16th Patras Workshop on Axions, WIMPs and WISPs

Ultralight vector dark matter search using KAGRA

Jun’ya Kume (U. Tokyo, RESCEU) on behalf of the KAGRA collaboration

Collaborators:
T. Fujita (WIAS, RESCEU), Y. Michimura (U. Tokyo)
S. Morisaki (Milwaukee), H. Nakatsuka (U. Tokyo, ICRR)
A. Nishizawa (U. Tokyo, RESCEU) and I. Obata (MPI)
Contents

- Ultralight vector DM and GW interferometer
- KAGRA and its auxiliary channels
- Detection pipeline
- Summary
Ultralight vector DM and GW interferometer

• Ultralight vector DM

Vast discovery space for the DM: \(10^{-22}\text{eV} \sim 10^{67}\text{eV}\)  
90 orders of magnitude!!

\[
\begin{align*}
10^{-22}\text{eV} & \quad \text{Excluded...} \\
\text{eV} & \quad \text{Wave-like} \\
\text{keV} & \quad \text{Particle} \\
\text{GeV} & \quad \text{Thermally produced} \\
& \quad \text{Fermionic} \\
& \quad \text{WIMPs}
\end{align*}
\]

If non-thermally produced, \(m_{DM} \ll \text{eV}\) is allowed for bosonic field!!

→ Ultralight vector DM is well-motivated:

ex.) \(U_B(1), U_{B-L}(1)\) gauge boson
Ultralight vector DM and GW interferometer

- Ultralight vector DM

\[ \mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_A^2 A^\mu A_\mu - \epsilon_D e J^\mu_D A_\mu \]

ex.) \( D = B, B - L \)

Ultralight \( \rightarrow \) “classical wave” oscillating with \( \omega \approx m_A(1 + v^2/2) \).

\( \vec{A} = \vec{A}_0 \cos(\omega t - \vec{k} \cdot \vec{x}) \) with \( v_{\text{DM}}^{\text{local}} \approx 10^{-3}, \ k = m_A v \ll \omega \)

\( \rightarrow \) electric wave-like

Extremely sensitive measurement is required...

From equivalence principle tests
Coupling to SM: \( \epsilon_D \lesssim 10^{-23} \)

Ultralight vector DM and GW interferometer

- Ultralight vector DM

\[ \mathcal{L} = -\frac{1}{4} F^{\mu \nu} F_{\mu \nu} + \frac{1}{2} m_A^2 A^\mu A_\mu - \epsilon_D e J^{\mu}_D A_\mu \]

\( \text{ex.} D = B, B - L \)

Ultralight → “classical wave” oscillating with \( \omega \approx m_A (1 + v^2/2) \).

\[ \vec{A} = \vec{A}_0 \cos[\omega t - \vec{k} \cdot \vec{x}] \] with \( v_{\text{DM}}^{\text{local}} \approx 10^{-3}, k = m_A v \ll \omega \)

→ electric wave-like

Extremely sensitive measurement is required...

For \( m_{DM} \sim 10^{-14} \sim 10^{-11} \text{ eV}, \) **GW interferometer** is a good probe!!

Ultralight vector DM and GW interferometer

- DM search with GW interferometer
  “Electric” DM wave acts on test masses:
  \[ \vec{F} = -\epsilon_D e Q_D \dot{A} \]

Displacement of the mirror:

\[ \delta \ddot{x} \sim -\frac{\epsilon_D e Q_D}{m_A M} \dot{A}_0 \sin[\omega t - \vec{k} \cdot \vec{x}] \]

The effect of the vector field can be read off!!

→ No detection = constraint on the coupling
Ultralight vector DM and GW interferometer

- DM search with GW interferometer
  LIGO and Virgo O3 data has been analyzed.

$U_B(1)$ model:
For $m_A \sim 10^{-12} \sim 10^{-11}$ eV,
largely surpass existing limit!!

**GW interferometer can be the best detector for Ultralight DM!!**

LVK Collaboration, arXiv:2105.13085

---

“Ultralight vector dark matter search using KAGRA”

Jun’ya Kume (Univ. of Tokyo, RESCEU)
Ultralight vector DM and GW interferometer

• DM search with GW interferometer
  LIGO and Virgo O3 data has been analyzed!!

\[ U_B(1) \]

For
largely surpass existing limit!!

GW interferometer can be the best detector for Ultralight DM!!

LIGO’s sensitivity is best.

LVK Collaboration, arXiv:2105.13085

“Ultralight vector dark matter search using KAGRA”
Contents

- Ultralight dark matter and GW interferometer
- KAGRA and its auxiliary channels
- Detection pipeline
- Summary
KAGRA and its auxiliary channels

- Difficulty in Ultralight DM search

GW interferometers → sensitive to the **differential motion** of the arms
But DM wave almost **commonly** affects the test mass...

\[ \lambda = \frac{2\pi}{m_A v} \sim 3 \times 10^8 \text{km} \]

→ DM “signal” is significantly attenuated...
To enhance the signal, we need **asymmetric response!!**
KAGRA and its auxiliary channels

- Advantage of KAGRA in DM search (Y. Michimura et al. 2020)

Auxiliary channels:

\[ \delta L_{\text{MIC}} = \delta(l_x - l_y) \]
\[ \delta L_{\text{PRCL}} = \delta((l_x + l_y)/2 + l_p) \]
\[ \delta L_{\text{SRCL}} = \delta((l_x + l_y)/2 + l_s) \]

<table>
<thead>
<tr>
<th></th>
<th>(L_{\text{arm}})</th>
<th>(l_x)</th>
<th>(l_y)</th>
<th>(l_p)</th>
<th>(l_s)</th>
<th>(l'_p)</th>
<th>(l'_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAGRA</td>
<td>3000</td>
<td>26.7</td>
<td>23.3</td>
<td>66.6</td>
<td>66.6</td>
<td>19.5</td>
<td>19.4</td>
</tr>
</tbody>
</table>

\[ \delta L_{\text{DARM}} = \delta(L_x - L_y) \]

“Ultralight vector dark matter search using KAGRA”
Jun'ya Kume (Univ. of Tokyo, RESCEU)
KAGRA and its auxiliary channels

- Advantage of KAGRA in DM search (Y. Michimura et al. 2020)

Auxiliary channels:

\[ \delta L_{\text{MICH}} = \delta(l_x - l_y) \]

\[ \delta L_{\text{PRCL}} = \delta[(l_x + l_y)/2 + l_p] \]

\[ \delta L_{\text{SRCL}} = \delta[(l_x + l_y)/2 + l_s] \]

Due to the **charge difference**, displacement becomes asymmetric!!

<table>
<thead>
<tr>
<th></th>
<th>( L_{\text{arm}} )</th>
<th>( l_x )</th>
<th>( l_y )</th>
<th>( l_p )</th>
<th>( l_s )</th>
<th>( l'_p )</th>
<th>( l'_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAGRA</td>
<td>3000</td>
<td>26.7</td>
<td>23.3</td>
<td>66.6</td>
<td>66.6</td>
<td>19.5</td>
<td>19.4</td>
</tr>
</tbody>
</table>

\[ \delta L_{\text{DARM}} = \delta(L_x - L_y) \]
KAGRA and its auxiliary channels

- Advantage of KAGRA in DM search (Y. Michimura et al. 2020)

For $U_{B-L}(1)$ model, KAGRA reaches the unexplored region!!
KAGRA and its potential application...

- Advantage of KAGRA

For $U_{B-L}(1)$ model, KAGRA

$$\frac{Q_B}{M} \approx \frac{N_B}{N_B m_n} = \frac{1}{m_n} \rightarrow 10^{-5} \text{ difference...}$$

$$\frac{Q_B - Q_L}{M} \approx \frac{N_B - N_L}{N_B} \frac{1}{m_n} \rightarrow \text{ Silica: 0.501}
\text{ Sapphire: 0.51}$$
Contents

- Ultralight dark matter and GW interferometer
- KAGRA and its auxiliary channels
- Detection pipeline
- Summary
Detection pipeline

- Signal properties
  “DM wave” → superposition of waves with various momentum

\[
\bar{A} = \sum_i A_i \bar{e}_i \cos[m_A (1 + \frac{v_i^2}{2}) t - m_A \bar{v}_i \cdot \bar{x} + \phi_i]
\]

\( v_i \sim v_{\text{DM}}^{\text{local}} \sim 10^{-3} \) (※ Standard Halo model is assumed)

Sharp spectrum with
\( f \sim m_A / 2\pi \) and \( \Delta f \sim f v_{DM}^2 \sim 10^{-6} f \)
→ DM signal is localized.
Detection pipeline

• Signal properties

“DM wave” → superposition of waves with various momentum

\[
\tilde{A} = \sum_i A_i \tilde{e}_i \cos[m_A (1 + v_i^2/2)t - m_A \vec{v}_i \cdot \vec{x} + \phi_i]
\]

\[v_i \sim v_{\text{local}} \sim 10^{-3}\] (※Standard Halo model is assumed)

Sharp spectrum with

\[f \sim m_A / 2\pi\] and \(\Delta f \sim f v_{\text{DM}}^2 \sim 10^{-6} f\)
→DM signal is localized.
Detection pipeline

- Search Method
Collect the spectra at the frequency bins: \( m_A \leq 2\pi f_k \leq m_A(1 + \kappa v_{DM}^2) \)

\[ \rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\text{obs}}S_n(f_k)} \]

\( S_n \): Power Spectrum Density
\( T_{\text{obs}} \): Observational time

For Gaussian noise, \( \rho \) obeys \( \chi^2_{2n} \) distribution when there is no signal. (\( n \): number of the bins)
100(1 – \( \alpha \))% upper limit of \( \chi^2_{2n} \rightarrow 100\alpha\% \) FAR.
Detection pipeline

• Search Method

From the SNR $\rho$, 95\% upper limit of the “coupling” is obtained as

$$\int_{\rho_{obs}}^{\infty} p(\rho|\epsilon_d^{95\%}) d\rho = 0.95.$$  
(When signal is present, $\rho$ obeys non-central $\chi^2_{2n}$)

But we should care stochastic nature of DM.
(See G. P. Centers et al. 2020)
Detection pipeline

- Search Method

From the SNR $\rho$, 95% upper limit of the “coupling” is obtained as

$$\int_{\rho_{\text{obs}}}^{\infty} p(\rho | \epsilon_{95\%}^D) d\rho = 0.95.$$  
(When signal is present, $\rho$ obeys non-central $\chi^2_{2n}$)

But we should care stochastic nature of DM.
(See G. P. Centers et al. 2020)

→ In our pipeline, random amplitude of the wave is taken into account.

(H Nakatsuka et al. in prep)
Detection pipeline

• Towards the analysis of KAGRA data
KAGRA performed a joint observing run with GEO600 in April 2020. (referred as **O3GK**)

While the SNR $\propto T_{\text{obs}}^{1/4}$, the observation was performed for two weeks. **not so long... 😞**
(※ 1yr assumed in Y. Michimura et al. 2020)

Sufficient sensitivity of DM search is not expected with the latest data...

---

KAGRA collaboration

“Ultralight vector dark matter search using KAGRA”
Jun’ya Kume (Univ. of Tokyo, RESCEU)
Detection pipeline

• Towards the analysis of KAGRA data GW interferometer suffers from various noise sources.

→ Line noise mimics the “signals”.

Such false signals needs to be systematically distinguished.

Veto procedure:
✓ Sharpness of the spectrum
✓ Coincidence btw several segments

estimated sensitivity
Contents

- Ultralight dark matter and GW interferometer
- KAGRA and its auxiliary channels
- Detection pipeline in KAGRA
- Summary
Summary

• **GW interferometer** can probe the coupling between SM particles and the **Ultralight vector DM**.

• **KAGRA** probes unexplored discovery space of *e.g.* $U_{B-L}(1)$ gauge boson by making use of its **auxiliary monitor**.

• Pipeline construction is ongoing. Veto process and the formulation considering the **stochasticity** is now being developed.