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Searching for ultralight vector dark matter with the cryogenic gravitational wave telescope KAGRA

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Dark Matter Searches

- Previous searches focused mainly on WIMPs
- Need for new ideas to search for huge variety of other candidates



Ultralight DM with Interferometry

- Bosonic ultralight fields (<~1 eV) are well motivated by cosmology
- Behaves as classical wave fields $f = 242 \text{ Hz} \left(\frac{m_{\rm DM}}{10^{-12} \text{ eV}}\right)$
- Laser interferometers are sensitive to tiny length changes from such oscillations



Our Target: Gauge Boson

 Possible new physics beyond the standard model: New gauge symmetry and gauge boson

Proton

Neutron

Electron

Nucleus

gauge

field

- New gauge boson can be dark matter
- B-L (baryon minus lepton number)
 - Conserved in the standard model
 - Can be gauged without additional ingredients
 - Equals to the number of neutrons
 - Roughly 0.5 per neutron mass, but slightly different between materials Fused silica: 0.501 Sapphire: 0.510
- Gauge boson DM gives oscillating force

Oscillating Force from Gauge Field

Acceleration of mirrors



- Almost no signal for symmetric cavity if cavity length is short (phase difference is 10⁻⁵ rad @ 100 Hz for km cavity)
- How about using interferometric GW detectors?

Search with GW Detectors

- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)



Search with KAGRA 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_r





Search with KAGRA KAGRA



KAGRA Gauge Boson Sensitivity

- Auxiliary length channels have better sensitivity than DARM (GW cannel) at low mass range
- Sensitivity better than equivalence principle tests



KAGRA's Observing Run in 2020

- KAGRA performed joint observing run in April 2020 with GEO600 (O3GK)
- Displacement sensitivity still not good
 ~ 6 orders of magnitude to go at 10 Hz
- We have developed a data analysis pipeline to search for gauge boson DM



Data Analysis Pipeline

- Nearly monochromatic signal $\omega_i = m_A \left(1 + \frac{v_i^2}{2} \right)$
- Stack the spectra in this frequency region to calculate SNR $\rho = \sum_{n \to \infty} \frac{4 |\tilde{d}(f_k)|^2}{T_{\rm obs} S_n(f_k)} \text{Data}$

$$m_A \le 2\pi f_k \le m_A (1 + \kappa i)$$

- Detection threshold Obs. time determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ , 95% upper limit on coupling constant calculated

PSD

• Applied the pipeline to mock data for verification



Stochastic Nature of DM Signal

- DM signal is from superposition of many waves with various momentum, phase and polarization
- The amplitude fluctuates at the time scale of

 $\tau = 2\pi/(m_A v_{\rm DM}^2)$

- At low frequencies, DM signal could be too small by chance and elude detection
- Method to calculate upper limit taking into account this stochasticity developed

H. Nakatsuka+, in preparation





Preliminary Results from O3GK

- Applied the pipeline for two sets of 10⁴ sec data
- Veto using
 - sharpness of the peak ($\Delta f/f \sim 10^{-6}$ for DM)
 - consistency between segments
- Some candidates found (mostly in noise contaminated region)
 DARM: 470 candidates
 MICH: 33 candidates
 PRCL: 103 candidates
- Preliminary upper limits calculated
- Working on further veto by
 - shape of the peaks
 - line noise investigations
 - consistency between channels etc.



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Summary and Outlook

- KAGRA can do unique gauge boson dark matter search since the interferometer consist of sapphire and fused silica mirrors
- Data analysis pipeline developed
- Applied the pipeline to real KAGRA data in 2020 and got preliminary results
- Further veto studies in progress
- Observing run in 2022 planned with better sensitivity (O4)
- Stay tuned!



Additional Slides

With Space and 3G Detectors



S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, PRD 103, L051702 (2021)

Freq-Mass-Coherence Time

Frequency	Mass	Coherent Time	Coherent Length
0.1 Hz	4.1e-16 eV	0.32 year	3e12 m
1 Hz	4.1e-15 eV	1e6 sec 12 days	3e11 m
10 Hz	4.1e-14 eV	1.2 days	3e10 m
100 Hz	4.1e-13 eV	2.8 hours	3e9 m
1000 Hz	4.1e-12 eV	17 minutes	3e8 m
10000 Hz	4.1e-11 eV	1.7 minutes	3e7 m