Vector Dark Matter Search with KAGRA

-updates for O3GK data analysis-

@ Kavli IPMU, March 9th 2023

Jun'ya Kume (UTokyo, RESCEU → Univ. of Padova)

on behalf of the KAGRA collaboration

Collaborators:

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S. Morisaki(ICRR), K. Nagano (JAXA), H. Nakatsuka(UTokyo, ICRR)

A. Nishizawa(UTokyo, RESCEU) and I. Obata(IPMU)

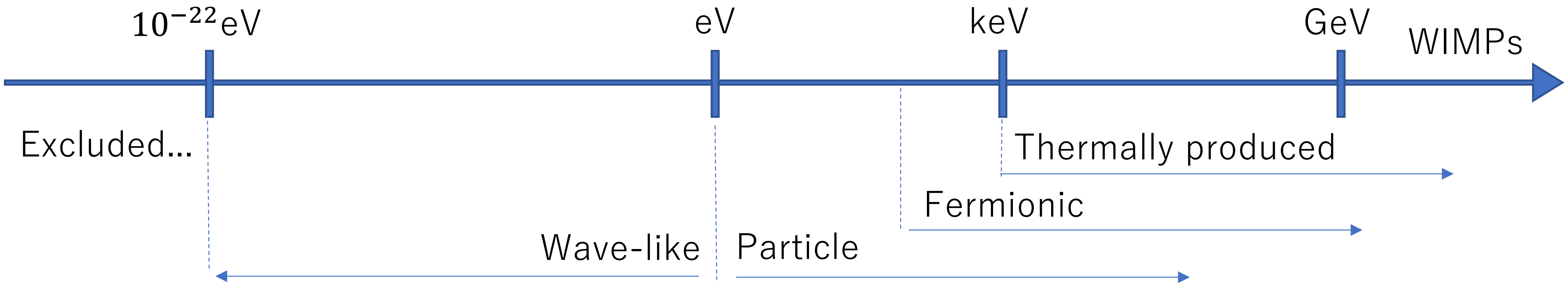
Contents

- KAGRA as a vector DM detector
- Statistics of ultralight vector DM
- Status of pipeline construction
- Summary

KAGRA as a vector DM detector

- Ultralight vector DM

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



If non-thermally produced, $m_{DM} \lesssim$ eV is allowed for bosons.

→**Ultralight "vector" DM** is well-motivated:

ex.)$U_{B-L}(1)$ gauge boson as an extension of the SM

- How can we probe vector DM?

Let them couple to the SM as

ex.) $D = B, B - L$

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

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

(S. Schlamminger+ 2008, T. A. Wagner+ 2009)

large occupation number → classical wave

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

"dark" electric force on matter → severely bounded...

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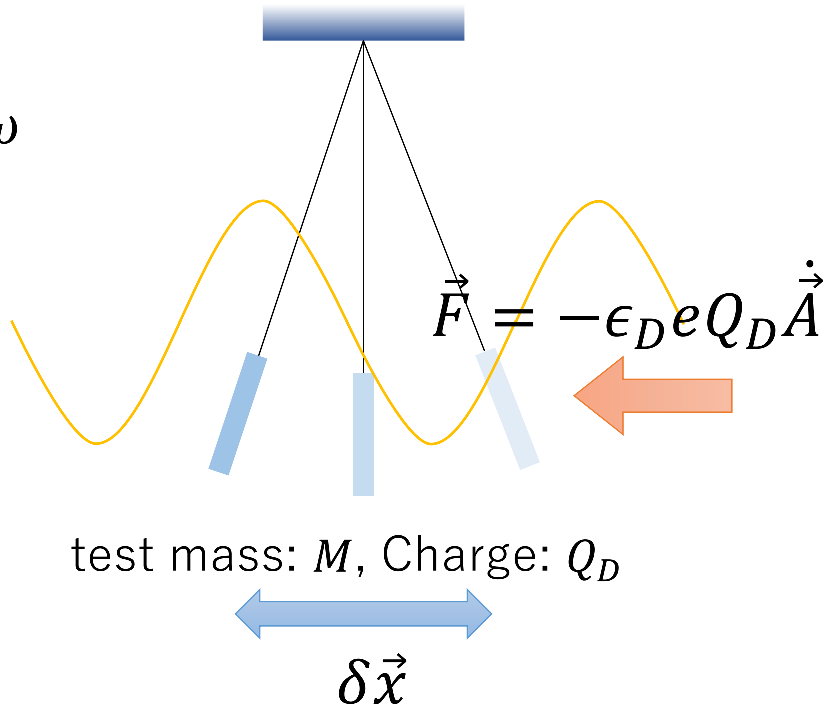


For $m_{DM} \sim 10^{-14}$~10^{-11} eV,

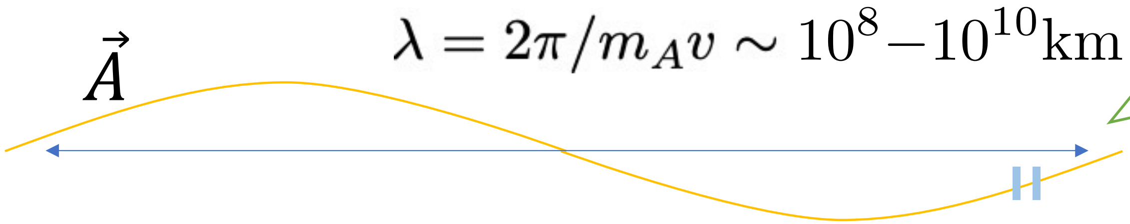
GW interferometer can probe further!!

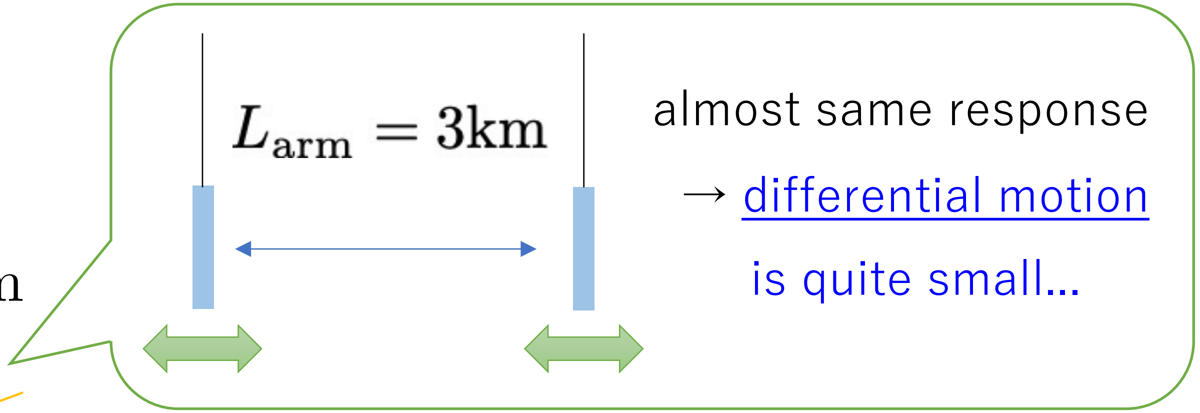
← displacement due to oscillating dark force

※challenge to quantum gravity...!? (→ talks from C01 group)

- DM search with GW interferometer

Things are not so simple…!



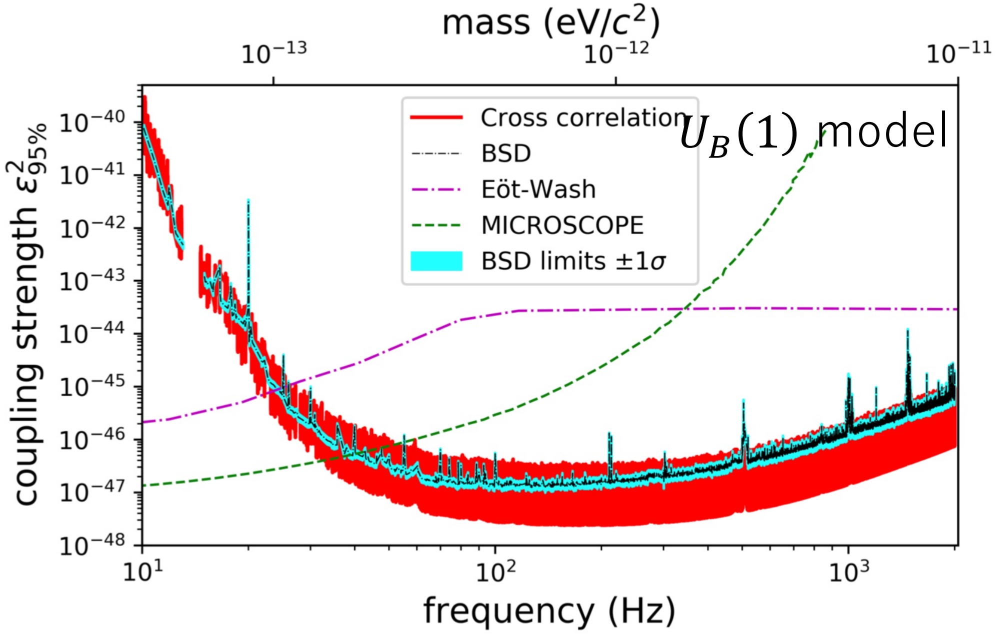


Nevertheless, LIGO & Virgo are awesome!

O3 data analysis:

For $m_A \sim 10^{-12} \sim 10^{-11}$ eV,

largely surpass existing limit!

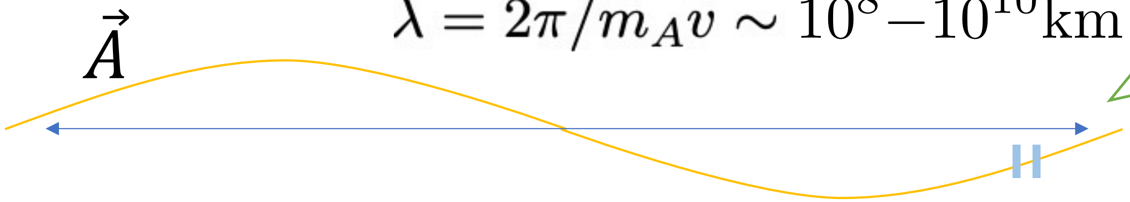


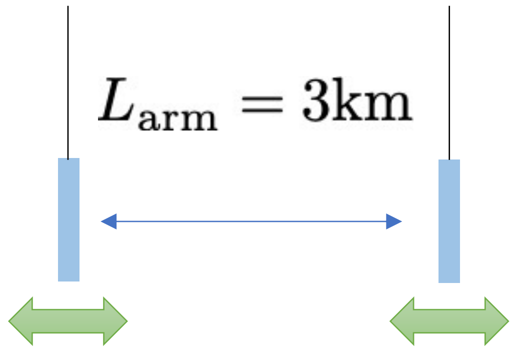
LVK Collaboration, arXiv:2105.13085

- DM search with GW interferometer

Things are not so simple…!

$\lambda = 2\pi/m_A v \sim 10^8 – 10^{10}\text{km}$





almost same response

→ differential motion

is quite small…

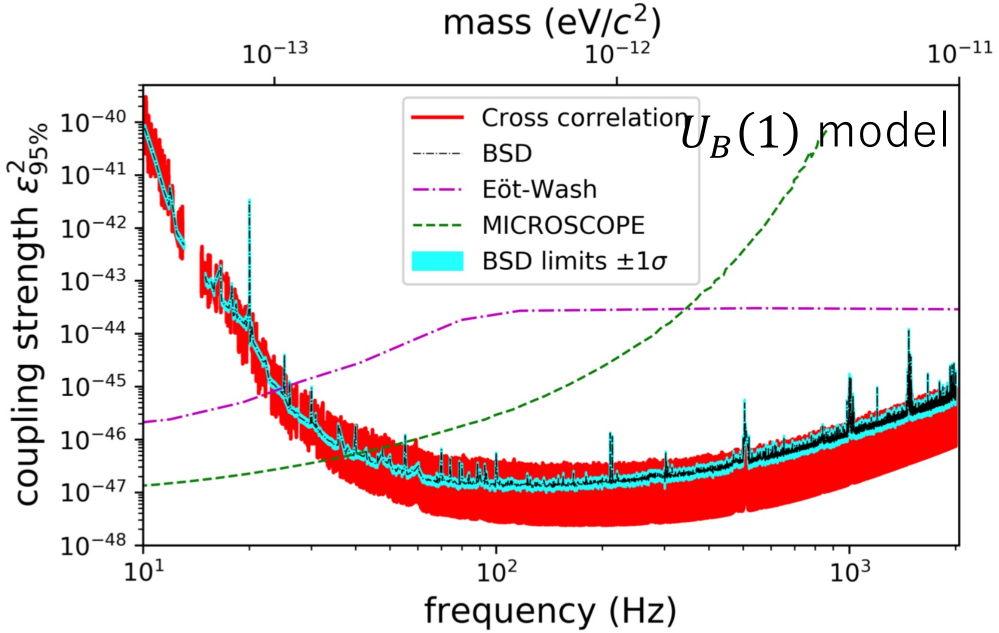
Nevertheless, LIGO & Virgo are awesome!

O3 data analysis:

For $m_A \sim 10^{-12} \sim 10^{-11}$ eV,

largely surpass existing limit!

Why "less sensitive" KAGRA…??



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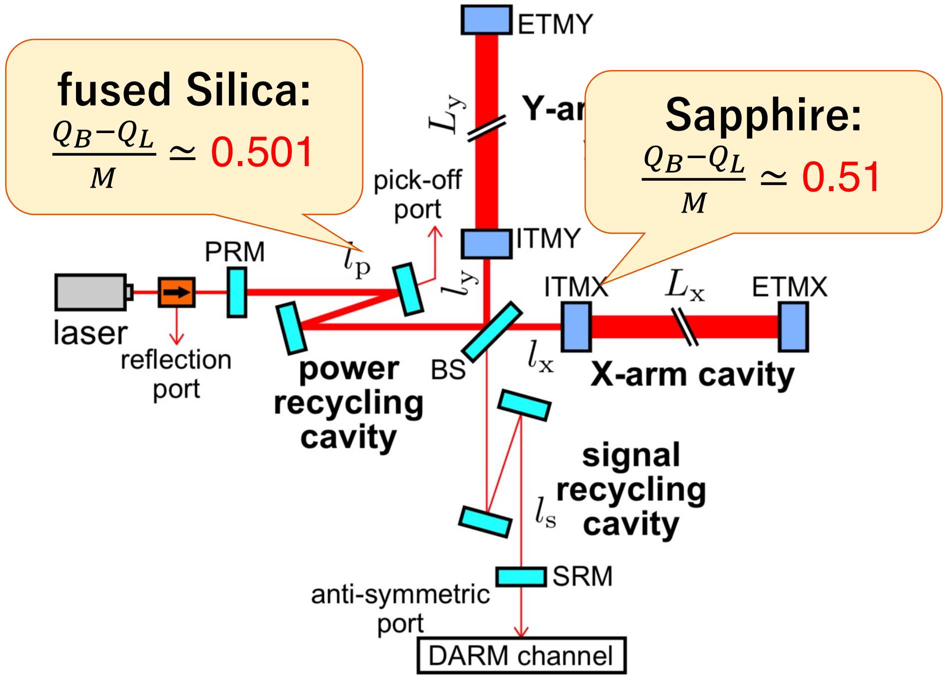
- Asymmetric response to vDM in KAGRA (Y. Michimura+ 2020)



$$\delta L_{\mathrm{MICH}} = \delta(l_x - l_y)$$

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

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

※for GW obs. $\delta L_{\mathrm{DARM}} = \delta(L_x - L_y)$

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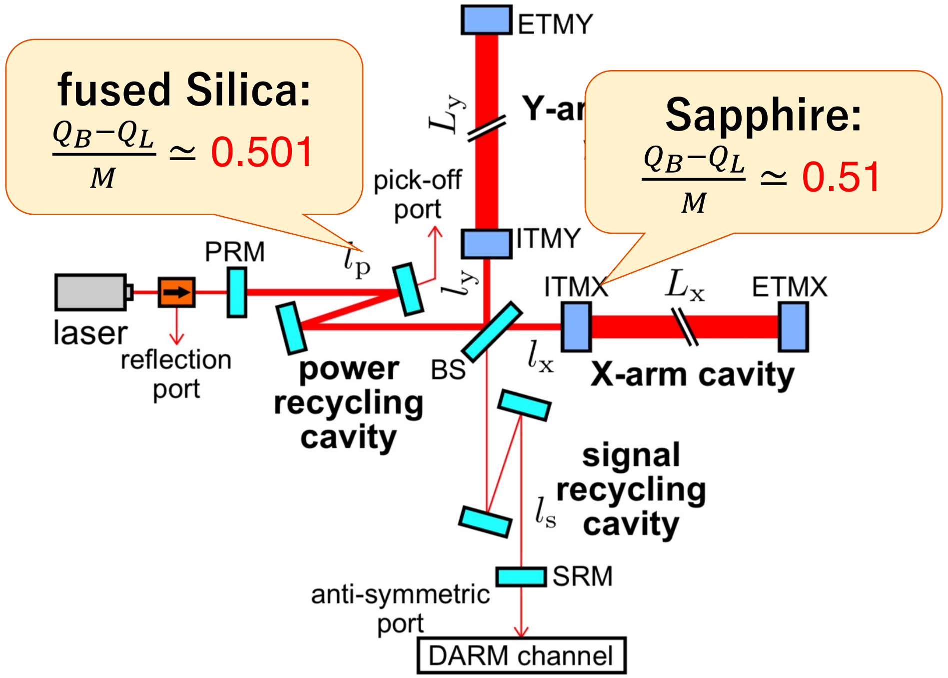

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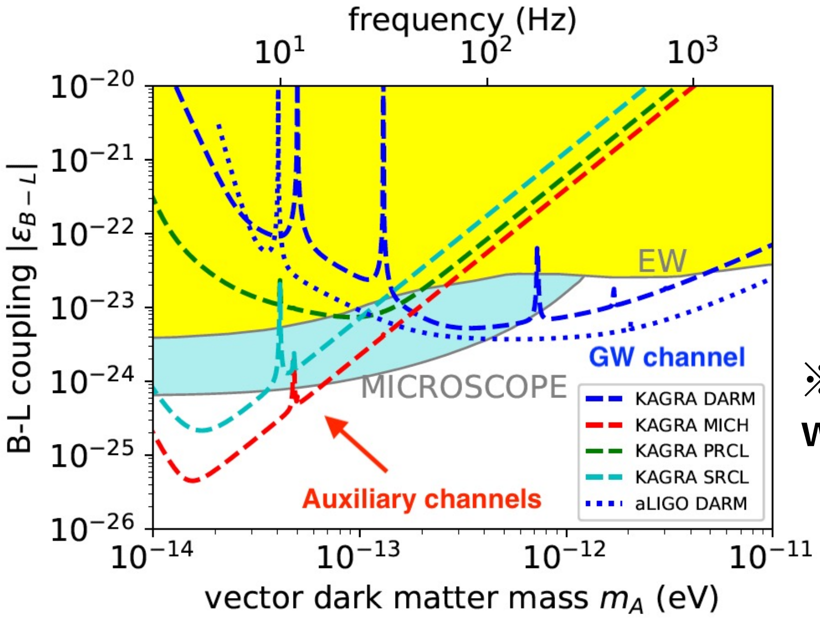
Auxiliary DoFs are useful for DM search!!



※1 year obs.
w/ design sensitivity

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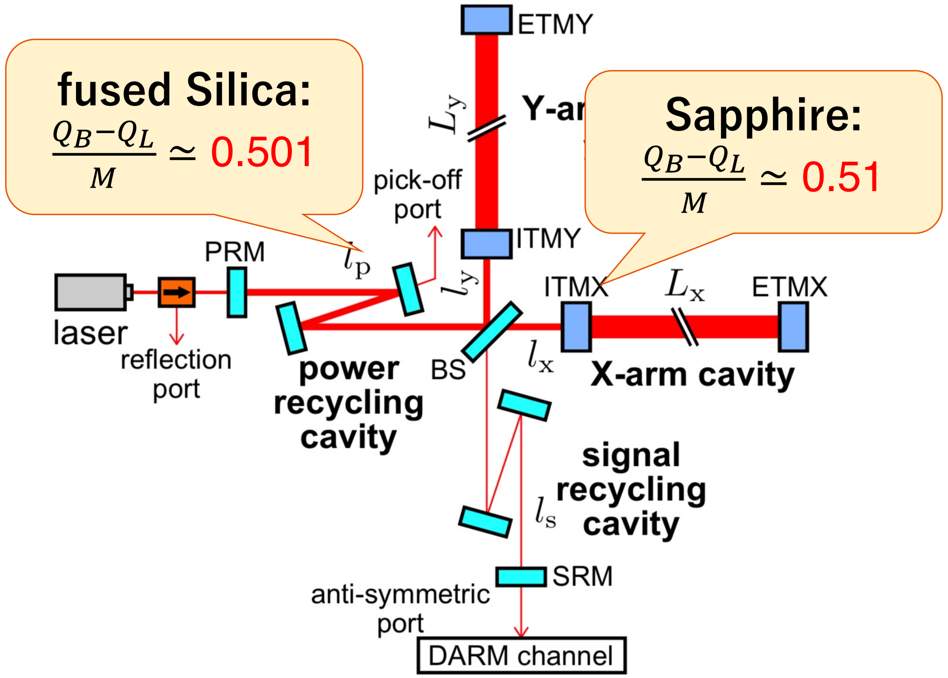

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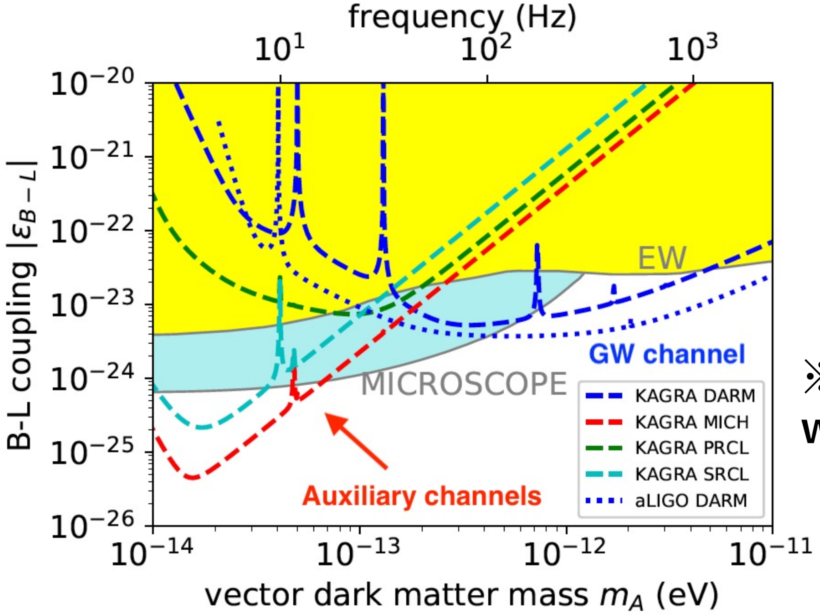

※1 year obs. w/ design sensitivity

At present, we've been working on

- ➢ Refinement of the vDM formulation
- ➢ Pipeline construction & KAGRA data analysis

Contents

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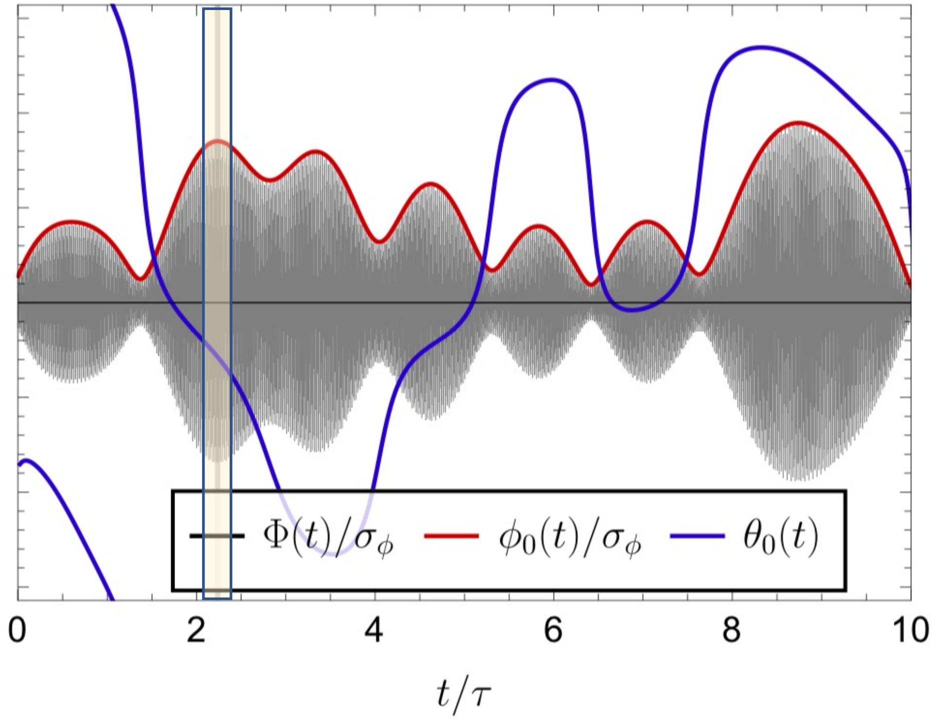
Statistics of ultralight vector DM

- Stochastic behavior of ultralight DM

superposition of partial waves:

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

→ neither monochromatic nor coherent!!



coherence time:

$$\tau \equiv \frac{2\pi}{m\bar{v}^2} \simeq 0.3\ \mathrm{day}\ \frac{10^{-13}\ \mathrm{eV}}{m}$$

$$m = 4.1\times 10^{-13}\ \mathrm{eV}\left(\frac{f_{\mathrm{DM}}}{10^2\mathrm{Hz}}\right)$$

Statistics of ultralight vector DM

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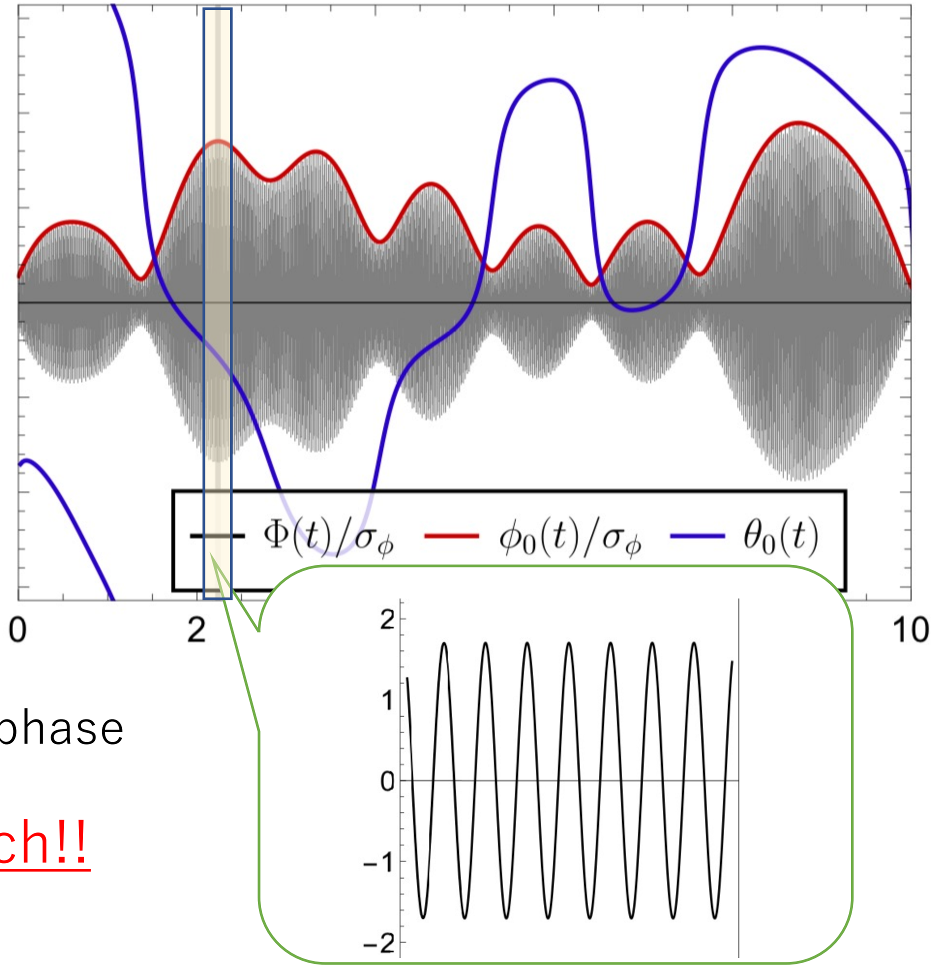

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For $\Delta t \ll \tau$

≃const. amplitude & phase

→ affects DM search!!

- Effects on scalar DM search

ex)Axion search (cf. DANCE experiment)

Fourier transform of the field over T:

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

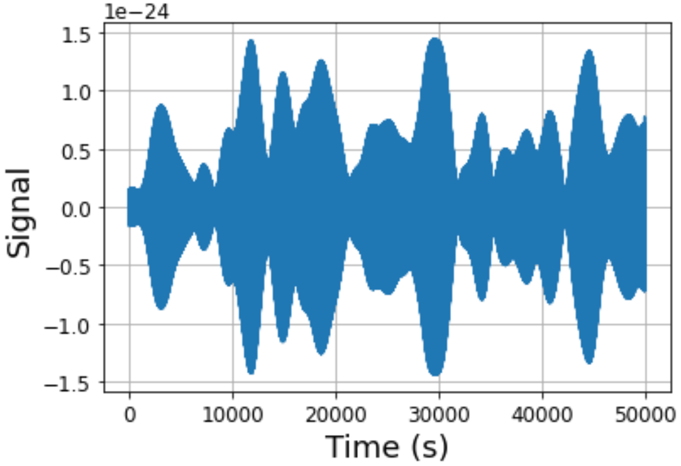
broadened spectra
due to velocity dispersion

θ_n: uniform dist.

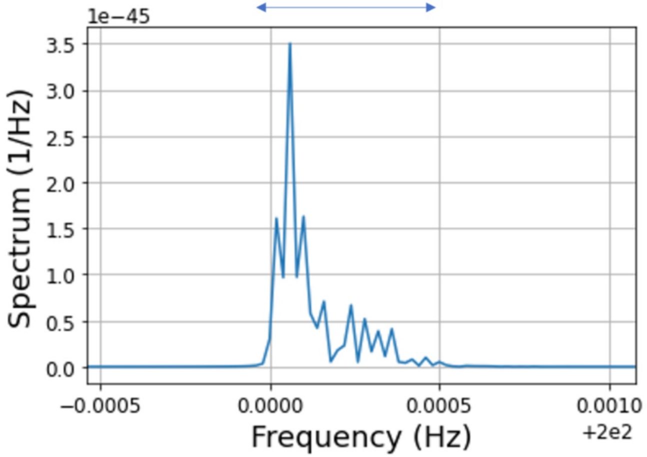
r_n: Rayleigh dist.
→random amplitude

(※summation of the random phase → 2d random walk)

$\propto \dot{\Phi}(t) \rightarrow im\tilde{\Phi}(f_n)$



$m\bar{v}^2$



$$\Delta_s(f_n) = \int_{f_n-\Delta f/2}^{f_n+\Delta f/2} \bar{f}_{\mathrm{SHM}}(v)\frac{\mathrm{d}v}{\mathrm{d}f}\mathrm{d}f$$

$\Delta f = T^{-1}$: resolution

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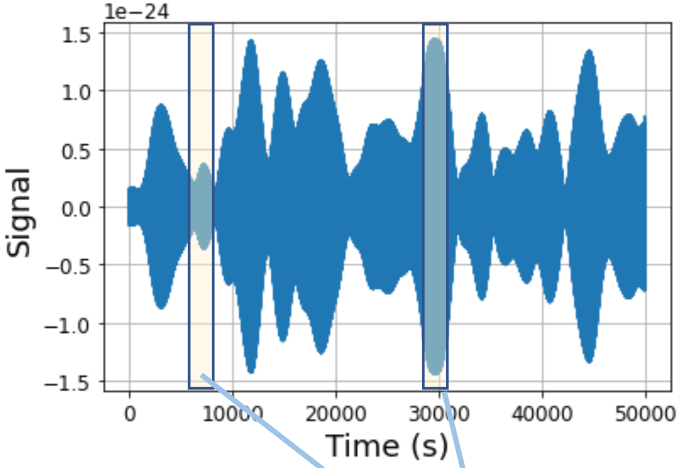

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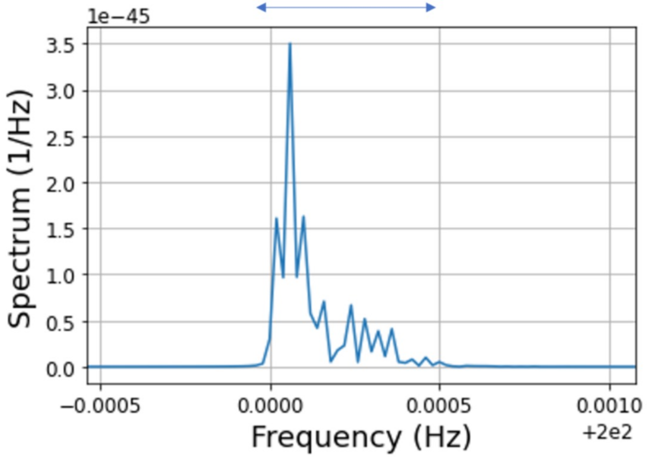
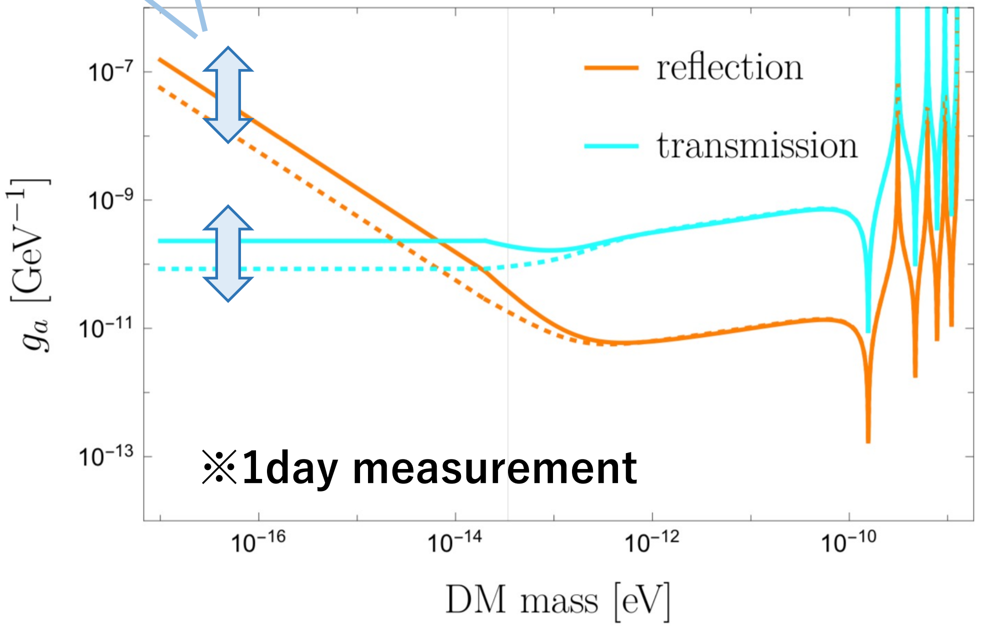


(Nakatsuka+ 2022)

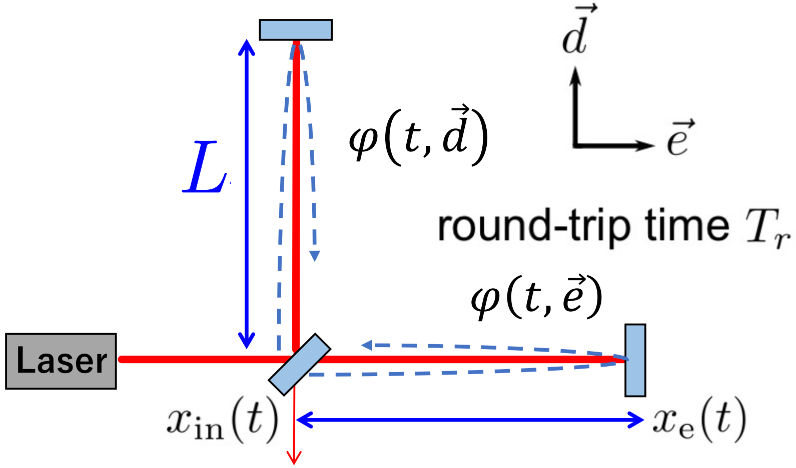


For $T < \tau$ (lighter mass w/ fixed T),
randomness of amplitude loosens bound!

(e.g. G. P. Centers et al. 2020)

– How about vector DM? 🧐

- Interferometric signals from vector DM (Nakatsuka+ 2022)



output: $h(t) = \dfrac{\varphi(t,\vec{e}) - \varphi(t,\vec{d})}{4\pi\nu L}$

phase:

$$\varphi(t,\vec{e}) = \varphi_0 + 2\pi\nu(t-2L) - 2\pi\nu(\delta L_{\rm time} + \delta L_{\rm space} + \delta L_{\rm charge})$$

→ 3 contributions from vDM!!

- Spatial variation of DM field value:

$$\delta L_{\rm space} \simeq \frac{2e\epsilon_D (Q/M)_{\rm in}}{m^2} L \frac{\partial}{\partial t} \sum_{k,j} e_k e_j \nabla_j A_k(t-L,\vec{0})$$

- Light travels finite time: (Morisaki+ 2021)

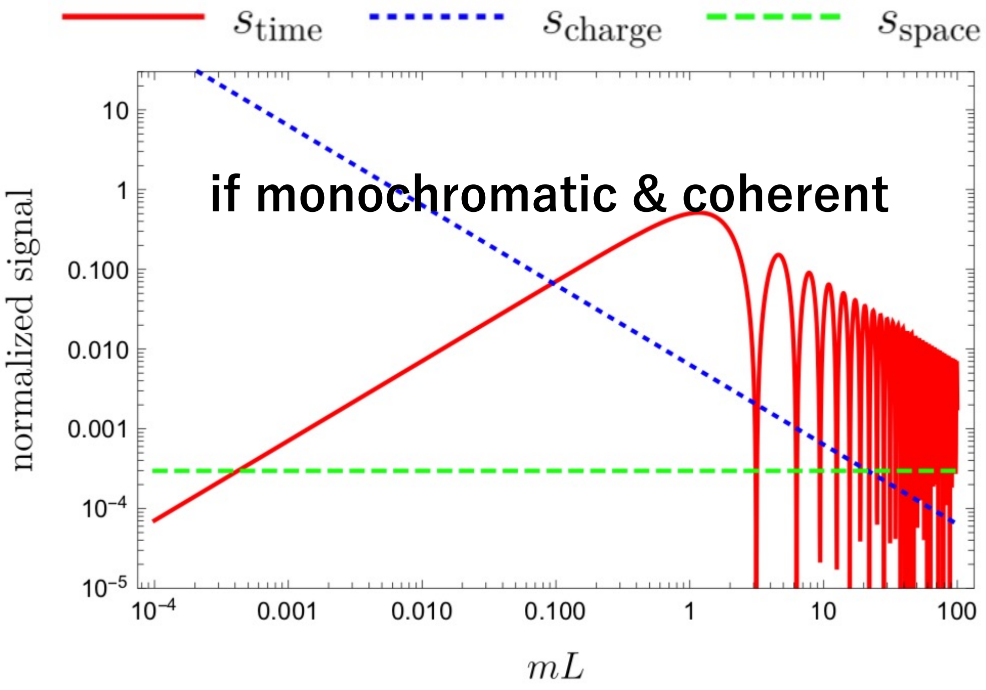
$$\delta L_{\rm time} \simeq \frac{4e\epsilon_D (Q/M)_{\rm in}}{m^2} \sin^2\left(\frac{mL}{2}\right) \frac{\partial}{\partial t} \sum_{k} e_k A_k(t-L,\vec{0})$$

- Asymmetry in charge-to-mass ratio: ← as KAGRA

$$\delta L_{\rm charge} \simeq \frac{2e\epsilon_D ((Q/M)_e - (Q/M)_{\rm in})}{m^2} \frac{\partial}{\partial t} \sum_{k} e_k A_k(t-L,L\vec{e})$$

→ dominant for lower frequency

- Interferometric signals from vector DM (Nakatsuka+ 2022)



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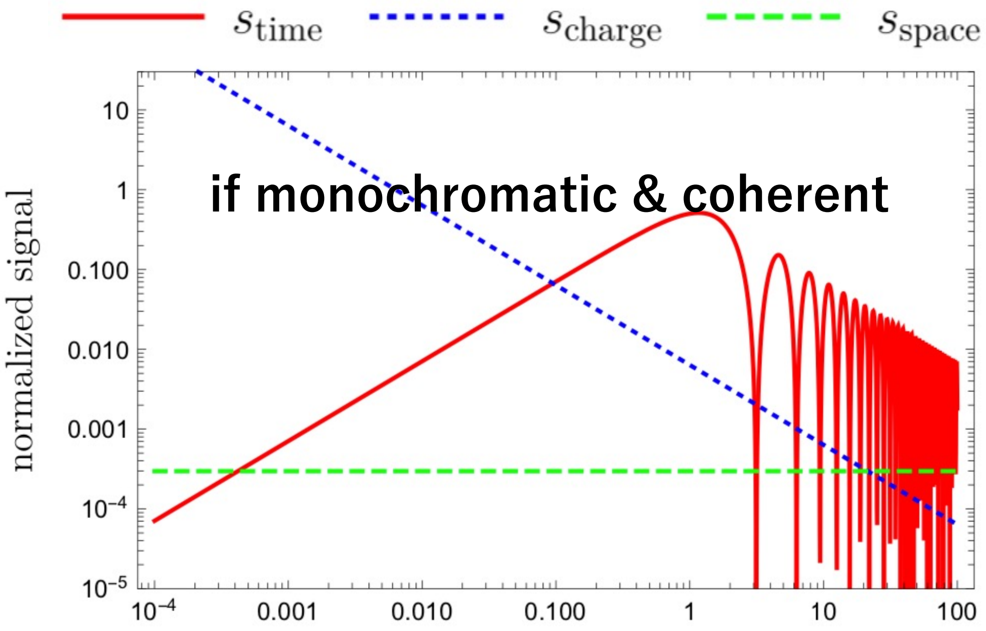

Stochastic behavior + gradient

$$\tilde{A}_k(f_n,\vec{0}) = \frac{T}{2}\sigma_A\sqrt{\Delta_s(f_n)}\,\frac{r_{k,n}}{\sqrt{2}}\exp(i\theta_{k,n})$$

$$\nabla_j\tilde{A}_k(f_n,\vec{x})\Big|_{\vec{x}=0} = \frac{T}{2}\sigma_A m\bar{v}\sqrt{\Delta_j(f_n)}\,\frac{r_{k,n}}{\sqrt{2}}\exp(i\theta_{k,n})$$

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→ dominant for lower frequency

- Stochastic behavior of vector DM (Nakatsuka+ 2022)

Fourier component of the signals:

$$s_{\rm time}(f_n) = \left(e\epsilon_D T \left(\frac{Q}{M}\right)_{\rm in} \frac{\sigma_A}{mL} \sin^2\left(\frac{mL}{2}\right)\sqrt{2}\right) \times \sqrt{\Delta_s(f_n)} \left[\frac{r_n}{\sqrt{2}} \exp(i\theta_n)\right]$$

$$s_{\rm charge}(f_n) = \left(e\epsilon_D T \left|\left(\frac{Q}{M}\right)_e - \left(\frac{Q}{M}\right)_{\rm in}\right| \frac{\sigma_A}{2Lm}\sqrt{2}\right) \times \sqrt{\Delta_s(f_n)} \left[\frac{r_n}{\sqrt{2}} \exp(i\theta_n)\right]$$

θ_n: uniform dist.

r_n: Rayleigh dist.

Same factors as the scalar signal appears

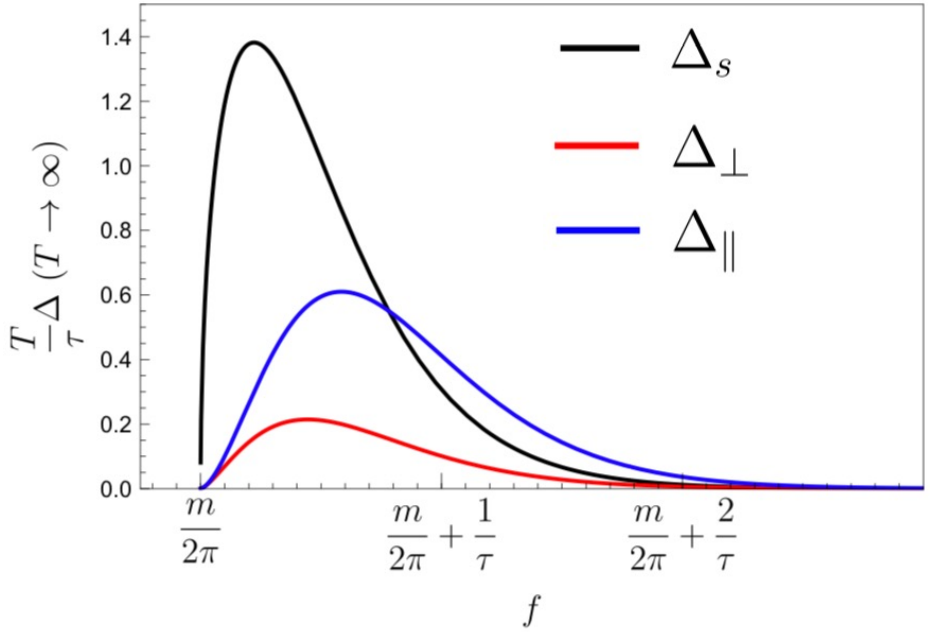
$$\tilde{\Phi}(f_n) \simeq \frac{T}{2}\sigma_\phi \sqrt{\Delta_s(f_n)} \left[\frac{r_n}{\sqrt{2}} \exp(i\theta_n)\right]$$

→ unified treatment in data analysis

※Our code is applied to DANCE analysis (cf. talk by Y. Oshima)

→ arXiv:2303.03594

Spectral shape

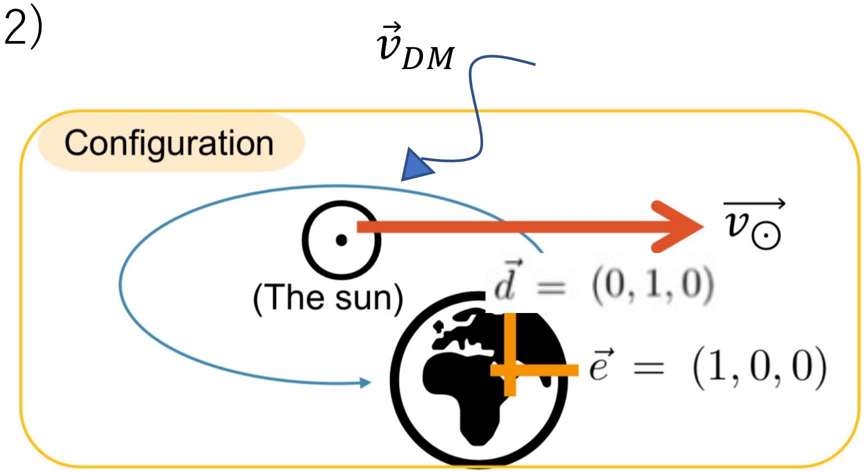


- Stochastic behavior of vector DM (Nakatsuka+ 2022)

For spatial contribution:

$$s_{\rm space}(f_n) = \left(e\epsilon_D T \left(\frac{Q}{M}\right)_{\rm in} \frac{\sigma_A \bar{v}}{2}\right) \times \sqrt{\Delta_x(f_n) + \Delta_y(f_n)} \left[\frac{r_n}{\sqrt{2}} \exp(i\theta_n)\right]$$

$$\Delta_j(f_n) = \int_{f_n-\Delta f/2}^{f_n+\Delta f/2} v^2 \frac{{\rm d}v}{{\rm d}f} {\rm d}f \int {\rm d}^2\Omega_e \times f_{\rm SHM}(\vec{v}(f,\vec{e}) + \vec{v}_\odot) \frac{[v_j(f_n, \vec{e}_l)]^2}{\bar{v}^2}$$



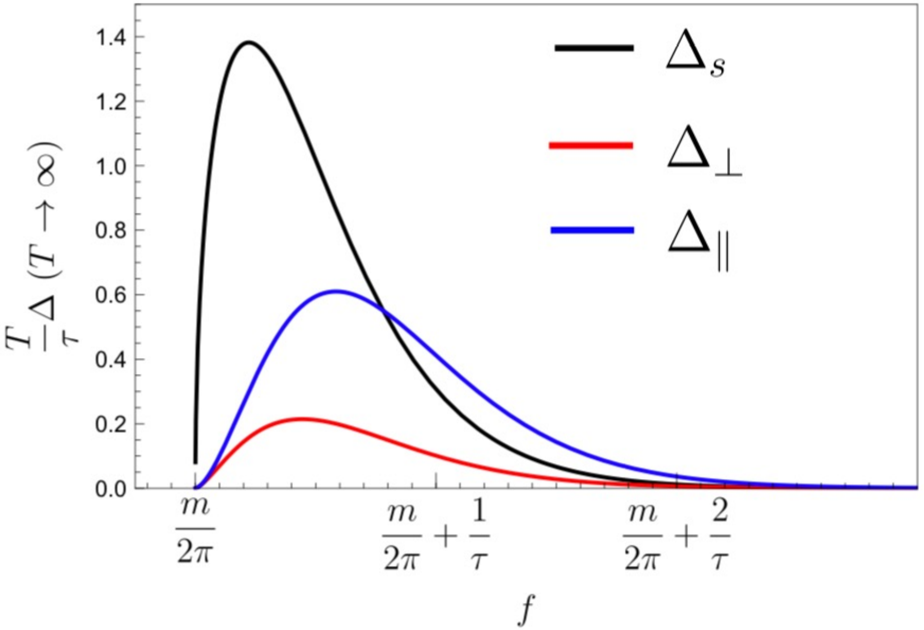
: linear comb. of $\Delta_\perp(f_n)$ $(\vec{e}_j \perp \vec{v}_\odot)$ and $\Delta_\parallel(f_n)$ $(\vec{e}_j \parallel \vec{v}_\odot)$

→ broader spectra than $\Delta_s(f_n)$

※ Δ_j varies due to the rotation of Earth (e.g. Lisanti+ 2021)

→ For longer T_{obs}, directional dep. needs to be averaged.

On this basis, pipeline is under construction!



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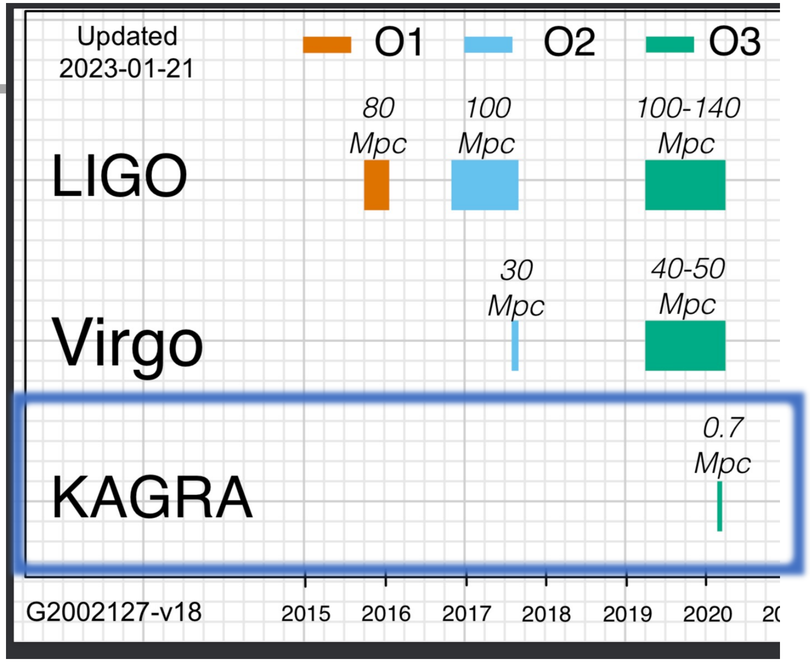


real data analysis is ongoing!

Status of pipeline construction

- Search Method (JK+, LVK in prep.)

κ: $O(1)$ const.

Narrow band signal → collect spectra at $m_A \leq 2\pi f_k \leq m_A(1+\kappa v_{DM}^2)$

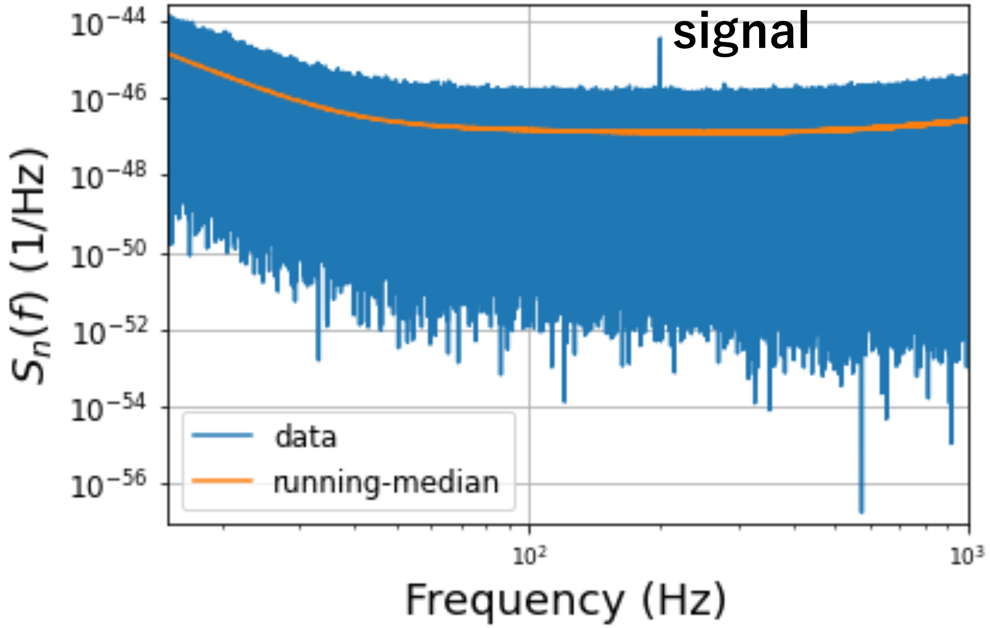
→ Detection statistic: $\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\rm obs} S_n(f_k)}$

S_n: Power Spectrum Density
T_{obs}: Observational time

For Gaussian noise, ρ obeys $\chi^2_{2N_{bin}}$ dist.

when there is no signal. (N_{bin}: number of the bins)

95% upper limit of $\chi^2_{2N_{bin}}$ → 5% FAR.



Spectrum of mock data

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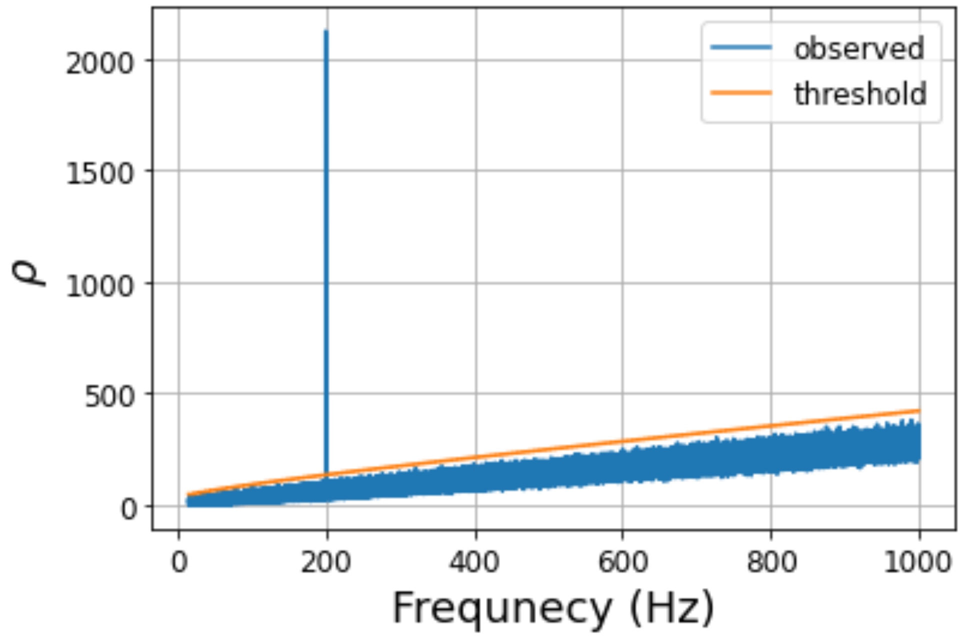


- Calculation of upper bound

We've derived the likelihood function:

$$\mathcal{L}(\rho|\{\lambda_n\}) = \sum_n^{N_{\rm bin}} \frac{w_n}{2(1+\lambda_n^2)} \exp\left(-\frac{\rho}{2(1+\lambda_n^2)}\right)$$

← Marginalized over the random amplitude

$\lambda_n \equiv \bar{\lambda}_X \sqrt{\Delta_X(f_n)}$: normalized signal

$$w_n \equiv \prod_{n'(\neq n)}^{N_{\rm bin}} \frac{1+\lambda_n^2}{\lambda_n^2 - \lambda_{n'}^2}$$

→ numerically unstable for not so large N_{bin}…

Observed ρ → 95% upper limit on the amplitude

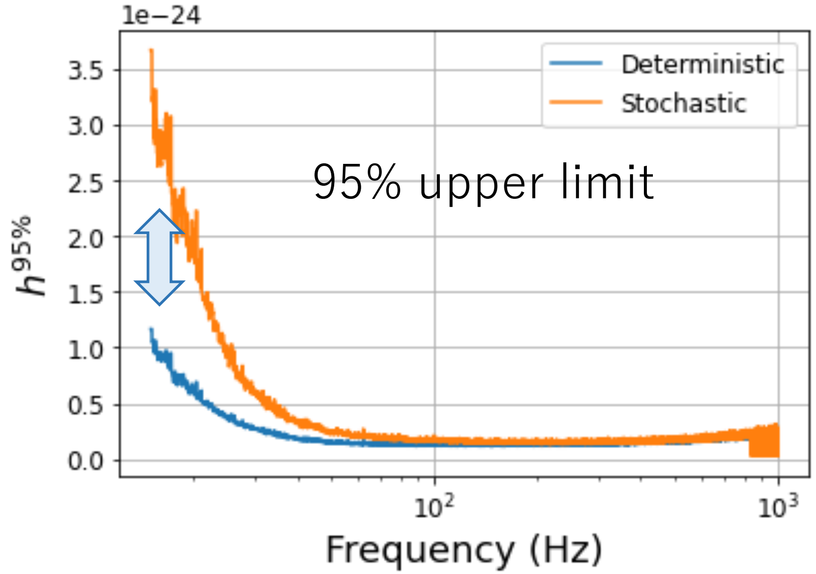
$\int_{\rho_{obs}}^{\infty} \mathcal{L}(\rho|\bar{\lambda}_X^{95\%})d\rho = 0.95.$ → translation into $\epsilon_D^{95\%}$

(Nakatsuka+ 2022)

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

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

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



- Current status of the pipeline & analysis

Veto procedure:

✓ Width of the peaks

✓ Coincidence btw. several segments

Upper limit calculation:

✓time & charge → implemented

spatial → being improved (directional dep.)

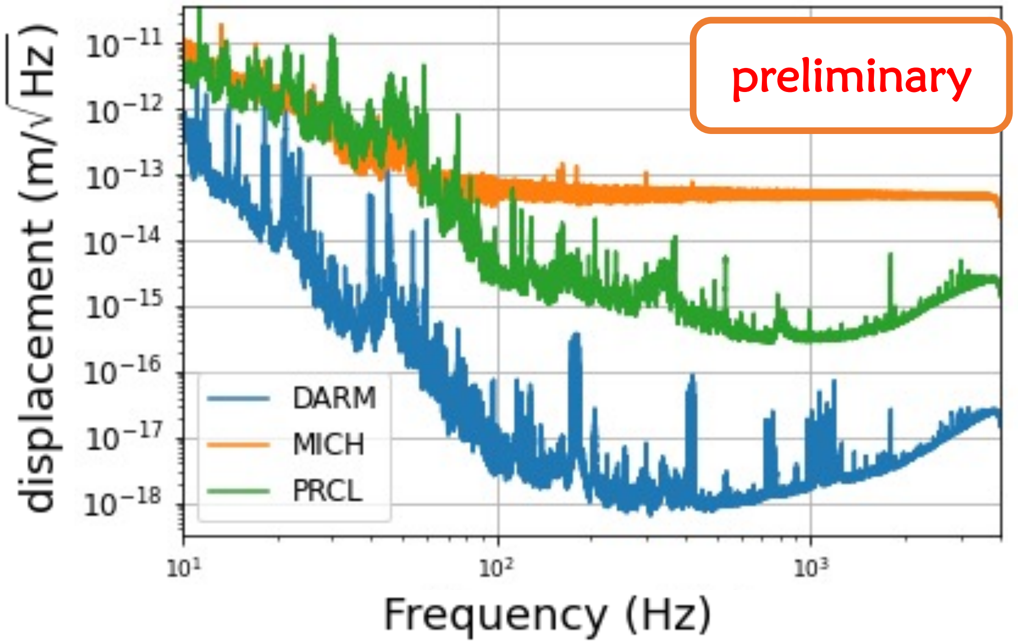
(**MICH, PRCL → almost OK**, DARM → on going)

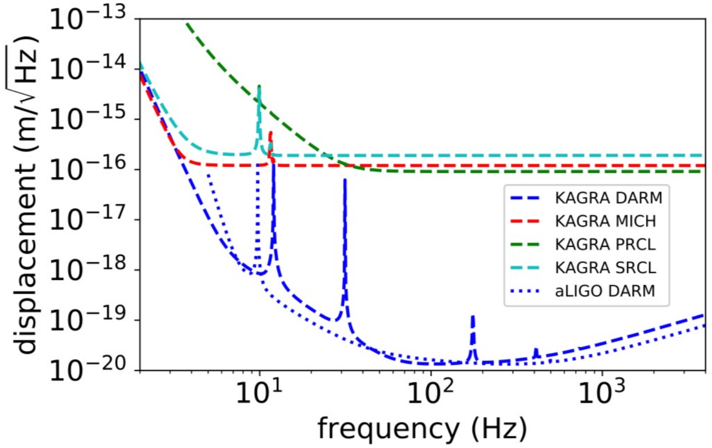
Test run: most stable segment in <u>O3GK</u> (~7 hours)

→ incoherent search w/ 30min. segments

≳ 200 segments are now available!!

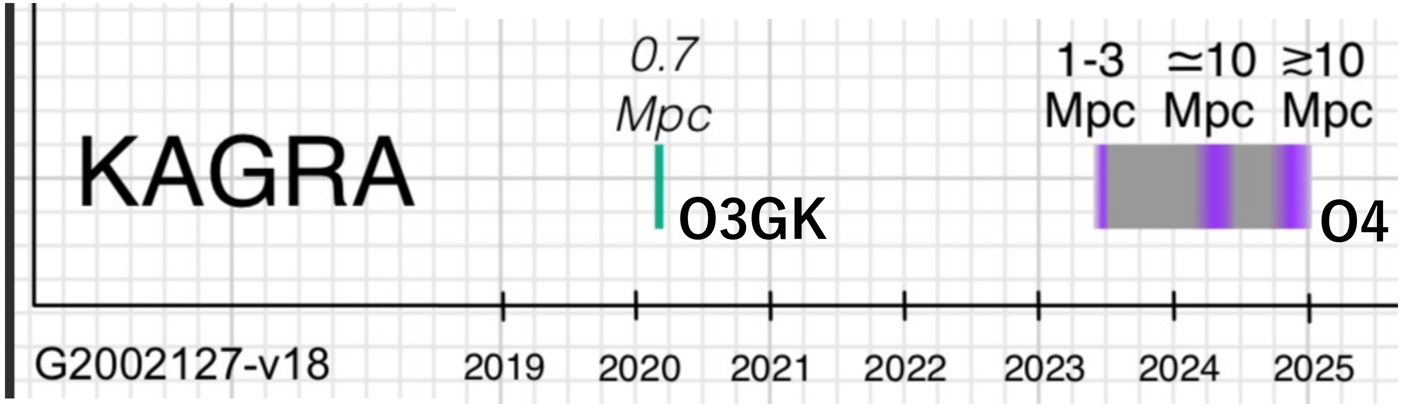
estimated noise spectrum for O3GK





Contents

- Publication plan and future study



O3GK data analysis (present) → Circulation in LVK (~June 2023) → Publication

- Stochastic effects are properly included
- MICH, PRCL
- DARM → our code may also be applied to O4 LV...?

⇨ Improvements of the pipeline (Towards O4)

⇨ O4 data analysis → (Part of) LVK DM paper?

Summary

- GW interferometer can probe Ultralight vector DMs.

KAGRA's auxiliary DoFs are useful especially for $U_{B-L}(1)$ boson!

- We have **refined formulations of vDMs**, taking into account statistics.

Pipeline is being constructed based on it (e.g. likelihood function).

Future sensitivity of experiments are also estimated in Nakatsuka+ 2022.

- Test analysis has been performed with a single data segment of O3GK.

We are now extending the method to deal with multiple chunks.

Publishing the results – by the summer of 2023.

Backup slides

- O3GK KAGRA data

During April 7–21 2020, KAGRA conducted its first scientific observation (in conjunction with GEO600 → referred to as **O3GK**)

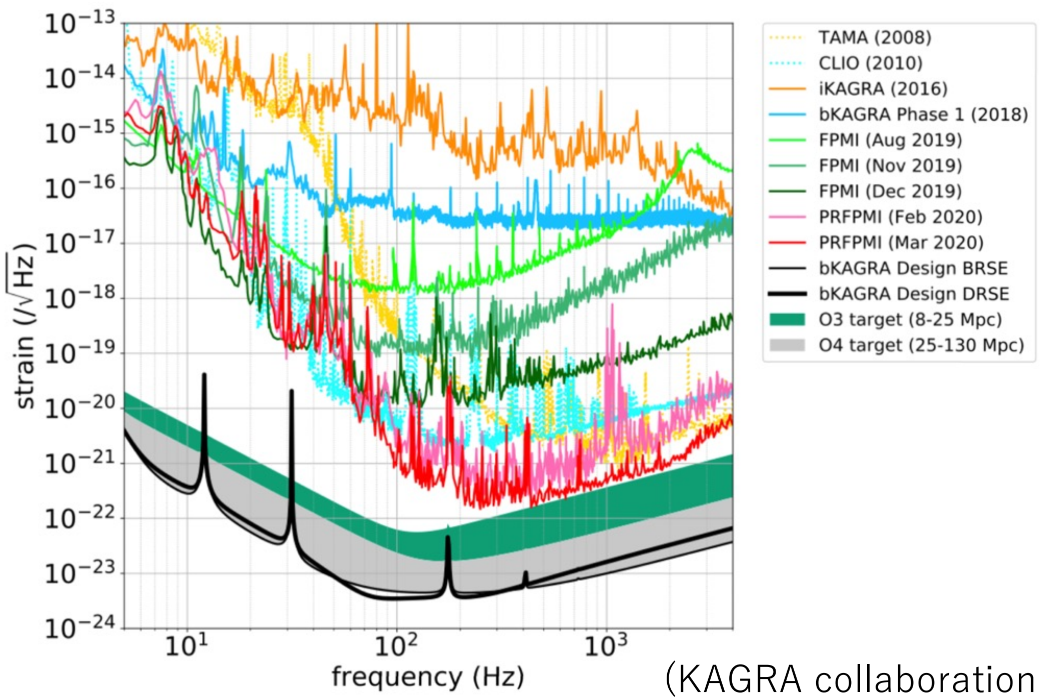
While the SNR $\propto T_{obs}^{1/4}$,
the observation lasts for two weeks.

not so long... 😢

(※ 1yr. assumed in Michimura+ 2020)

Sufficient sensitivity to vDM is not expected with the latest data...

→ demonstration & playground towards O4
DARM is also analyzed.



(KAGRA collaboration 2020)

About KAGRA

- Towards O4

KAGRA is now in the update stage to join O4 with

-Dual-Recycled FPMI

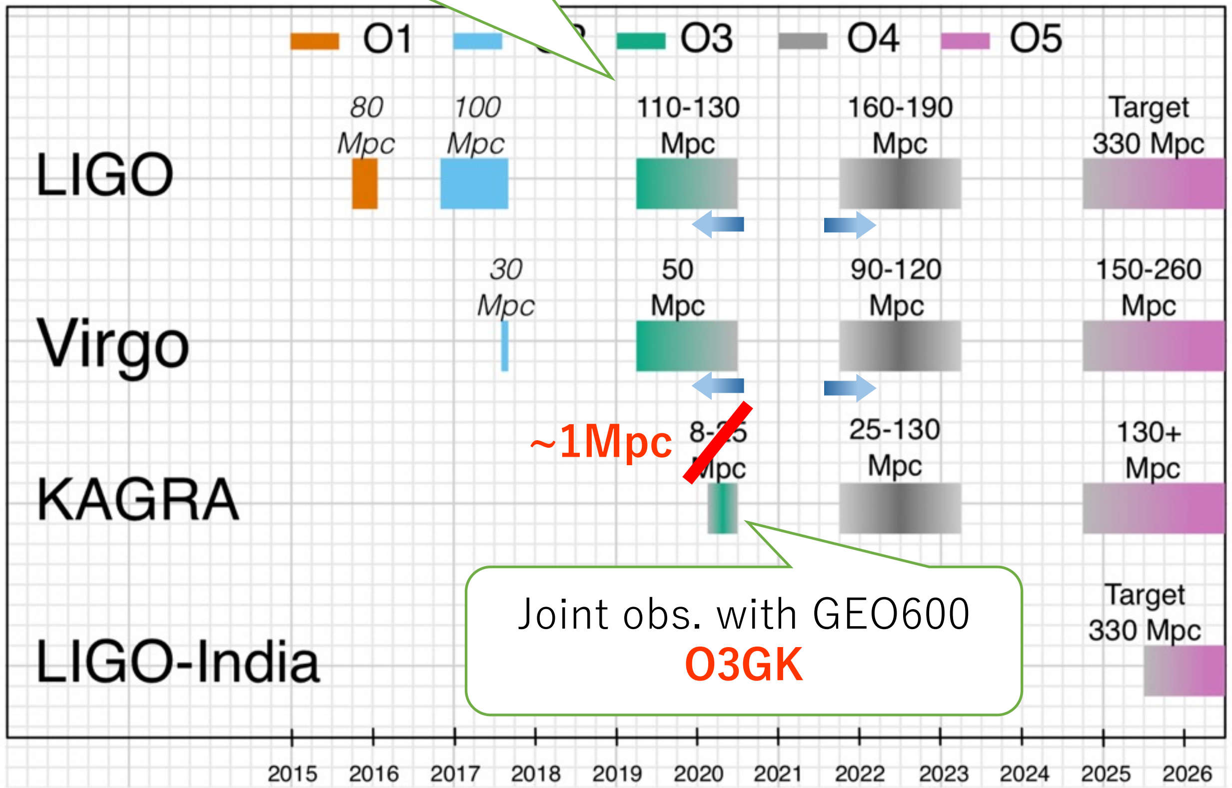
-high power laser

-Refurbishment of the suspension

-operating temperature ~20K...etc.

LVK O4 is now planned to start from ~June 2023.

O3 of LV was shortened for 1month due to COVID-19



arXiv:1304.0670

KAGRA and its auxiliary channels

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

Auxiliary channels:

$\delta x \propto Q_D / M$

$$\delta L_{\mathrm{MICH}} = \delta(l_x - l_y)$$

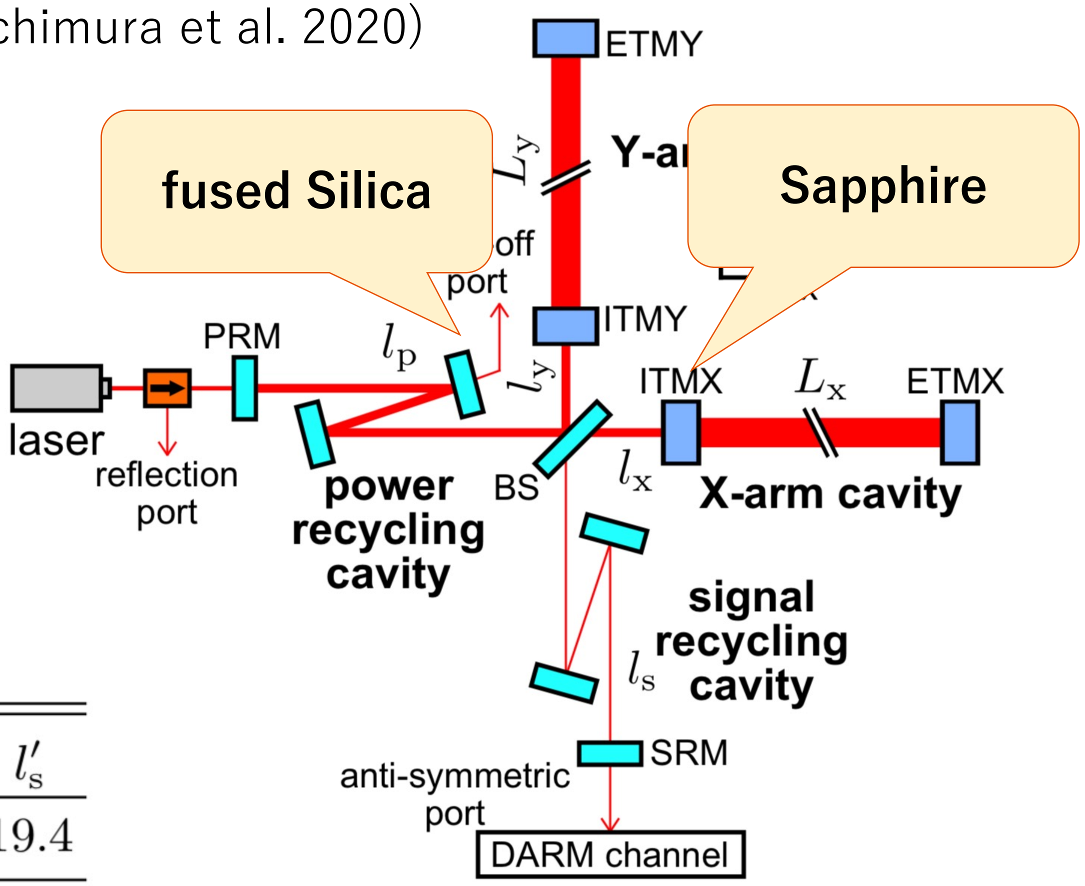
$$\delta L_{\mathrm{PRCL}} = \delta[(l_x + l_y)/2 + l_p]$$

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

Due to the **charge difference**,

displacement becomes asymmetric!!

	L_{arm}	l_{x}	l_{y}	l_{p}	l_{s}	l'_{p}	l'_{s}
KAGRA	3000	26.7	23.3	66.6	66.6	19.5	19.4



$$\delta L_{\mathrm{DARM}} = \delta(L_x - L_y)$$

KAGRA and its

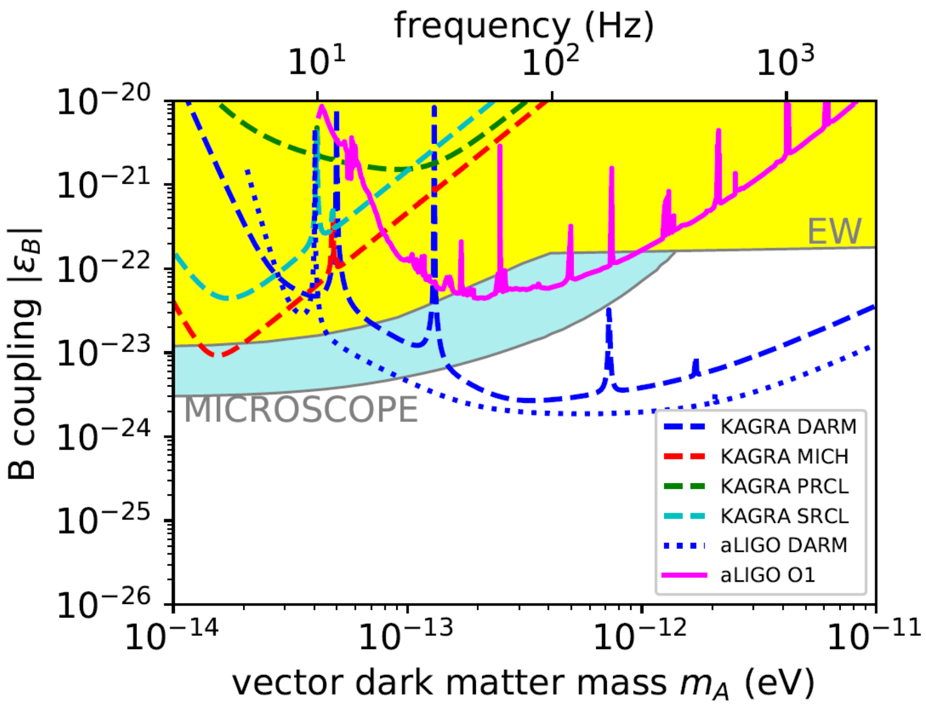
- Advantage of KAGRA

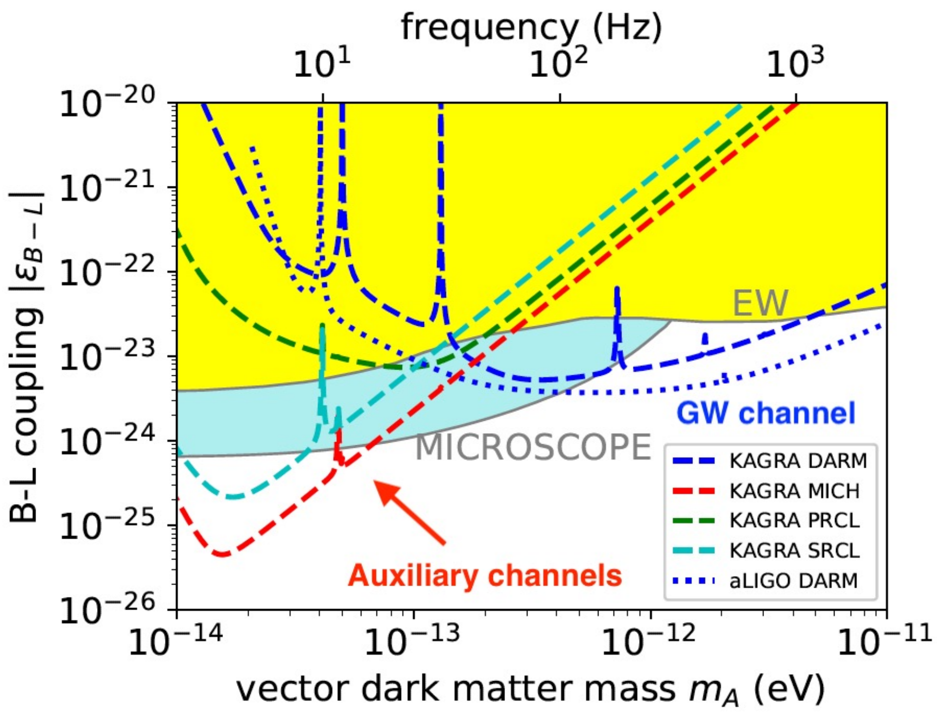
For $U_{B-L}(1)$ model, **KA** !

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

$$\frac{Q_B - Q_L}{M} \approx \frac{N_B - N_L}{N_B} \frac{1}{m_n} \quad \rightarrow$$

Silica: 0.501
Sapphire: 0.51





About KAGRA

- Noise budget