2021年度 学術変革領域「ダークマター」シンポジウム

# Status Report of B01 Group

(DM search w/ interferometer)

Tomohiro Fujita (Waseda IAS)

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H. Nakatsuka, A. Nishizawa (U. Tokyo)
S. Morisaki (Milwaukee) K. Nagano (JAXA)
and I. Obata (MPA)

@ Online symposium on 29th Mar. 2022

# Outline

1. News
2. Ultralight DM (Intro.)
3. Status of Vector DM search
4. Stochastic Effect
5. Summary

# ● Nikkei Newspaper [March 20$^{th}$ (Sun)]

## 宇宙の暗黒物質を探せ　素粒子実験が難航、研究広がる

小玉 祥司

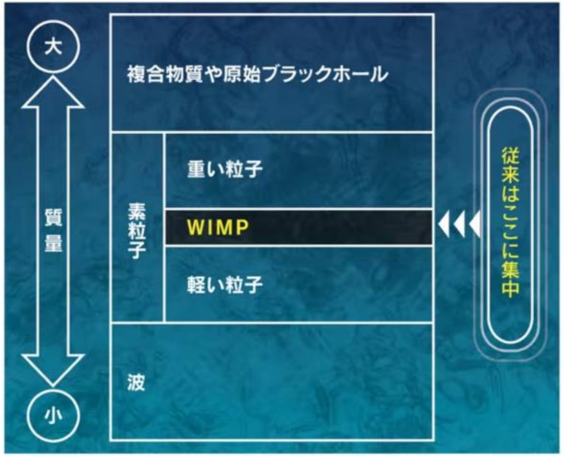
2022年3月19日 2:00 [有料会員限定]

宇宙に存在する物質の約8割を占めるが正体がわかっていない暗黒物質（ダークマター）を探す研究が大きく変わりつつある。有力候補と考えられていた素粒子を探す実験が難航、探索する範囲を広げる必要があるという見方が台頭しているためだ。既存の研究施設も活用しながら、視野を広げて暗黒物質を探す研究が始まっている。

岐阜県飛騨市の神岡鉱山跡に建設された重力波望遠鏡「KAGRA（かぐら）」は、アインシュタインが理論的に予想した重力波を観測する施設だ。いま、当初の目的とは違った暗黒物質を見つけようという実験の準備が進んでいる。アクシオンと呼ばれる極めて軽い粒子を探す実験だ。「次の運転が始まる2022年末にはデータがとれる」と実験に取り組む道村唯太東京大学助教は説明する。

重力波の観測には偏光の変化は影響しない。重力波の観測と暗黒物質の探索を同時にできることもメリットだ。重力波を世界で初めて観測することには間に合わなかったKAGRAだが、本来の目的である重力波観測をしながら、見つかればノーベル賞確実な暗黒物質探索にも活用できる。

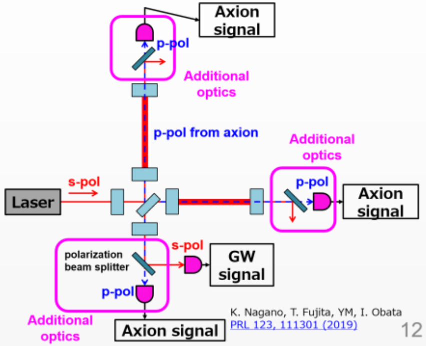
暗黒物質の候補はいろいろ

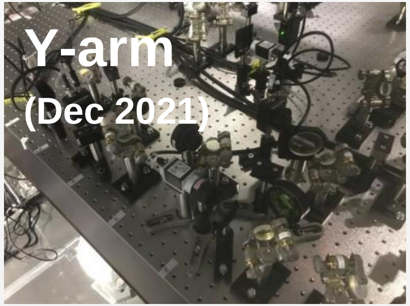


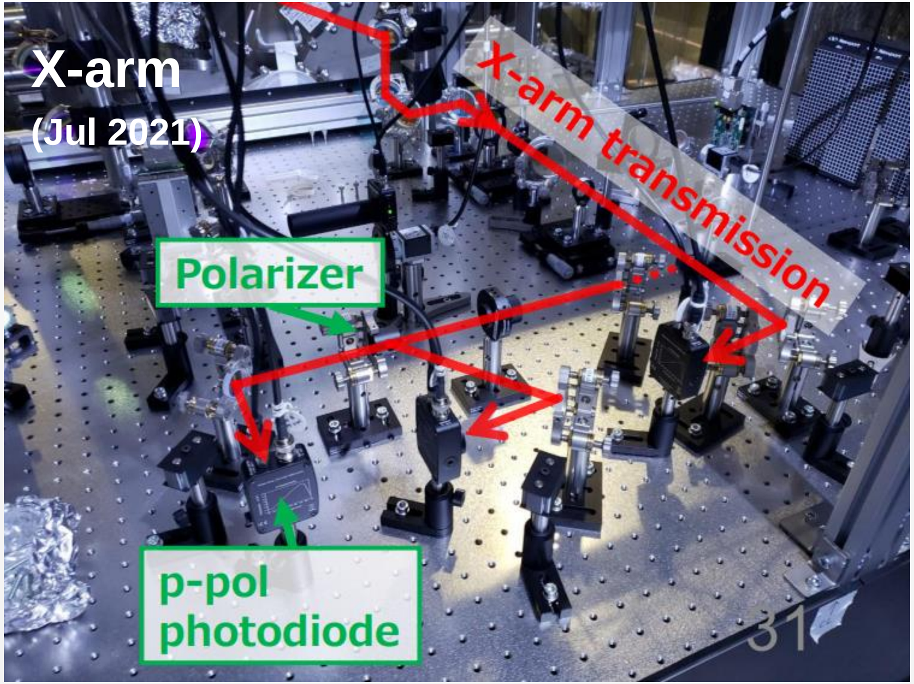
Nagano, TF, Obata & Michimura
PRL123,111301(2019)

# We installed our pol. monitor system in KAGRA!

Almost ready for Axion DM search in O4 run. → Nagano-kun's talk

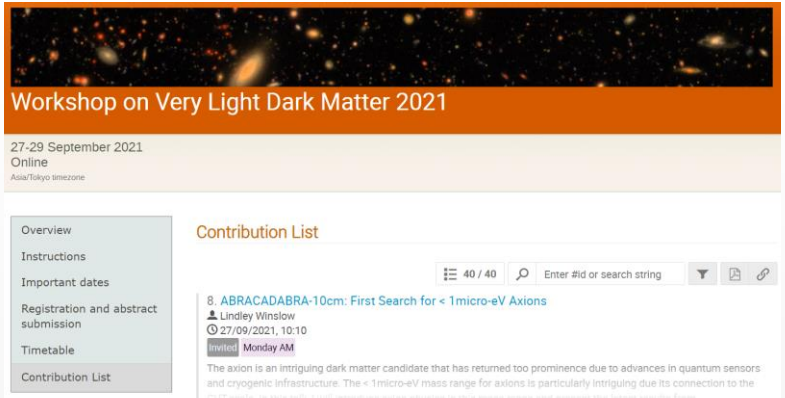






## Workshop w/ A01 Group

### “WS on very light DM 2021”



Workshop on Very Light Dark Matter 2021

27-29 September 2021
Online
Asia/Tokyo timezone

Contribution List

8. ABRACADABRA-10cm: First Search for < 1micro-eV Axions
Lindley Winslow
27/09/2021, 10:10
Invited Monday AM

The axion is an intriguing dark matter candidate that has returned too prominence due to advances in quantum sensors and cryogenic infrastructure. The < 1micro-eV mass range for axions is particularly intriguing due its connection to the

- 184 participants (dom 67, Intr 117)
- 40 talks/3days
- Recorded talks are still available

## Joint Seminar Series

### “Paris-Tokyo DM Seminar”

### w/ SYRTE (observatoire de Paris)

- Almost every month
- Discuss exp. techniques and data analysis
- DAMNED experiment (Scalar DM) carefully analyzed the data

→ **Inspired us to work on stochastic effect**

# Awards for B01 family members

- T.Fujita won JPS young scientist award
- J. Kume won **two** JPS student presentation awards
- A. Nishizawa won MEXT young scientists’ prize
- I. Obata won S. Nakamura award

# New position

- Prof. Michimura (PI) moves to Caltech

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② Ultralight DM (Intro.)

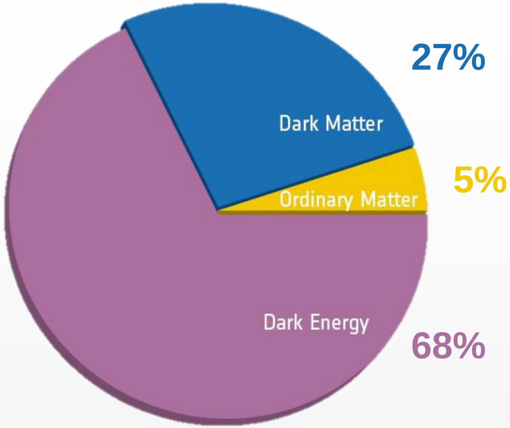
③ Status of Vector DM search

④ Stochastic Effect

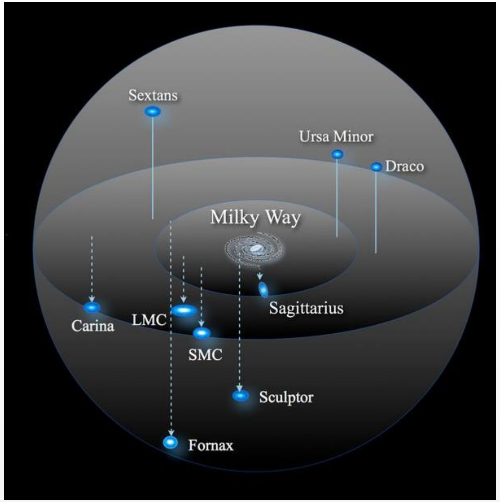
⑤ Summary

# Dark Matter

Cosmic pie chart

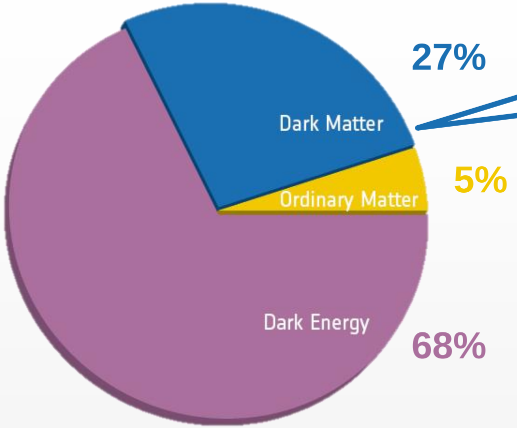


Local DM Halo



# Dark Matter

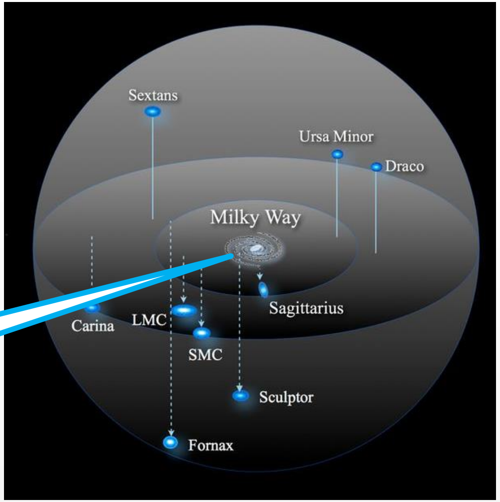
Cosmic pie chart



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

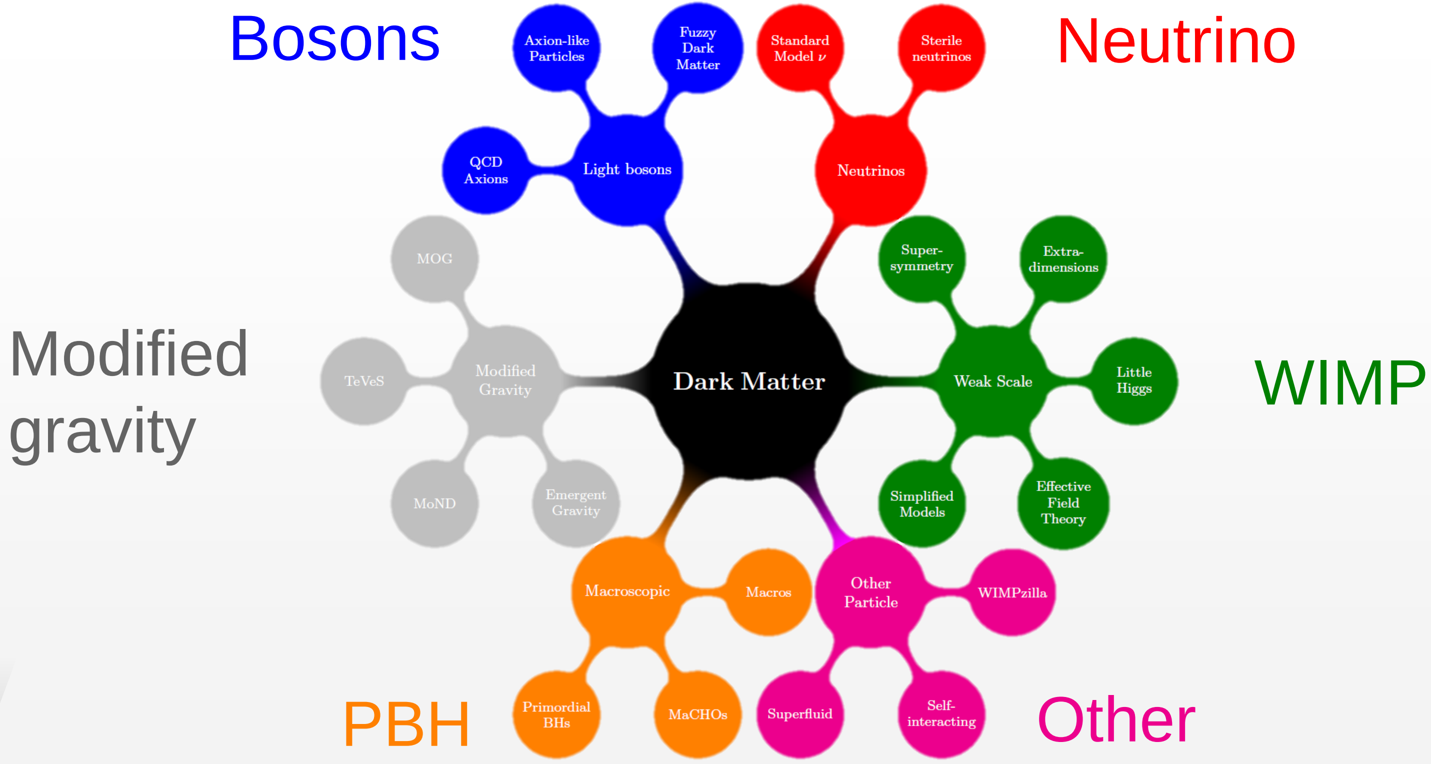
$\rho_{\mathrm{DM}}^{\mathrm{local}} = 0.3\mathrm{GeV/cm}^3$

Local DM Halo

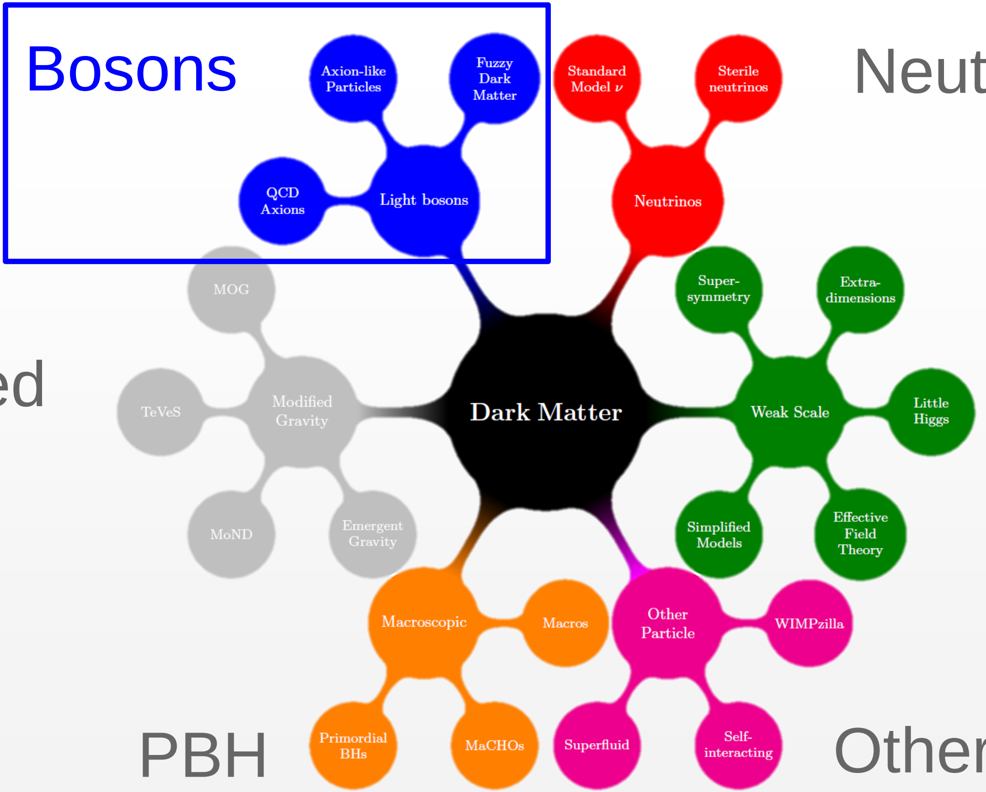


**We live inside a high density DM halo!**

# DM Candidates



# DM Candidates



Neutrino

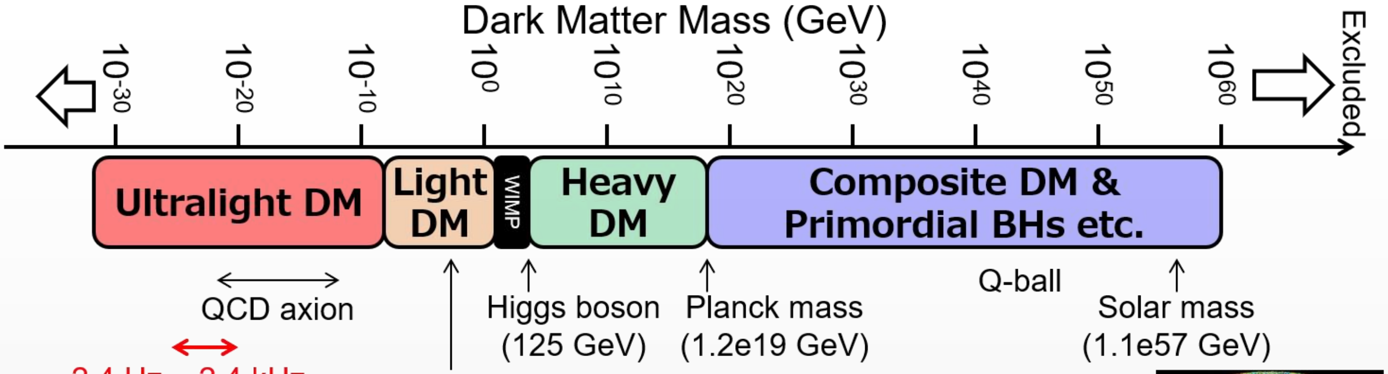
Modified gravity

WIMP

PBH

Other

# 90digits discovery space



Dark Matter Mass (GeV)

$10^{-30}$ $10^{-20}$ $10^{-10}$ $10^{0}$ $10^{10}$ $10^{20}$ $10^{30}$ $10^{40}$ $10^{50}$ $10^{60}$

Excluded

**Ultralight DM**

**Light DM**

**WIMP**

**Heavy DM**

**Composite DM & Primordial BHs etc.**

QCD axion

Higgs boson (125 GeV)

Planck mass (1.2e19 GeV)

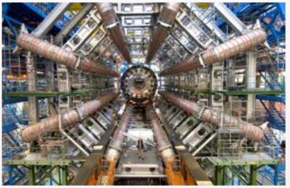
Q-ball

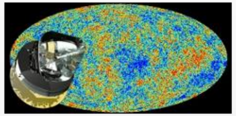
Solar mass (1.1e57 GeV)

2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)

XENON1T limits on ALP
(1-210 keV)

Laser Interferometry





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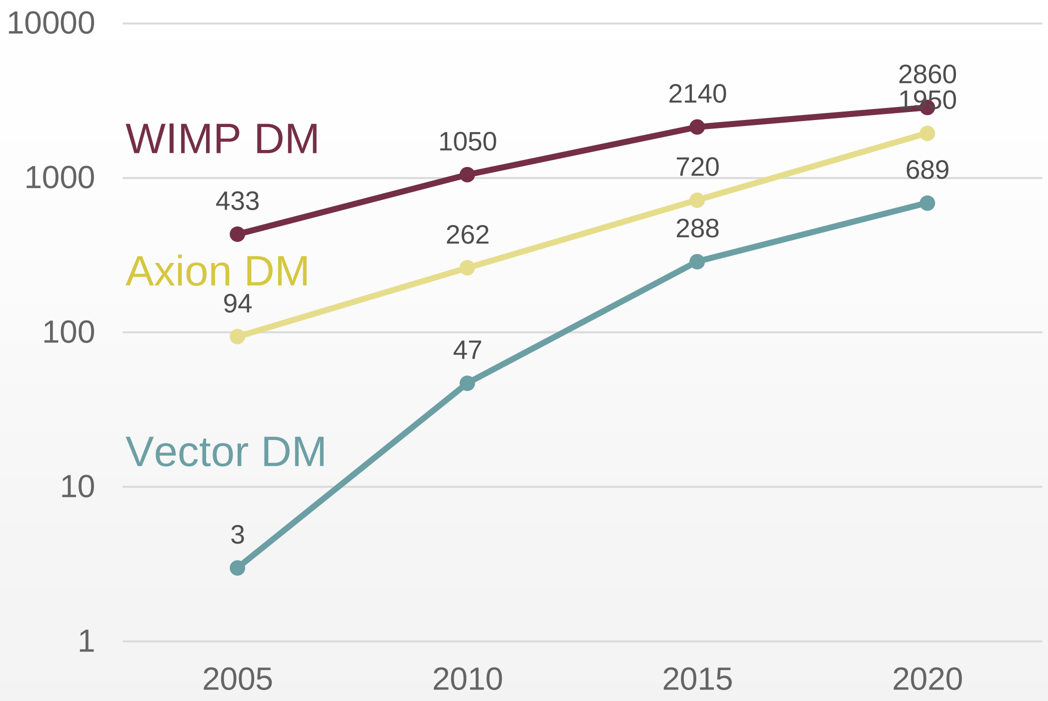
# Who’s popular?

## # of paper

Hit count of
“XX dark matter”
in Google scholar
for every 5 years



# Vector DM (a.k.a. Dark photon DM)

**VDM = Electric wave with a mass**

Theory : $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$

Electromagnetism
with a mass

Electric part : $\boldsymbol{E} = -\dot{\boldsymbol{A}} \sim \omega \boldsymbol{A},$

Magnetic part : $\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A} \sim k\boldsymbol{A},$

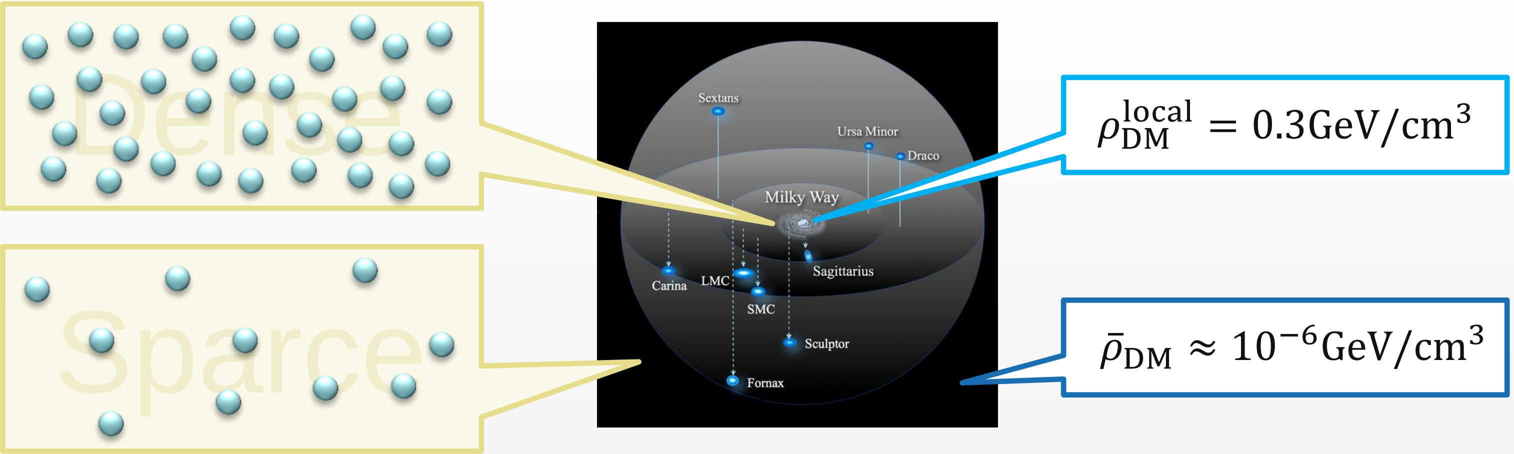
Dispersion relation : $\omega^2 = k^2 + m_A^2 \simeq m_A^2 \gg k^2,$ $\left(k = m_A v, \quad v_{\mathrm{DM}}^{\mathrm{local}} \approx 10^{-3}c\right)$

⇒ $\boldsymbol{E} \simeq \boldsymbol{E}_0 \cos(m_A t) \gg \boldsymbol{B}$

Electr~~omagnet~~ic wave!

# DM density

**WIMP**



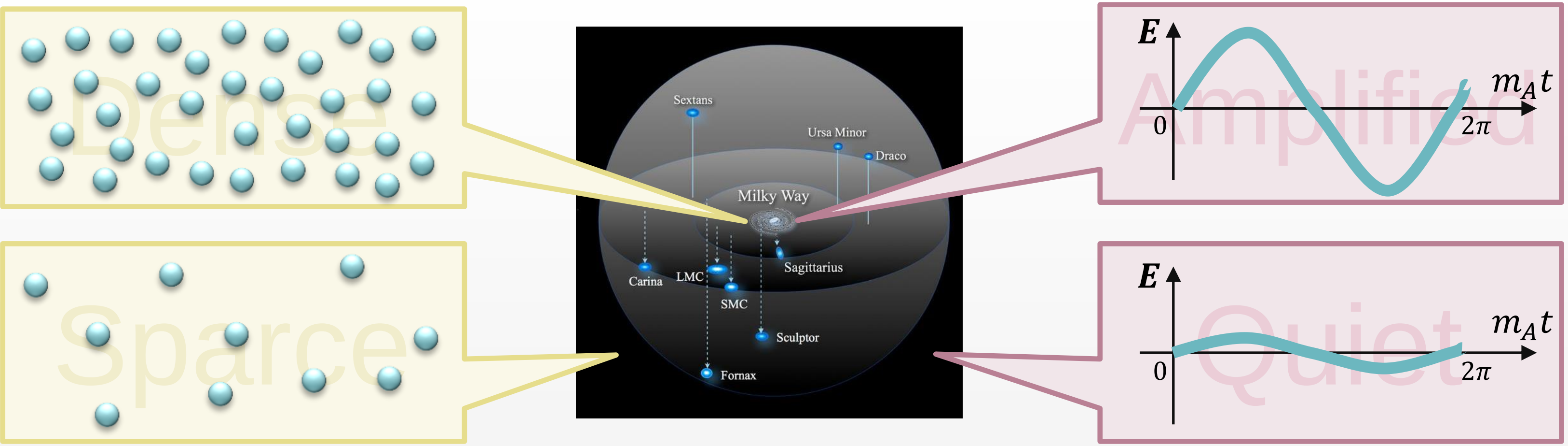
$$\rho_{\mathrm{DM}}^{\mathrm{local}} = 0.3\mathrm{GeV/cm^3}$$

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

# DM density

**WIMP**

**Vector DM**



**Wave-like DM is also a good candidate!**

# VDM Coupling

**VDM = Electric wave with a mass**

Theory : $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \underline{\underline{\epsilon_D e J_D^\mu A_\mu}}$ $(D = B \text{ or } B - L)$

Additional Interaction

Charge for VDM = B (baryon #) or B-L (baryon # - Lepton #)

[Note: B(proton)=B(neutron)=L(electron)=1, otherwise=0 ]

Coupling strength relative to electromagnetism : $\boxed{\epsilon_B, \epsilon_{B-L} \lesssim 10^{-23}}$

➡ **Need to be extremely sensitive!**

# Axion DM (a.k.a. ALP DM)

Similar to VDM. Wave-like DM $\phi = \phi_0 \cos(m_\phi t)$

But, 3 differences. ADM is

① **Scalar :** no direction

② **Parity violating :** Left & right become asymmetric

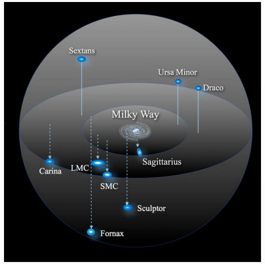
③ **Coupled to photons :** $\mathcal{L}_{\mathrm{int}} = \frac{1}{4} g \phi F^{\mu\nu} \tilde{F}_{\mu\nu}$ (Chern-Simons coupling)

⇒ **ADM = Birefringent media**

# Photon in ADM

EoM for photon with ADM $\phi$ is

$$[\partial_t^2 - \nabla^2]\boldsymbol{A} = \underbrace{-g\dot{\phi}\boldsymbol{\nabla}\times\boldsymbol{A}}_{\text{Additional Interaction}} \quad \Leftarrow \quad \phi = \phi_0 \cos(m_\phi t)$$



live in ADM

Dispersion relations of left/right polarization are modified as

$$\omega_{L,R}^2 = k^2\left[1 \pm g\phi_0 \frac{m}{k}\sin(mt)\right] \qquad (i\hat{\boldsymbol{k}}\times\boldsymbol{e}_{L,R} = \pm\,\boldsymbol{e}_{L,R})$$

Speed of light changes depending on circular polarization!

→ **ADM = Birefringent media**

# DM Summary

| | Vector | Axion | WIMP |
|---|---|---|---|
| Image | **Electric wave with a mass** | **Birefringent media** | **Massive Particle** |
| Interaction | **B** or **B-L** | **Photon** | **Nuclei** |
| Search | **aLIGO DARM**<br>**KAGRA Aux.** | **Add PD to KAGRA**<br>**Data take in O4** | **Particle collider**<br>**Undergrond exp.** |

$\underbrace{\hspace{5cm}}$

**Nagano-kun's talk**

# Outline

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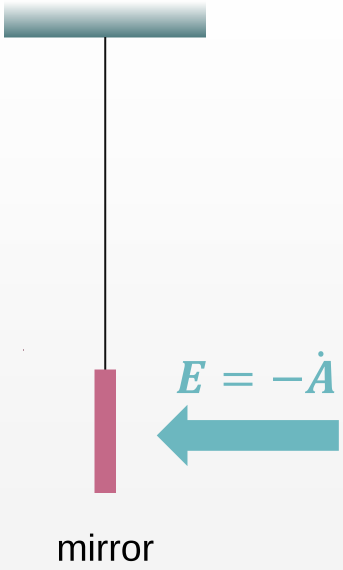
# VDM acts on Mirrors

VDM (≈ electric wave) pushes mirrors, just as $\vec{E}$ does electrons.

VDM : $\boldsymbol{A} = \boldsymbol{A_0} \sin[m_A(t - \boldsymbol{v} \cdot \boldsymbol{x})]$

Force : $\boldsymbol{F} = -\epsilon_D e Q_D \dot{\boldsymbol{A}}$

Mirror : $\delta \boldsymbol{x} = \dfrac{\epsilon_D e Q_D}{m_A M} \boldsymbol{A_0} \sin[m_A t]$



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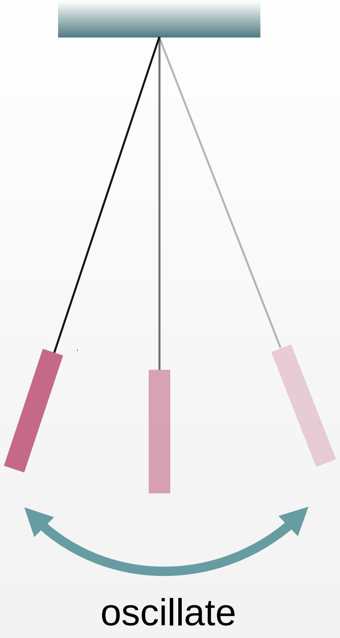
**VDM oscillates mirrors**



# Common Motion

Pierce, Riles and Zhao, PRL121, 061102 (2018)

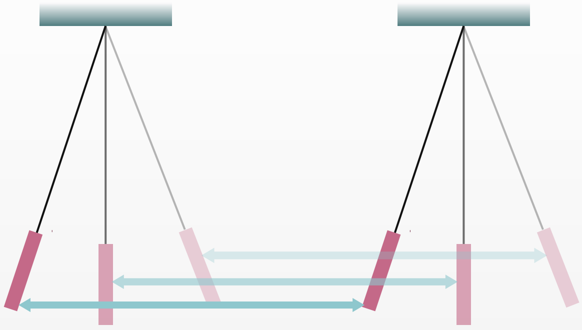
GW detectors measure the differential motion of the mirrors

Wavelength of VDM is

$$\lambda_{\mathrm{VDM}} = \frac{2\pi}{m_A v_{\mathrm{DM}}} \simeq 10^7 \mathrm{km} \left( \frac{m_A}{10^{-13} \mathrm{eV}} \right)^{-1} \gg L_{\mathrm{arm}}$$

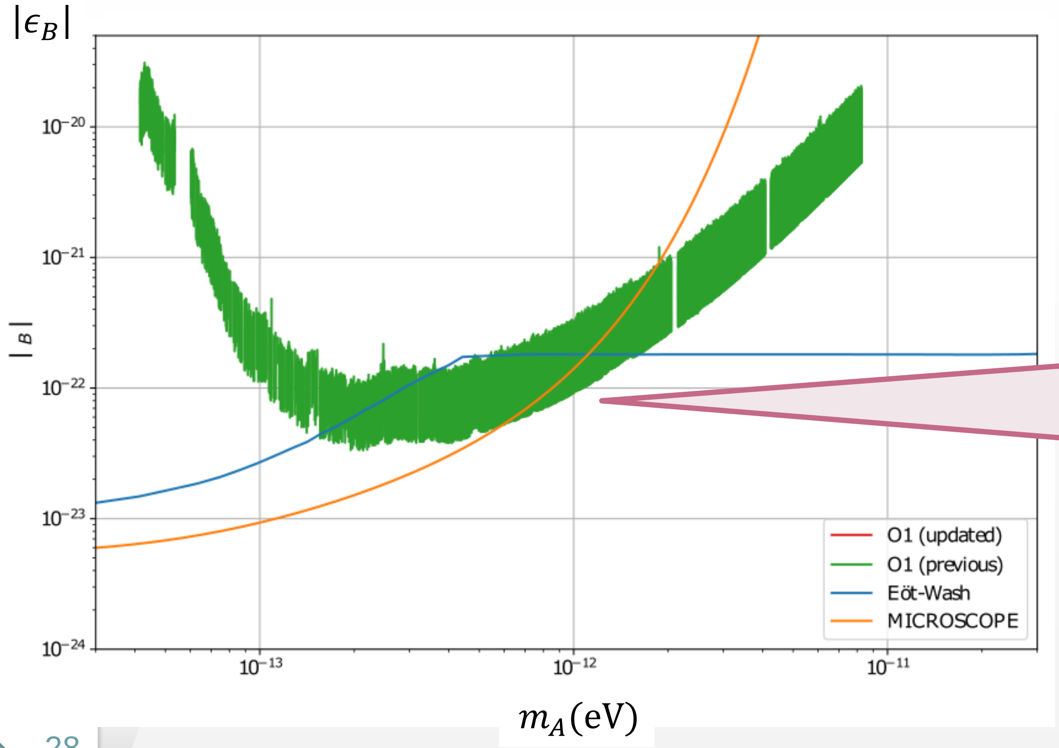
VDM looks like homogeneous $\boldsymbol{E}$

→ Signal suppressed by $(m_A v_{\mathrm{DM}} L_{\mathrm{arm}})$



distance unchanged

# Previous bound on VDM coupling to B from aLIGO O1 data

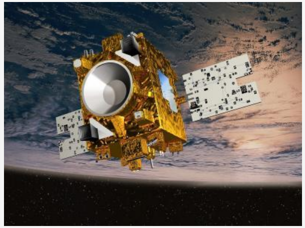


Pierce, Riles and Zhao,
PRL121, 061102 (2018)

Guo, Riles, Yang and Zhao,
Commun.Phys.2, 155 (2019)

comparable to the other constraints by EP test

Eöt-Wash torsion pendulum



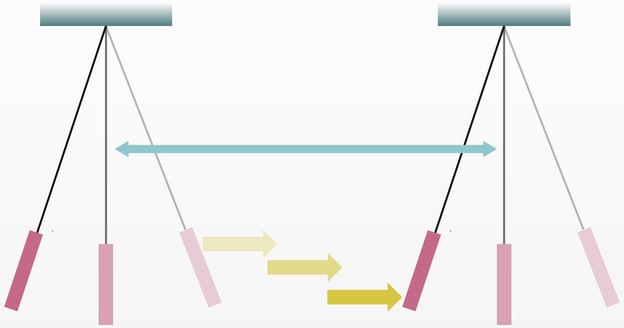
MICROSCOPE mission

# $c \neq \infty$ Effect

Morisaki, TF, Michimura, Nakatsuka and Obata [PRD**103**,051702 (2021)]

There exists a VDM signal even if the mirror motion is common.

**“Finite light-traveling time effect”**



If round-trip time = period of VDM

$$(L_{\mathrm{arm}}/c = \pi/m_A)$$

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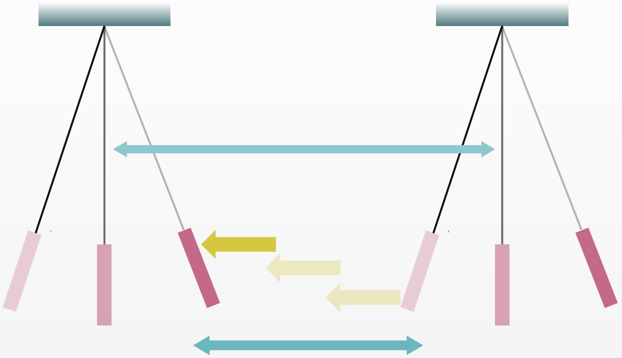

Effective distance changes

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There exists a VDM signal even if the mirror motion is common.

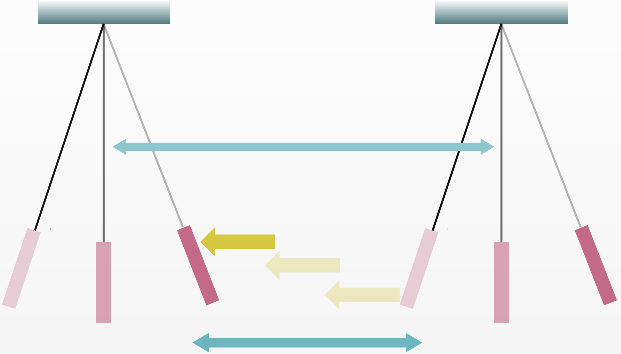
**“Finite light-traveling time effect”**

$$c\tau_{\mathrm{VDM}} = \frac{2\pi c}{m_A} \simeq 10^4\mathrm{km}\left(\frac{m_A}{10^{-13}\mathrm{eV}}\right)^{-1} \gg L_{\mathrm{arm}}$$

Signal suppressed by $(m_A L_{\mathrm{arm}})^2$

But still, it yields the dominant signal

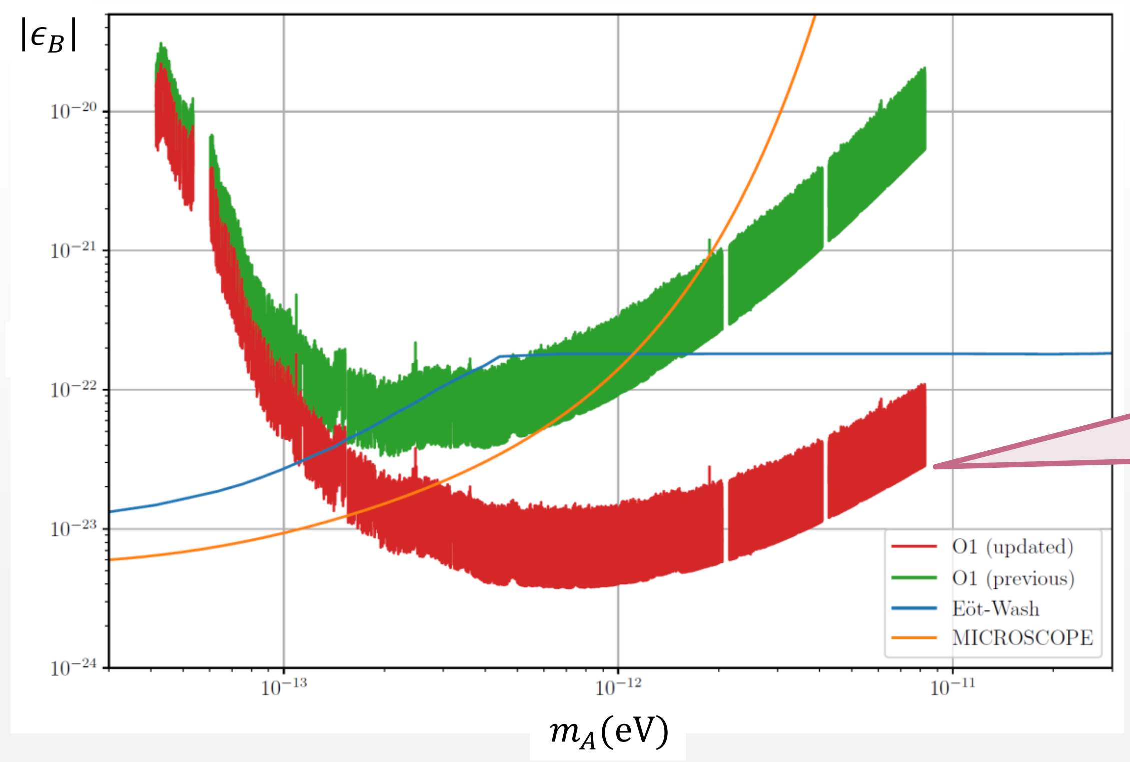
**Actual bound is better!**



Effective distance changes

# Updated bound on VDM coupling to B from aLIGO O1 data

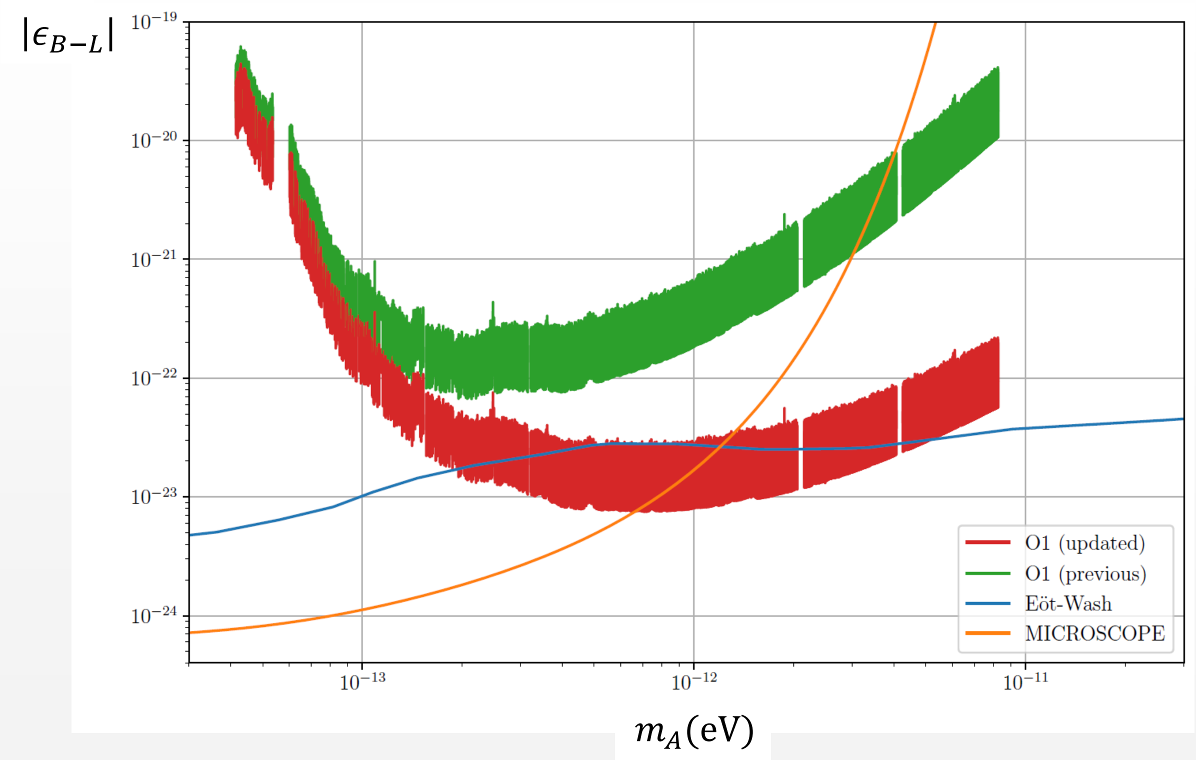
Morisaki, TF, Michimura, Nakatsuka and Obata [PRD**103**,051702 (2021)]



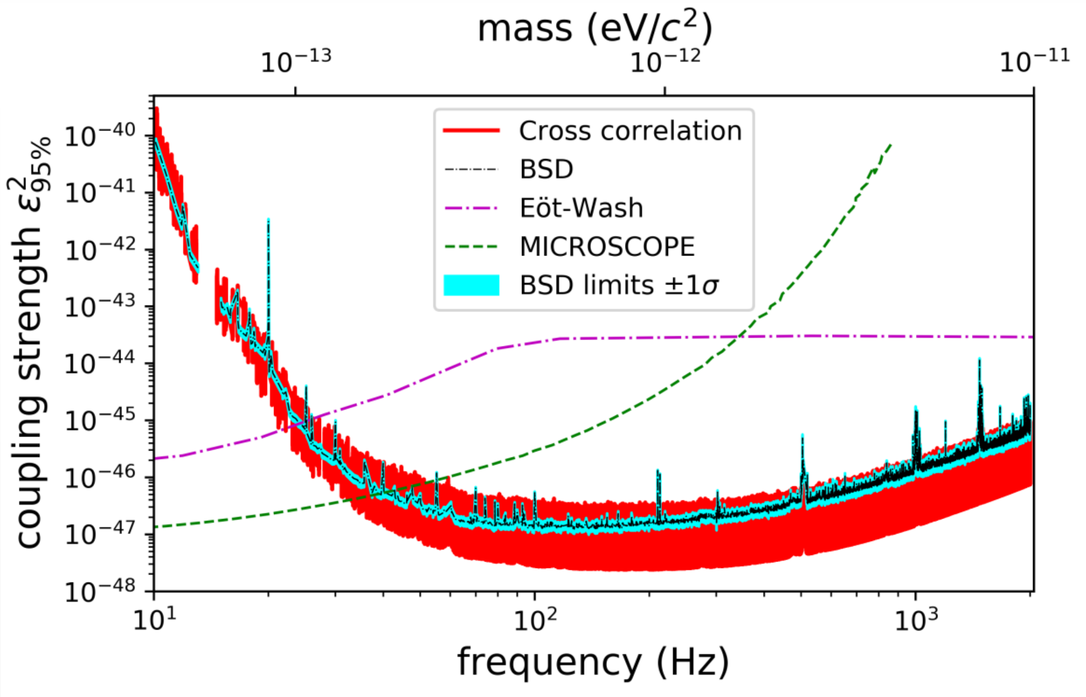
×10 improved the constraint

# Updated bound on VDM coupling to B-L from aLIGO O1 data

Morisaki, TF, Michimura, Nakatsuka and Obata [PRD**103**,051702 (2021)]



# Updated bound from aLIGO O3 data (LVK collaboration)



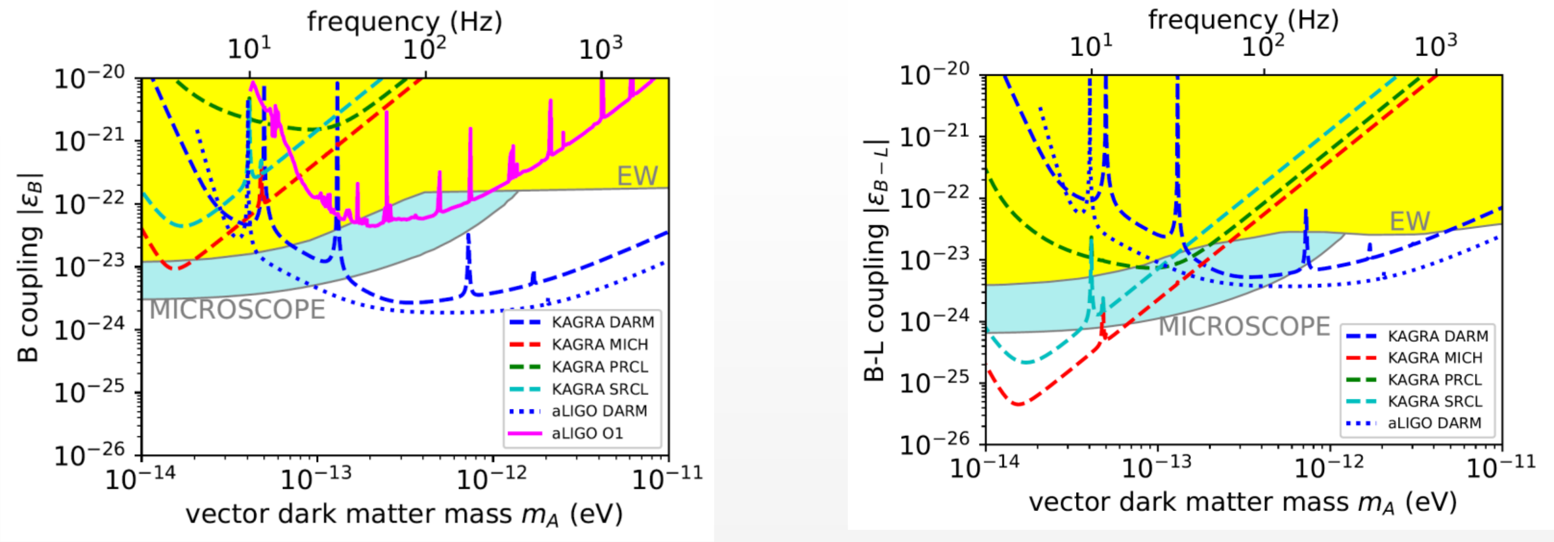
[arXiv:2105.13085]

- O3 result includes the $c \neq \infty$ effect.
- ~10 times better bound than O1 run.
- Stochastic effect is not took into account

# How about **KAGRA?**

# KAGRA beats aLIGO

You might guess KAGRA < aLIGO in the sensitivity to VDM…

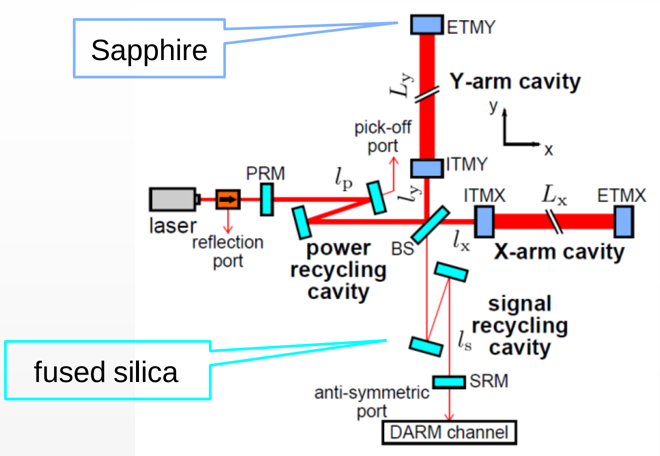


**For B-L coupling, KAGRA goes beyond aLIGO**

Michimura, TF, Morisaki,
Nakatsuka and Obata
PRD102, 102001(2020)

# Auxiliary channels

All mirrors in aLIGO are fused silica, but KAGRA uses **sapphire** mirrors.



KAGRA measures

Michimura, TF, Morisaki, Nakatsuka and Obata PRD102, 102001(2020)

DARM : $\delta(L_x - L_y)$

MICH : $\delta(l_x - l_y)$

SRCL : $\delta[(l_x + l_y)/2 + l_s]$

MICH & SRCL observe distance btw mirrors made of different material

→ **VDM acts differently**

# B-L Charge

Different material ⟺ different charge for VDM

Acceleration : $\boldsymbol{a} = \boldsymbol{F}/M \propto Q_D/M$ charge/mass is important

$B$ coupling : $Q_D = N_B$ ⟹ $\frac{N_B}{M} \approx \frac{N_B}{N_B m_n} = \frac{1}{m_n}$

$B - L$ coupling : $Q_D = N_B - N_L$ ⟹ $\frac{N_B - N_L}{M} \approx \underline{\underline{\frac{N_B - N_L}{N_B}}}\frac{1}{m_n}$

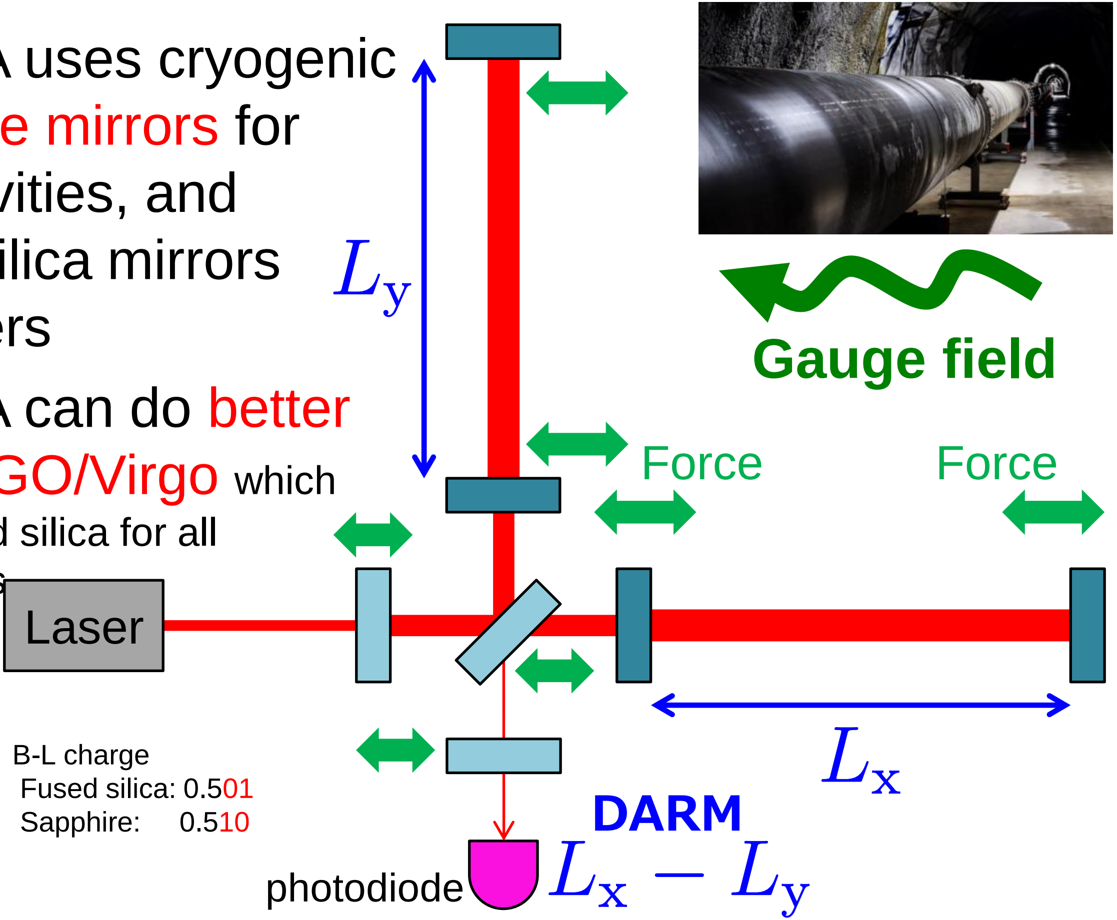
Silica: 0.501, Sapphire: 0.51

**VDM with B-L coupling differentiates mirror motion by 2%**

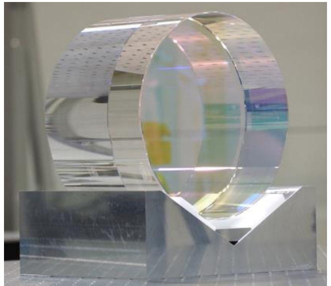
By courtesy of
Prof.Michimura

# Search with KAGRA

- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others
- KAGRA can do better than LIGO/Virgo which uses fused silica for all the mirrors

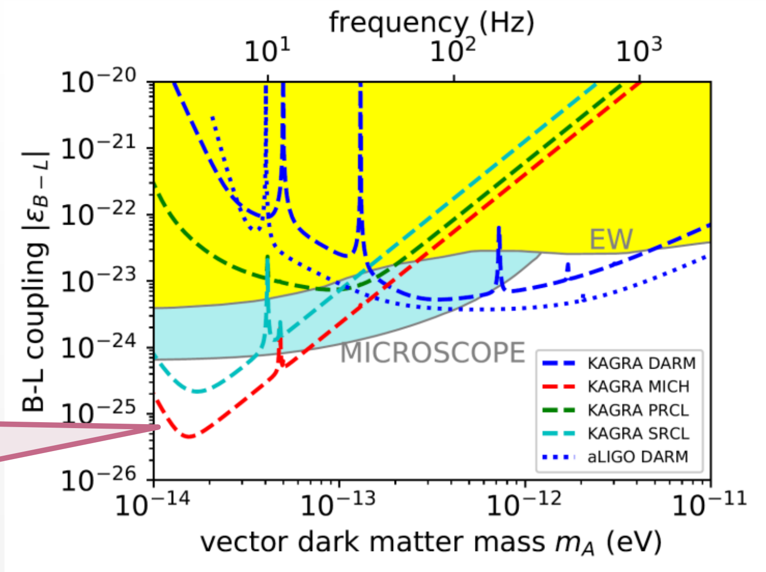


B-L charge
Fused silica: 0.501
Sapphire: 0.510



# KAGRA’s sensitivity to VDM

Michimura, TF, Morisaki,
Nakatsuka and Obata
PRD102, 102001(2020)

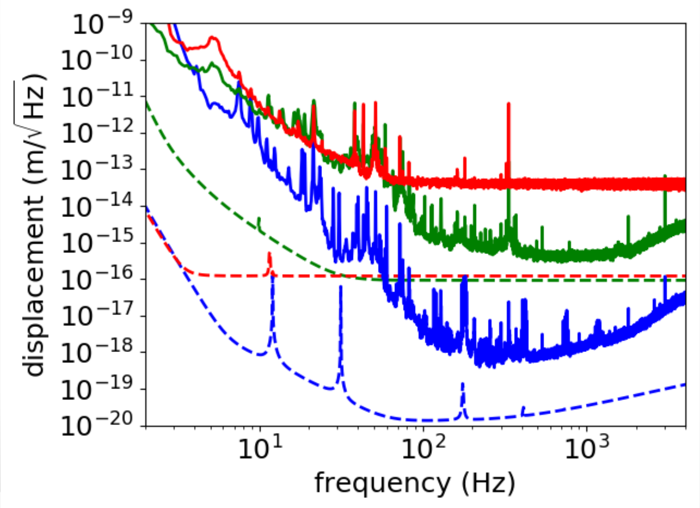


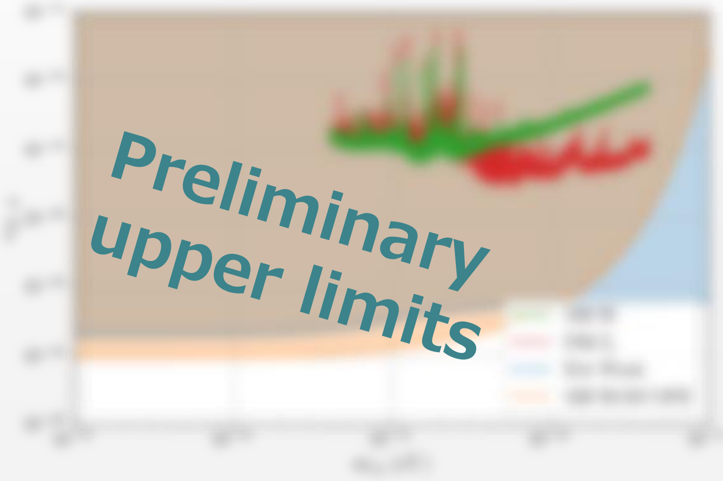
×10 improve the constraint

KAGRA will achieve the best sensitivity to VDM with B-L coupling by using the auxiliary **length channels**.

# O3GK Data Analysis Underway

- KAGRA performed joint observing run in April 2020 with GEO600 = **O3GK**
- We have developed a data analysis pipeline to search for VDM
- Applying the pipeline for **two sets of $10^4$ sec data** & working on veto analysis





Preliminary upper limits

# Outline

1. News
2. Ultralight DM (Intro.)
3. Status of Vector DM search
4. **Stochastic Effect**
5. Summary

# Demonstration

Nakatsuka, Morisaki, TF+
[in preparation]

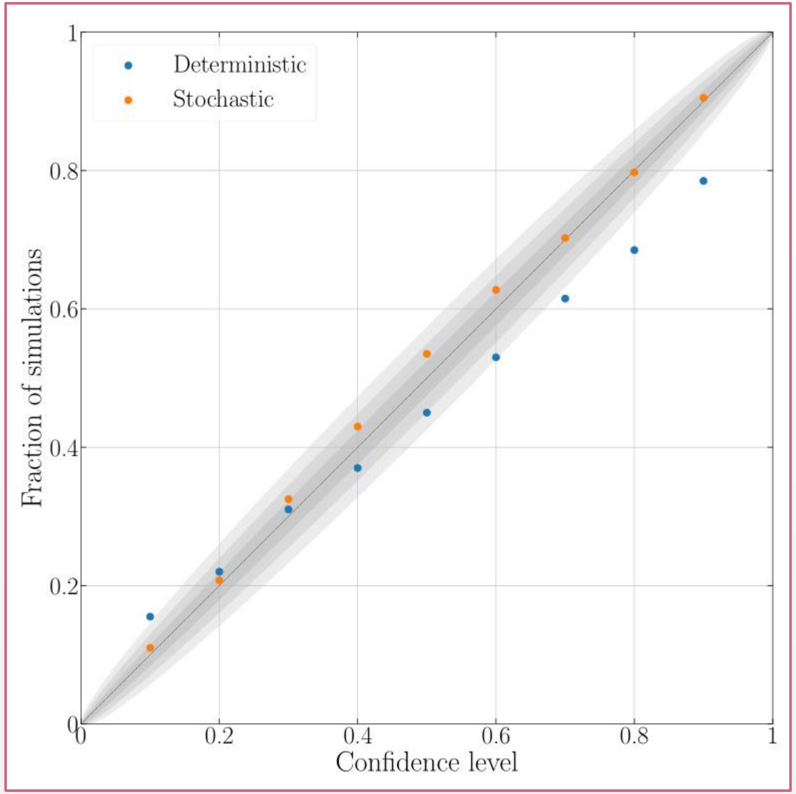
- 400 realization of simulated data.

  $(f_{\mathrm{DM}}, T, \epsilon_B) = (20\,\mathrm{Hz},\ 3.6 \times 10^3\,\mathrm{s},\ 1.1 \times 10^{-22}),$

- Every time estimate the upper bound on $\epsilon_{\mathrm{est}}$ and check whether $\epsilon_{\mathrm{est}} \lessgtr \epsilon_{\mathrm{true}}$

- For 90%C.L., 90% of trials should yield $\epsilon_{\mathrm{est}} > \epsilon_{\mathrm{true}}$, however….

→ **Stochastic effect is crucial!**



# Model wave-like DM

- Wave-like DM
  = **Superposition of many waves**

$$\phi(t,\mathbf{0}) \sim \Sigma_i \cos(\omega_i t + \theta_i)$$

- Wave has own velocity $(v_i \sim 10^{-3})$

$$\omega_i = \sqrt{m^2 + \boldsymbol{p}_i^2} \simeq m + \frac{1}{2} m v_i^2$$

- Coherent time $\tau \equiv 2\pi/(m\bar{v}^2)$

For $t \ll \tau,\ \frac{1}{2} m v_i^2 t \simeq \frac{t}{\tau} \ll 1$

- For t $\ll \tau$, DM coherently oscillates
  with **random but constant** amp. & phase

$$\cos(mt + \theta_1) + \cos(mt + \theta_2)$$
$$= \sqrt{2 + 2\cos(\theta_1 - \theta_2)}\ \cos(mt + \phi)$$

$$\tan\phi = \sqrt{(\sin^2\theta_1 + \sin^2\theta_2)/(\cos^2\theta_1 + \cos^2\theta_2)}$$

# Stochastic amp. & phase

- For $t \gtrsim \tau$, however, the correction term in $\omega_i$ becomes significant.

$$\frac{1}{2} m v_i^2 t \simeq \frac{t}{\tau} = \mathcal{O}(1)$$

- Expand around $t = t_* \gtrsim \tau$ and absorb $m v_i^2 t_*/2$ into the phase.

$$\frac{1}{2} m v_i^2 t + \theta_i = \underbrace{\frac{1}{2} m v_i^2 (t - t_*)}_{\ll\, \mathcal{O}(1)} + \tilde{\theta}_i$$

- For $\mathrm{t} - \mathrm{t}_* \ll \tau$, DM coherently oscillates again with **different** amp. & phase

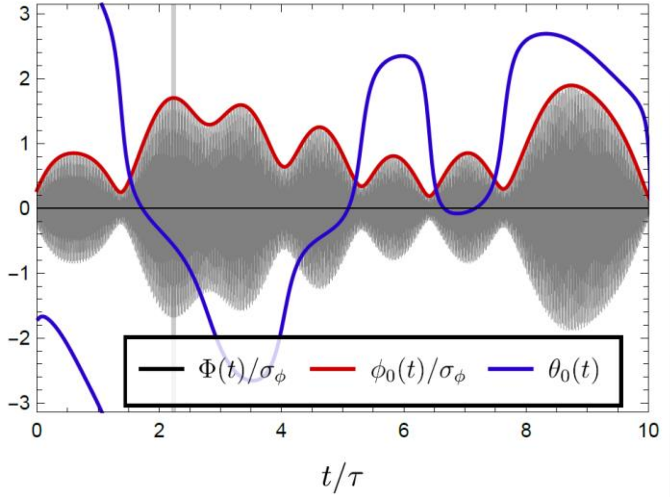
$$\cos(mt + \tilde{\theta}_1) + \cos(mt + \tilde{\theta}_2)$$
$$= \sqrt{2 + 2\cos(\tilde{\theta}_1 - \tilde{\theta}_2)} \cos(mt + \tilde{\phi})$$

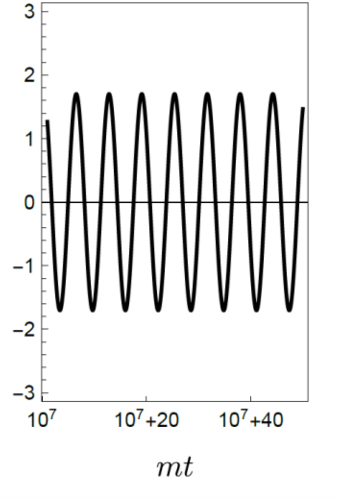
⇒ **Stochastic behavior**

$$\tan \tilde{\phi} = \sqrt{(\sin^2 \tilde{\theta}_1 + \sin^2 \tilde{\theta}_2) / (\cos^2 \tilde{\theta}_1 + \cos^2 \tilde{\theta}_2)}$$

# Numerical result

Nakatsuka, Morisaki, TF+
[in preparation]





Superposition of $N_\phi = 10^4$ waves

$$\Phi(t,\vec{x}) = \sigma_\phi N_\phi^{-1/2} \sum_{i=1}^{N_\phi} \cos\left(m(1+v_i^2/2)t + m\vec{v}_i\cdot\vec{x} + \theta_i\right),$$

$t \ll \tau$ : Coherent oscillation

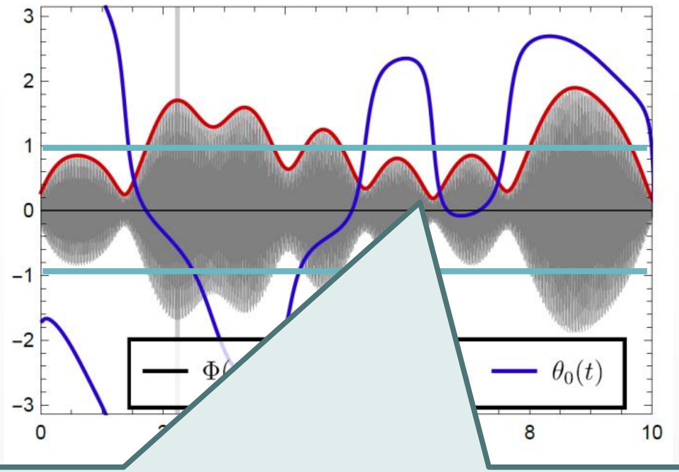
$t \gtrsim \tau$ : Amp.& phase vary **stochastically**

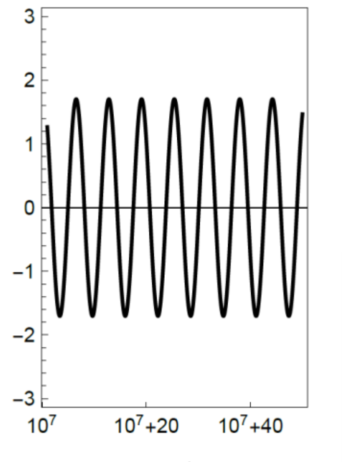
$$\sigma_\phi \equiv \sqrt{\frac{2\rho_{\rm DM}}{g_* m^2}},$$

$$\tau \equiv \frac{2\pi}{m\bar{v}^2} \simeq 4\times 10^6 m^{-1}.$$

# Numerical result

Nakatsuka, Morisaki, TF+
[in preparation]





If measurement time $T \ll \tau$,

you maybe **unlucky** and $\Phi(0 < t < T) \ll \langle \Phi \rangle$

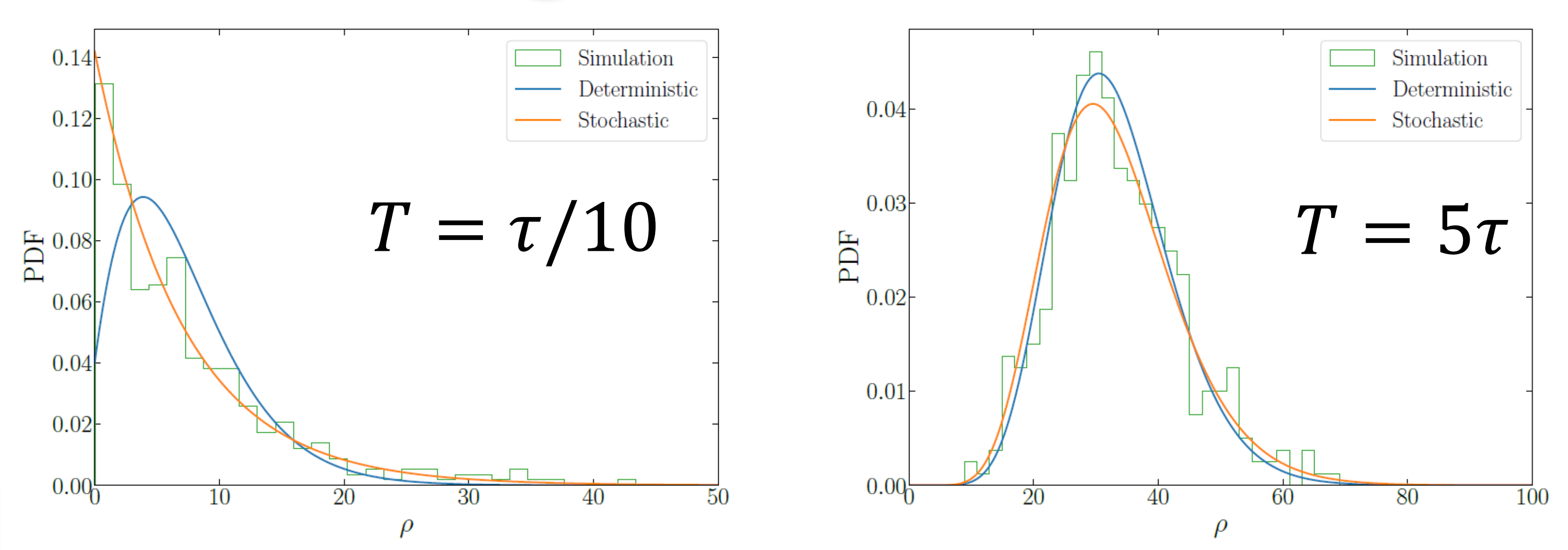
➡ **Risk of too tight constraint.**

$\cdot \vec{x} + \theta_i)$ ,

$10^6 m^{-1}$.

# PDF of signal

Nakatsuka, Morisaki, TF+
[in preparation]

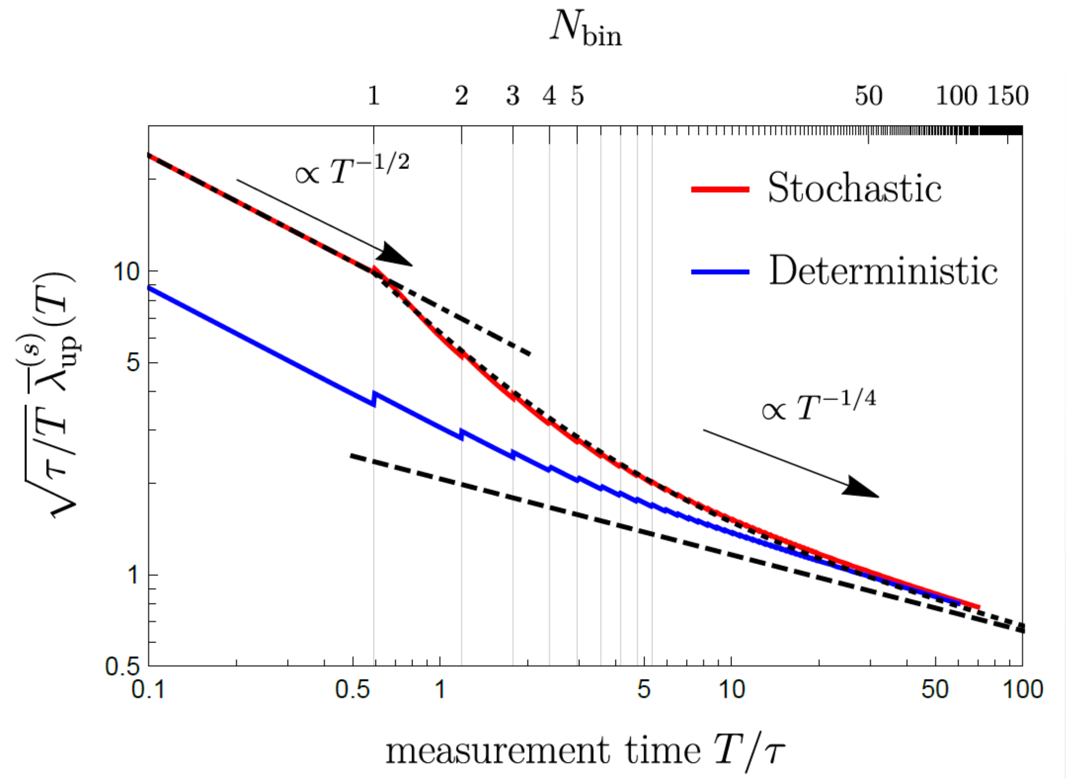


Fourier amplitude $\tilde{\Phi}(f_n) \simeq \frac{T}{2}\sigma_\phi \sqrt{\Delta_s(f_n)} \left[\frac{r_n}{\sqrt{2}}\exp(i\theta_n)\right],$

Sum it over $m \leq 2\pi f_n$
w/ velocity distribution weight

Stochastic variable $P_{\rm R}(r)\mathrm{d}r = r\exp\left(-\frac{r^2}{2}\right)\,\mathrm{d}r.$ : Rayleigh distribution

# Time dependence of bound



$$\bar{\lambda}_{\rm axion} = \frac{T}{\sqrt{T S_{\rm noise}}} g_a \sqrt{\frac{\rho_{\rm DM}}{m^2}} \frac{m}{2k},$$

$$\bar{\lambda}_{\rm space} = \epsilon_D e \frac{2T}{\sqrt{T S_{\rm noise}}} \sqrt{\frac{2\rho_{\rm DM}}{3m^2}} \frac{(Q/M)_{\rm in} \bar{v}}{2\sqrt{2}},$$

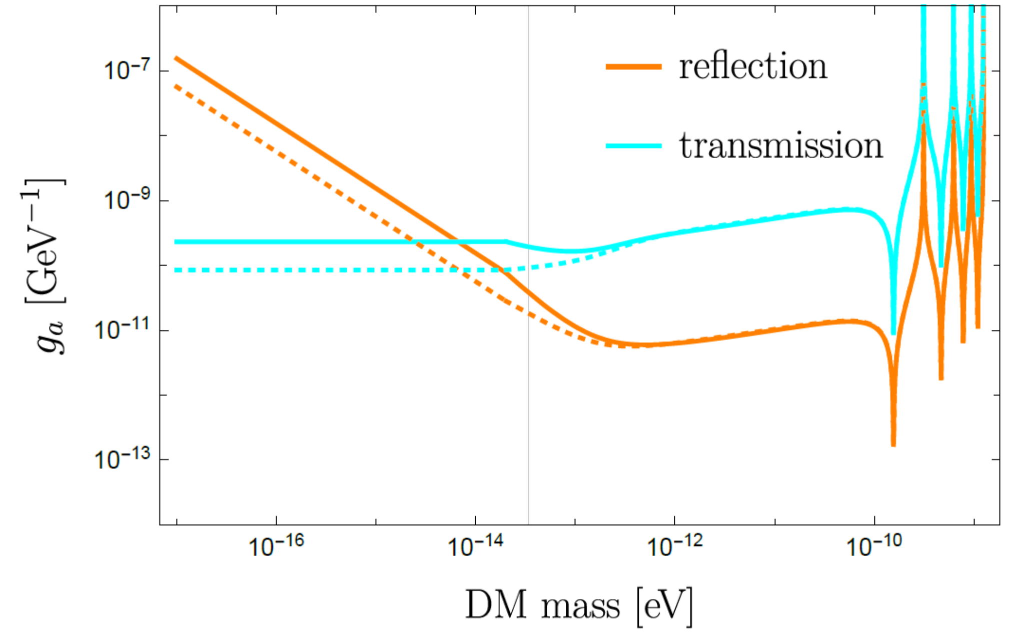
$$\bar{\lambda}_{\rm time} = \epsilon_D e \frac{2T}{\sqrt{T S_{\rm noise}}} \sqrt{\frac{2\rho_{\rm DM}}{3m^2}} \frac{(Q/M)_{\rm in}}{mL} \sin^2\left(\frac{mL}{2}\right),$$

$$\bar{\lambda}_{\rm charge} = \epsilon_D e \frac{2T}{\sqrt{T S_{\rm noise}}} \sqrt{\frac{2\rho_{\rm DM}}{3m^2}} \frac{|(Q/M)_e - (Q/M)_{\rm in}|}{2Lm}.$$

**For long enough data, we can ignore it. Currently important.**

# aLIGO case $(T = 1\mathrm{day})$

Nakatsuka, Morisaki, TF+
[in preparation]



**We'll apply this analysis method to O3GK data & others!**

# Summary

## B01: laser interferometer search for ULDM

- Use GW observatory to hunt **ultralight vector DM** (B, B-L coupling)
- Developed a new analysis method including the **stochastic effect**
- Analyze **O3GK data** and get ready for O4 run!

# Thank You!