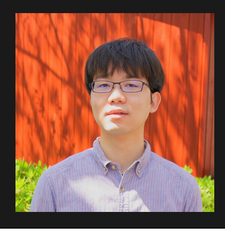
Dead-time Free Broadband Spectrometer for Wavy Dark Matter Search - dSpec

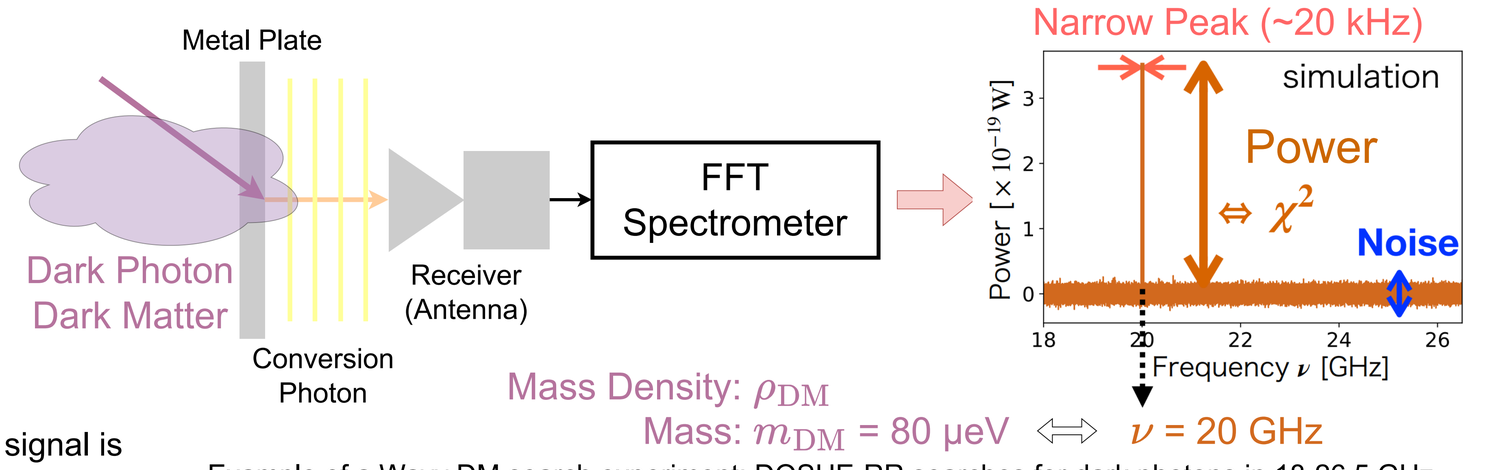
Hiroki Takeuchi, Junya Suzuki, Shunsuke Adachi, Osamu Tajima
Kyoto University



1. Introduction

- Majority of matters in our universe is dark matter (DM), and they are located in galaxy halos.
  - Mass density in the Galaxy: $\rho_{\rm DM}$~0.4 GeV/cm^3
- Wavy DM is one of DM candidates.
  - Dark photon, Axion, and so on.
  - Mass region of interest: μeV - meV (i.e., ultra light).
  - Very weakly interacting with electromagnetic field.

They can convert to photons (electromagnetic waves). The conversion signal is very weak (≦ 10^{-18} W). Its frequency(ν) is proportional to the DM mass ($m_{\rm DM}$), i.e., $m_{\rm DM}c^2 \cong h\nu$, and has narrow peak ($\Delta\nu/\nu \sim 10^{-6}$).



Example of a Wavy DM search experiment; DOSUE-RR searches for dark photons in 18-26.5 GHz.

2. Requirements

We need to explore for wide mass range because we do not know the DM mass. Unexplored region is interesting, i.e., 0.1 - 1 meV.
In this regime, conversion photon frequencies reach 10-100 GHz, while previous studies achieved only 2.5 GHz Instantaneous bandwidth[1]. Broader bandwidth spectrometers are essential for search efficiency.

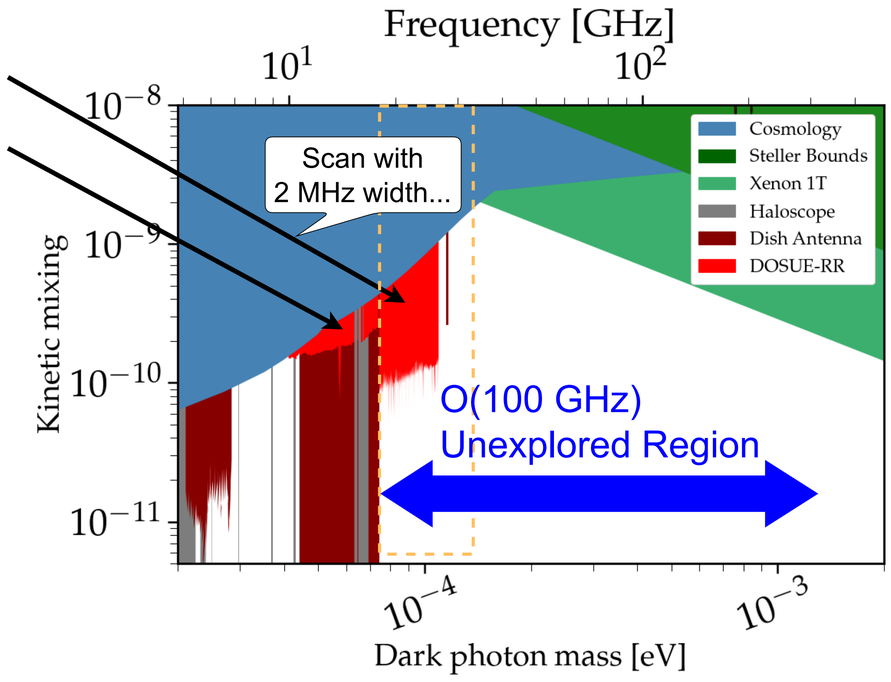
For efficient search, the spectrometer must meet these requirements:

- Broadband: **>1 GHz**, wider bandwidth is better.
- Frequency Resolution: $\Delta\nu/\nu \sim 10^{-6}$ ➡ **10 - 100 kHz**
- Time Efficiency: **Dead time free**.

1. Instantaneous Bandwidth: The measurable width of frequencies at one time.

18-26.5 GHz (2023) PRL 130.071805
10-18 GHz (2024) PRD 109.012008

18-26.5 GHz Receiver



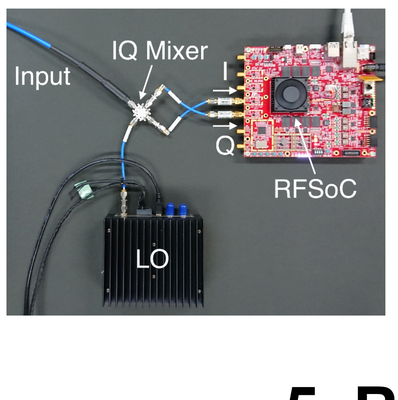
3. Specification of dSpec

To achieve these requirements, we developed dead-time free broadband spectrometer, "dSpec." It is built on AMD Xilinx RFSoC, which include ADC/DAC, CPU, and FPGA in a single chip. We developed two designs prioritizing either bandwidth or resolution.

Key Features

- FPGA-Based FFT Spectrometer
- Broadband and Fine Resolution
- Real Time Spectroscopy

Schematic of dSpec

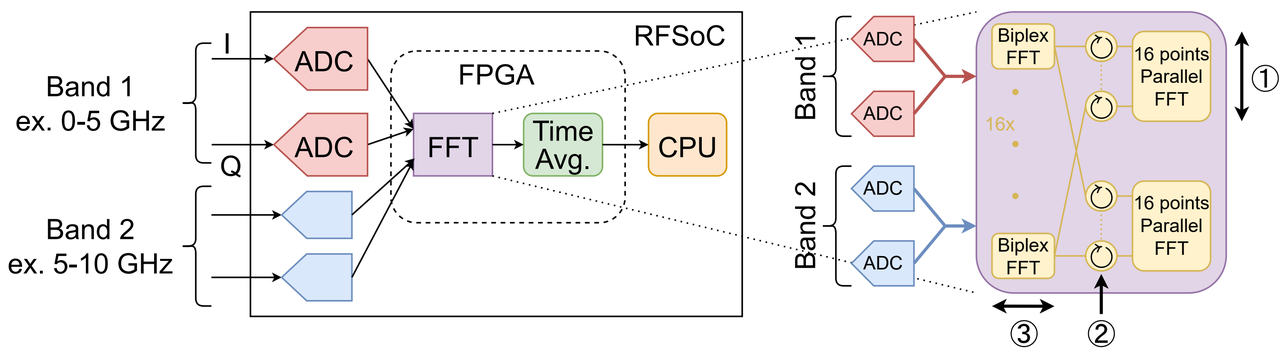


Specification of dSpec

Version of Spectrometer	4 ADCs (2nd Design)	2 ADCs (1st Design)	arXiv: (2501.12003)
RFSoC Board	RFSoC 4x2	RFSoC 2x2	
Instantaneous Bandwidth	**9.8 GHz**	4.1 GHz	
Frequency Resolution	41.8 kHz	**15.6 kHz**	
Current Status	Implemented, Evaluation on Going	Developed, Working in Physical Run	

4. Design Details

The implementation of high-performance spectrometer faces challenge in clock frequency and size of FFT circuits. We developed an FFT architecture optimize for size and throughput.

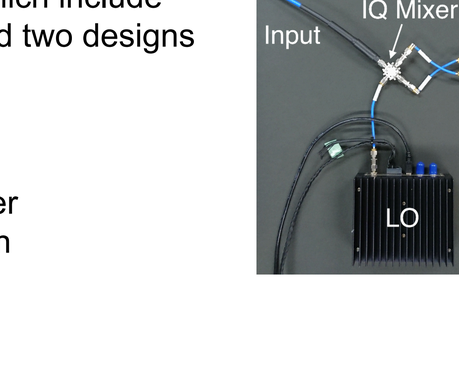


①Parallel FFT Circuit

We parallelized **16 FFT circuits** at 307 MHz to handle all 4.9 GHz ADC inputs. For avoiding the increase of circuit area by parallelization, we employed **Radix-2^4 architecture** and **memory-efficient rotation circuit**.

②Memory-Efficient Rotation Circuit

While conventional rotation circuits use LUTs with pre-calculated twiddle factors requiring **O(N)** memory, our approach achieves **O(√N)** by decomposing the LUT into coarse and fine rotation stages.



② Memory-Efficient Rotation Circuit

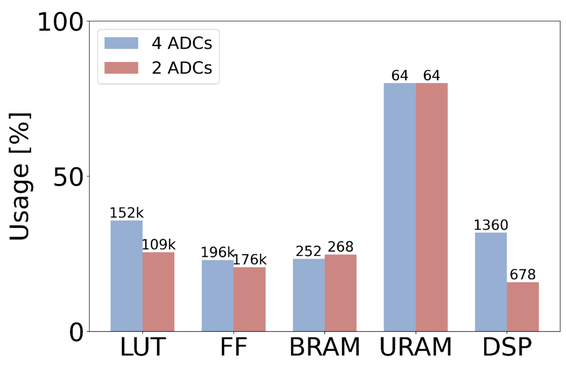
③Biplex FFT Architecture

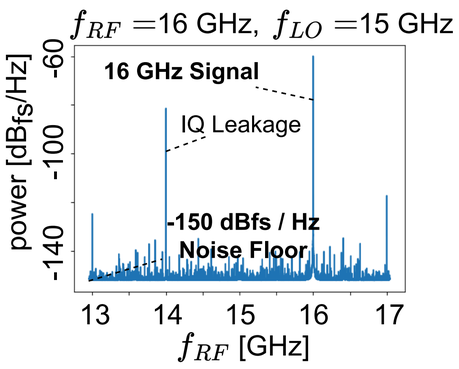
We improved throughput efficiency by employing a Biplex FFT architecture[1] that processes two input streams, overcoming the typical 50% utilization rate of adder/subtractor circuits in serial FFT circuits. Despite this method has some constraints, it is effective for DM searches.

③ Biplex FFT Architecture

5. Results & Evaluated Performances

Our design met the timing constraints of the FPGA and has extra resource available to add further circuits for other applications.
With its 10 GHz bandwidth, it achieves 4 times the search speed of previous broadband spectrometer studies.





Performance Comparison

	dSpec (Ours)		Previous Study		
	4 ADCs	2 ADCs	Ref. [2]	Ref. [3]	Ref. [4]
Device	FPGA	FPGA	FPGA	FPGA	GPU
Instantaneous Bandwidth [GHz]	9.8	4.1	2.5	2.0	4.1
Frequency Resolution [kHz]	37.5	15.6	88.5	7.8	0.025
Time Efficiency [%]	~100	~100	~100	~100	60
Effective Total Bandwidth [GHz] (Search Speed)	**9.8**	4.1	2.5	2.0	2.5

6. Conclusion

We developed a broadband spectrometer for Wavy DM Search, achieving 10 GHz bandwidth and <100 kHz resolution with dead-time free. This system offers 4x better search efficiency than previous studies. We are conducting DM searches with it, expect to achieve more than 10 times better sensitivity compared to our previous experiments. The spectrometer also has potential applications, such as superconducting detector readout.

References
[1] R. F. Emerson. The Deep Space Network Progress Report, pp. 42–34 (1976)
[2] B. Klein, et.al. A&A 542, L3 (2012)
[3] S. Knirck, et. al. PRL **132**, 131004 (2024)
[4] F. Bajjali, et al. JCAP08(2023)077 (2023)