PRESENTATION

Axion Dark Matter coupled to Photons and Gravitons

Tomohiro Fujita
(ICRR Tokyo U.)

Obata, TF & Michimura PRL**121,**161301(2018)
TF, Tazaki & Toma PRL**122,**191101(2019)
Nagano, TF, Obata & Michimura PRL**123,**111301(2019)
TF, Tanaka, Obata & Yamada in prep.(2020)

23rd. Jun. 2020@IPMU

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Outline of Talk

1. Introduction
2. Protoplanetary Disk (Photon)
3. GW Interferometer (Photon)
4. GW Amplification (Graviton)
5. Summary

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Who is Dark Matter?

DM candidates

Scalar

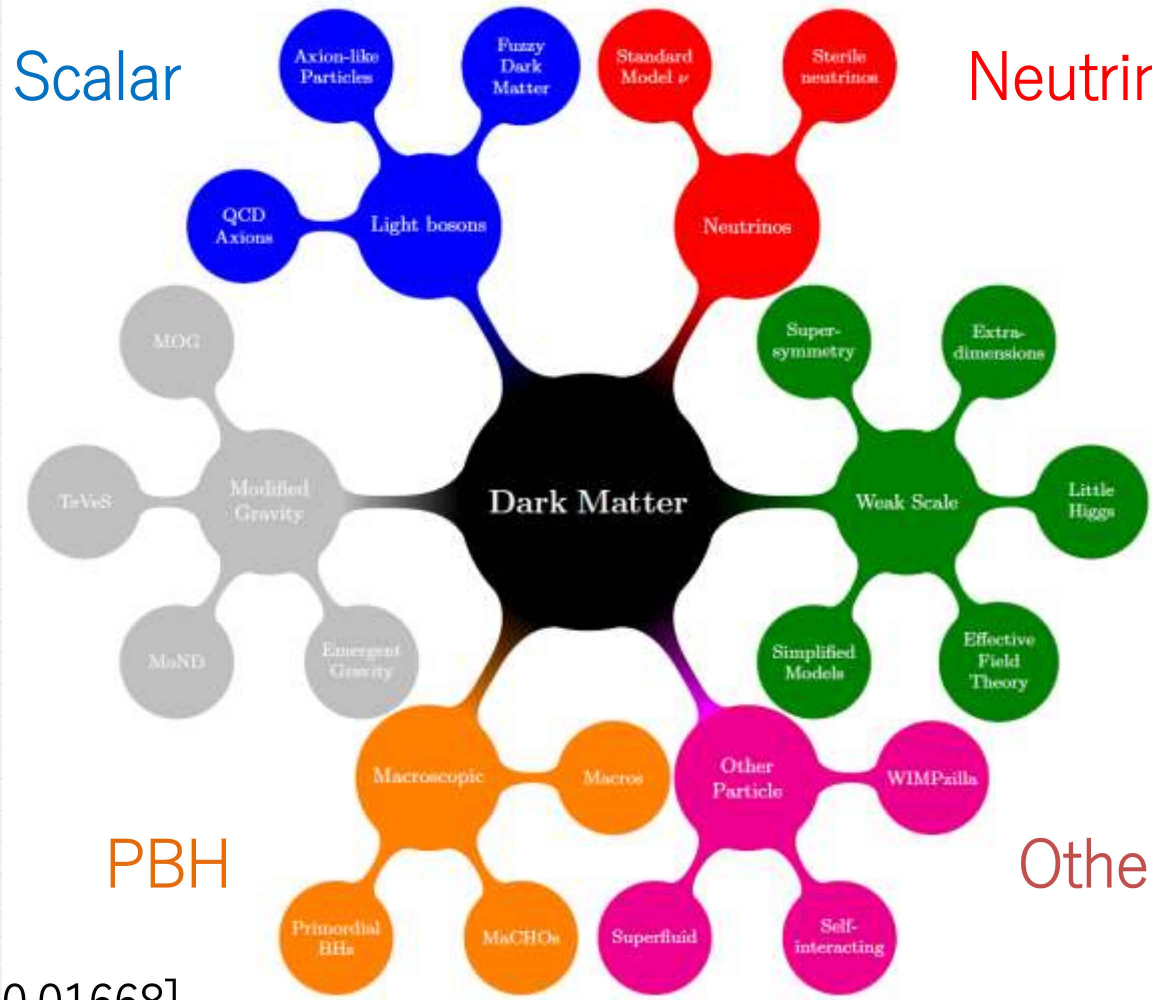
Neutrino

M-Gravity

WIMP

PBH

Other



Berton&Tait[1810.01668]

introduction

PRESENTATION

DM candidates

Scalar DM

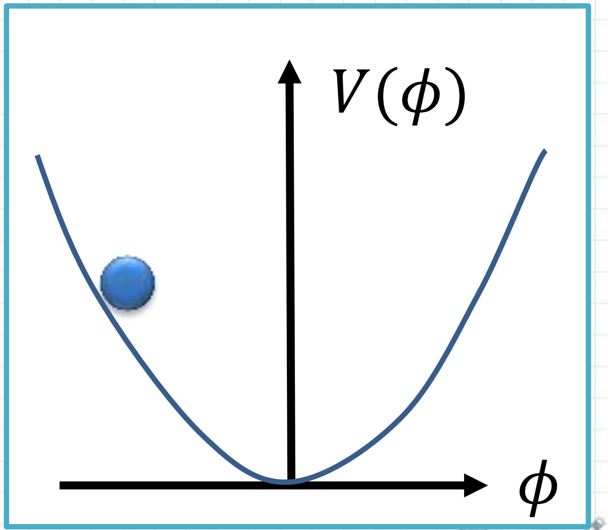
Berton&Tait[1810.01668]

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: $m \gg H$



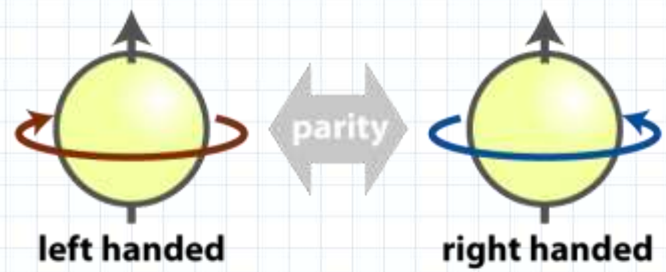
$$\phi = (a/a_0)^{-\frac{3}{2}} \phi_0 \cos(mt + \delta)$$

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

What characterizes ADM?

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

- ADM breaks parity



- ADM may be coupled to gauge fields!

Useful to Search for DM

Axion-Photon Coupling

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

$$\tilde{F}^{\mu\nu} \equiv \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

Axion-Graviton Coupling

- Interaction term: $\mathcal{L}_{\phi g} = \frac{1}{4} g_{\mathrm{CS}} \phi R_{\mu\nu\rho\sigma} \tilde{R}^{\mu\nu\rho\sigma}$

$$\tilde{R}^{\mu\nu\rho\sigma} \equiv \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} R^{\mu\nu}{}_{\alpha\beta}$$

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Axion-Photon Coupling

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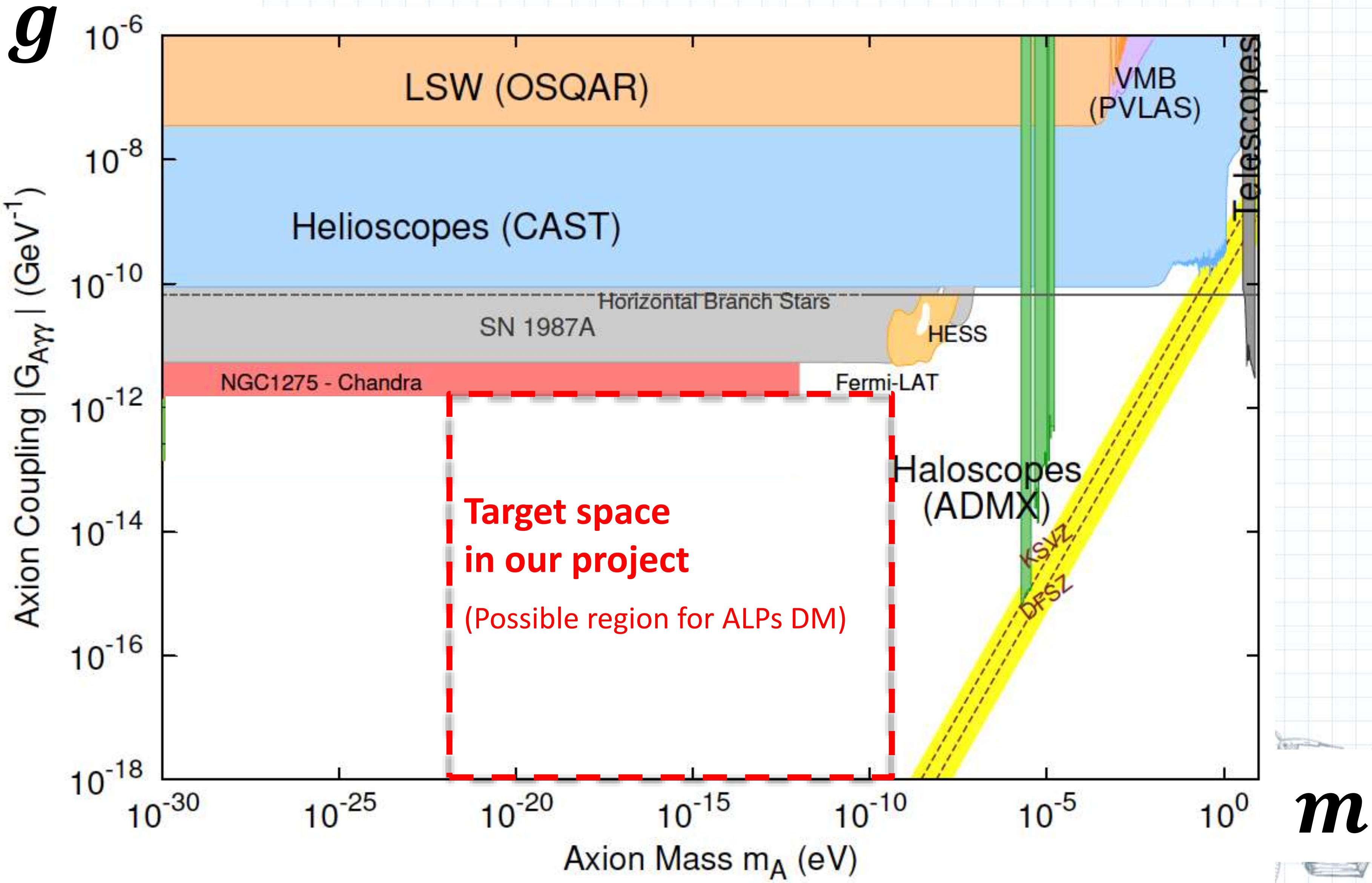
Photon: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla}\times\boldsymbol{A}$

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

Current constraint



Birefringence

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

$-m\phi_0 \sin(mt)$

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

Birefringence

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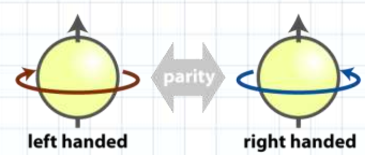
Photon EoM: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla}\times\boldsymbol{A}$

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

⇨ 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

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

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

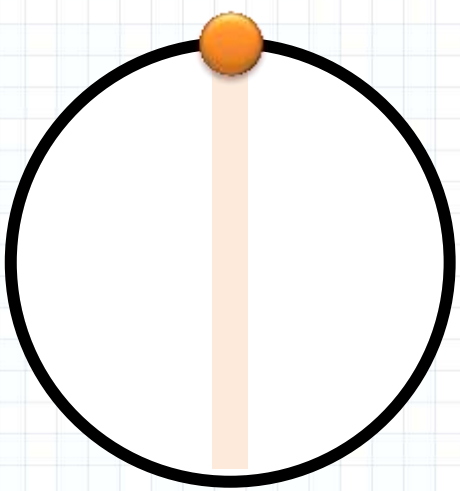
Birefringence

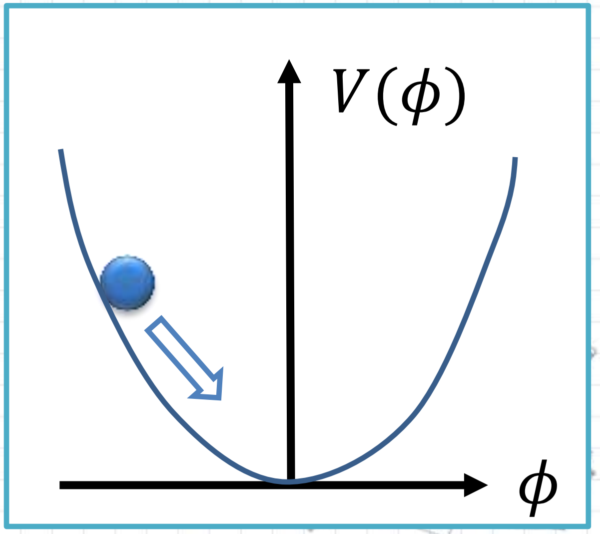
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- 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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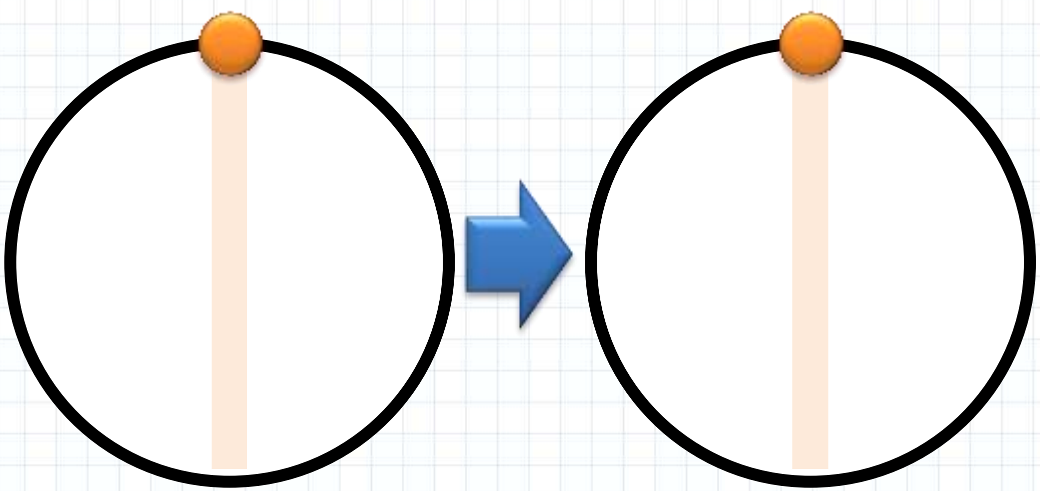

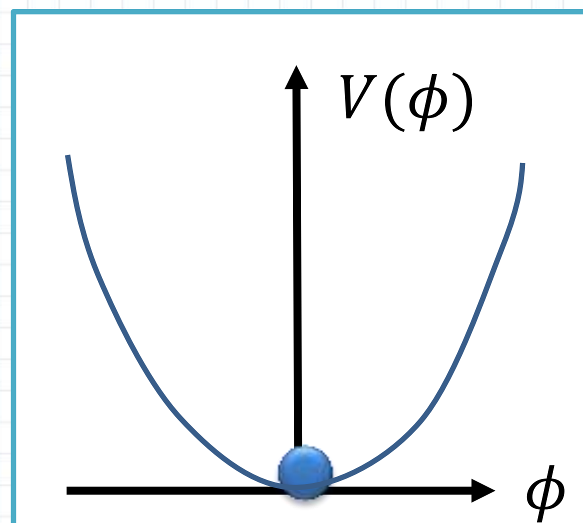

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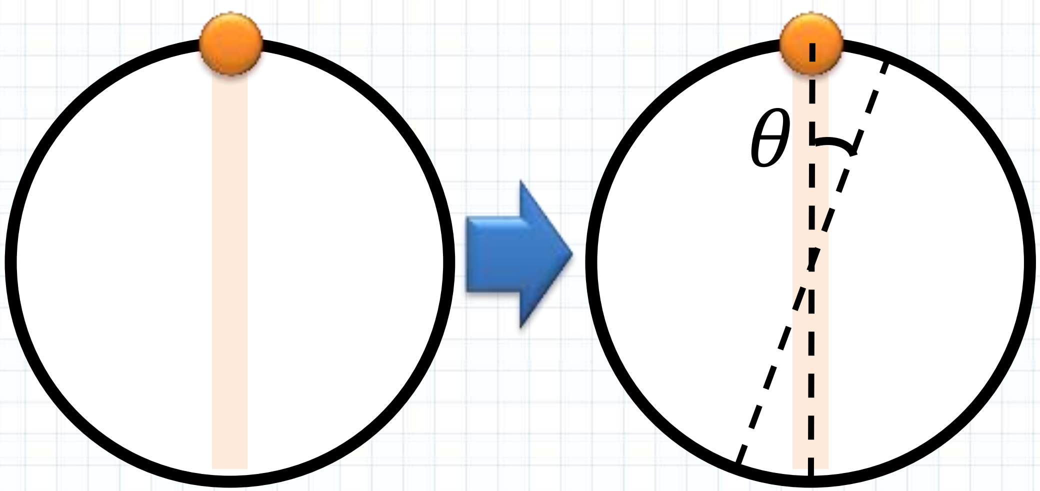
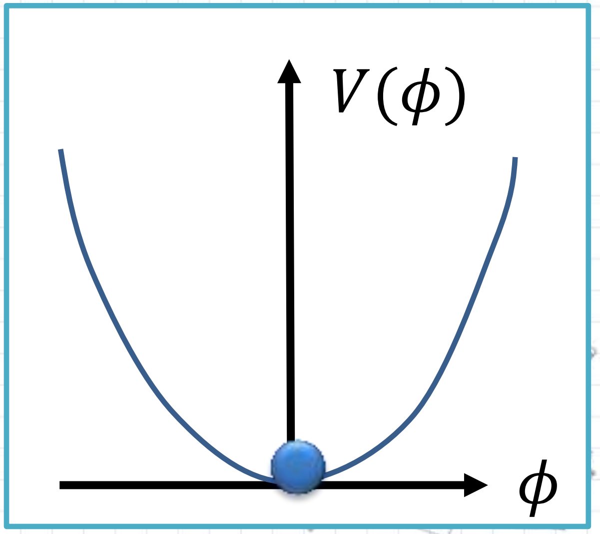




Birefringence

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

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

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

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

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

- How can we observe this?

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

ProtoPlanetary Disk

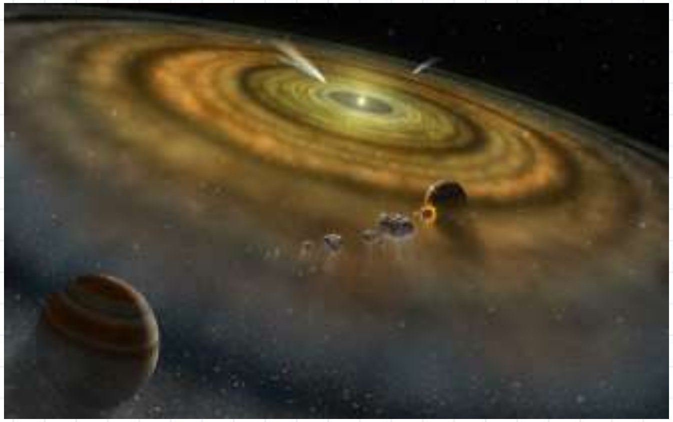
- Observations of PPD can be used!

PPD is a flattened gaseous object surrounding a young star.

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

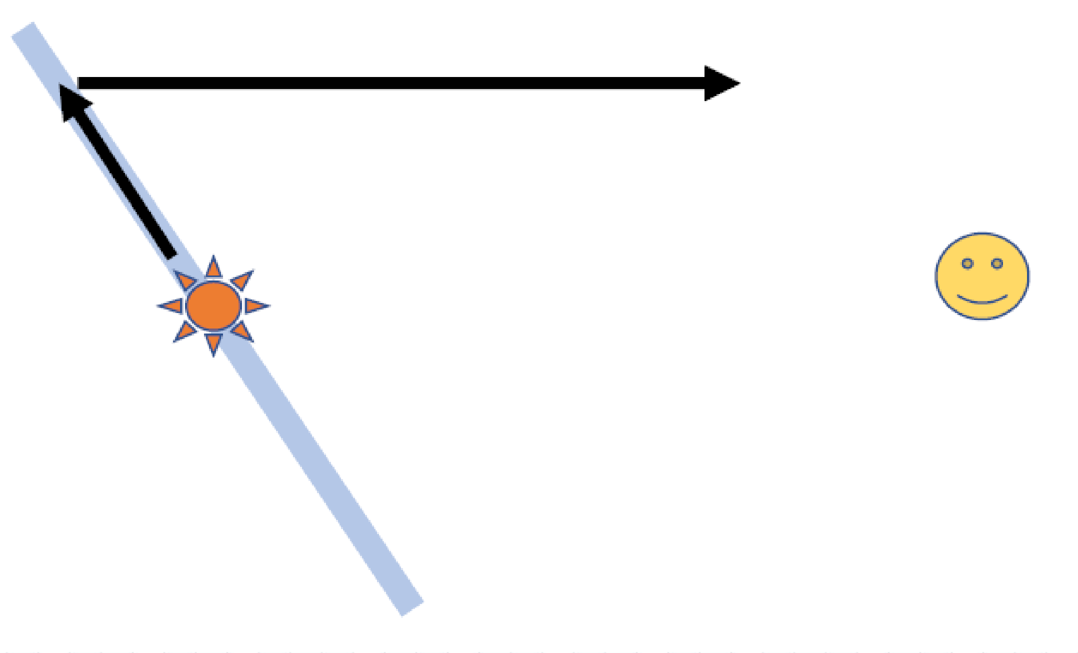
Real data

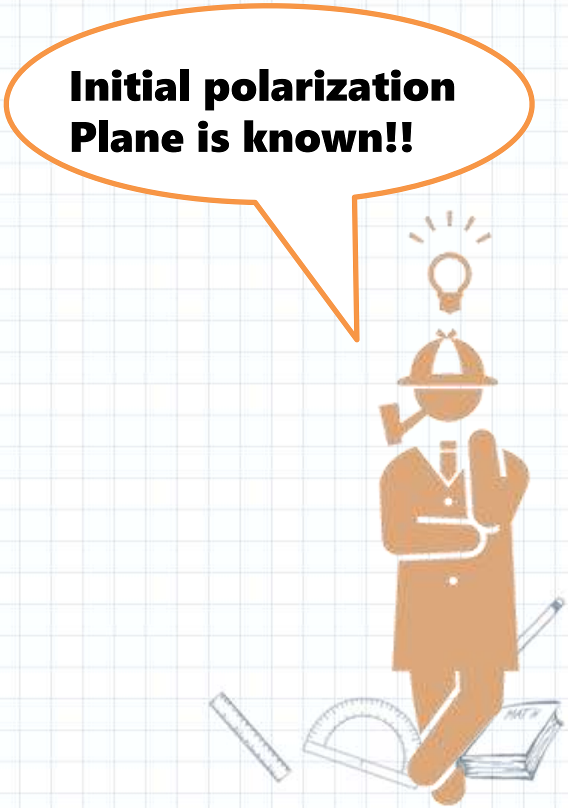
Artist's image



Polarization of PPD

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



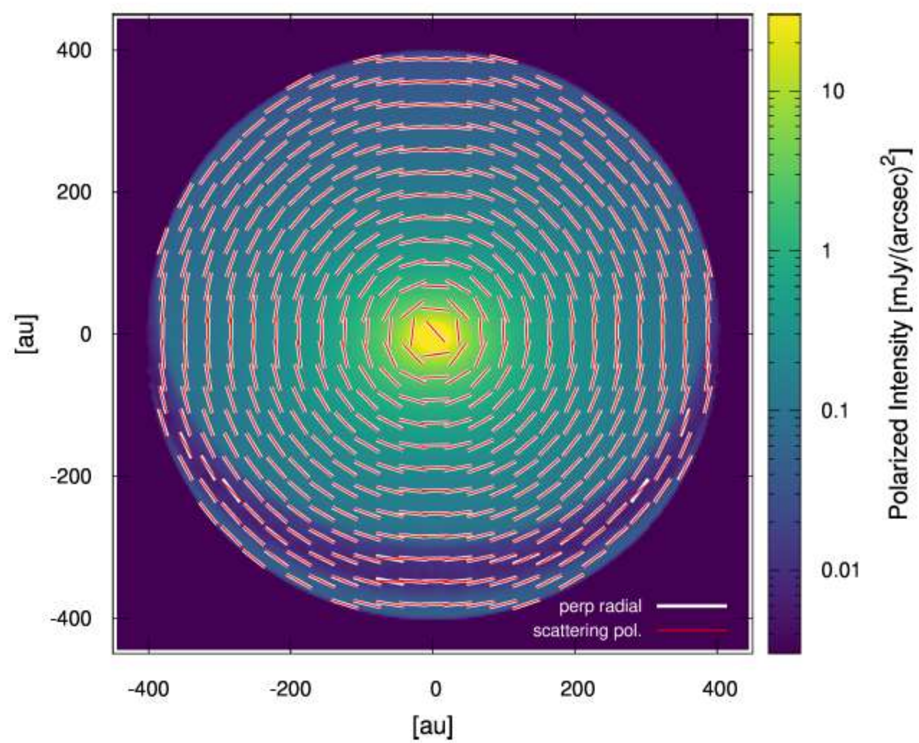


Obsevation of PPD

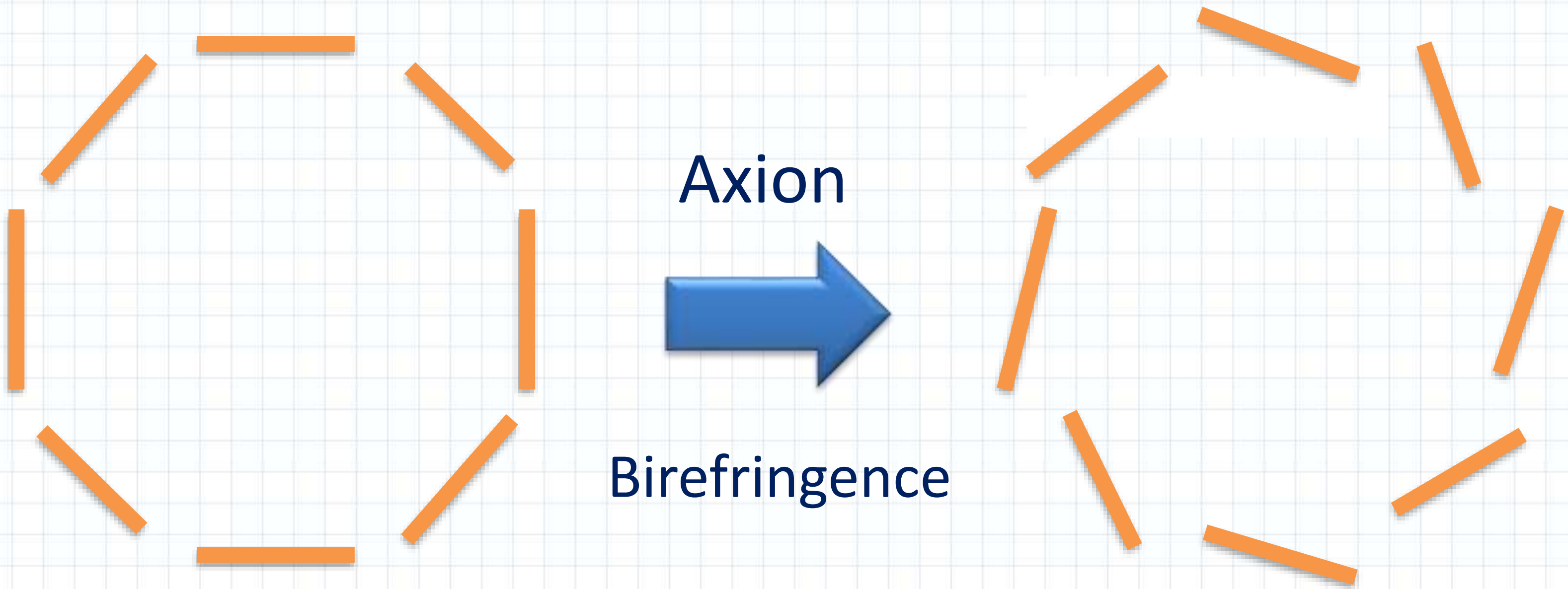
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM

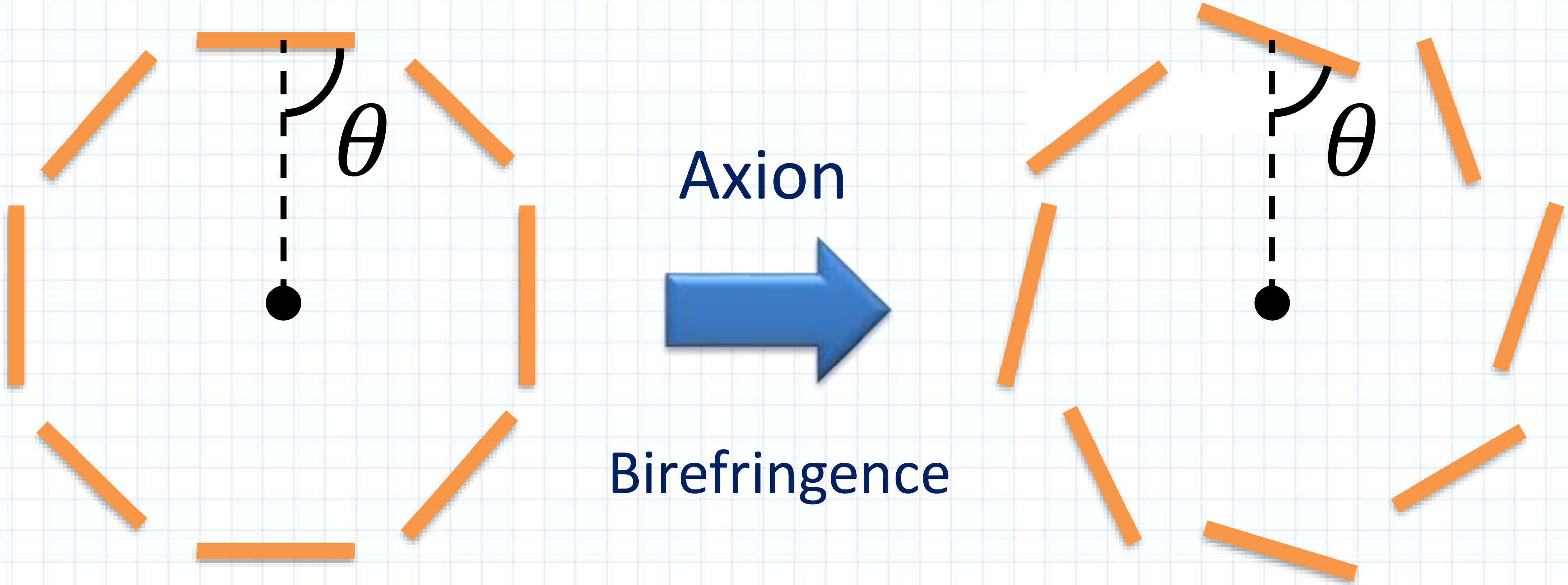


Axion DM rotates pol. plane?



New Observation

Axion DM rotates pol. plane?



Is this angle 90° or not?

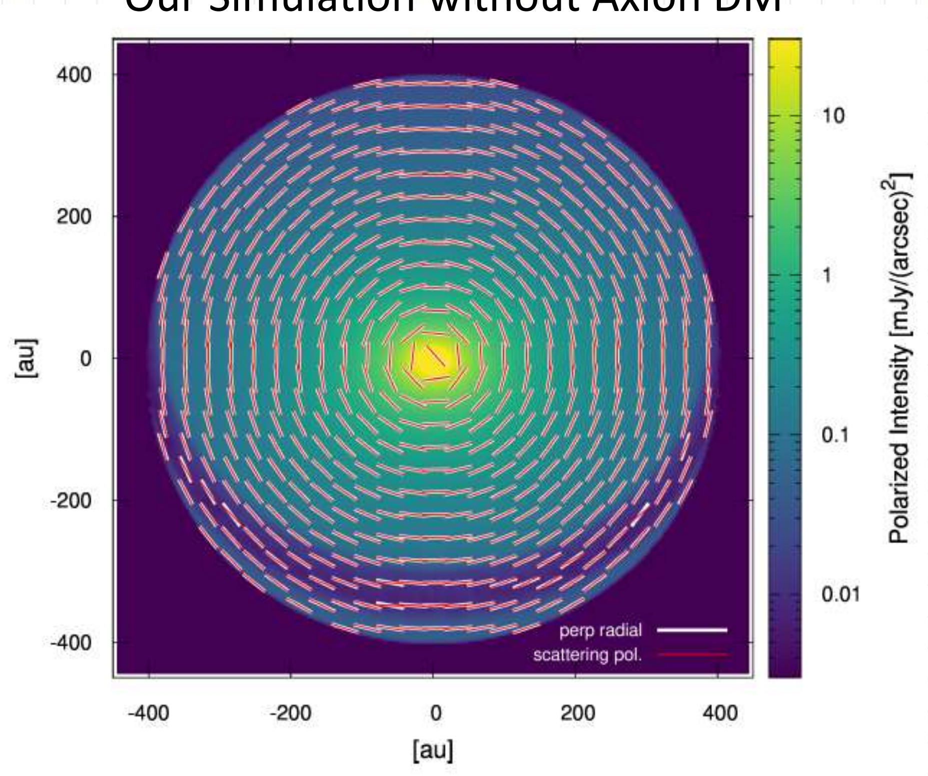
New Observation

Obsevation of PPD

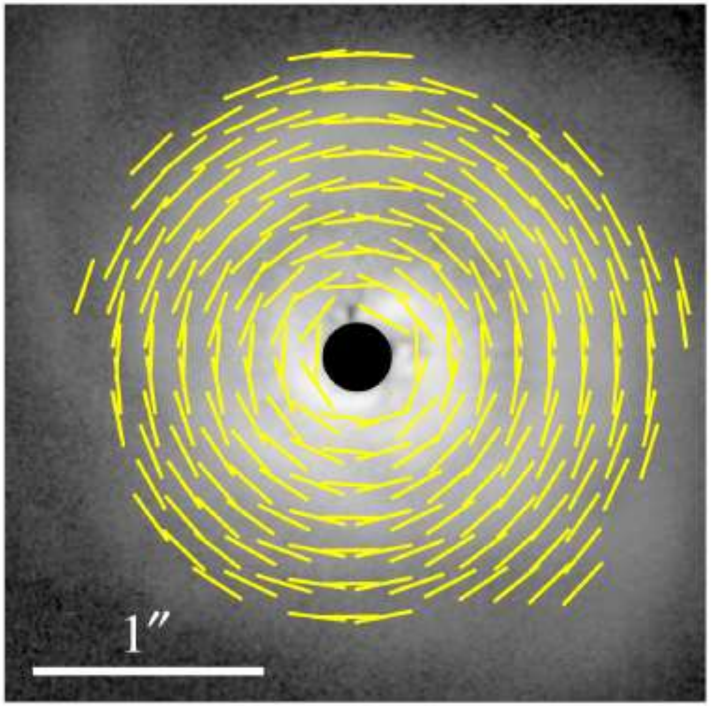
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM



Observation by SUBARU



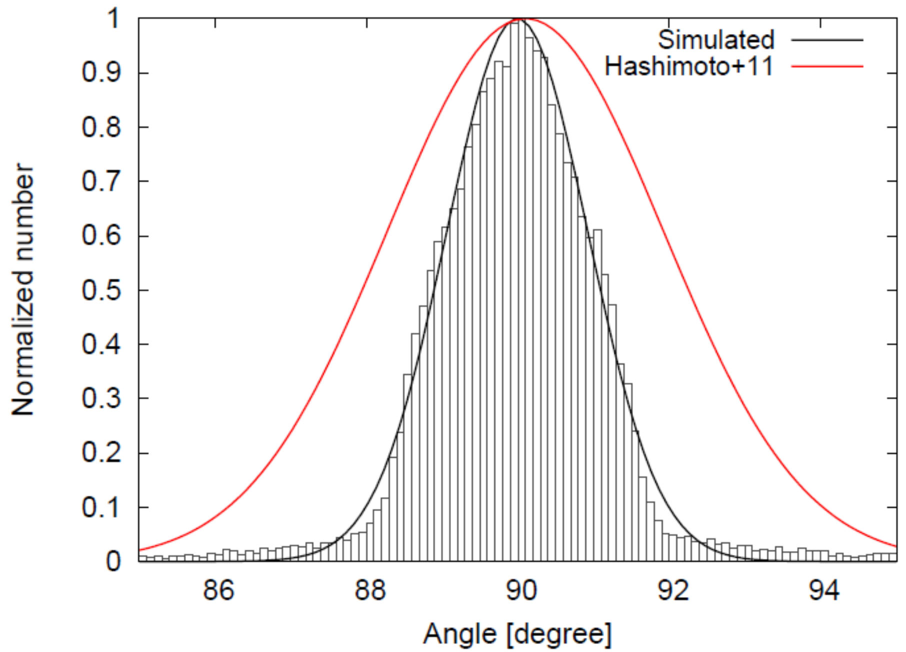
AB Aurigae (160pc away)

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

Obsevation of PPD

The observation data reveals

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



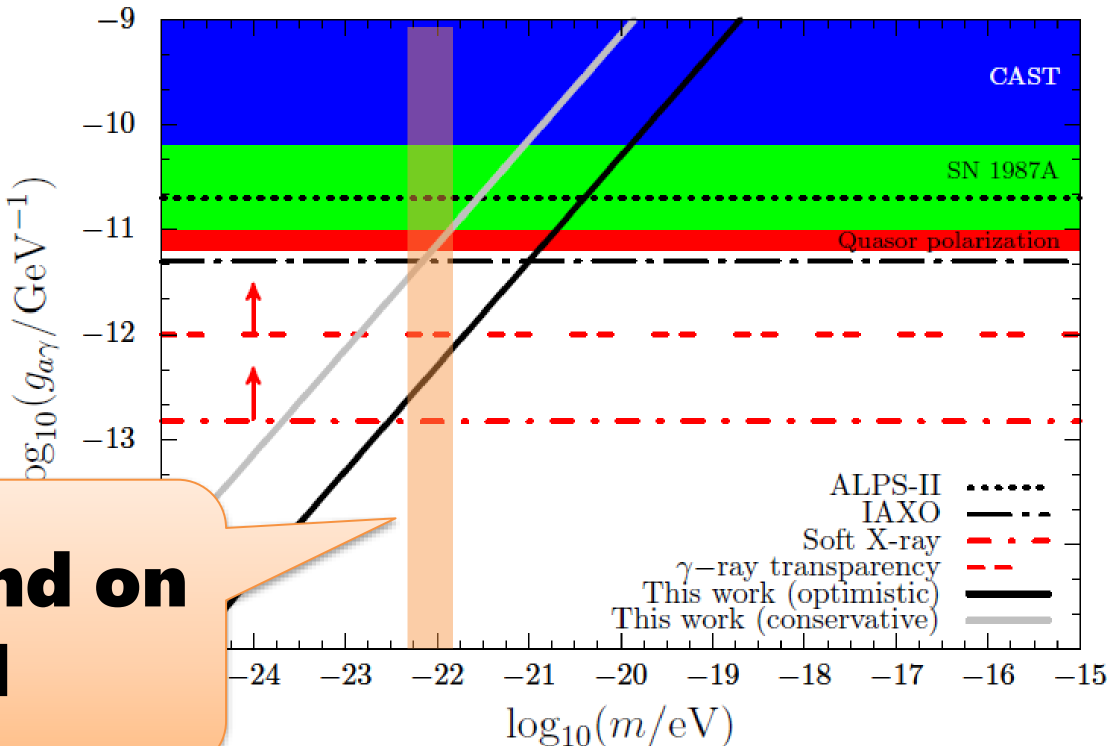
Our simulation confirms the effect of multiple Scatterings is negligible.

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)

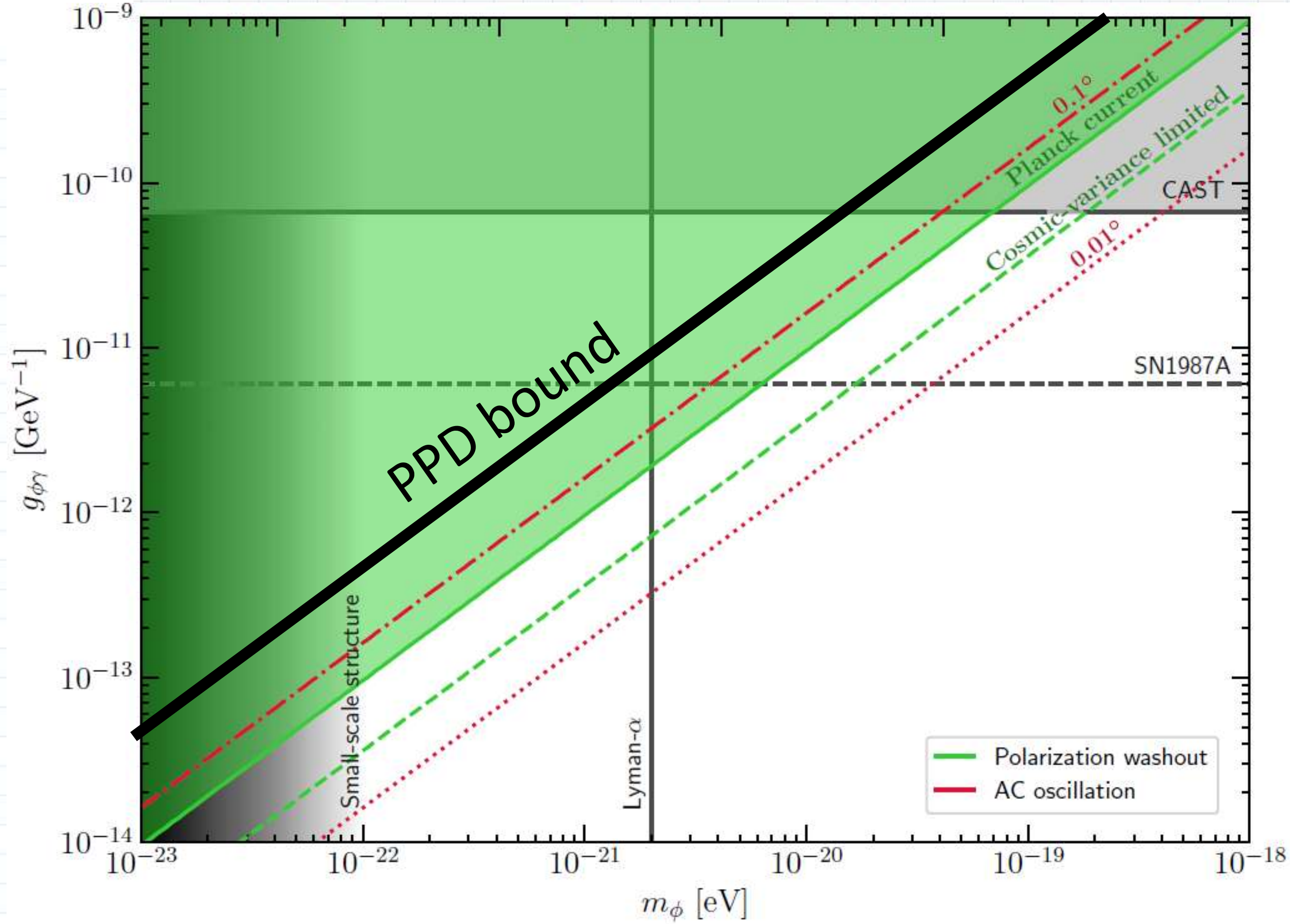
g



m[eV]

Best bound on Fuzzy DM

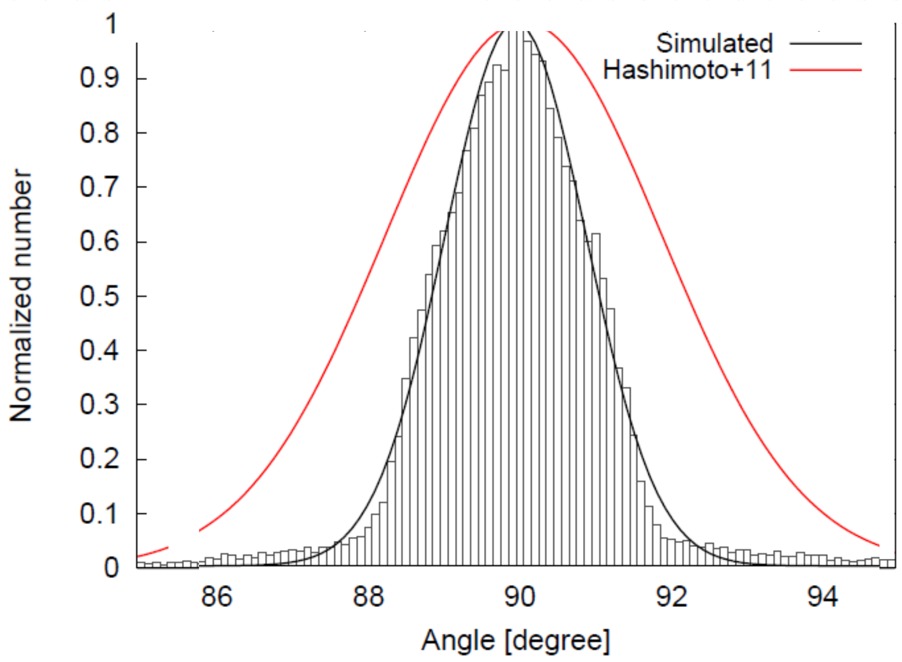
Fedderke+ PRD**100**,015040(2019)



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

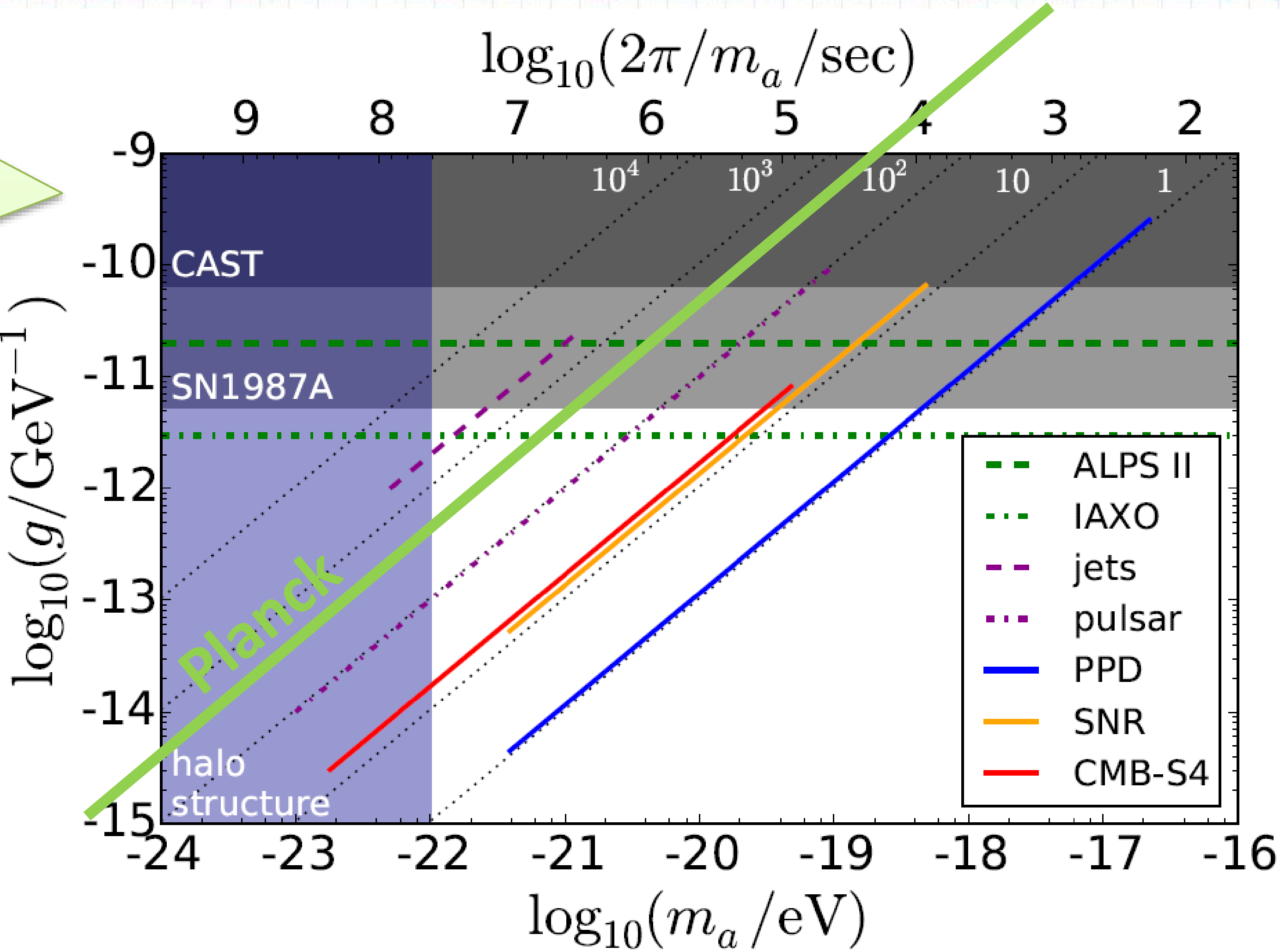
Long-term Obs of PPD

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



Chigusa, Moroi & Nakayama: 1911.09850

Forecast of future ADM Search



PPD has the biggest potential

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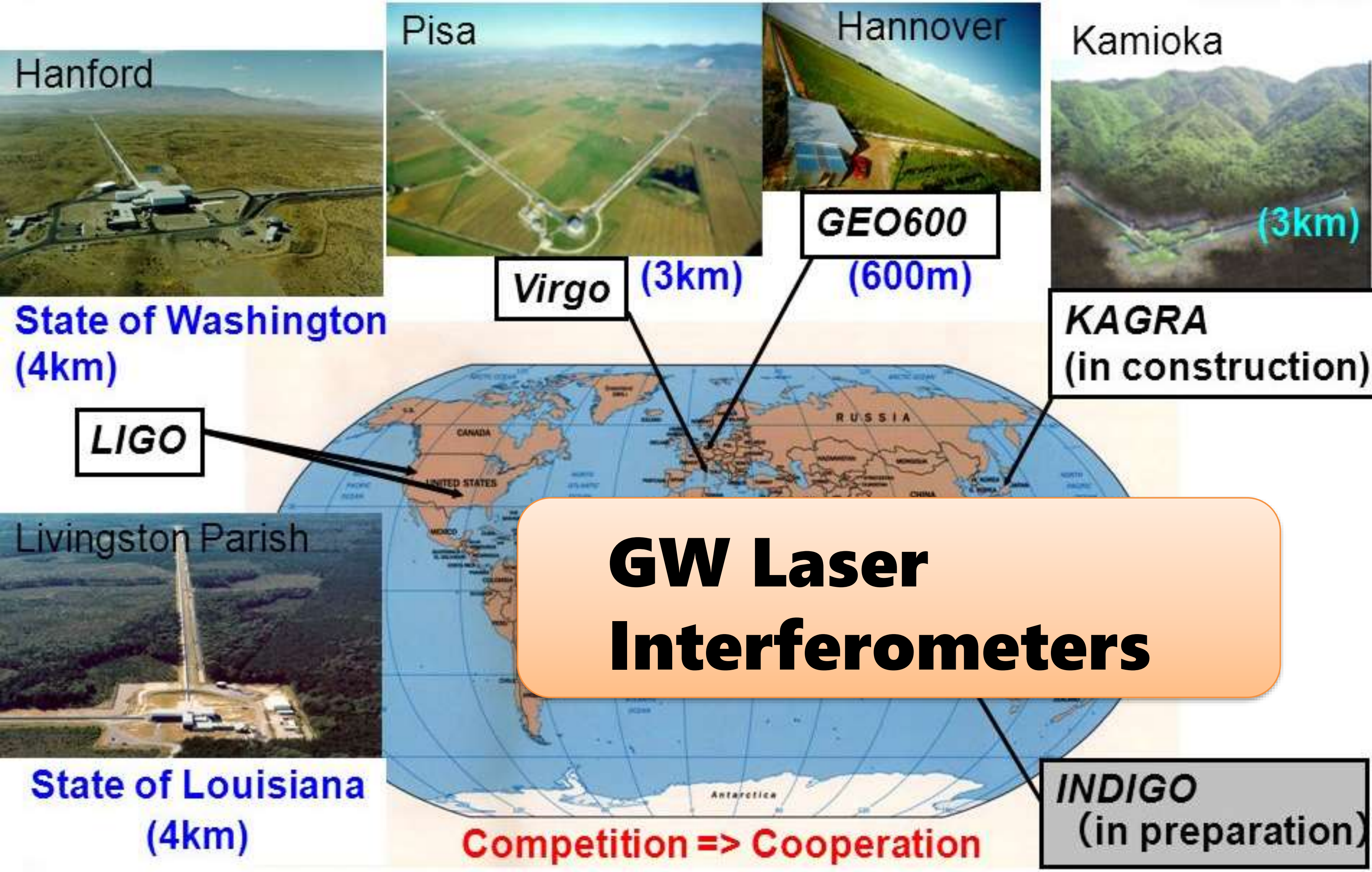
New experiment



New experiment

Can we use GW interferometers

to search for Axion DM?

New experiment

[DeRocco & Hook, PRD **98**, 035021 (2018)]

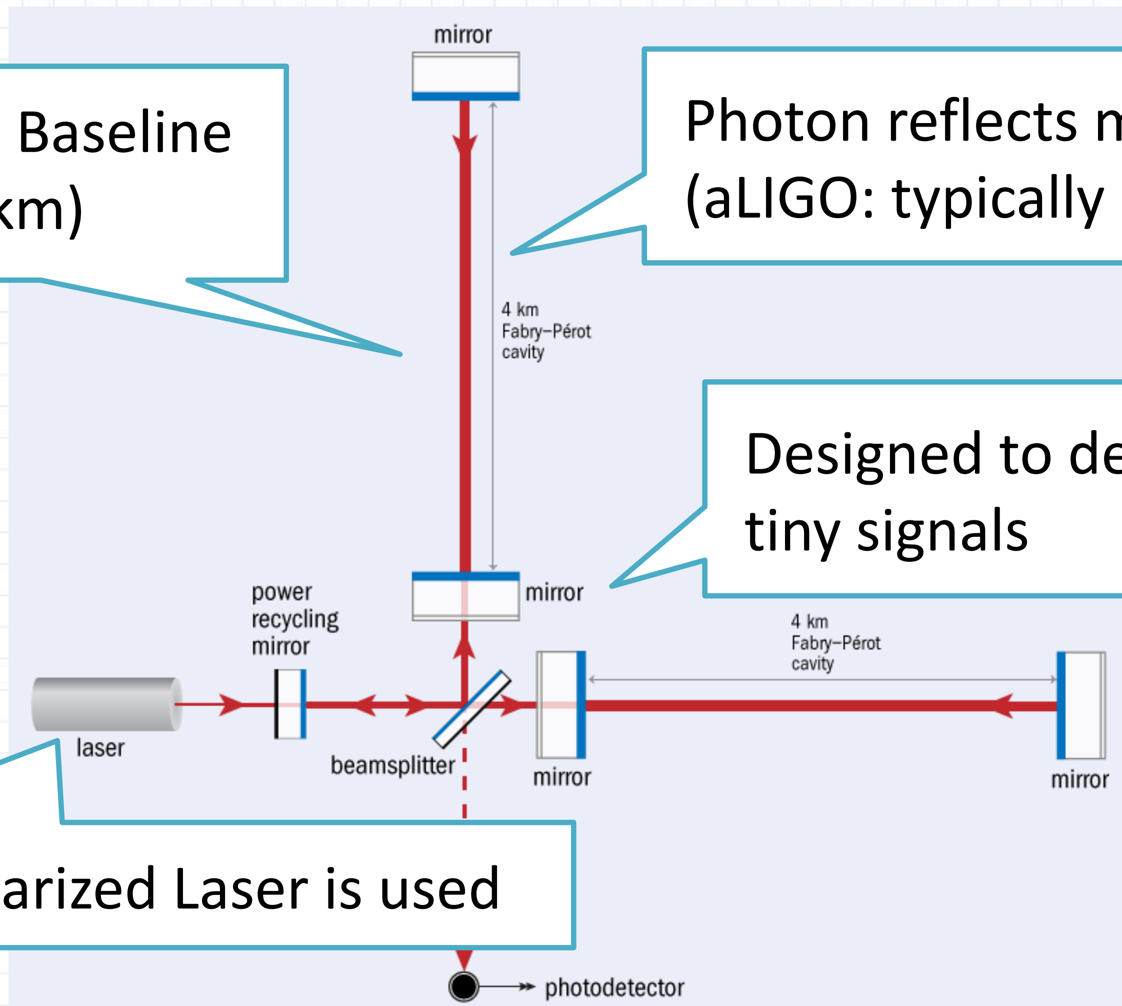
Yes!! Because GW interferometer is

Very Long Baseline
(aLIGO: 4km)

Photon reflects many times
(aLIGO: typically 500 times)

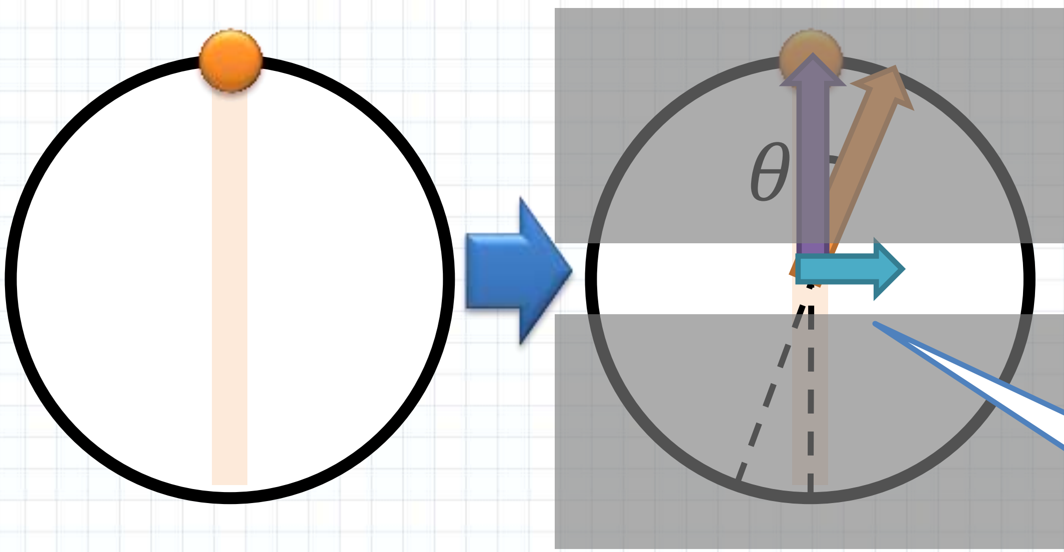
Designed to detect
tiny signals

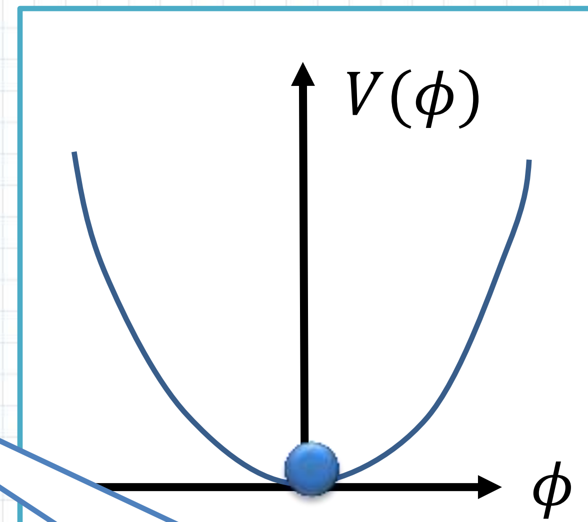
Linear Polarized Laser is used



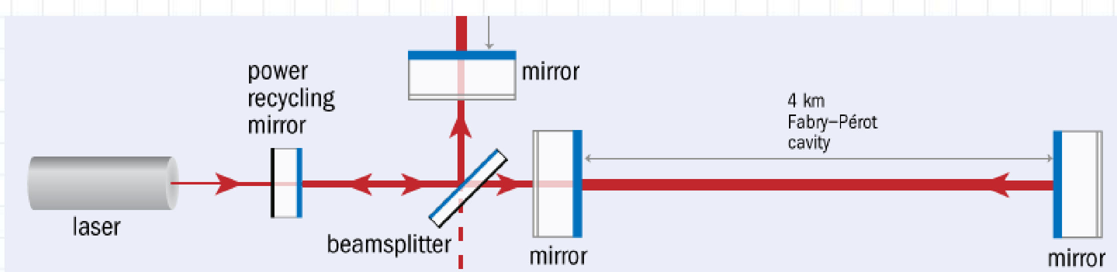
New Observation

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



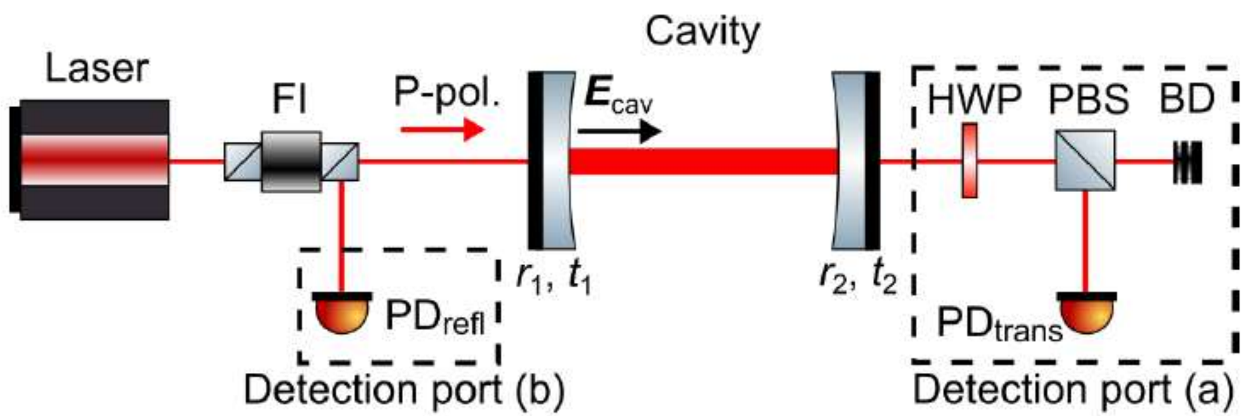


Only if $\theta \neq 0$ by ADM, we detect signal



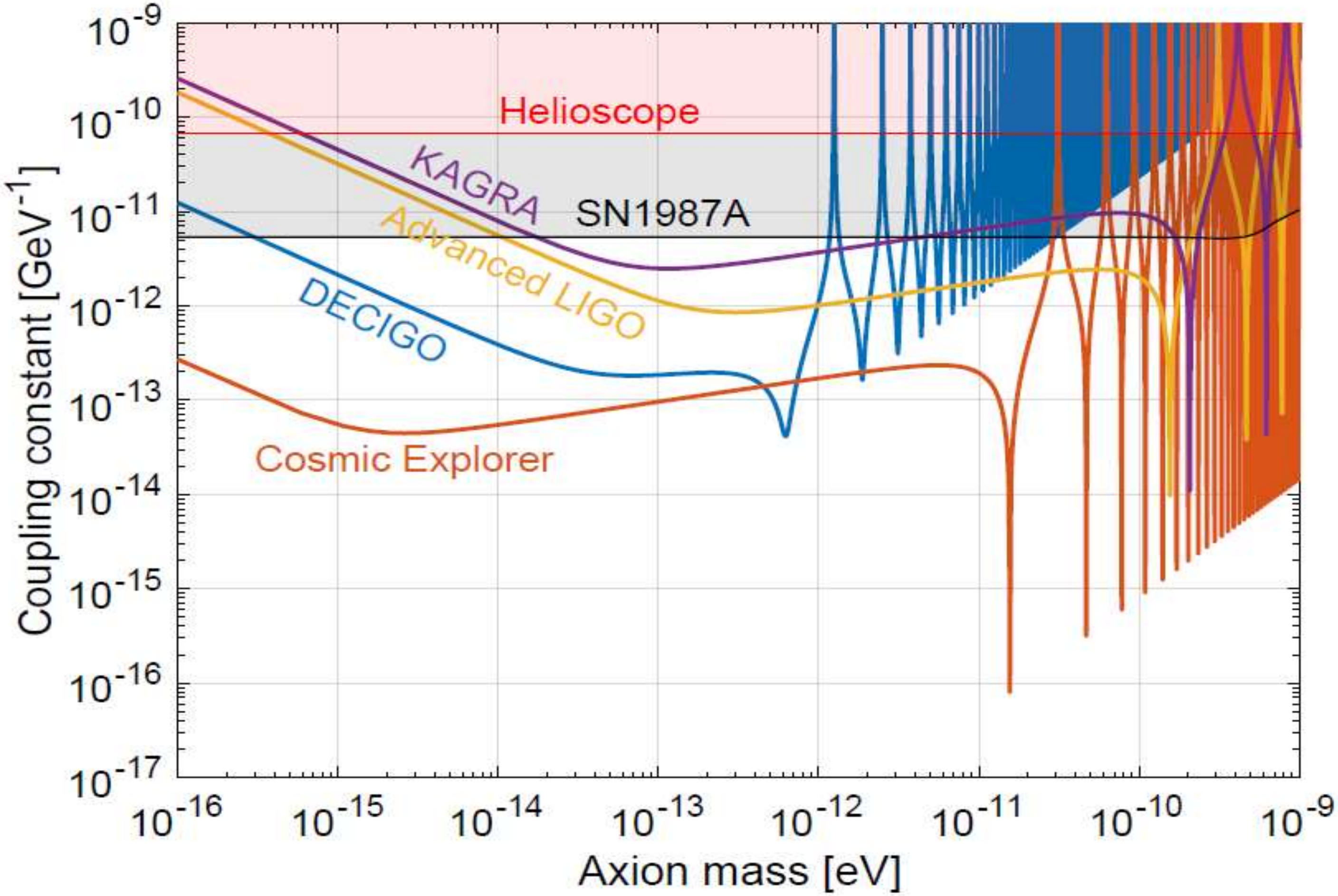
Coexist with GW observation

- Tiny signal compensated by long operation time



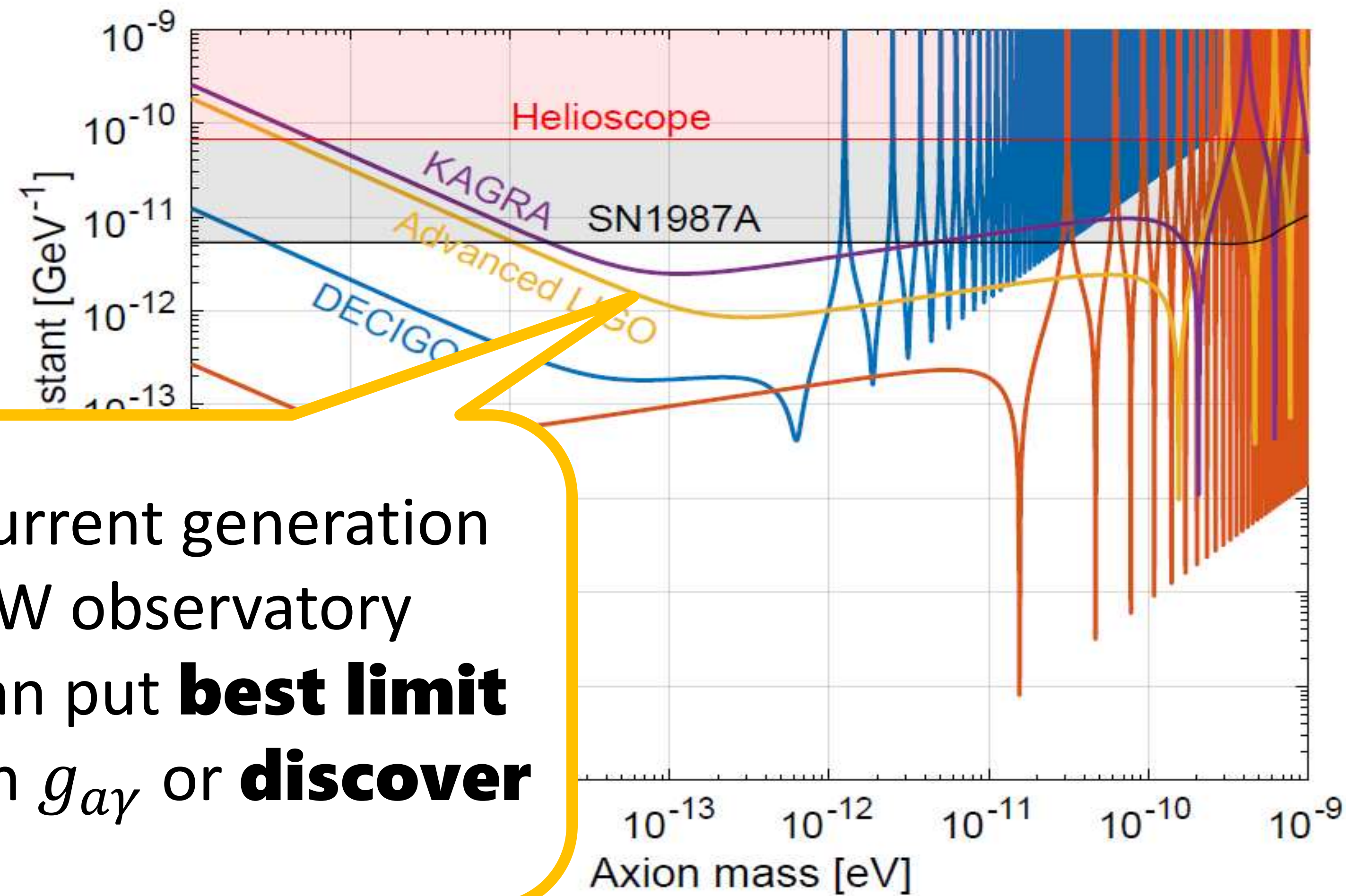
Additional instruments at the tail enable interferometers to probe ADM during the GW observation run **without loosing any sensitivity to GWs** ⇨ **Long Run!**

Sensitivity Curve for 1 year run



New Experiment

Sensitivity Curve for 1 year run



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

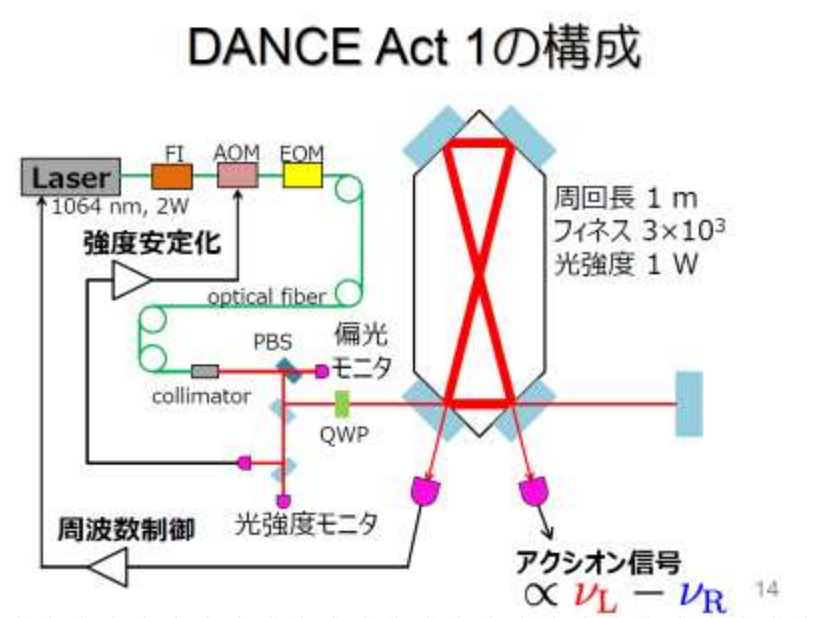
New experiment

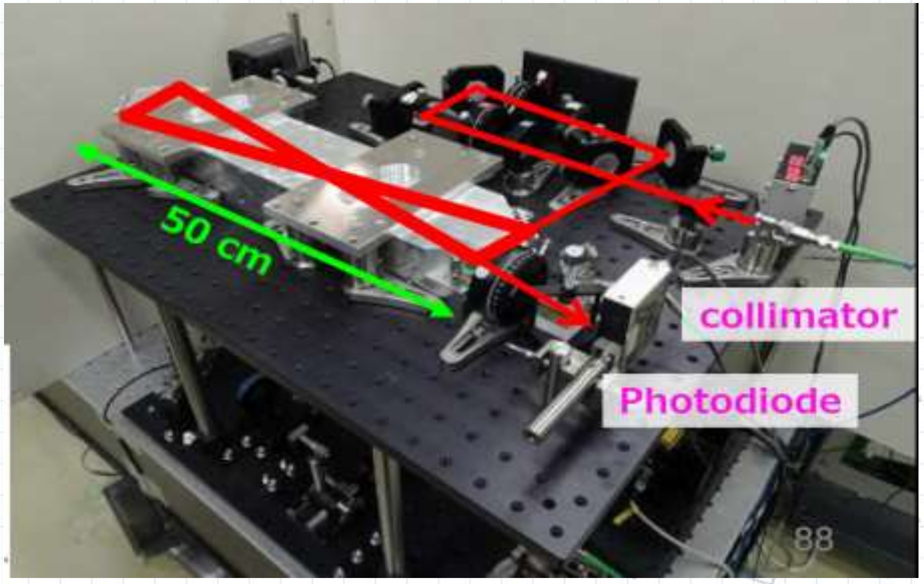
World’s first
GW & ADM
Observatory

DANCE Act.1 has started!

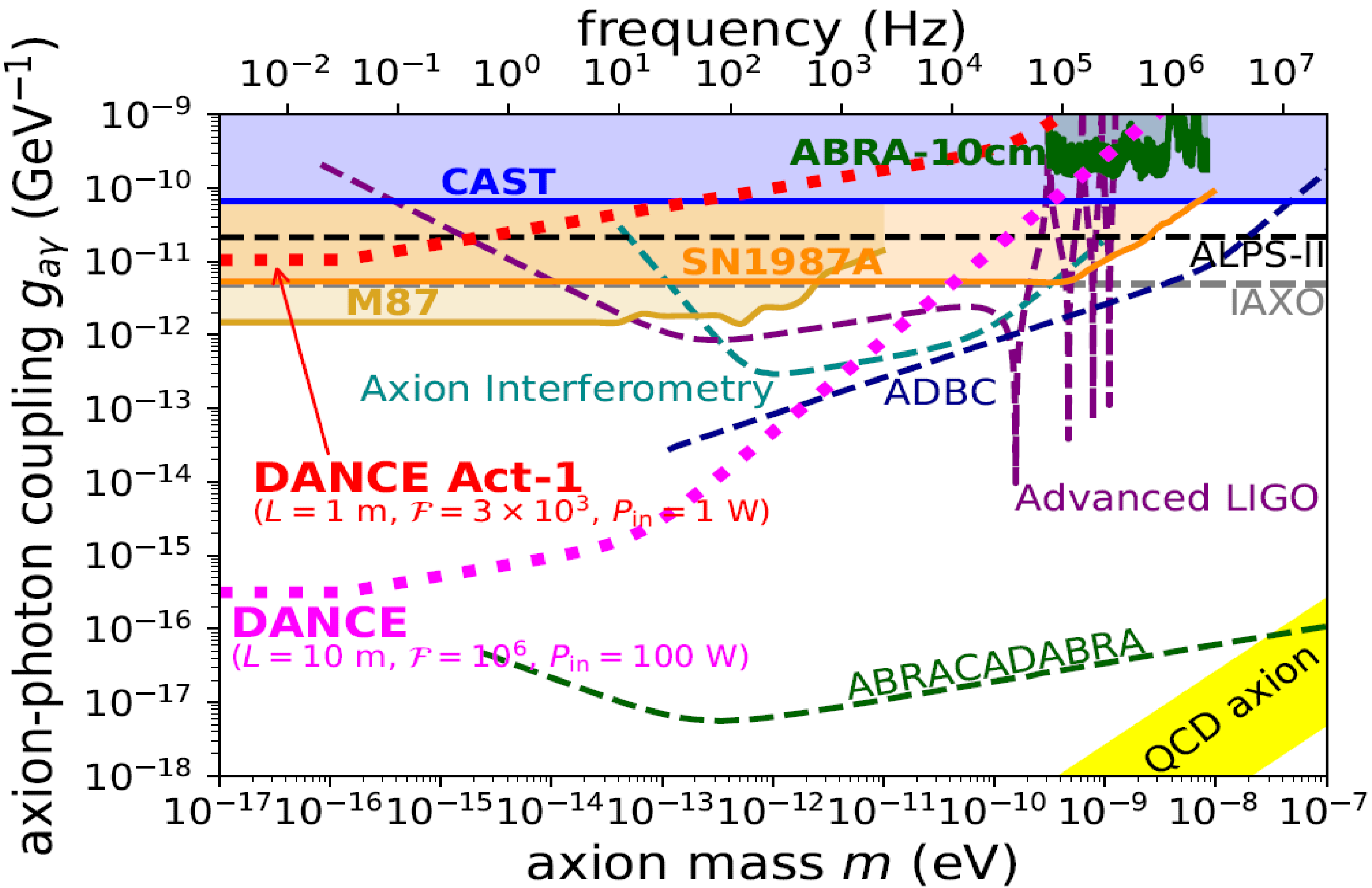
PRESENTATION

- Prototype exp. (Act.1) is being constructed in U. Tokyo. (Ando lab.)
- We got a grant (35kUSD/yr) and applied for another one to extend our experiment.
- The first result (1m, 3months) will be obtained within a year





Recent Proposals for ADM Search



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Previous Works

[Yoshida & Soda (2017)]

GW amplification

[arXiv:1708.09592v2]

Exploring the string axiverse and parity violation in gravity with gravitational waves

Daiske Yoshida* and Jiro Soda†
Physics Department, Kobe University.
(Dated: October 17, 2018)

We study gravitational waves in the presence of the string axion dark matter and the gravitational Chern-Simons coupling. We show that the parametric resonance of gravitational waves occurs due to the axion coherent oscillation and the circular polarization of gravitational waves is induced by the Chern-Simons coupling. For example, the gravitational waves should be enhanced ten times every 10^{-8} pc in the presence of the axion dark matter with mass 10^{-10} eV provided the coupling constant $\ell = 10^8$ km. After 10 kpc propagation, the amplitude of GWs are enhanced by $10^{10^{12}}$ and the polarization of GWs becomes completely circular. However, we have never observed these signatures. This indicates that the Chern-Simons coupling constant and/or the abundance of the light string axion should be strongly constrained than the current limits $\ell \leq 10^8$ km and $\rho \leq 0.3$ GeV/cm^3.

PACS numbers: 04.30.-w, 14.80.Va,95.35.+d

Keywords: string axiverse, parity violation in gravity, gravitational waves

Previous Works

[Yoshida & Soda (2017)]

GW amplification

[arXiv:1708.09592v2]

Interaction term

$$S_{\rm CS} = \frac{1}{4}\alpha \int_{\mathcal{V}} dx^4 \sqrt{-g}\,\Phi \tilde{R} R$$

Oscillating axion

$$\Phi = \Phi_0 \cos(m\eta) \ ,$$

EoM for GWs

$$h_{\rm A}'' + \frac{\epsilon_{\rm A}\delta\,\cos(m\eta)}{1+\epsilon_{\rm A}\frac{k}{m}\delta\,\sin(m\eta)} k\, h_{\rm A}' + k^2 h_{\rm A} = 0$$

Small parameter

$$\delta \equiv \frac{\alpha}{\kappa} m^2 \Phi_0$$

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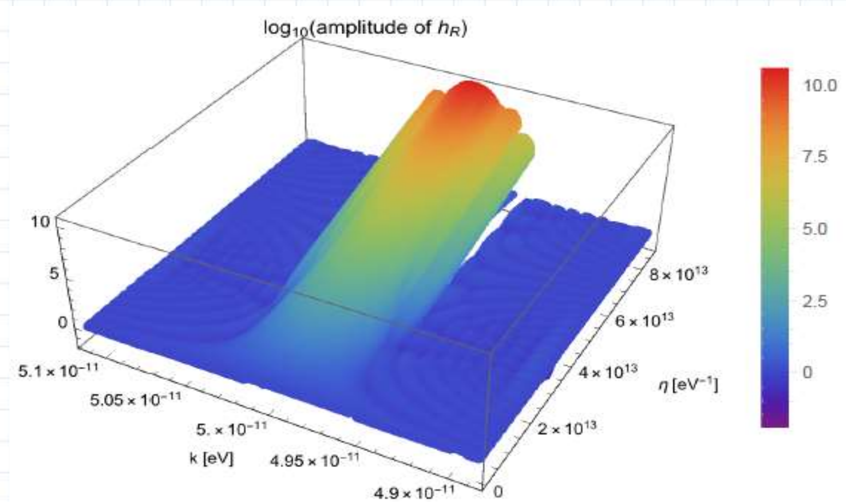
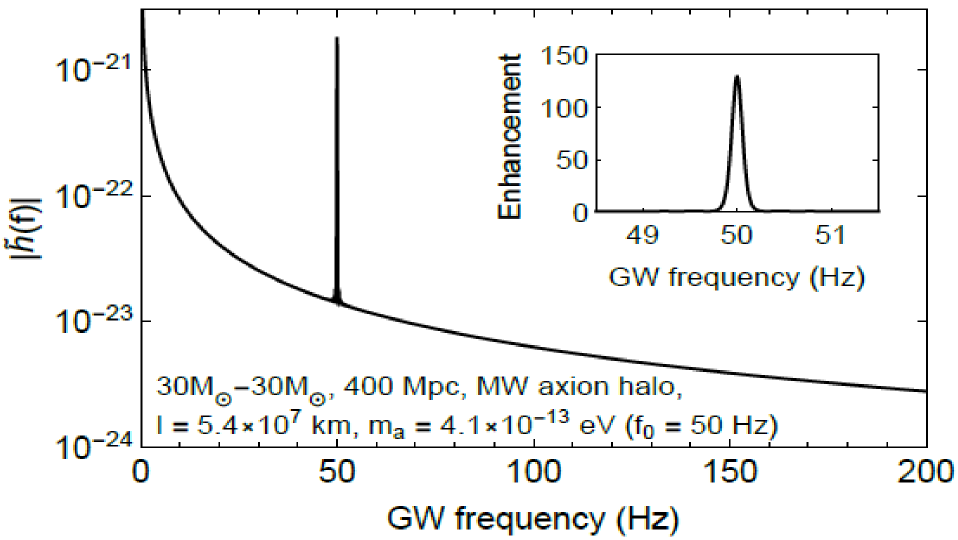


[Jung, Kim, Soda and Urakawa (2020)]

GW amplification

[arXiv:2003.02853]



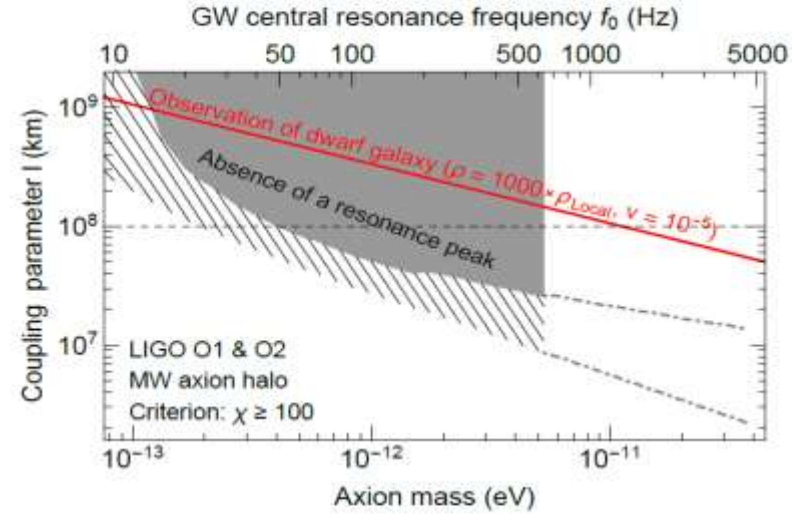


FIG. 2. The upper limit on the axion Chern-Simons coupling ℓ, assuming the absence of a resonance peak in the 11 GW observations at LIGO O1+O2. The gray shaded re-

Taking into account the axion coherence, the amplification becomes mild.

But they still claim a sharp resonant peak in GW spectrum is produced.

Our on-going work

[TF, Obata, Tanaka & Yamada in prep]

Setup

Action:

$$S \equiv \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + \frac{M_{\rm Pl}\ell_{\rm dCS}^2}{4\sqrt{2}}\phi\,{}^*RR - \frac{1}{2}\left(\nabla_\mu\phi\nabla^\mu\phi + 2V(\phi)\right) + \mathcal{L}_{\rm mat}\right]$$

Oscillating axion

$$\phi(t,x) = \frac{1}{2}\left(\phi_0(x)e^{-imt} + \phi_0^*(x)e^{imt}\right)$$

Axion amplitude

$$\varepsilon(x) \equiv \frac{\sqrt{2}\ell_{\rm dCS}^2}{M_{\rm Pl}}m^2\phi_0(x)$$

EoM for GWs

$$(\partial_t^2 - \partial_x^2)h_{\rm R/L} - \frac{1}{2}i\lambda_{\rm R/L}\left(\varepsilon(x)e^{-imt} + \varepsilon^*(x)e^{imt}\right)\partial_t\partial_x h_{\rm R/L} = 0,$$

So far, the same as Kobe group.

Our on-going work

Analysis on resonance

Landau says a resonance is caused by the interaction btw 2 opposite modes, $\omega \approx m/2$ and $\omega \approx -m/2$.

Ansatz in the constant amplitude & phase case ($\epsilon = const.$)

$$h_{\mathrm{R/L}}(t,x) = A_0 e^{-i\omega t + ikx} + B_0 e^{-i(\omega - m)t + ikx} + \mathrm{c.c.}$$

EoM yields the dispersion relation

$$\delta\omega^2 = \delta k^2 - \frac{m^2}{64}|\varepsilon|^2 \qquad \omega \approx k \approx m/2.$$

Resonant amplification within the band $|\delta k| < \dfrac{m|\varepsilon|}{8}$

Wave packet

We know how a plane wave behaves:

$$h_{\delta\omega} \propto \exp\left[-i\delta\omega\left(t - x\,\hat{\delta k}\right)\right], \quad \hat{\delta k} \equiv \sqrt{1 + \frac{|\varepsilon|^2}{64}\frac{m^2}{\delta\omega^2}},$$

As more realistic GW signal, consider a Gaussian wave packet $\propto \exp[-\delta\omega^2/2K^2]$.

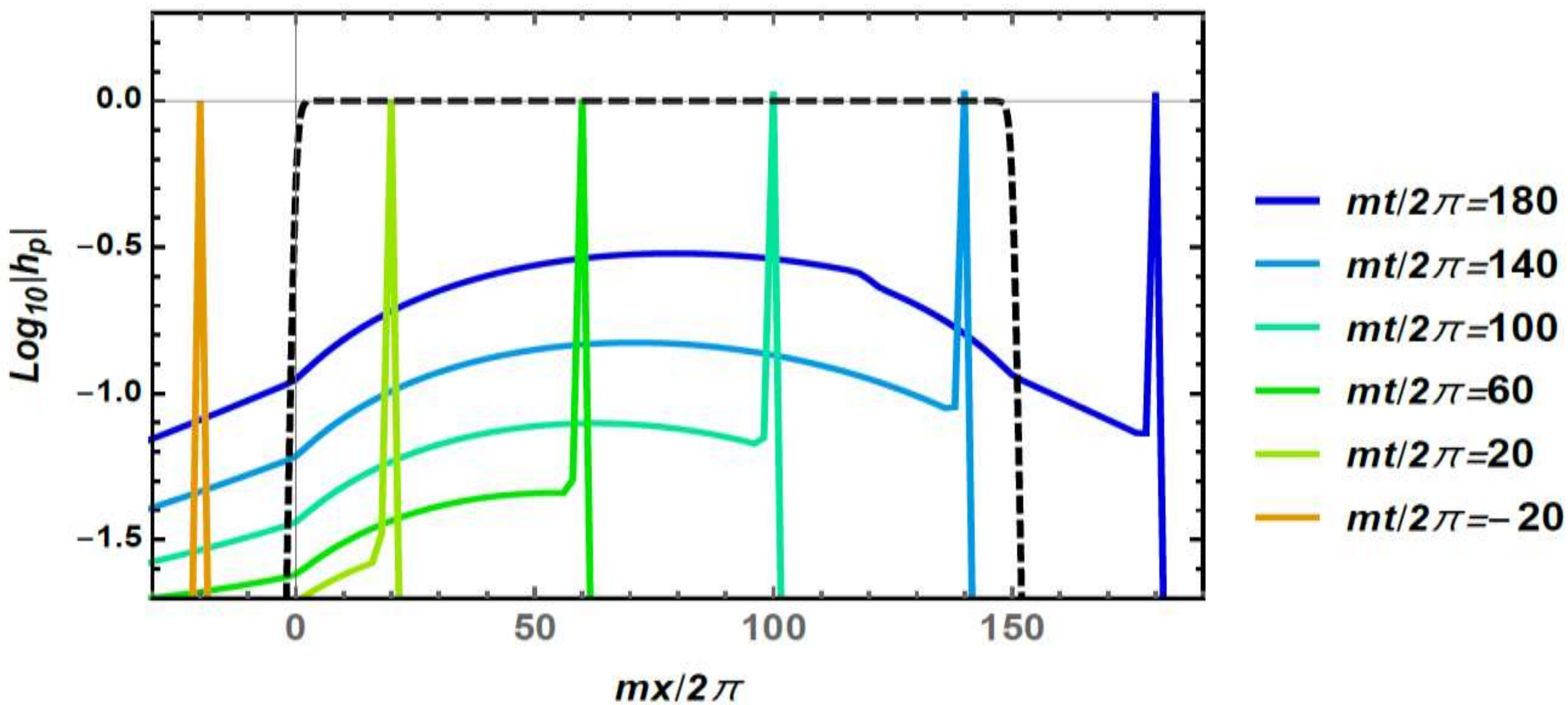
$$h_{\text{packet}} = \frac{1}{\sqrt{2\pi}K} e^{-im(t-x)/2} \int \mathrm{d}\delta\omega\, e^{f(\delta\omega)} \qquad f(\delta\omega) = -i\delta\omega\left(t - x\sqrt{1 + \frac{|\varepsilon|^2}{64}\frac{m^2}{\delta\omega^2}}\right) - \frac{\delta\omega^2}{2K^2}$$

Saddle point integral gives analytic results which respect the causality

$$h_{\text{packet}}(t > x) \sim \exp\left[\frac{m|\varepsilon|}{8}\sqrt{t^2 - x^2}\right]$$

$$h_{\text{packet}}(t < x) \sim \exp\left[-\frac{1}{2}K^2(x-t)^2\right]$$

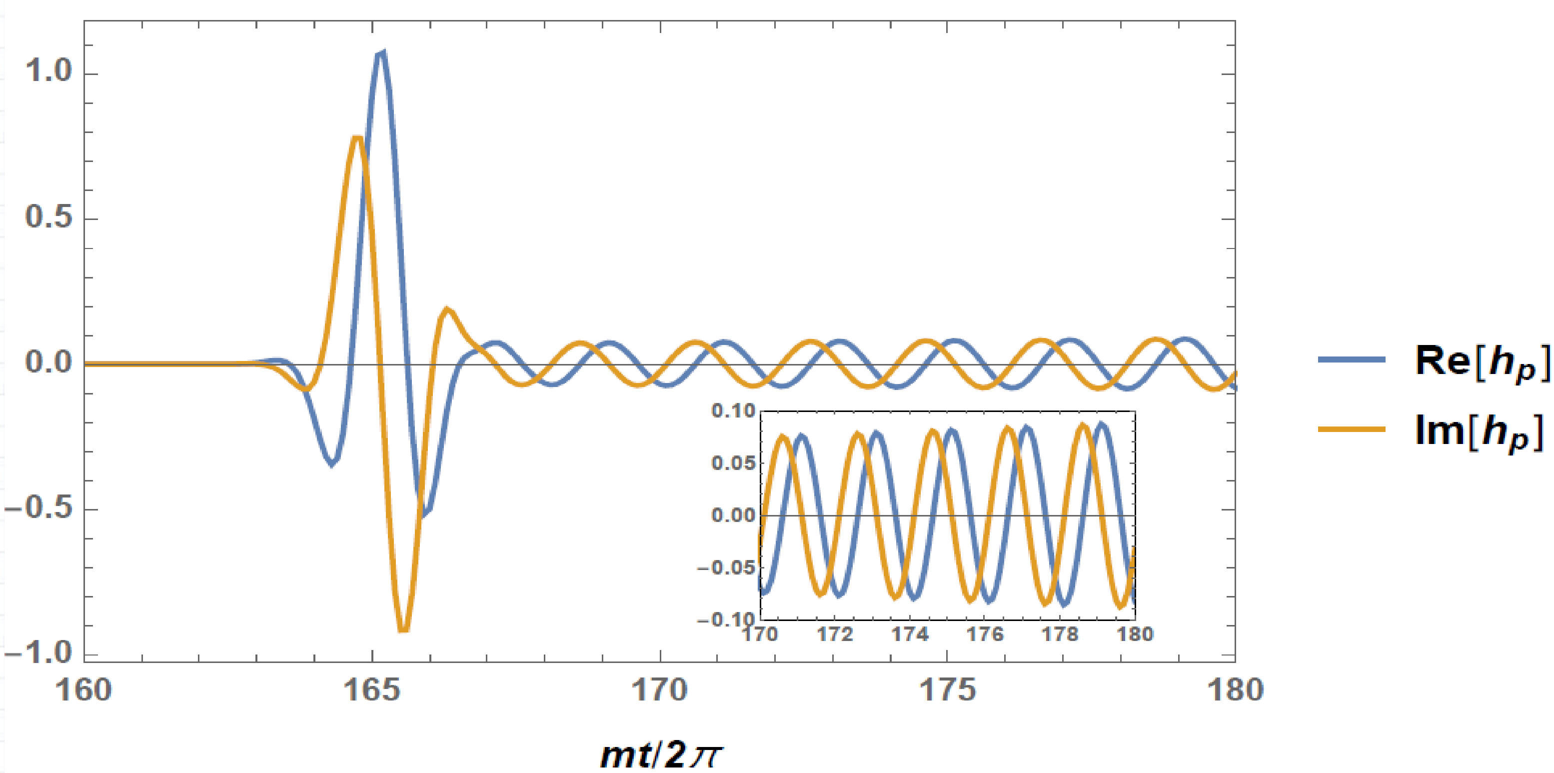
Causal amplification



GW packet itself is not amplified much,
but it gets a long growing tail behind it.

Numerical results

How we observe?



GW packet itself is not amplified much,
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[TF, Obata, Tanaka & Yamada in prep]

Axion Coherence

Axion oscillation is NOT coherent over a scale $\lambda_c \approx (mv)^{-1}$.

$\phi(t,x) = \Phi(x)\cos\big(mt + \delta(x)\big)$ and $\delta(x)$ varies

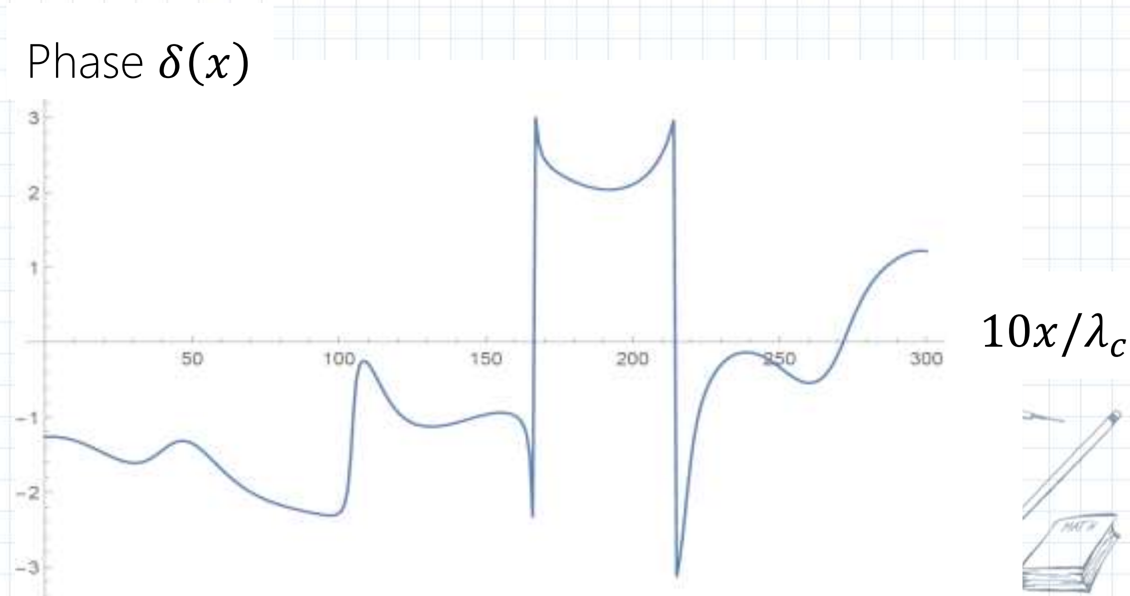
In our formulation

$\phi_0(x) = \Phi(x) e^{i\delta(x)}$

$$\varepsilon(x) \equiv \frac{\sqrt{2}\ell_{\rm dCS}^2}{M_{\rm Pl}} m^2 \phi_0(x)$$

Account for $\epsilon(x)$!

A simple simulation inside Milky way galaxy ($v \approx 10^{-3}$)



Re-analysis on resonance

Ansatz in the varying amplitude & phase case ($\epsilon \neq const.$)

$$h_{\mathrm{R/L}}(t,x) = \left(A(x)\,e^{-imt/2} + B(x)\,e^{imt/2}\right) e^{-i\delta\omega(t-x)+im/2x}$$

EoM yields our master equation w.r.t. $X \equiv A'/A$

$$X' + X^2 + \left(2i\delta\omega - \frac{\varepsilon'}{\varepsilon}\right) X + \frac{m^2}{64}|\varepsilon|^2 = 0$$

We found a consistent analytic solution for $|\epsilon| \ll 1$

$$X(x) = \frac{m^2}{64}\int_x^{x_{\mathrm{end}}} \mathrm{d}y\,\varepsilon(x)\varepsilon^*(y)e^{-2i\delta\omega(x-y)}$$

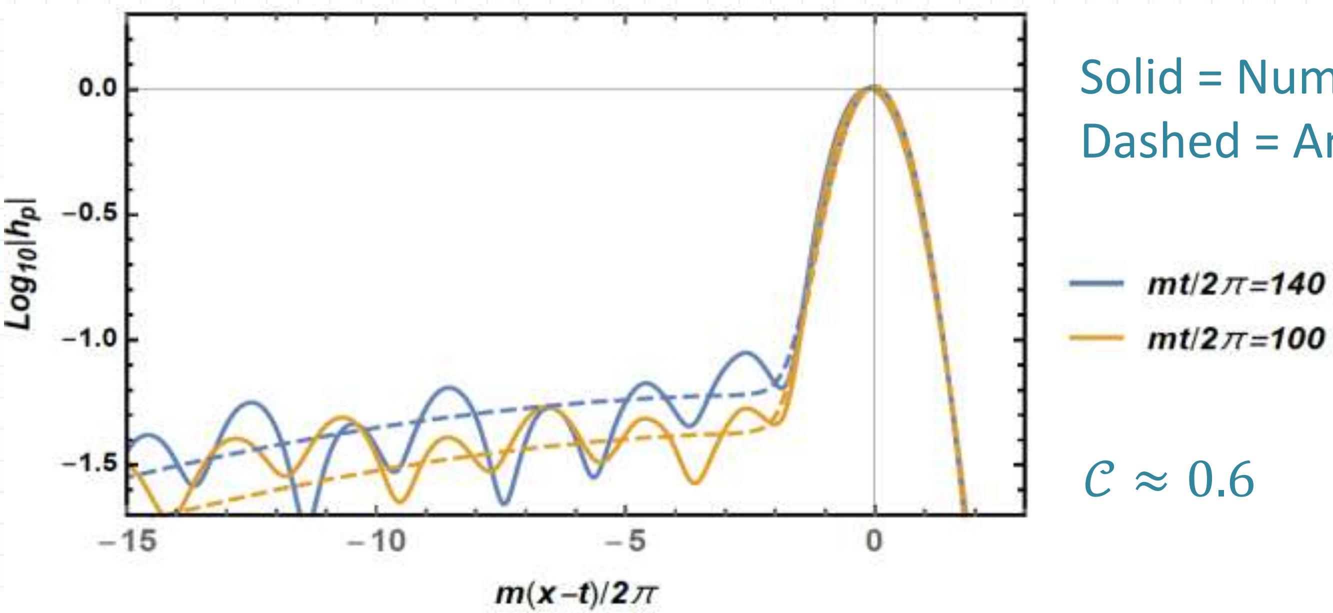
Evaluate it with a Gaussian ϵ $\langle\varepsilon(x)\varepsilon^*(y)\rangle = |\bar{\varepsilon}|^2 \exp\left[-\frac{(x-y)^2}{2\lambda_{\mathrm{coh}}^2}\right]$

Our on-going work

Incoherent amplification

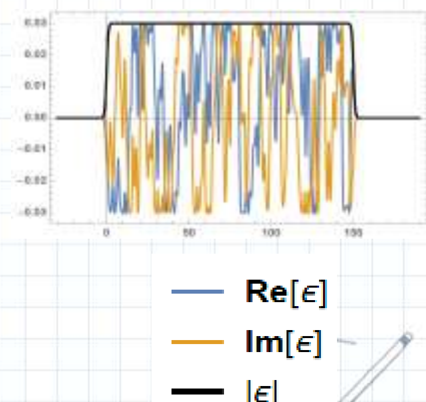
$$\langle h_{\rm packet}\rangle \propto \frac{1}{\sqrt{2}\lambda_{\rm coh}} e^{-\frac{1}{2}im(t-x)} \int {\rm d}\Omega\, e^{-\frac{\Omega^2}{4K^2\lambda_{\rm coh}^2}}\, e^{-i\frac{t-x}{\sqrt{2}\lambda_{\rm coh}}\Omega}\, e^{\mathcal{C}e^{-\Omega^2}(1+{\rm erf}(i\Omega))} \xrightarrow{\mathcal{C}\gg 1} {\rm e}^{3.25\mathcal{C}}$$

$\mathcal{C} \equiv \frac{\sqrt{\pi^3/2}}{32}\frac{mL\varepsilon^2}{v}$ controls the amplification.



Solid = Numerical
Dashed = Analytic

$\mathcal{C} \approx 0.6$



Analytic and numerical results are in good agreement

How large is C?

Axion DM starts oscillating at $m = H(t_{\rm osc})$ and then ϕ is homogeneous.

After that, the amplitude decreases and the incoherence develops.

Amplification is most efficient at $t_{\rm osc}$ in the early universe!?

Require the backreaction not to alter the Axion DM dynamics.

GW Amplification $h_{\rm after} = e^{N_*} h_{\rm before}$ is mild $N_* < 10$ at $H = H_*$

Then we can estimate the parameter $\mathcal{C}$ at present

$$\mathcal{C} \approx 3 \times 10^{-2}\, \Omega_A^{-1}(t_{\rm eq}) \left(\frac{N_*}{10}\right) \left(\frac{L}{10\,\mathrm{kpc}}\right) \left(\frac{\rho_{\rm DM}}{0.3\,\mathrm{GeV}/\,\mathrm{cm}^3}\right) \left(\frac{v}{7 \times 10^{-4}}\right)^{-1} \left(\frac{H_*}{H(t_{\rm eq})}\right)^{-1/2}$$

No significant amplification by Axion DM....

Way out??

If the axion is not DM, there may be a chance to have great amplifications.

Conditions

- Axion has to start oscillating well after $m = H$
- Non-DM axion forms clouds

Preliminary estimate

$$\mathcal{C} = \frac{1}{2}\left(\frac{3\sqrt{\pi^7/2}N_*^2\,(m\ell_{\rm dCS})^4}{(L_1 H_*)^4}\right)^{1/3} \approx 10\left(\frac{N_*}{10}\right)^{2/3}(m\ell_{\rm dCS})^{4/3}\,(L_1 H_*)^{-4/3}$$

Outline of Talk

1. Introduction
2. Protoplanetary Disk (Photon)
3. GW Interferometer (Photon)
4. GW Amplification (Graviton)
5. Summary

Summary

- Axion DM may be coupled to photon & graviton

- Photon coupling causes Birefringence

  Observations of protoplanetary disks are useful
  to search for ultralight ADM ($\mathbf{m \sim 10^{-22}}$)

  GW interferometer are sensitive to ADM
  with $\mathbf{10^{-16}eV < m < 10^{-12}eV}$

- Graviton coupling causes GW amplification

  GW packet itself is not enhanced but gets a amplified tail

  Considering cosmology, ADM won't cause significant amplification.

THE THEME
OF CHAPTER IS...

Thank you！