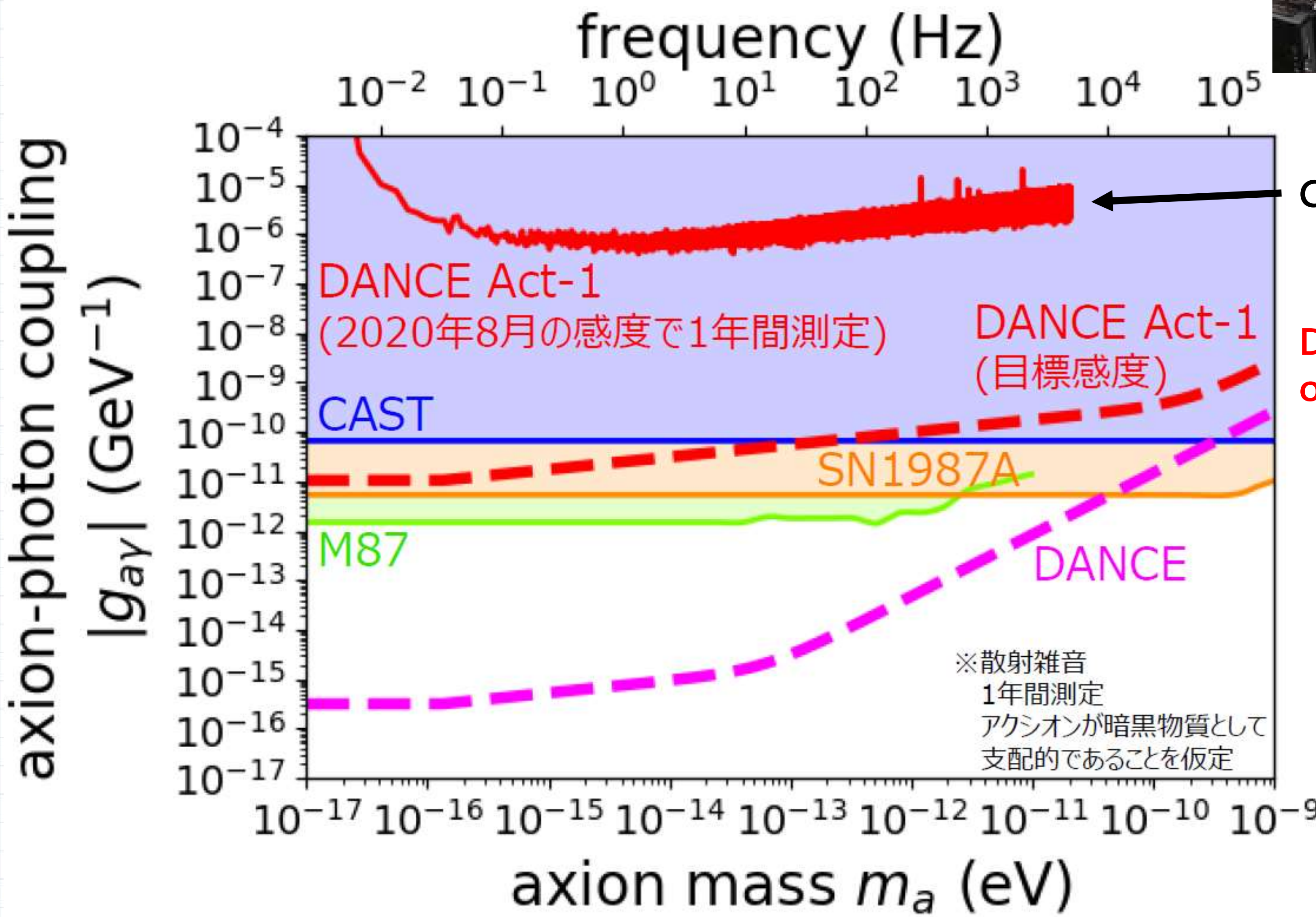
- We got a grant (35kUSD/yr) last year and started with a 1m-size prototype.
- We finished constructing prototype experiment (Act.1) in U. Tokyo. (Ando lab.)
- The first test result was obtained 2 month ago





Current Status of DANCE Act-1

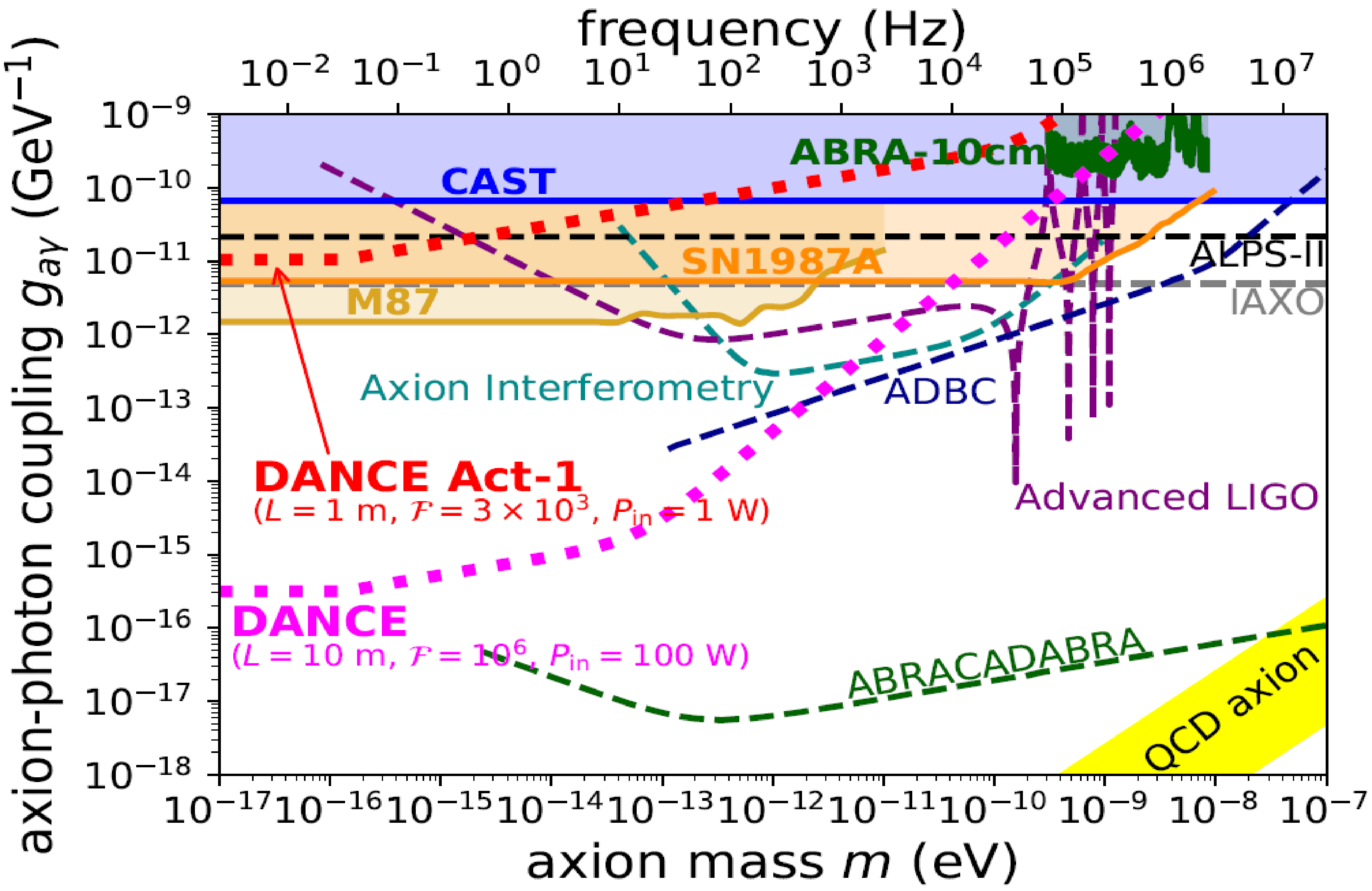
- **The first test result**



Current sensitivity

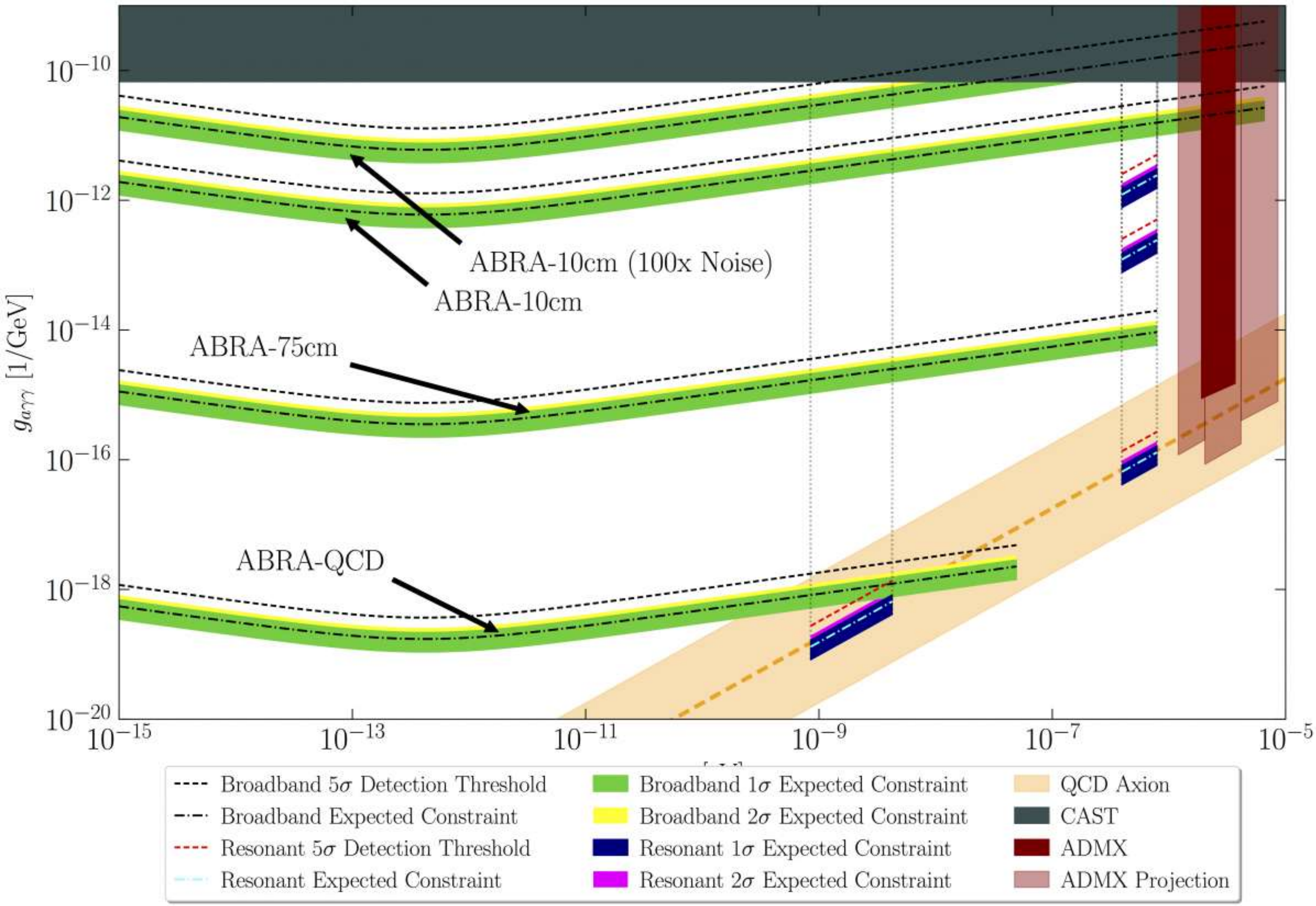
Design sensitivity of the prototype

Recent Proposals for ADM Search



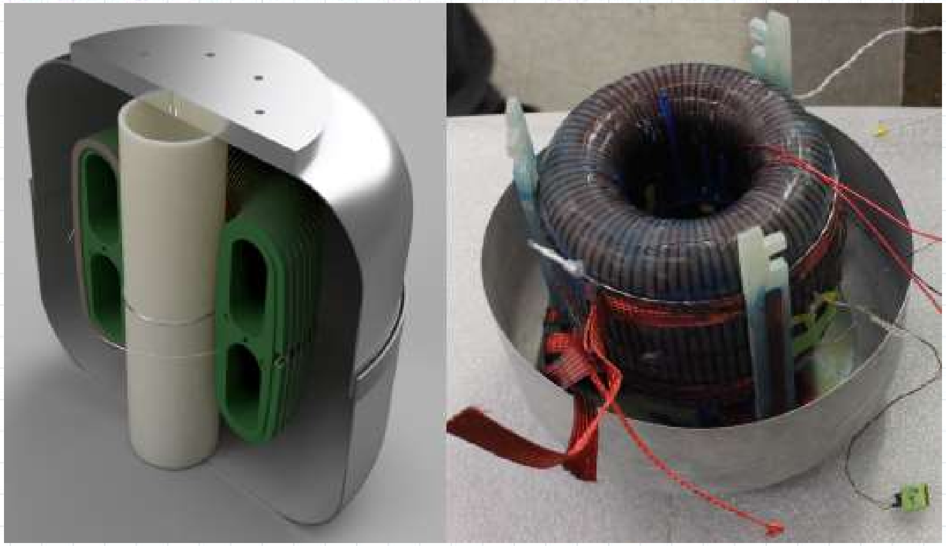
ABRACADABRA Projected Sensitivity

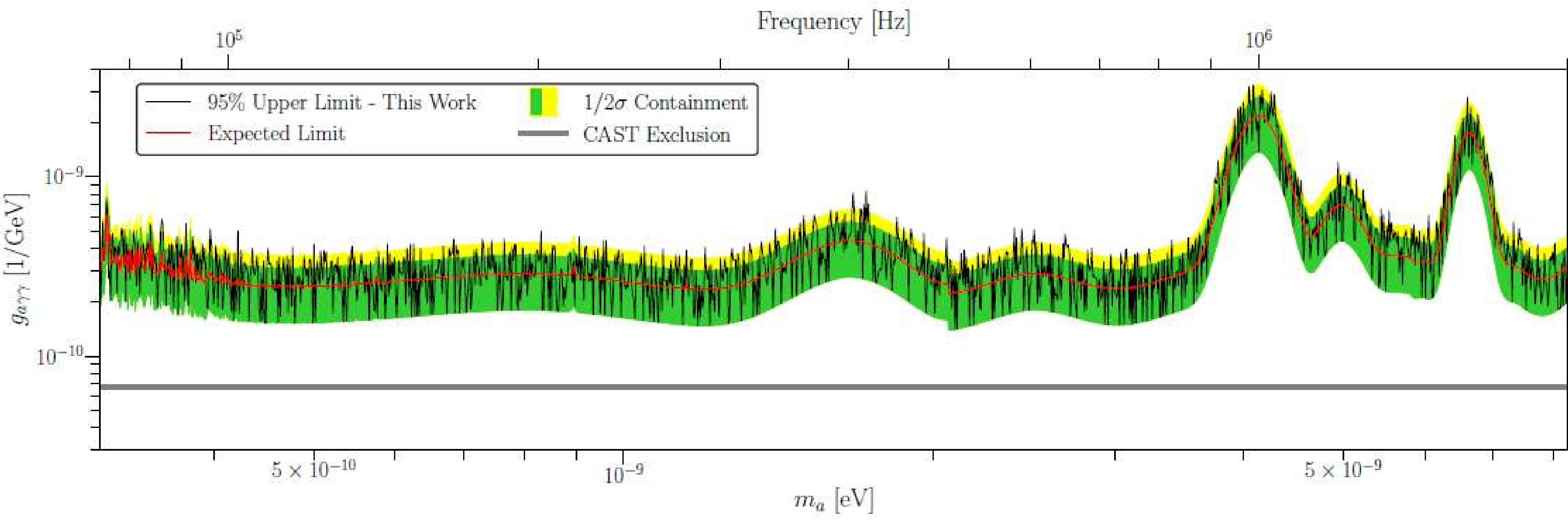
[Ouellet+(2018)]



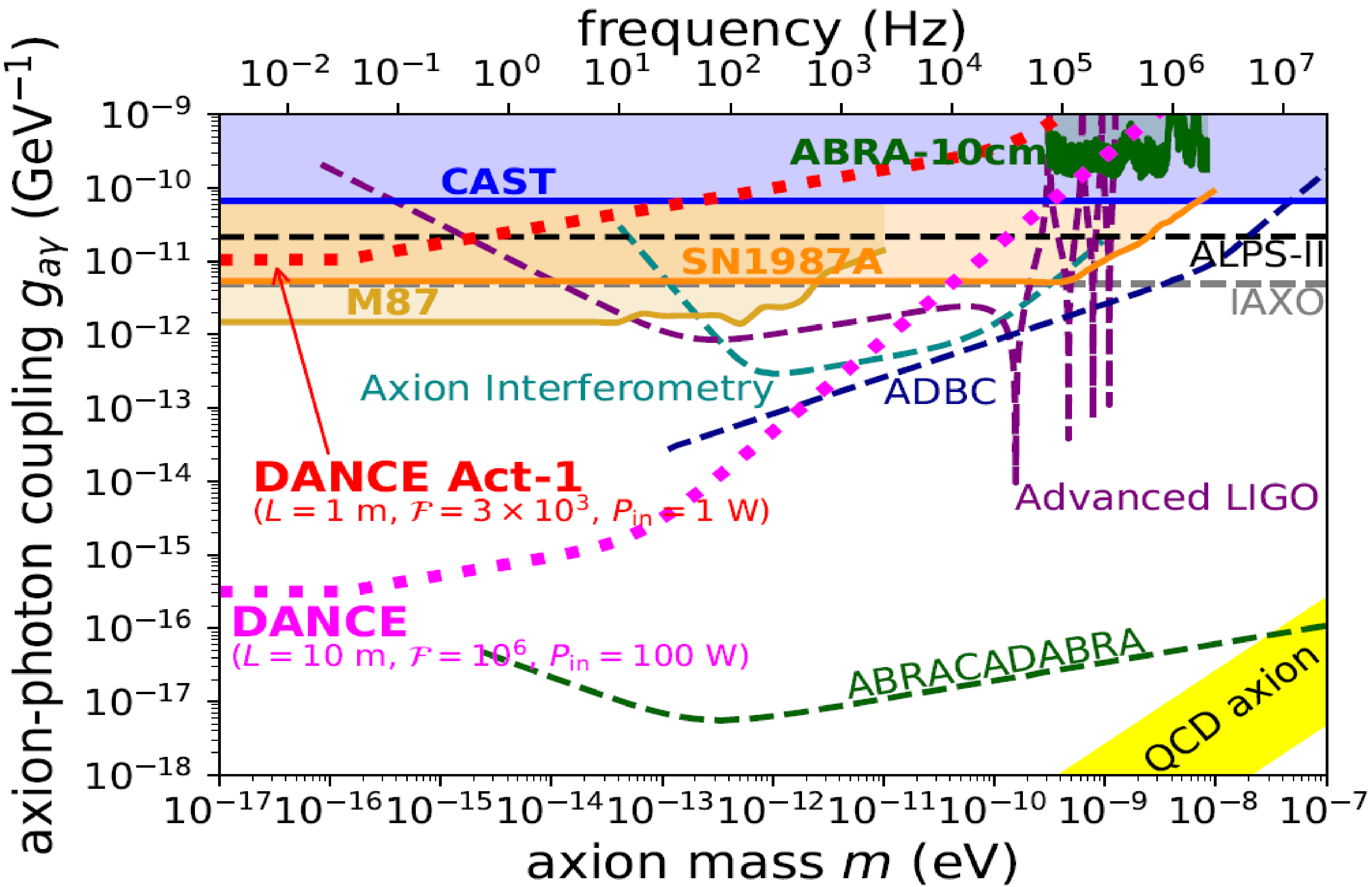
ABRACADABRA Prototype Sensitivity

[Ouellet+(2018)]



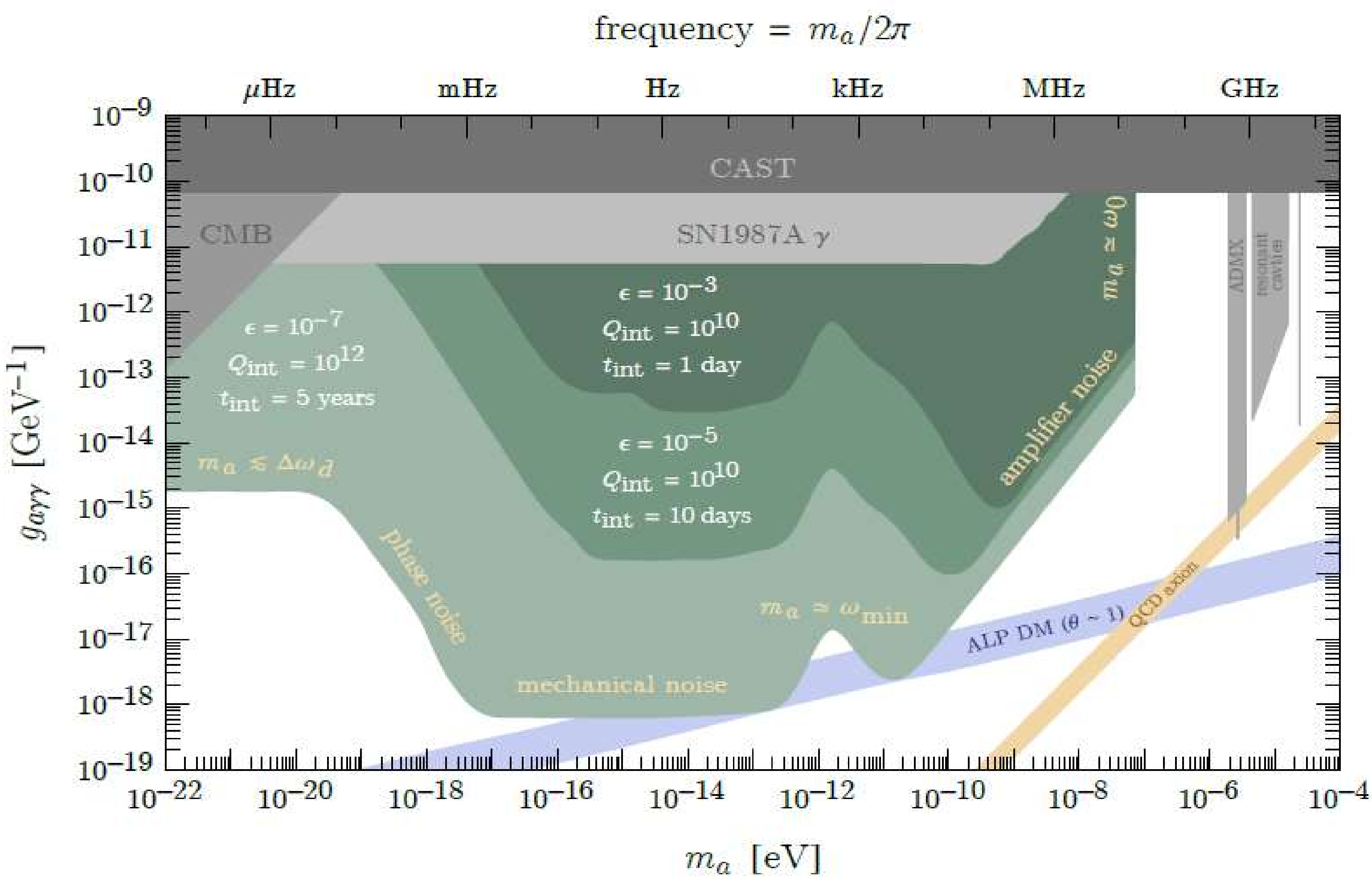


Recent Proposals for ADM Search



[Berlin+(2020)]

Even better way!?



Plan of Talk

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

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 $10^{-16} < m < 10^{-12}\mathrm{eV}$
- Observations of protoplanetary disks are useful to search for ultralight ADM ($m \sim 10^{-22}\mathrm{eV}$)
- CMB Birefringence probes ALP Dark energy

  TF, Minami, Murai, Nakatsuka[2008.02473]

THE THEME
OF CHAPTER IS...

Thank you！