PRESENTATION

Hunting ALPs

by Observations and Experiments

Tomohiro Fujita
(Waseda Inst. Adv. Study)

TF, Murai, Nakatsuka & Tsujikawa PRD**103,** 043509(2021)
Obata, TF & Michimura PRL**121,**161301(2018)
TF, Tazaki & Toma PRL**122,**191101(2019)
Nagano, TF, Obata & Michimura PRL**123,**111301(2019)

10th. May. 2021 @Nagoya E-lab Seminar

WIAS
早稲田大学高等研究所
Waseda Institute for Advanced Study

Today’s menu

Normal Seminar

One plate meal

Today’s Seminar

Buffet

In the Buffet dishes, I use the same spice

Axion Birefringence

Outline of Talk

1. Introduction of ALPs

2. ALP Dark Energy

3. ALP Dark Matter

4. QCD Axion Search by Astro. Obs.

Outline of Talk

1. Introduction of ALPs
2. ALP Dark Energy
3. ALP Dark Matter
4. QCD Axion Search by Astro. Obs.

(Conventional) motivation of ALPs

- QCD axion
  - Strong CP problem:

Baker, et al. (2006)

$$\mathcal{L}_{\theta_{QCD}} = \frac{\theta_{QCD}}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \theta_{QCD} \lesssim 10^{-10}$$

by the electric dipole moment of neutron

  - One of the solutions is QCD axion:

$$\mathcal{L}_{\theta_{QCD}} \to \left(\theta_{QCD} + \frac{\phi}{f}\right)\frac{1}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Peccei&Quinn. (1977)
Winberg(1978),Wilczek (1978)

- Axion-like particles by String Axiverse

"*String theory predicts many ultralight axions*"

Arvanitaki+ (2009)

  - ALPs have mass nonperturbatively, which is exponentially suppressed:

$$m_\phi^2 \propto \left(\frac{\mu^4}{f^2}\right)e^{-S_{\mathrm{inst}}}$$

Marsh (2015)

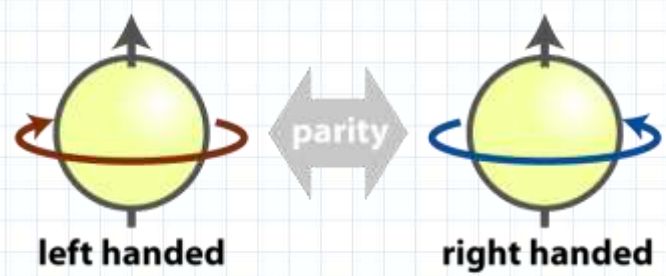
  - ALP as Dark Matter: $10^{-22}\mathrm{eV} \lesssim m_\phi$
  - ALP as Dark Energy: $m_\phi \lesssim H_0 \sim 10^{-33}\mathrm{eV}$

Observational hints motivate the studies of ALP!

What characterizes ALPs?

- ALP can be very light ($m \lll 1\mathrm{eV}$) by its shift sym.

- ALP breaks parity



- ALP may be coupled to photon!!

Useful to Search for it

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

Axion-Photon Coupling

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New terms!

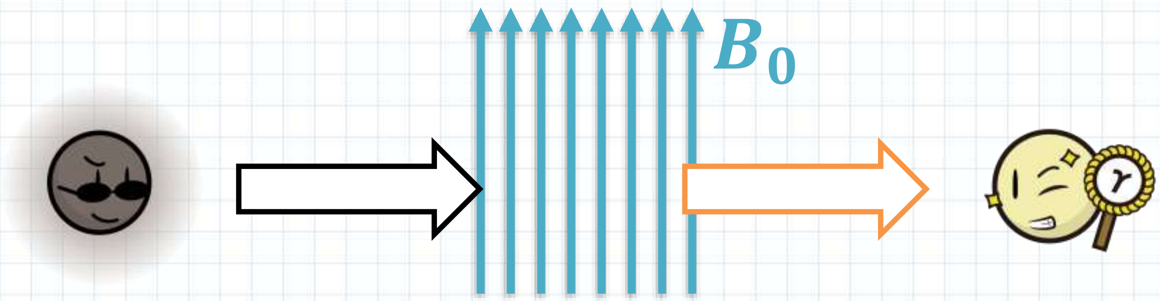
Conventionally constant magnetic field is introduced

Axion-Photon Conversion

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

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

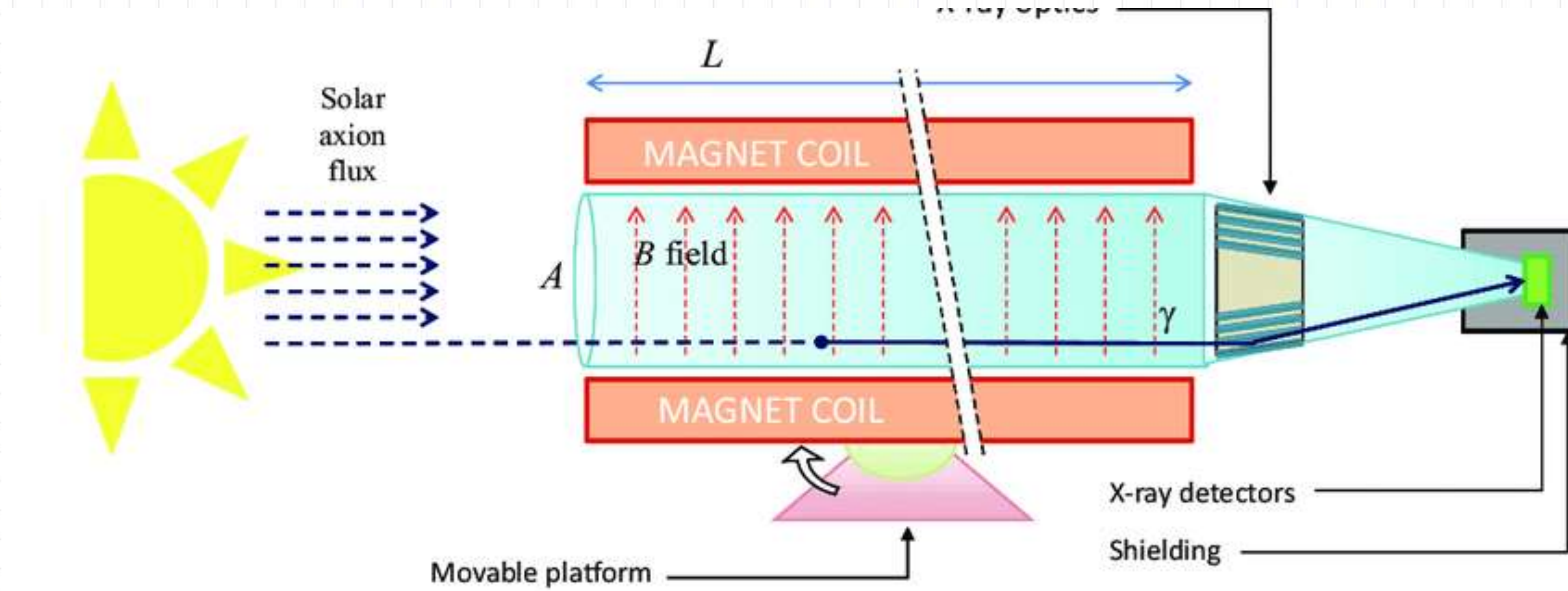
Axion: $$\left[\partial_t^2 - \partial_i^2 + m^2\right]\phi = -g\boldsymbol{B_0}\cdot\dot{\boldsymbol{A}}$$



introduction

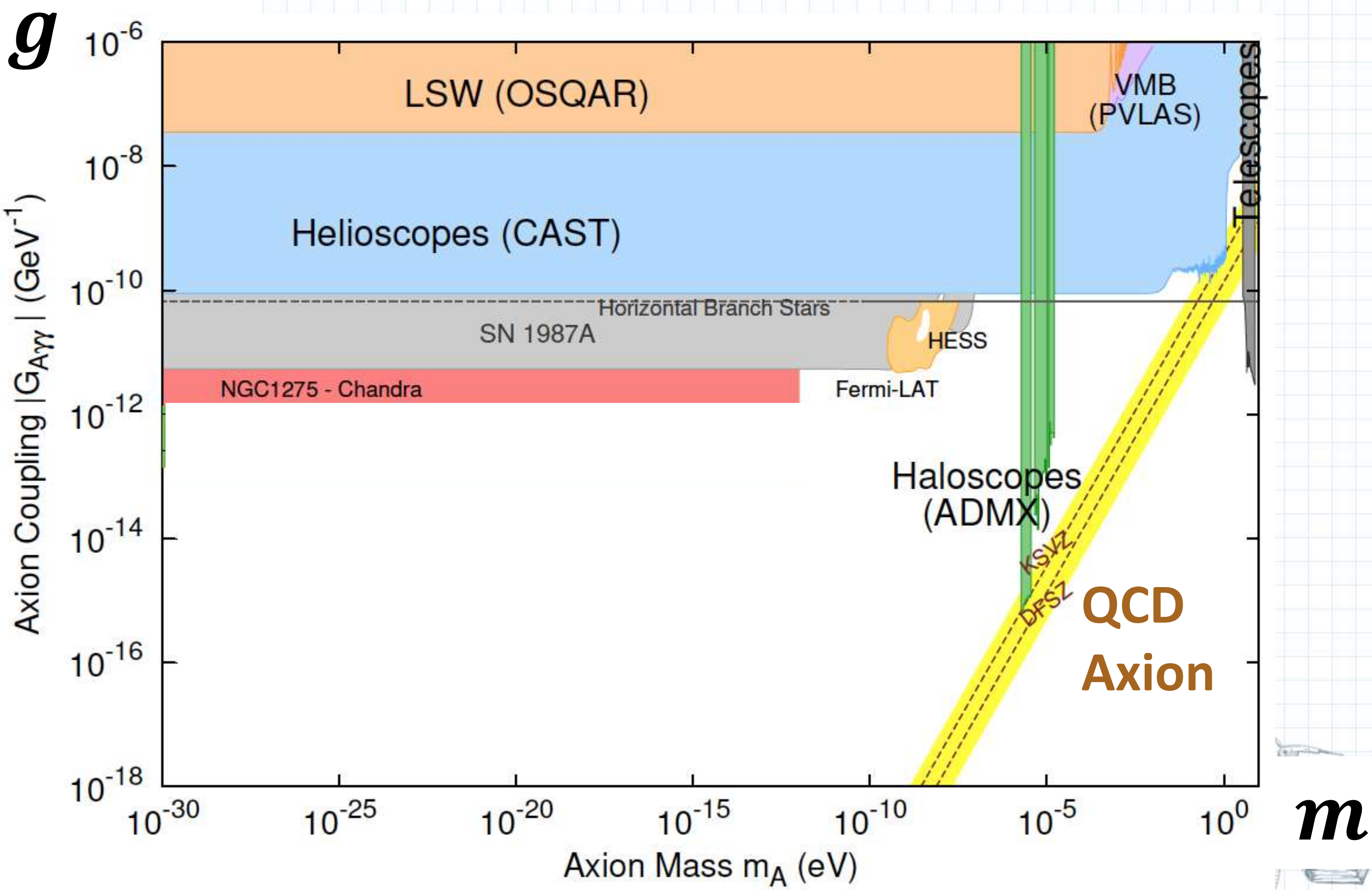
Experiments with $a\gamma$ conversion

- Axion Helioscope

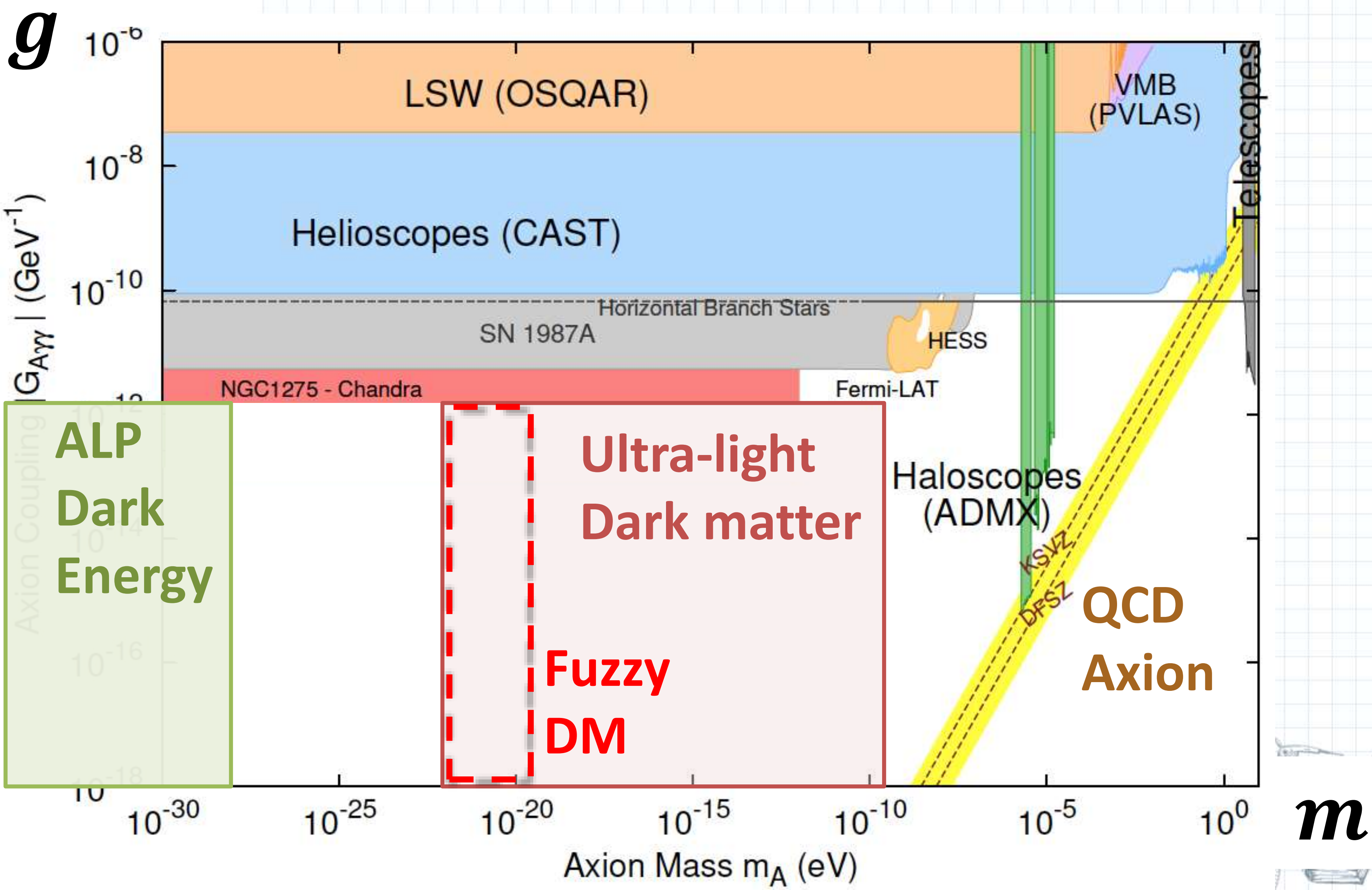


[Irastorza&Redondo(2018)]

Current constraint



Current constraint



New idea

How can we detect

Axion like particles?

Axion-Photon Coupling

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

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

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

New terms!

Anything other than magnetic fields?

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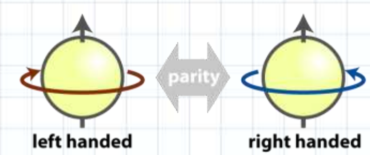
$i\hat{\boldsymbol{k}} \times \boldsymbol{e}_{L,R} = \pm\, \boldsymbol{e}_{L,R}$

⇒ 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!

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 → $t+T$

With ADM BG phase velocity are different, ⇒ polarization plane rotates

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

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

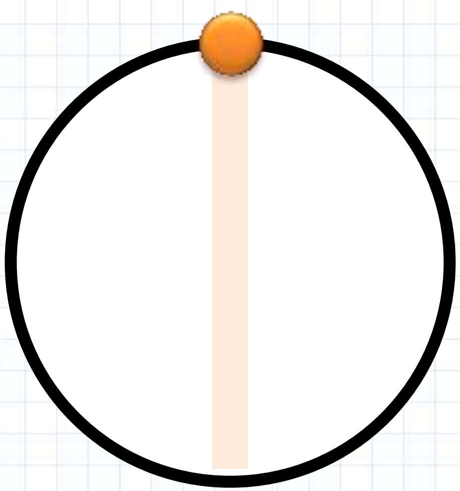
Birefringence

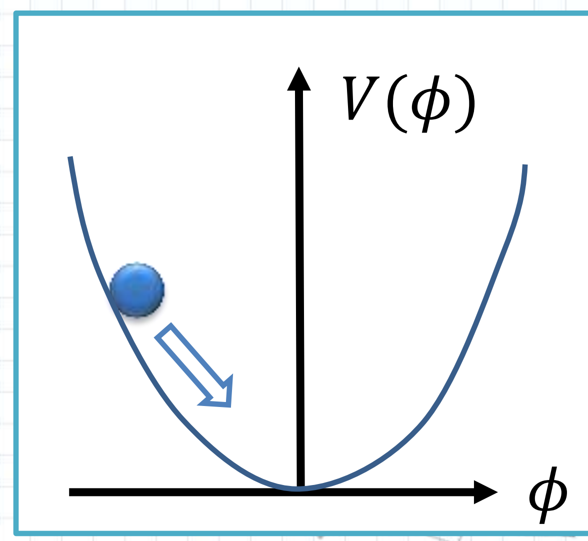
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- 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





Birefringence

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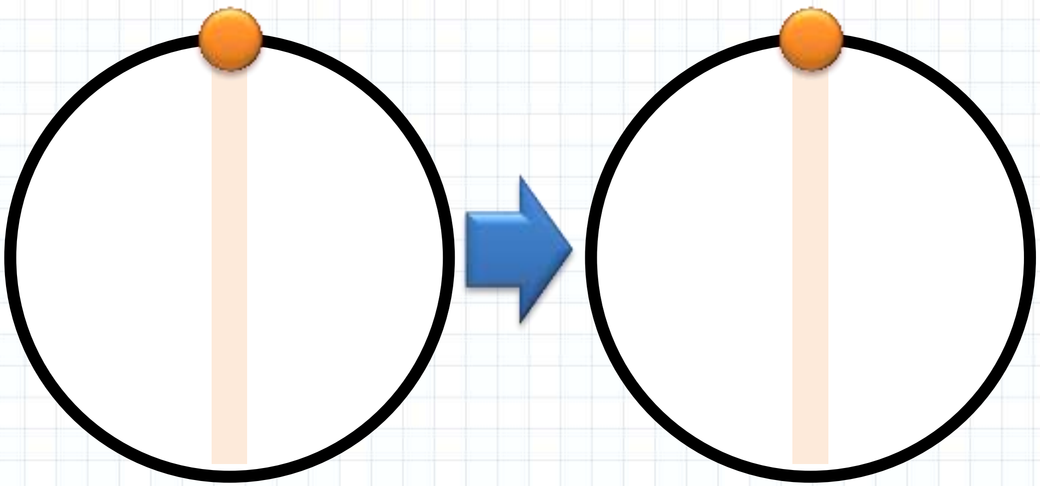

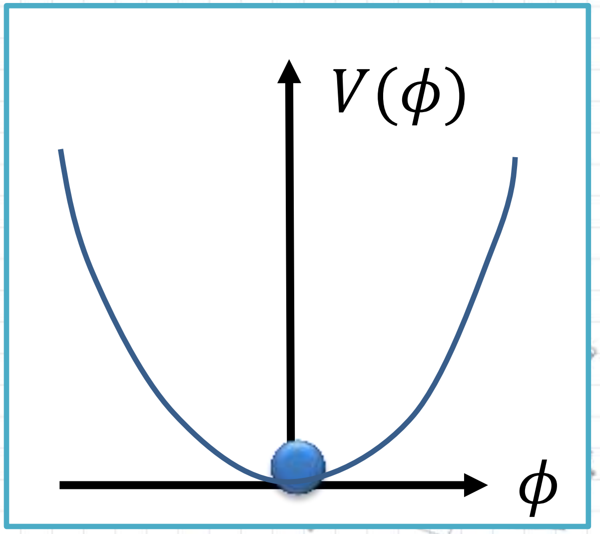

Birefringence

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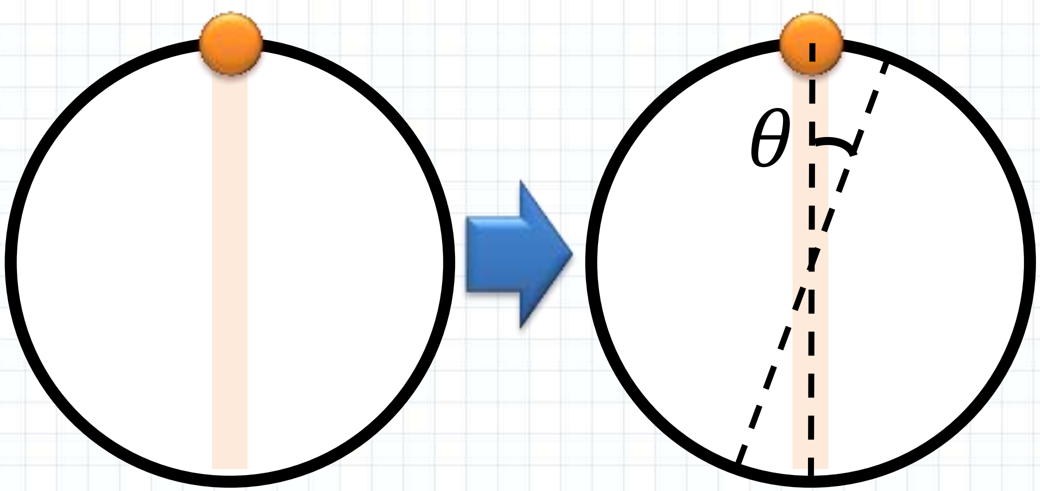

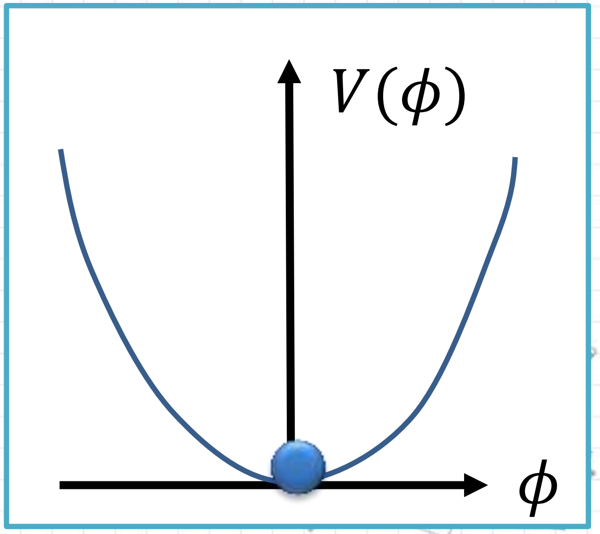

Outline of Talk

1. Introduction of ALPs
2. ALP Dark Energy
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4. QCD Axion Search by Astro. Obs.

The standard cosmology

ΛCDM Paradigm

- All the cosmological observations are explained by the DE+DM universe. (but for the Hubble tension)

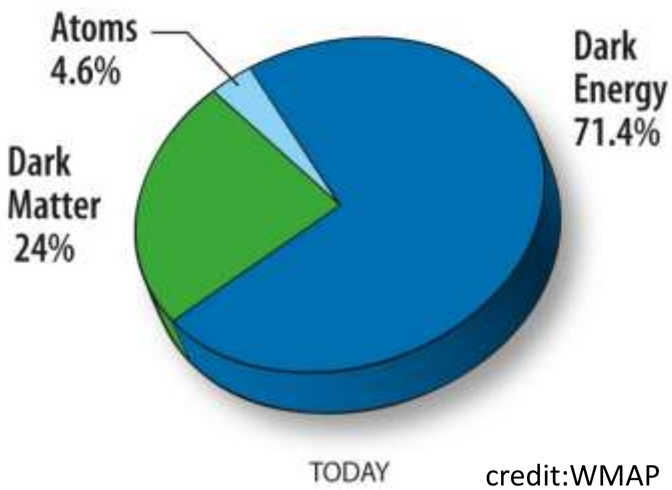
Dark Energy (DE)

- Measuring the current Hubble parameter indicates the accelerated expansion.
- Dynamics : constant or scalar potential $V(\phi)$ which slowly rolling

$$w \equiv \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}, \quad -1 \leq w < -0.95 \text{ (95\% C.L.)}$$

, [Planck2018]

Energy component of current universe



credit:WMAP

Review of Cosmic Birefringence

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami and Eiichiro Komatsu

Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

ABSTRACT

We search for evidence of parity-violating physics in the Planck 2018 polarization data and report on a new measurement of the cosmic birefringence angle β. The previous measurements are limited by the systematic uncertainty in the absolute polarization angles of the Planck detectors. We mitigate this systematic uncertainty completely by simultaneously determining β and the angle miscalibration using the observed cross-correlation of the E- and B-mode polarization of the cosmic microwave background and the Galactic foreground emission. We show that the systematic errors are effectively mitigated and achieve a factor-of-2 smaller uncertainty than the previous measurement, finding $\beta = 0.35 \pm 0.14$ deg (68% C.L.), which excludes $\beta = 0$ at 99.2% C.L. This corresponds to the statistical significance of 2.4σ.

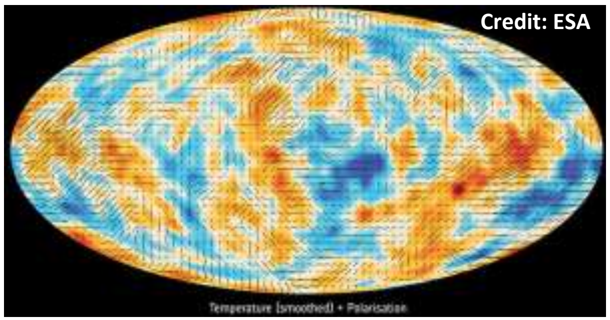
"cosmic birefringence angle β"
New signal?

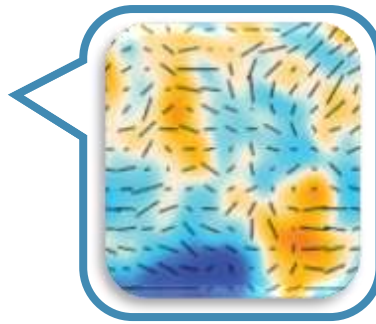
"finding β = 0.35 ± 0.14 deg (68% C.L.), which excludes β = 0 at **99.2% C.L.** This corresponds to the statistical significance of **2.4σ**."

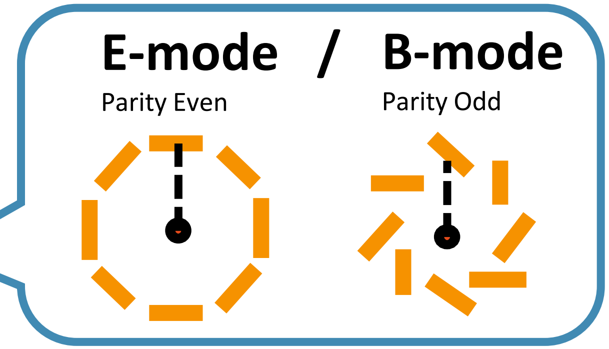
What is Cosmic Birefringence ?

Review of Cosmic Birefringence

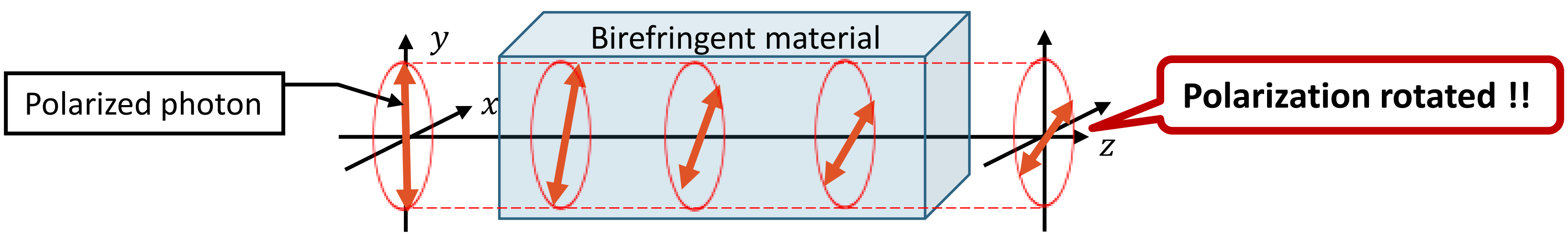
- Polarization signal in Cosmic Microwave Background (CMB)







- Birefringent material rotates direction of polarization

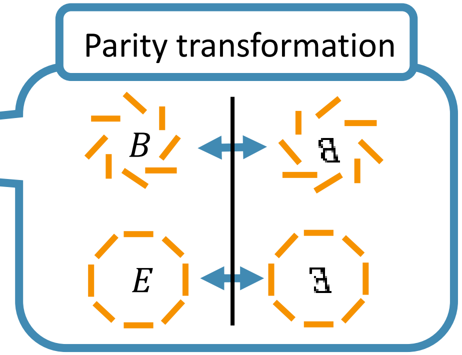


cosmic birefringence = polarization rotation signal

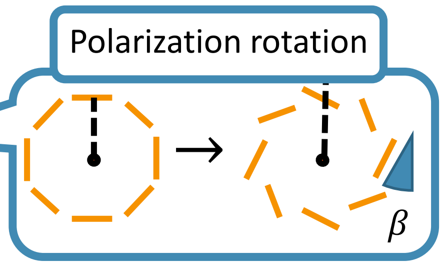
How to measure ?

Review of Cosmic Birefringence

- W/o cosmic birefringence, *parity* is conserved,
  - Parity of B-mode: $\mathrm{P}(B) = -B$, E-mode: $\mathrm{P}(E) = +E$
  - $\mathrm{P}(\langle E_l B_{l'} \rangle) = -\langle E_l B_{l'} \rangle$, so when parity is conserved,
    $\langle E_l B_{l'} \rangle = \mathrm{P}(\langle E_l B_{l'} \rangle) = 0$

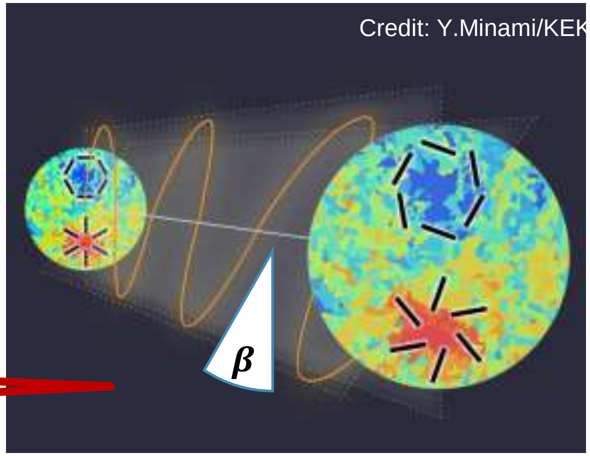


- With Cosmic Birefringence,
  - Mixing E-mode to B-mode



  - Parity violating $\langle E_l B_{l'} \rangle$ is produced
    $$\langle E_l B_l \rangle = \frac{1}{2}(\langle E_l E_l \rangle - \langle B_l B_l \rangle)\sin(4\beta)$$

Minami&Komatsu reported rotation angle
β = 0.35 $\pm$ 0.14 deg



CMB Birefringence

How to explain

this observation?

Axion causes CMB Biref.

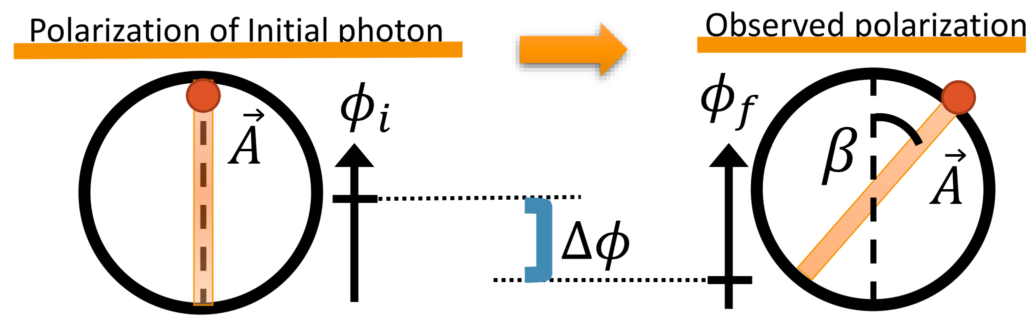
- Axion-Photon coupling

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$

Polarization rotation angle

$$\beta = \frac{g}{2}\int \mathrm{d}\eta \frac{\mathrm{d}\phi}{\mathrm{d}\,\eta} = \frac{g}{2}(\phi_f - \phi_i)$$

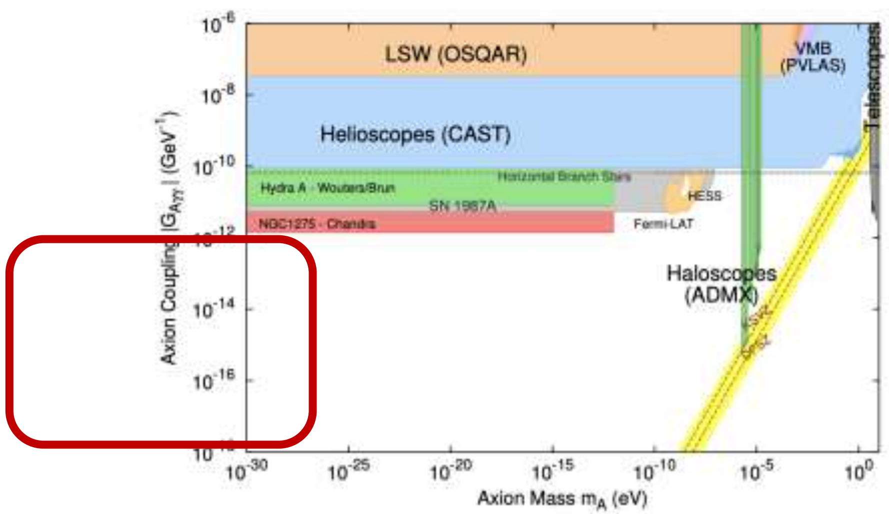
Harari&Sikivie (1992)



- Different mass range

What kind of axion can reproduce the observed β?

Lighter Axion



Axion causes CMB Biref.

How to calculate Cosmic Birefringence:

- In this talk, focus on background motion.

$$\phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x)$$

(perturbations $\delta\phi$ result in anisotropic birefringence signal: Pospelov, et.al., (2008), Caldwell, et.al., (2011))

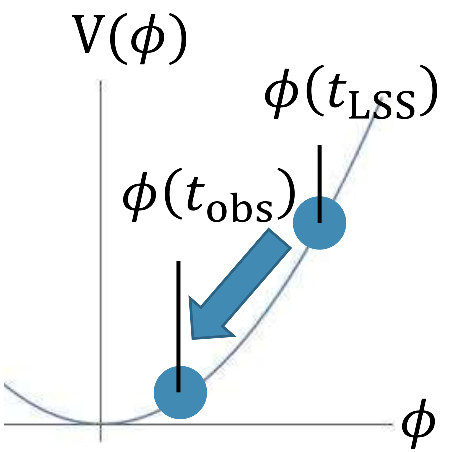
- If $V(\phi) = m^2\phi^2/2$, background field dynamics is governed by axion mass m

$$\ddot{\bar{\phi}} + 3H\dot{\bar{\phi}} + m^2\bar{\phi} = 0$$, H: Hubble expansion rate

- Axion-photon coupling

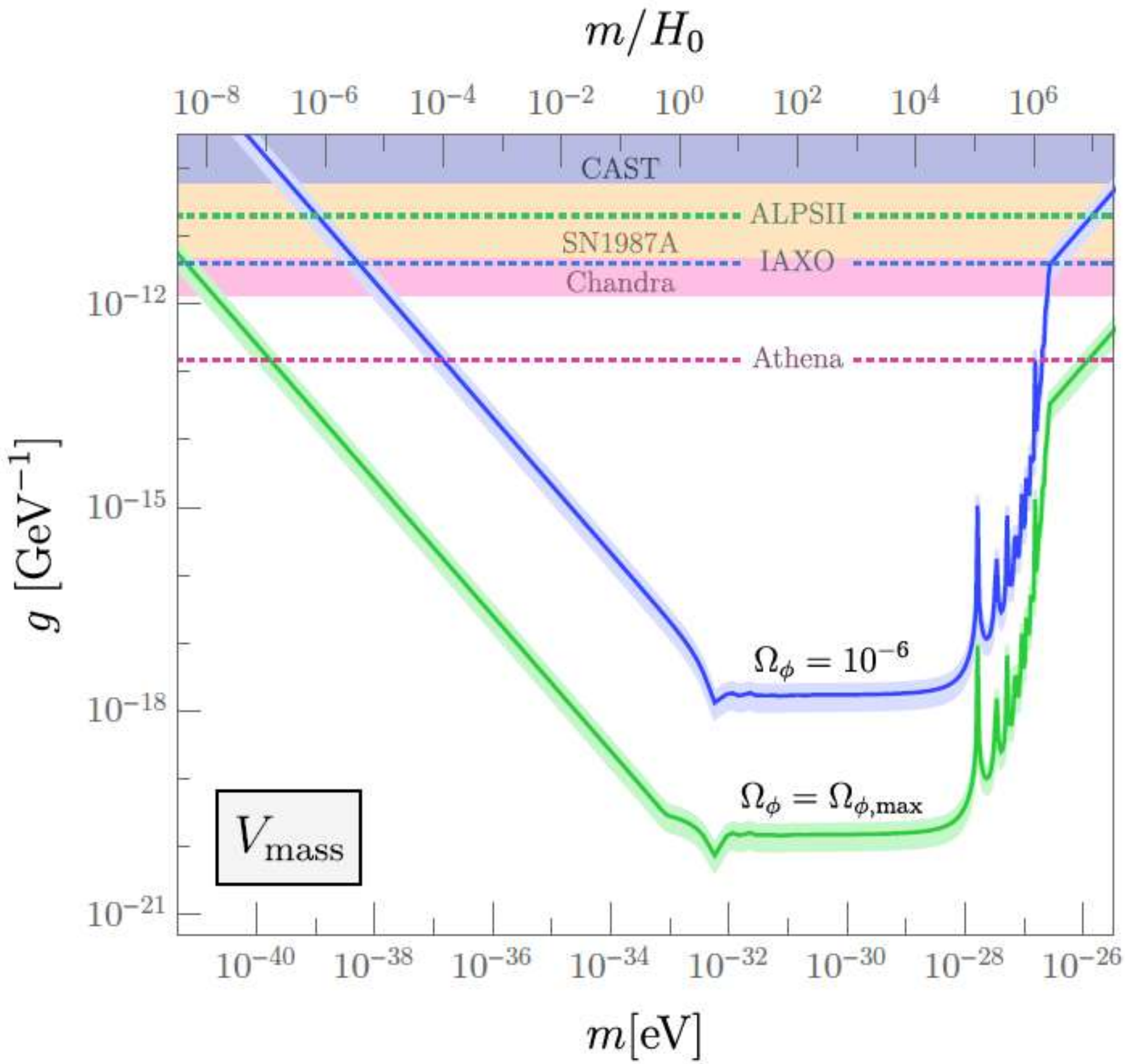
$$g = 2\,\beta(\,\bar{\phi}(t_0) - \bar{\phi}(t_{\rm LSS})\,)^{-1}$$, β = 0.35 deg

Hereafter, we write $\bar{\phi}$ as ϕ.



Determine axion-photon coupling g for a given m

Axion causes CMB Biref.



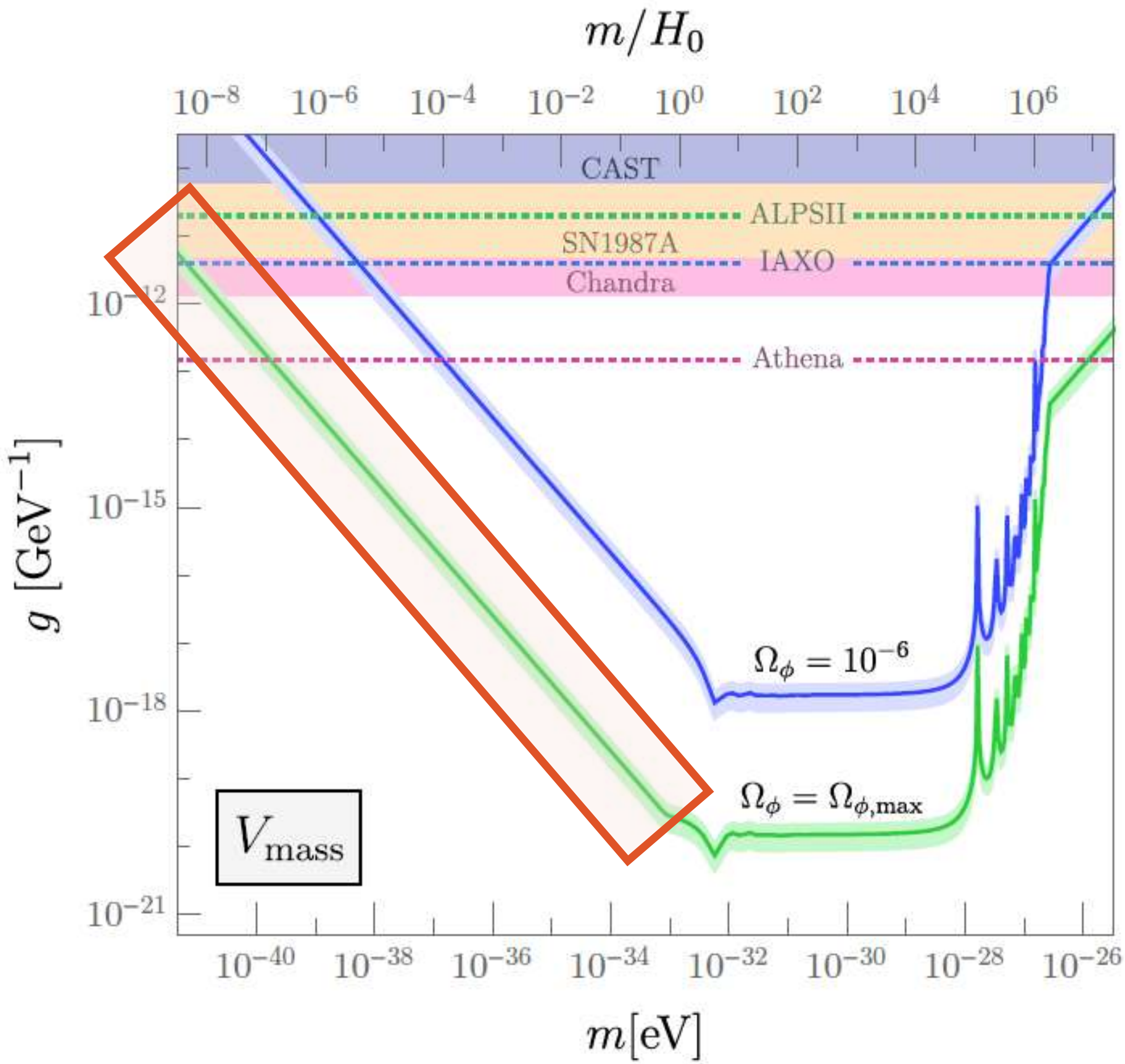
- Model: $V = m^2\phi^2/2$

  m : axion mass

  Ω_ϕ: present energy fraction

  On the lines, the rolling axion explains the observed β!!

Axion causes CMB Biref.



- Model: $V = m^2\phi^2/2$

  m : axion mass

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  On the lines, the rolling axion explains the observed β!!

- Axion dark energy

  For $m < 10^{-33}$eV, we find $\Omega_{\phi,\mathrm{max}} = \Omega_\Lambda$.

  The axion explains the current accelerated expansion, too!

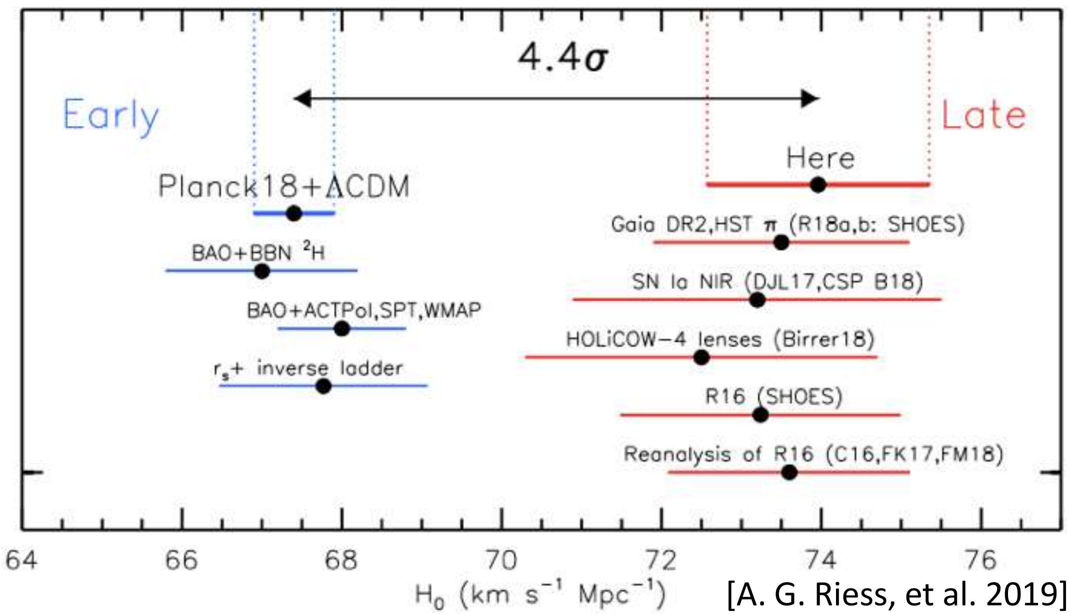
- We also study cos potential

  $$V_{\cos}(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

Hubble tension

Early Dark Energy (EDE) is scheme to alleviate “Hubble tension” problem.

- Discrepancy between:
  - local astrophysical measurements at low redshifts (cosmic distance ladder)
  - CMB and large scale structures



[A. G. Riess, et al. 2019]

Hubble Space Telescope

$74.03 \pm 1.42\,\mathrm{km/s/Mpc}$

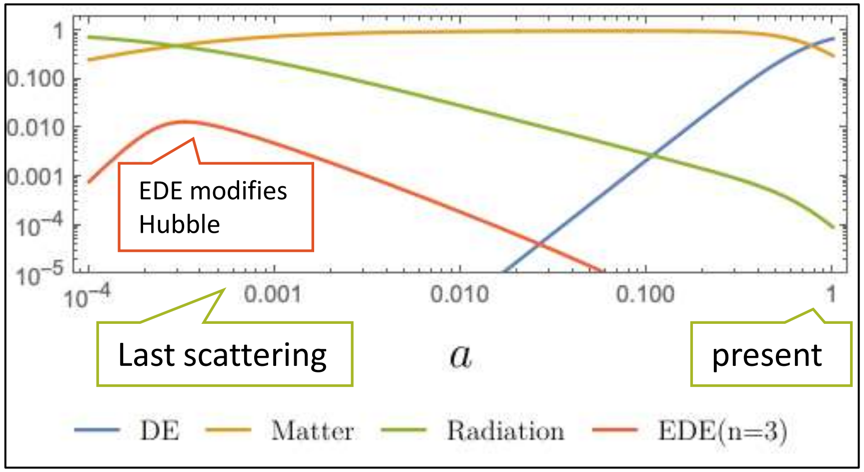
Planck 2018

$67.4 \pm 0.5\,\mathrm{km/s/Mpc}$

How does EDE work?

Early dark energy alleviates H_0 tension

Energy fraction of each component Ω_X

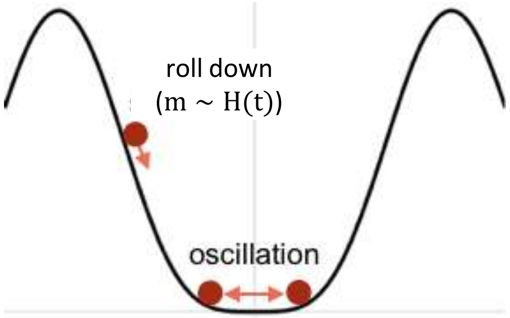


- EDE modify cosmology around last scattering.
  - Reduce sound horizon at last scattering.
  - Increase H_0 estimated by CMB observation
    $H_0 \sim\ 68 \rightarrow (70 - 72)[\mathrm{km} \cdot \mathrm{s/Mpc}]$

- How to achieve the above dynamics?

$$V_{\cos}^{(n)} \equiv m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n, \quad n \geq 2$$ [Poulin+ 2018]

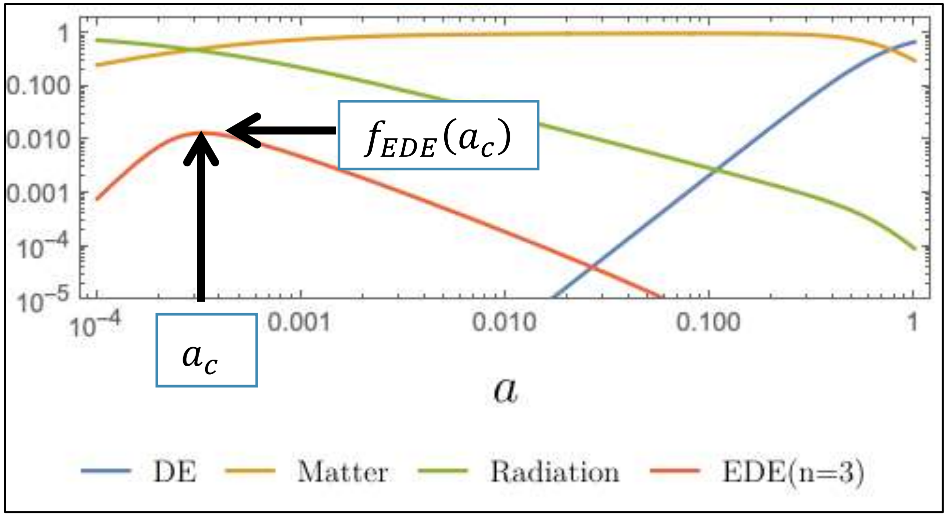
$$V_{\mathrm{RnR}}^{(n)}(\phi) = V_0 \left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^{2n} \quad n \geq 2$$ [Agrawal+ 2019]



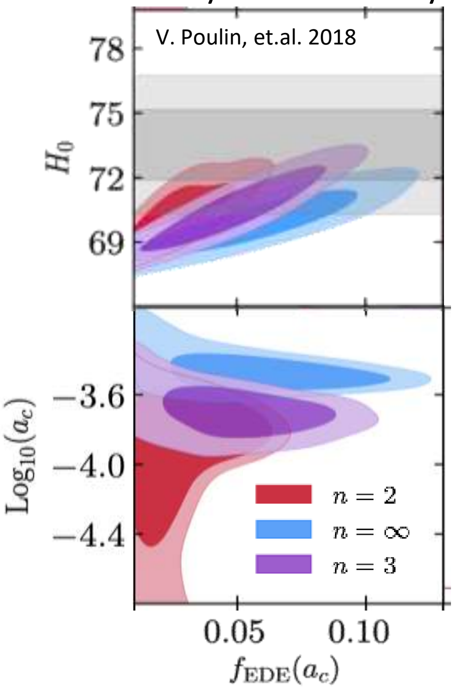
- Before oscillation, V is almost constant
- After oscillation, V decreases like or faster than radiation for $\mathrm{n} \geq 2$.

Early dark energy alleviates tension

- Required abundance of EDE   V. Poulin, et.al. (2018)
  - a_c: scale factor to start oscillation
  - $f_{EDE}(a_c) \equiv \rho_\phi(a_c)/\rho_{\rm tot}(a_c)$: energy fraction at a_c



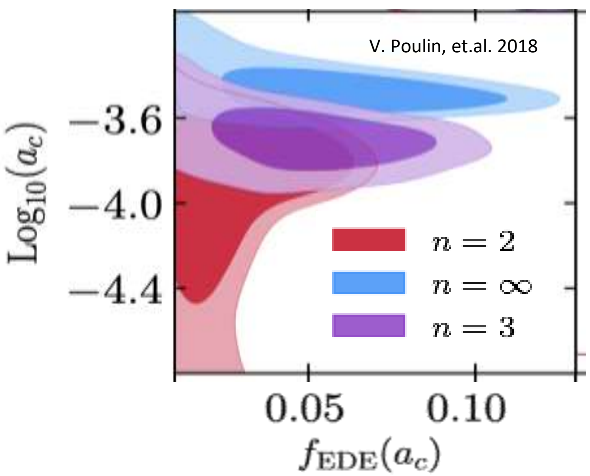
Probability distribution by MCMC

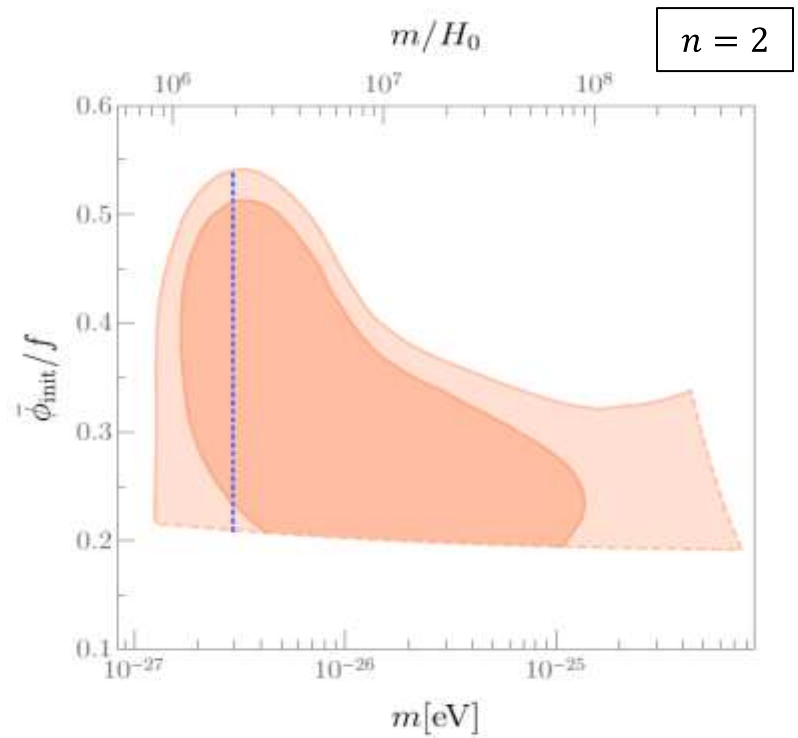


Does EDE produce cosmic birefringence?

Does EDE reproduce CMB Biref.?

- Cosmic birefringence of EDE
  - Let ϕ have the CS coupling to photon
  - Convert (f_{EDE}, a_c) into (ϕ_i, m_ϕ) by assuming $f = M_{pl}$

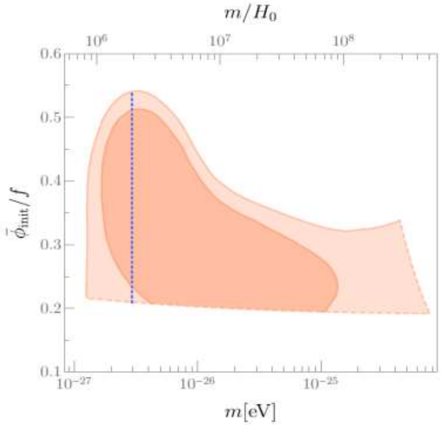




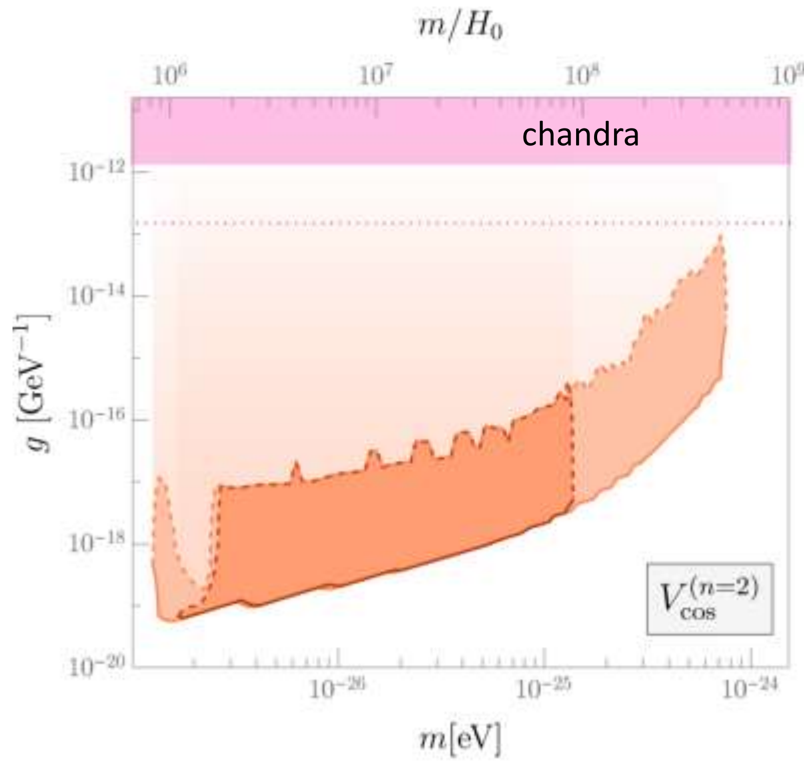
Allowed mass range is limited for EDE.

Does EDE reproduce CMB Biref.?

(ϕ_i, m)



(g, m)



The observed CMB birefringence

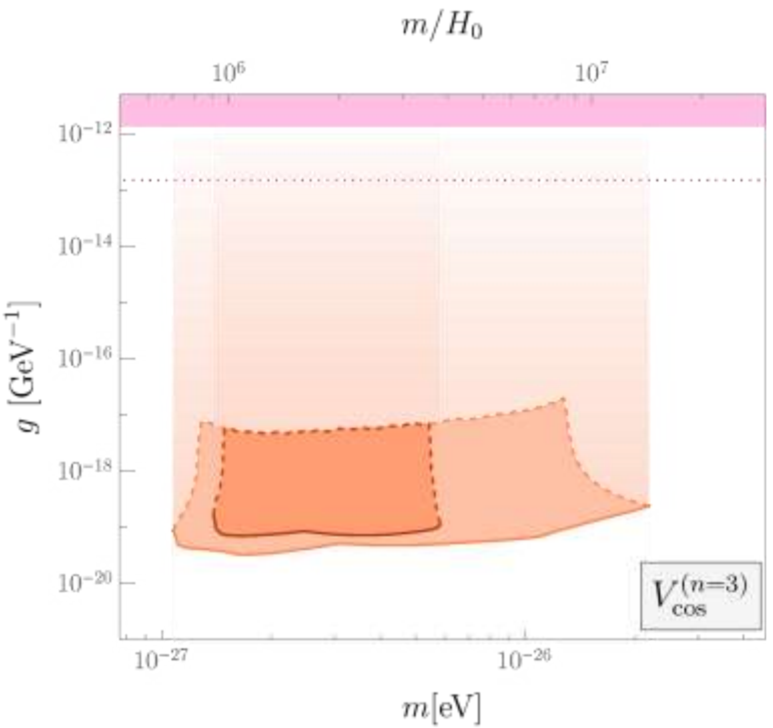
$$g = 2\,\beta(\,\phi(t_0) - \langle\phi\rangle_{LSS}\,)^{-1}$$

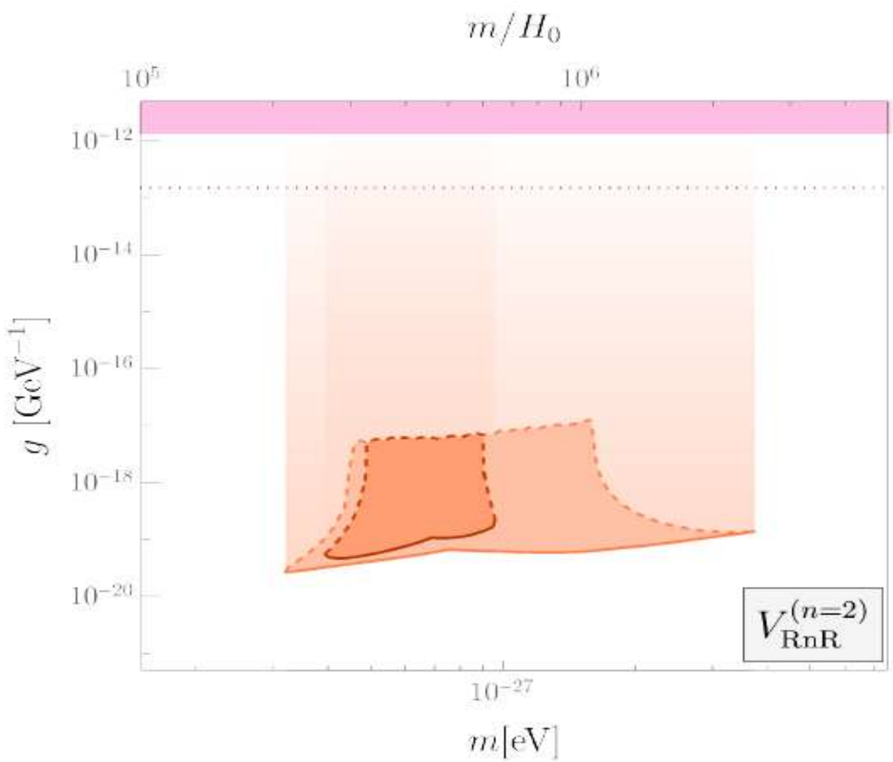
β = 0.35 deg

Does EDE reproduce CMB Biref.?

- Other models

n=2 case : $V_{\rm RnR}^{(n)}(\phi) = V_0 \left(\frac{\phi}{M_{\rm Pl}}\right)^{2n}$





n=3 case : $V_{\cos}^{(n)} \equiv m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$

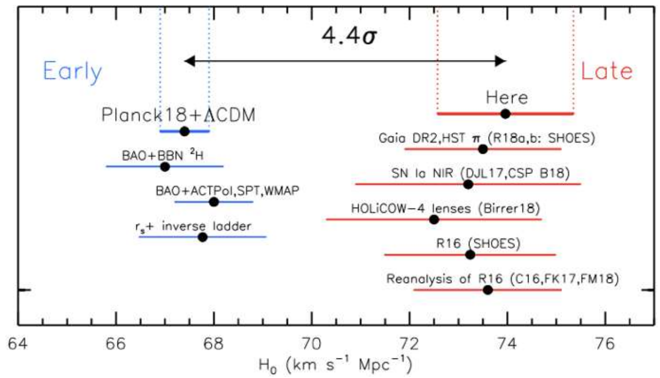
EDE models typically constrained
$g \sim (10^{-20} - 10^{-17})\ \mathrm{GeV}^{-1}$

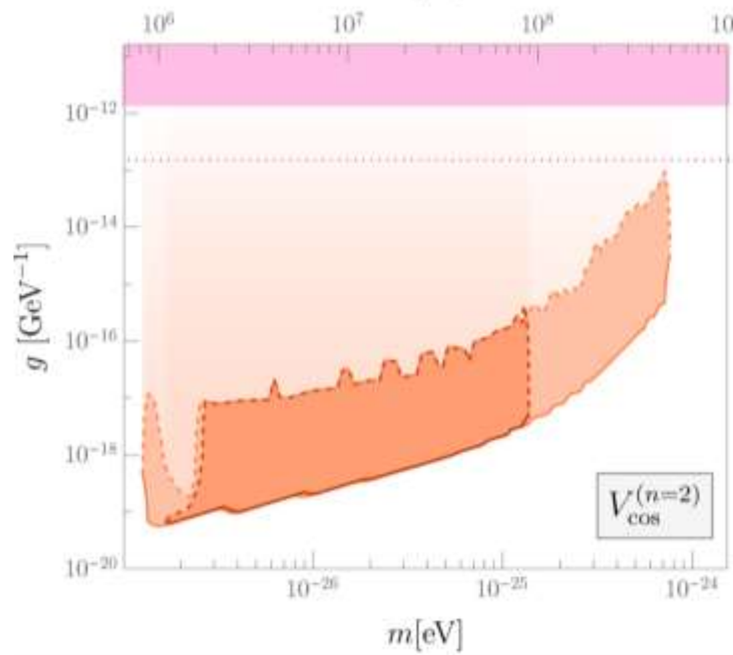
Summary of EDE as ALP

- EDE model is expected to alleviate "Hubble tension problem".

- ALP as EDE can explain reported rotation angle
$$\beta \sim 0.35 \text{ deg.}$$

- Typical coupling constant is expected to be
$$g \sim (10^{-20} - 10^{-17})\ \text{GeV}^{-1},$$
which means following nontrivial relation:
$$g \sim M_{Pl}^{-1}.$$





$$V_{\cos}^{(n)} \equiv m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n, \quad n \geq 2$$

Future Prospect of ALP EDE

In this talk, I focused on the background ϕ(t).

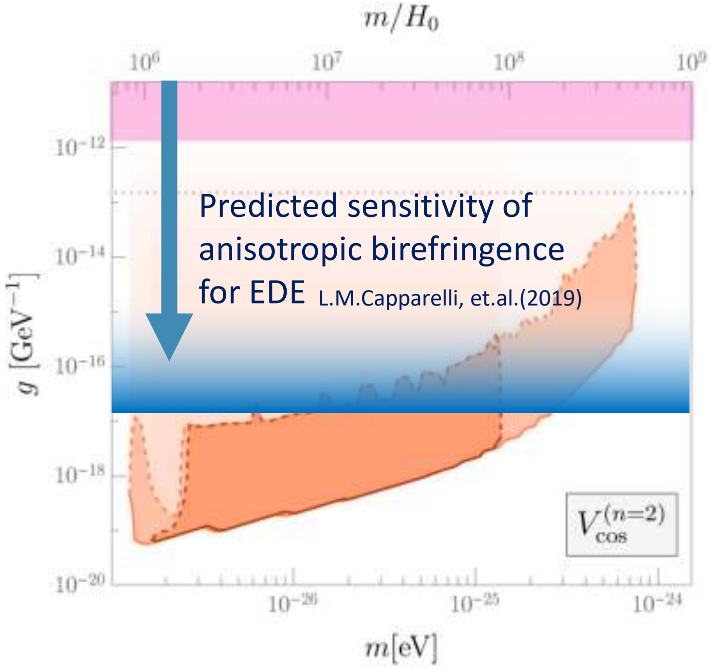
- fluctuation modes $\delta\phi(x,t)$
  - Hubble fluctuation during inflation
  - gravitational growth of adiabatic perturbation

- $\delta\phi_{obs}$: another source of isotropic rotation angle
- $\delta\phi_{LSS}$: direction dependent rotation angle (anisotropic cosmic birefringence)

Pospelov, et.al., (2008), Caldwell, et.al., (2011)

$$\delta\beta(\hat{n}) = \frac{g}{2}(-\delta\phi_{LSS}(\hat{n}))$$

Anisotropic cosmic birefringence is useful tool to investigate axion-photon coupling.



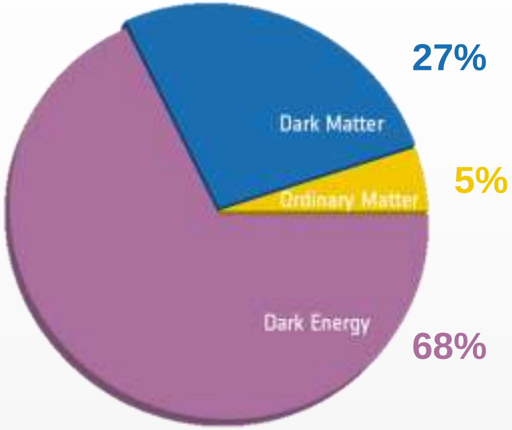
Outline of Talk

1. Introduction of ALPs
2. ALP Dark Energy
3. ALP Dark Matter
4. QCD Axion Search by Astro. Obs.

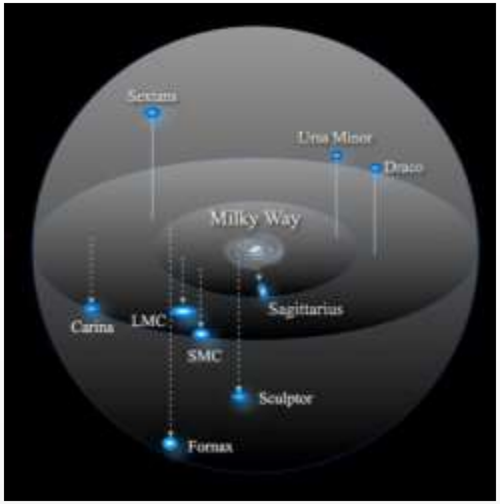
Who is Dark Matter?

Dark Matter

Cosmic pie chart

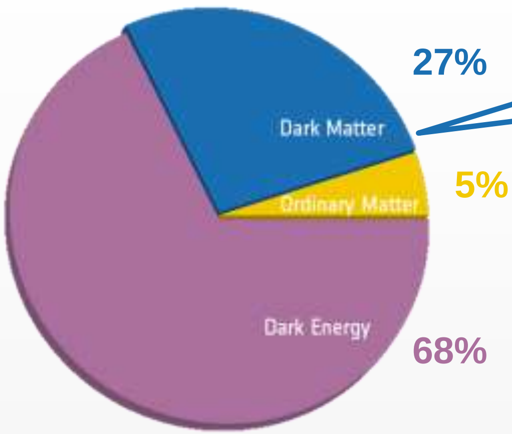


Local DM Halo



Dark Matter

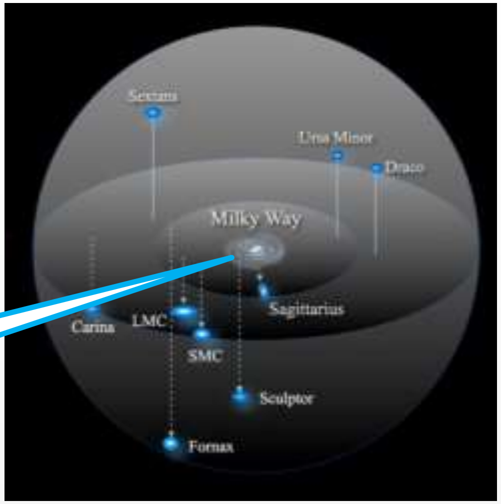
Cosmic pie chart



$$\bar{\rho}_{\rm DM} \approx 10^{-6} {\rm GeV/cm^3}$$

$$\rho_{\rm DM}^{\rm local} = 0.3 {\rm GeV/cm^3}$$

Local DM Halo



We live inside a high density DM halo!

DM candidates

Scalar

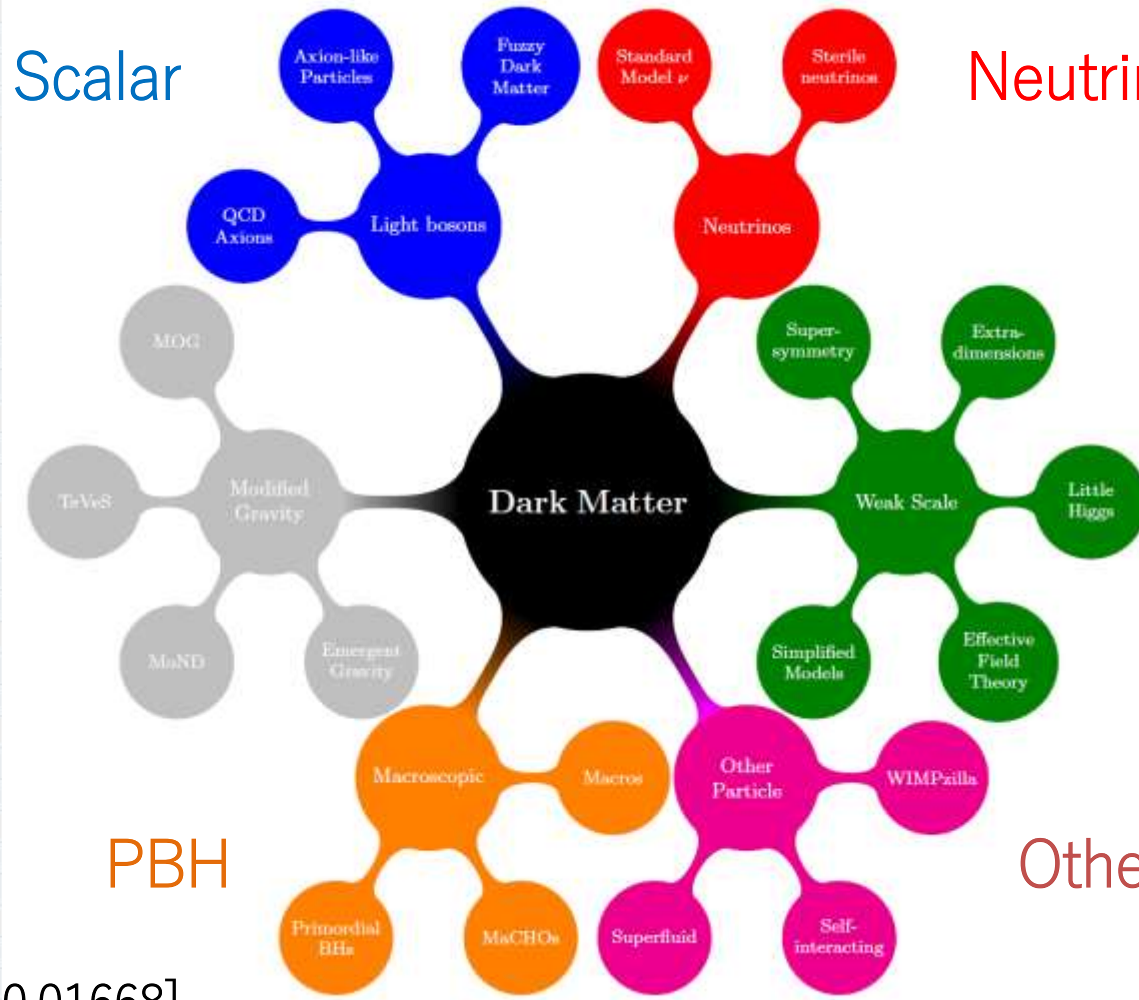
Neutrino

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

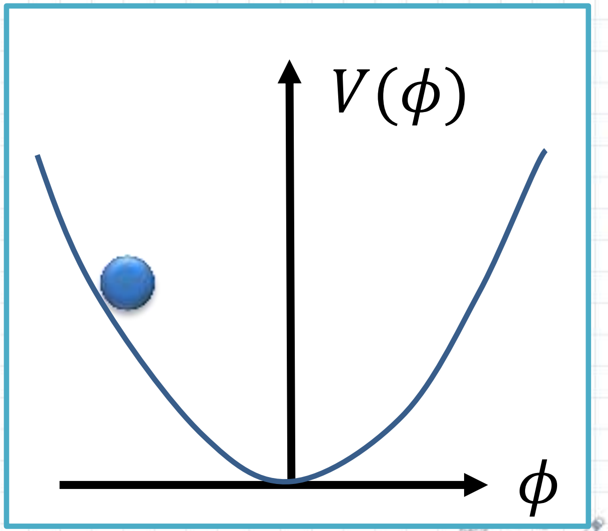
  (In this talk, we don't specify its production mechanism.)

- Oscillating Scalar Field: $m \gg H$

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

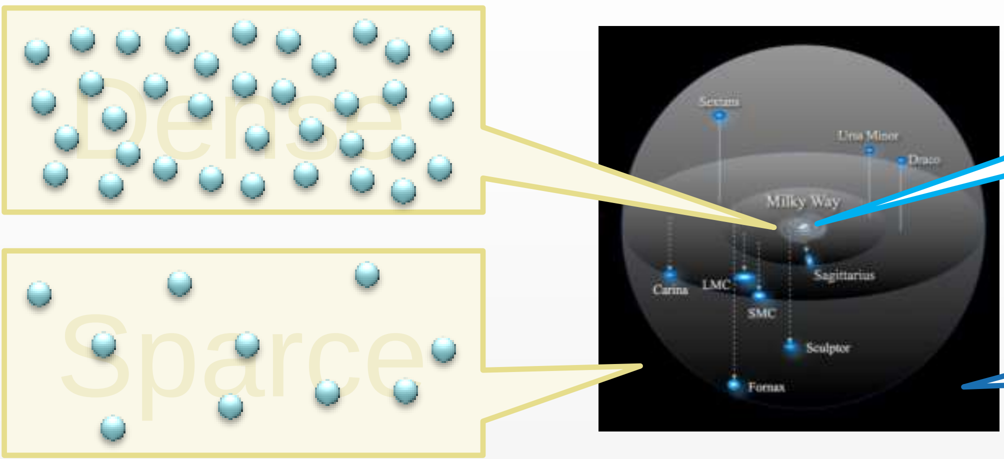
$$\rho_\phi \propto a^{-3}$$

What about perturbation?



DM density

WIMP

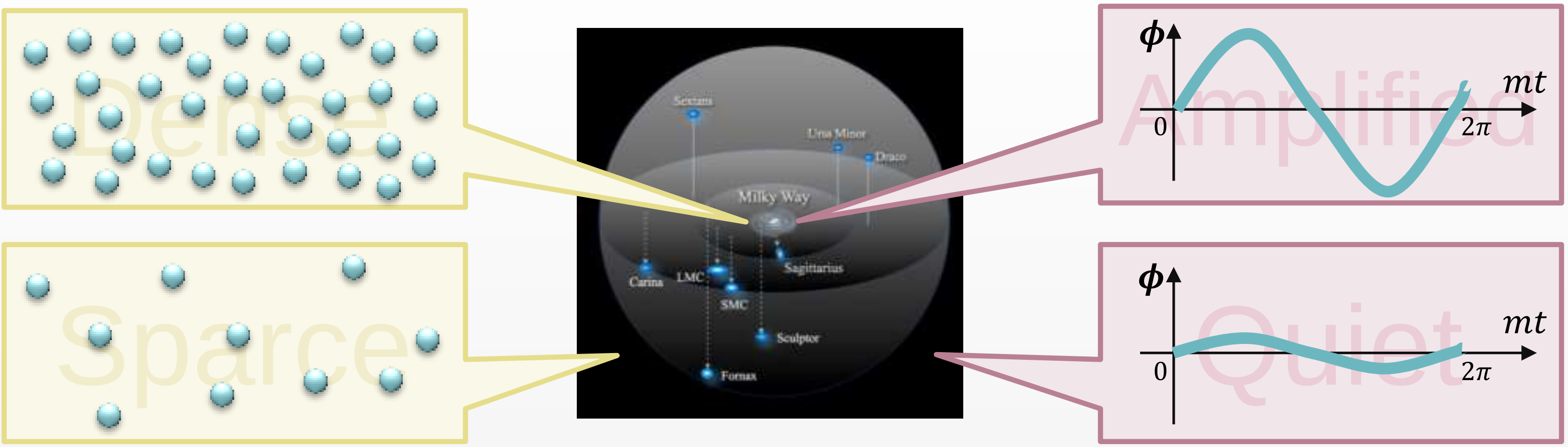


$\rho_{\mathrm{DM}}^{\mathrm{local}} = 0.3\mathrm{GeV/cm^3}$

$\bar{\rho}_{\mathrm{DM}} \approx 10^{-6}\mathrm{GeV/cm^3}$

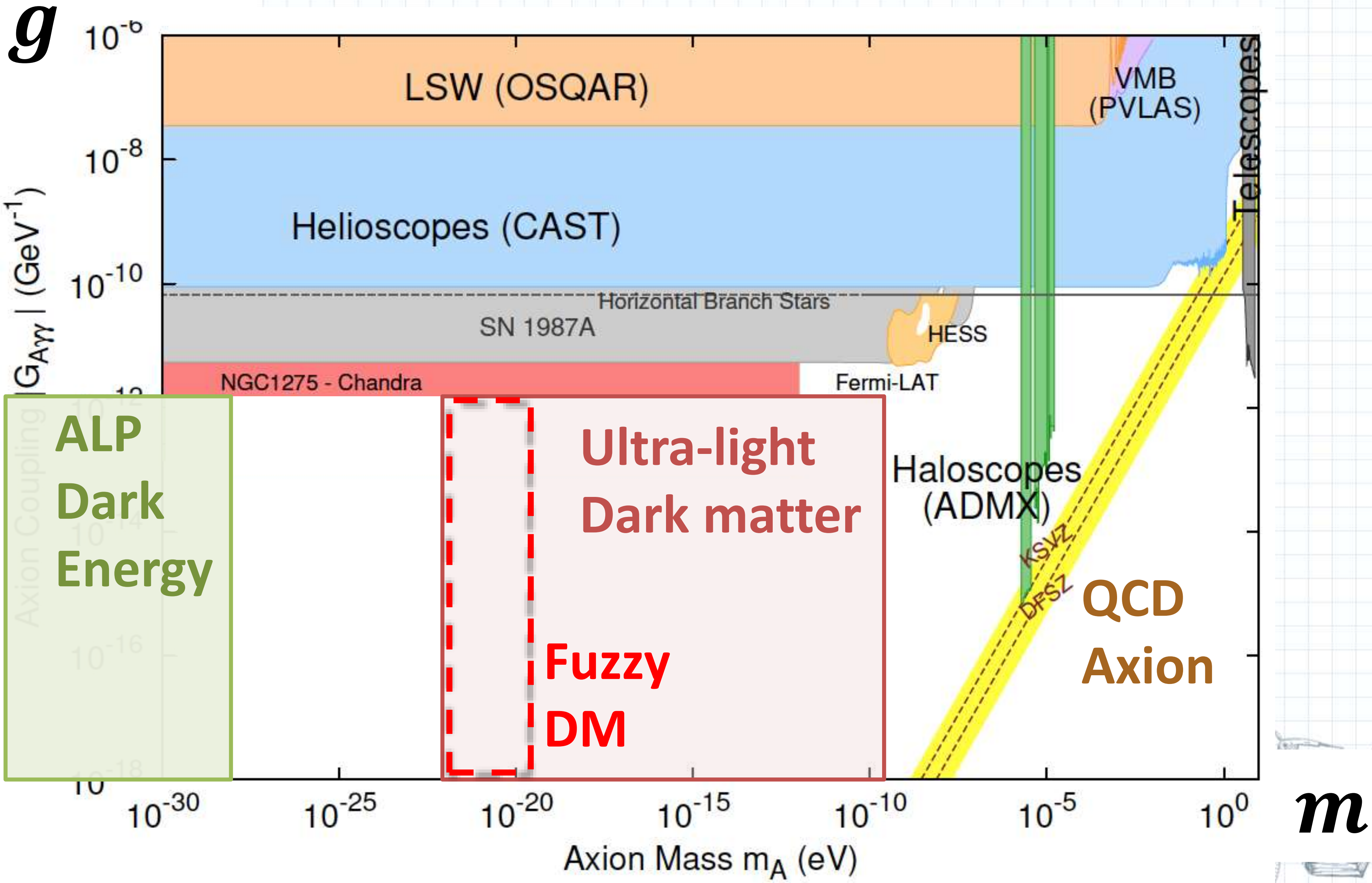
DM density

WIMP **Scalar DM**



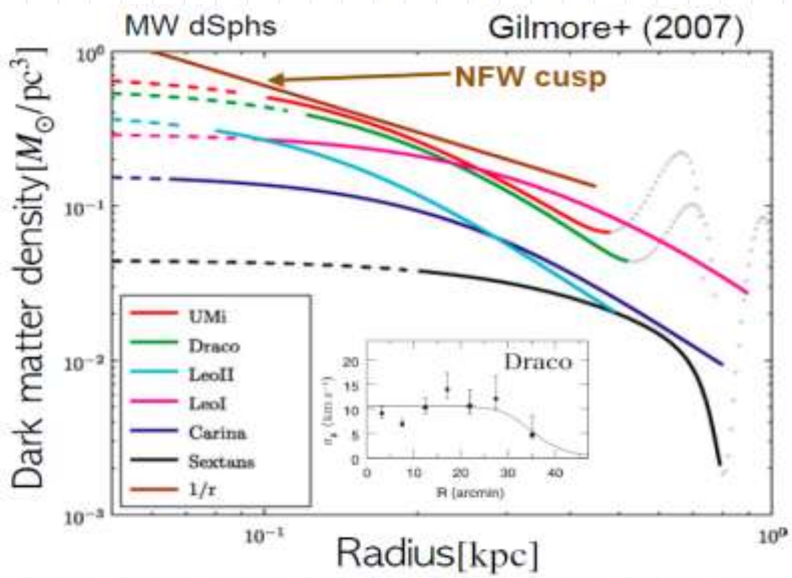
Wave-like DM is also a good candidate!

Current constraint



Fuzzy dark matter

- Core-cusp problem



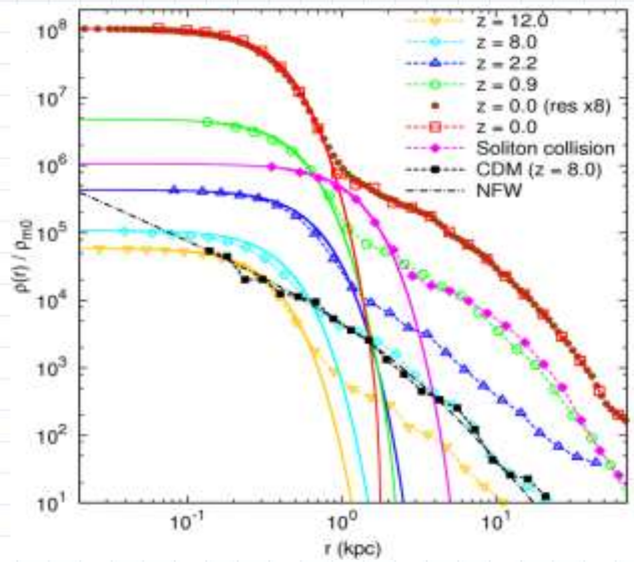
$\rho_{\rm DM}$ profile @ galaxy center

N-body sim. ⇒ cusp

Observation ⇒ core

- ADM resolves it!

Schive et al. (2014)



Uncertainty Principle

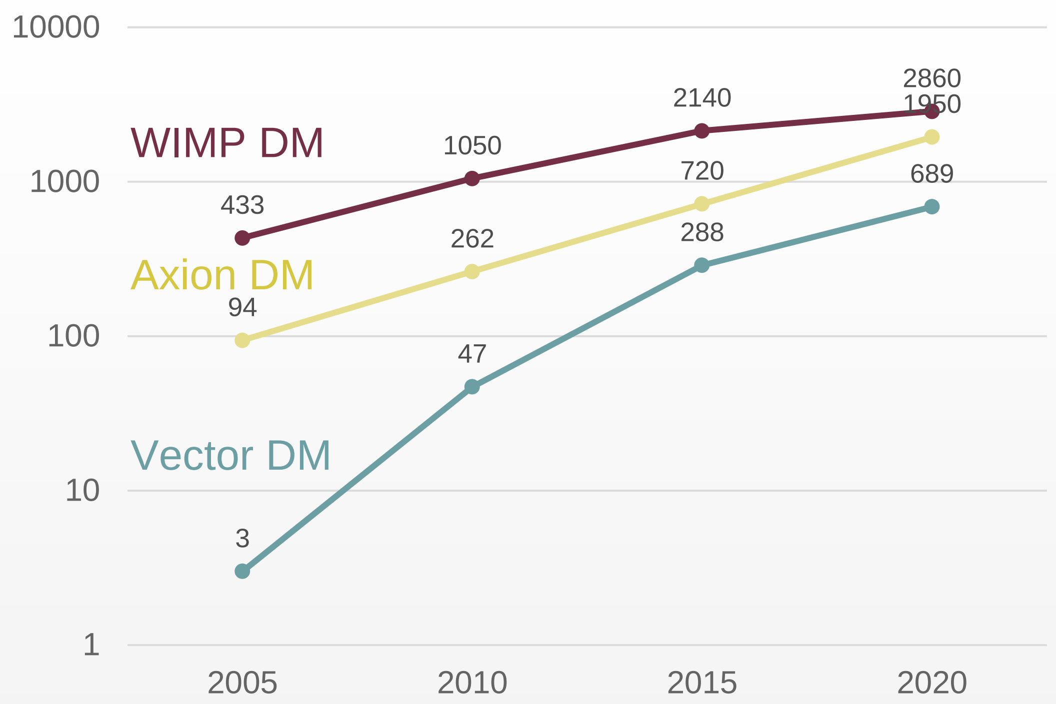
$$p_{\rm DM} = mv \sim {\rm kpc}^{-1}\left(\frac{\rm m}{10^{-22}{\rm eV}}\right)$$

DM can't condensate

Who's popular?

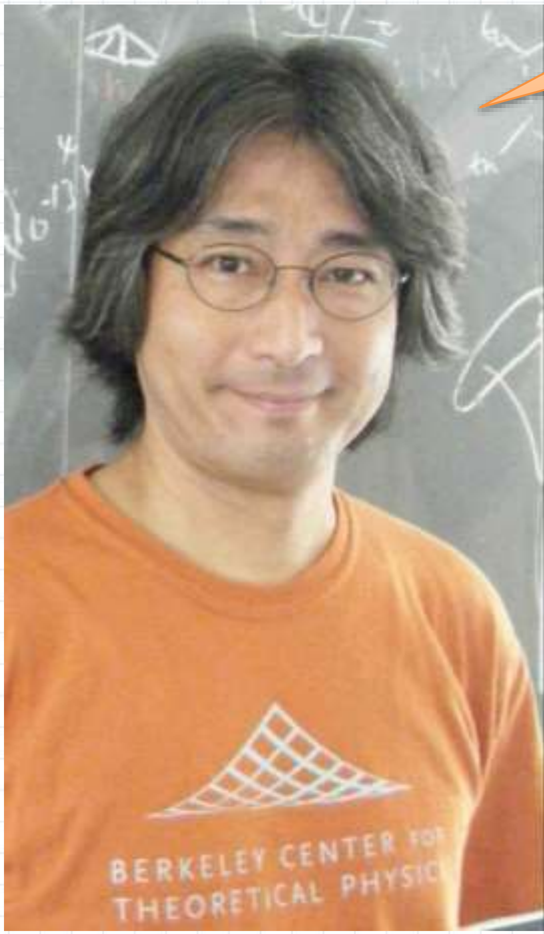
of paper

The hit count of
"XX dark matter"
in Google scholar
for every 5 years



New grant

Era of non-WIMP DM!



Prof. Hitoshi Murayama

Big grant for DM Search
(Comprehensive study of the huge discovery space in dark matter).

- 14M USD/ 4yr in total
- 1.5M USD/ 4yr for my team

You can apply for jobs
and open-solicited Research

研究項目

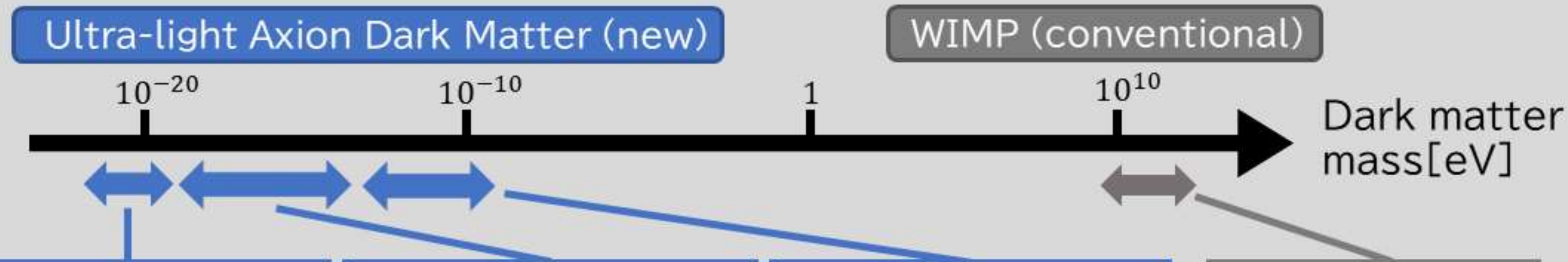
- 総括班
- A01 軽いダークマターの生成と進化に関する理論的探究
- A02 マルチメッセンジャーで探る重いダークマター
- A03 原始ブラックホール・巨視的ダークマターの探究
- B01 重力波望遠鏡とレーザー干渉計実験による超軽量ダークマター探索
- B02 すばる多天体分光観測によるダークマター探索
- B03 広視野かつ高時間分解能天体イメージングによるダークマター探索
- B04 X 線領域の観測技術の革新によるダークマター探索
- B05 電子陽電子加速器によるダークマター探索
- B06 宇宙マイクロ波背景放射によるダークマター探索
- C01 量子重力理論から迫るダークマター
- C02 宇宙構造形成理論から迫るダークマター

CMB Birefringence

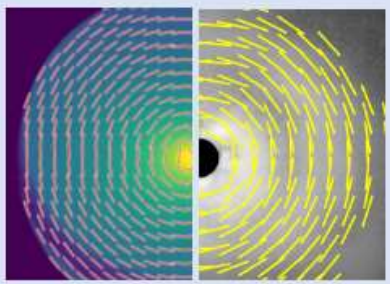
How to search for

Axion like DM?

New ALP searches

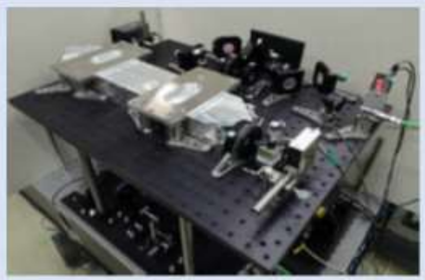


①PPD observation



- 惑星が形成される円盤から出る光を偏光観測
- アクシオンの影響を測定昨年、世界最高感度達成
- 新観測で感度向上図る

②Table-top exp.

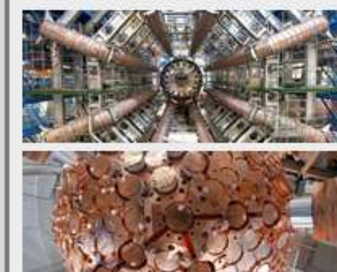


- ADM探査専用卓上実験
- 住友財団助成金を獲得、東大で50cm試作機完成
- さきがけ4000万円獲得5mの大規模版制作へ

③GW Observatory

- 重力波望遠鏡がアクシオン探査に並行利用可能
- KAGRAでの実現に向け学術変革申請済(1.6億)
- 来年O4で試験運用予定

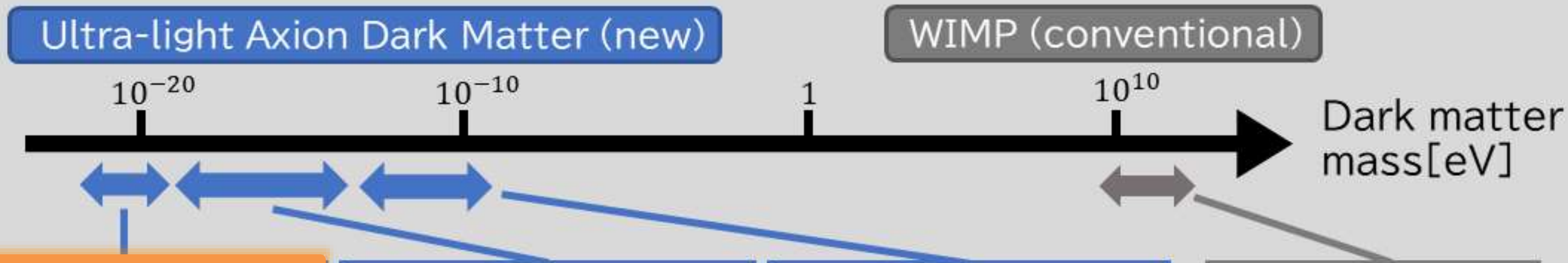
WIMP Search



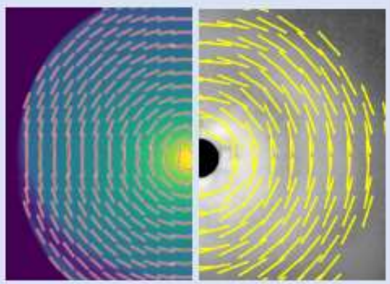
- 加速器や地下実験で長年WIMP探査
- シグナルは未発見
- 実験巨大化が課題

Looking into new light mass window, New obs/exp. will reveal DM!!

New ALP searches



①PPD observation



- 惑星が形成される円盤から出る光を偏光観測
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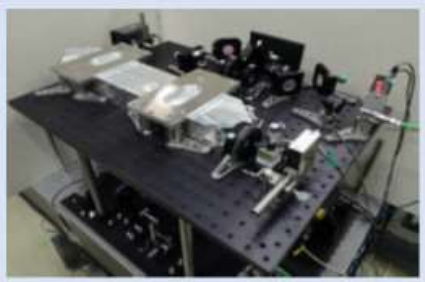
- 新観測で感度向上図る

②Table-top exp.



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WIMP Search

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- シグナルは未発見
- 実験巨大化が課題

Looking into new light mass window, New obs/exp. will reveal DM!!

ProtoPlanetary Disk

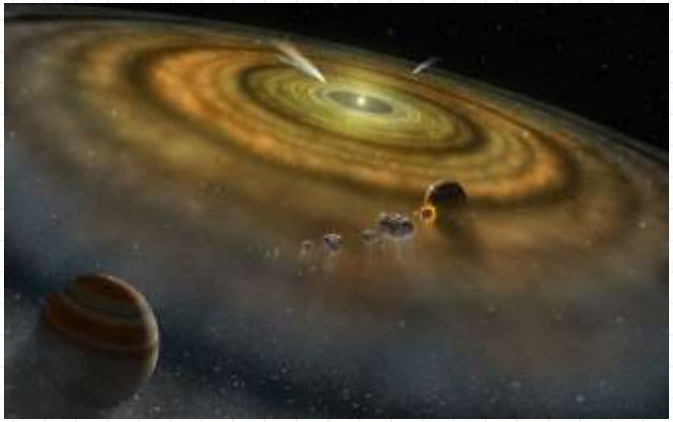
- Observations of PPD can be used!

PPD is a flattened gaseous object surrounding a young star.

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

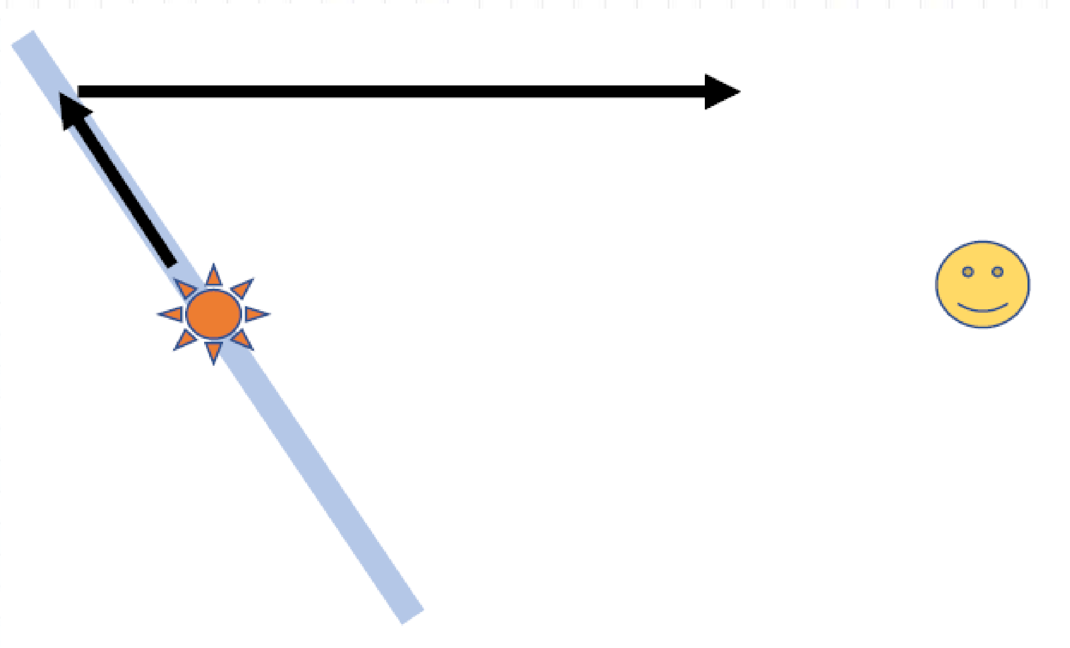
Real data

Artist's image



Polarization of PPD

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



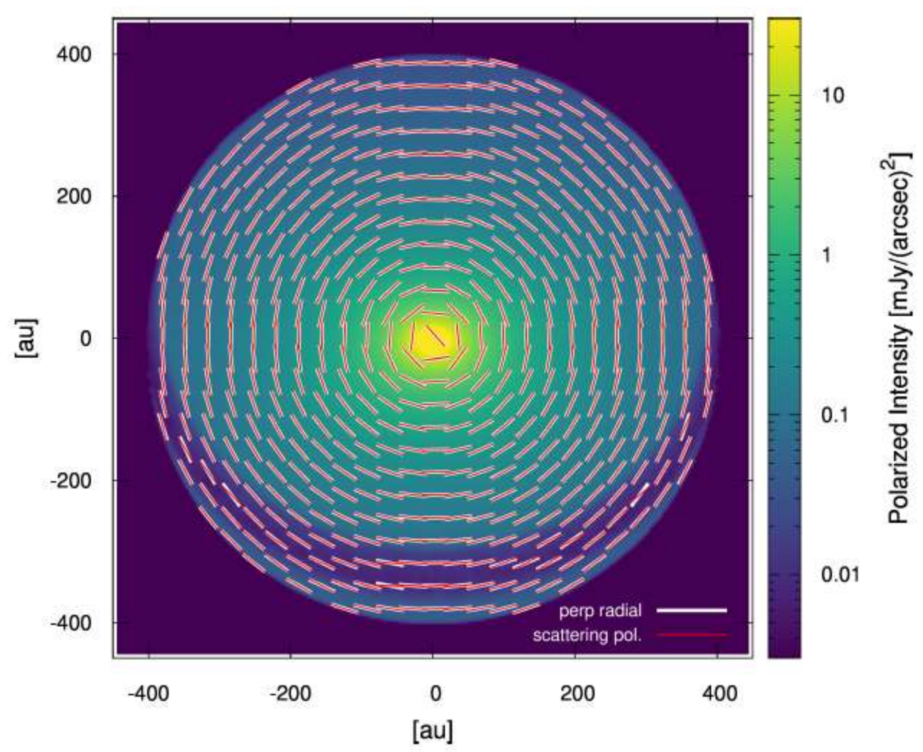
Initial polarization Plane is known!!

Obsevation of PPD

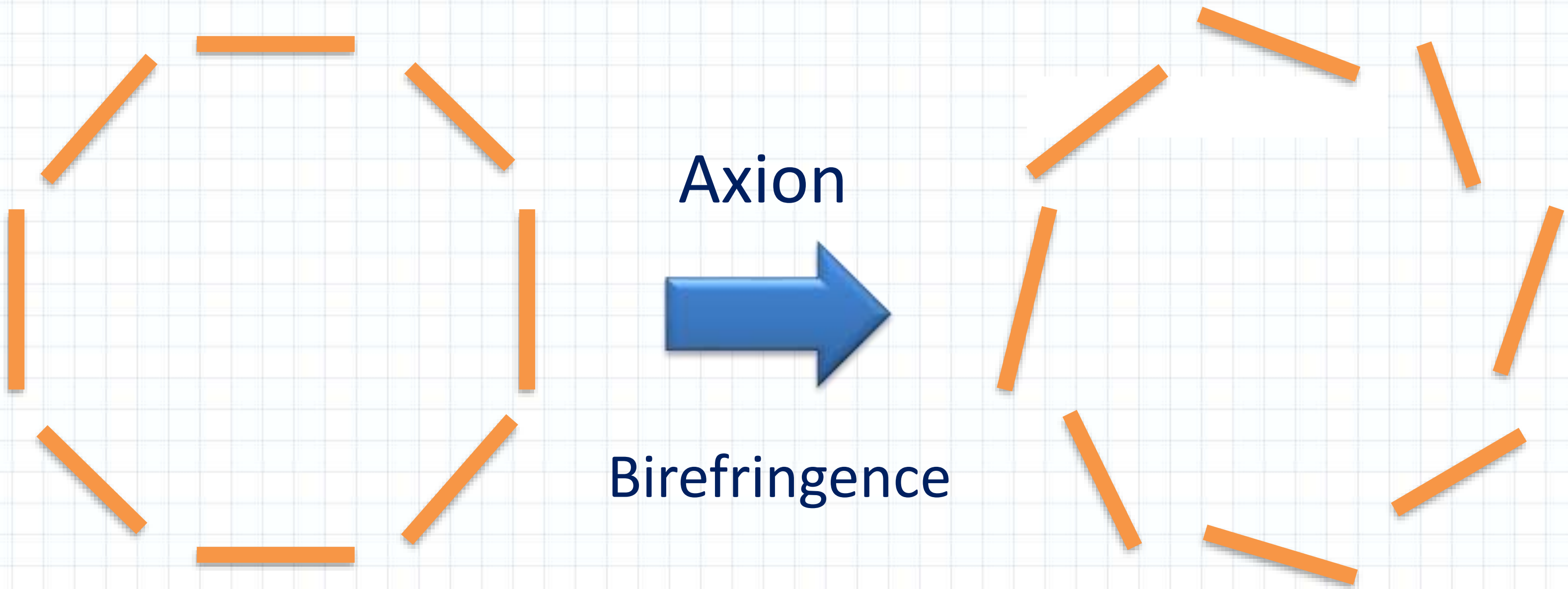
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

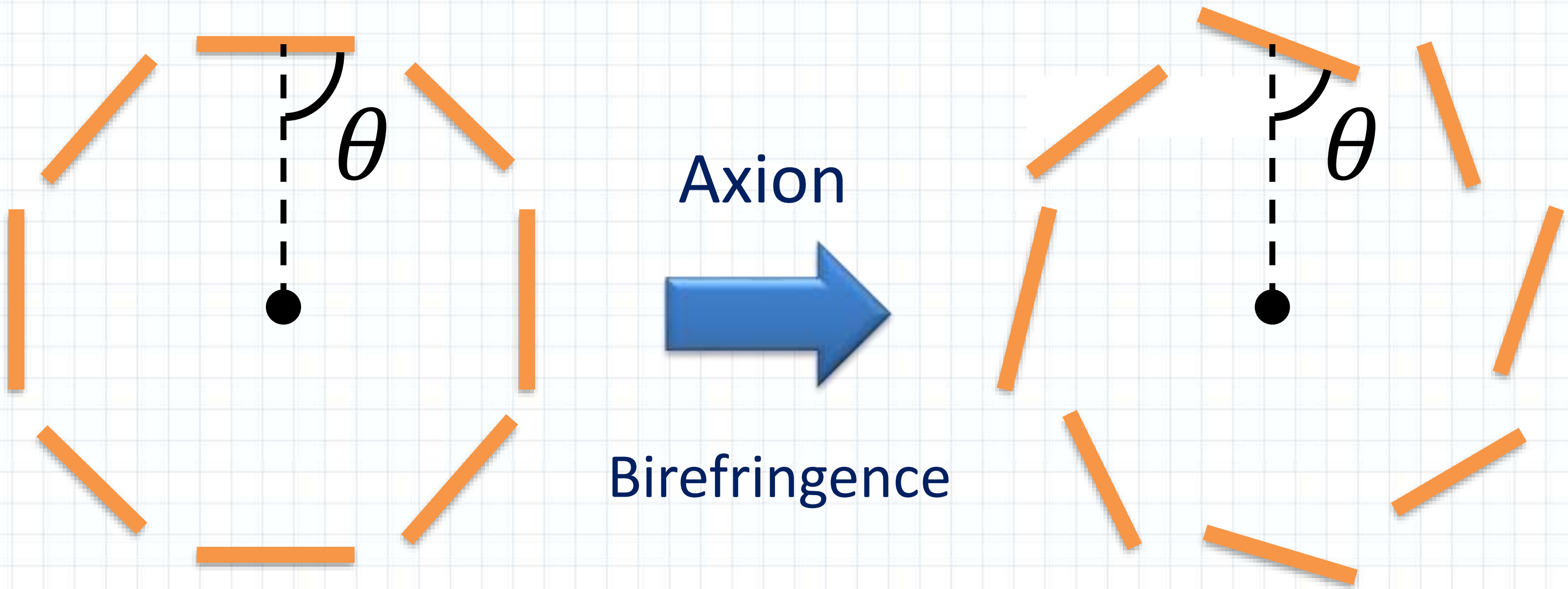
Our Simulation without Axion DM



Axion DM rotates pol. plane?



Axion DM rotates pol. plane?



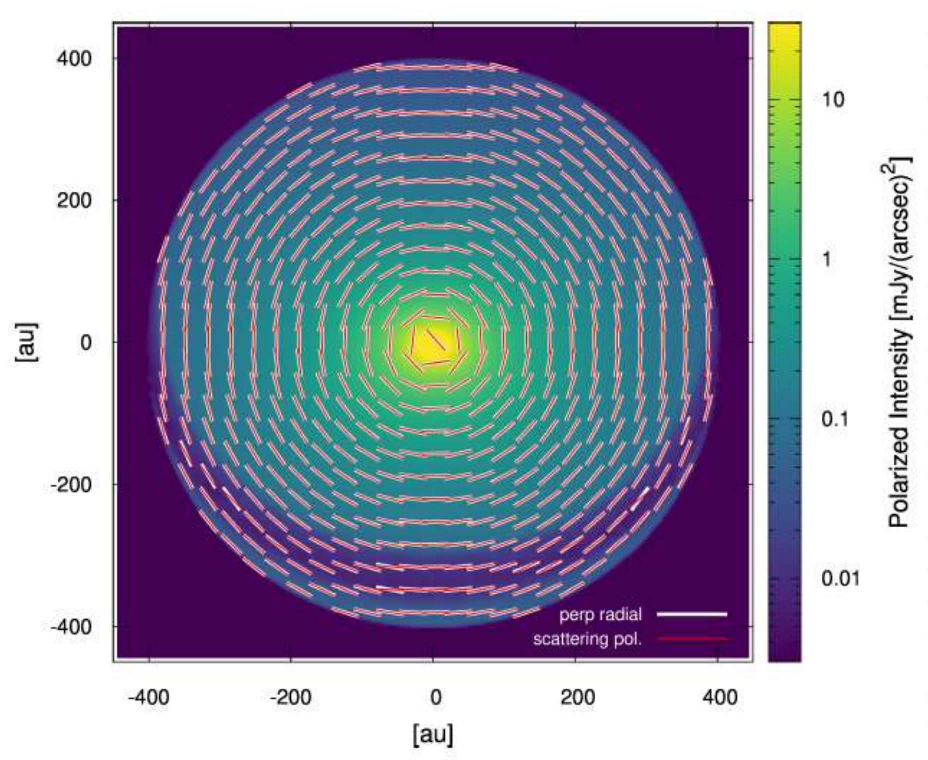
Is this angle 90° or not?

Obsevation of PPD

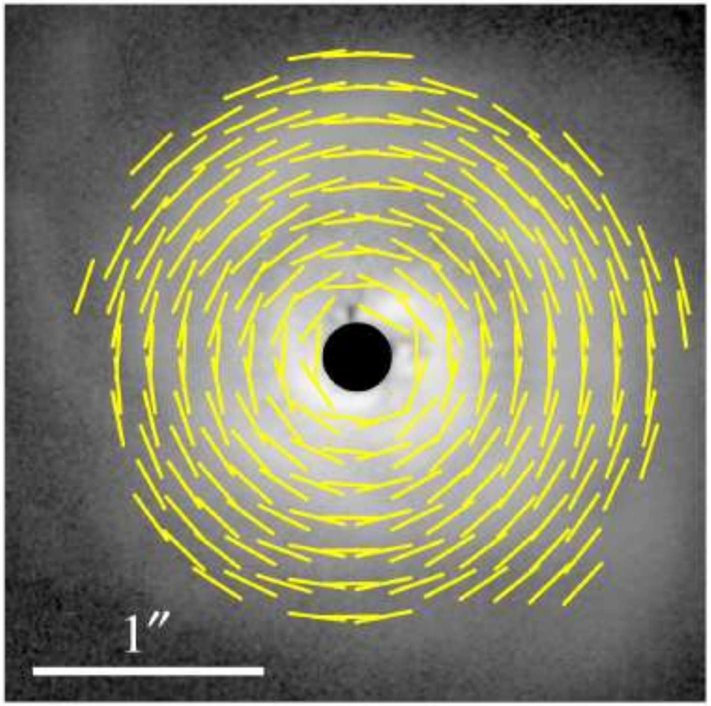
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM



Observation by SUBARU



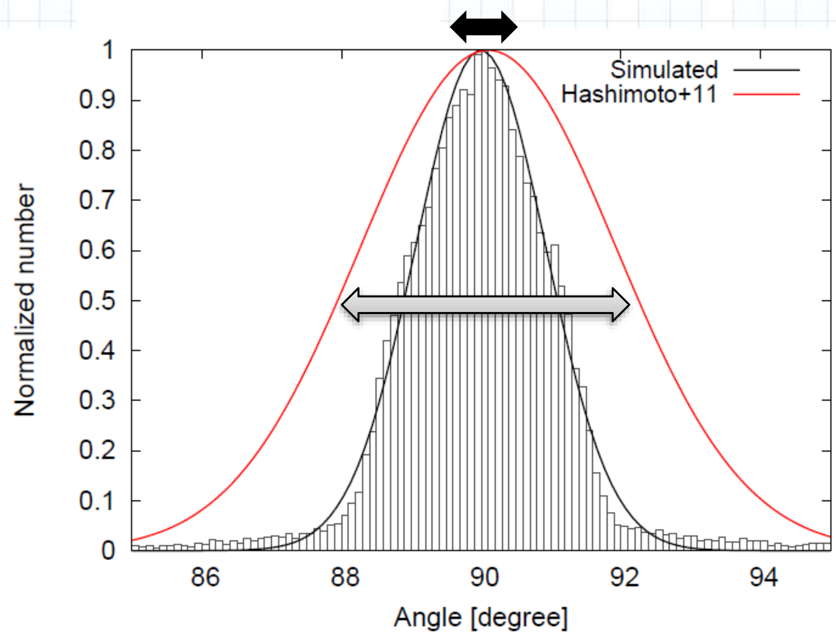
AB Aurigae (160pc away)

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

Obsevation of PPD

The observation data reveals

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



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

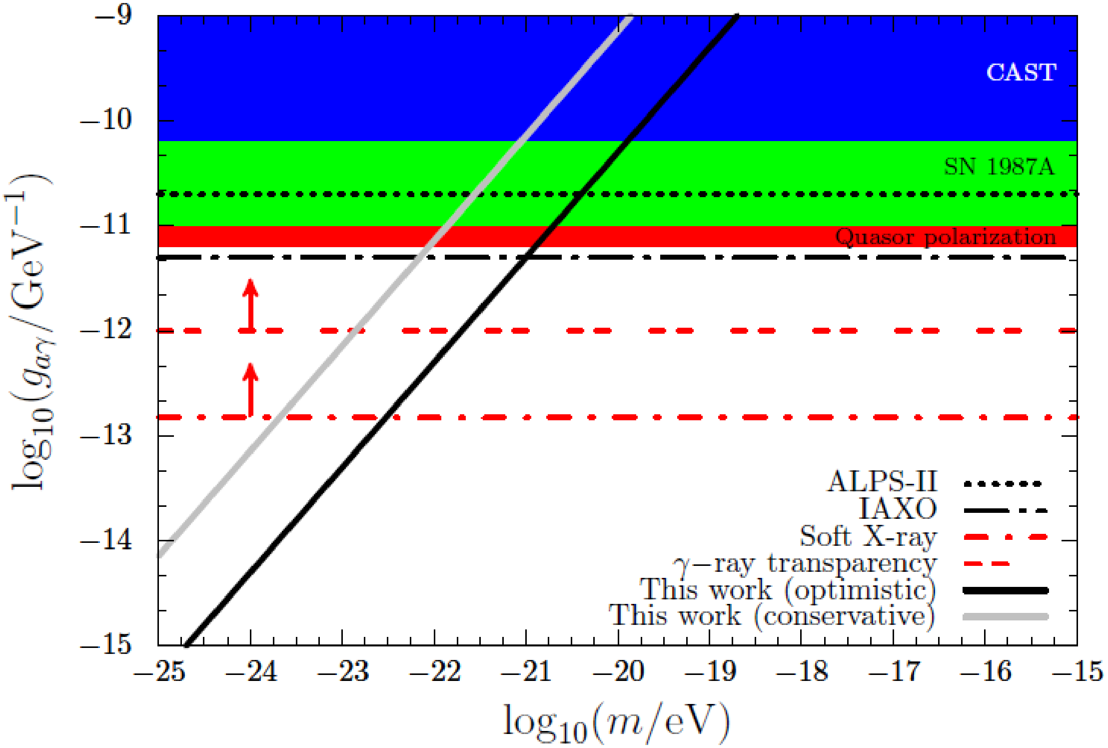
Our simulation confirms the effect of multiple Scatterings is negligible.

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]

New constraint

[TF. Tazaki & Toma (2018)]
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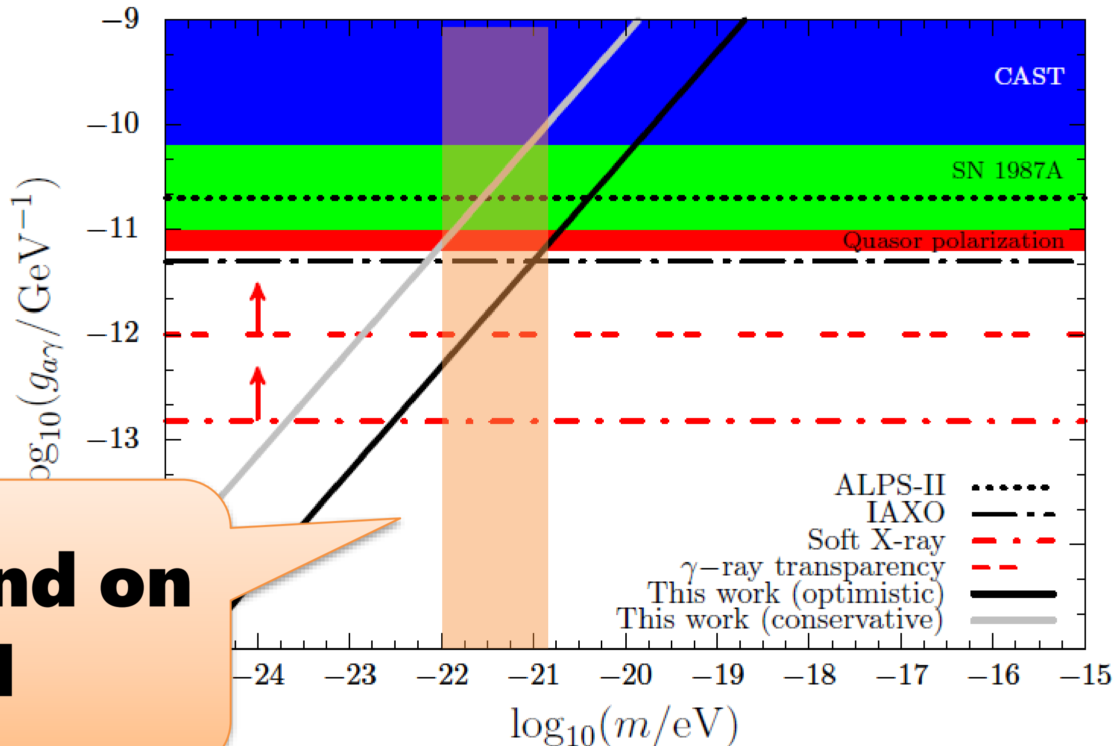
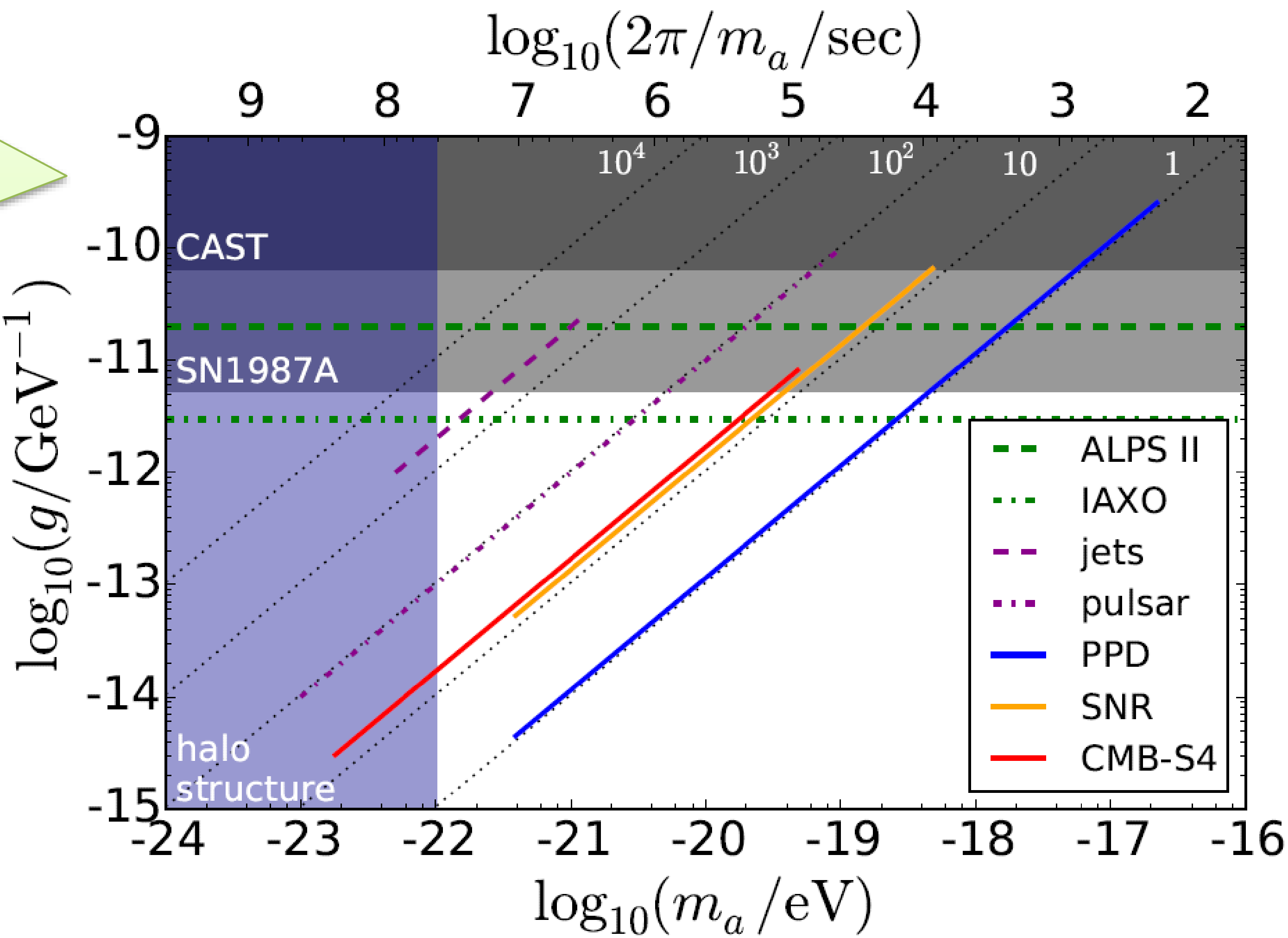
g



m[eV]

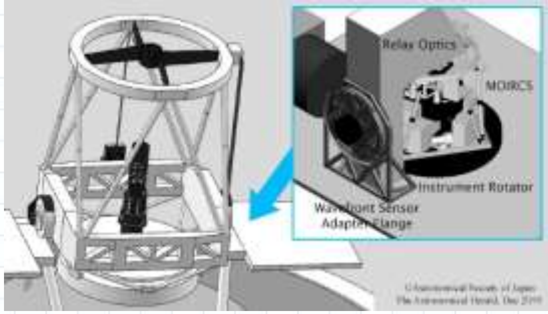
Best bound on Fuzzy DM

Forecast of future ADM Search



PPD has the biggest potential

New Observation



- Never give up!
  We should pursue our approach.

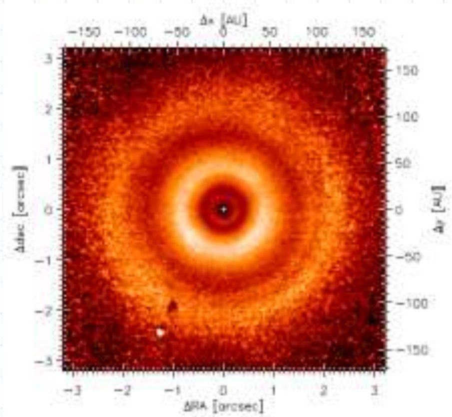
- We used old data (Hashimoto+ 2011)
  whose exposure time was 3mins.

- Now Subaru's detector is upgraded!
  Many PPDs have been found.

- Let's make **our own observations** of PPDs!

- Applied for 萌芽 to hire postdoc analyzing data

[Van Boekel+(2017)]



Subaru Application

(Page 1)

Subaru Telescope
National Astronomical Observatory of Japan

Semester	S21B
Proposal ID	S21B0132N
Received	03/09/2021

Application Form for Telescope Time (Normal+Intensive Programs)

1. Title of Proposal

Polarimetry of Six Protoplanetary Disks to Search for Axion Dark Matter

2. Principal Investigator

Name: Toma Kenji
Institute: Tohoku Univ.
Mailing Address: Sendai 980-8578, Japan
E-mail Address: toma@astr.tohoku.ac.jp Phone: +81-22-795-4402

3. Scientific Category

- [ ] Solar System
- [ ] Extrasolar Planets
- [★] Star Formation and Young Disk
- [ ] ISM
- [ ] Normal Stars
- [ ] Metal-Poor Stars
- [ ] Compact Objects and SNe
- [ ] Milky Way
- [ ] Local Group
- [ ] Nearby Galaxies
- [ ] IGM and Abs.Line Systems
- [ ] Cosmology
- [ ] Gravitational Lenses
- [ ] Clusters and Proto-Clusters
- [ ] Galaxy Properties and Environment
- [ ] High-z Galaxies(LAEs, LBGs)
- [ ] High-z Galaxies(others)
- [ ] AGN and QSO Activity
- [ ] Miscellaneous

4. Abstract *(approximately 200 words)*

We propose SCExAO fast-PDI imaging of six protoplanetary disks (PPDs) to search for axion dark matter. Axion is predicted by particle physics and has recently received great attention as a dark matter candidate. Axion weakly interacts with photon and particularly rotates its linear polarization vector. Thus we can search for a signature of axion dark matter by seeking small deviations in polarization angles from intrinsic circular pattern of polarization vectors of PPDs in the near-infrared wavelengths. Based on this new idea of ours, we have put the best bound on axion dark matter with polarimetric data of AB Aur previously observed by Subaru/HiCIAO (which employs slow-PDI, i.e., the detector read-out speed of H2RG is 1.4 second). Thanks to the new sophisticated fast-PDI imaging mode on SCExAO (which employs a very high frame rate C-RED ONE camera with $\gtrsim$1 kHz, and is available for the open use from S21B), we can achieve over one order of magnitude more stringent bound on axion dark matter, which may not be easily overcome by observations of other astronomical sources. If we detect a signal from one PPD or more, this will be a major discovery, and have a strong impact on astrophysics and particle physics.

Kenji Toma
Tohoku Univ.

Ryo Tazaki
Amsterdam Univ.

Jun Hashimoto
Astrobiology center

Subaru Application

(Page 3) Proposal ID S21B0132N

Title of Proposal
Polarimetry of Six Protoplanetary Disks to Search for Axion Dark Matter

12. Observing Run

Instrument	#Nights	Moon	Preferred Dates	Acceptable Dates	Observing Modes
FPDI+SCExAO+NGS	1.5	any	Jan.	Jan.	fast-PDI

2nd choice:

comments:

Total Requested Number of Nights: 1.5 — Minimum Acceptable Number of Nights: 1

13. Scheduling Requirements ☐ ToO ☐ Time Critical

Since 5 of 6 targets are only observable in 1st half night on January, we request to allocate one full night and one 1st half night. We also request to avoid the following dates since the angular separation from the moon is too close (<30 degrees): Jan. 11–17.

14. List of Targets

Target Name	RA	Dec	Magnitude (Band)
LkHa 330	034548.28	+322411.8	10.5 mag (R), i =30 deg
AB Aur	045545.84	+303304.2	6.9 mag (R), i =30 deg
V1247 Ori	053805.25	-011521.6	9.4 mag (R), i =30 deg
GW Ori	052908.39	+115212.6	8.7 mag (R), i =37 deg
MWC 758	053027.52	+251957.0	7.9 mag (R), i =20 deg
TW Hya	110151.90	-344217.0	9.5 mag (R), i =10 deg

Kenji Toma
Tohoku Univ.

Ryo Tazaki
Amsterdam Univ.

Jun Hashimoto
Astrobiology center

Subaru Application

Polarimetry of Six Protoplanetary Disks to Search for Axion Dark Matter

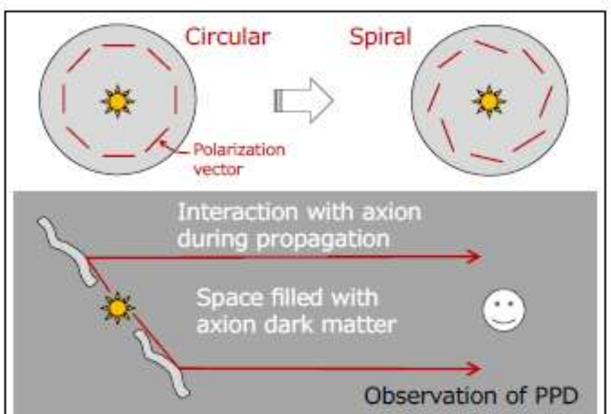
(Toma, K., Hashimoto, J., Fujita, T., Tazaki, R., Lozi, J., Kudo, T., Guyon, O., & Tamura, M.)

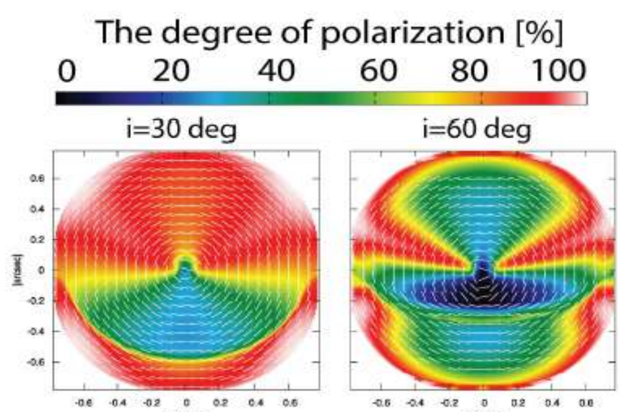
1 Scientific Motivation

Modern astronomy postulates the existence of dark matter, yet, the nature of dark matter has been an outstanding problem for about a century. **Among many candidates for dark matter, an elementary particle named "axion" has recently received great attention (for a review, e.g. Irastorza & Redondo 2018).** Axion is predicted by particle physics including string theory, and can resolve the astrophysical "core-cusp problem", which is a tension between observations and simulations of dark matter profile at galactic centers (Hu, Barkana & Gruzinov 2000; Hui et al. 2017). Many astronomical observations as well as laboratory experiments with various detection schemes pursue the first signal of axion dark matter and improve the best constraints on it.

2 Proposed Observations

Here we propose SCExAO fast-PDI imaging (which is newly available for the open use from S21B) of six PPDs (see § 3) to search for axion dark matter. Since we seek small deviations in polarization angles from the circular pattern of polarization vectors, precise measurements of polarization in PPDs are essential. In our previous studies of AB Aur (Hashimoto et al. 2011; Fig. 1), the error in measured polarization angles was 0.2° with total exposure time of ~3 min. In proposed new observations, thanks to (a) a high frame rate C-RED ONE camera (~1 kHz) in the fast-PDI mode, (b) a higher Strehl ratio with $\gtrsim$0.8 by the extreme adaptive optics system SCExAO, (c) precise distortion corrections (see Technical justification), and (d) longer exposure time of 75 min, we expect to achieve the error in polar-





Kenji Toma
Tohoku Univ.

Ryo Tazaki
Amsterdam Univ.

Jun Hashimoto
Astrobiology center

Subaru Application

3 Experimental Design

Errors in polarization angles — We calculate angles between the polarization vectors and lines from the central star to the vector position, and derive the mean ($\overline{\theta}$) and the standard deviation (σ_θ) of calculated angles. $\overline{\theta} = 90°$ corresponds to the exact circular pattern of polarization vectors. σ_θ represents the typical error in each of the polarization vector. The standard deviation of the mean ($\sigma_{\overline{\theta}}$) can be calculated as $\sigma_{\overline{\theta}} = \sigma_\theta/\sqrt{N}$, where N is the number of polarization vectors. **We expect that the value of $\sigma_{\overline{\theta}}$ is improved to an order of 0.01° in our new proposed observations (which is $\sim$ 10 times better than previous our observations in AB Aur in Fig. 1) as described in § 2.**

Improve the sensitivity
By a factor of 10 !!

Kenji Toma
Tohoku Univ.

Ryo Tazaki
Amsterdam Univ.

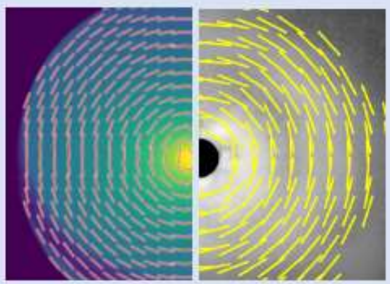
Jun Hashimoto
Astrobiology center

New ALP searches

Ultra-light Axion Dark Matter (new)

WIMP (conventional)

①PPD observation



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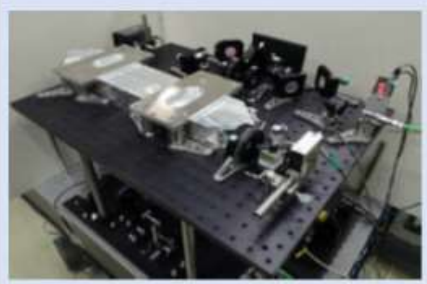

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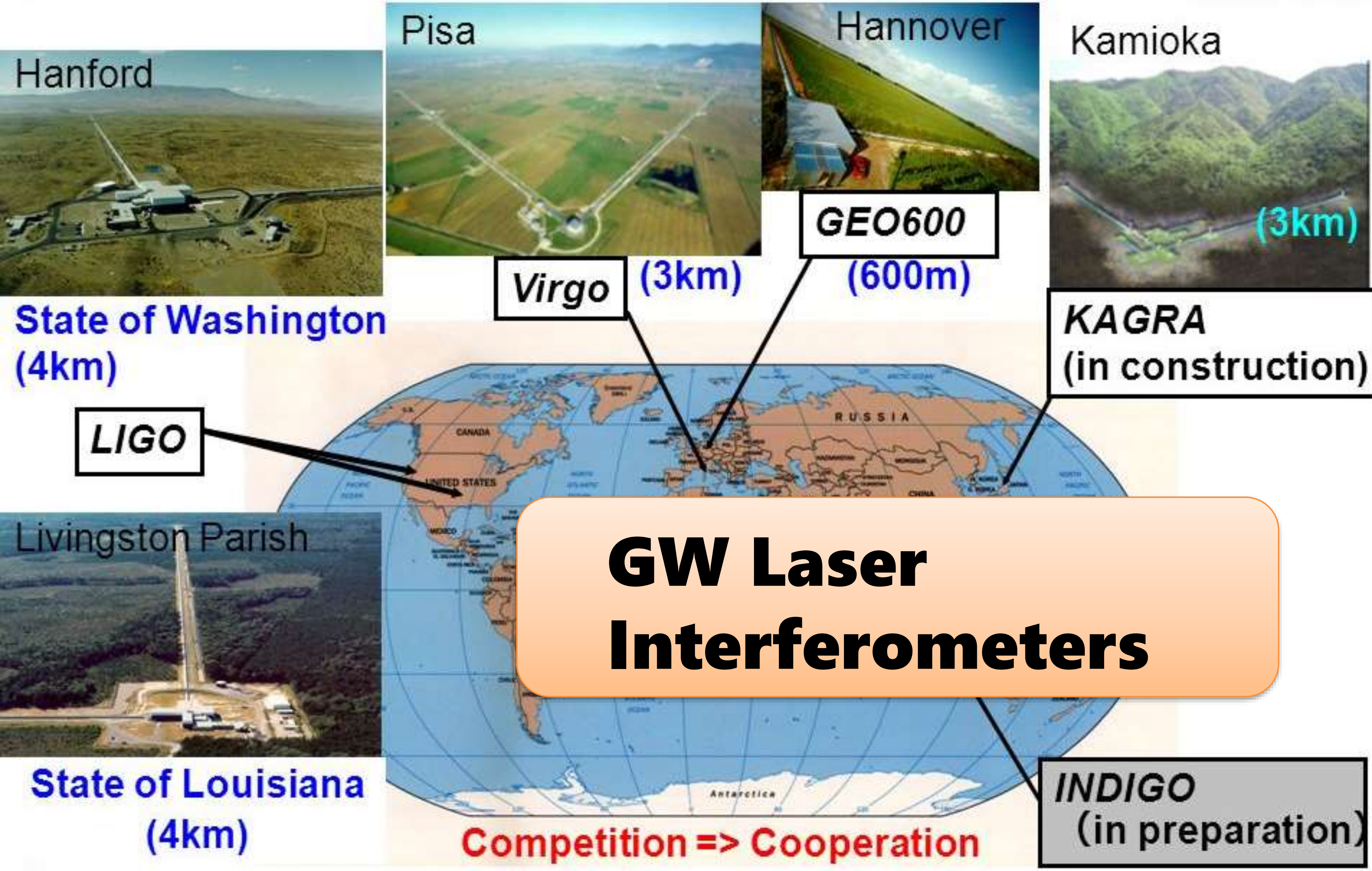
New experiment



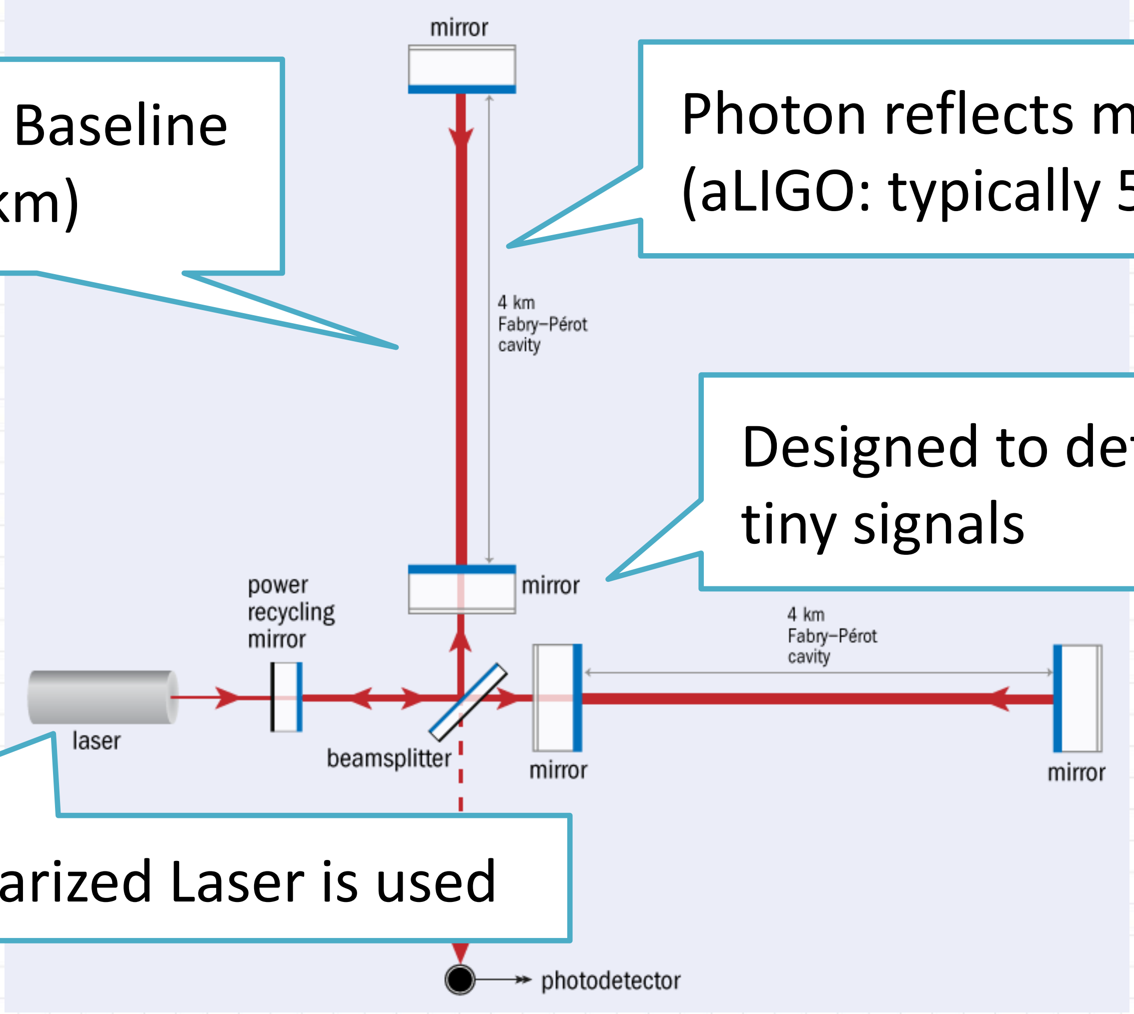
New experiment

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)

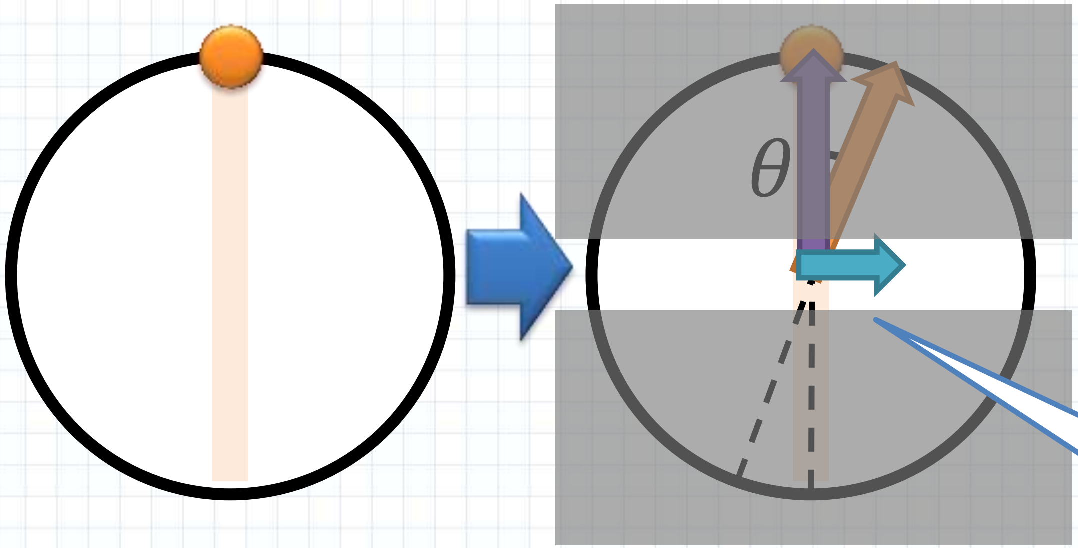
Photon reflects many times
(aLIGO: typically 500 times)

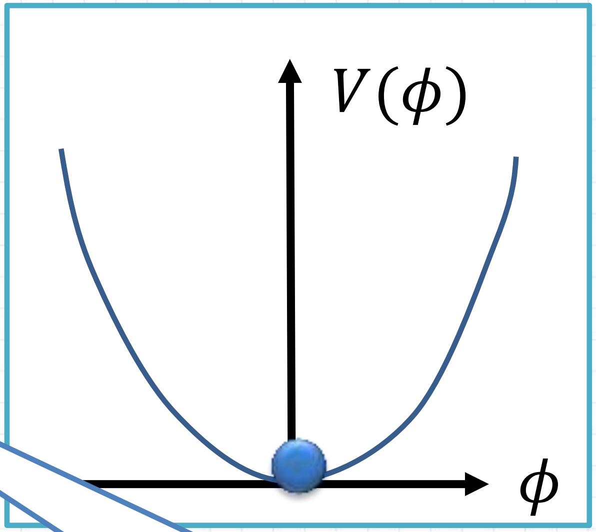
Designed to detect
tiny signals

Linear Polarized Laser is used

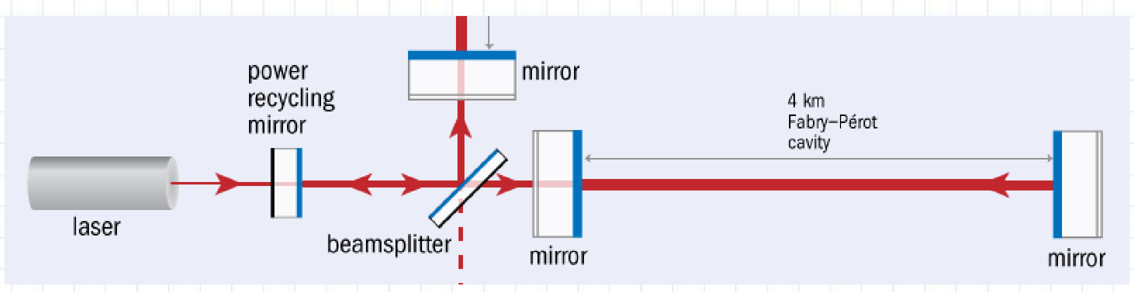
New Observation

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



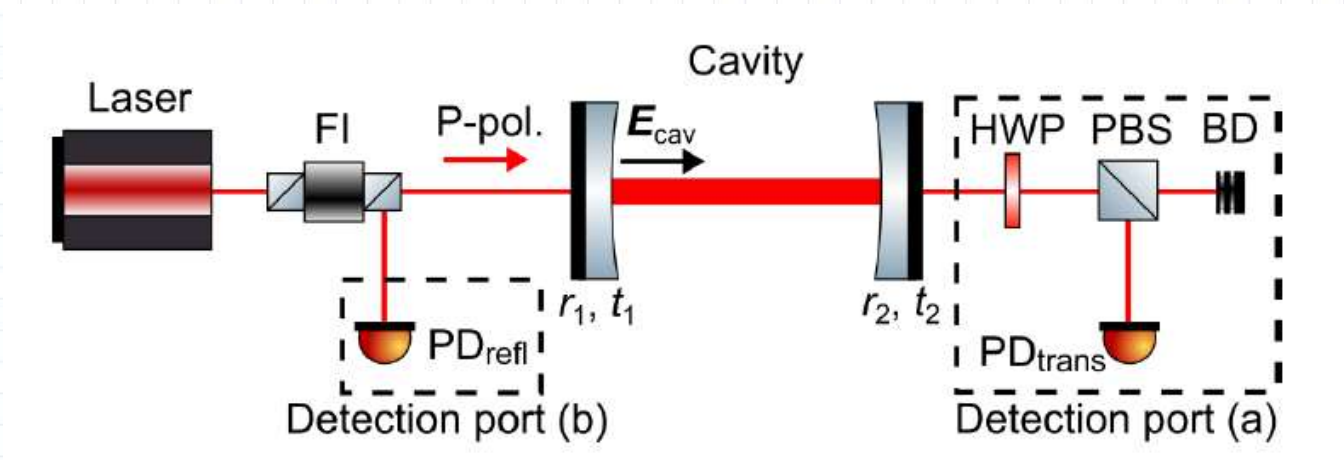


Only if $\theta \neq 0$ by ADM, we detect signal



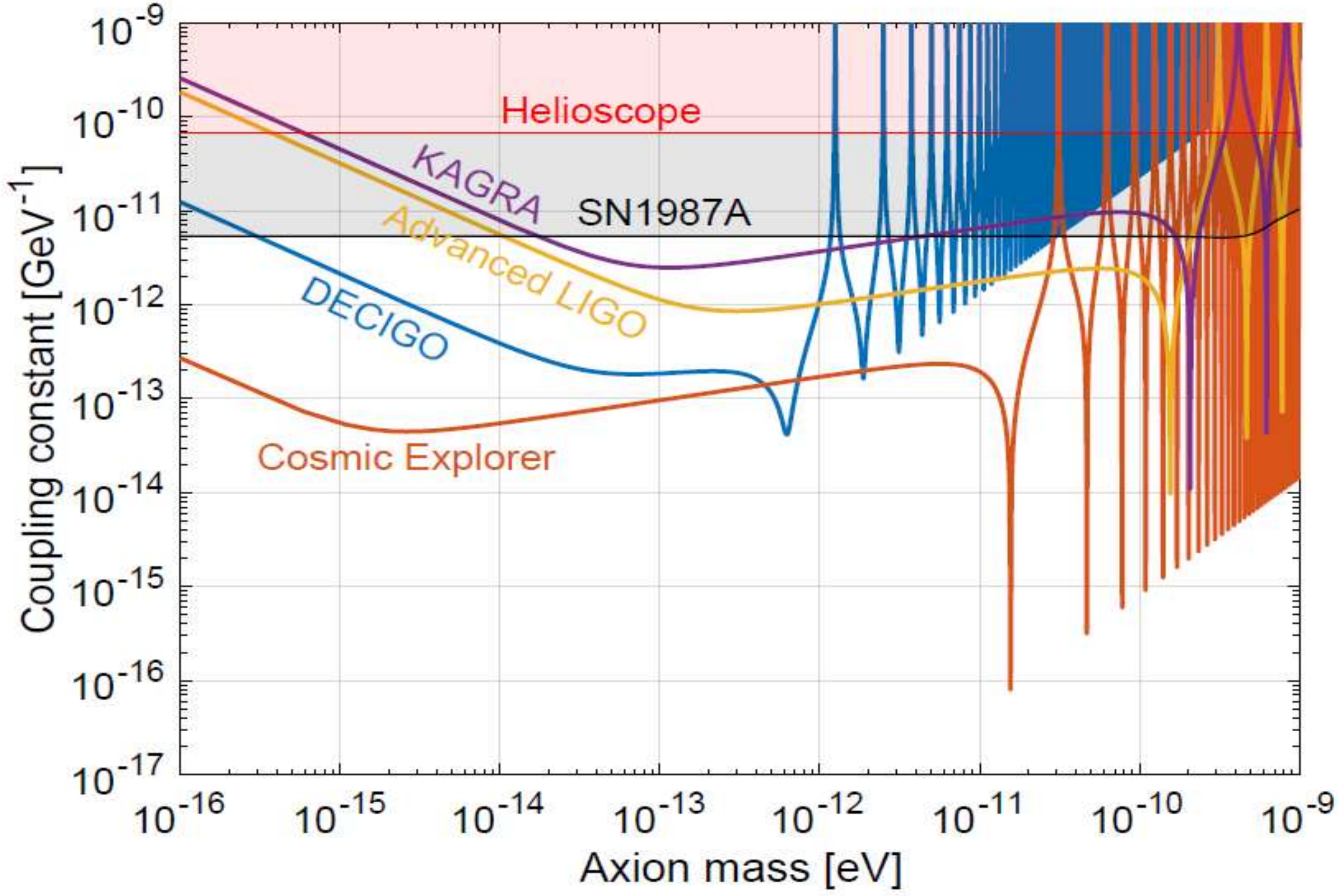
Coexist with GW observation

- Tiny signal compensated by long operation time

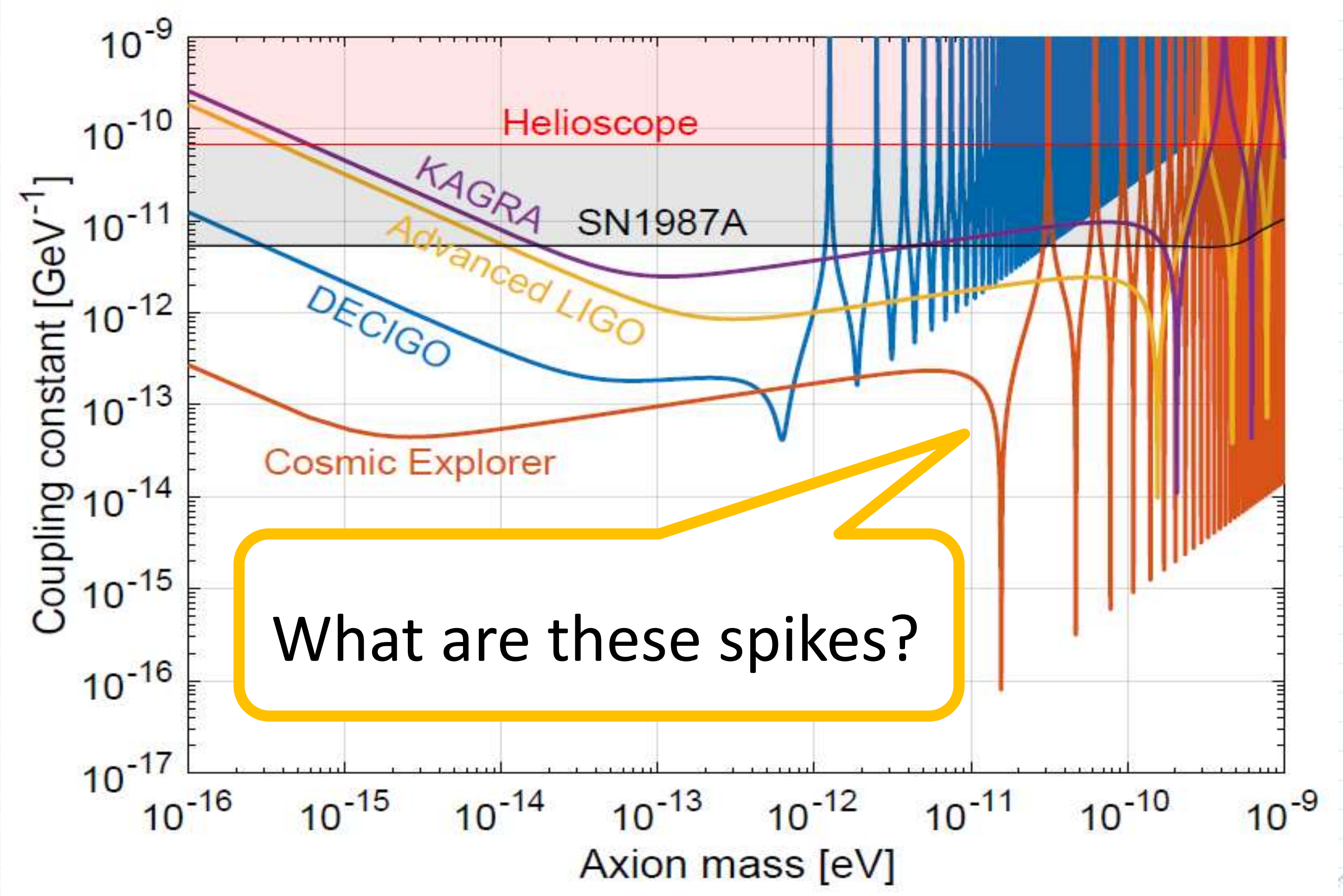


Additional instruments at the tail enable interferometers to probe ADM during the GW observation run **without loosing any sensitivity to GWs** ⇒ **Long Run!**

Sensitivity Curve for 1 year run



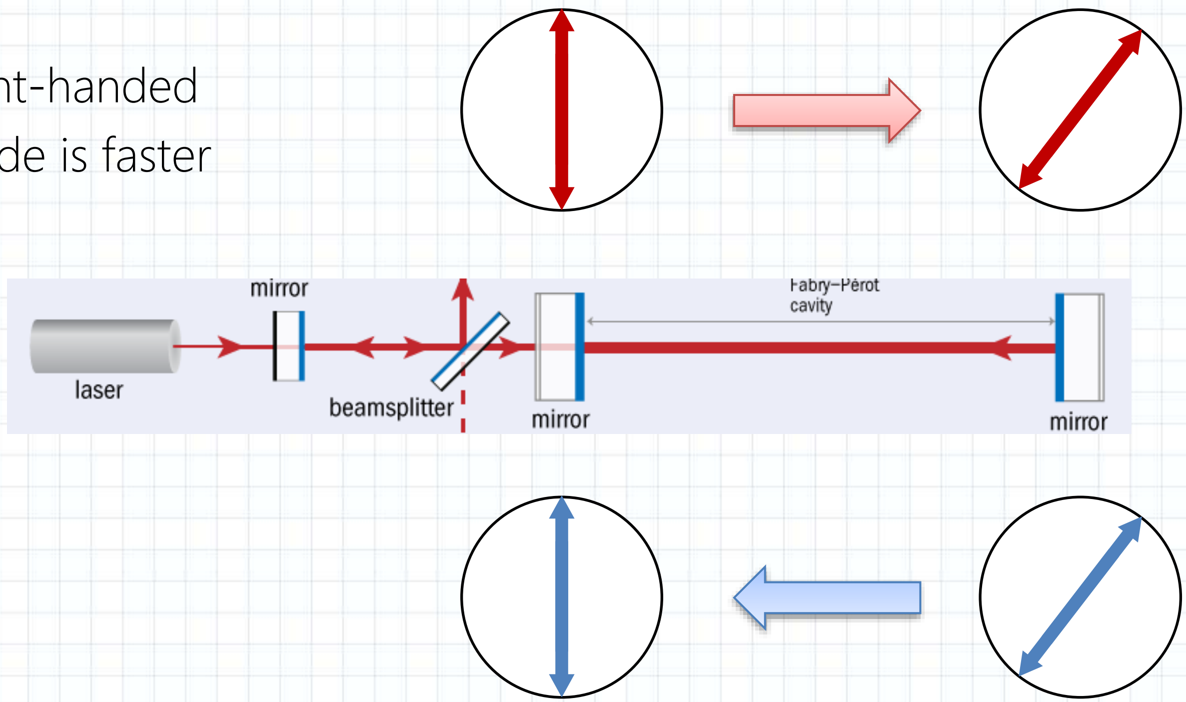
Sensitivity Curve for 1 year run



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

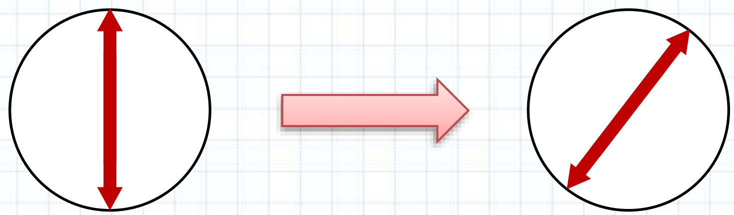
$$\omega_{L,R}^2 = k^2\left[1 \pm g\phi_0 \frac{m}{k}\sin(mt)\right]$$

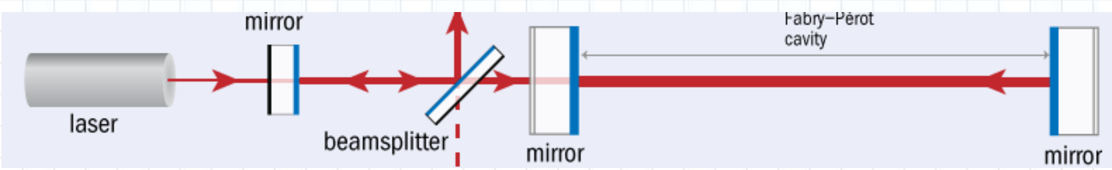
If axion oscillation period/2 = 4km/c,

rotation is accumulated.

Right-handed

mode is faster

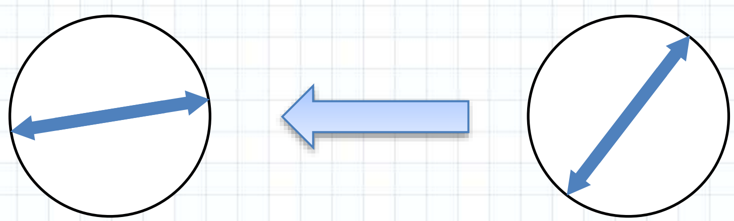




Then left-handed

mode gets faster

Rotation is addd!



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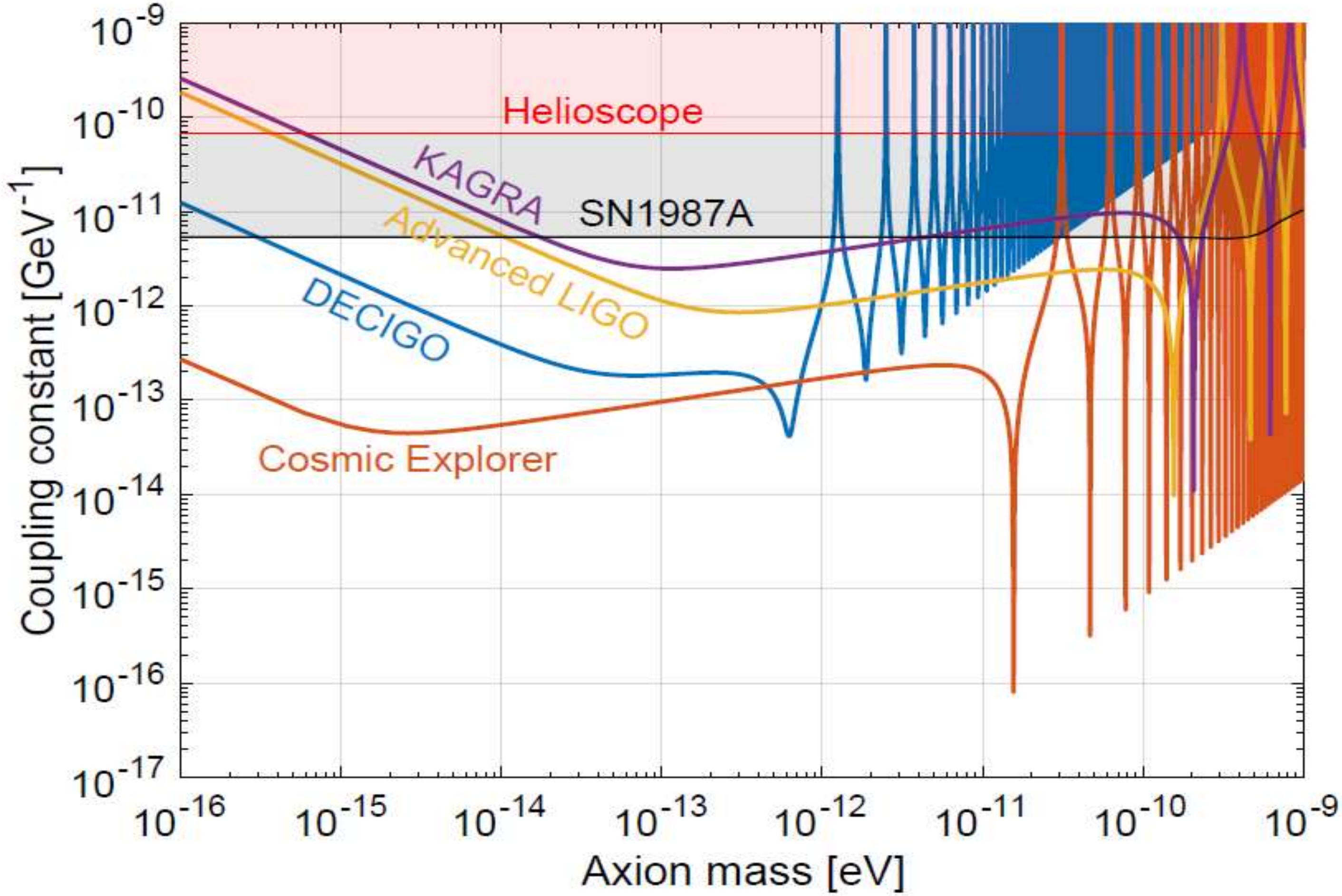

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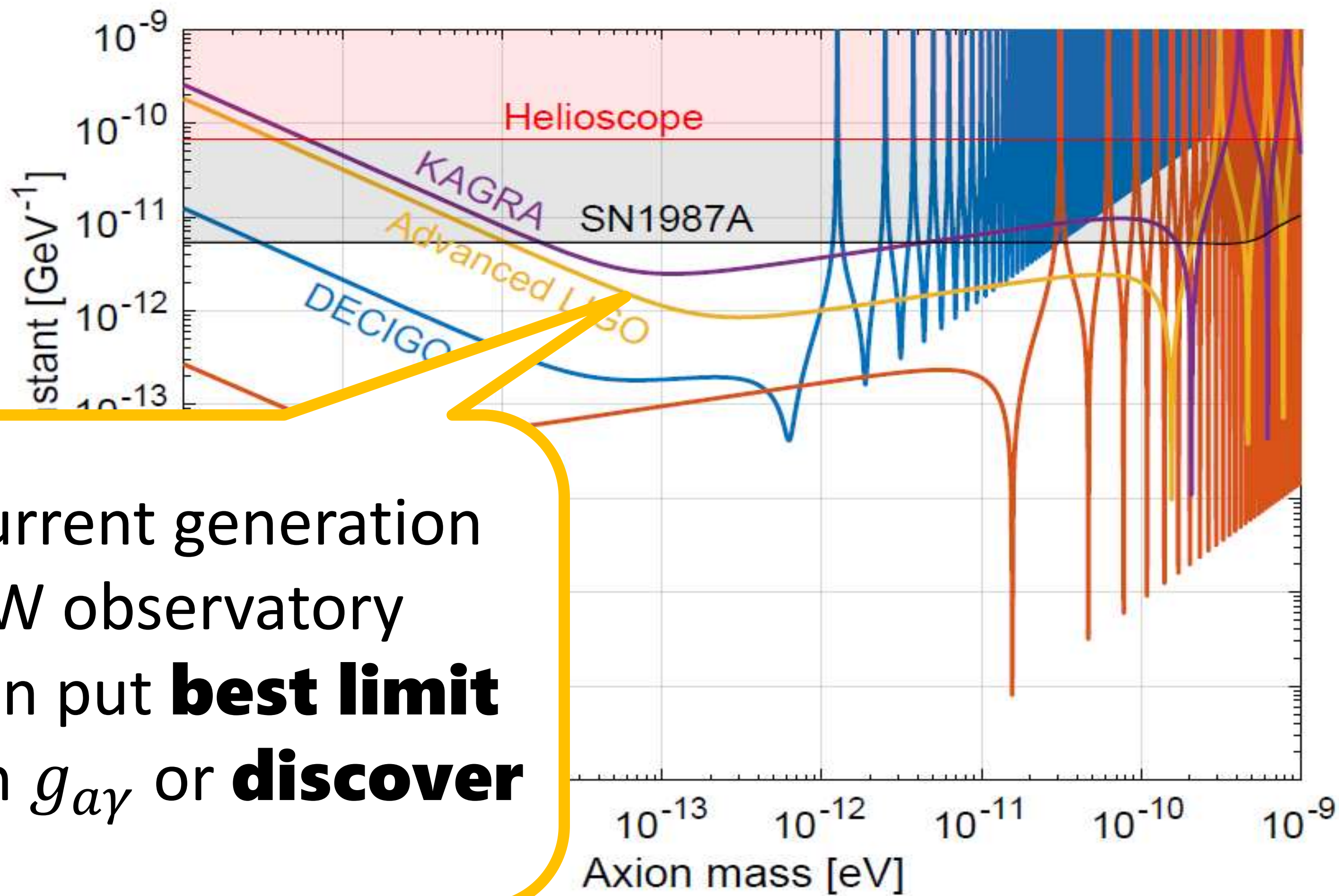
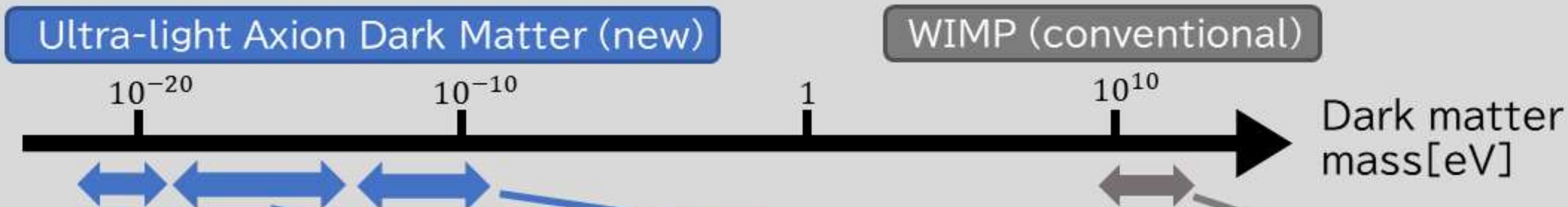
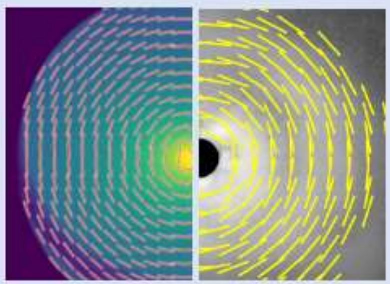


Current generation GW observatory can put **best limit** on $g_{a\gamma}$ or **discover**

New ALP searches



①PPD observation



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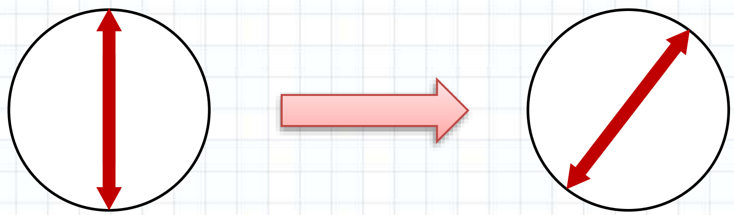
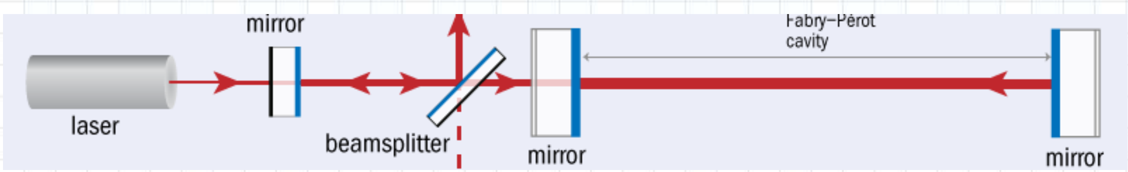
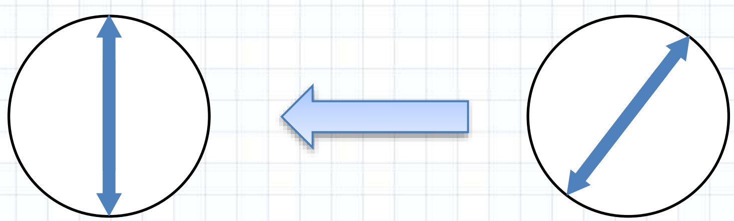


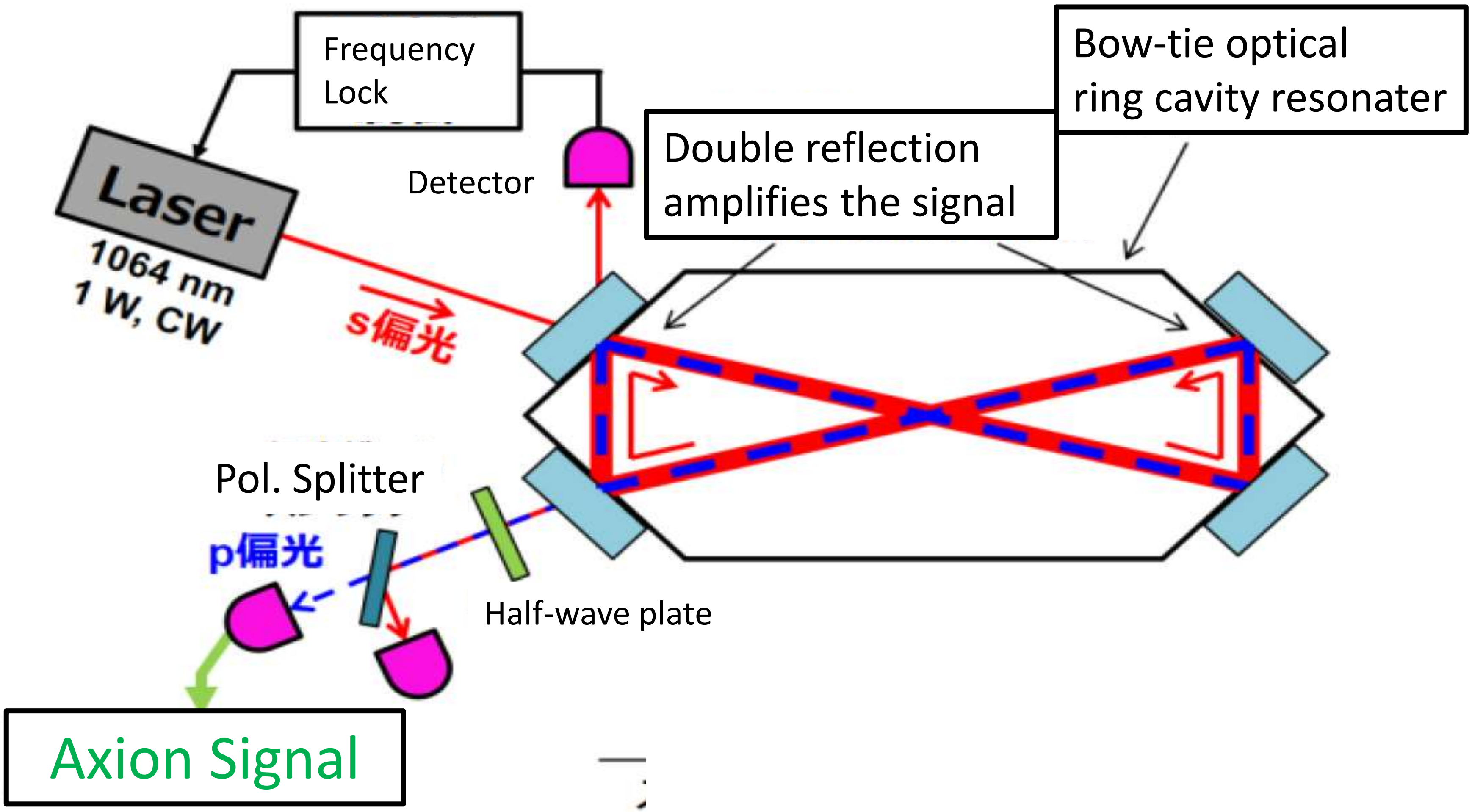




New experiment : DANCE

Dark matter Axion search with riNg Cavity Experiment

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



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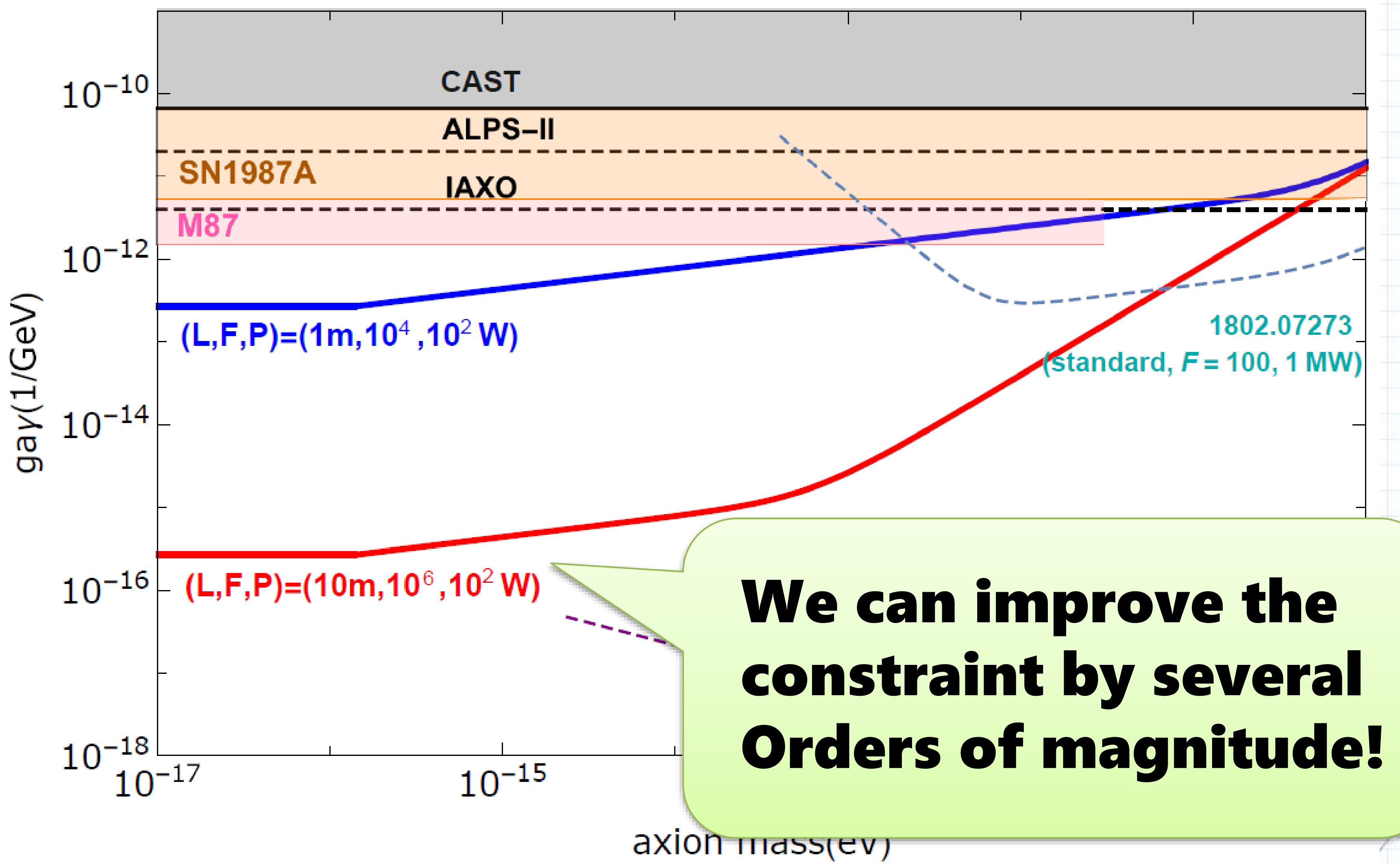
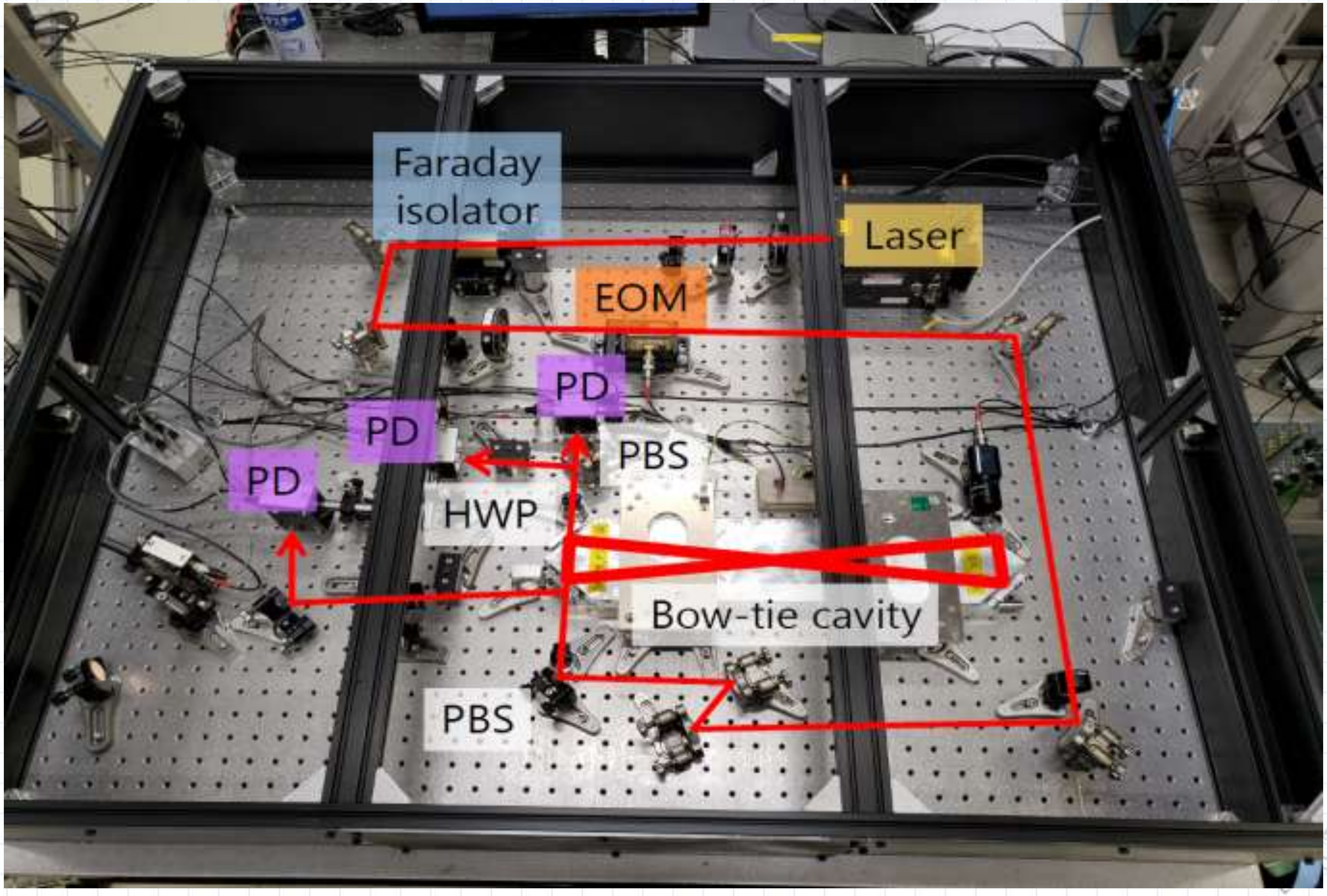


We can improve the constraint by several Orders of magnitude!

New experiment : DANCE

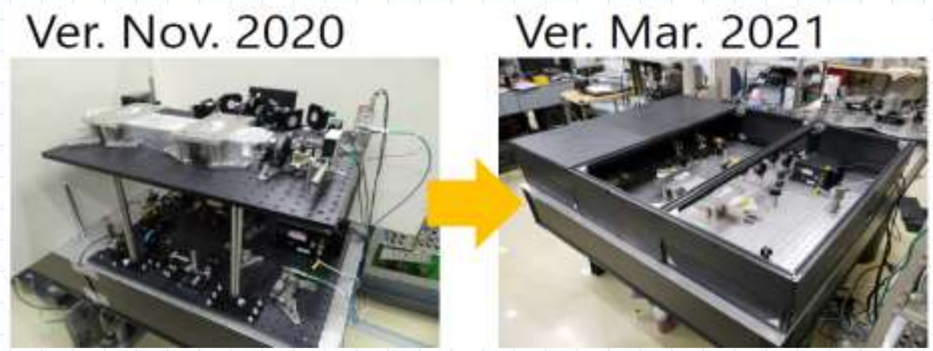
[Obata, TF, Michimura(2018)]

A prototype experiment is on-going in U. Tokyo!



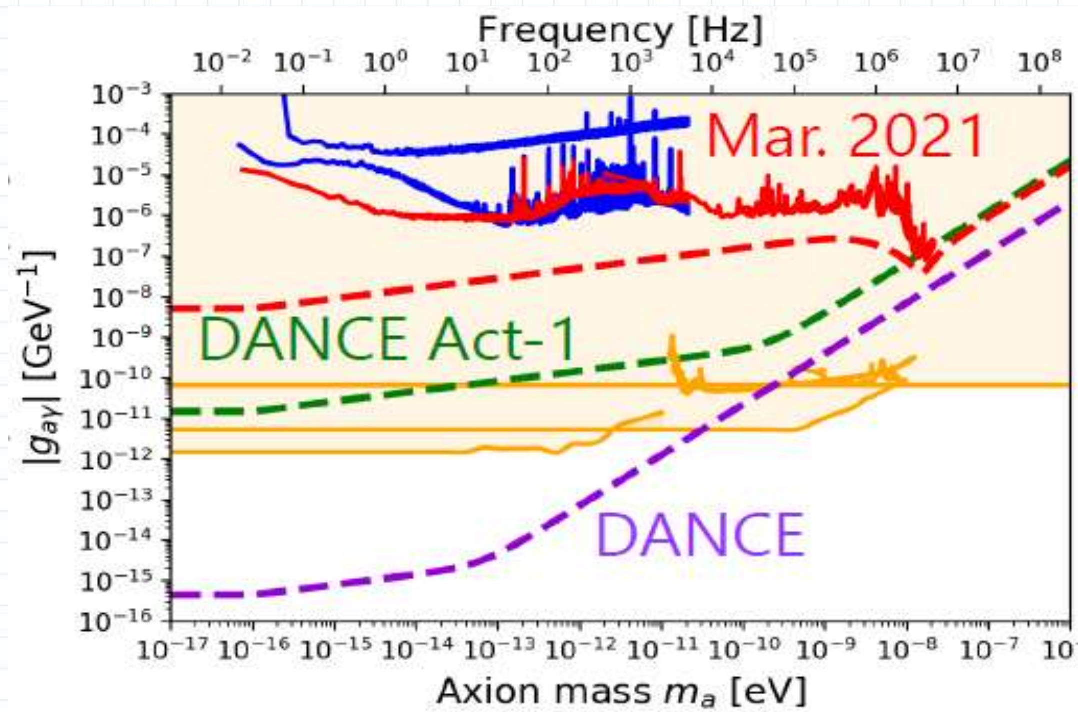
New experiment : DANCE

- We got a grant (35kUSD/yr) last year and started with a 50cm-size prototype.



- We (2 students) work on noise hunting and 1 postdoc will join in fall.

- Long way to go to get the ideal sensitivity, but we're proceeding!



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WIMP (conventional)

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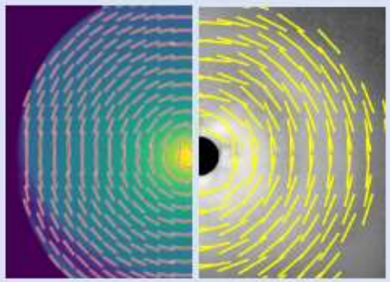

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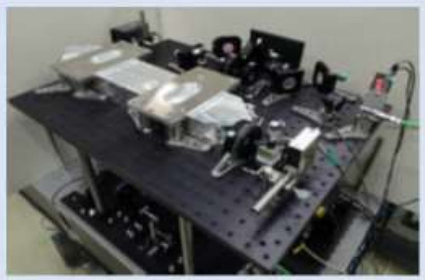

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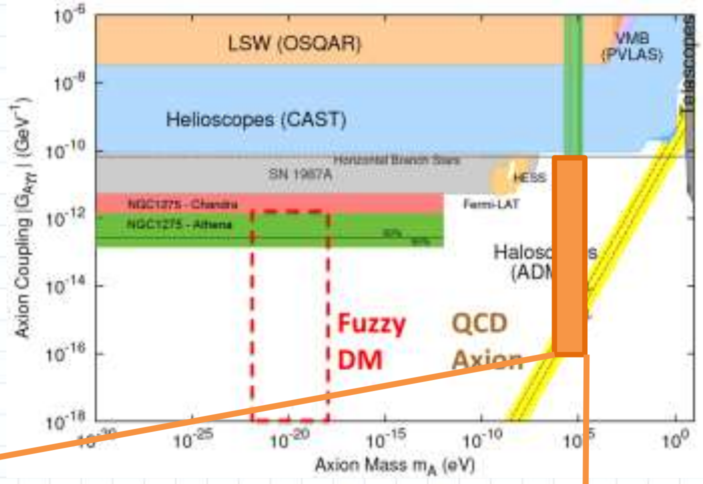
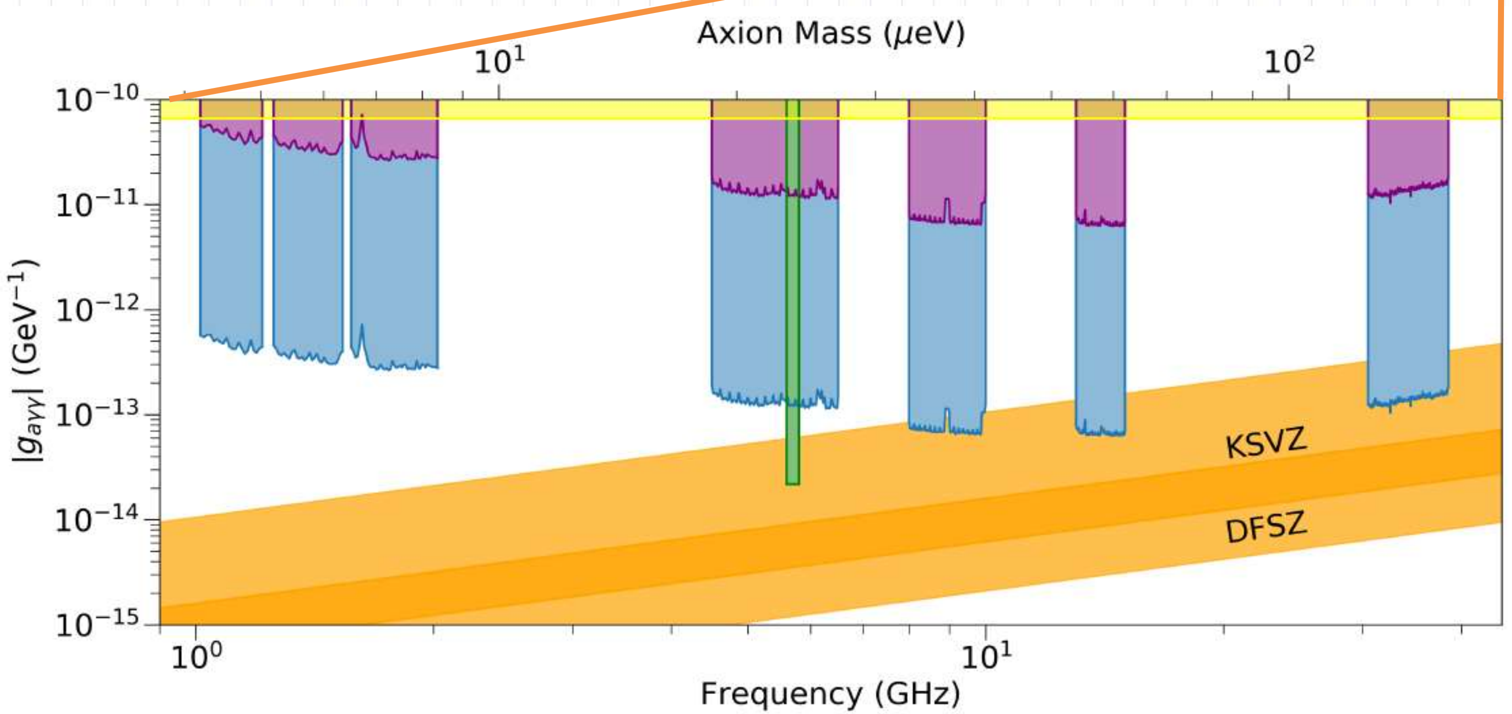
Outline of Talk

1. Introduction of ALPs
2. ALP Dark Energy
3. ALP Dark Matter
4. QCD Axion Search by Astro. Obs.

a-γ conversion around NS

Darling (2020) put a new limits on axion DM from a magnetar (PSR J1745-2900)





a-γ conversion around NS

- EoMs for a&γ in matrix form

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

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

$m_\gamma^2 = \omega_{pl}^2 = 4\pi\alpha n_e/m_e$

$$\left[\omega^2 + \partial_z^2 + \begin{pmatrix} -m_\gamma^2 & gB\omega \\ gB\omega & -m_a^2 \end{pmatrix}\right]\begin{pmatrix} \gamma \\ a \end{pmatrix} = 0\ ,$$

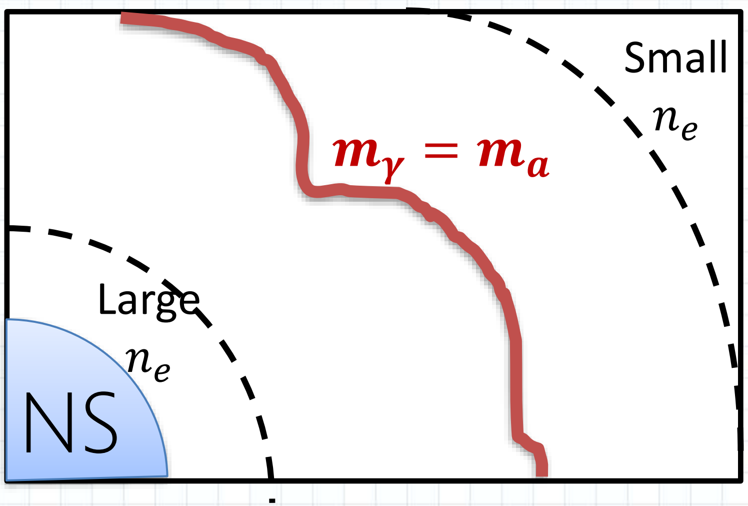
- Same as neutrino oscillation!

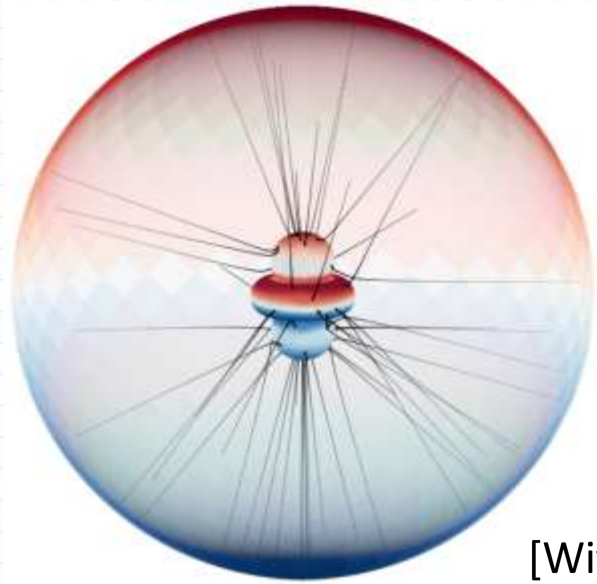
Mixing angle $\quad \sin 2\theta = \dfrac{\beta}{\sqrt{\beta^2 + (m_\gamma^2 - m_a^2)^2}} \qquad (\beta \equiv 2gB\omega)$

Conversion is maximized at $m_\gamma = m_a$

a-γ conversion around NS

When $m_\gamma = m_a$? ⇒ Notice $m_\gamma \propto n_e^{1/2}(x)$



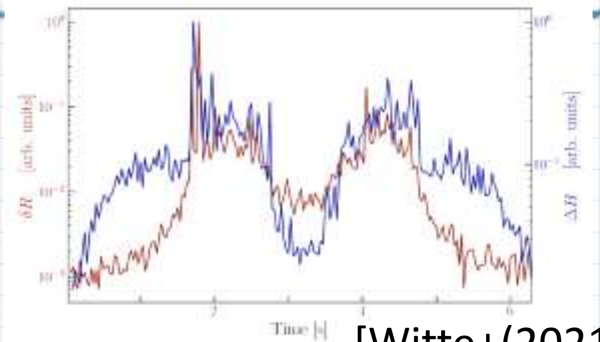


[Witte+(2021)]

At this sweet spot (surface), the most efficient a-γ conversion occurs: **ADM⇒radio wave**

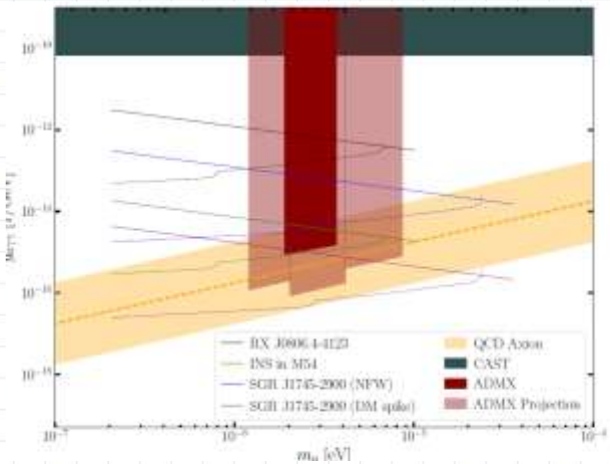
a-γ conversion around NS

Detailed studies are await to determine the spectrum, etc

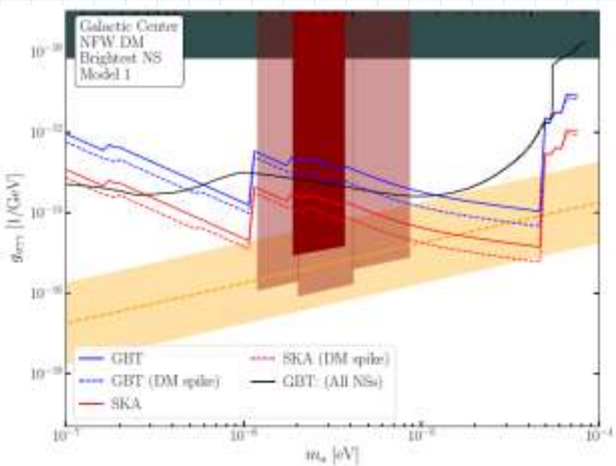


[Witte+(2021)]

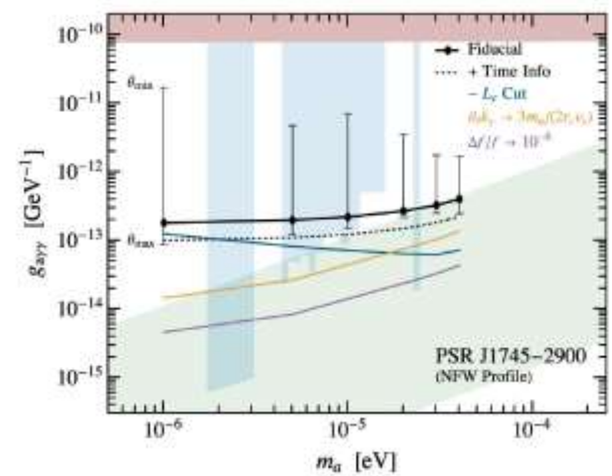
The sensitivity to ADM is unsettle...



[Hook+(2018)]



[Safdi+(2019)]



[Witte+(2021)]

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Summary

- ALPs are a well-motivated DM/DE candidate
  Its coupling to photon causes Birefringence

- CMB found cosmic birefringence $\beta = 0.35^\circ \pm 0.14^\circ$.
  It may indicate DE is ALP with $m \lesssim H_0 \simeq 10^{-33}\,\mathrm{eV}$

- Observations of protoplanetary disks are useful
  to search for ADM in Fuzzy DM range, $m \sim 10^{-22}\,\mathrm{eV}$.

- Laser experiments are sensitive to $10^{-17} < m/\mathrm{eV} < 10^{-10}$

- Radio waves from neutron stars provide a new
  probe of ADM in the QCD axion mass range

Thank you !

THE THEME
OF CHAPTER IS...

Backup Slides

SN1987A (2015)

JCAP **02**, 006 (2015)

- Absence of gamma-ray signal from SN1987A
  - ALPs would be emitted from core-collapse supernova via Primakoff process
  - ALPs eventually convert into gamma-ray in the magnetic field of Milky Way (~ μG ~ 0.1 nT over ~ kpc)

- data from GRS (Gamma Ray Spectrometer) of SMM (Solar Maximum Mission) satellite
  coincidence with neutrino signal was used
- Better limit possible by Fermi-LAT observation
- Dependent on supernova models and Milky Way magnetic field

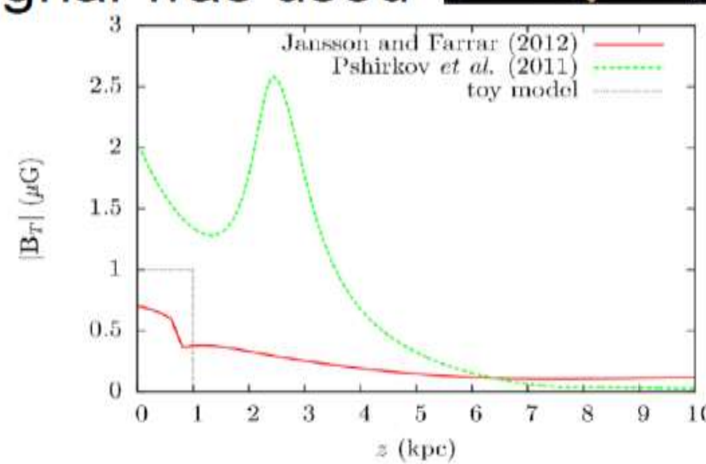


Figure 8. Norm of the transverse Galactic magnetic field as a function of the distance in the direction of SN1987A in various models.

By courtesy of Y. Michimura

M87 (2017)

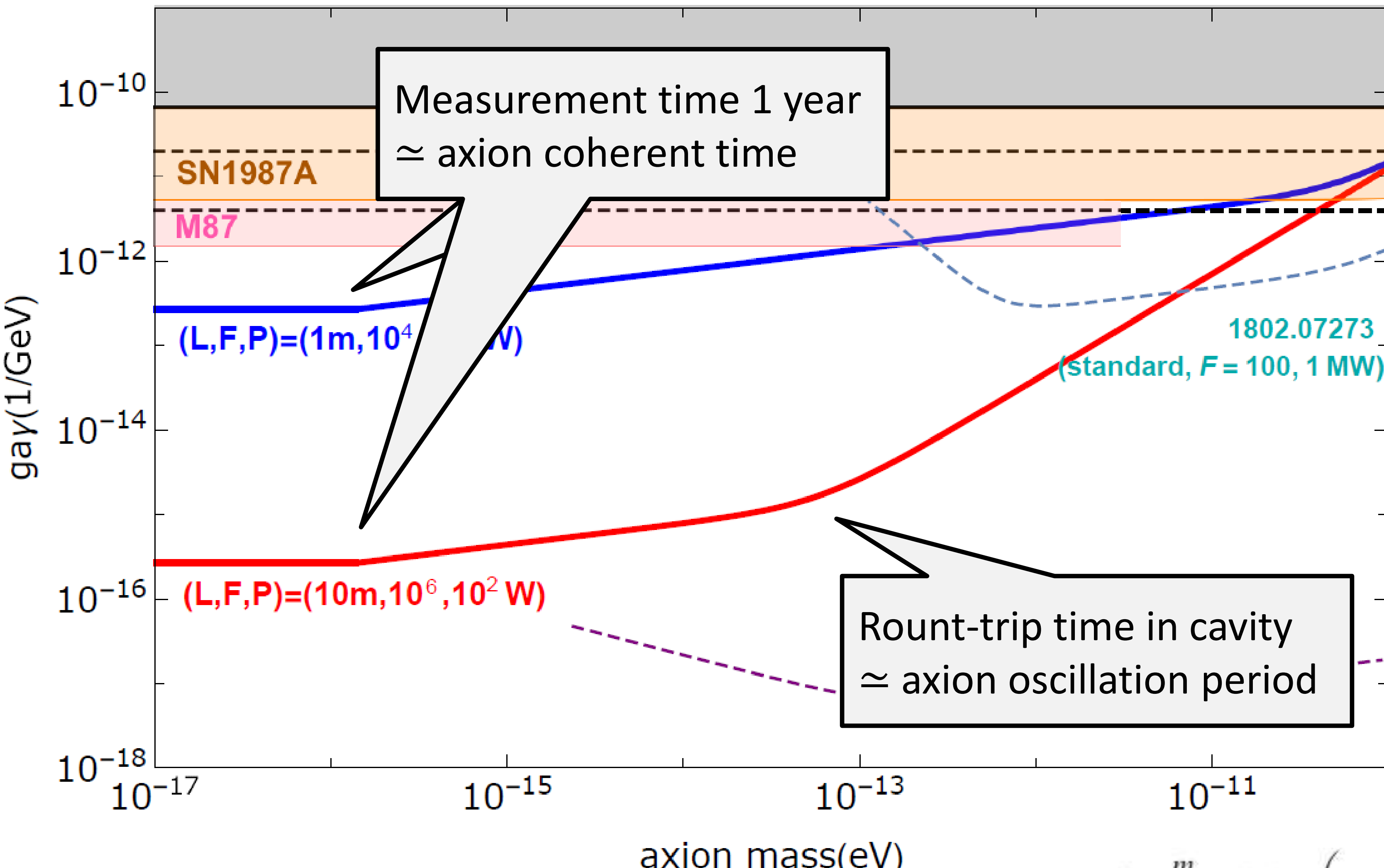
JCAP **12**, 036 (2017)

- Absence of substantial irregularities in the X-ray power law spectrum from M87 galaxy in Virgo cluster
  - close (16.4 Mpc) and hosts SMBH bright in X-ray
  - X-ray photon to ALPs conversion under magnetic field
  - magnetic field in Virgo (~35-40 μG) modeled from Faraday rotation measurements
    (magnetized plasma is birefringent and induces wavelength-dependent rotation of polarization of photons)
  - photon-ALP conversion probability is energy dependent and thus X-ray spectrum would change
- data from Chandra was used
- Dependent on Virgo magnetic field

By courtesy of Y. Michimura

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 τ_a, the sensitivity improves only slowly

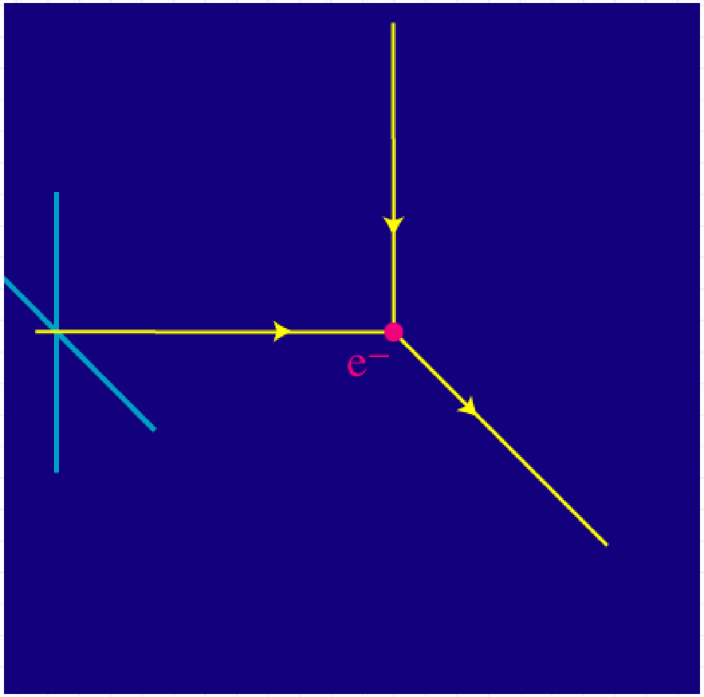
$$\mathrm{SNR} \propto \sqrt{T} \xrightarrow{\tau_a < T} (\tau_a T)^{1/4}$$

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

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

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

Polarization of scattered light

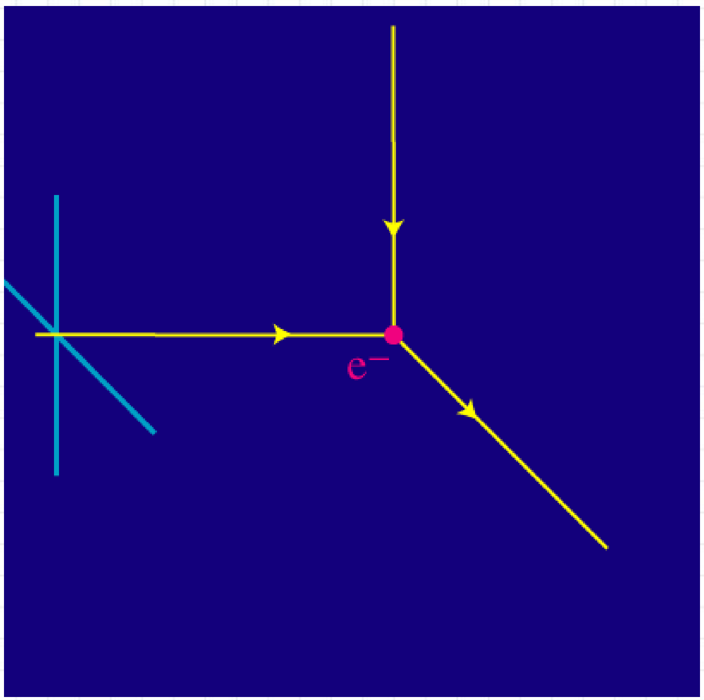


Consider incoming radiation from the left being scattered by 90 degrees out of the screen:

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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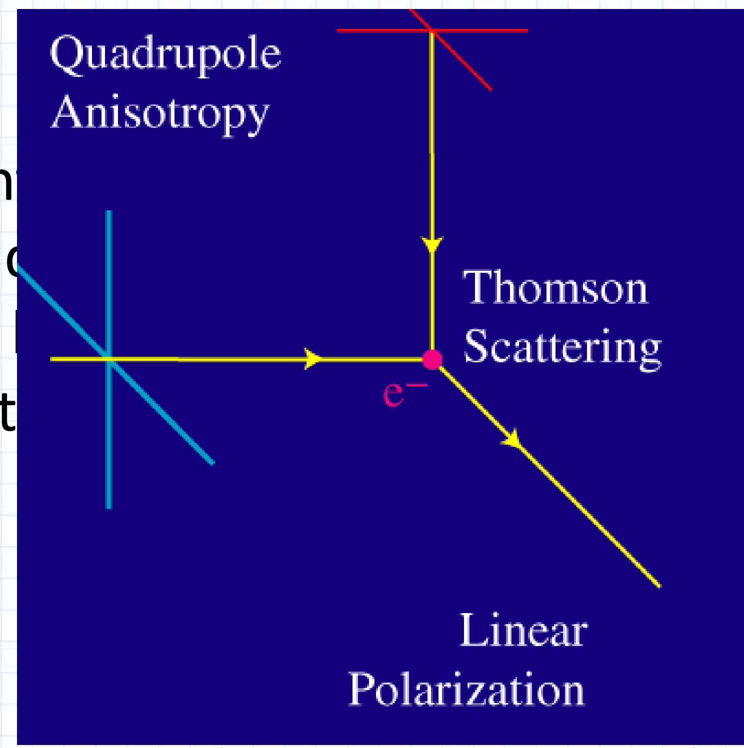
only one
gets scatt



[Credit: Weyne Hu's homepage]

Long-term Obs of PPD

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