Hunting Axion Dark Matter with New Techniques

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Obata, TF & Michimura PRL121, 161301(2018)
TF, Tazaki & Toma PRL122, 191101(2019)
Nagano, TF, Obata & Michimura [1903.02017]

2nd. Jul. 2019 @ Warsaw U
Optical ring cavity, Protoplanetary Disk, and GW interferometer provide new and best methods to search for axion dark matter!
Plan of Talk

1. Introduction
2. Optical Ring Cavity
3. Protoplanetary Disk
4. GW Interferometer
5. Summary
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Who is Dark Matter?
introduction

DM candidates

Scalar

QCD Axions

Axion-like Particles

Light bosons

Fuzzy Dark Matter

Standard Model ic

Sterile neutrinos

Neutrinos

Supersymmetry

Extra-dimensions

Weak Scale

Little Higgs

Simplified Models

Effective Field Theory

WIMP

M-Gravity

Modified Gravity

Emergent Gravity

ToVes

MoND

PBH

Macroscopic

Primordial BHs

MaCHOs

Superfluid

Self-interacting

Other

Other
introduction

DM candidates

Scalar DM

Axion-like Particles
Fuzzy Dark Matter
Standard Model
Sterile neutrinos
QCD Axions
Light bosons
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Super-symmetry
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Effective Field Theory
Simplified Models
Weak Scale
Little Higgs
WIMP(s)
Macroscopic
Macros
Other Particle
Self-interacting
Primordial BHs
MaCHOs
Superfluid
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: \( m \gg H \)

\[
\phi = \left(\frac{a}{a_0}\right)^{-\frac{3}{2}} \phi_0 \cos(mt + \delta)
\]

\( \rho_\phi \propto a^{-3}, \delta_m \propto \text{amplitude pert. } \delta\phi(t, x) \)
What characterizes ADM?

- ADM can be very light. \((10^{-22}\text{eV} \lesssim m)\)
- ADM breaks parity
- ADM may be coupled to photon!!

Useful to Search for DM
Axion-Photon Coupling

Interaction term: \( \mathcal{L}_{\phi\gamma} = \frac{1}{4} g \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \)
Axion-Photon Coupling

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

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

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New terms!

Conventionally constant magnetic field is introduced
**Axion-Photon Conversion**

Assume constant Magnetic Field $B_0$

Photon: \[ \left[ \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} \right] A = -g B_0 \dot{\phi} \]

Axion: \[ \left[ \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} + m^2 \right] \phi = -g B_0 \cdot \dot{A} \]
introduction
Current constraint

Target space in our project
(Possible region for ALPs DM)
Axion-Photon Coupling

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

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

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

New terms!

Anything other than magnetic fields?
New experiment

What if Axion is Dark Matter?
Assume background DM axion: \( \phi(t) = \phi_0 \cos(mt) \)

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

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

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

Dispersion relations of Left/Right Pol. are modified

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

Speed of light changes depending on polarization!
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New experiment

Dispersion relations for Left/Right pol. are different

Travel distance \((kx) \Leftrightarrow \) # of oscillation \((\omega \pm t)\)

How can we experimentally measure it?
New experiment

Dispersion relations for Left/Right pol. are different

Travel distance \((kx) \leftrightarrow \#\text{ of oscillation } (\omega_{\pm}t)\)

How can we experimentally measure it?

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

Dispersion relations for Left/Right pol. are different

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

How can we experimentally measure it?

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

- Dispersion relations for Left/Right pol. are different
- How can we experimentally measure it?
- Optical length changes for left/right pol.
- Resonant Frequency changes in optical cavity

[DeRocco & Hook (2018), Obata, TF, Michimura (2018)]
We proposed an exp. to test the birefringence of ADM via $\delta f_{\text{res}}$ btw right/Left $\gamma$. 

**DANCE experiment**

Dark matter Axion search with riNg Cavity Experiment

[Obata, TF, Michimura(2018)]
DANCE Sensitivity

[Obata, TF, Michimura (2018)]

\[ f = \frac{m}{2\pi} \approx 2.4 \text{ Hz} \left( \frac{m}{10^{-14} \text{ eV}} \right) \]
DANCE Sensitivity

We can improve the constraint by several Orders of magnitude!
DANCE Act.1 has started!

Prototype exp. (Act.1) is being constructed in U. Tokyo. (Ando lab.)

The first result (1m, 3months) will be obtained within a year.
DANCE Act.1 has started!

Even Act.1 can overcome CAST for $m_a \lesssim 10^{-14}$ eV
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Birefringence

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

Photon EoM: $\left[ \partial^2_t - \partial^2_i \right] A = -g\dot{\phi} \nabla \times A$

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 linear polarisation plane

Linear polarized photon can be decomposed into circular polarisation.

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

With ADM BG phase velocity are different, polarisation plane rotates

\[
e^{ikT} \left[ e^{i \int_t^{t+T} \delta \omega dt} \begin{pmatrix}
1 \\
i
\end{pmatrix} + e^{-i \int_t^{t+T} \delta \omega dt} \begin{pmatrix}
1 \\ -i
\end{pmatrix} \right]
= e^{ikT} \begin{pmatrix}
\cos(\int_t^{t+T} \delta \omega dt) \\
- \sin(\int_t^{t+T} \delta \omega dt)
\end{pmatrix}.
\]
New Observation

**Birefringence**

- Rotation angle synchronizes with Axion

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

- Motion of the linear polarization plane

\[
\delta\omega = -\frac{g_\alpha\gamma}{2} \left[ \dot{\phi} + \hat{k} \cdot \nabla \phi \right] = -\frac{g_\alpha\gamma}{2} \frac{d\phi}{dt}
\]
New Observation

**Birefringence**

- Rotation angle synchronizes with Axion
  \[
  \delta \omega = -\frac{g_a \gamma}{2} \left[ \dot{\phi} + \hat{k} \cdot \nabla \phi \right] = -\frac{g_a \gamma}{2} \frac{d\phi}{dt}
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\theta(t, T) = \int_{t}^{t+T} \delta \omega(t) \, dt = -\frac{g_a \gamma}{2} \left[ \phi(t + T) - \phi(t) \right],
\]
New Observation

**Birefringence**

- Rotation angle synchronizes with Axion
  \[ \theta(t, T) = \int_t^{t+T} \delta \omega(t) \, dt = -\frac{g_{a\gamma}}{2} [\phi(t + T) - \phi(t)] , \]

- Motion of the linear polarization plane
New Observation

**Birefringence**

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

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

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

How can we observe this?

In astro, we don’t know the initial polarization plane. Can’t measure $\theta$ ...

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

$$g_{12} \equiv g_{\alpha\gamma}/(10^{-12}\text{GeV}^{-1})$$

$$m_{22} \equiv m/(10^{-22}\text{eV})$$
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.
New Observation

**Polarization of PPD**

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

*Initial polarization Plane is known!!*
New Observation

**Observation of PPD**

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

We expect a concentric pattern of linear polarization.

Our Simulation without Axion DM
New Observation

**Axion DM rotates pol. plane?**

Axion

Birefringence
Axion DM rotates pol. plane?

Is this angle 90° or not?
New Observation

**Observation of PPD**

- We expect a concentric pattern of linear polarization.

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

**Our Simulation without Axion DM**

**Observation by SUBARU**

AB Aurigae (160pc away)
New Observation

Observation of PPD

The observation data reveals

\[ \theta = 90.1 \pm 0.2 \]

\[ |\Delta \theta| < 5 \times 10^{-3} \]

Our simulation confirms the effect of multiple Scatterings is negligible.
New Observation

New constraint

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

Best bound on Fuzzy DM
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New experiment

GW Laser Interferometers

State of Washington (4km)

State of Louisiana (4km)

Livingston Parish

Hanford

Pisa

Hannover

GEO600 (600m)

Virgo (3km)

Kamioka (3km)

KAGRA (in construction)

INDIGO (in preparation)

LIGO

Competition => Cooperation
New experiment

Can we use GW interferometers to search for Axion DM?
Yes!! Because GW interferometer is

- **Very Long Baseline** (aLIGO: 4km)
- **Linear Polarized Laser** is used
- **Photon reflects many times** (aLIGO: typically 500 times)

Designed to detect tiny signals
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
New Experiment

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!
New Experiment

**Sensitivity Curve** for 1 year run

![Graph showing sensitivity curve for axion mass vs. coupling constant]
New Experiment

**Sensitivity Curve** for 1 year run

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

![Graph showing sensitivity curve with limits on axion mass vs. cross-section](image)
New experiment

World's first GW & ADM Observatory

- Hanford
- Pisa
- Hannover
- Kamioka
- LIGO
- State of Washington (4km)
- Livingston Parish
- State of Louisiana (4km)
- VIRGO (3km)
- GEO600 (600m)
- KAGRA (in construction)
- INDIGO (in preparation)

Competition => Cooperation
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Axion has been constrained by $a \leftrightarrow \gamma$ conversion.

The same coupling causes Birefringence w/ ADM.

Optical ring cavity and GW interferometer are sensitive to ADM with $10^{-16} < m < 10^{-12}$.

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

Just beginning. Let’s think new one together!
Thank you!
Backup Slides
Bounds on Axion-Photon Coupling

- Extracted experiments to be reviewed here

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**Diagram:**
- Solid: achieved
- Dashed: proposals

**Axes:**
- y-axis: Axion-photon coupling $|g_{a\gamma}|$ (GeV$^{-1}$)
- x-axis: Axion mass $m_a$ (eV)

**Experiments:**
- ABRACADABRA-10cm 2018
- AS1987A 2015
- M87 2017
- CAST 2017
- ALPS-I 2010
- ALPS-II 2013
- IAXO 2012
- SN1987A 2015
- Sumico 2008
- ADMX 2010
- ADMX 2018
- ADBC 2018
- AXB Interferometry 2018
- Ring Cavity 2018

**NOTE:** $g_{a\gamma} \propto 1/f_a$
New experiment

Measurement time 1 year ≈ axion coherent time

Rount-trip time in cavity ≈ axion oscillation period

\( f = \frac{m}{2\pi} \approx 2.4 \text{ Hz} \left( \frac{m}{10^{-14} \text{ eV}} \right) \)
Axion coherent time

If measurement time $T$ is longer than axion coherent time $\tau_a$, the sensitivity improves only slowly.

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

People often discuss $\tau_a$ is (de Broglie wave length)/(relative velocity)

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

Therefore, for $m > 10^{-16} \text{eV}$, the sensitivity highly depends on $\tau_a$. 
Our proposal was featured in Nature Photonics.
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]
New Observation

**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]
DANCE experiment

Dark matter Axion search with riNg Cavity Experiment

[Obata, TF, Michimura(2018)]
DANCE experiment

Dark matter Axion search with riNg Cavity Experiment

[Obata, TF, Michimura(2018)]

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laser(1550nm)

frequency lock

Forget this part
DANCE experiment

Dark matter Axion search with riNg Cavity Experiment

[Obata, TF, Michimura(2018)]

Only left-handed Photons pass

laser(1550nm)

Pol. is flipped by mirror reflection

Mirrors

left-handed photon
right-handed photon

Forget this part
Cavity is vertically stretched. **Right mode is dominant**

Detector A sees resonance of **Right γ**

Dark matter **Axion search with riNg Cavity Experiment**

[Obata, TF, Michimura(2018)]
DANCE experiment

Dark matter Axion search with riNg Cavity Experiment

[Obata, TF, Michimura(2018)]

Left $\gamma$ travels other way in the cavity

Pol. is flipped by mirror reflection

Detector B checks resonance of Left $\gamma$

laser(1550nm)

mirrors
This experiment can test the birefringence of ADM via $\delta f_{\text{res}}$ btw right/Left $\gamma$.

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

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

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