PRESENTATION

Hunting Axion Dark Matter with Protoplanetary Disk Polarimetry

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(Waseda Univ.)

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

10^{th}, Feb, 2022. @Online

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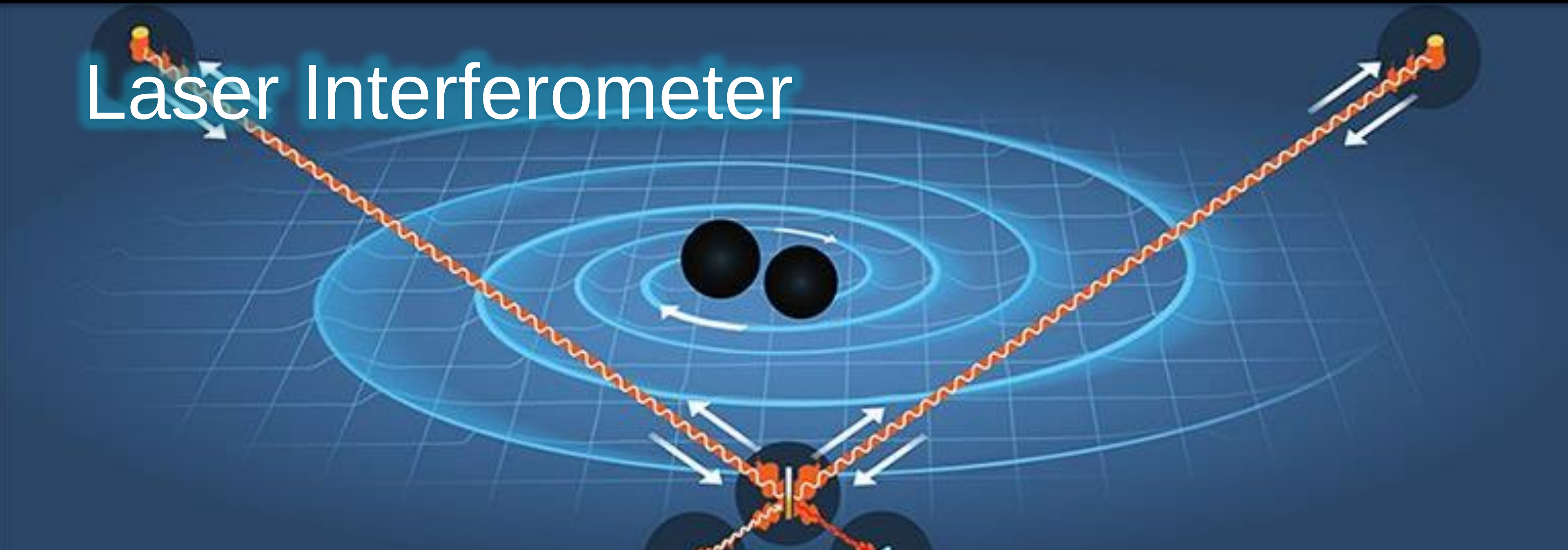
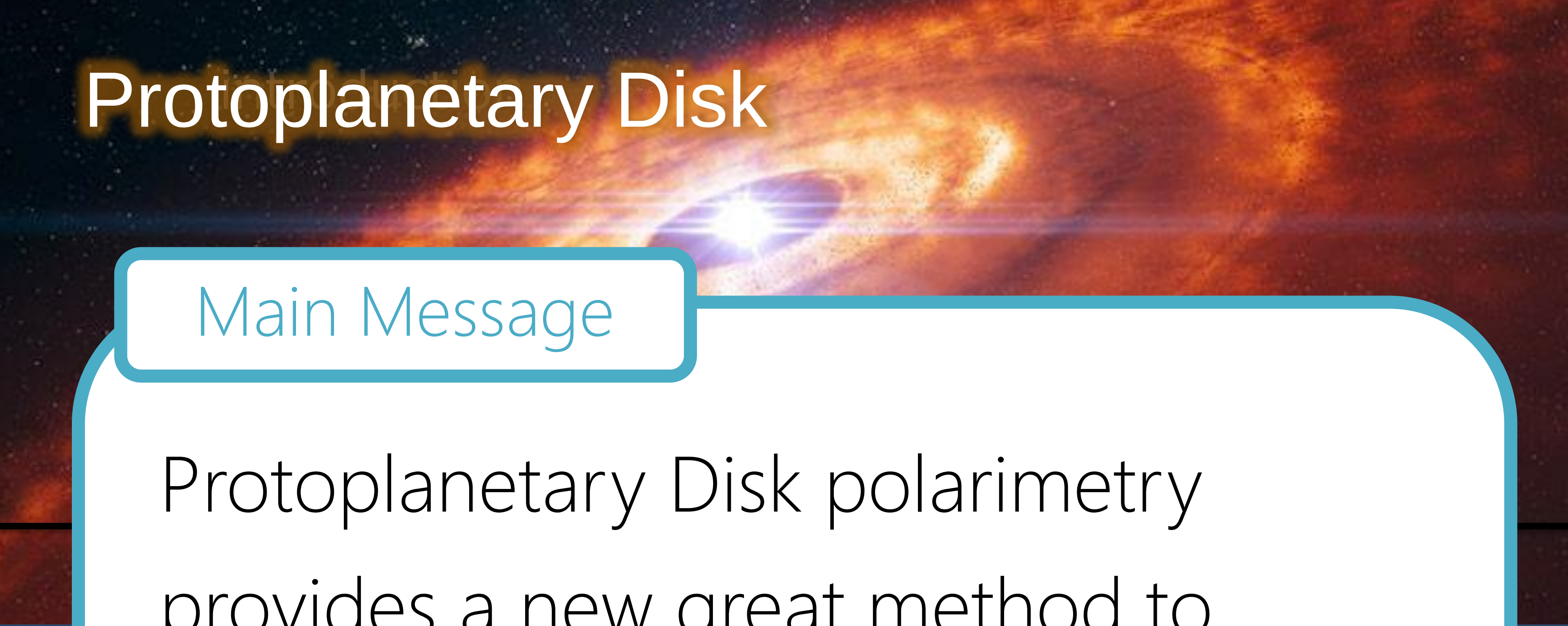
早稲田大学高等研究所
Waseda Institute for Advanced Study


Protoplanetary Disk


Laser Interferometer

Protoplanetary Disk



Main Message

Protoplanetary Disk polarimetry provides a new great method to search for axion dark matter!

New obs this spring ➡ Best Sensitivity

Plan of Talk

1. Introduction
2. ADM Birefringence
3. Protoplanetary Disk
4. New observation
5. Summary

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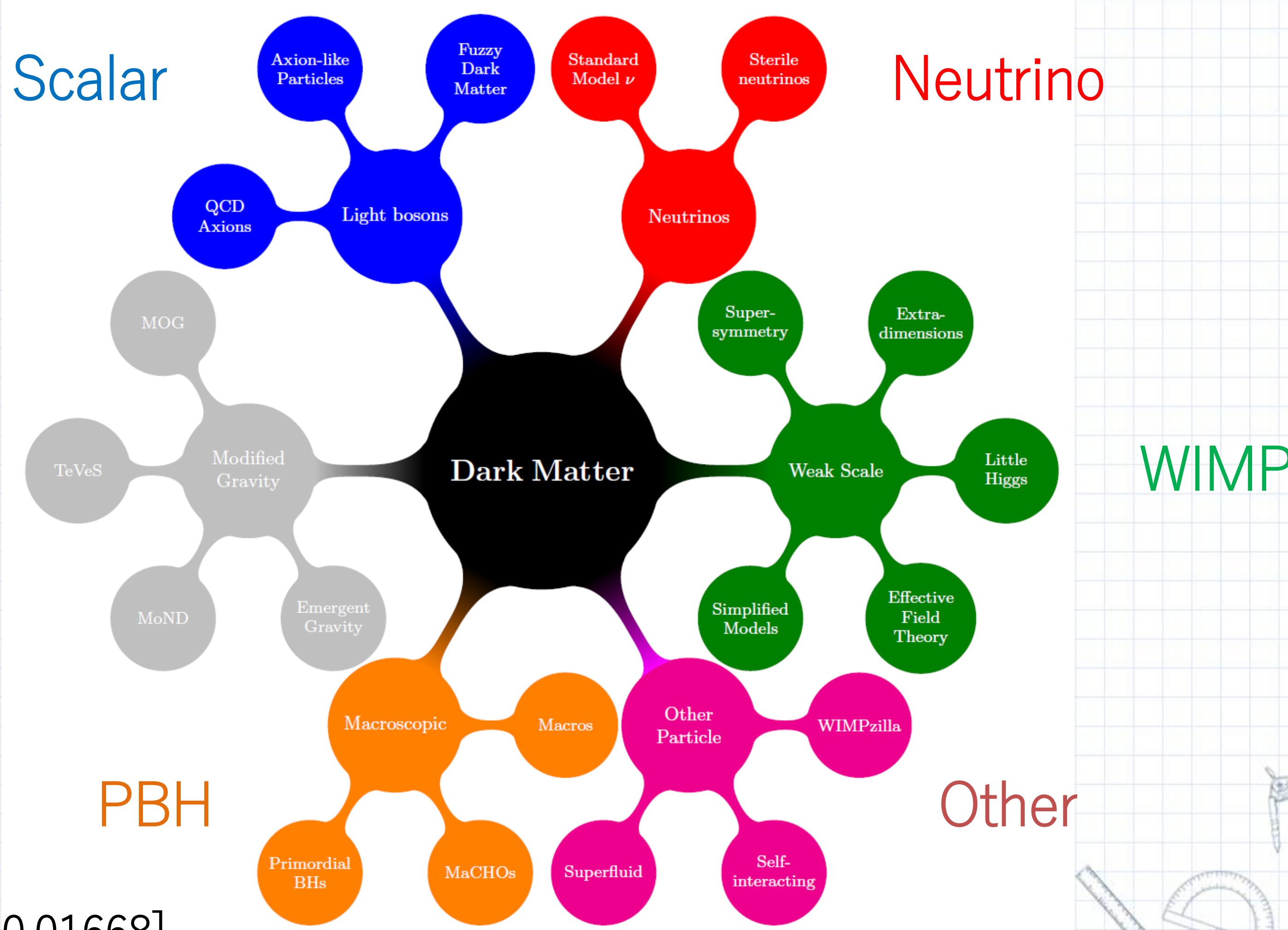
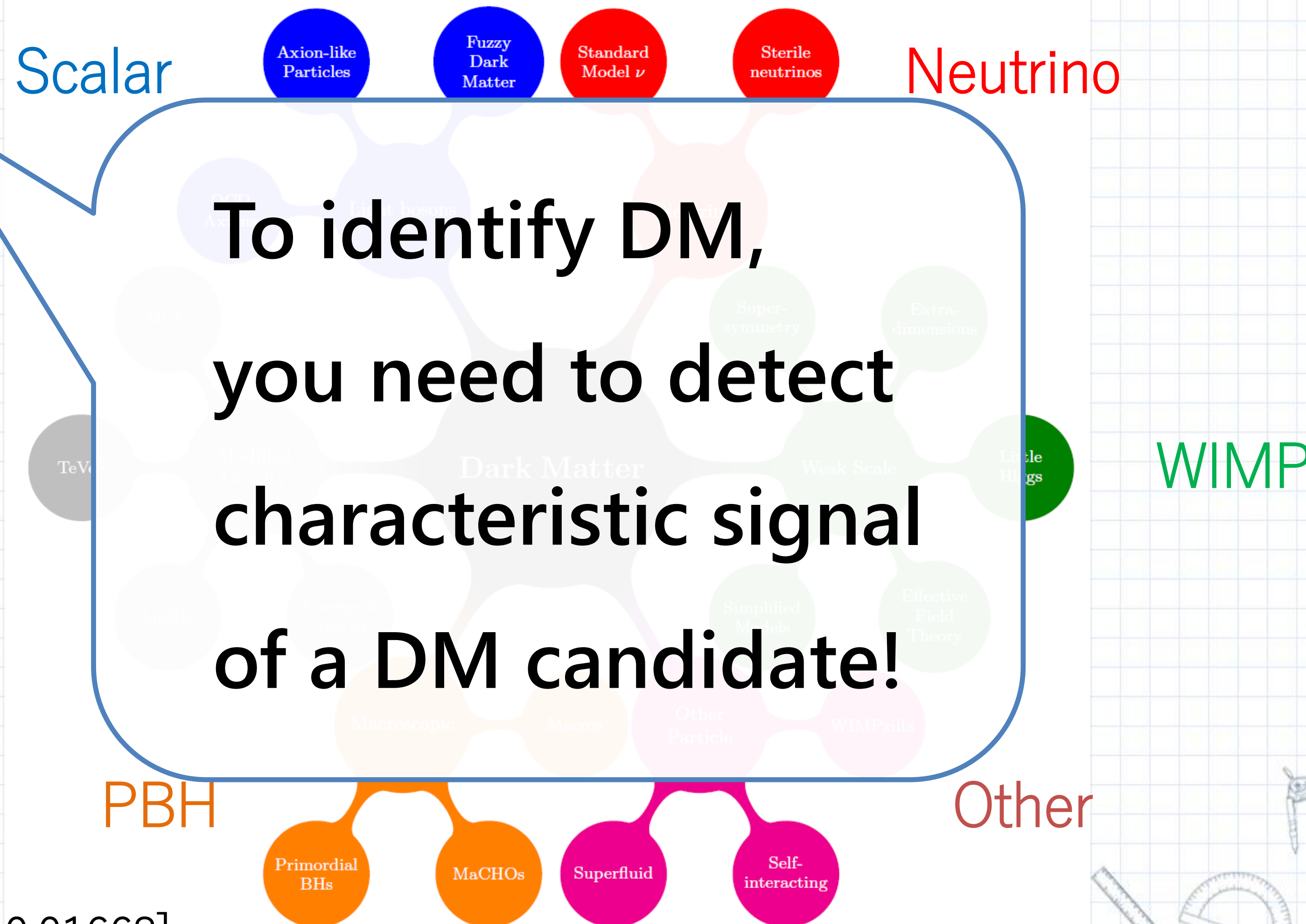
Who is Dark Matter?

DM candidates



Berton&Tait[1810.01668]

DM candidates



To identify DM,
you need to detect
characteristic signal
of a DM candidate!

Berton&Tait[1810.01668]

DM candidates

Scalar DM

Berton&Tait[1810.01668]

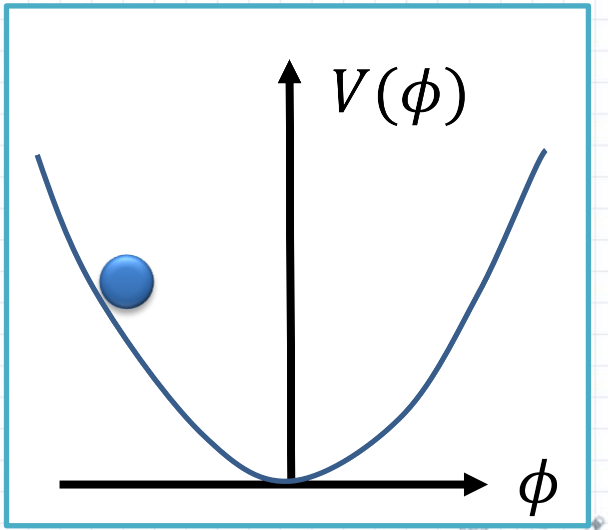
Scalar Dark Matter (∋ Axion & ALPs)

- Different from particle DMs: production & evolution

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

- Oscillating Scalar Field: $m \gg H$

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



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

What characterizes ADM?

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

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

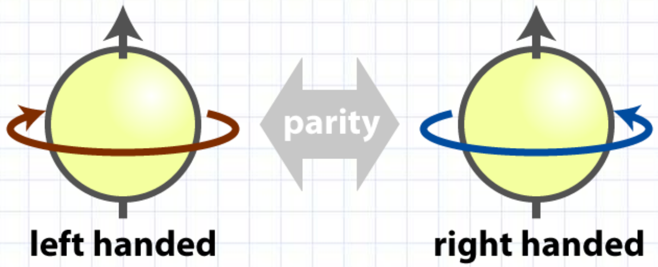
Fuzzy DM
(cf. Lyman-α limit)

Decay into γ
(hopeless to detect)

What characterizes ADM?

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

- ADM breaks parity



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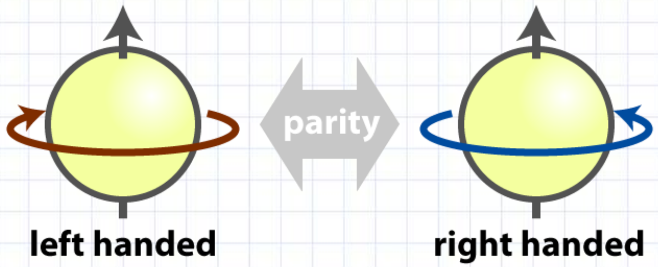

- ADM may be coupled to photon!!

What characterizes ADM?

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- 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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New terms!

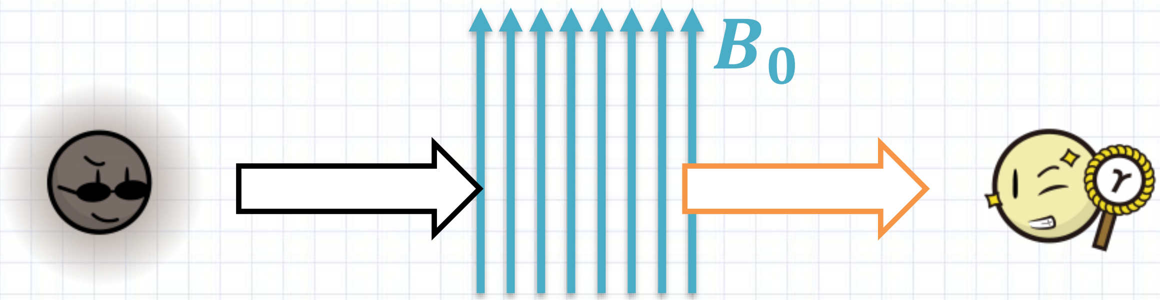
Conventionally constant magnetic field is introduced

Axion-Photon Conversion

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

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

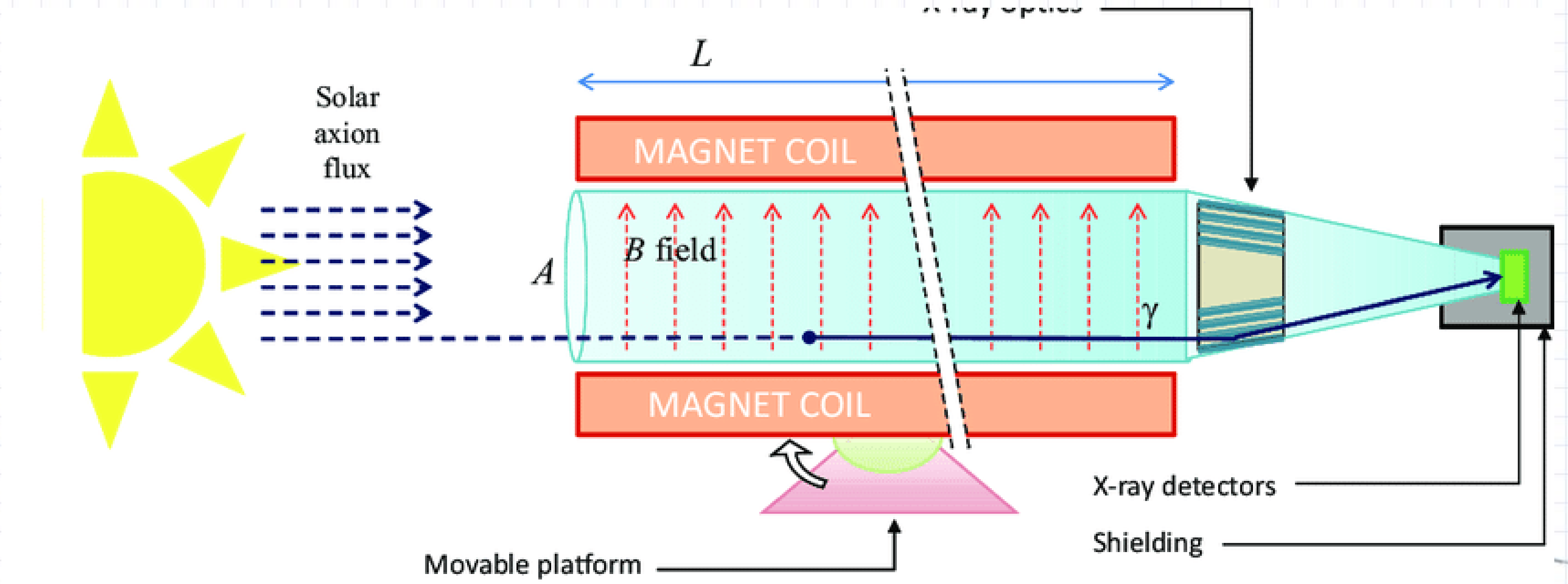
Axion: $$\left[\partial_t^2 - \partial_i^2 + m^2\right]\phi = -g\boldsymbol{B_0}\cdot\dot{\boldsymbol{A}}$$



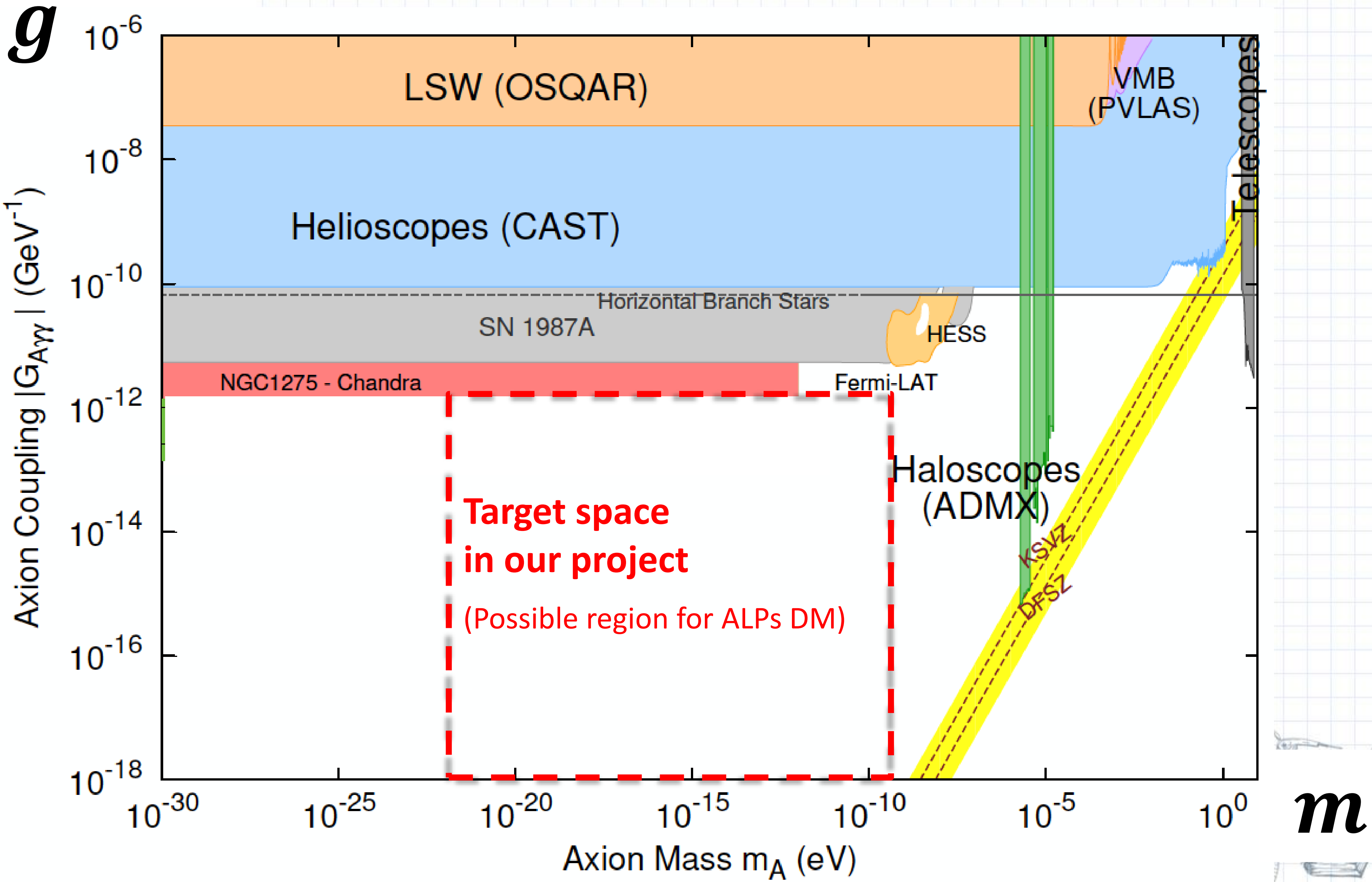
introduction

Experiments with AP conversion

- Axion Helioscope



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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New terms!

Anything other than magnetic fields?

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New experiment

What if Axion is Dark Matter?

Birefringence

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

$-m\phi_0 \sin(mt)$

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

[No superluminality: 1201.4935]

Birefringence

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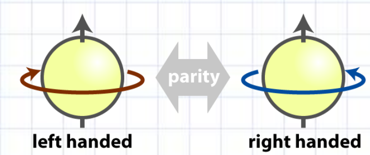
$-m\phi_0 \sin(mt)$

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

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

⇒ Dispersion relations of Left/Right Pol. are modified

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



Speed of light changes depending on polarization!

Birefringence

- Another consequence: Rotation of liner pol. Plane

Linear pol. Photon can be decomposed into circular pol.

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

$t \longrightarrow t+T$

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

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

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

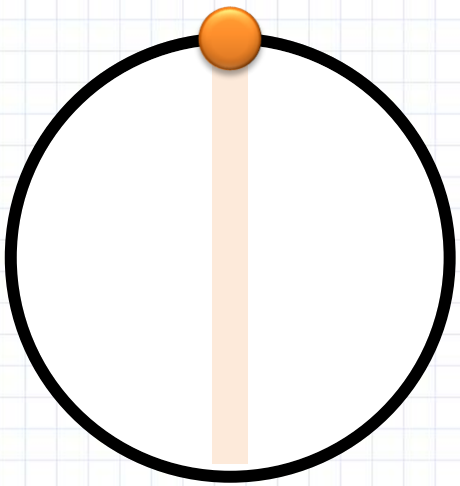
Birefringence

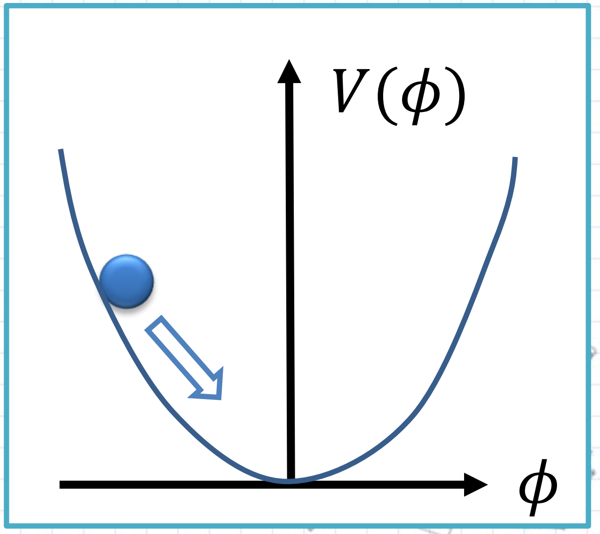
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- Rotation angle depends on Axion at boundaries

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

- Motion of the linear polarization plane





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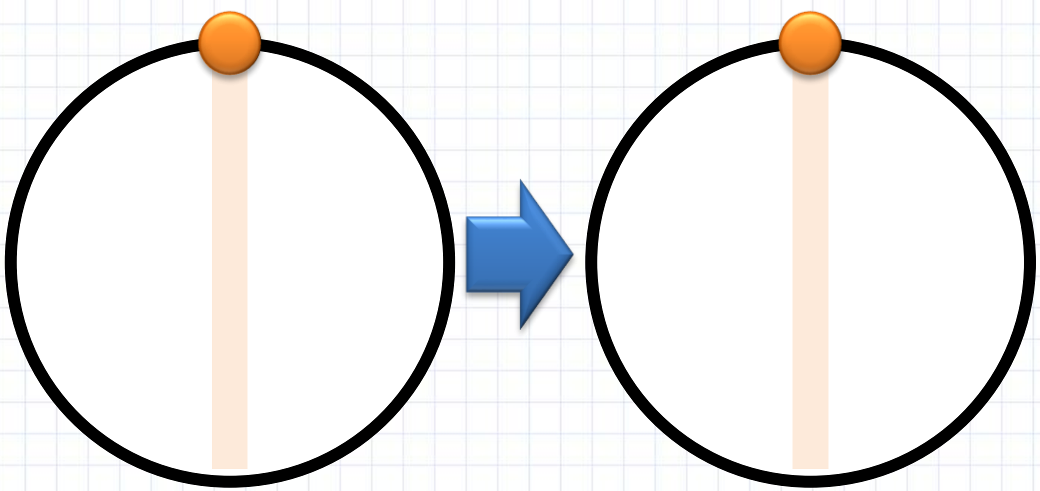

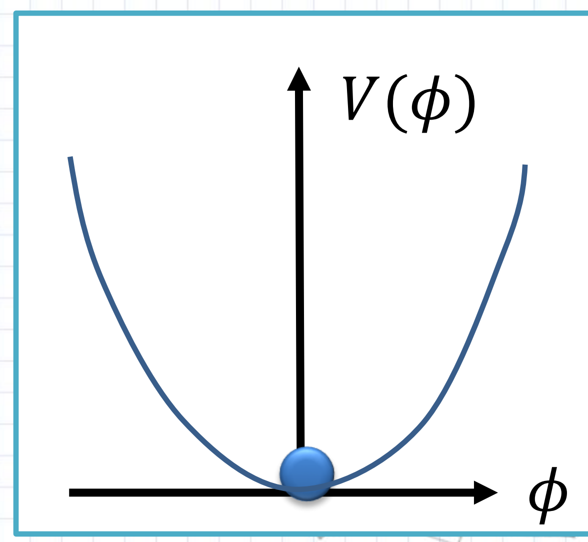

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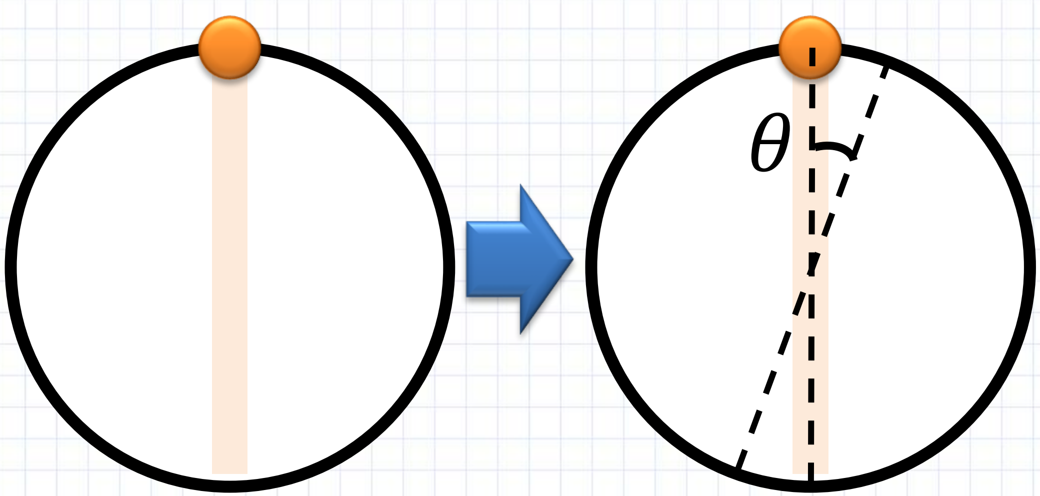

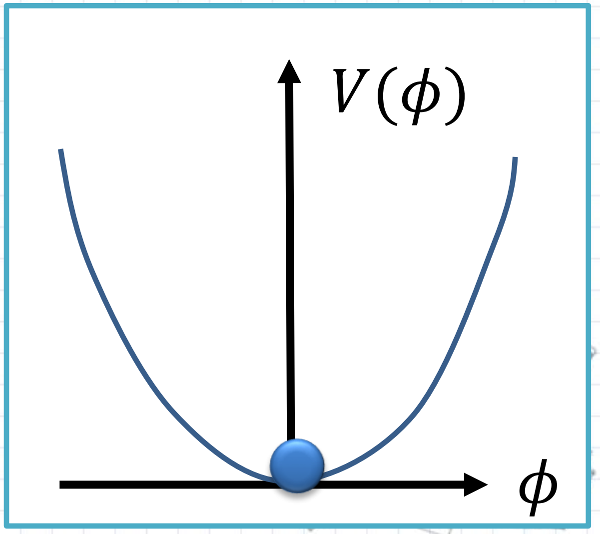

$$\rho_{\rm DM} = m^2\phi_0^2/2 \approx 0.3\ {\rm GeV/cm^3}$$

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 …

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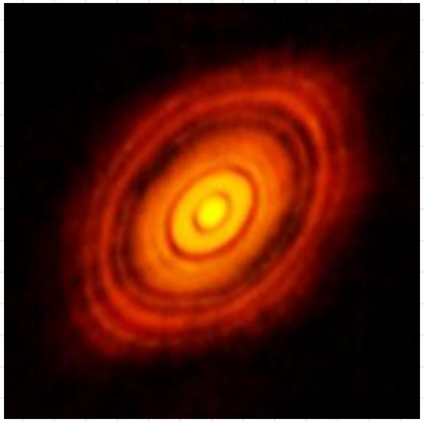
ProtoPlanetary Disk

- Observations of PPD can be used!

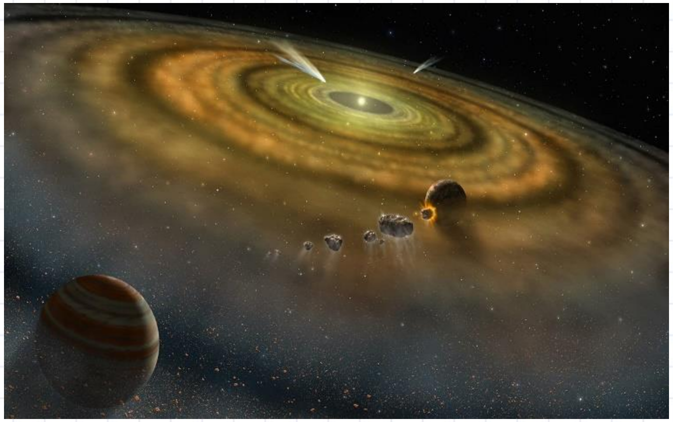
PPD is a flattened gaseous object surrounding a young star.

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

Real data

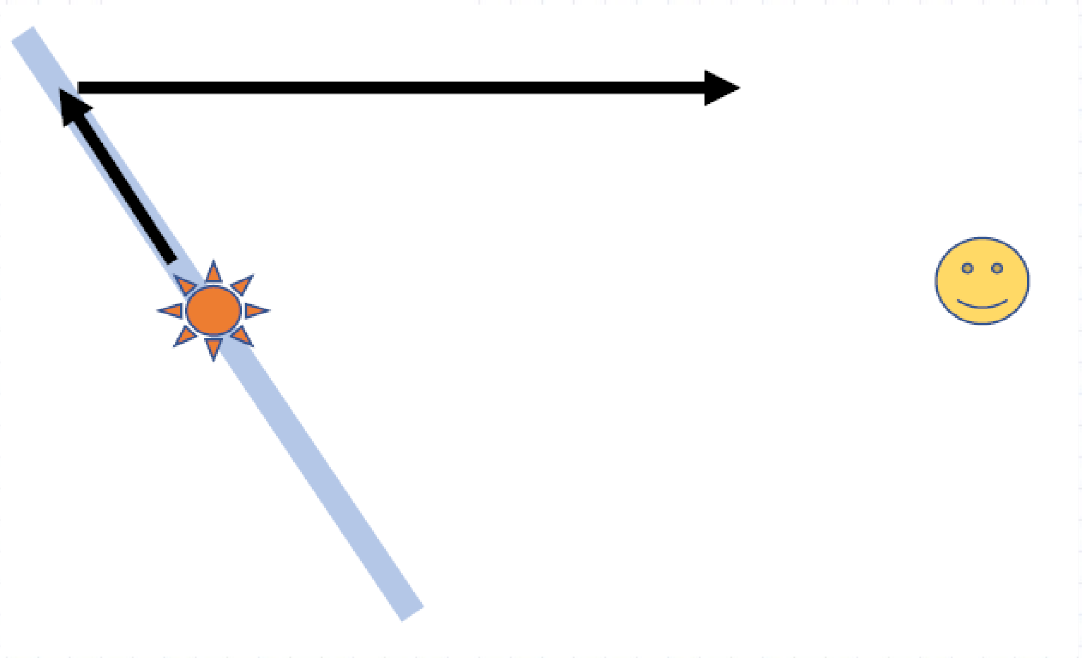


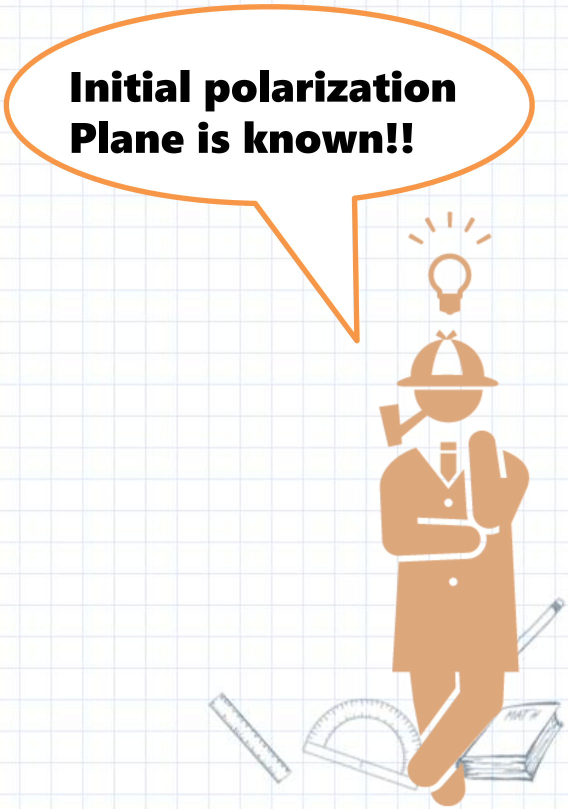
Artist's image



Polarization of PPD

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



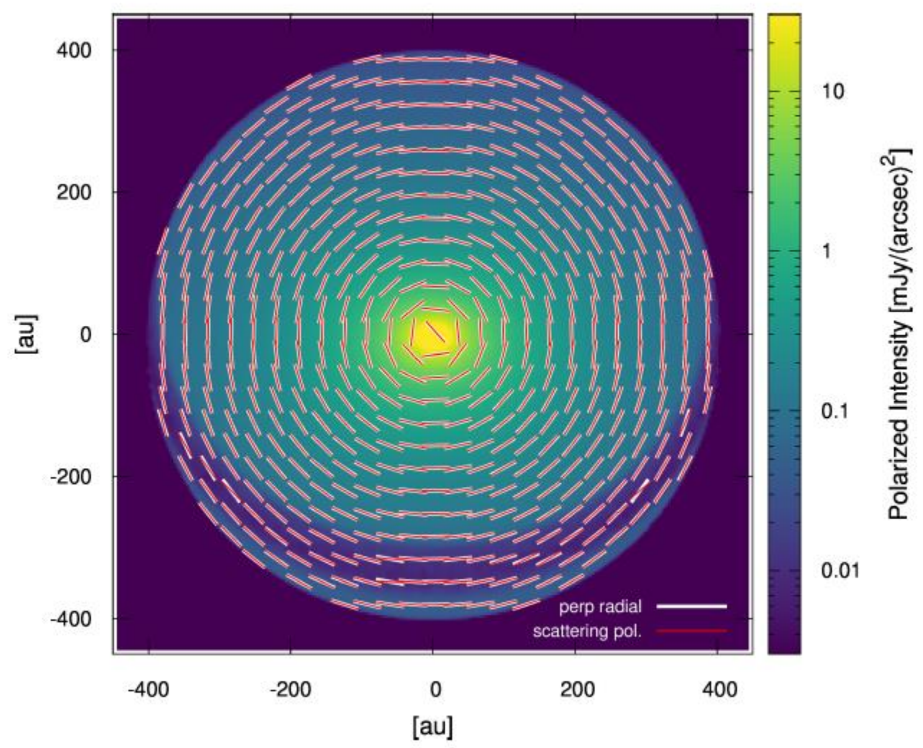


Obsevation of PPD

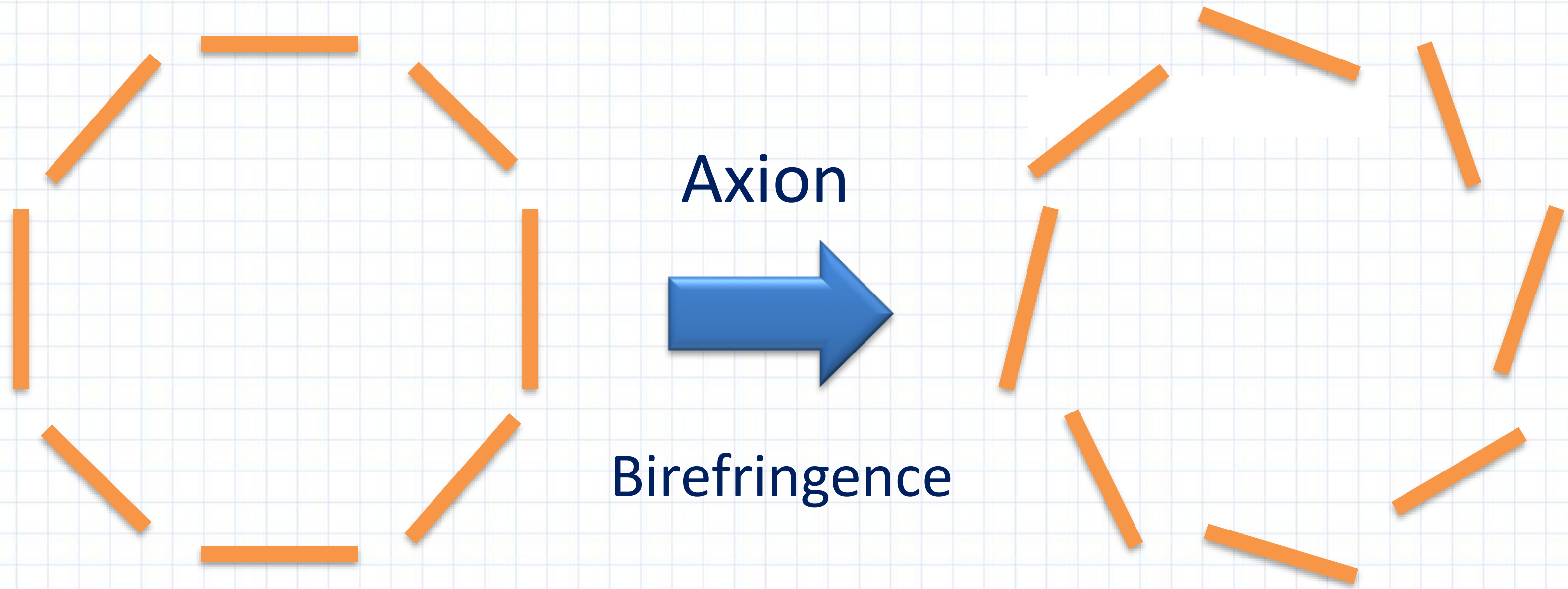
[Hashimoto et al. APJL729:L17(2011)]

- We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM



Axion DM rotates pol. plane?



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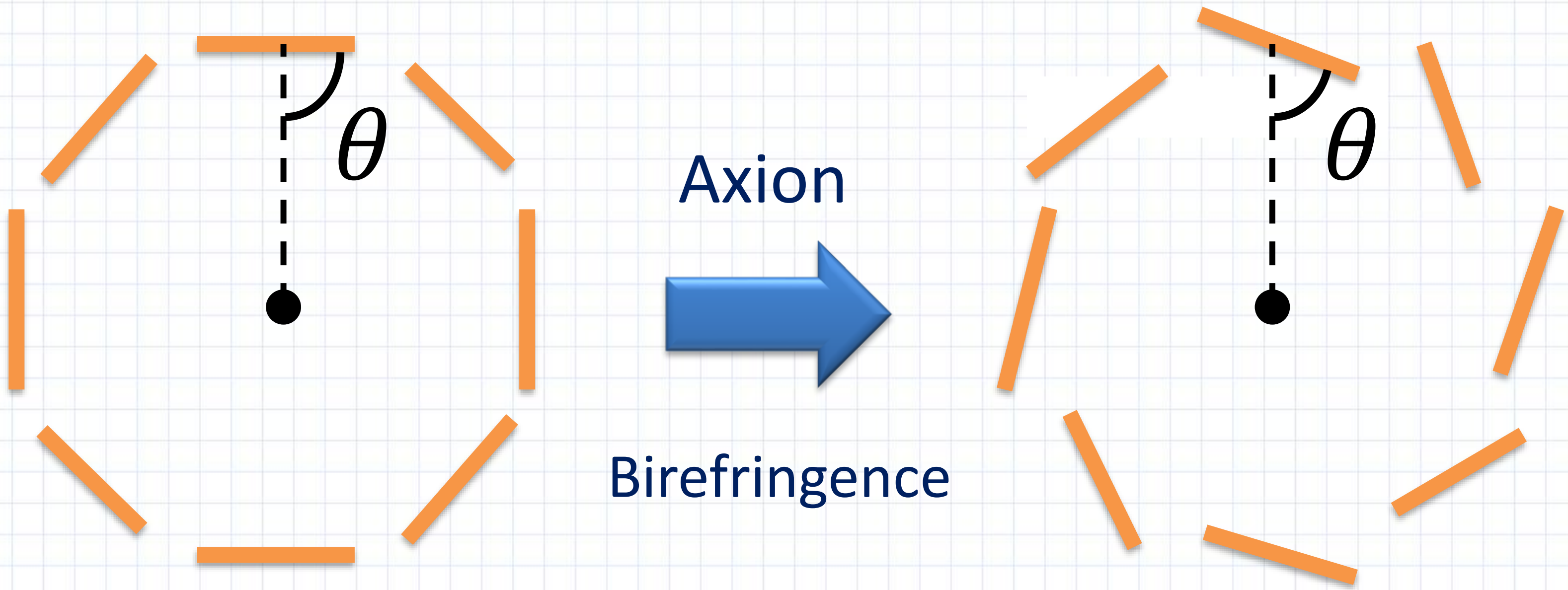

Is this angle 90° or not?

Obsevation of PPD

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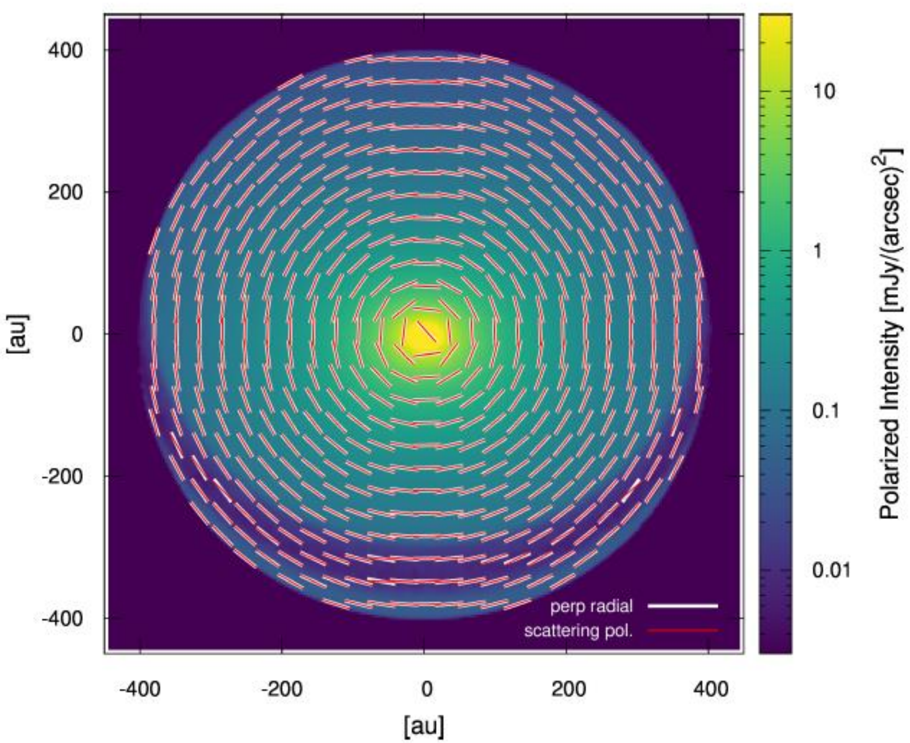
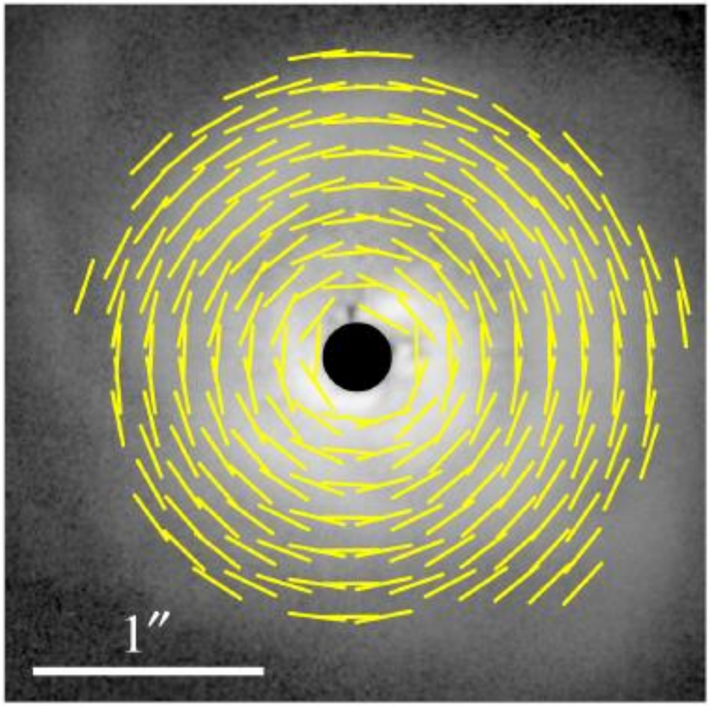


Observation by SUBARU



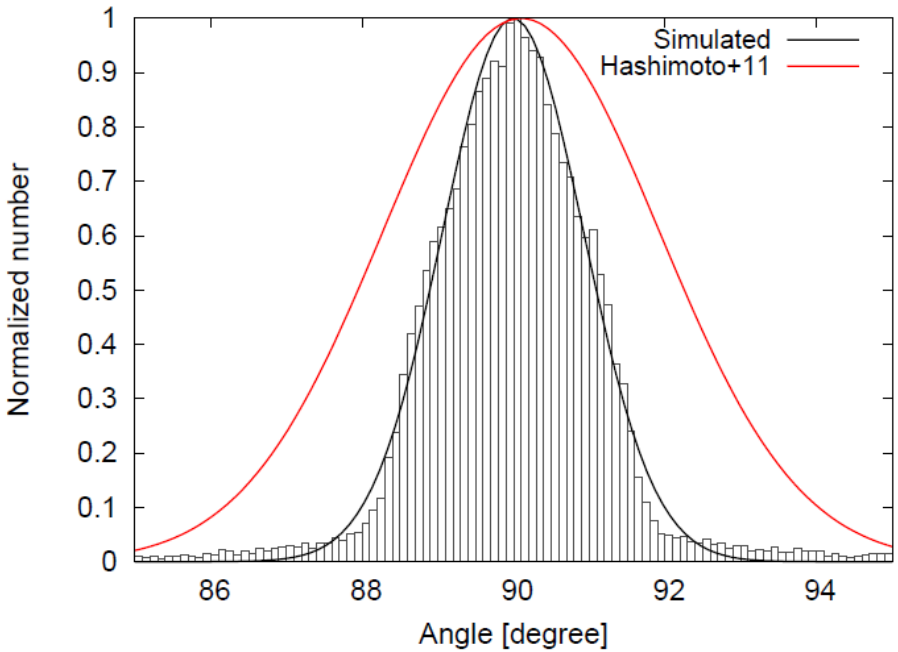
AB Aurigae (160pc away)

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

Obsevation of PPD

The observation data reveals

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



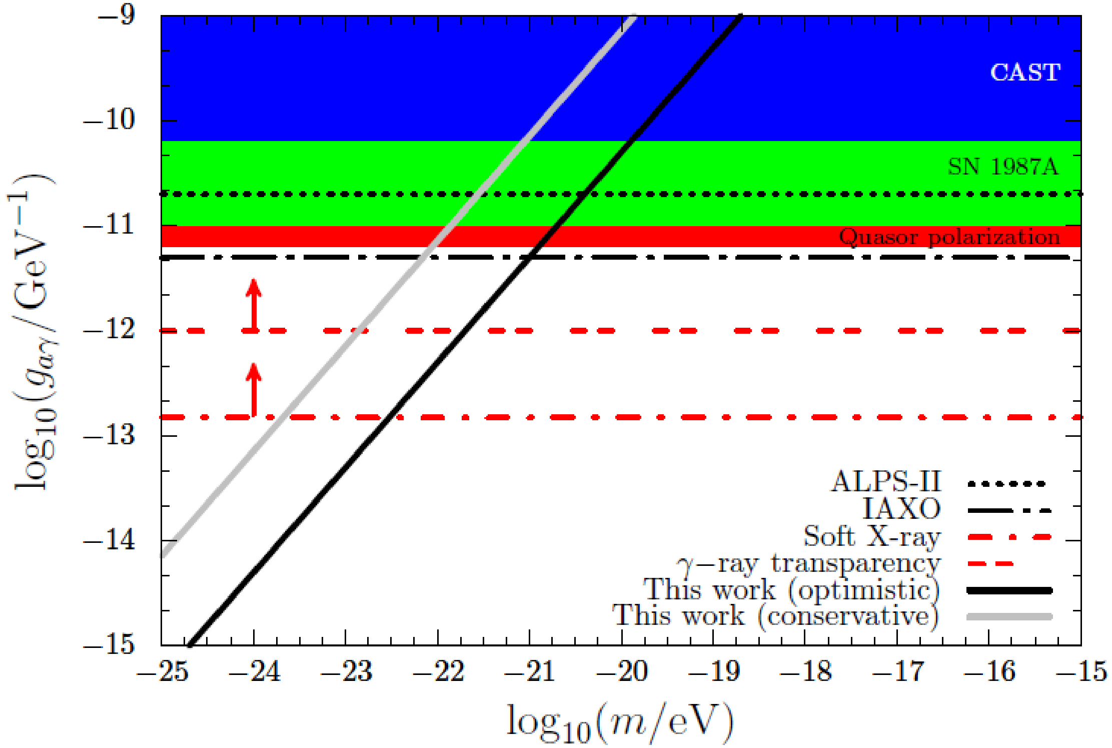
Our simulation confirms the effect of multiple Scatterings is negligible.

[TF. Tazaki & Toma (2018)]

New constraint

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

g



m[eV]

[TF. Tazaki & Toma (2018)]

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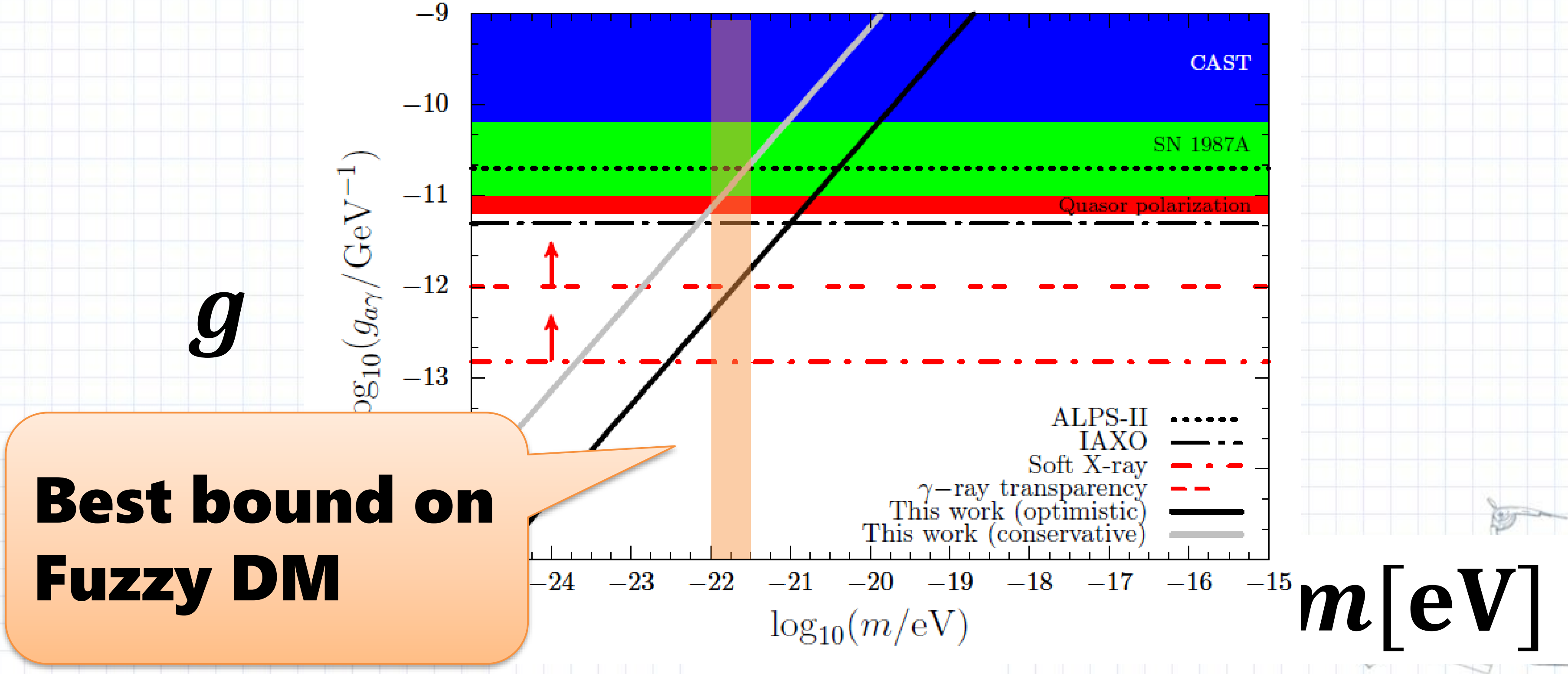

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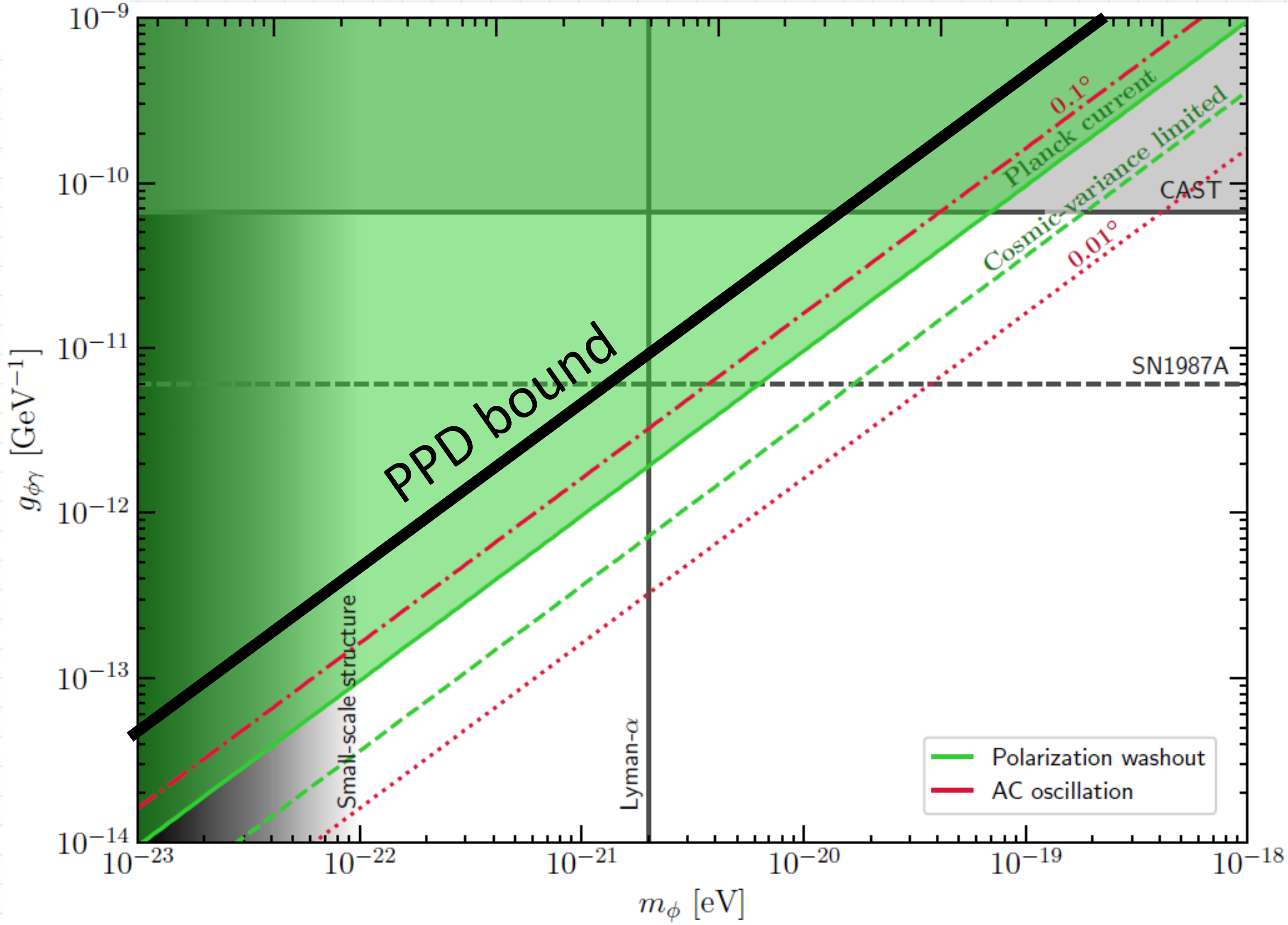
Fedderke, Graham & Rajendran: 1903.02666



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

CMB constraint on Axion dark matter

The constraint on ADM is

Different from `cosmic birefringence' α

- CB α : polarization planes rotated (homogeneously) on full-sky
- Physical motivation: e.g. axionic quintessence (dark energy)
- Oscillating ADM does not produce CB α !!

⇨ **Search for α never discovers ADM**

CMB constraint on Axion dark matter

- Rotation angle depends on Axion at boundaries

$$\theta_{\mathrm{CMB}} = -\frac{g}{2}\left[\phi(t_{\mathrm{obs}}) - \phi(t_{\mathrm{LSS}})\right]$$

$$\frac{\phi_{\mathrm{LSS}}}{\phi_{\mathrm{obs}}} \sim 10^2 \quad \Rightarrow \quad \theta_{\mathrm{CMB}} \simeq \frac{g}{2}\phi_{\mathrm{LSS}}$$

ADM causes cosmic birefringence??

[Finelli & Galaverni (2009)]

CMB constraint on Axion dark matter

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$$\frac{\phi_{\mathrm{LSS}}}{\phi_{\mathrm{obs}}} \sim 10 \ldots$$

$$\theta \ldots \simeq \frac{g}{2}\phi_{\mathrm{LSS}}$$

ADM causes c… …refringence??

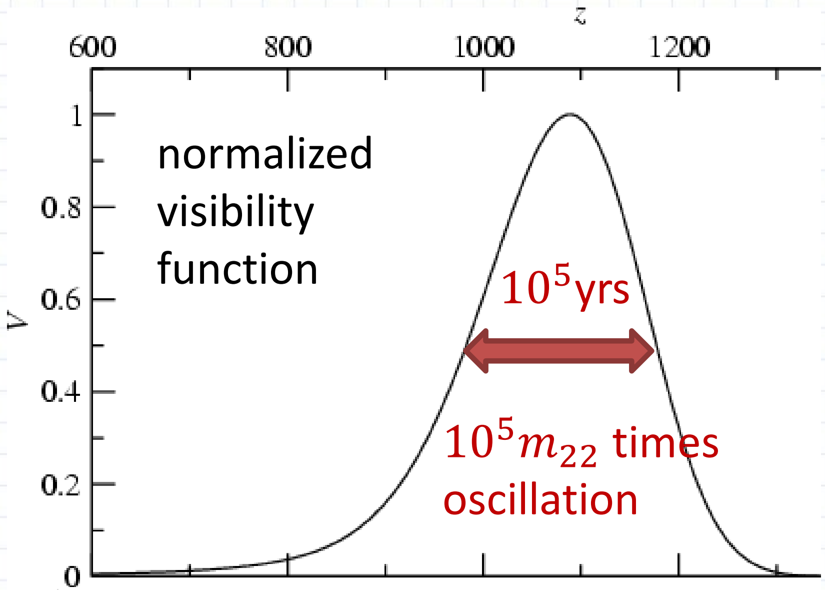
[Fine… …alaverni (2009)]

CMB constraint on Axion dark matter

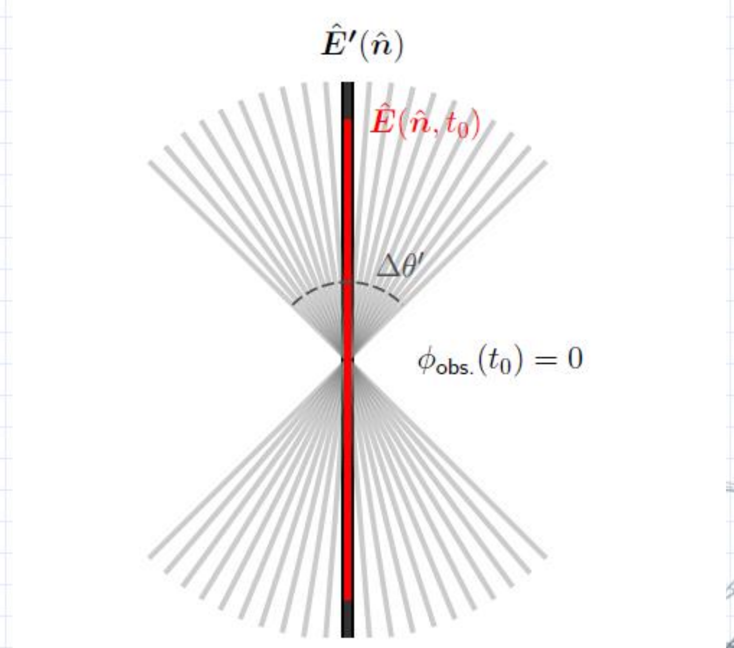
This term washes out CMB pol.

$$\theta_{\mathrm{CMB}} = -\frac{g}{2}[\phi(t_{\mathrm{obs}}) - \phi(t_{\mathrm{LSS}})]$$

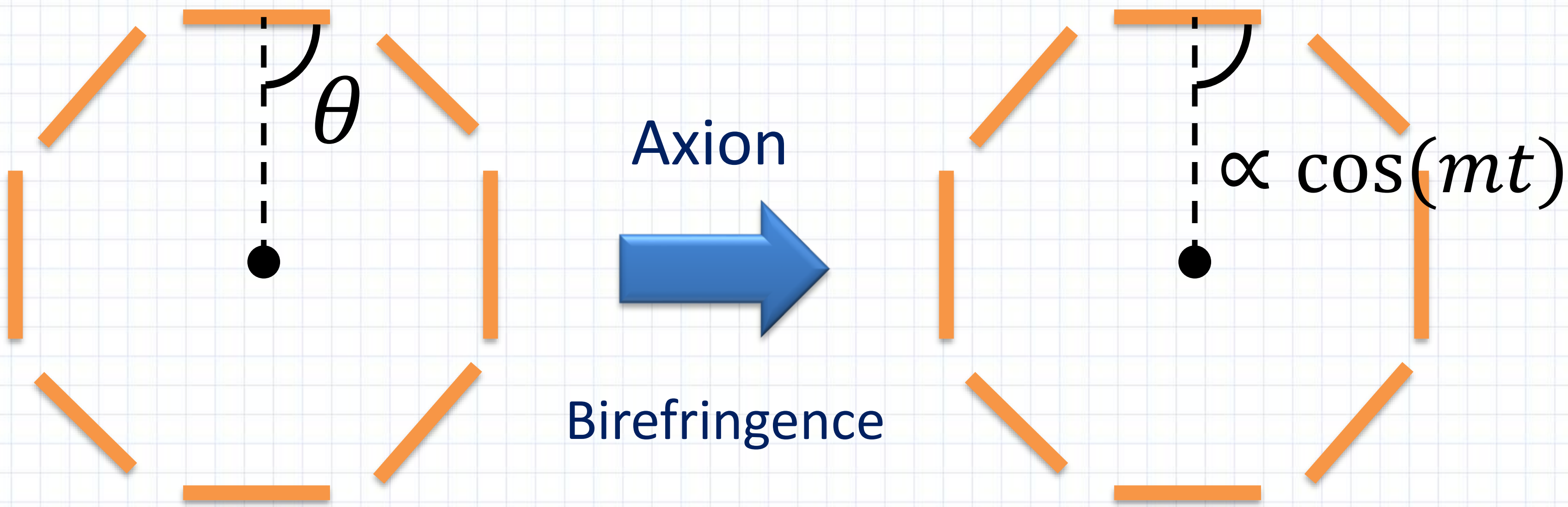
Last scattering surface is thick!
Random phases of ϕ_{LSS} pile up.



Accumulation of random rotation decreases the polarization degree



Pol. plane oscillates in phase



Same is true for CMB

[Fedderke+(2019)]

Two ADM effects on CMB

$$\frac{[Q\pm iU]_{\rm ADM}}{[Q\pm iU]_0} = \underbrace{\left(1-\frac{1}{4}g^2\langle\phi\rangle^2_{\rm LSS}\right)}_{\equiv J}\underbrace{\left(1\pm ig\phi_0\cos(mt)\right)}$$

Wash out effect

Oscillating Pol. Plane effect

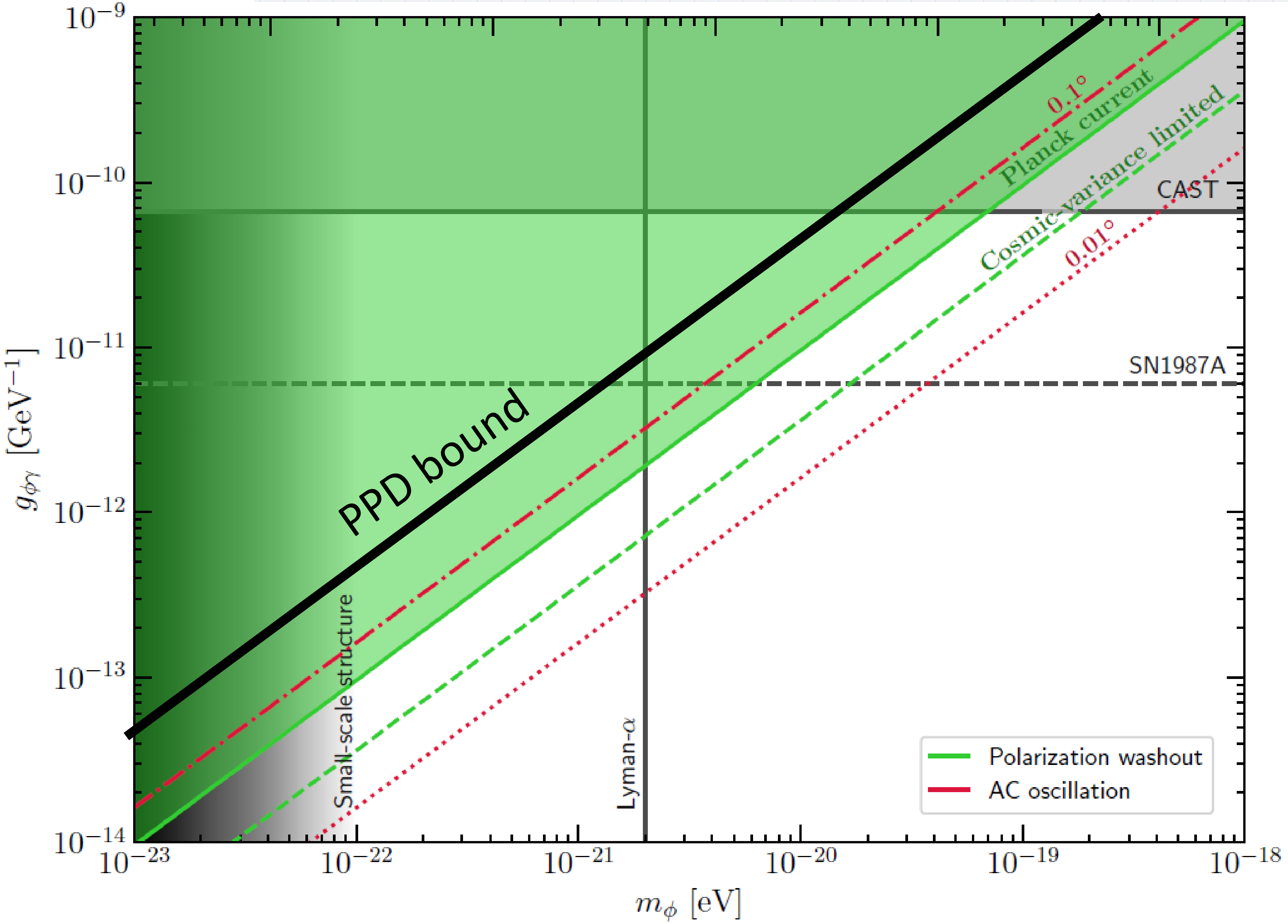
- Washout: $C_{TT}\propto J^0, C_{TE}\propto J^1, C_{EE}\propto J^2$.

  Standard MCMC puts a constraint on g from map data

- Oscillating PP: needs non-public time series data

  Planck $\Delta\alpha_{\rm stat}\approx 0.05^\circ$ may imply 0.01° sensitivity in future??

Fedderke, Graham & Rajendran: 1903.02666



Short Summary on CMB

- Prediction of ADM is distinct from cosmic biref. α
  Quite interesting and strong motivation!

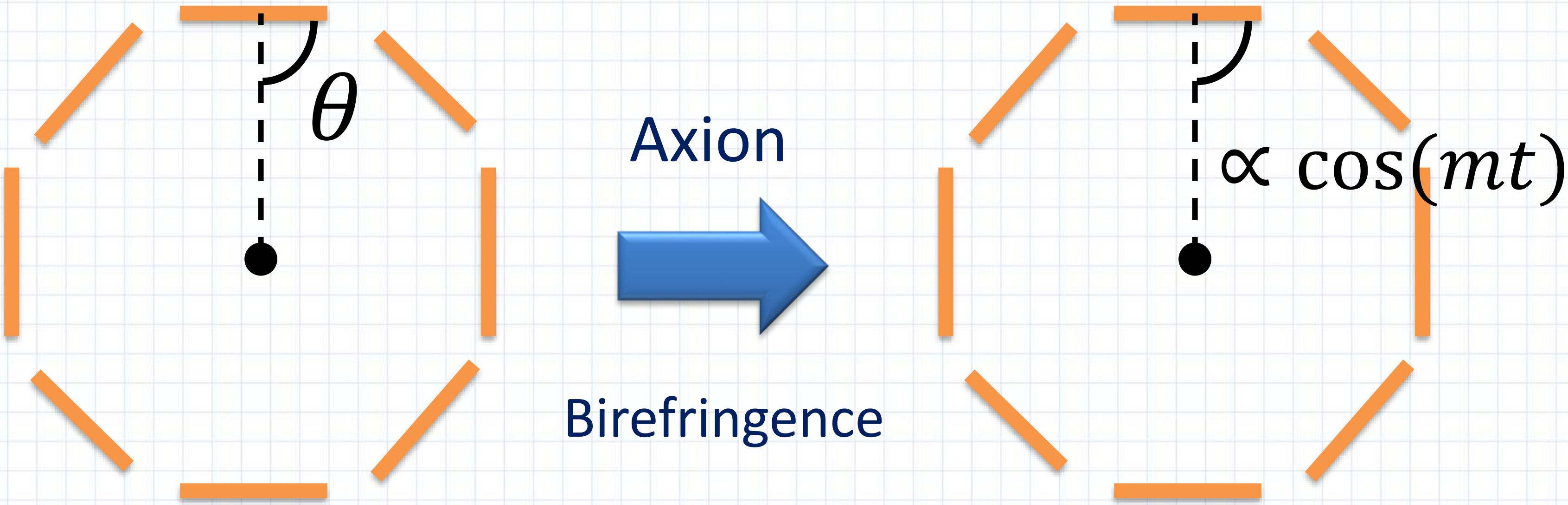
- 2 effects: (i) washout from thickness of LSS
  (ii) oscillating pol. plane during obs.

- (ii) extracted from time-varying part of time series data
  Not so bothered by calibration!!??

- Observe many^2 oscillations for higher mass region
  Doesn't it improve the sensitivity??

New Observation

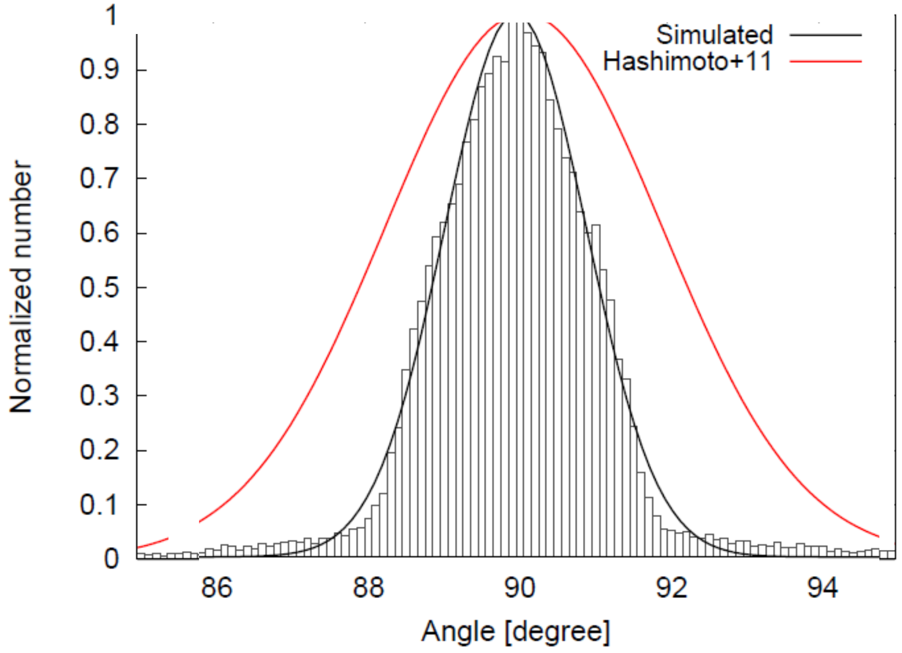
Pol. plane oscillates in phase



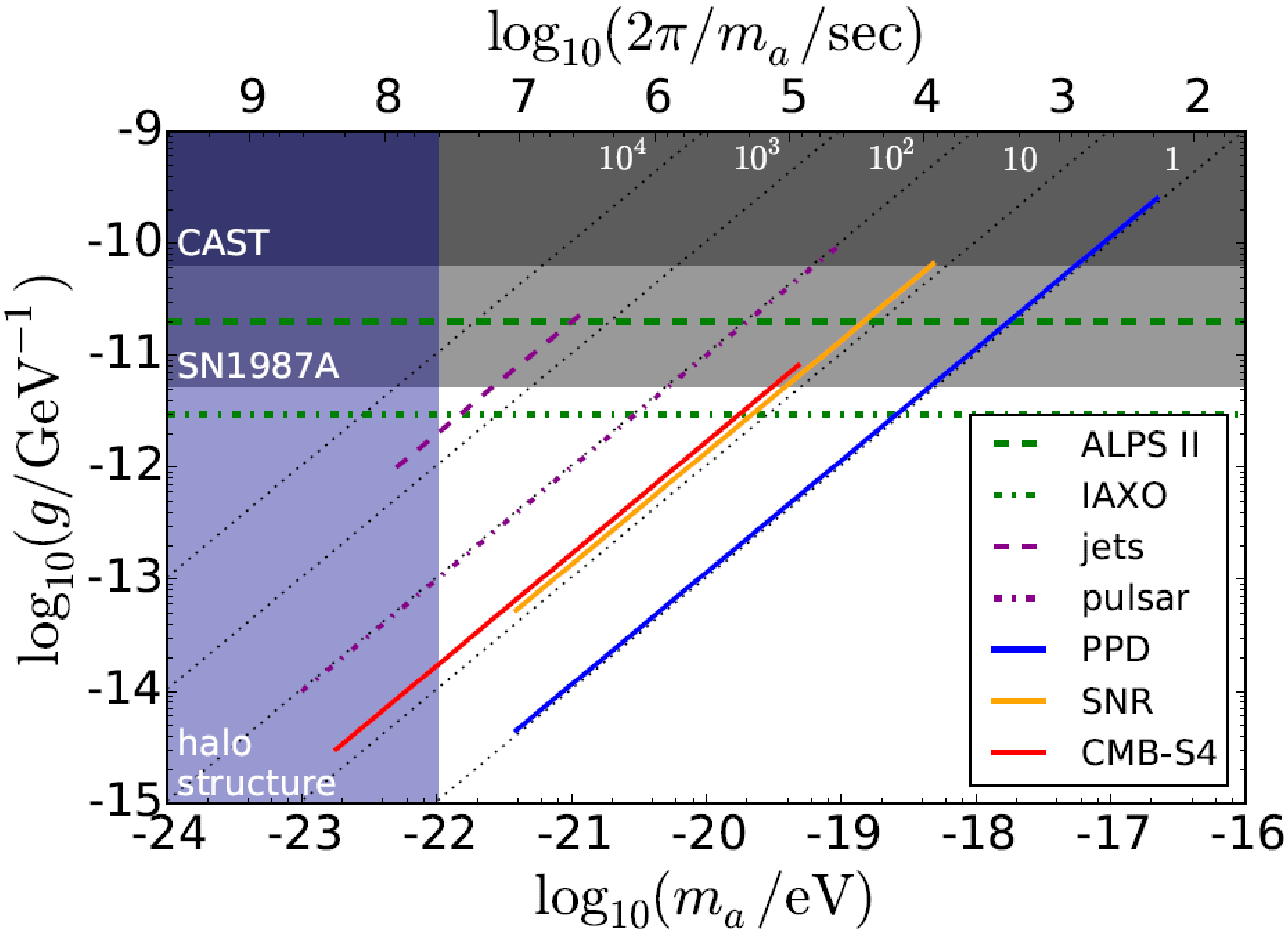
Repeated obs may find it!

Long-term Obs of PPD

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



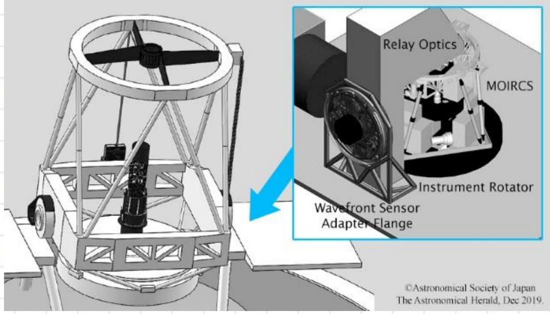
Chigusa, Moroi & Nakayam: 1911.09850



PPD has the biggest potential

New Observation

- Never give up!
  We should pursue our approach.

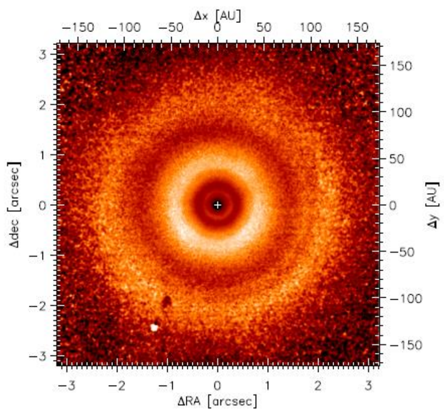


- We used old data (Hashimoto+ 2011)
  whose exposure time was 3mins.

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

ULTIMATE Subaru

[Van Boekel+(2017)]



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

- Applied for 萌芽 to hire postdoc analyzing data

New Observation

Accepted!

Dear Dr. Kenji Toma,

We are pleased to inform you that 1 night with FPDI+SCExAO+NGS was awarded to your proposal S22A0049N entitled with "Polarimetry of a Protoplanetary Disk to Search for Axion Dark Matter".

- We originally got two half nights of April 7th and 19th.
- Additionally, Feb. 25th and 26th (this month!) are also accepted.
- We also got a grant（萌芽）and will hire a postdoc from Thai. He will work on the data analysis.

Plan of Talk

1. Introduction
2. ADM Birefringence
3. Protoplanetary Disk
4. New observation
5. Summary

Summary

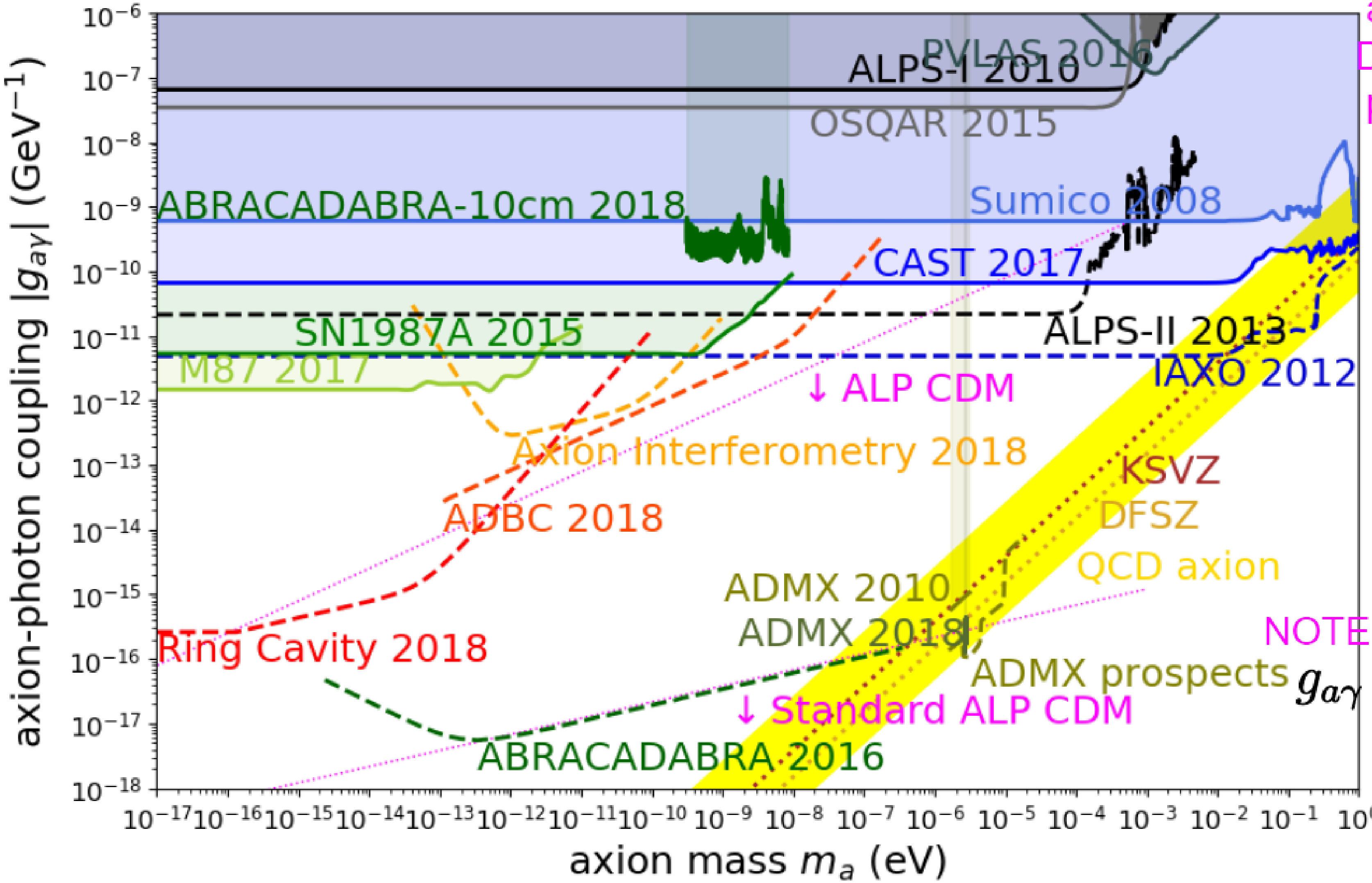
- Axion has been constrained by $a \leftrightarrow \gamma$ conversion
- The same coupling causes Birefringence with ADM
- Observations of protoplanetary disks are useful to search for ultralight ADM ($m \sim 10^{-22}\mathrm{eV}$)
- (CMB polarization is also powerful. cf. LiteBIRD)
- We'll make our own observation this spring.
  Stay tuned!

THE THEME
OF CHAPTER IS...

Thank you ！

Bounds on Axion-Photon Coupling

- Extracted experiments to be reviewed here



Solid: achieved
Dashed: proposals

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