Identification of Ultra-Light Dark Matter Models Utilizing The Signal Correlation

Takumi Fujimori (Osaka Metropolitan University)

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Gravitational Waves and the Early Universe: Accelerated Expansion, Dynamical Inhomogeneity, and Beyond
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Contents

- **Introduction**
  - Ultra-Light Dark Matter and its models
  - ULDM signals and the search
- **Utilization of signal correlation for model identification**
  - ULDM signal correlation
  - Correlation of the simulated signals
- **Injection test with real data**
- **Conclusion**

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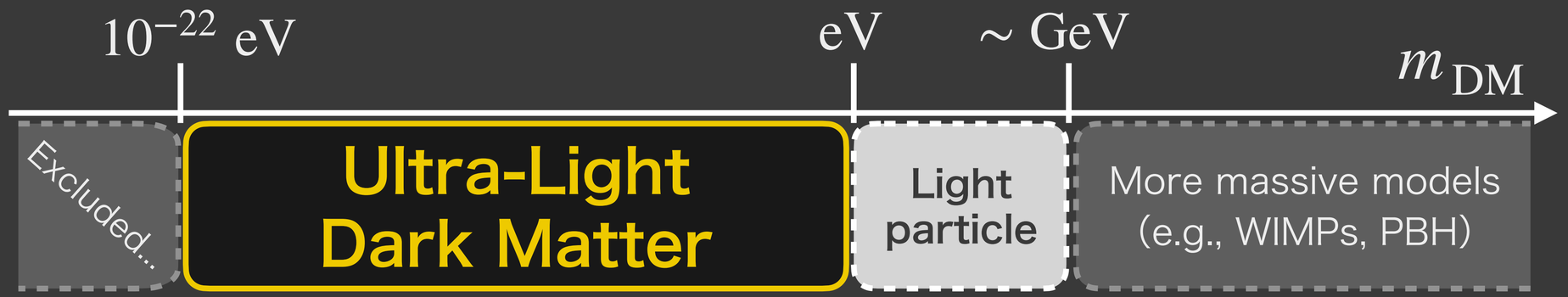
About Dark Matter

- ✳ Dark Matter: A Messenger from the Early Universe
- ✳ Broad discovery space → ~90 orders of magnitude



- ✳ Identifying its nature is **the key to unlocking cosmic history**

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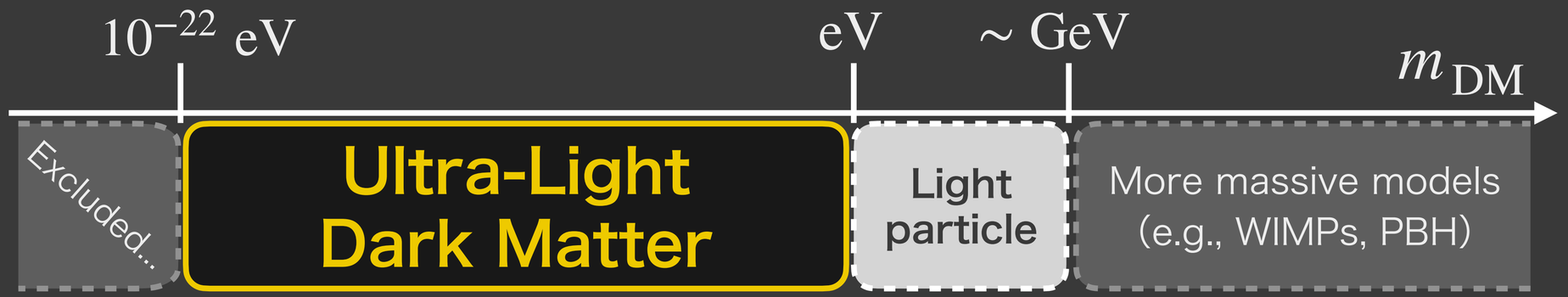

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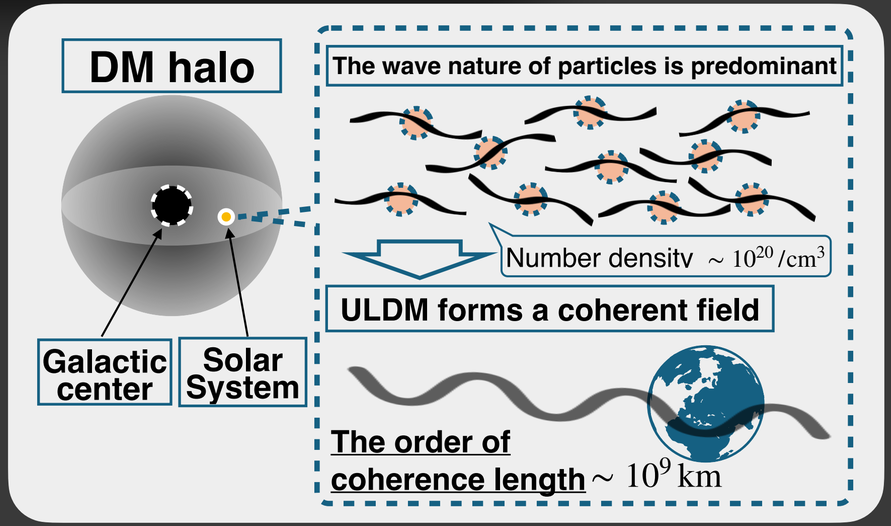
Ultra-Light Dark Matter (ULDM)

✳ Ultra-light dark matter halo

- ULDM halo behaves as a superposition of particle waves and forms **a classical wave field**
- The amplitude fluctuates stochastically with the timescale $\mathcal{T}$



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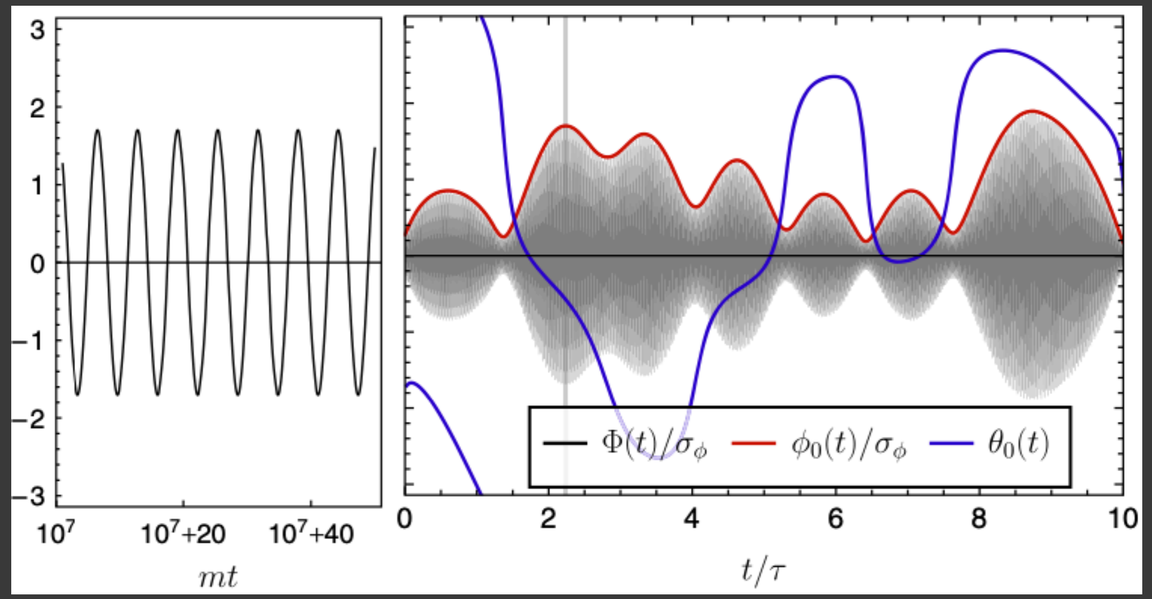
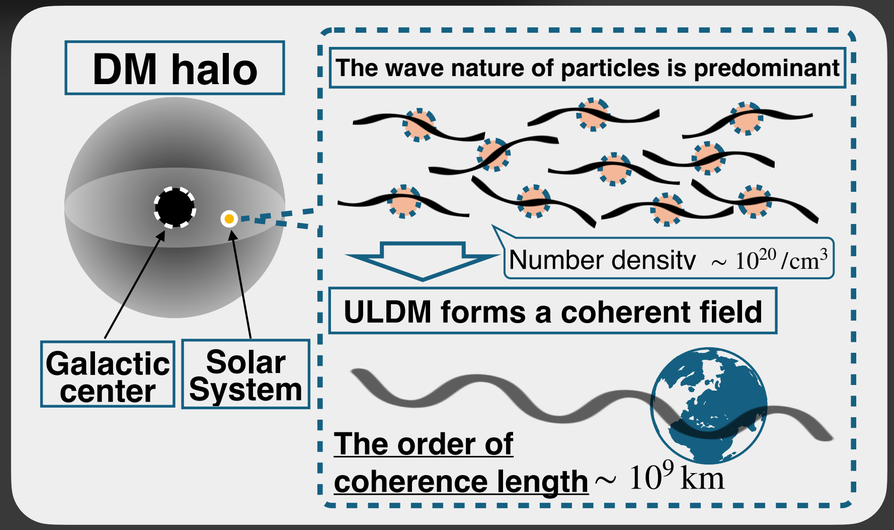


Nakatsuka et. al., P.R.D 108, 092010 (2023)



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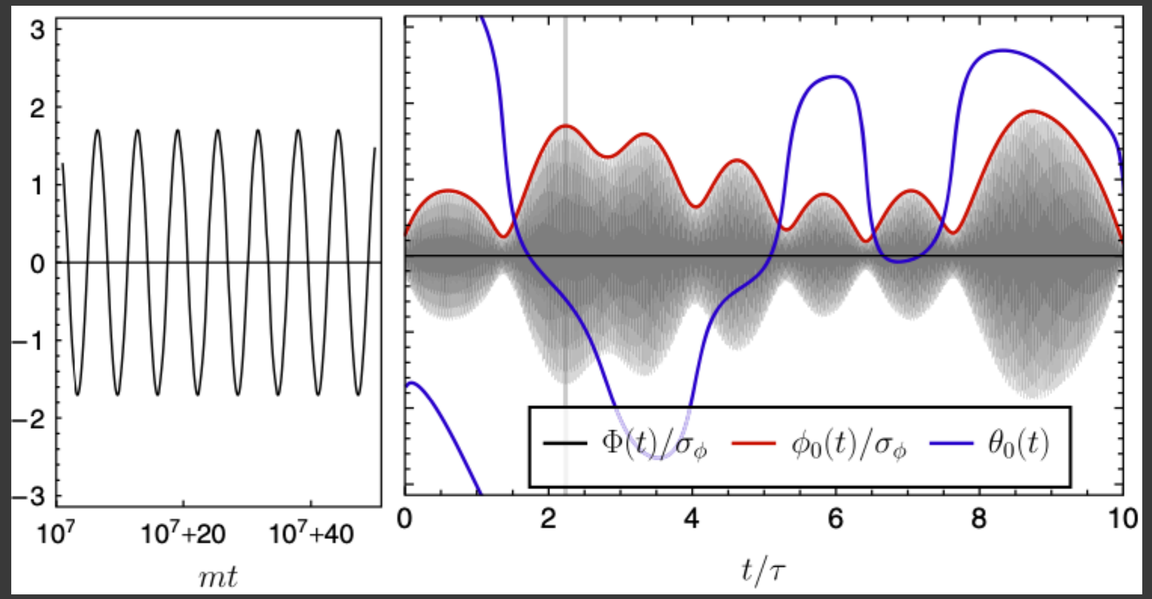

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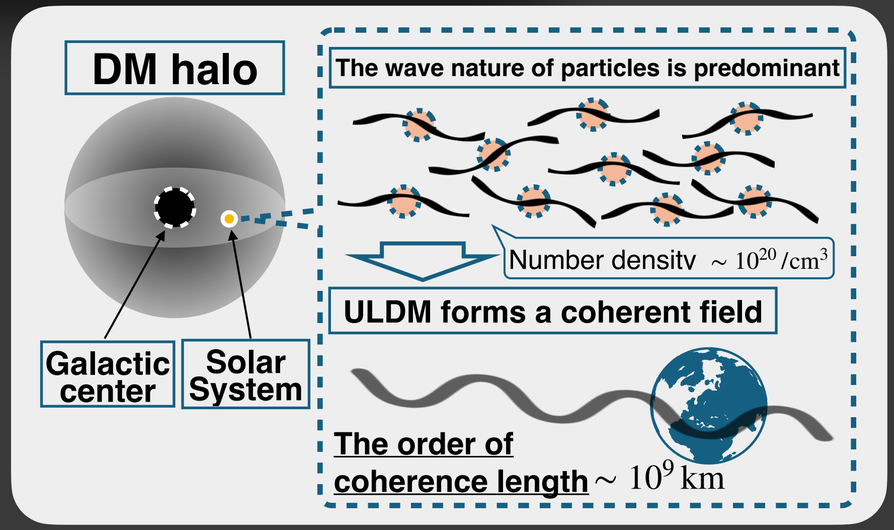


$$f_{\rm DM} \sim \frac{m_{\rm DM}}{2\pi} = 242\ {\rm Hz} \left(\frac{m_{\rm DM}}{10^{-12}\ {\rm eV}} \right)$$

$$\tau \sim 2\pi / m_{\rm DM} v^2$$

v: typical velocity of ULDM particles $\sim \mathcal{O}(10^{-3})$

ULDM Models

✳ According to the number density, $m_{\rm DM} \leq 1\ {\rm eV}$ is allowed for **bosons**

$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

1. R. Peccei, H. Quinn, PRL 38, 1440 (1977)
2. K, Choi+, Annual Review Nuclear and Particle Science. 71:225-252

dilaton (scalar field)

$\mathcal{L} \supset$ (Interaction term with EM, gluon, Fermion fields)

1. T. Damour+, PRD 82 084033 (2010)
2. K. Fukusumi+, PRD 108, 095054 (2023)

Spin-1 candidate:

dark photon

$$\mathcal{L} \supset e\epsilon_D J_D^\mu A_\mu$$

※ $D = B - L$ or B

1. Y. Michimura+, PRD **102**, 102001 (2020)
2. S. Morisaki+, PRD **103**, L051702 (2021)
3. LVK Collab., PRD **110**, 042001 (2024)

Spin-2 candidate:

Massive graviton

$$\mathcal{L} \supset -\frac{\alpha}{2M_{\rm Pl}} \Phi_{ij} T^{ij}$$

1. Y. Manita+, PRD **107**, 104007 (2023)
2. Y. Manita+, PRD **109**, 095012 (2024)

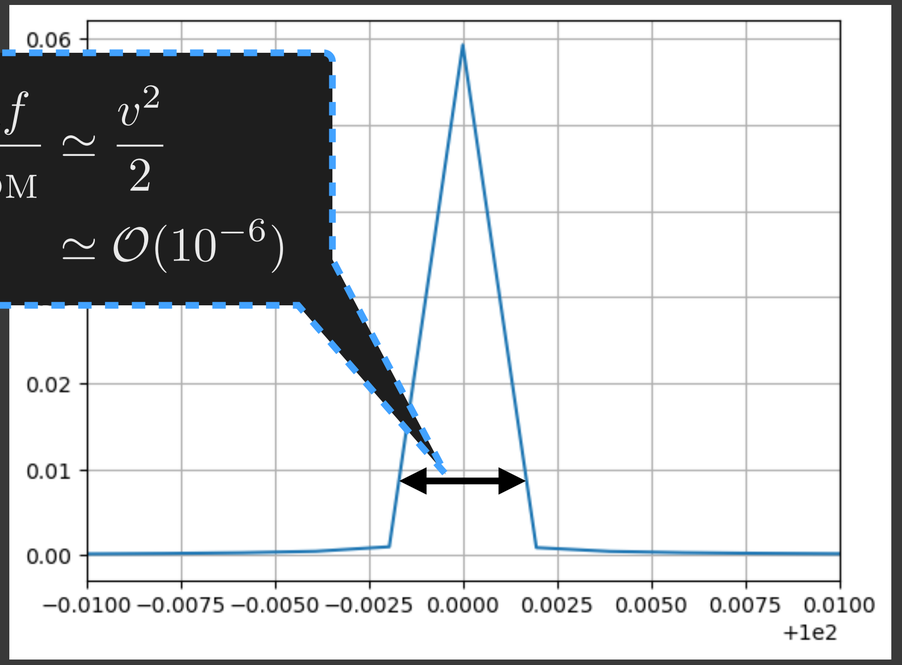
✳ Quasi-monochromatic oscillation nature is **common among models**

The ULDM signals and search

✳ The ULDM field interacts with detectors

- The ULDM signal appears as a **narrow-band peak** in the frequency domain
- The amplitude varies stochastically
- Conventional searches have focused on **detecting excess power**

$$\frac{\Delta f}{f_{\rm DM}} \simeq \frac{v^2}{2} \simeq \mathcal{O}(10^{-6})$$



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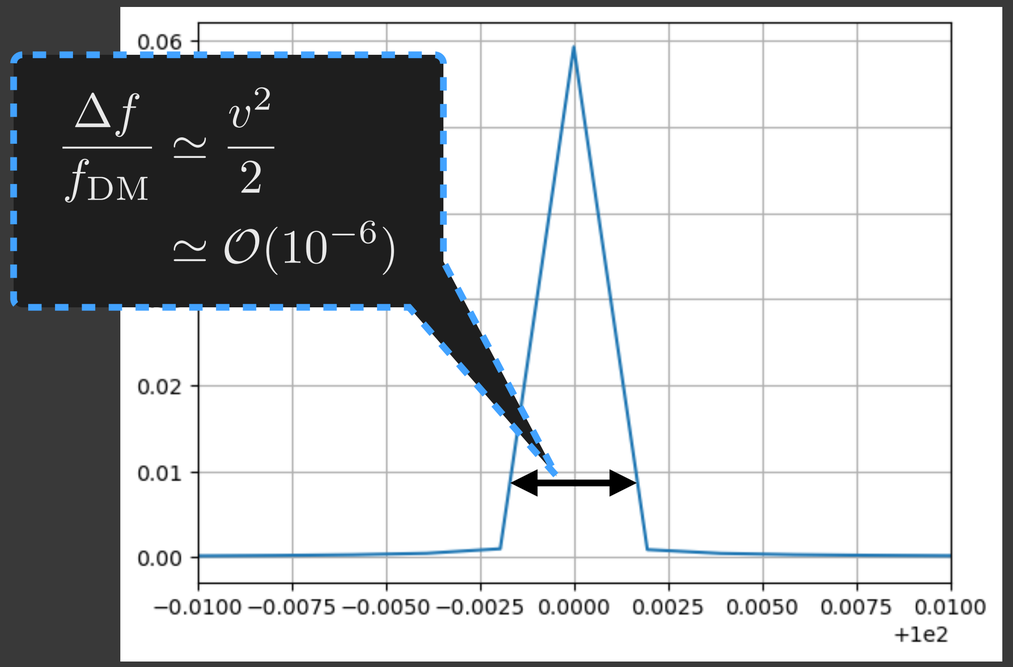

Problem:

1. Sensitivity degradation due to stochastic amplitude fluctuations
2. Inability to distinguish the signal origin, even after successful detection

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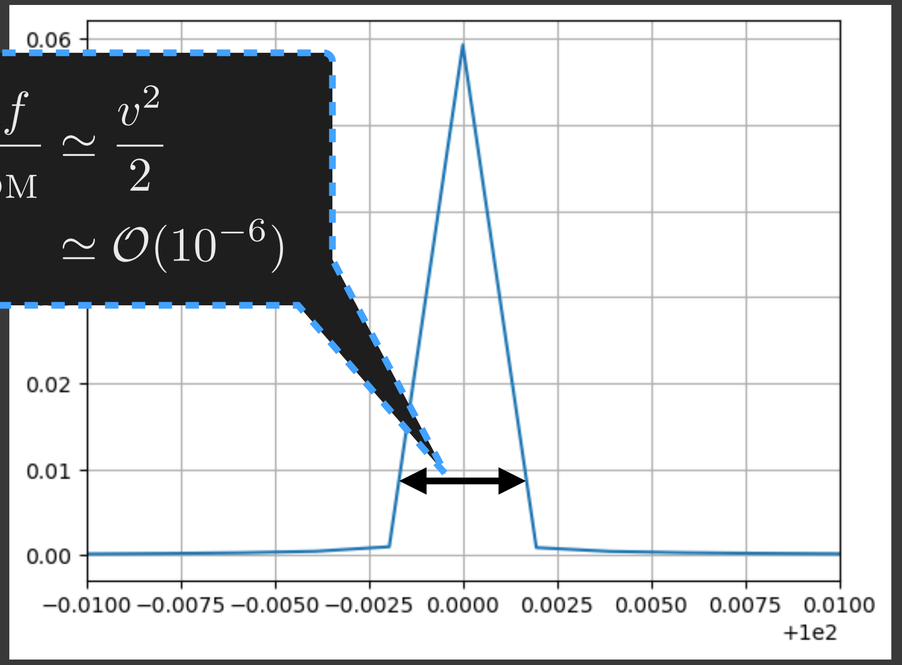

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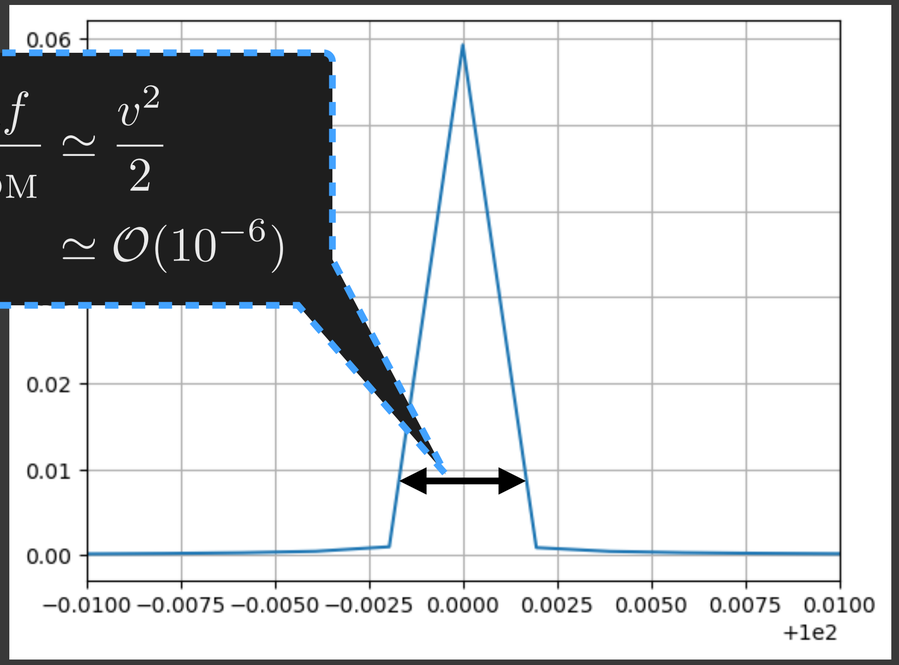

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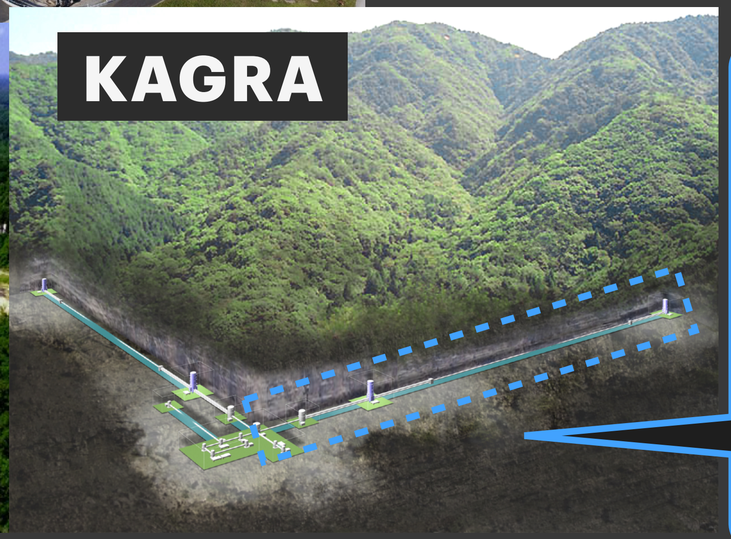

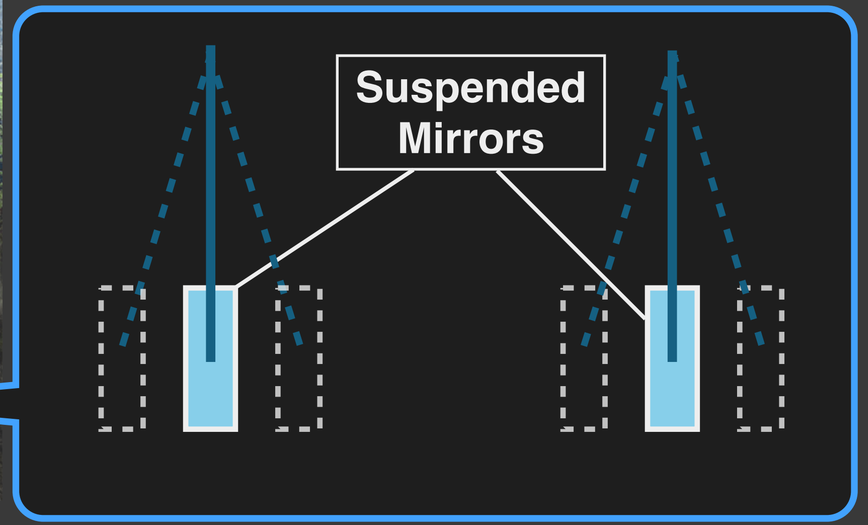

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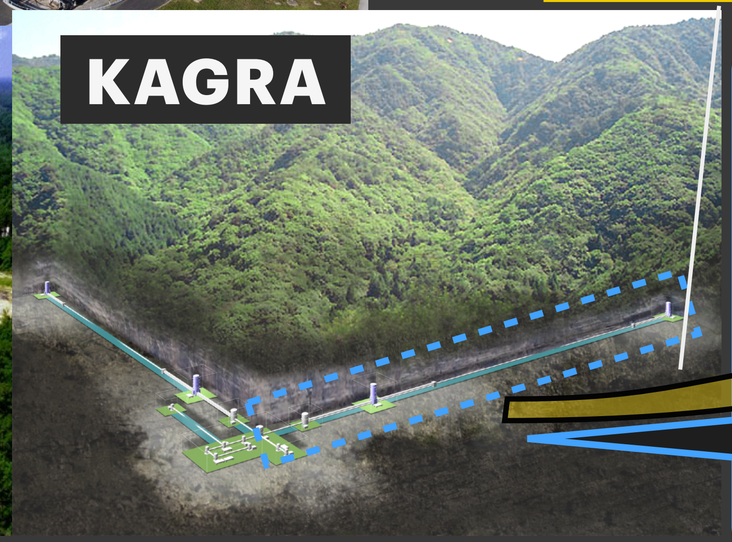
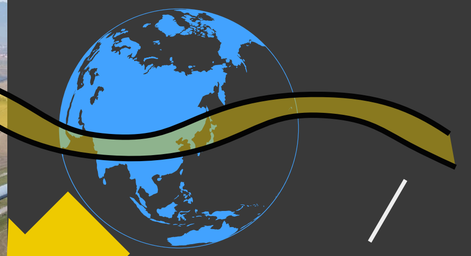
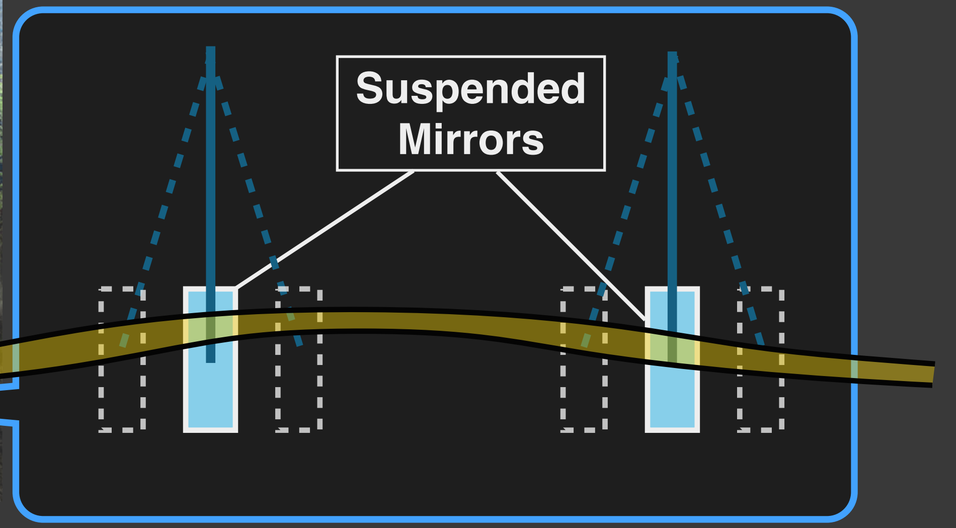




ULDM field



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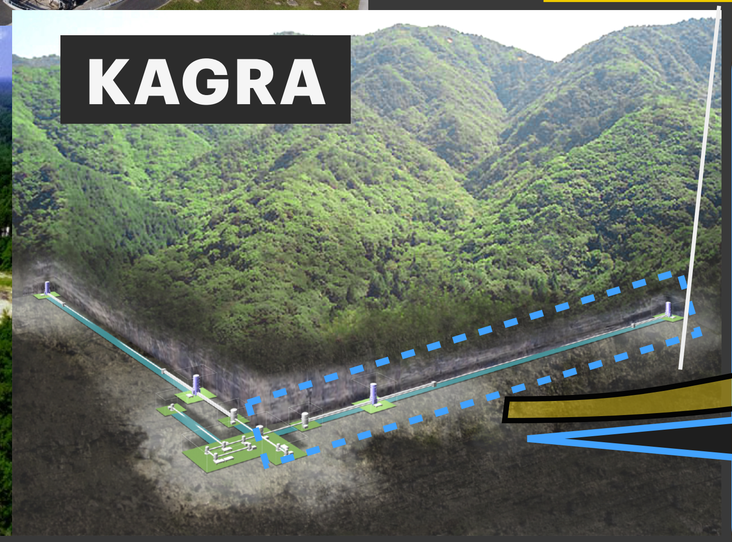

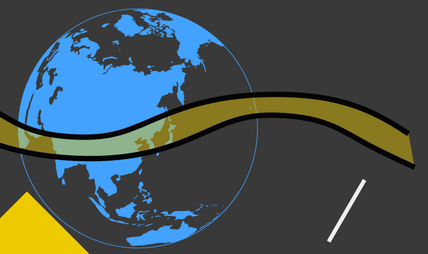

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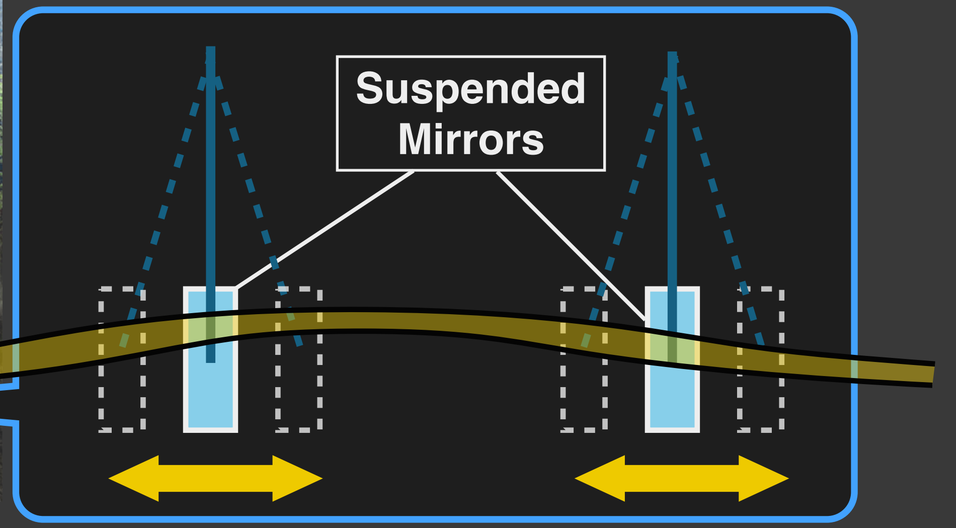

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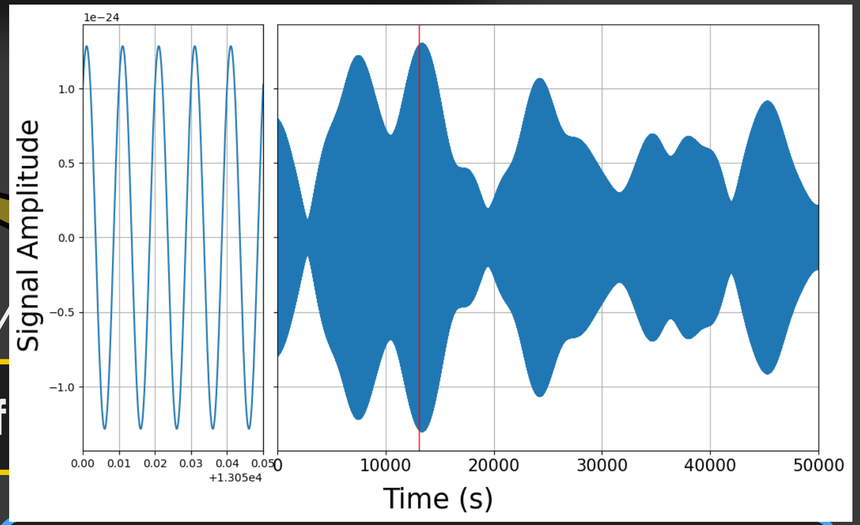
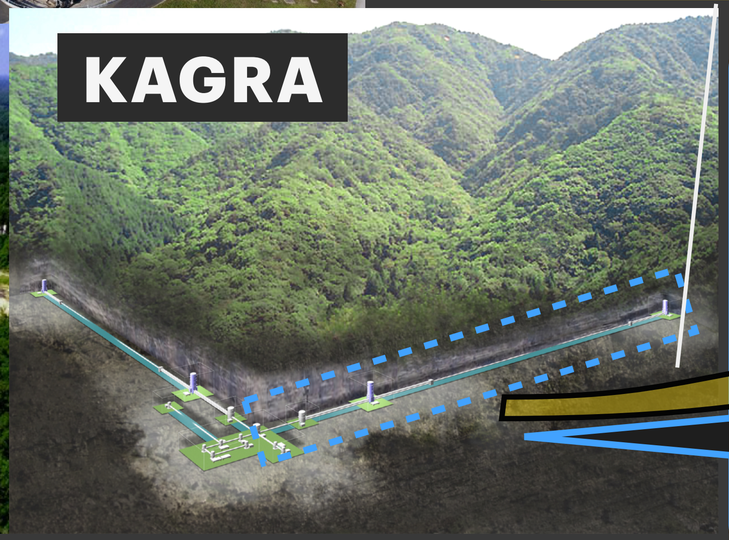
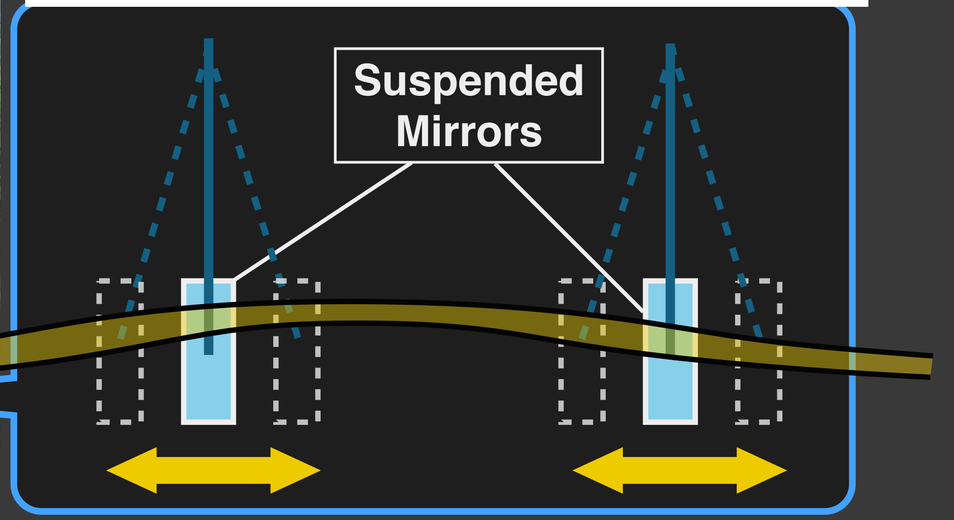
ULDM Search with GW detectors

ULDM f







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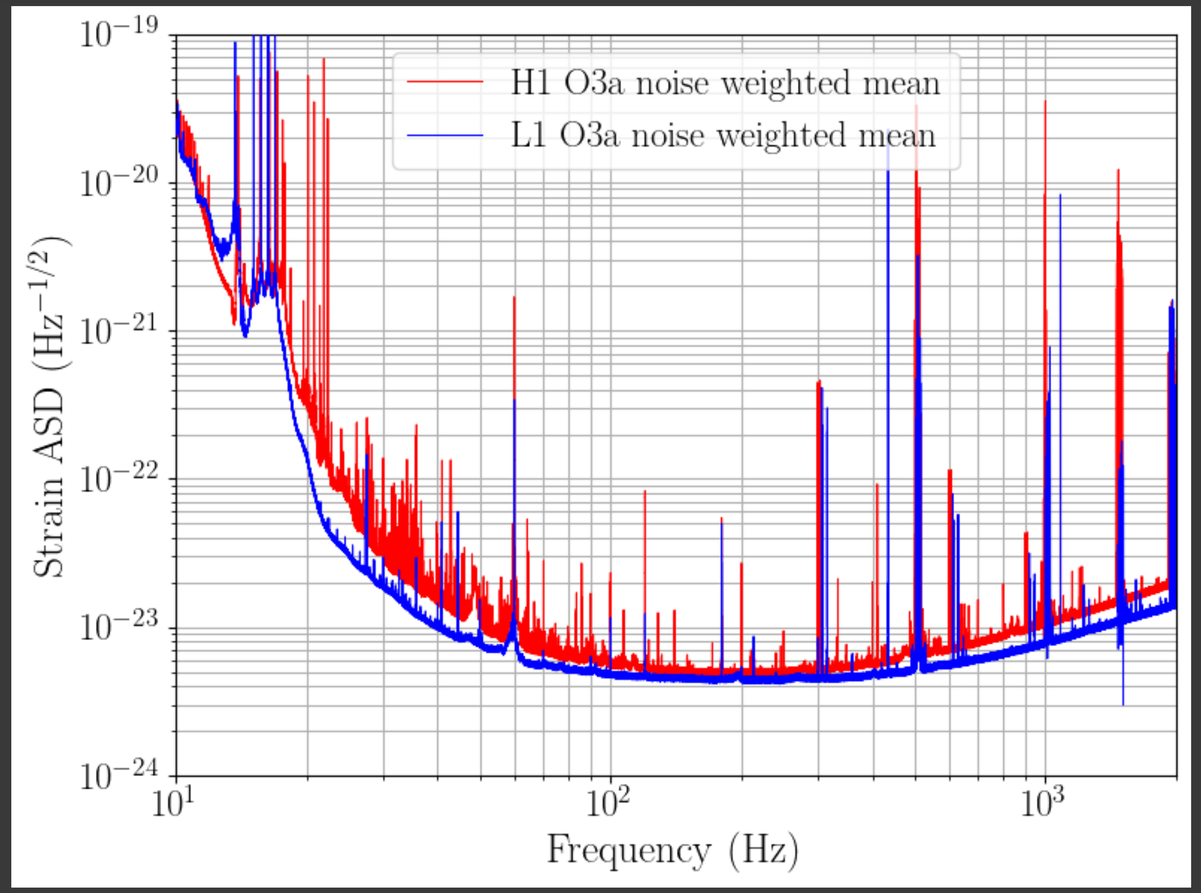
Artifacts similar to ULDM signal

✳ **Narrow-band spectral artifacts**

- Suspension violin noise
- Noise by power supply (Power line noise)
- And other noise sources
  (including unidentified sources)

We also need a new approach
to deny these artifacts

high-resolution ASDs computed during O3a for the LIGO detector
https://gwosc.org/O3/o3speclines/



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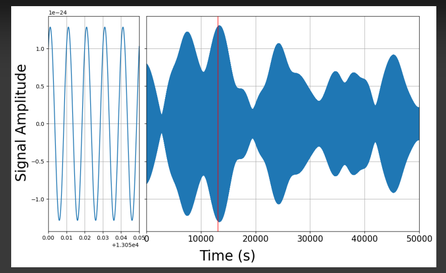
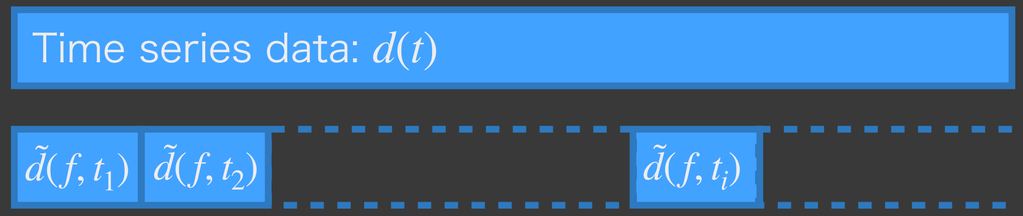
Correlation of the ULDM signal

✳ Data analysis process

- Segment the time-series data & apply Fourier transform





Coupling constant

$$\tilde{d}(f;t_i) = \tilde{n}(f;t_i) + \tilde{\epsilon}\tilde{h}(f;t_i)$$

$\tilde{n}(f;t_i)$: **Noise** of the i-th segment

$\tilde{h}(f;t_i)$: **ULDM signal** of the i-th segment

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Correlation of the ULDM signal

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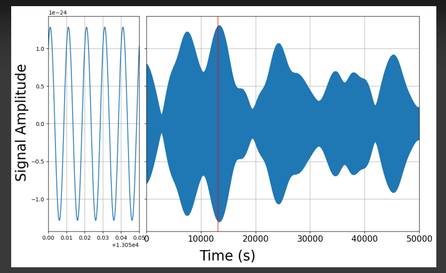

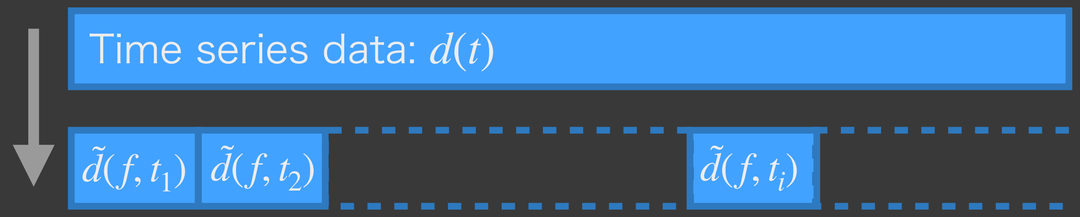

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✳ **Auto-correlation of the Fourier-transformed signal**

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Correlation of the ULDM signal

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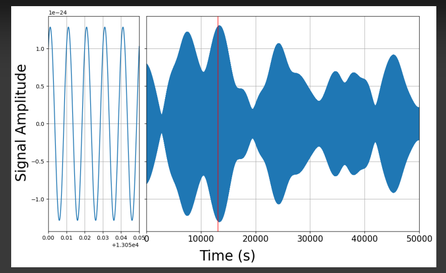

Time series data: $d(t)$

$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

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$$\mathcal{H}_{ft_i,f't_j} \equiv \langle \tilde{h}(f;t_i)\tilde{h}^*(f';t_j)\rangle$$

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Correlation of the ULDM signal

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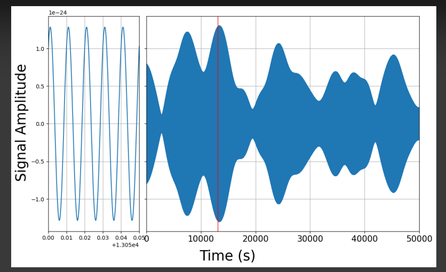

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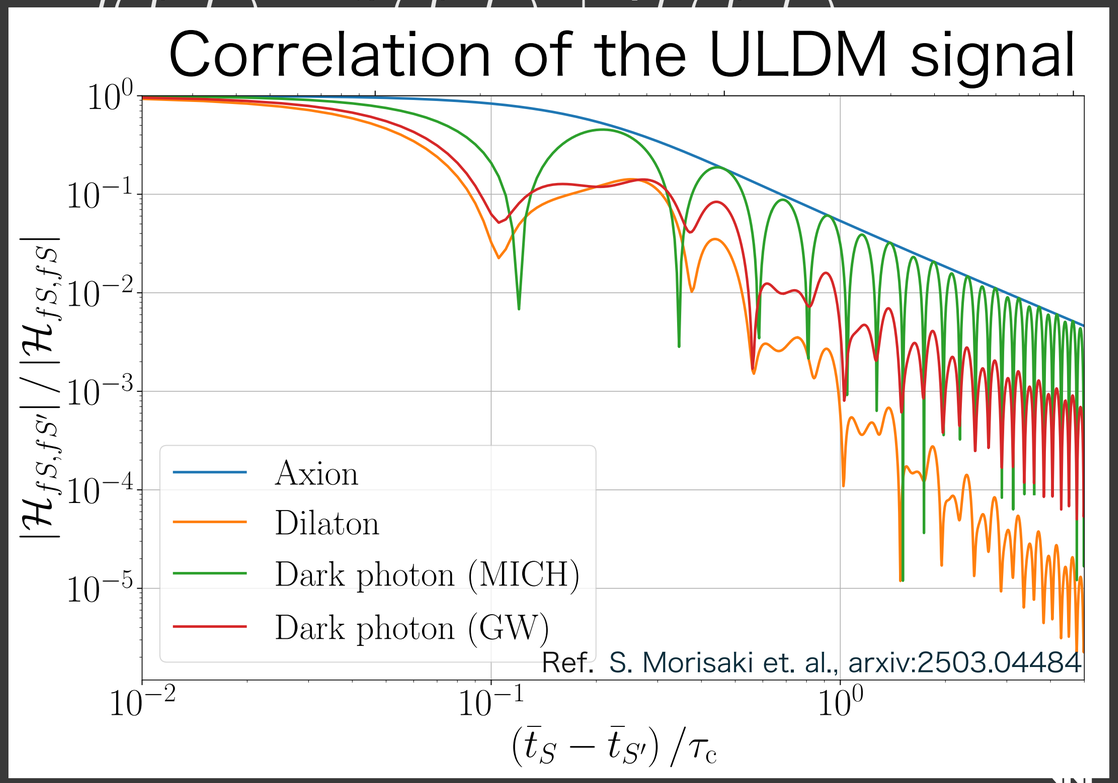

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Time scale of signal variation $\tau \sim 2\pi/m_{\rm DM}\langle v^2\rangle$

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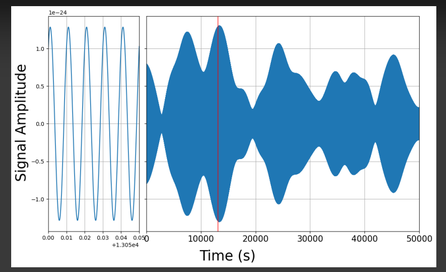

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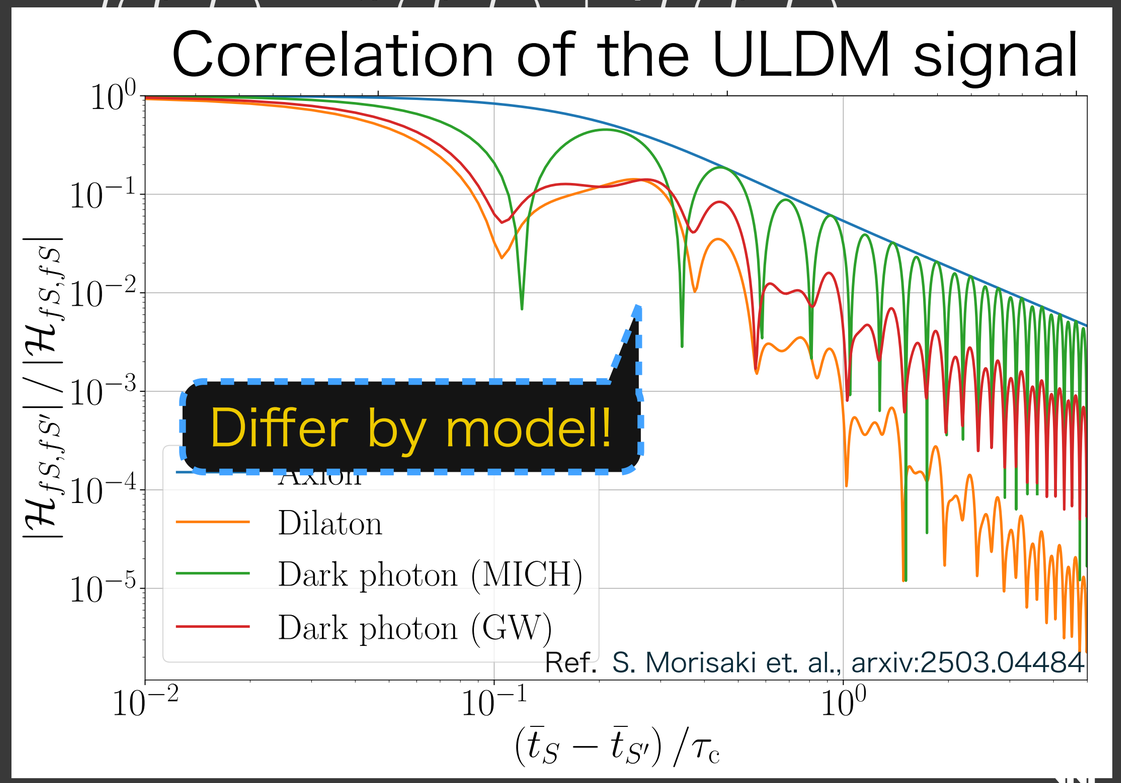

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Correlation of the ULDM signal

✳ **Verification of ULDM Signal Behaviour**

・Calculate the correlation from simulated data

$$\tilde{d}(f;t_i) = \tilde{n}(f;t_i) + \epsilon\tilde{h}(f;t_i)$$

Simulation properties

ULDM model:

$U(1)_{B-L}$ gauge boson,

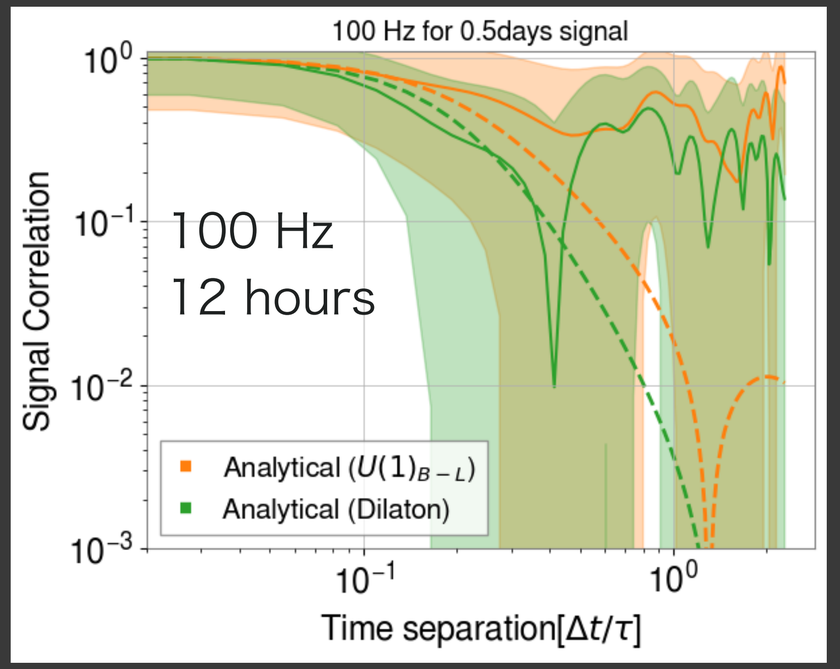
dilaton(scalar field DM)

Signal frequency:

100 Hz

Coherent time

$\tau \sim 3$ hours



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Shaded regions: 1-sigma deviation

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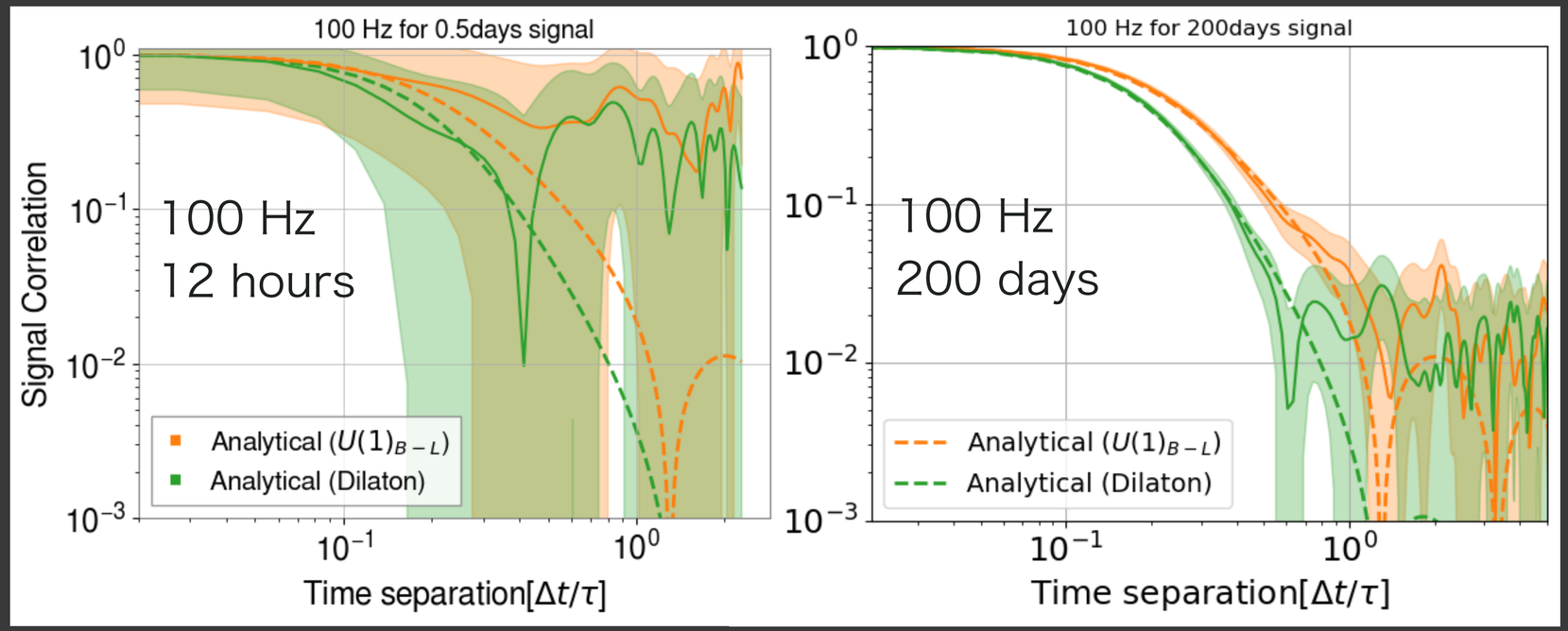

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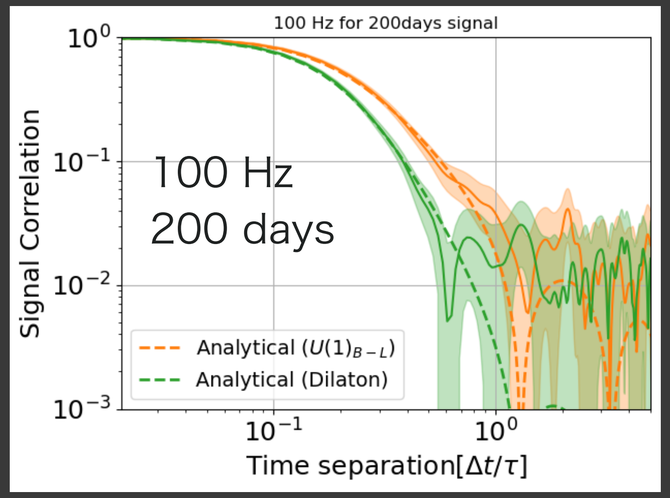
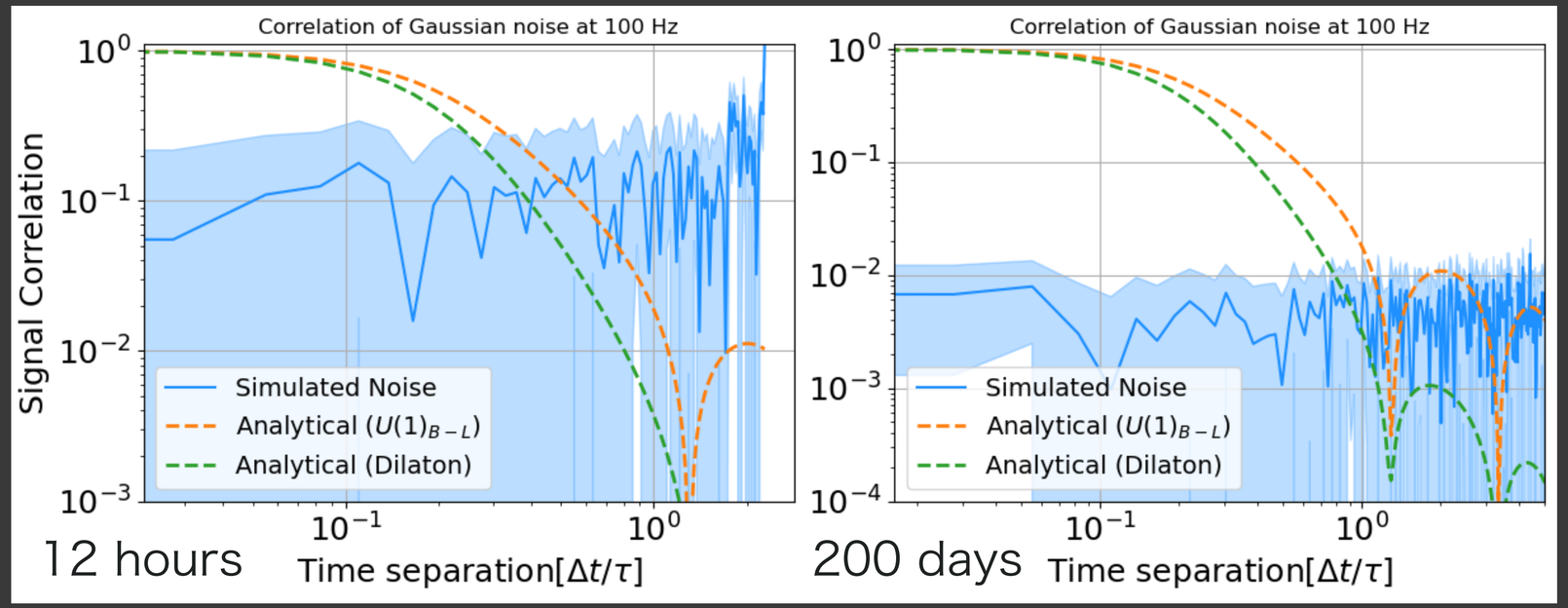
Correlation of the ULDM signal

✳ **Verification of Gaussian Noise Behaviour** $\tilde{d}(f;t_i) = \tilde{n}(f;t_i) + \tilde{\epsilon}(f;t_i)$

Correlation of ideal Gauss noise

$$E[\tilde{n}^*(f;t_i)\tilde{n}(f;t_j)]$$
$$\propto \delta(t_j - t_i)|\tilde{n}(f;t_i)|^2$$





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- $U(1)_{B-L}$ gauge boson signal was injected at 100 Hz

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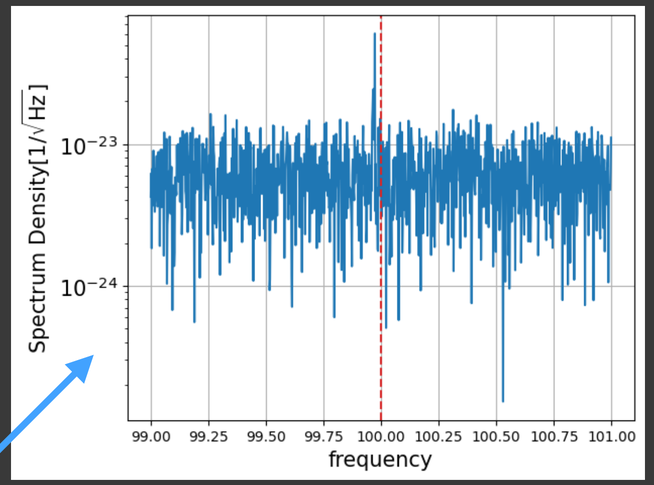

$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

Takumi Fujimori (Osaka Metropolitan University)

Injection Test

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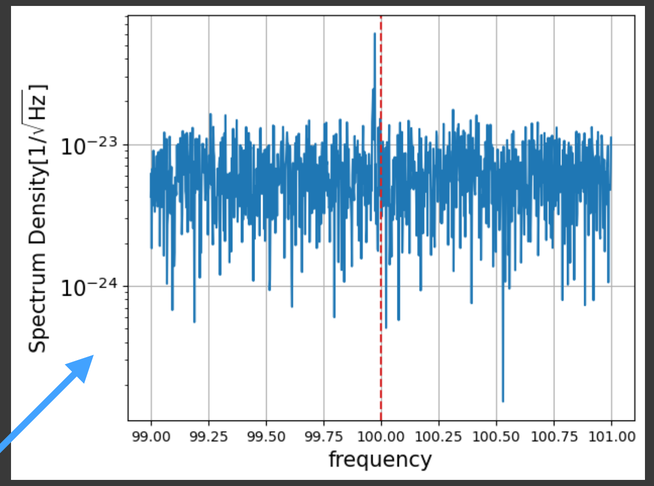

$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

Coherent statistic

$$\rho = \vec{d}^{\dagger}\mathcal{N}^{-1}\mathcal{H}\mathcal{N}^{-1}\vec{d}$$

👉 arxiv:2503.04484

Takumi Fujimori (Osaka Metropolitan University)

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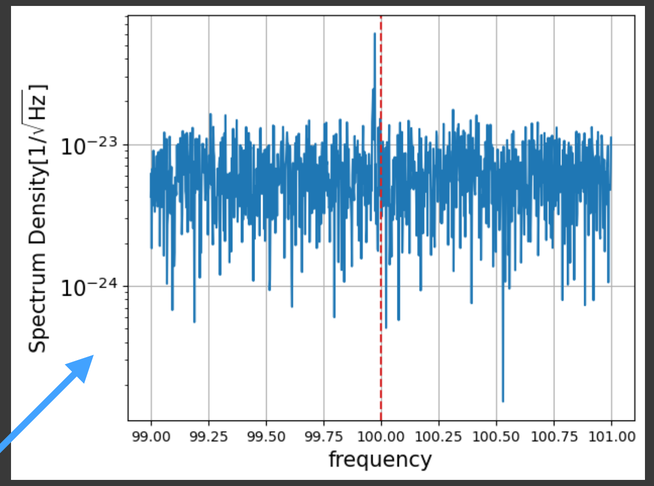

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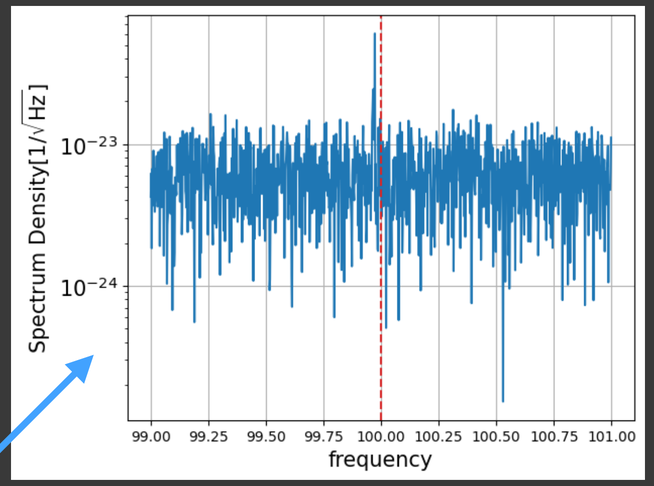

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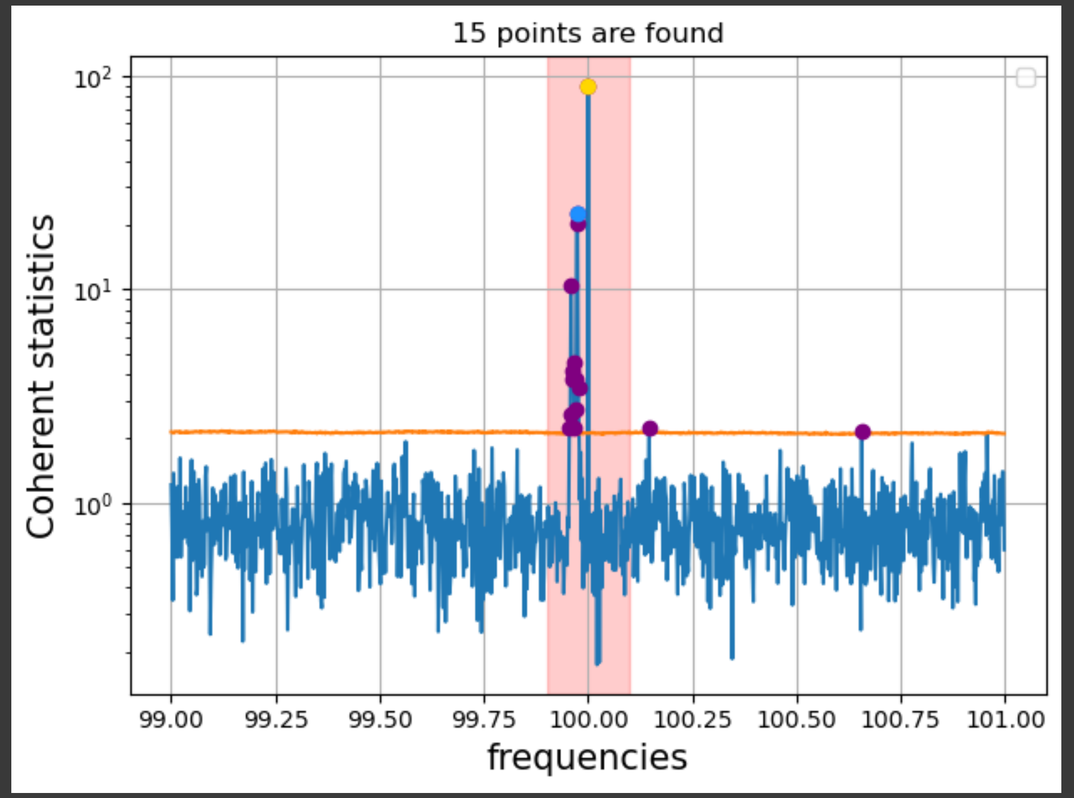

👉 arxiv:2503.04484

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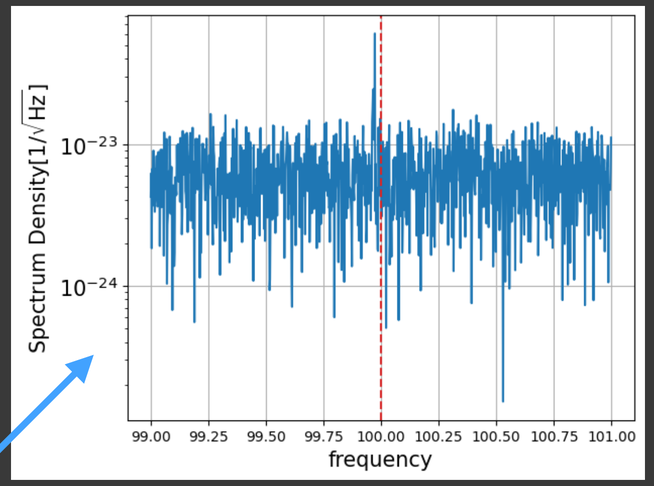

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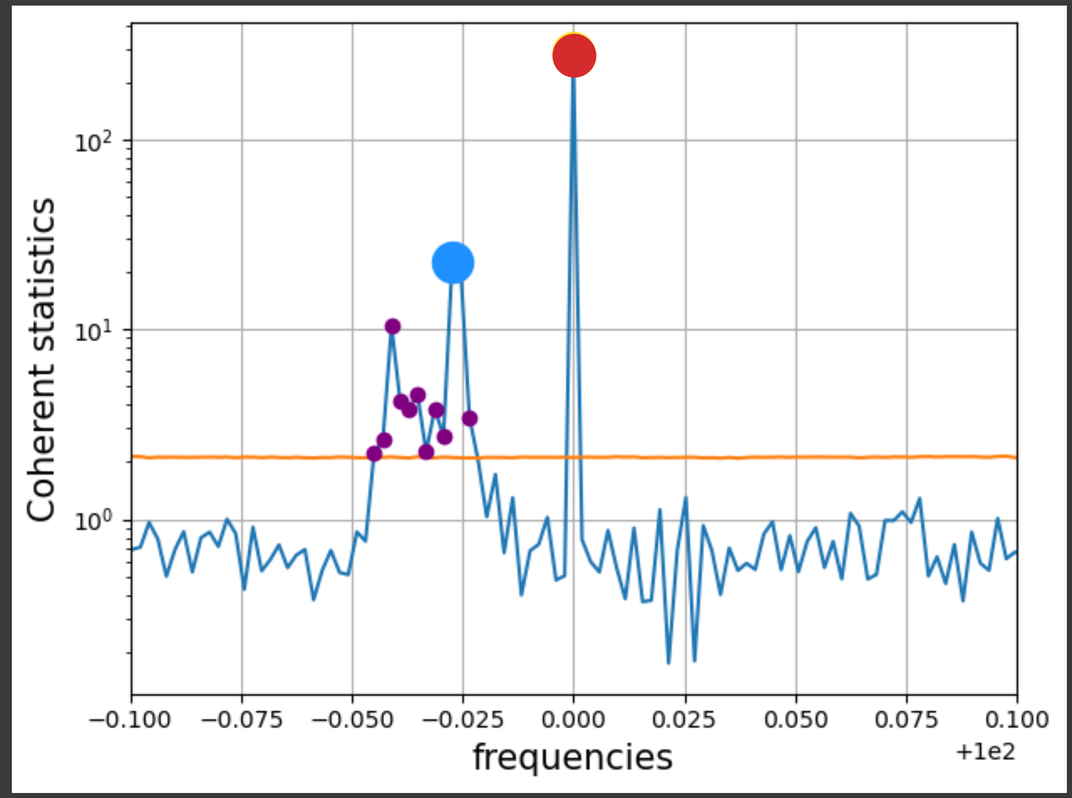


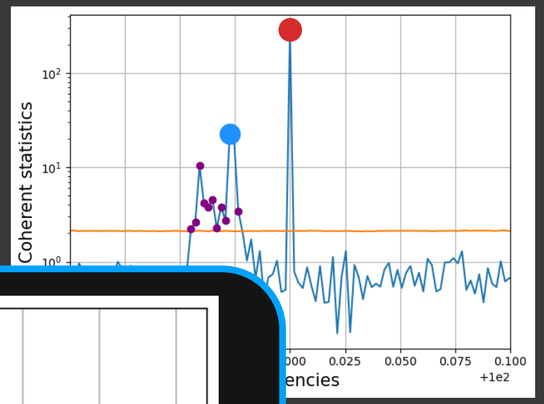
Takumi Fujimori (Osaka Metropolitan University)

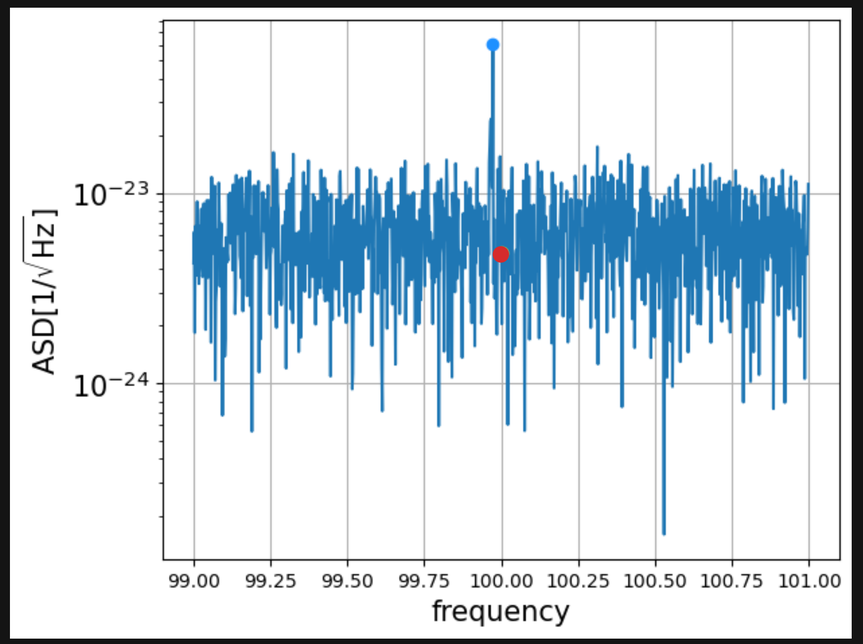
Correlation of the data

- ✳ Calculate the correlation
  - For large exceeding peaks

$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

$$\langle \tilde{d}^*(f;t_i), \tilde{d}(f;t_j) \rangle$$





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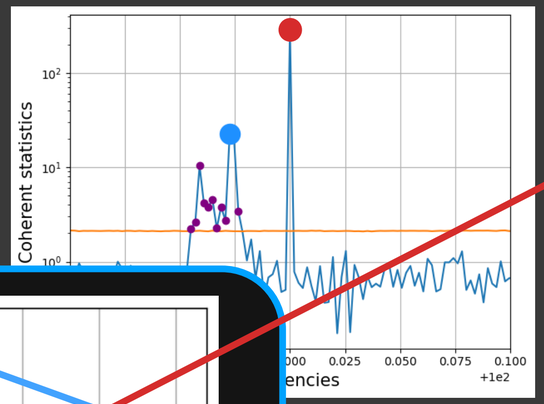

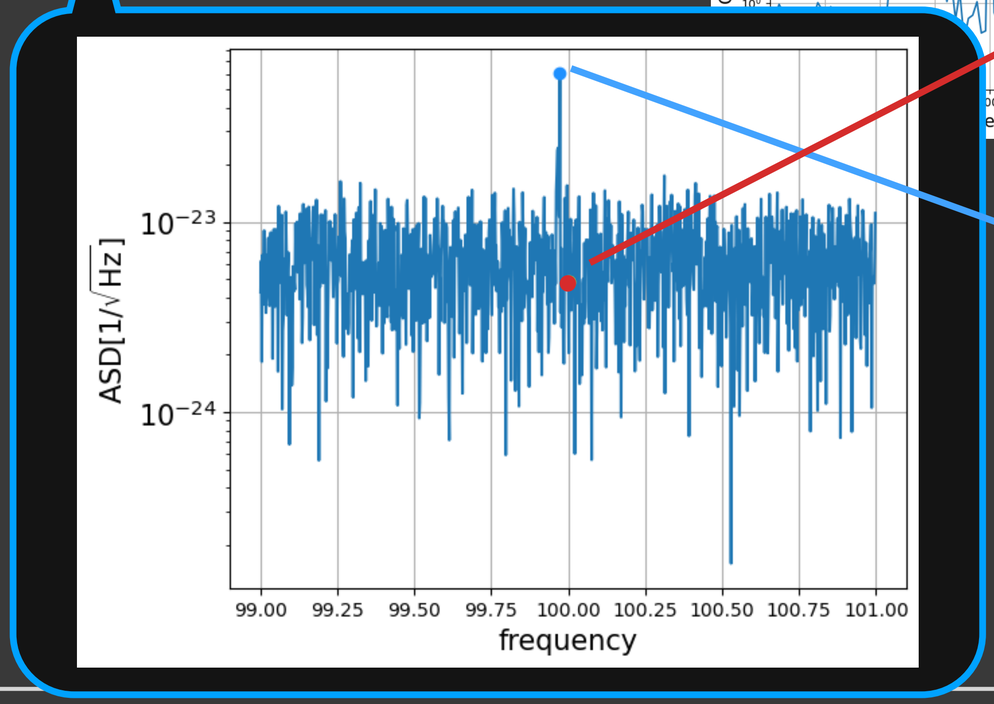

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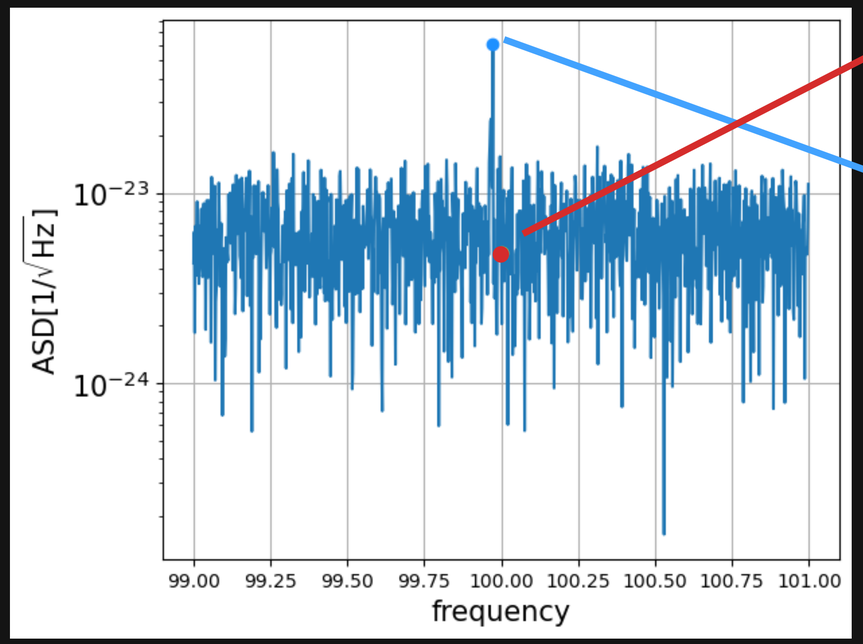
Injected frequency



Takumi Fujimori (Osaka Metropolitan University)

Correlation of the data

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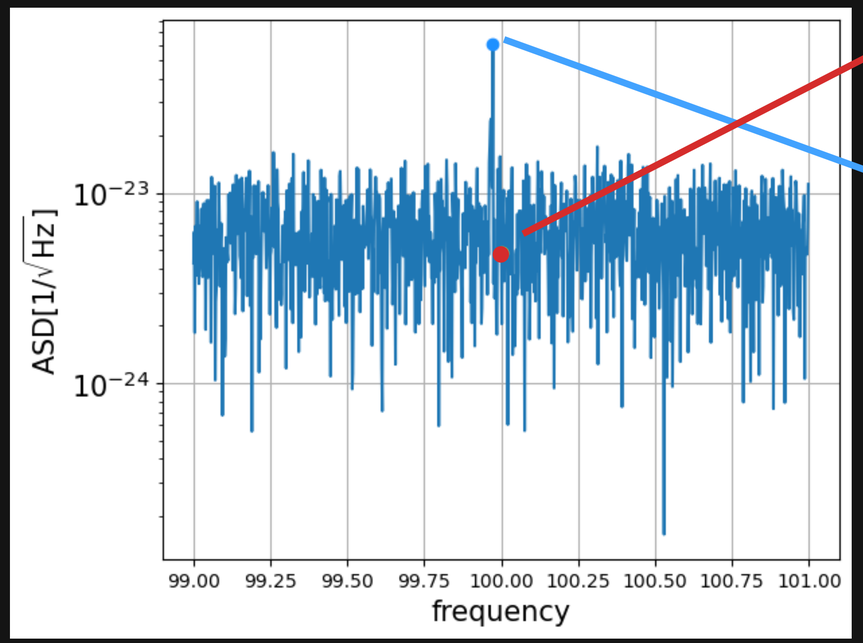

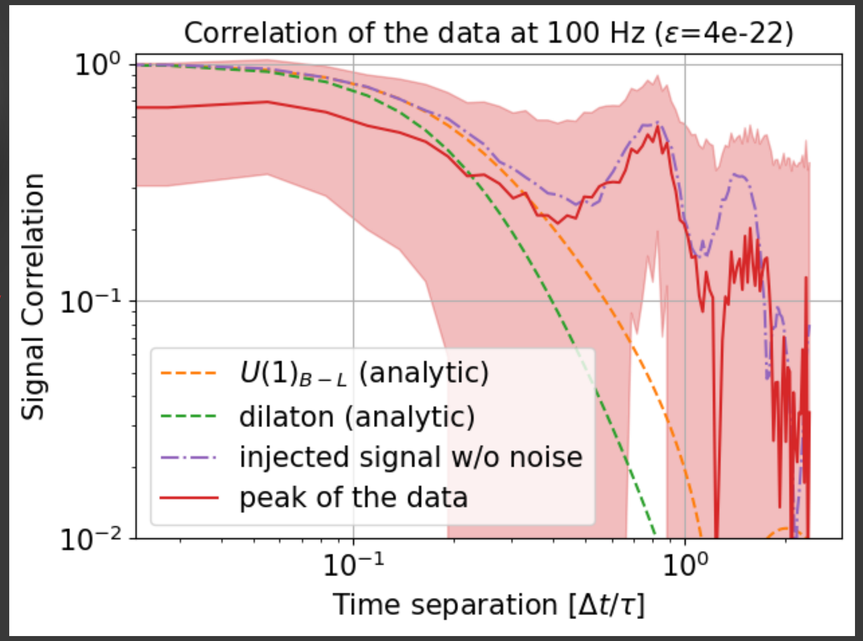

Takumi Fujimori (Osaka Metropolitan University)

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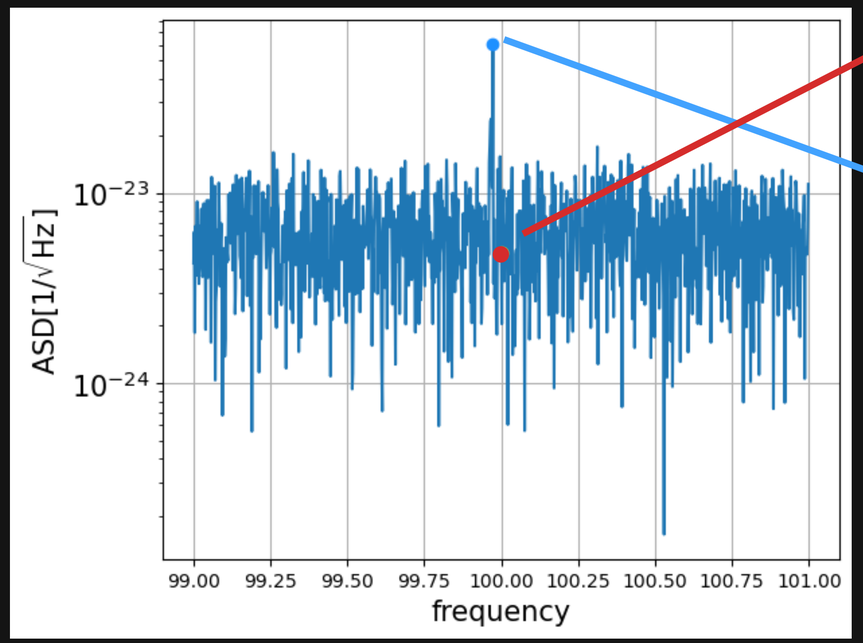

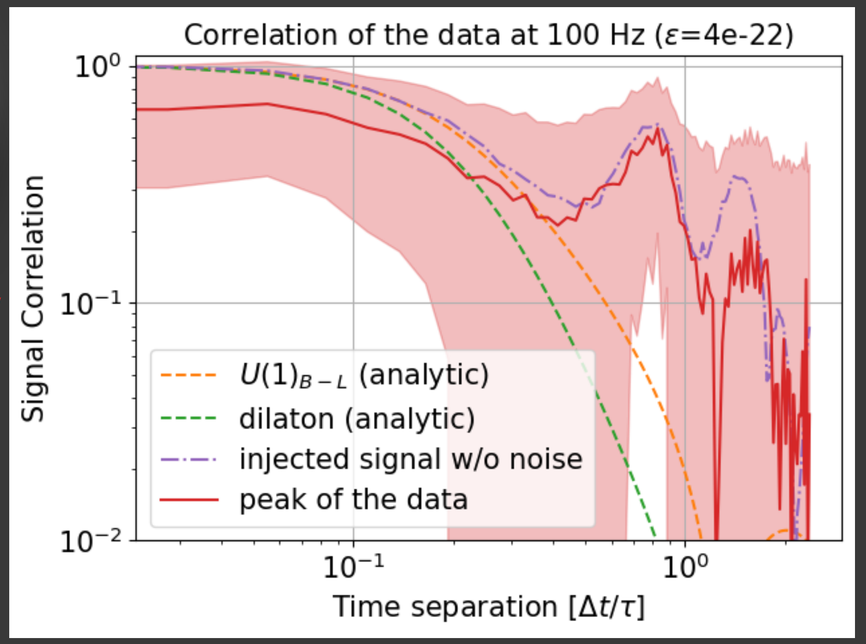

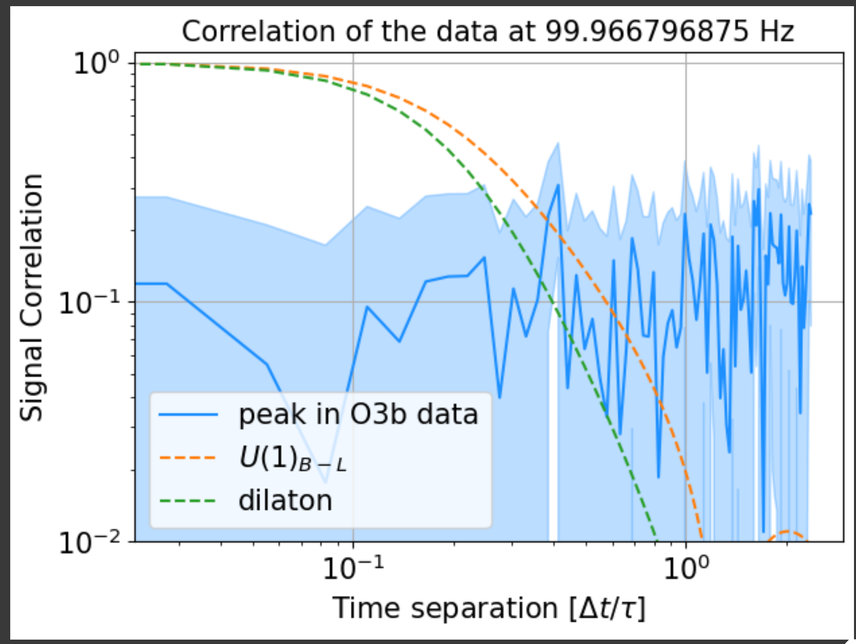

Takumi Fujimori (Osaka Metropolitan University)

Correlation of the data

- ✳ Calculate the correlation
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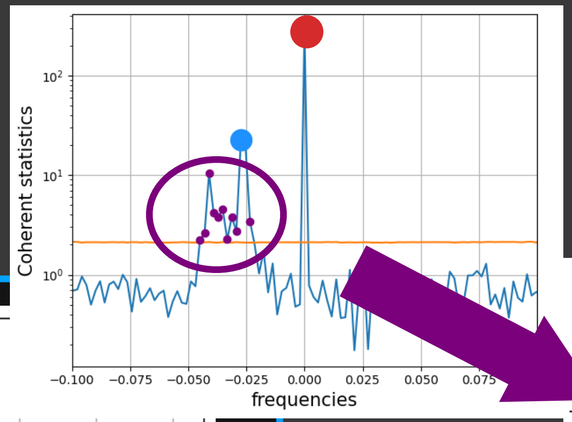
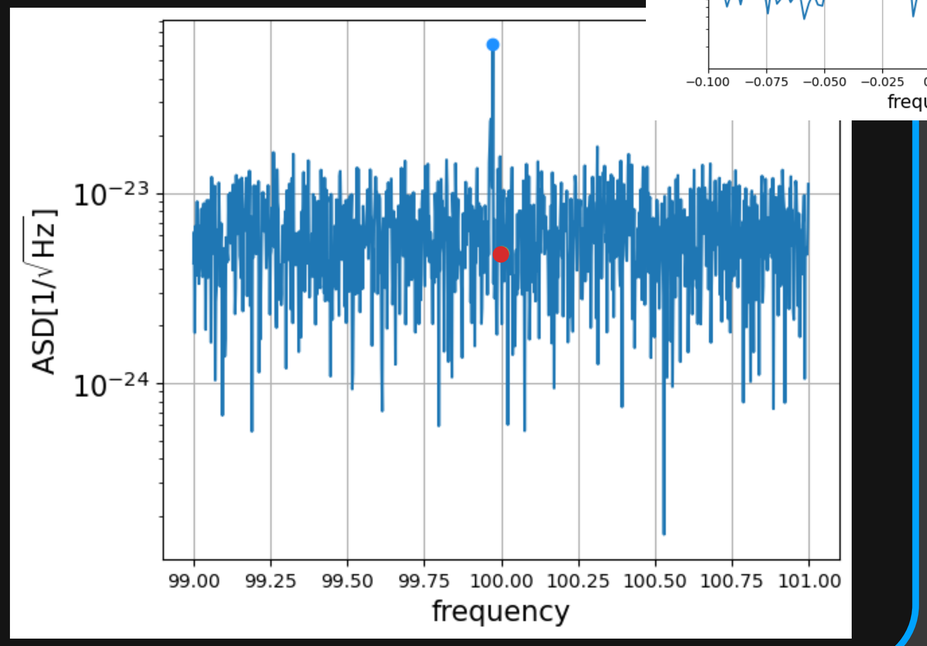
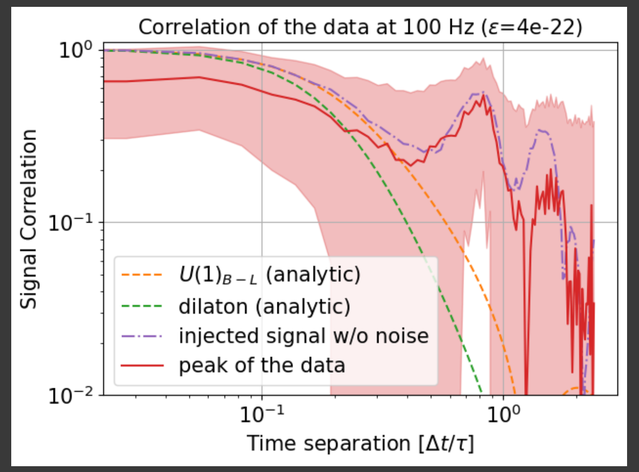
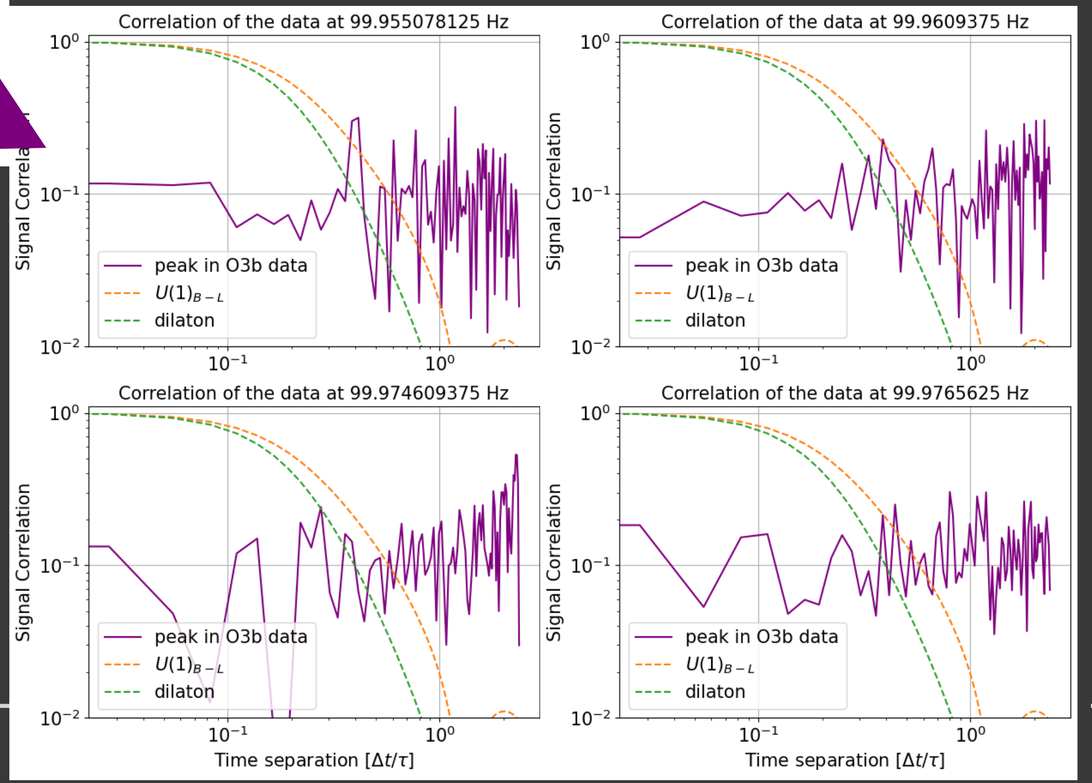






Results (for a few points)



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Correlation of the data

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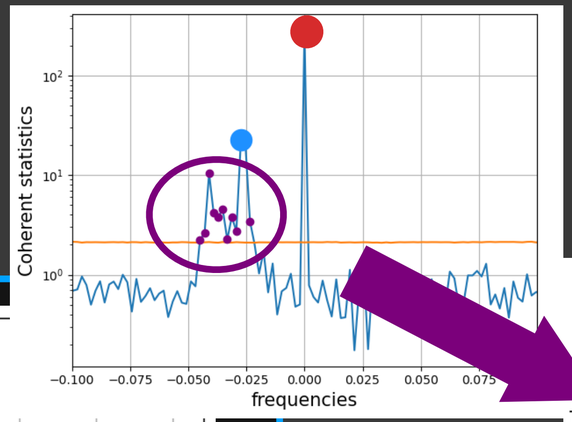

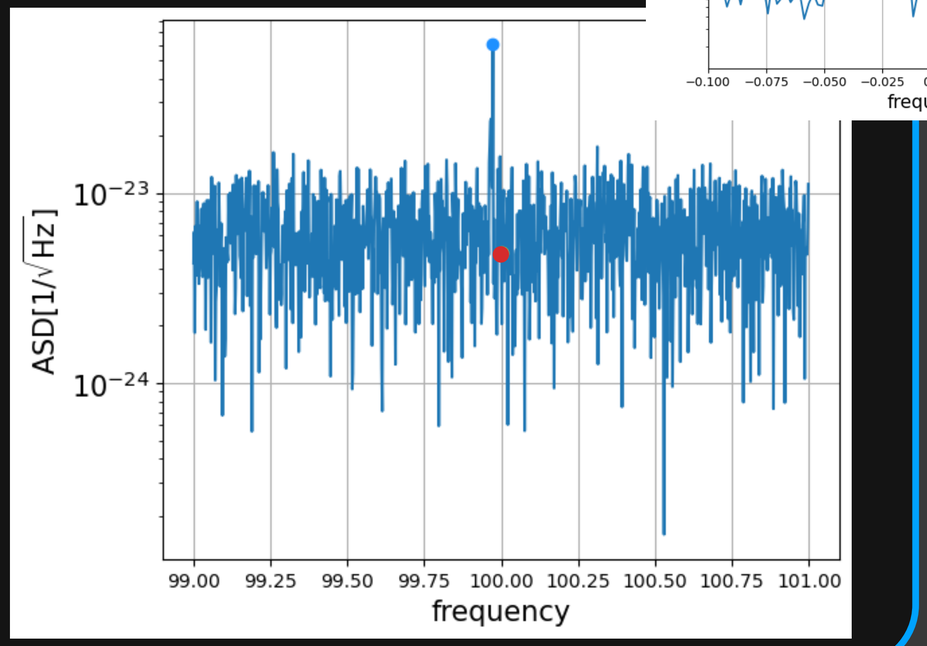

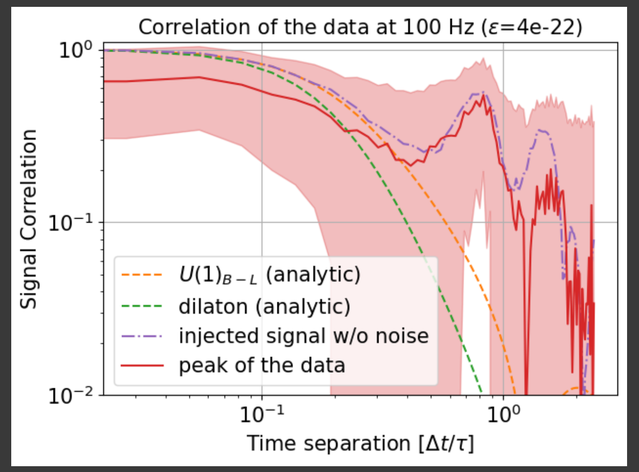

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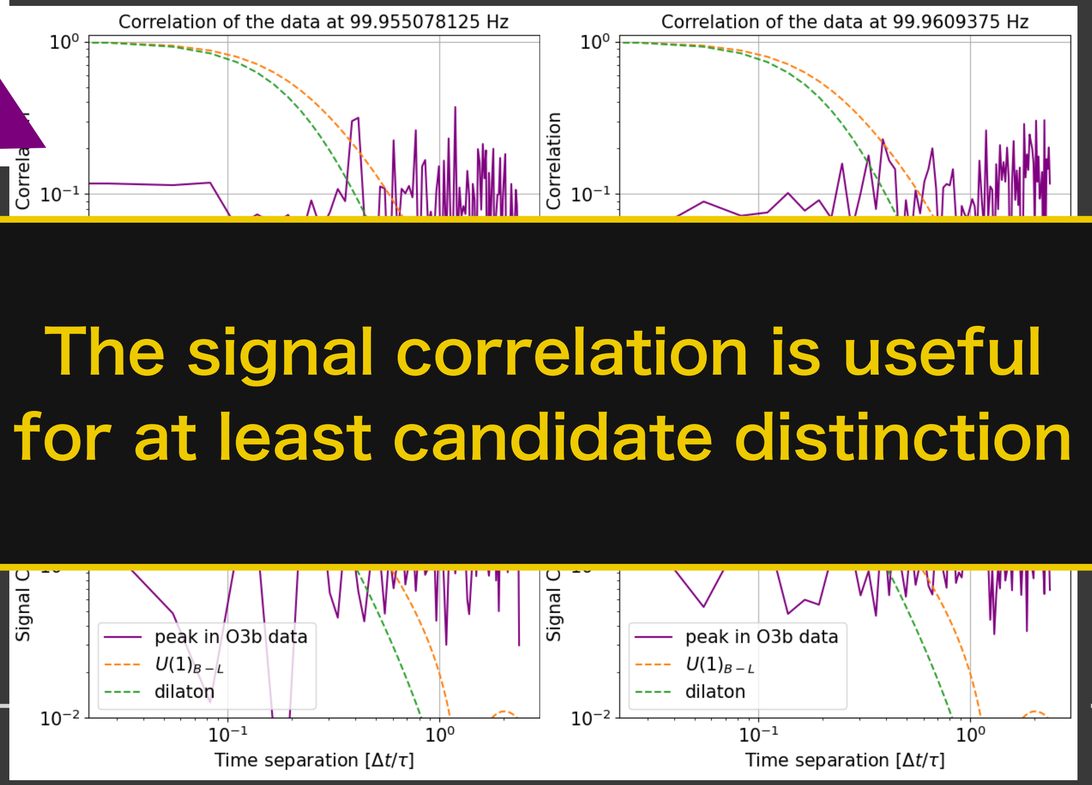

The signal correlation is useful for at least candidate distinction

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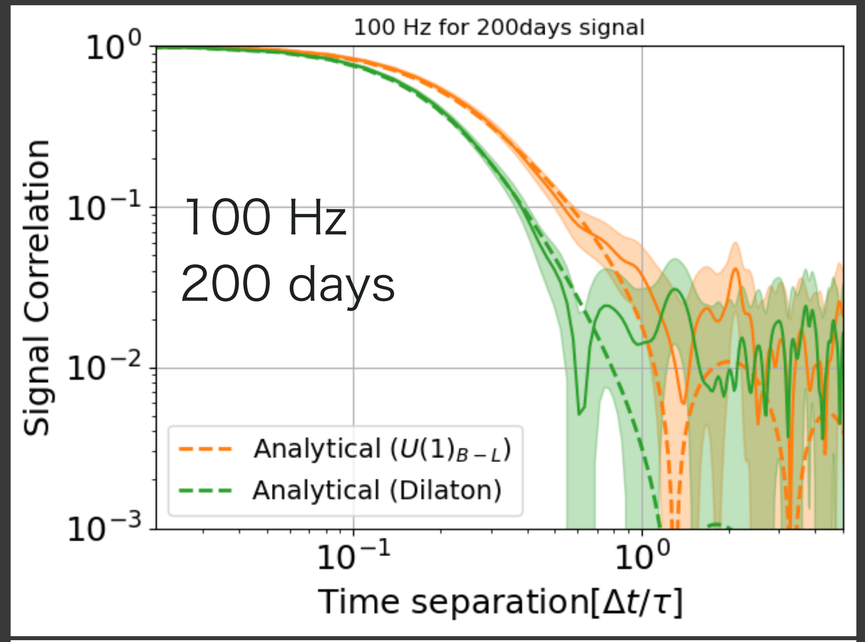
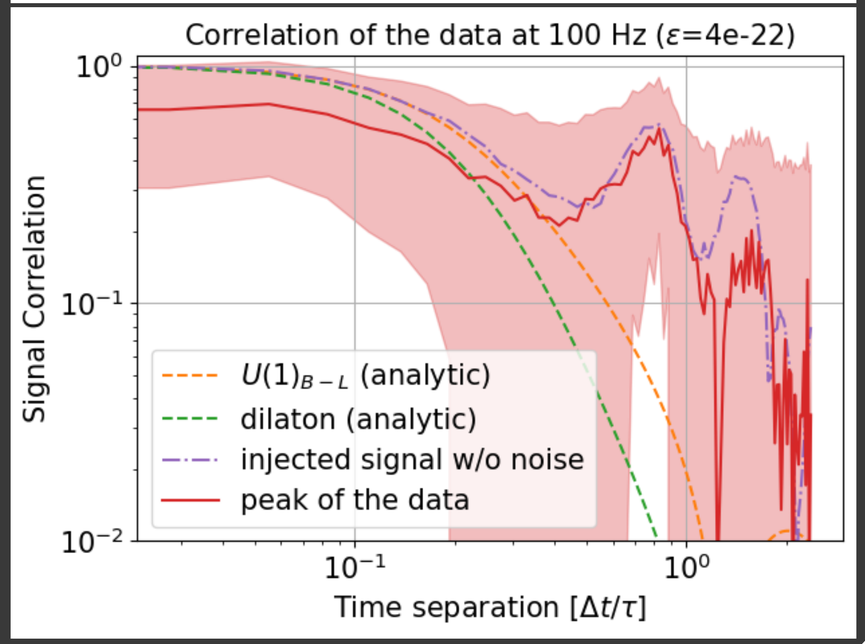
Contents

Conclusion

- **The possibility of a new method to estimate the ULDM origin**
  - **Autocorrelation** can serve as a robust discriminator for **ULDM model identification**
  - Injection tests demonstrated that autocorrelation **successfully distinguishes ULDM signals** from excess noise
- **Future work**
  - Determine the minimum observation time required for robust model discrimination
  - Apply the proposed method to the latest LVK observation data





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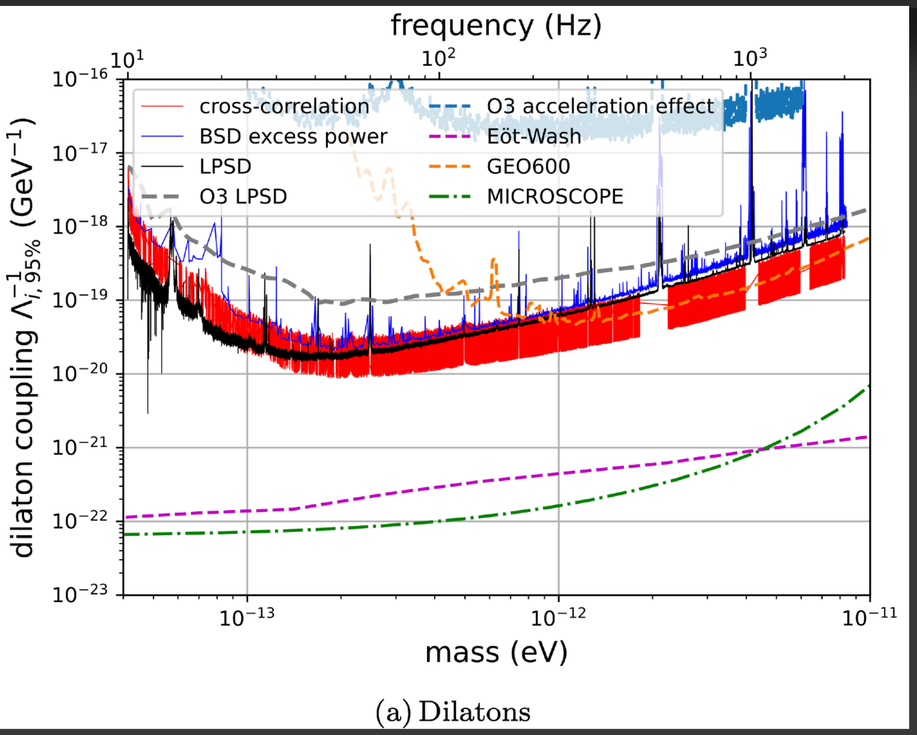
Appendix

Limits from O4b observation



(a) Dilatons

https://dcc.ligo.org/LIGO-P2500252/public

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Limits from O4b observation

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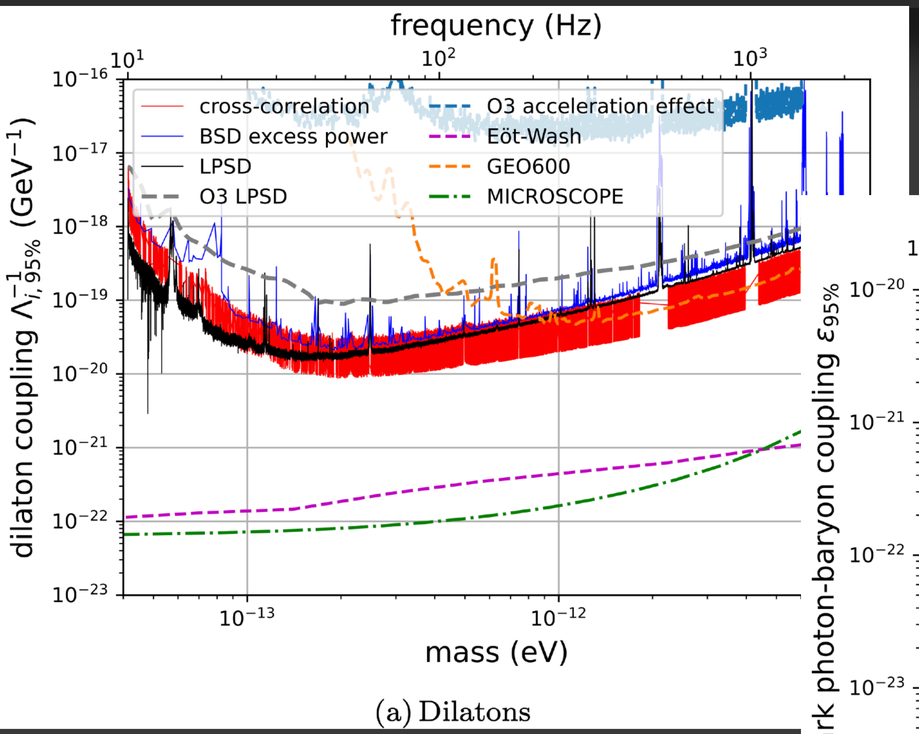

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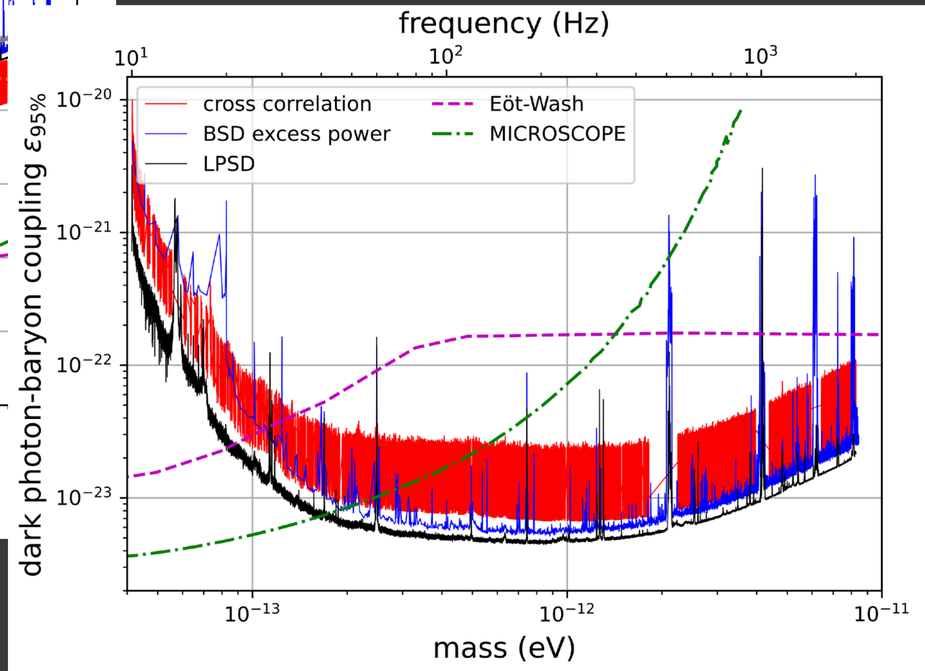

(b) Dark photons

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Limits from O4b observation

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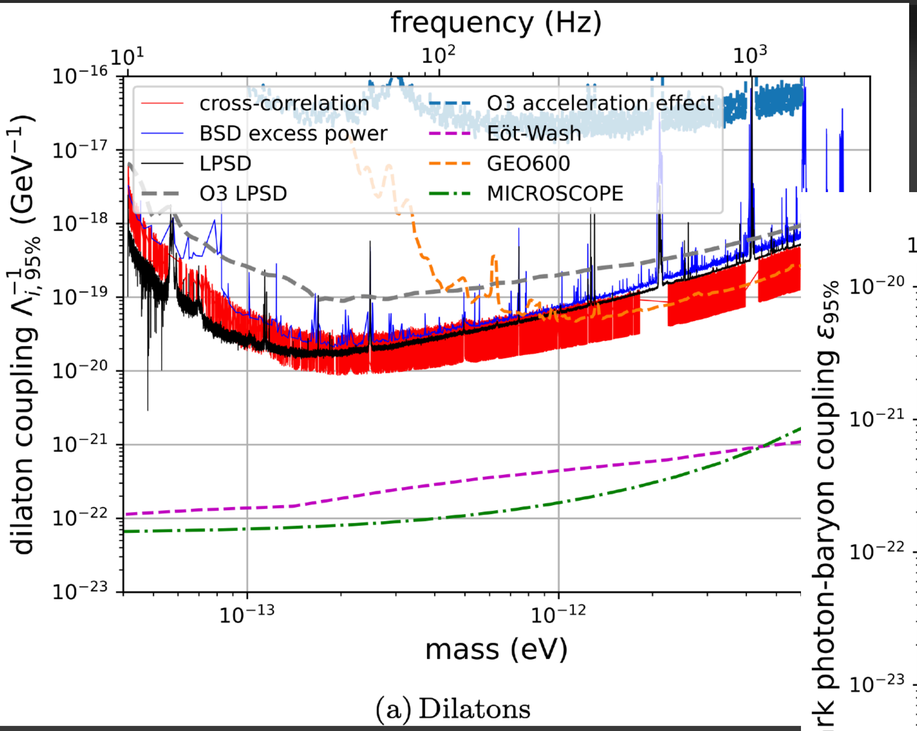

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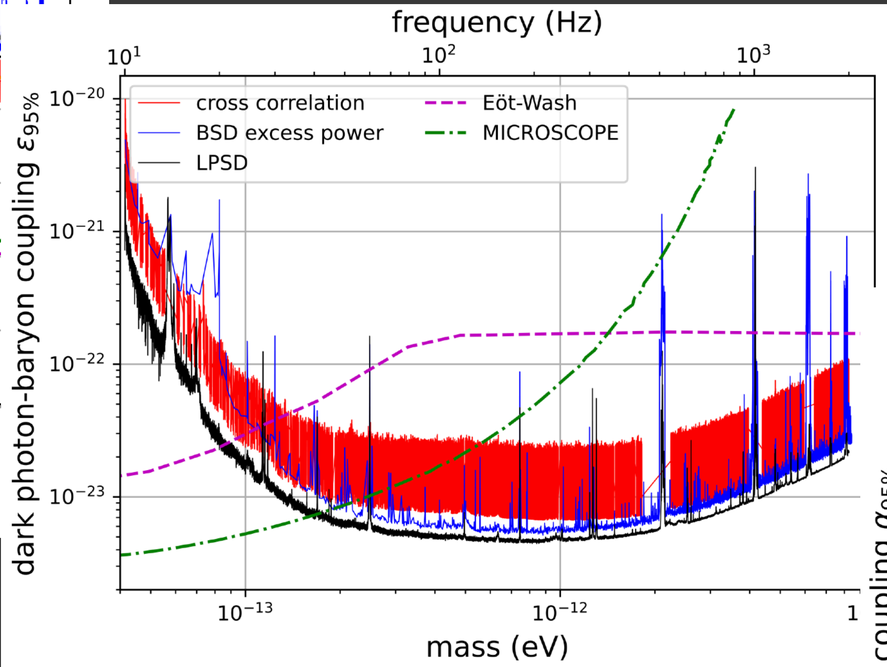

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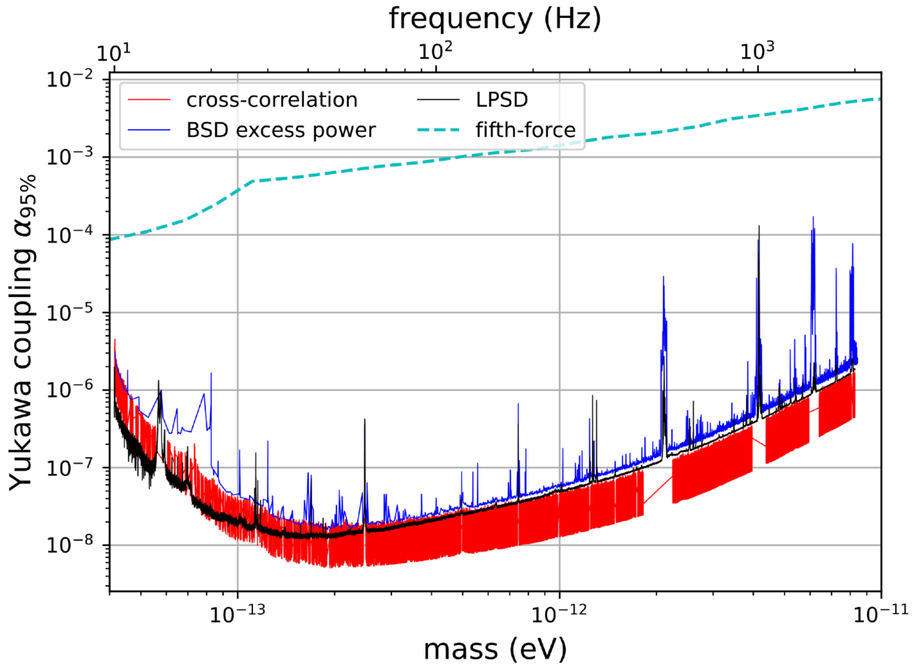

(c) Tensor bosons

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Construction of Optimal statistics

👉 arxiv:2503.04484

Consider a quadratic form,

$$\rho = \vec{d}^{\dagger}\mathcal{K}\vec{d}$$

$$\rho = \frac{\vec{d}^{\dagger}\mathcal{K}\vec{d} - \mathrm{Tr}\left[\mathcal{N}^{-1}\mathcal{H}\right]}{\sqrt{\mathrm{Tr}\left[\left(\mathcal{N}^{-1}\mathcal{H}\right)^2\right]}}$$

and determine $\mathcal{K}$ to maximize SNR

$$\mathrm{SNR} \equiv \langle\rho\rangle / \sqrt{\mathrm{Var}[\rho]}$$

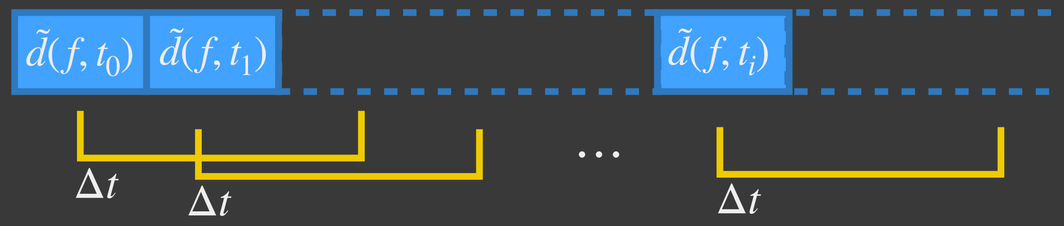
$$\langle\rho\rangle \equiv \mathrm{Tr}[\mathcal{K}\Sigma] \qquad \mathrm{Var}[\rho] \equiv \mathrm{Tr}[\mathcal{K}\Sigma\mathcal{K}\Sigma] \qquad \Sigma = \mathcal{N} + \epsilon^2\mathcal{H}$$

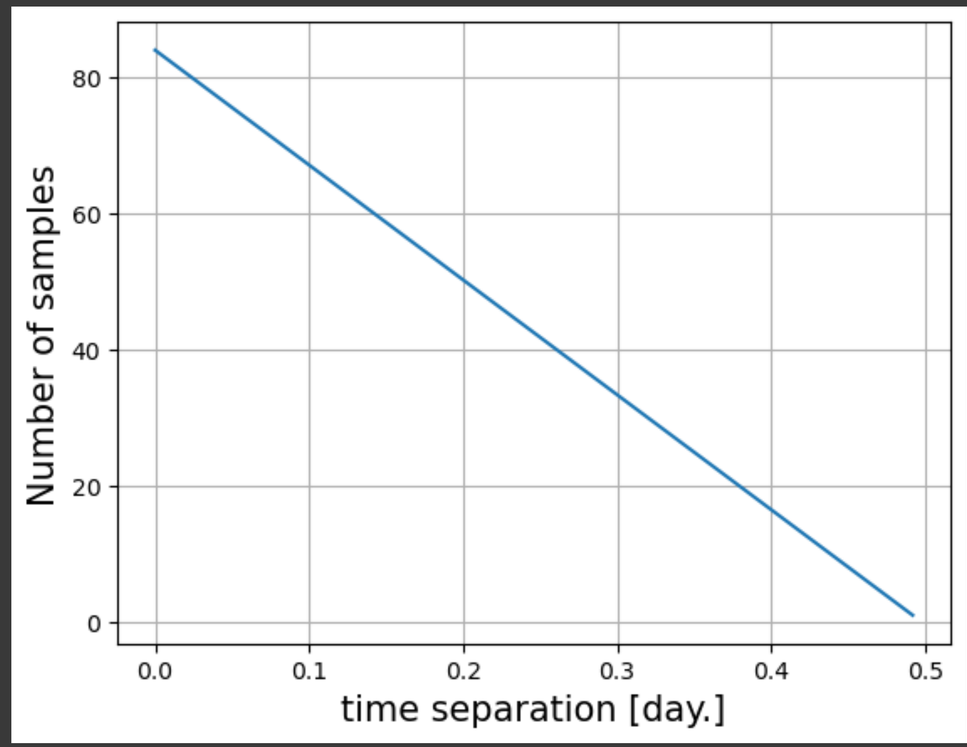
$$\rho = \frac{\vec{d}^{\dagger}\mathcal{N}^{-1}\mathcal{H}\mathcal{N}^{-1}\vec{d} - \mathrm{Tr}\left[\mathcal{N}^{-1}\mathcal{H}\right]}{\sqrt{\mathrm{Tr}\left[\left(\mathcal{N}^{-1}\mathcal{H}\right)^2\right]}}$$

Calc. of the correlation from the data

$$\mathcal{H}_{ft_i,f't_j} \equiv \langle \tilde{h}^*(f;t_i), \tilde{h}(f';t_j) \rangle$$

$$\mathcal{H}(f;t_i,t_i+\Delta t) = \frac{1}{N}\sum_{i=0}^{N-1} \tilde{h}^*(f;t_i)\tilde{h}(f;t_i+\Delta t)$$





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Correlation variation & C.C.

$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

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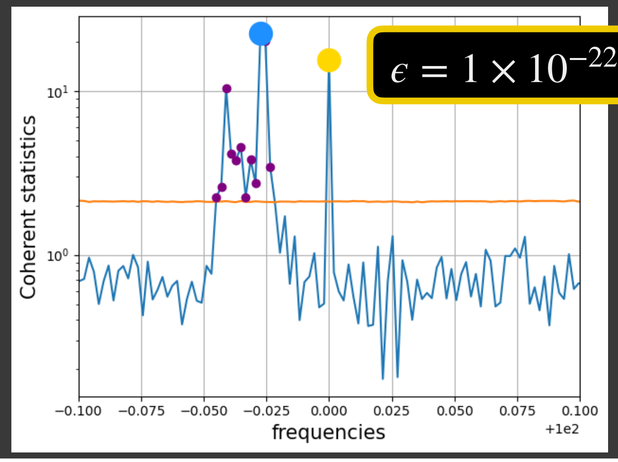

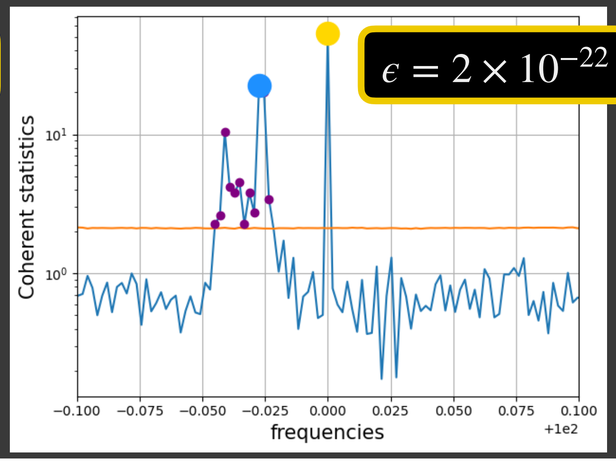

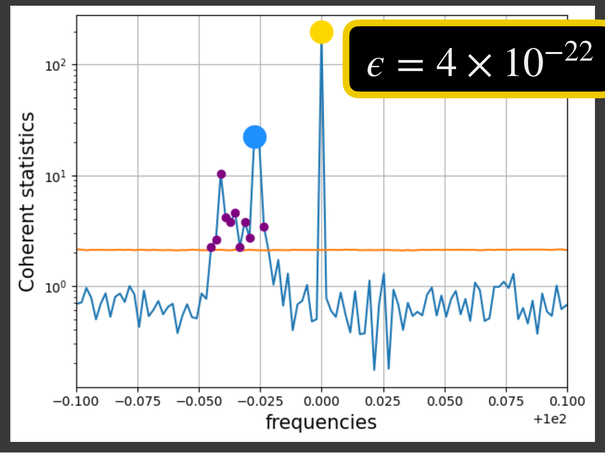

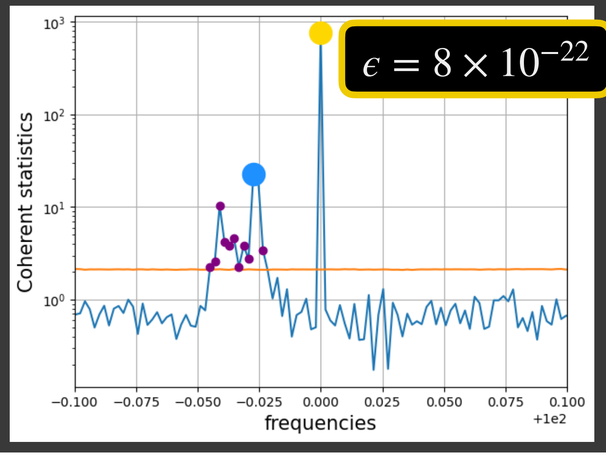

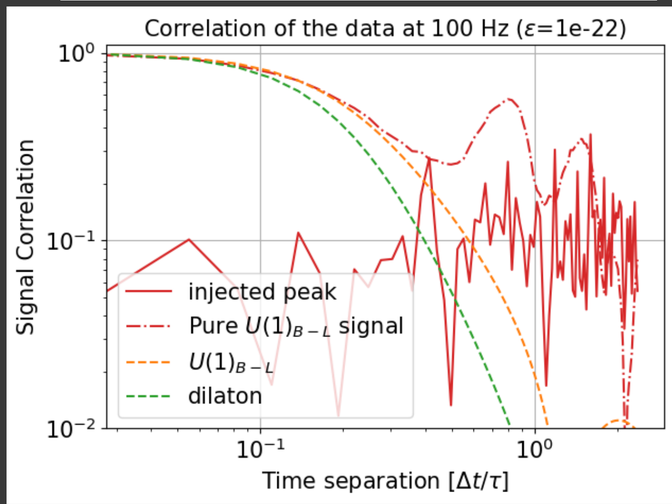

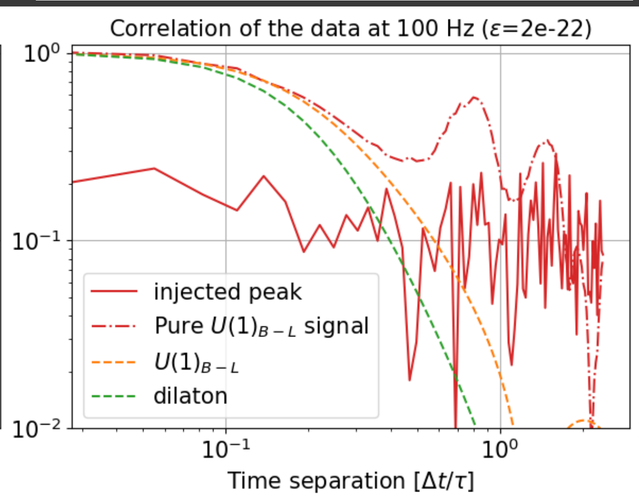

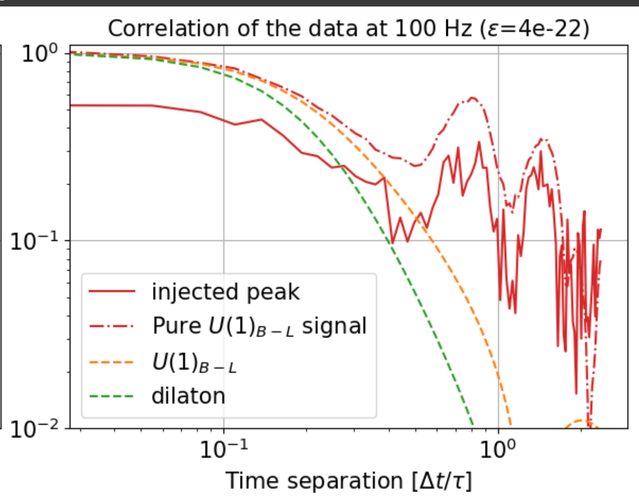

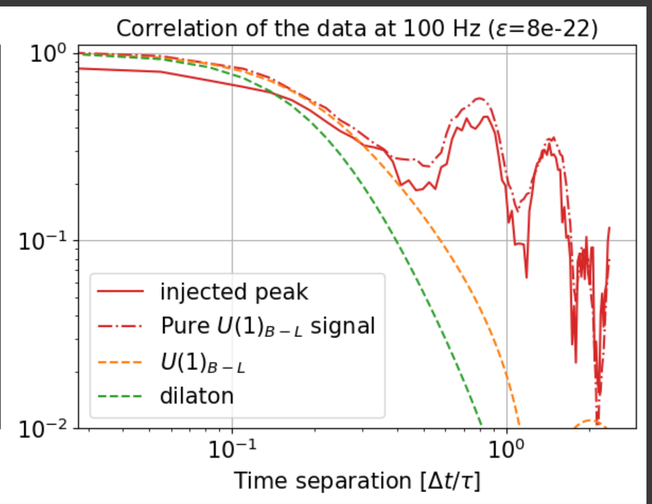

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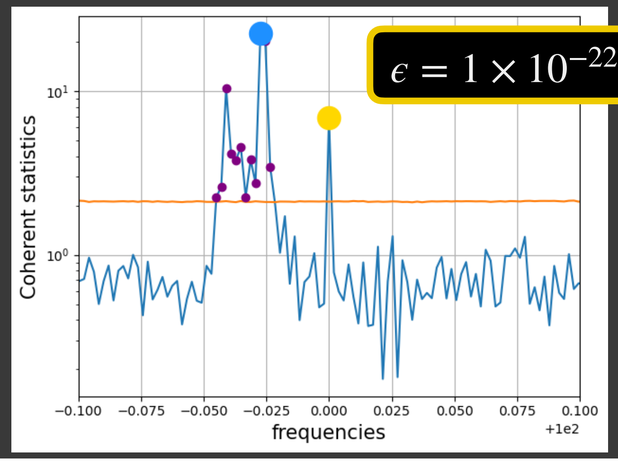
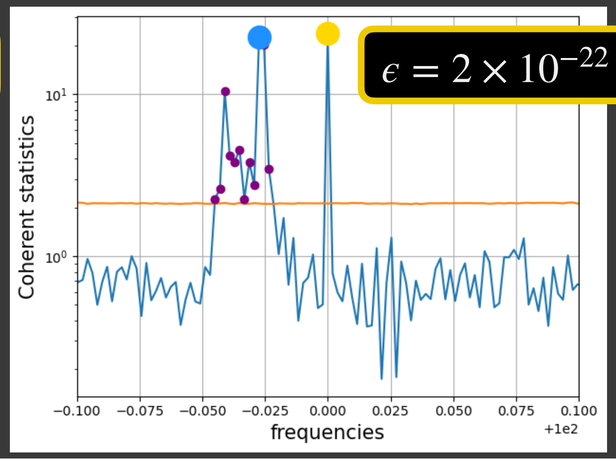
Results of other realizations

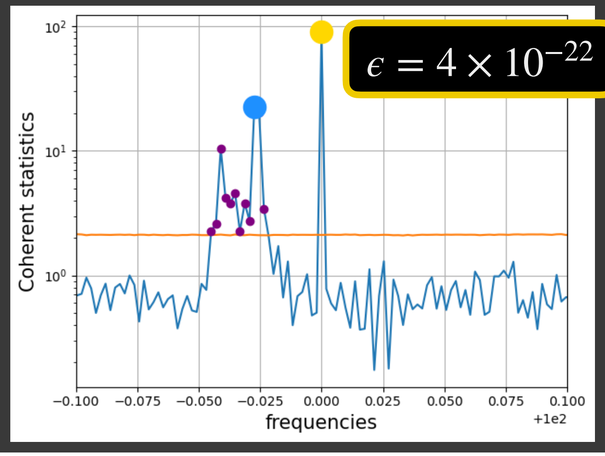
$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

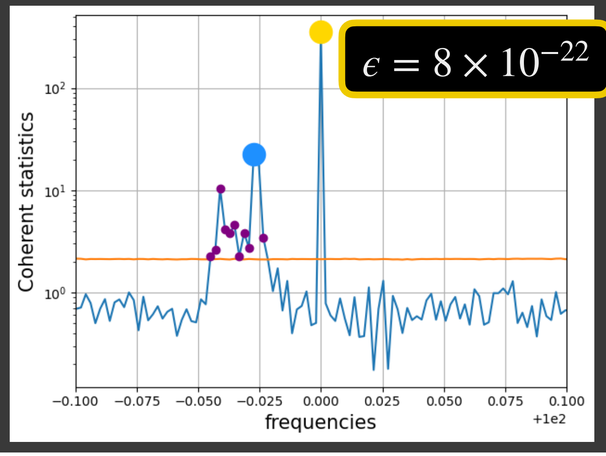
$$\langle \tilde{d}^*(f;t_i), \tilde{d}(f;t_j) \rangle$$

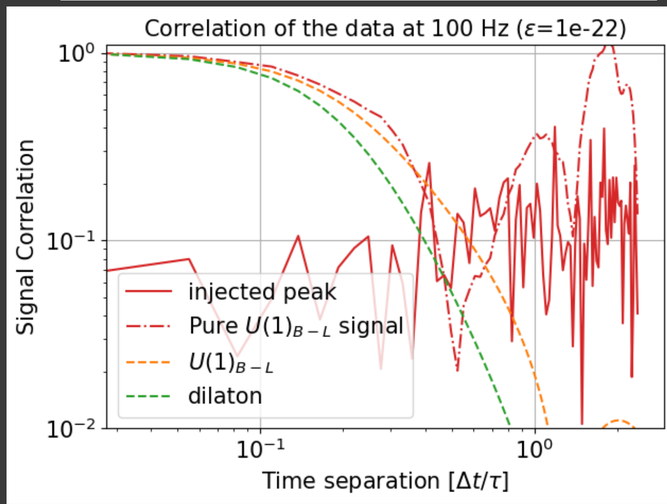
$$\tilde{d}(f;t_i) = \tilde{n}(f;t_i) + \epsilon \tilde{h}(f;t_i)$$

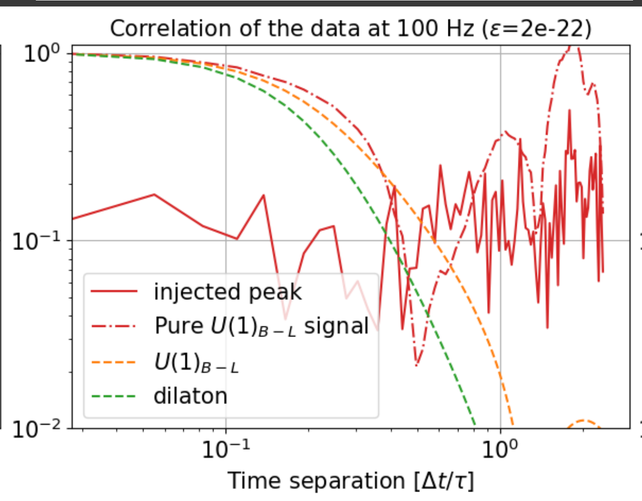


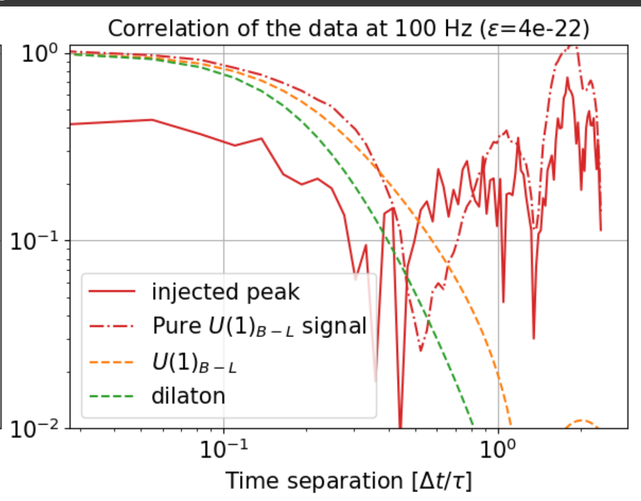


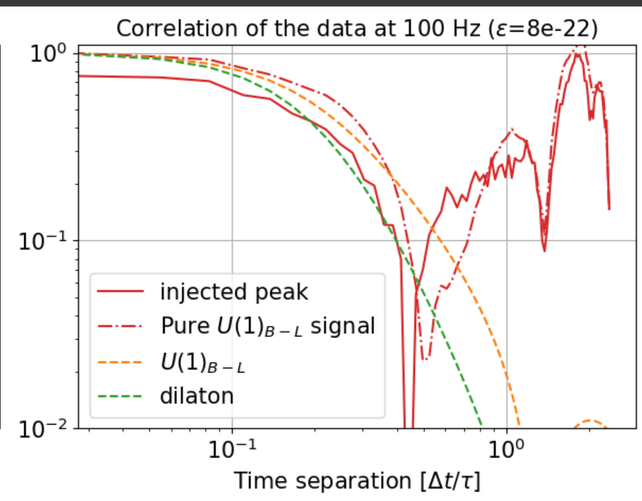




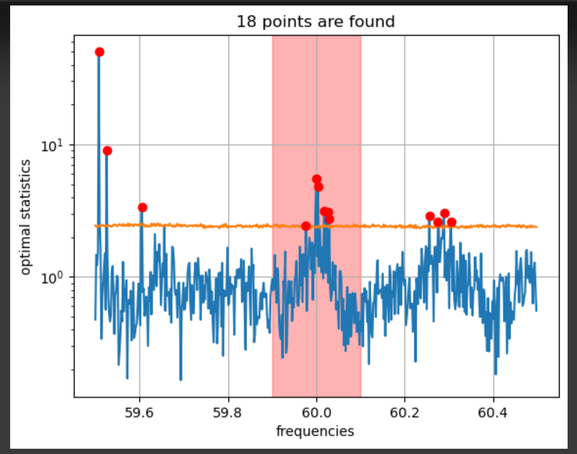


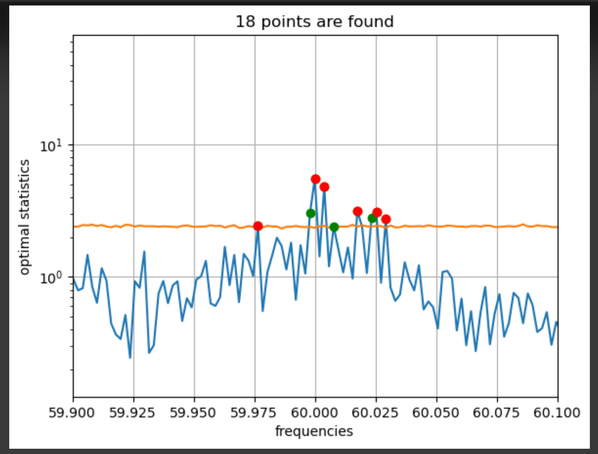






Correlation at 60 Hz of real data

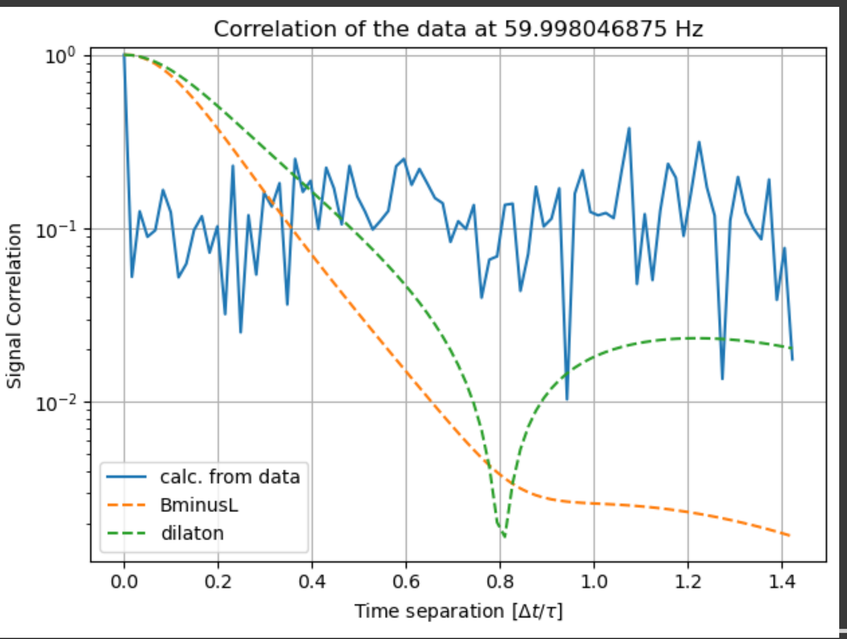


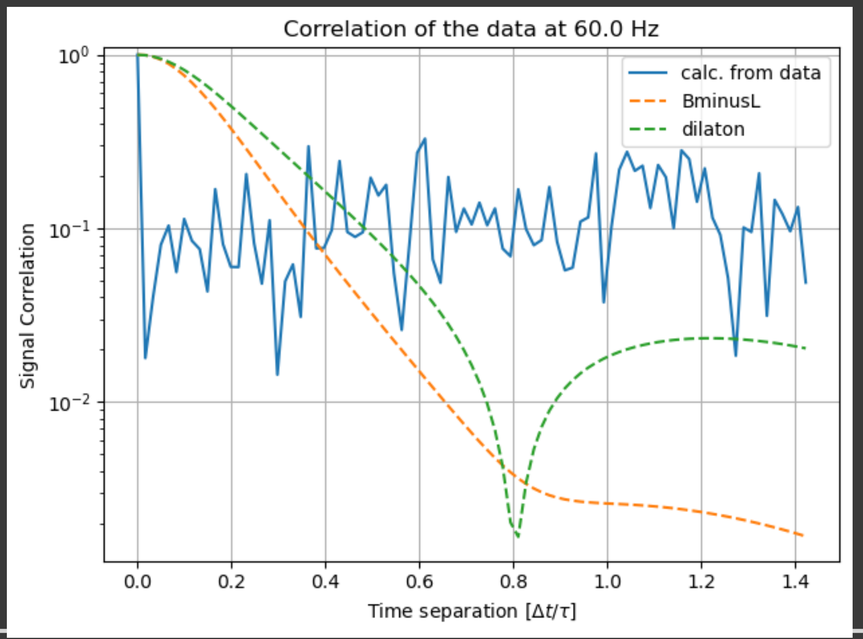


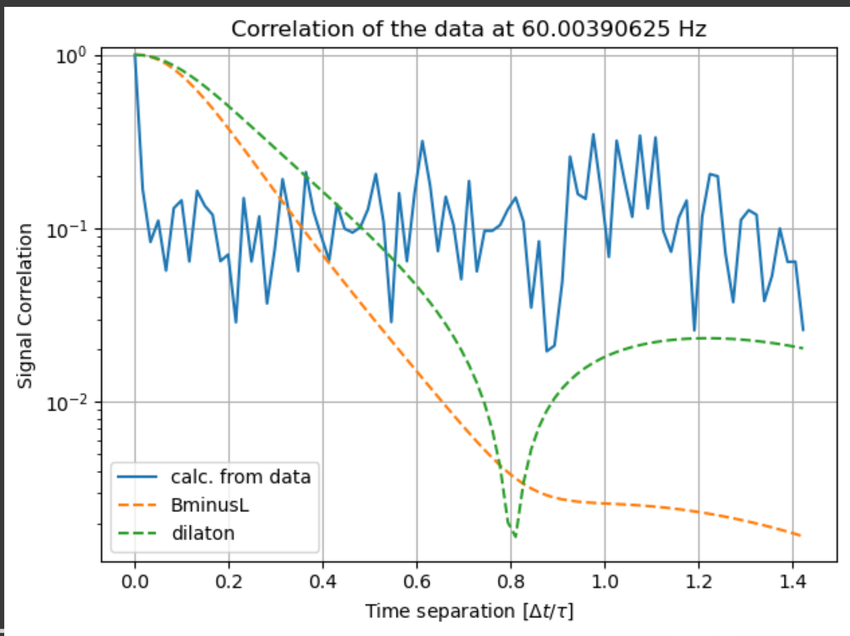
$\tilde{d}(f,t_1)$ $\tilde{d}(f,t_2)$ $\tilde{d}(f,t_i)$

$$\langle \tilde{d}^*(f;t_i), \tilde{d}(f;t_j) \rangle$$

$$\tilde{d}(f;t_i) = \tilde{n}(f;t_i) + \epsilon \tilde{h}(f;t_i)$$







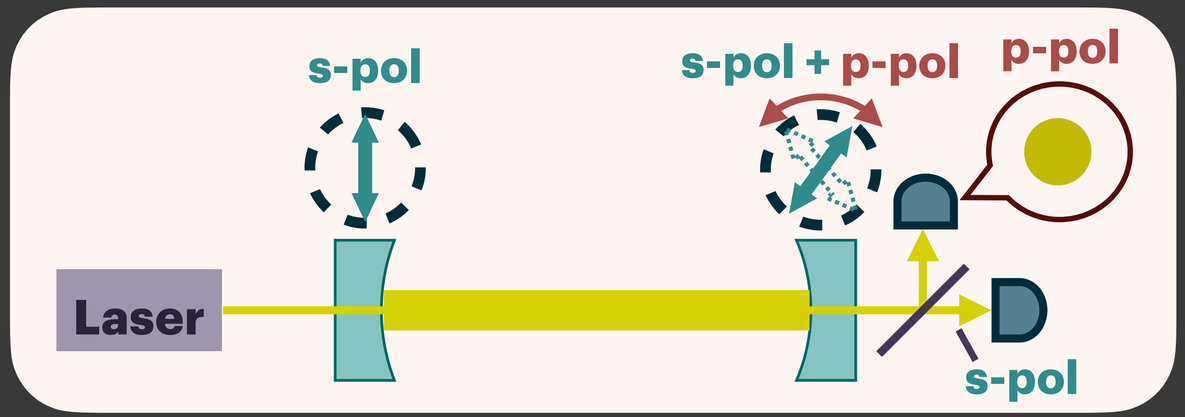
Other ULDM searches

✳ Spin-0 **Axion** (or Axion-like particle): $\frac{g_{a\gamma}}{4} a(t) F_{\mu\nu} \tilde{F}^{\mu\nu}$

- Phase velocity caused by the axion field -> polarised photon occurs

  Y. Michimura+, arXiv:1912.09123 [hep-ph]

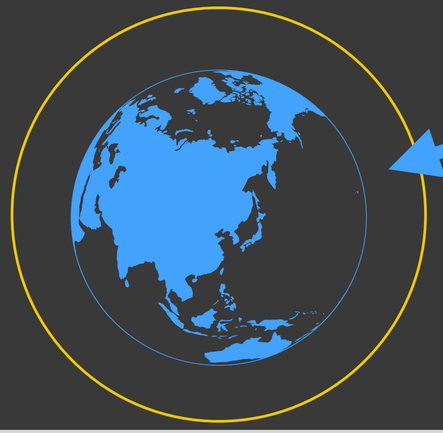
$$c_{L/R} = \sqrt{1 \mp \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

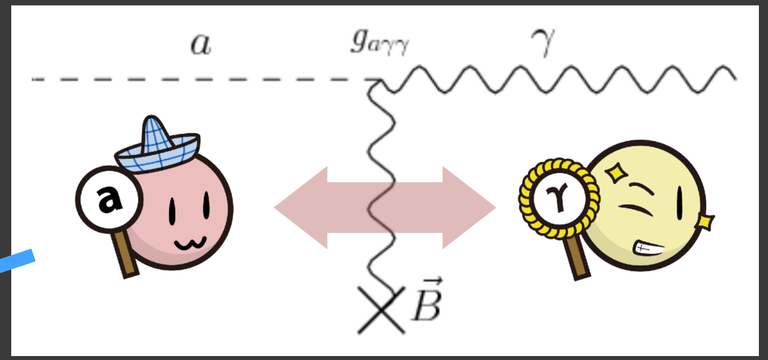


- Interaction w/ terrestrial magnetic field

  → Detect axion-induced M field

  A. Taruya+, arXiv:2504.06653 [hep-ph]





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