New results of the DOSUE-RR experiment and future

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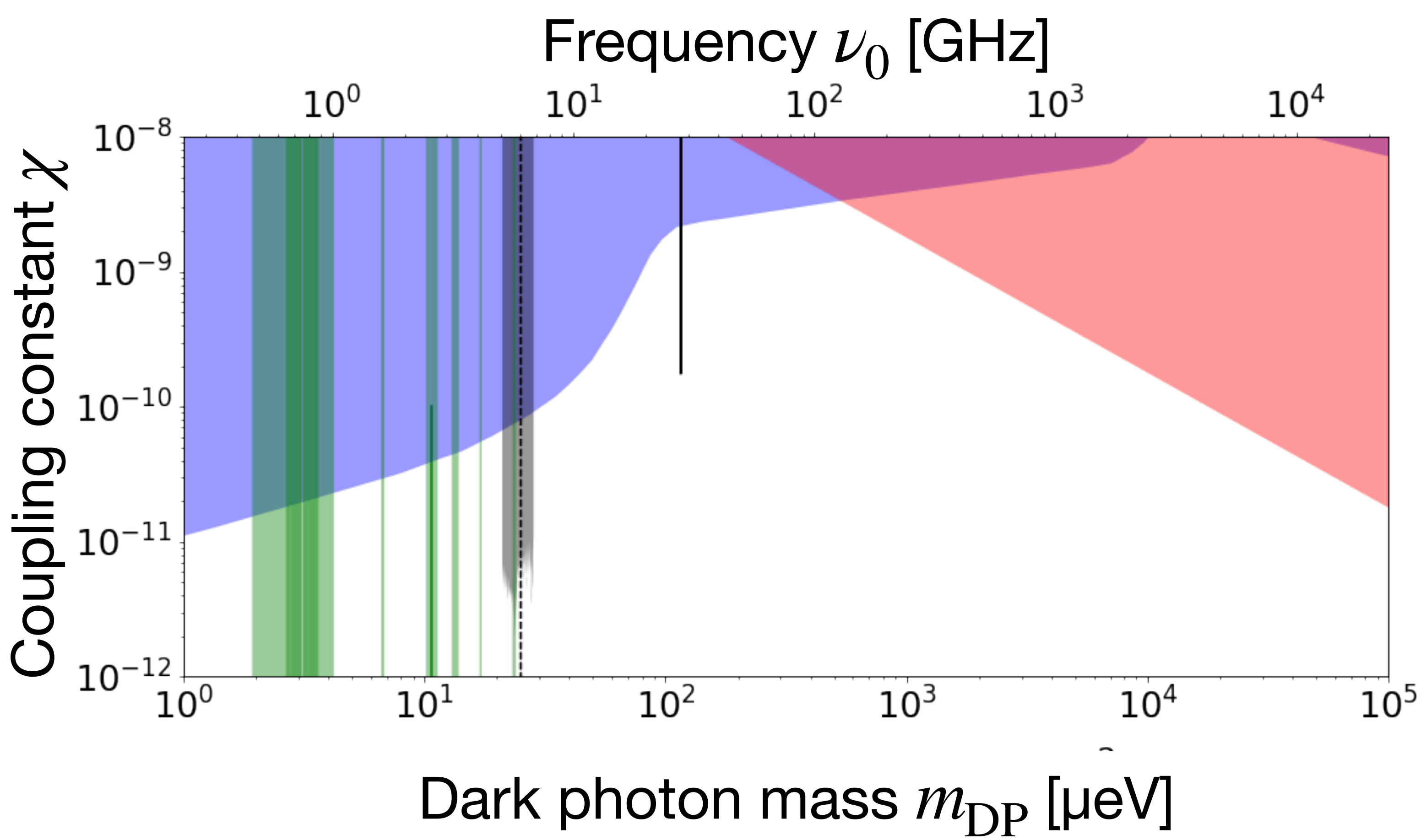
Kyoto Univ., Univ. of Tsukuba[A], Nagoya Univ.[B], Osaka Metropolitan Univ.[C]

6 July 2023 18th Patras Workshop @ Rijeka (Croatia)

DOSUE-RR

- Dark-Photon Dark-Matter (DP-DM) search using **millimeter-wave receiver**
- Dark photon has a kinetic mixing with photons
    - Coupling constant: χ
- Target Mass of DP-DM: ≈ 100–1000 μeV
    - Frequency ($h\nu_0 = mc^2$): 10–O(100) GHz



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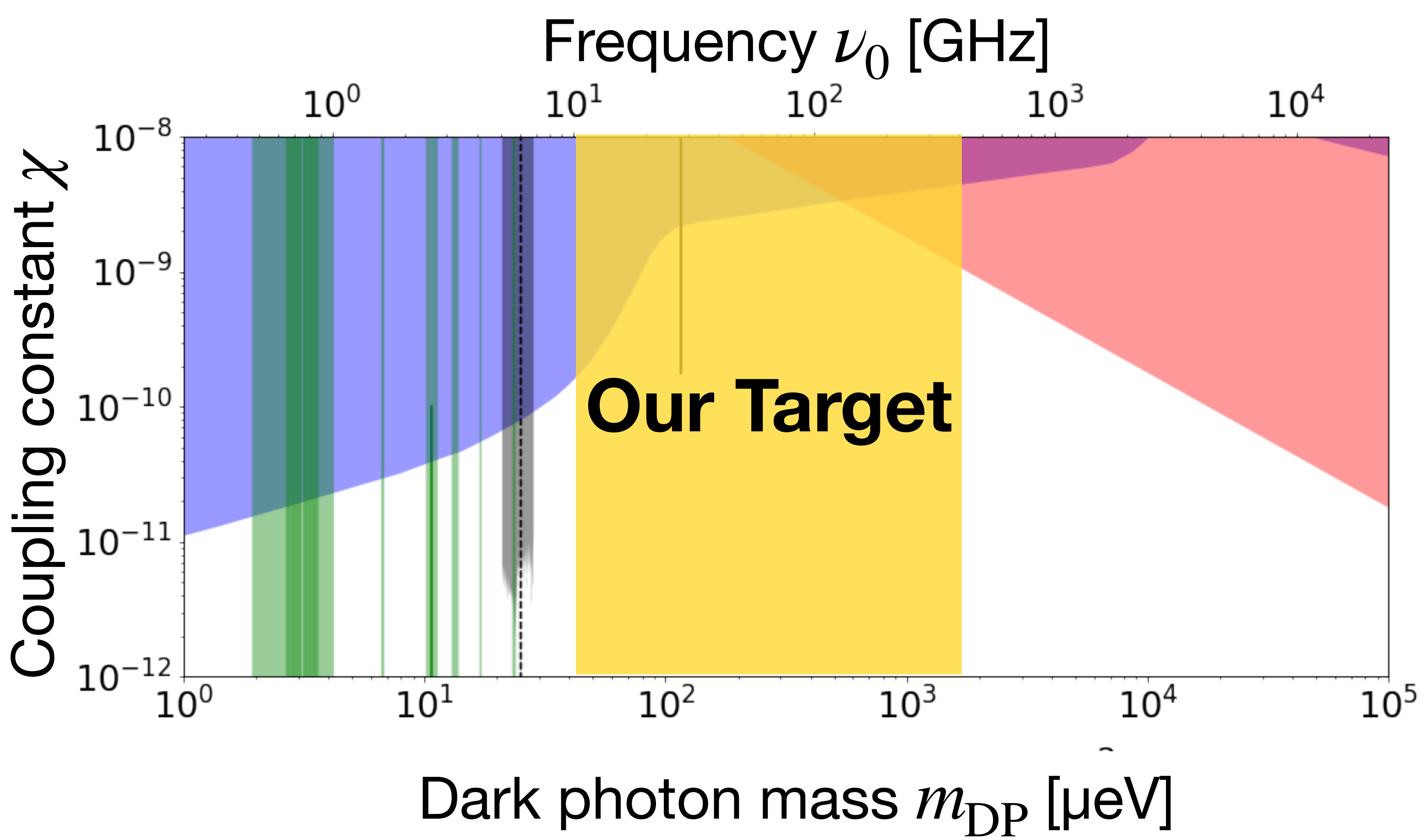

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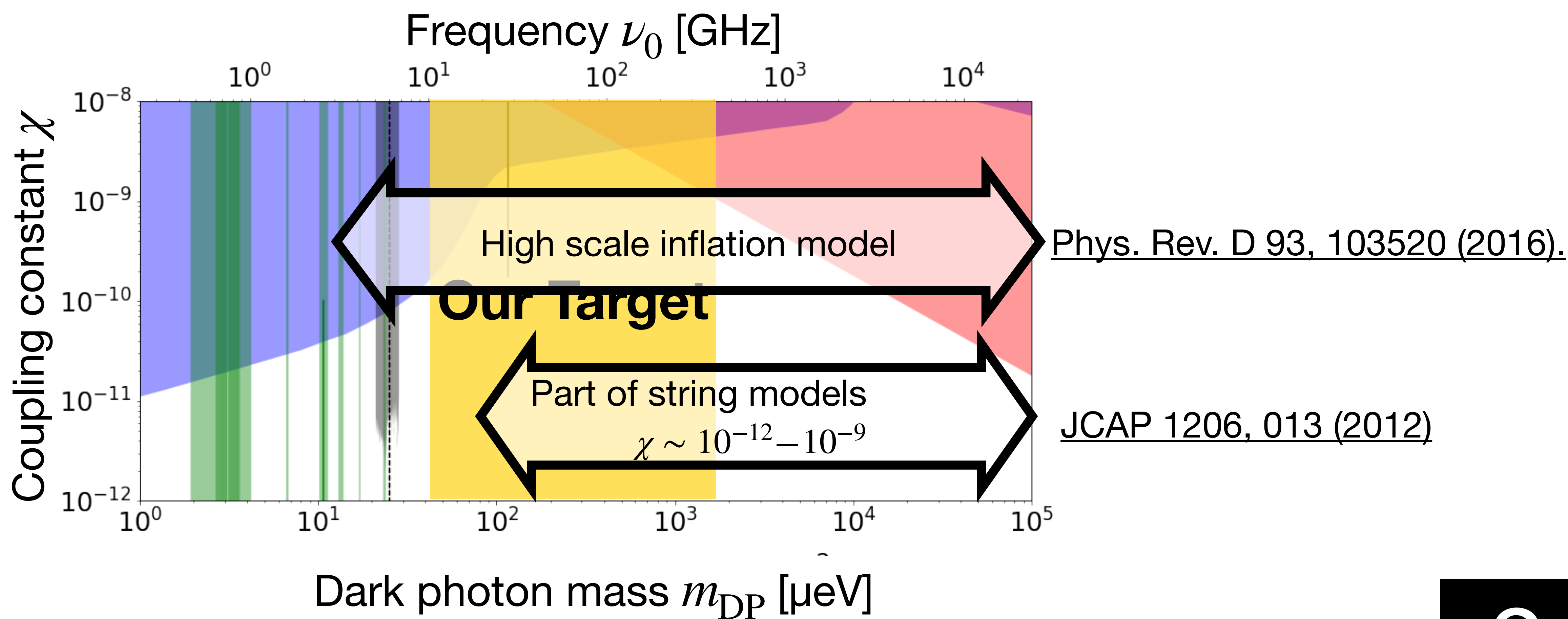
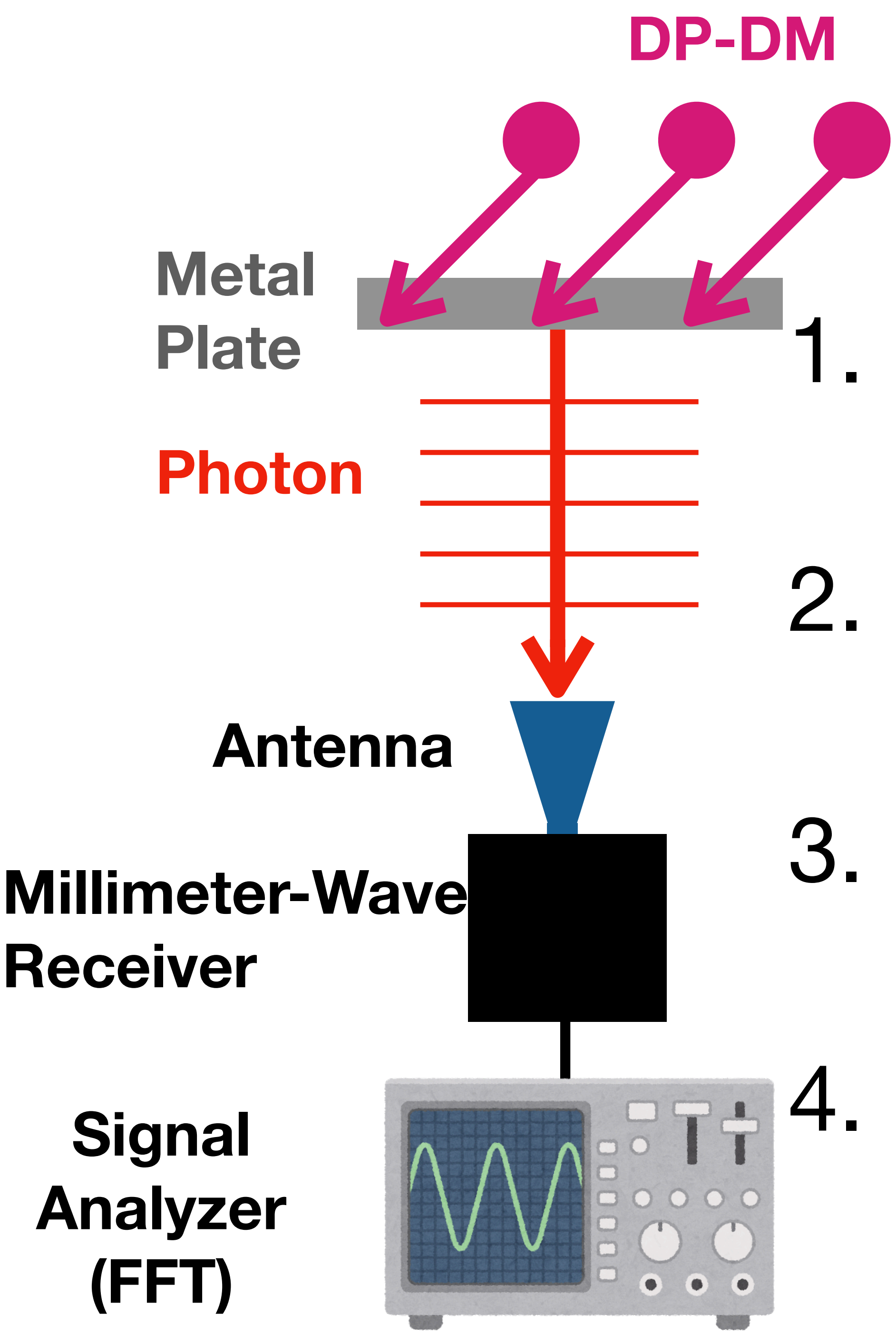


DOSUE-RR: Detection Principle

- Dark-Photon Dark-Matter (DP-DM) search using **millimeter-wave receiver + metal plate**

Dish antenna search: D. Horns et al, JCAP04 (2013) 016

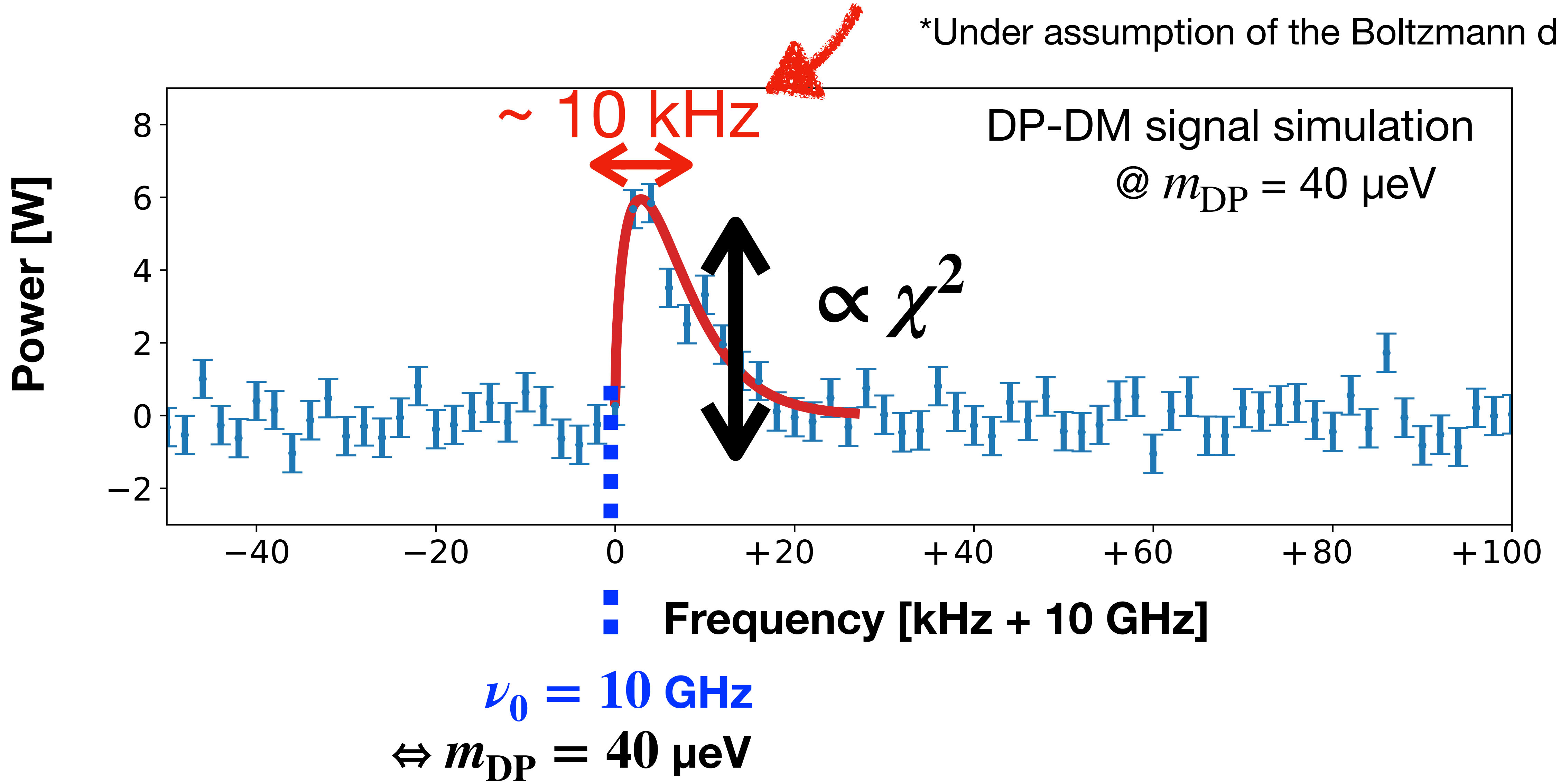


1. DP-DM converts into photons on the metal plate surface (bottom side).
2. Conversion photons travel down **perpendicularly to the plate**
3. We correct the photons with an antenna under the plate and
4. measured them with a signal analyzer as frequency spectra.

Expected Signal

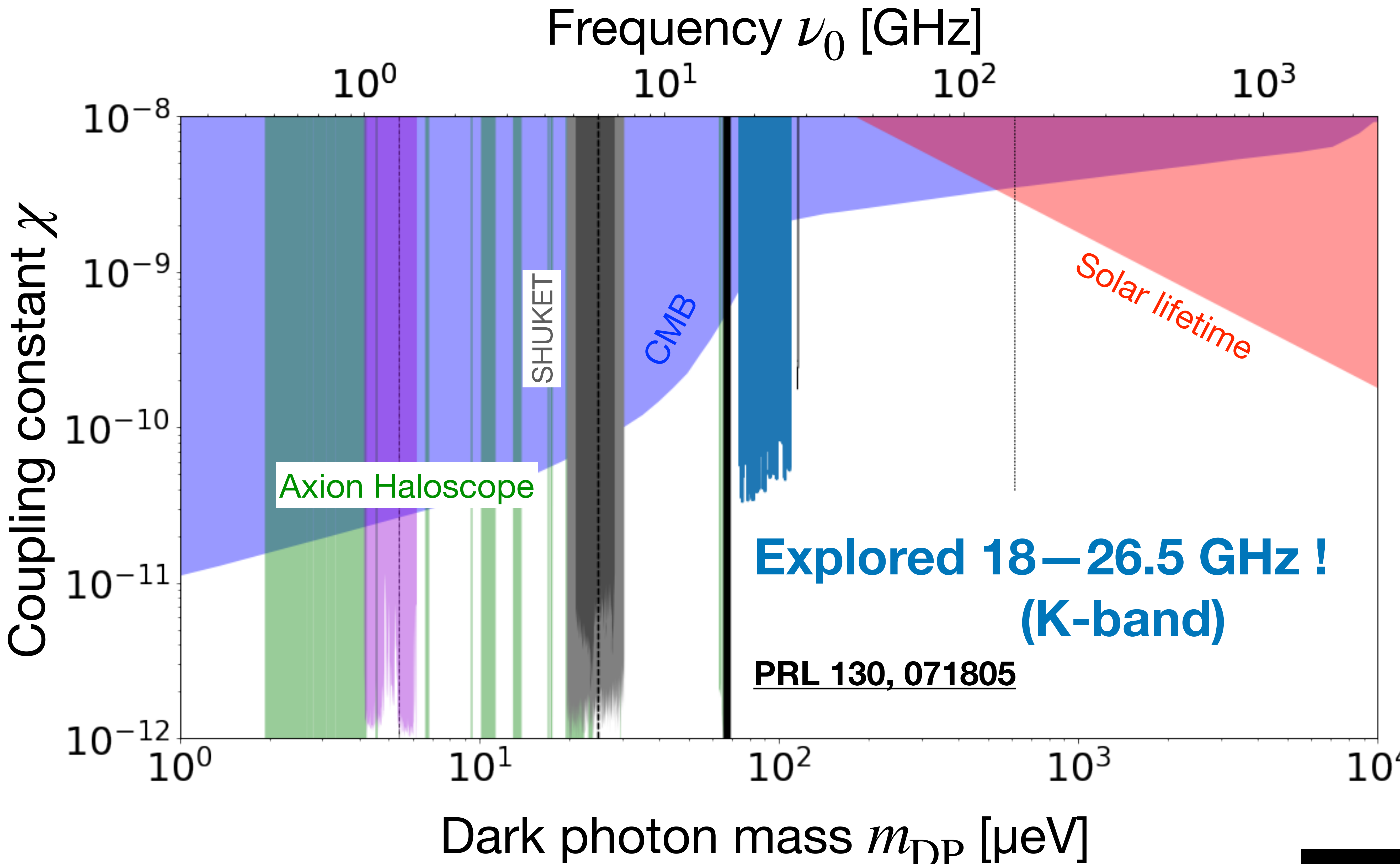
Signal is a narrow frequency peak: $\Delta\nu/\nu_0(=\beta^2) \sim 10^{-6}$

*Under assumption of the Boltzmann distribution



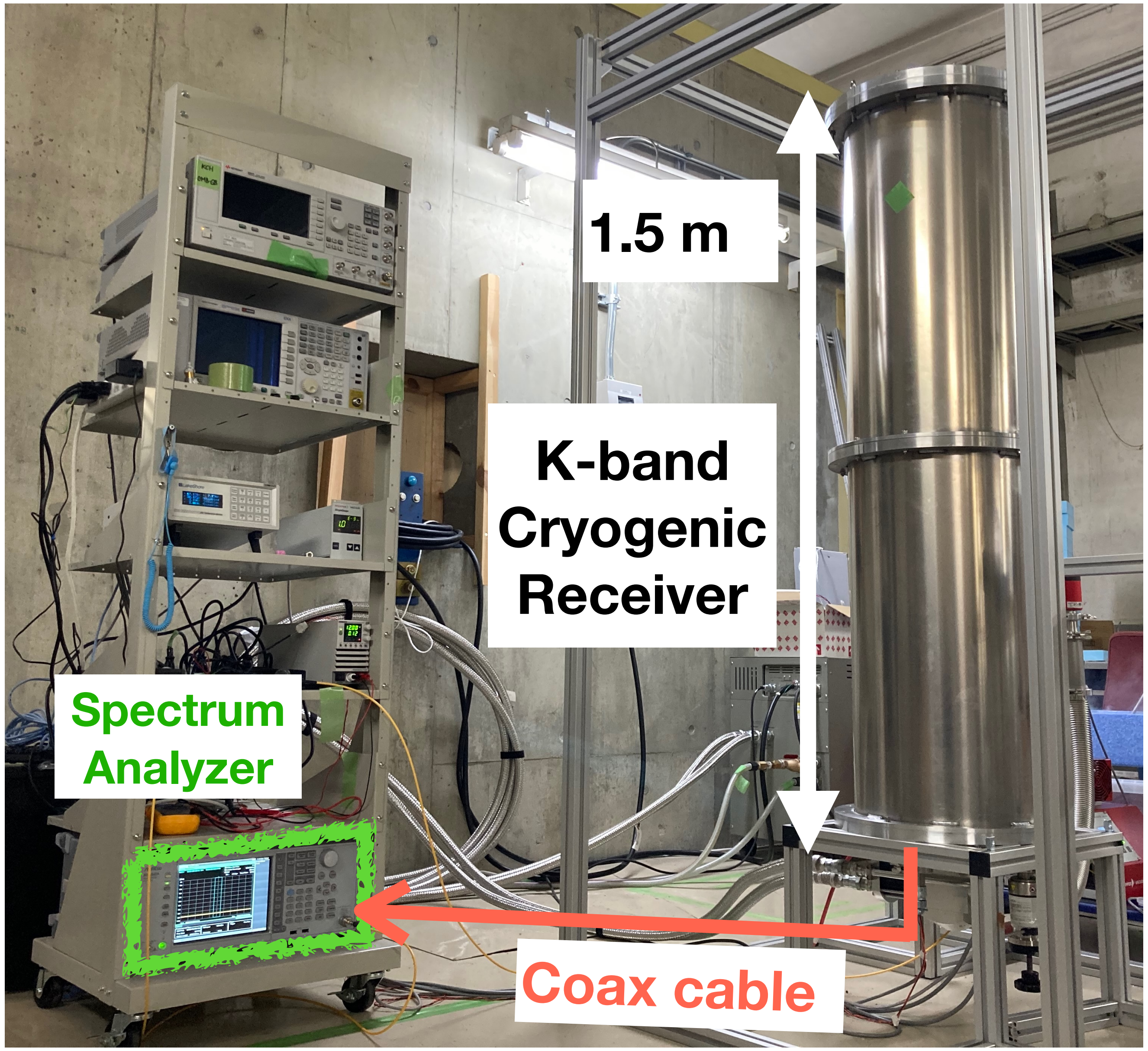
Peak position	$\Leftrightarrow$ Dark photon mass m_{DP}
Peak height	$\Leftrightarrow$ Coupling constant χ

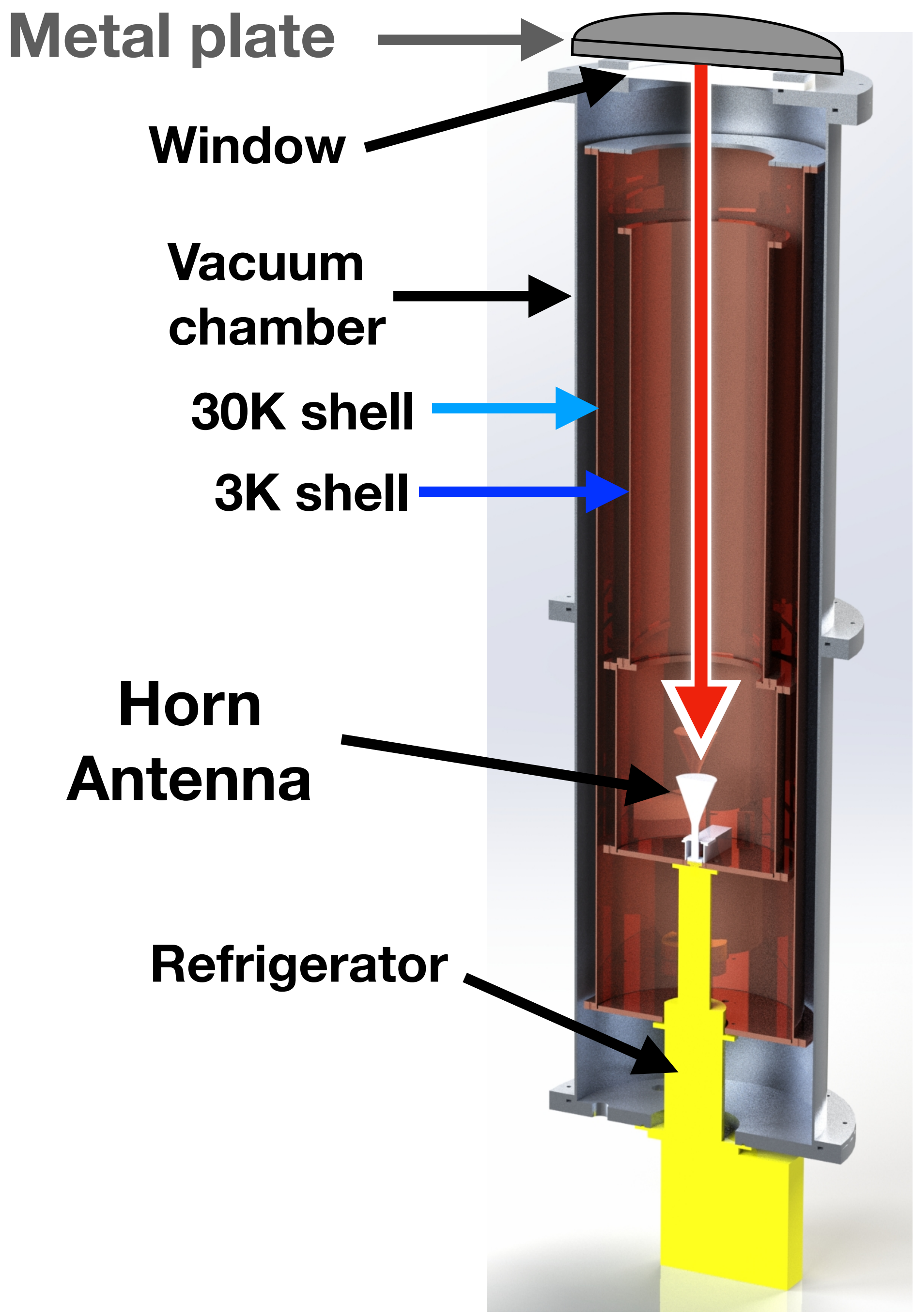
Our 1st Results in 2022



PRL 130, 071805

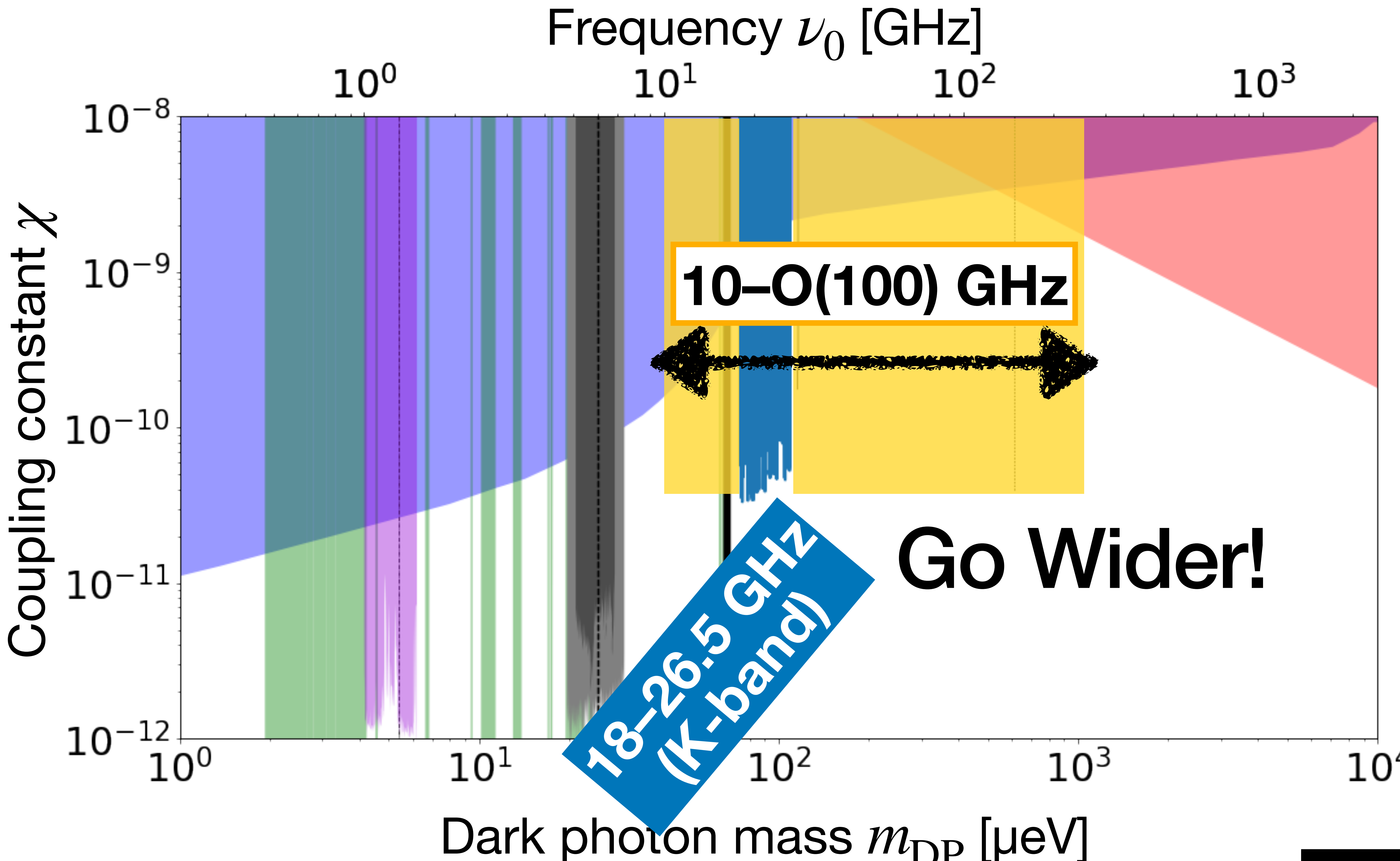
System for 18–26.5 GHz Search





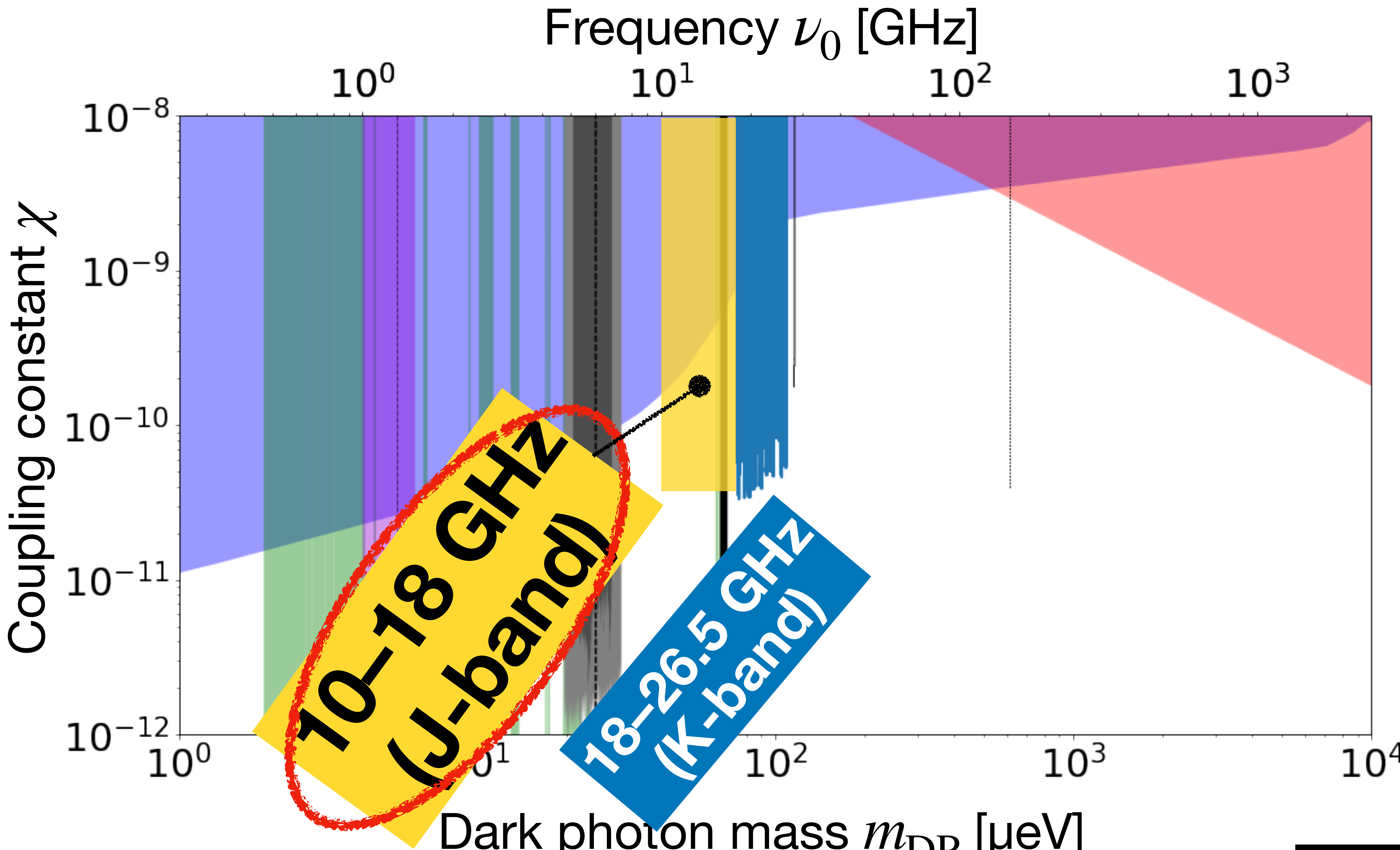
- Cryogenically cooled receiver (3K)
- Search for the conversion photons from the plate outside of the receiver
- Aperture diameter of the horn antenna: ϕ 6 cm

Next Steps

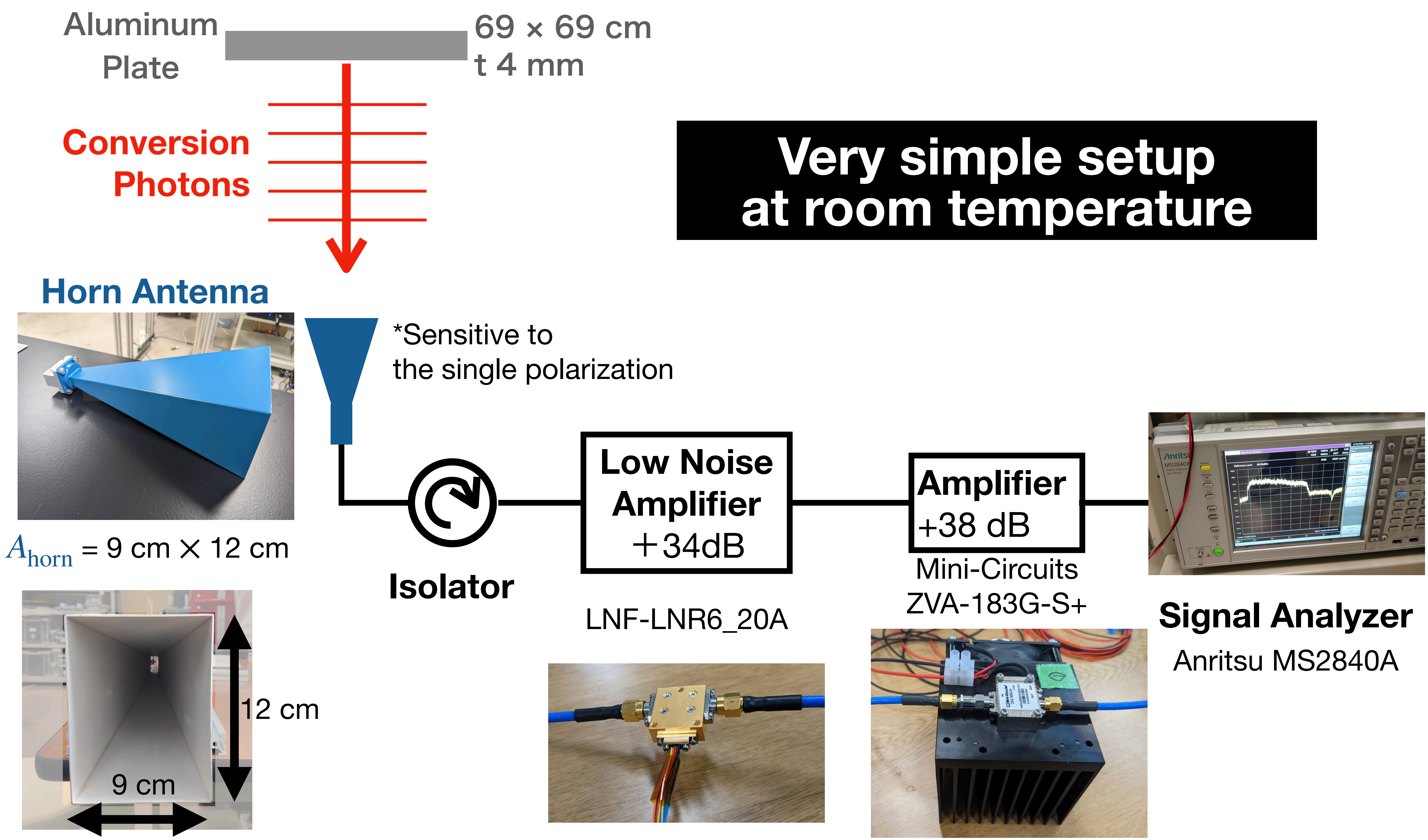


Frequency ν_0 [GHz]
10^0
10^1
10^2
10^3
Coupling constant χ
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10–O(100) GHz
18–26.5 GHz (K-band)
Go Wider!
10^0
10^1
10^2
10^3
10^4
Dark photon mass $m_{\rm DP}$ [μeV]

New Topic Today: 10–18 GHz Search

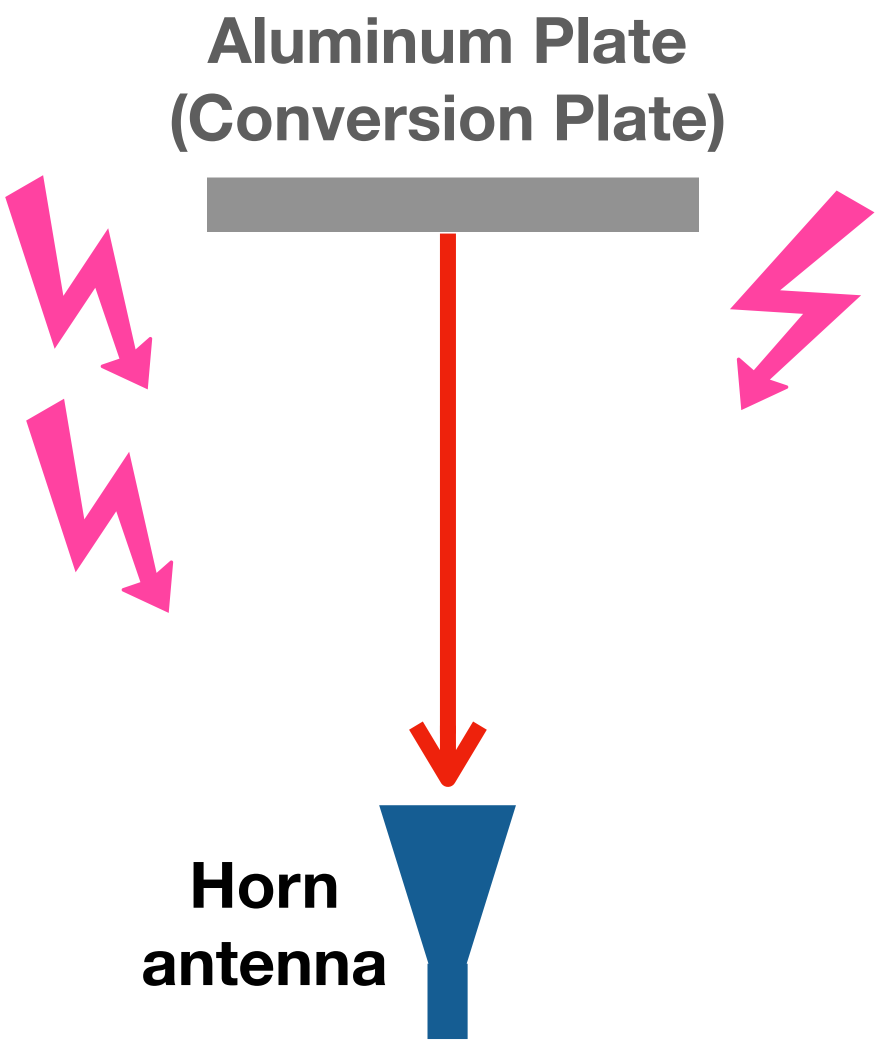


New Receiver for 10–18 GHz (J-band)

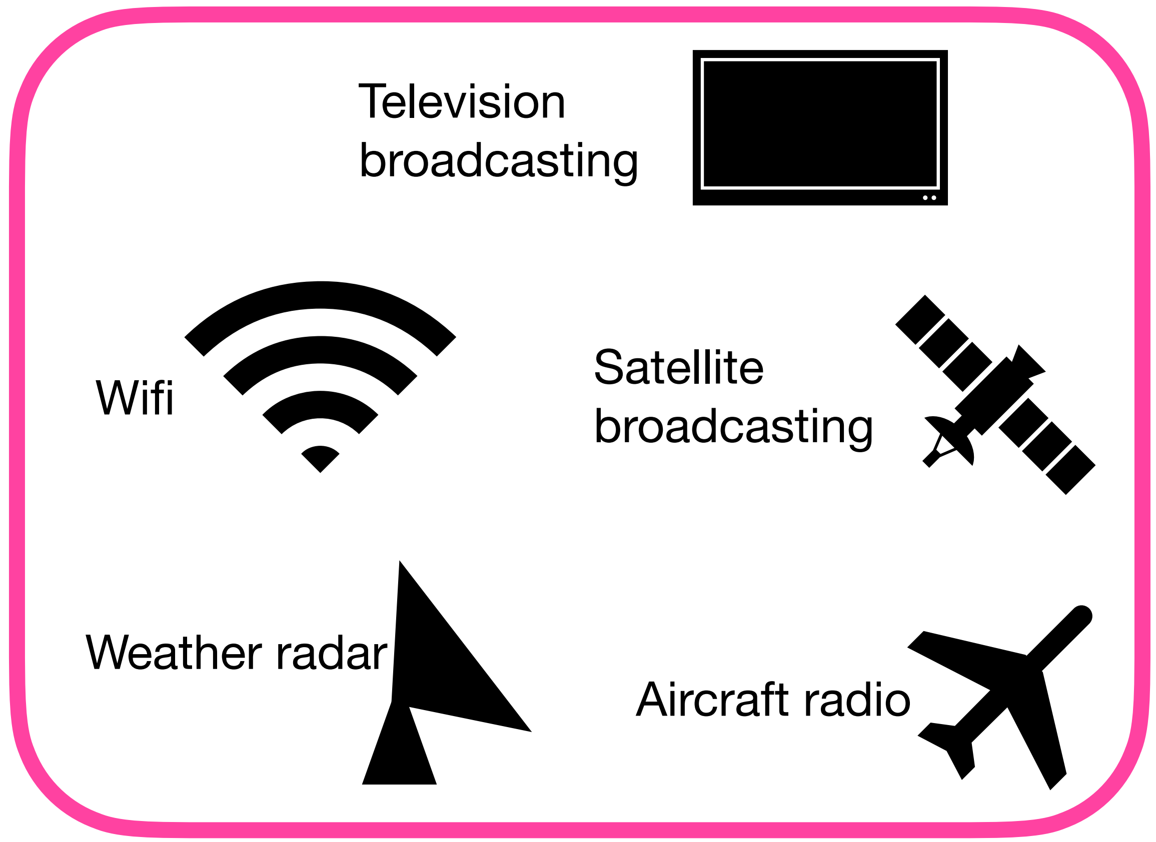


Passing through SMA cables

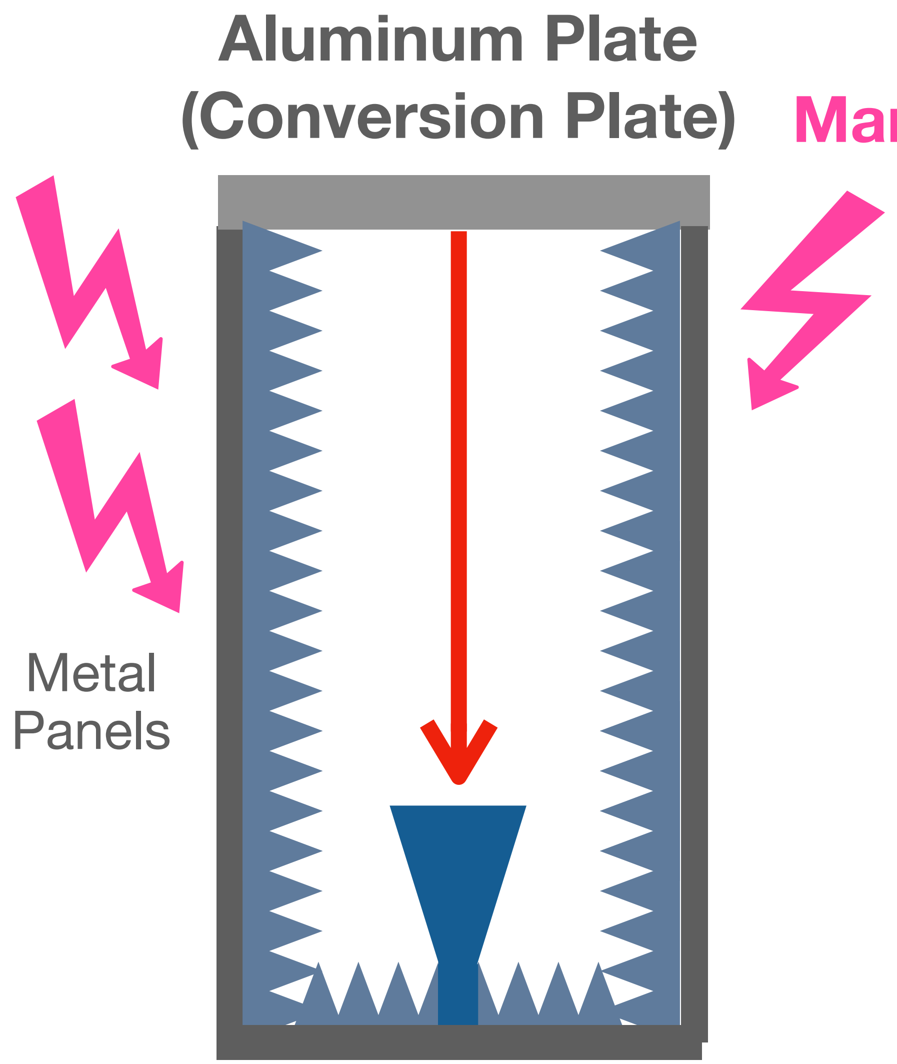
Challenge: Man-made Noises

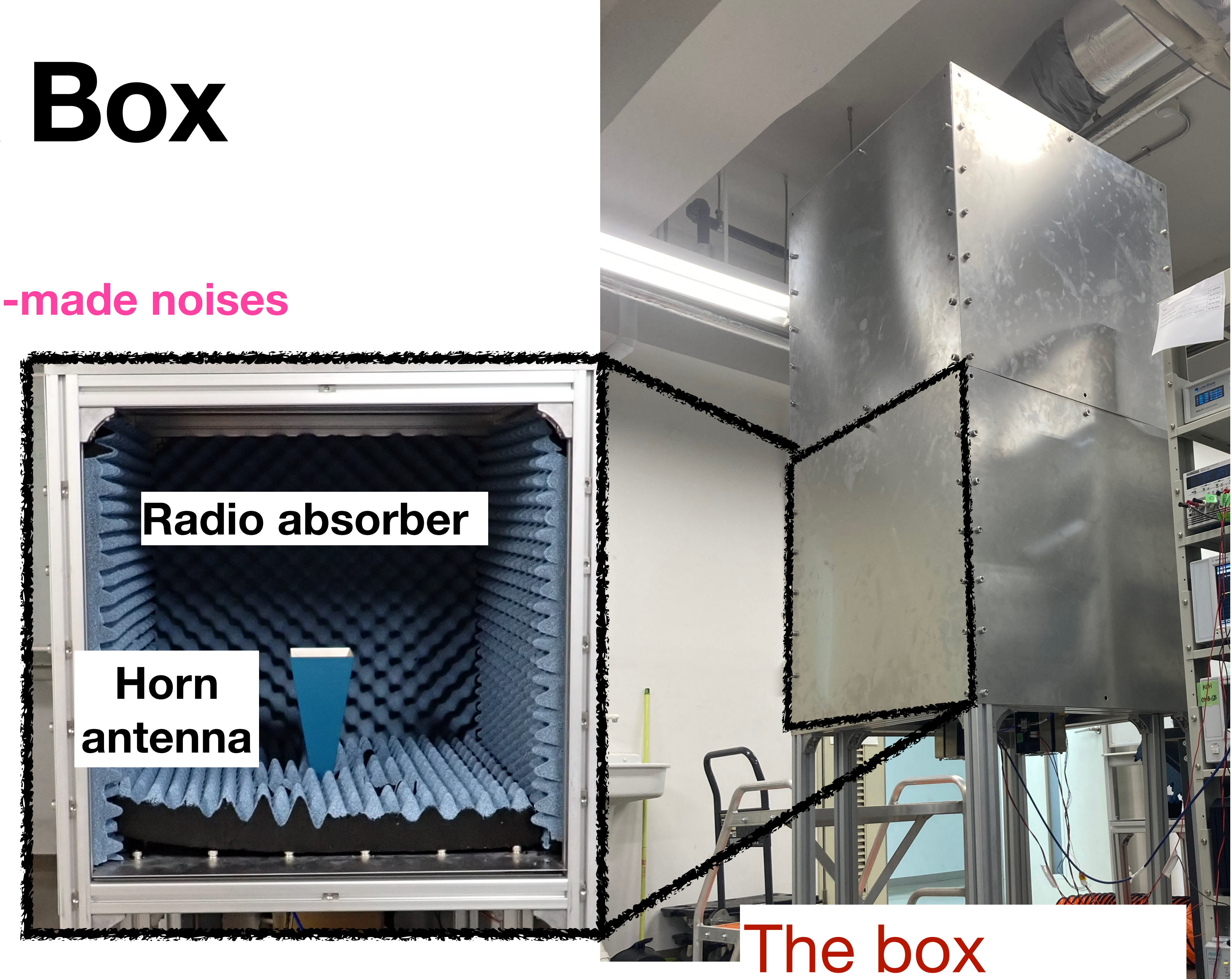


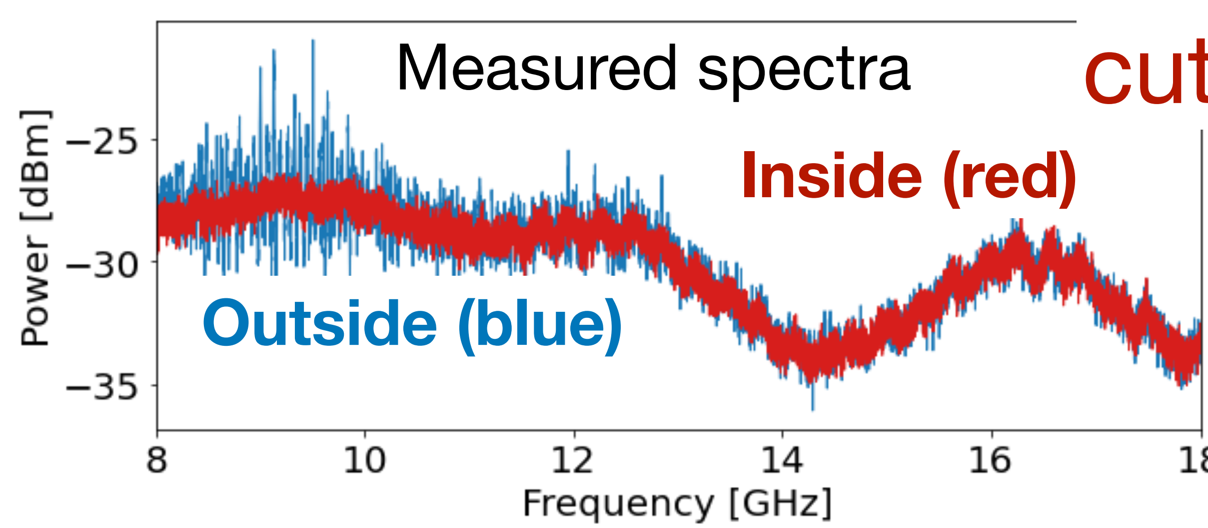
Man-made noises
are serious for our research



Radio Dark Box







Sensitivity and Aperture Area

$$\chi = 1.2 \times 10^{-10} \left(\frac{P_{\rm DP}}{1\,\rm aW} \frac{100\,\rm cm^2}{A_{\rm eff}} \frac{0.4\,\rm GeV/cm^3}{\rho_{\rm DM}} \right)^{1/2}$$

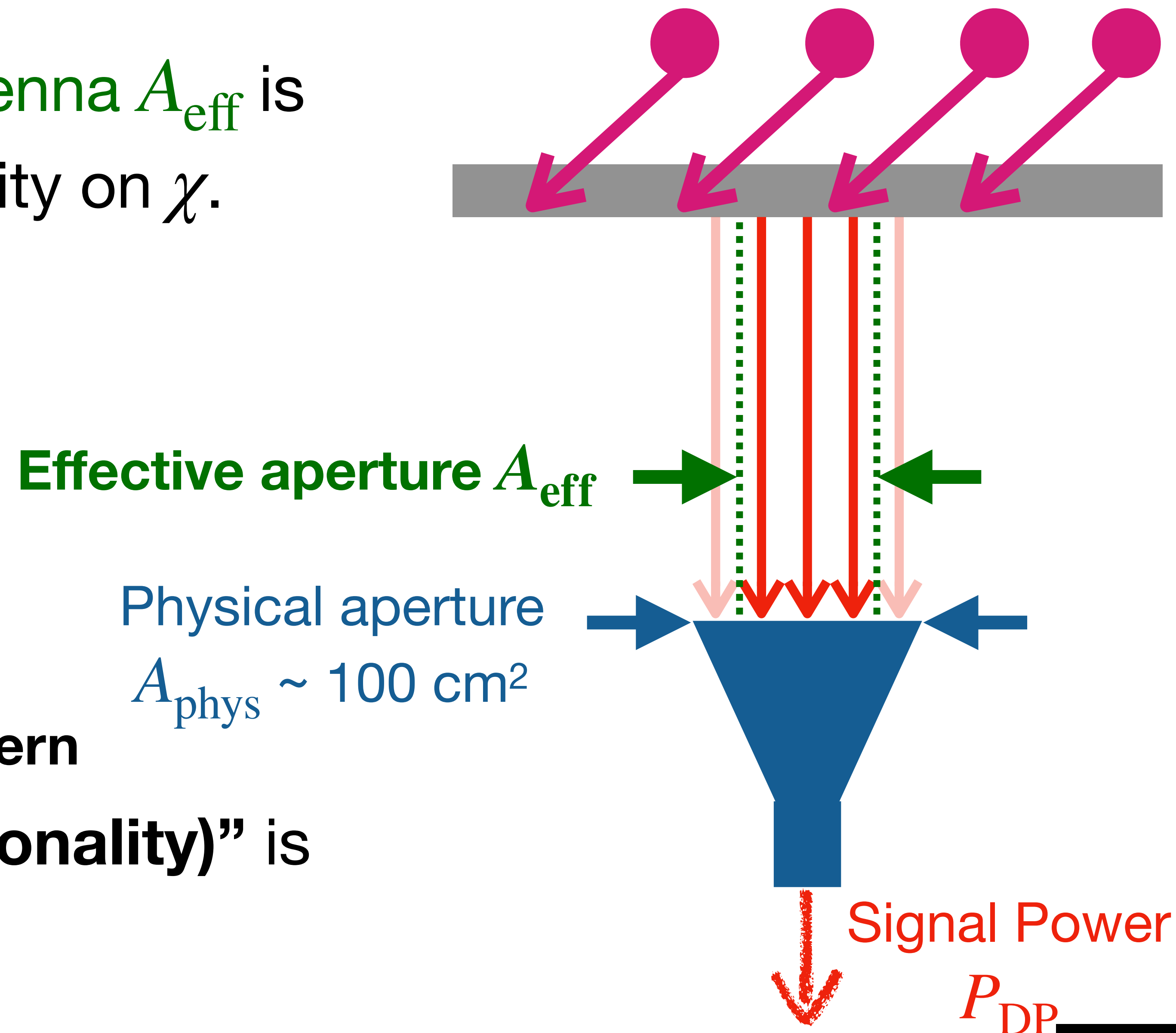
D. Horns et al, JCAP04 (2013) 016

- Effective aperture area of the antenna $A_{\rm eff}$ is important to evaluate the sensitivity on χ.
- $A_{\rm eff}$ is estimated by

$$\begin{cases} A_{\rm eff}\,\Omega = \lambda^2 \\ \Omega \equiv \int d\Omega\, B(\theta,\phi) \,. \end{cases}$$

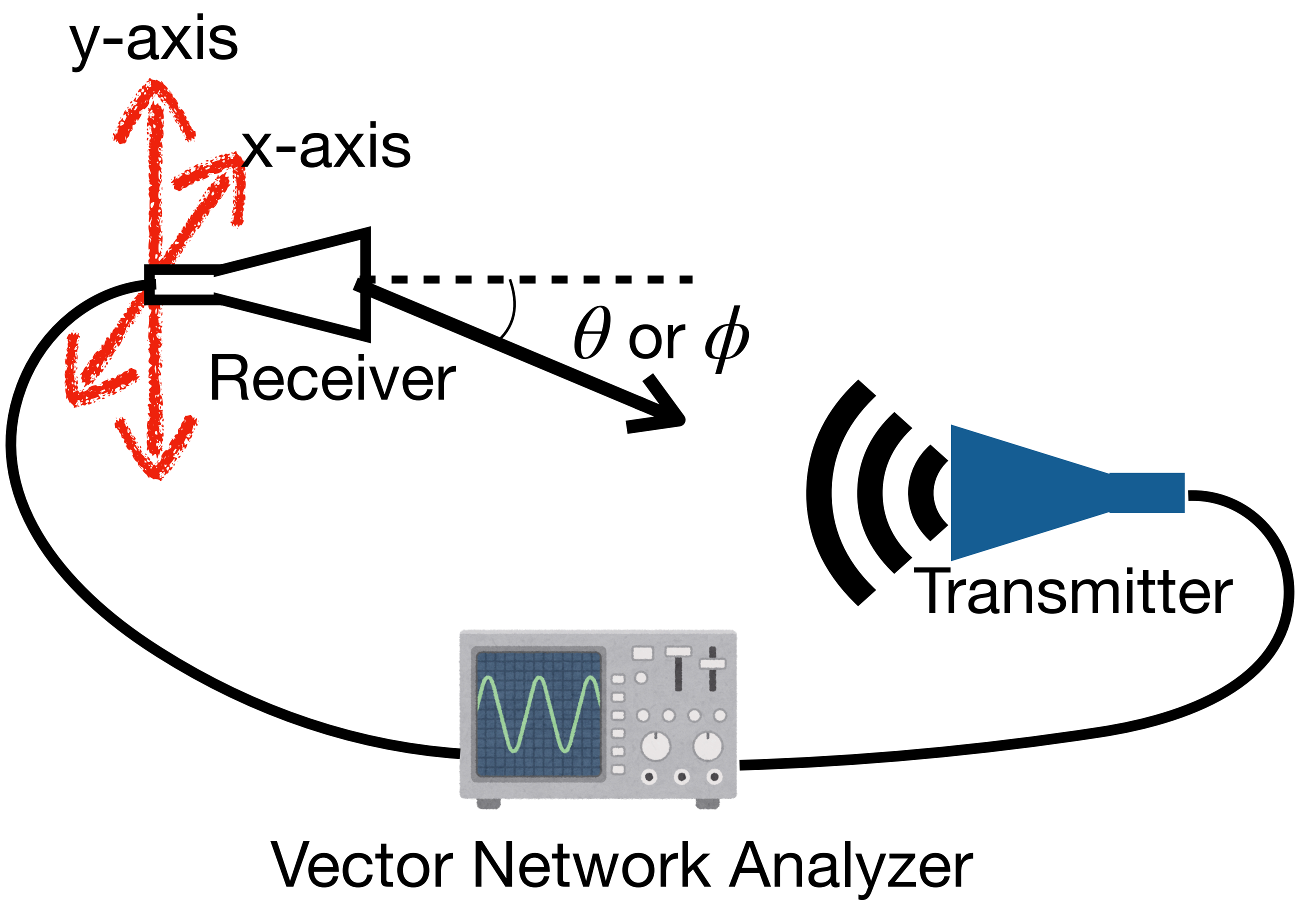
Antenna beam pattern

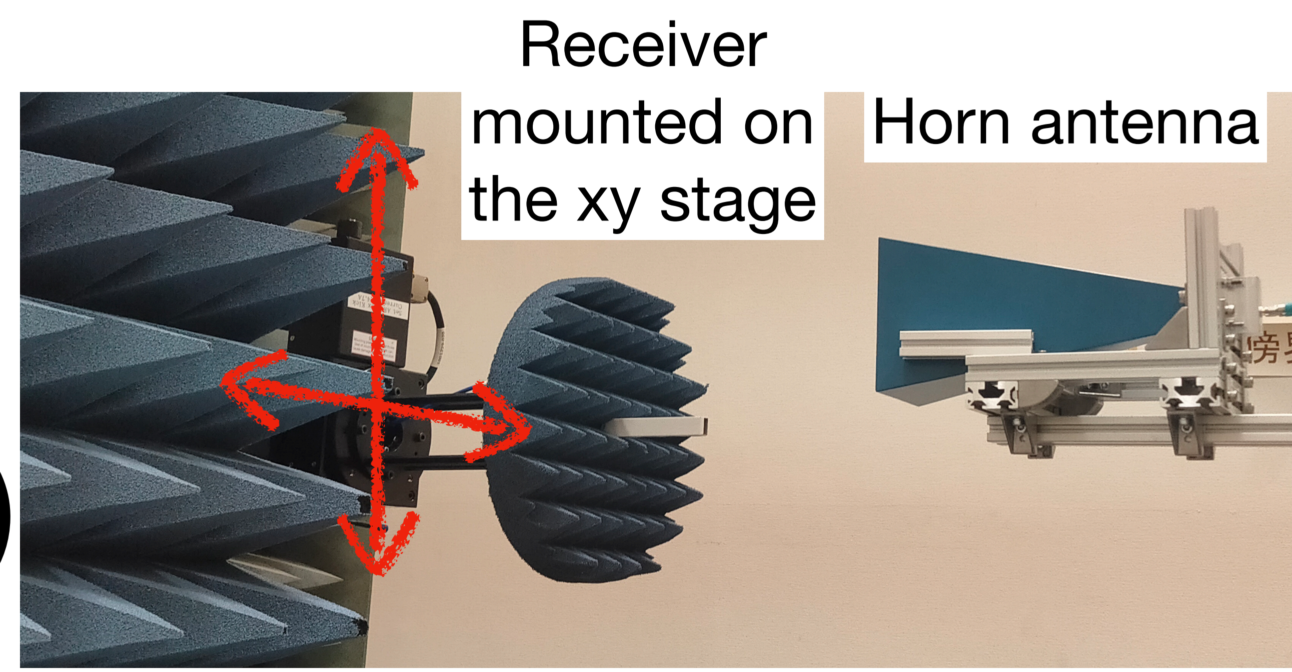
- **"Antenna beam pattern (directionality)"** is needed to evaluate.



Antenna Beam Pattern

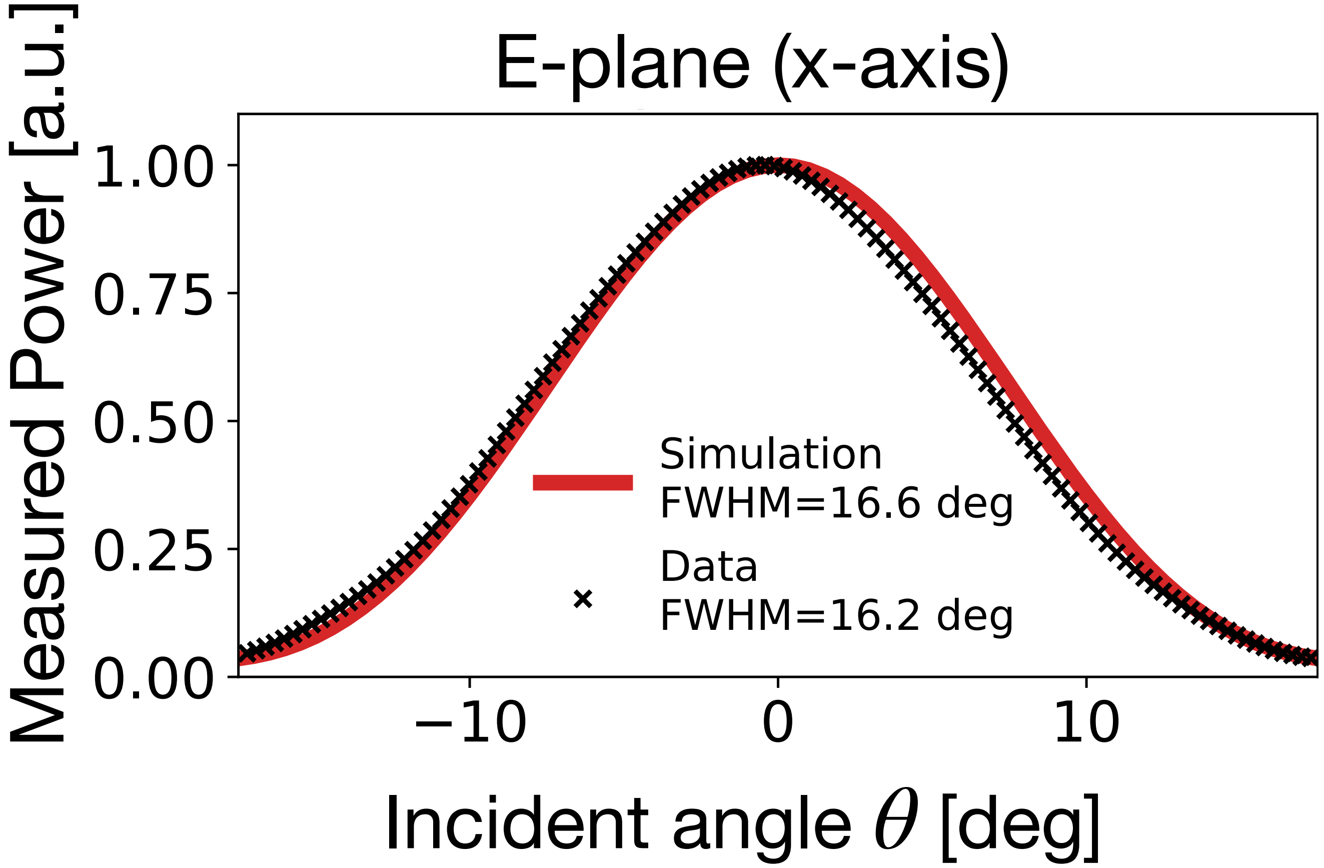
Measured with a NSI near-field antenna measurement system at the Microwave Energy Transmission Lab. in Kyoto U

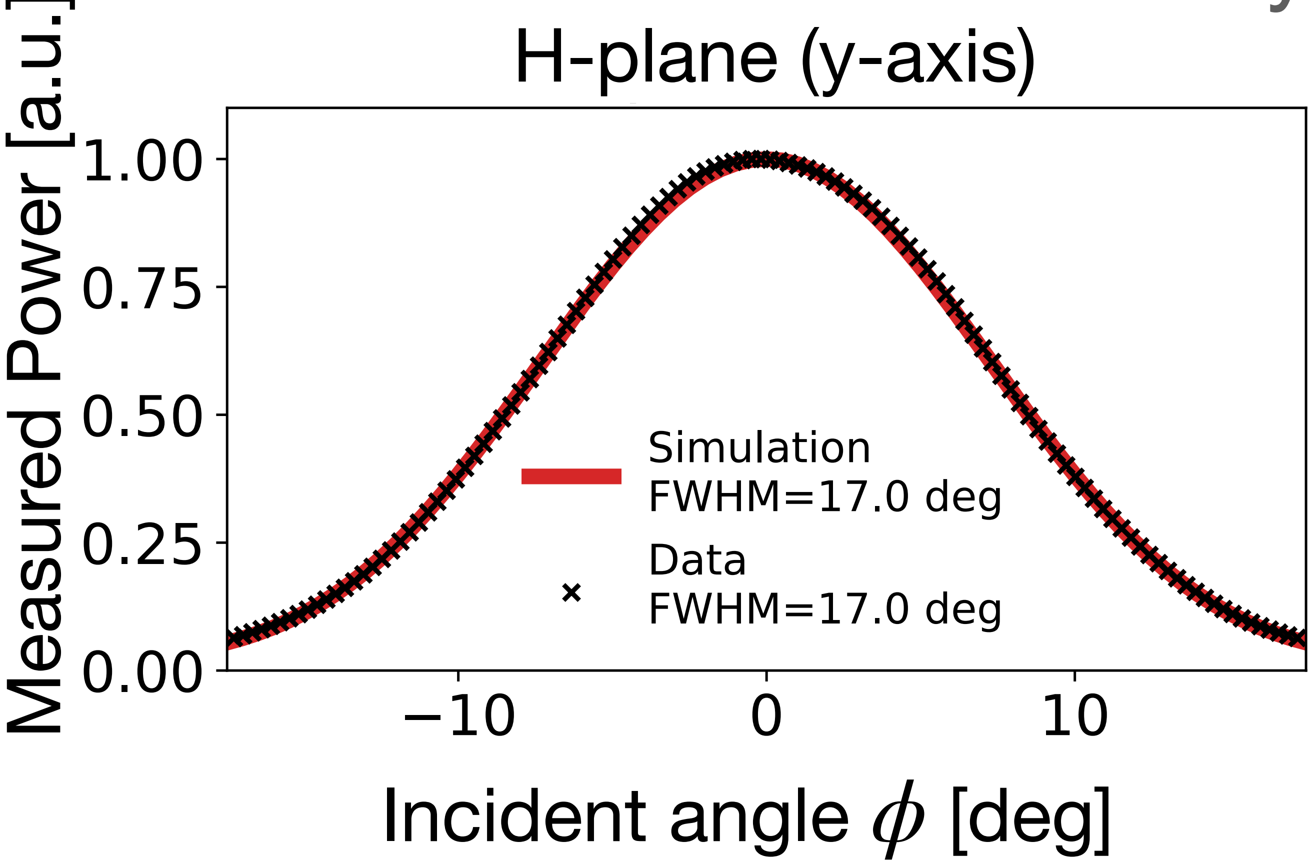




Antenna Beam Pattern

* Preliminary

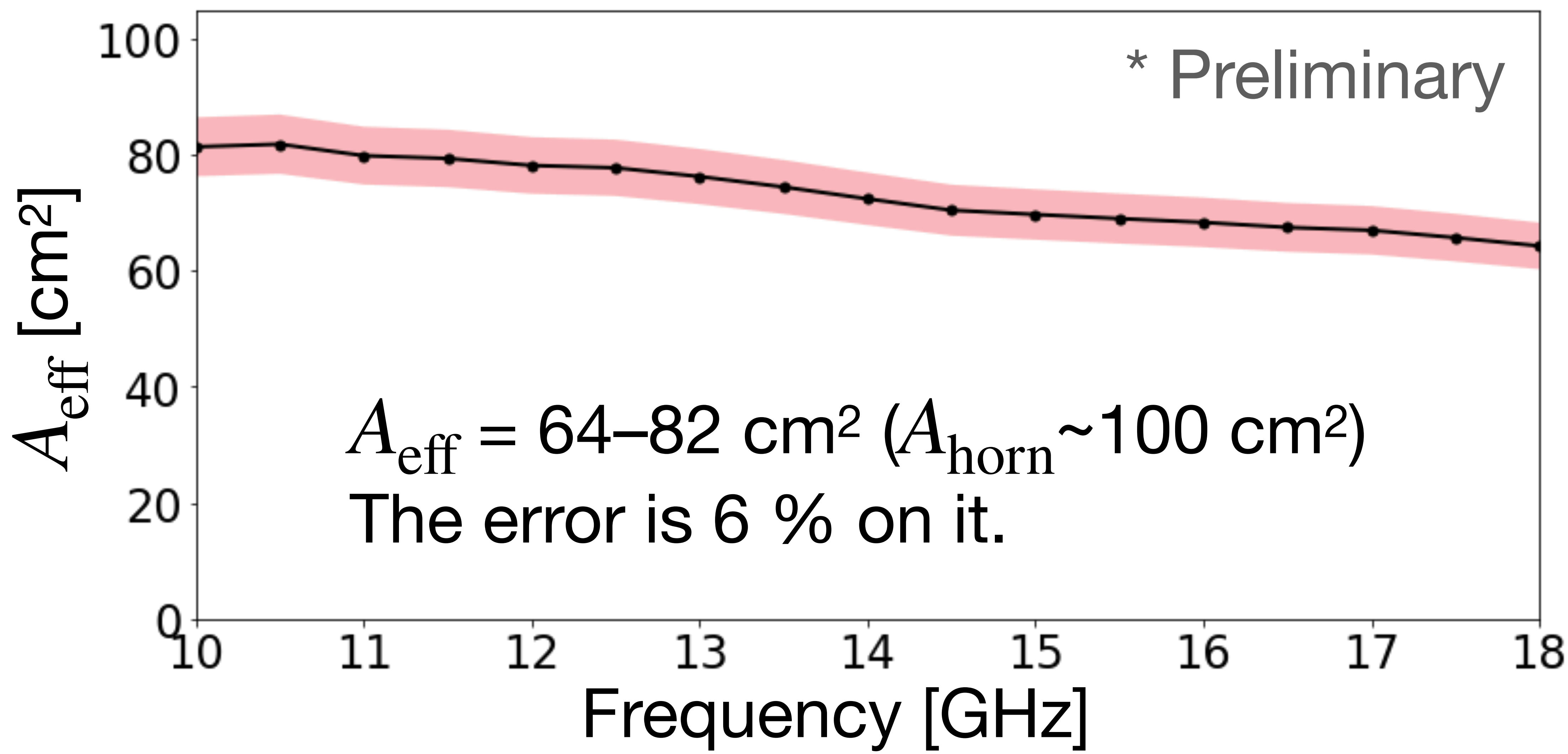




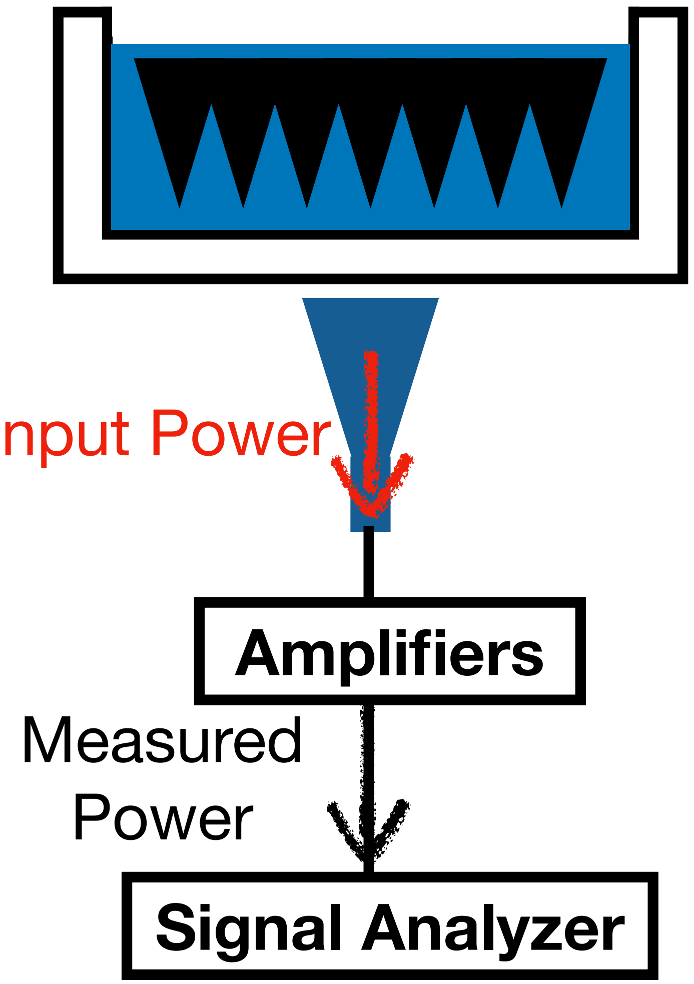
- Also simulated the beam pattern with ANSYS-HFSS
- The discrepancy is taken into account as a systematics error.

Effective Aperture Area A_{eff}

- A_{eff} was estimated from the ANSYS-HFSS simulation.
- The error band is derived from the discrepancy in the beam pattern measurement.



Gain Calibration (Hot & Cold)

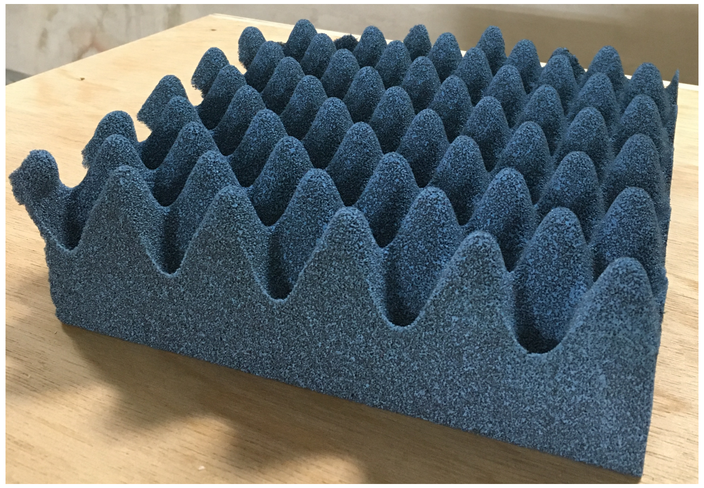


Two blackbody radiation sources

1. Liquid N_2 temperature (77K)
2. Room temperature (300K)

Liquid N_2 bath (77K)

Blackbody radiation source @ room temperature (300K)

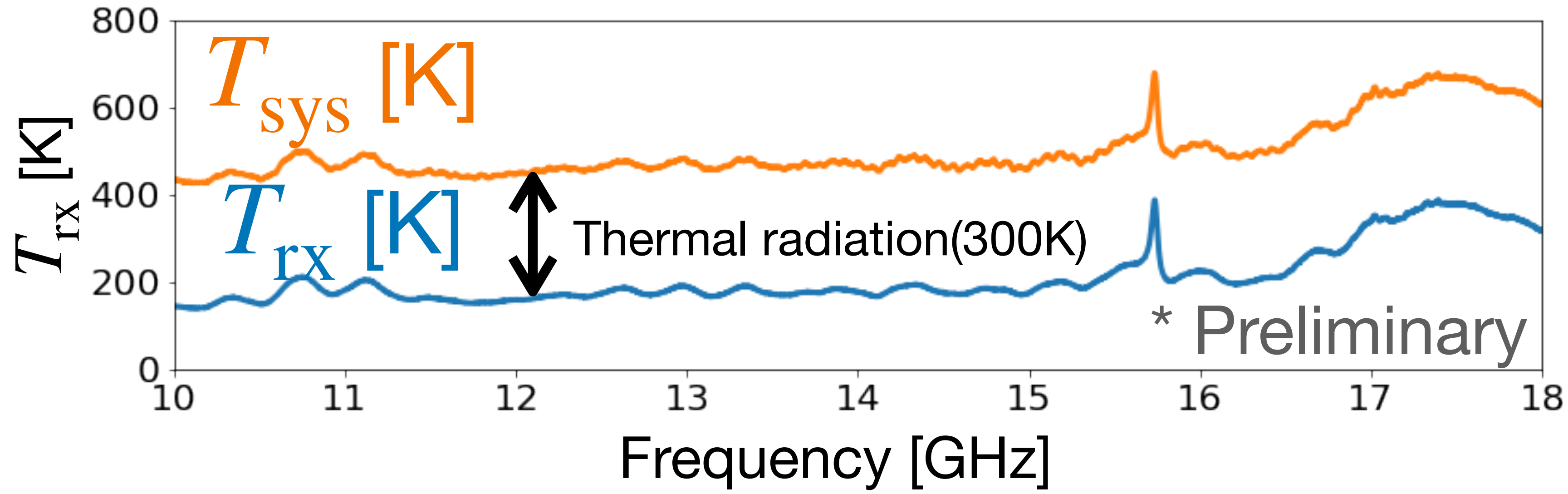


G ~ +60 dB

T_{rx} = 200–400 K

*G: Gain of the receiver

*T_{rx}: Receiver noise temperature



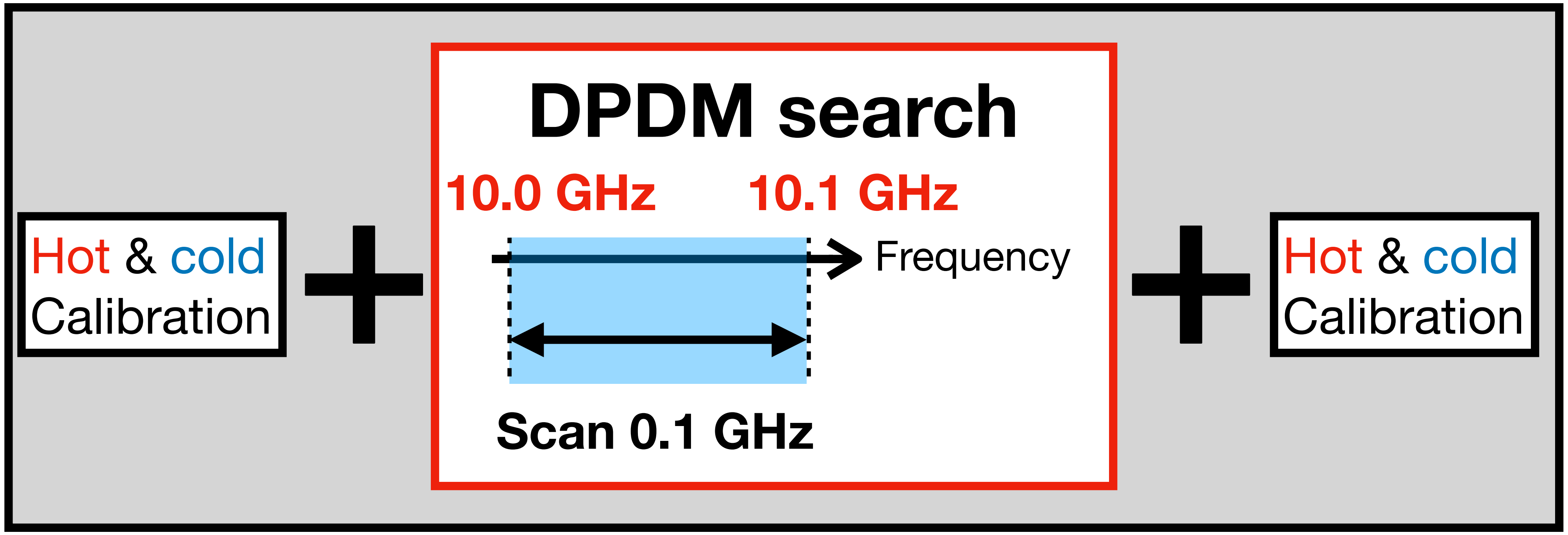
*T_{sys} is calculated from the measured spectrum for the search.

Search Measurement

Frequency bandwidth is 2 MHz at one measurement due to the capability of the signal analyzer.

- Scan frequency range: **10.0–18.0 GHz**
- Measurement time: **24 sec** at each frequency

One measurement cycle (~40 min)



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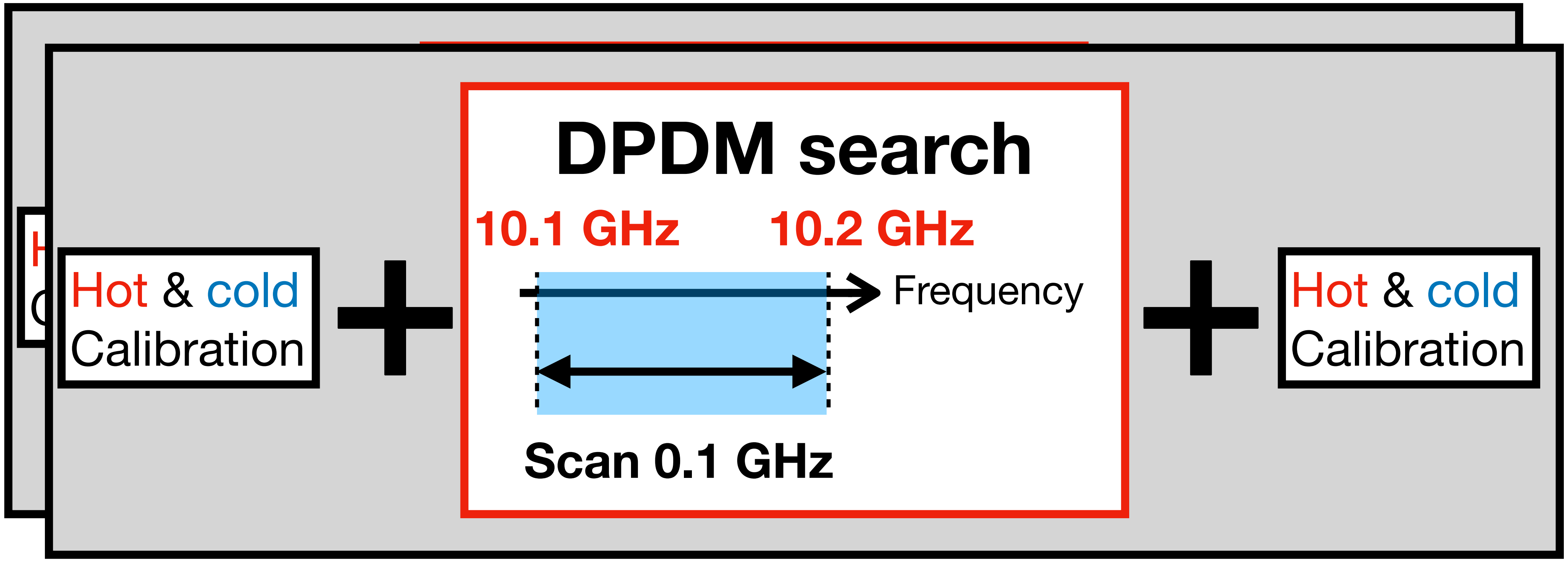

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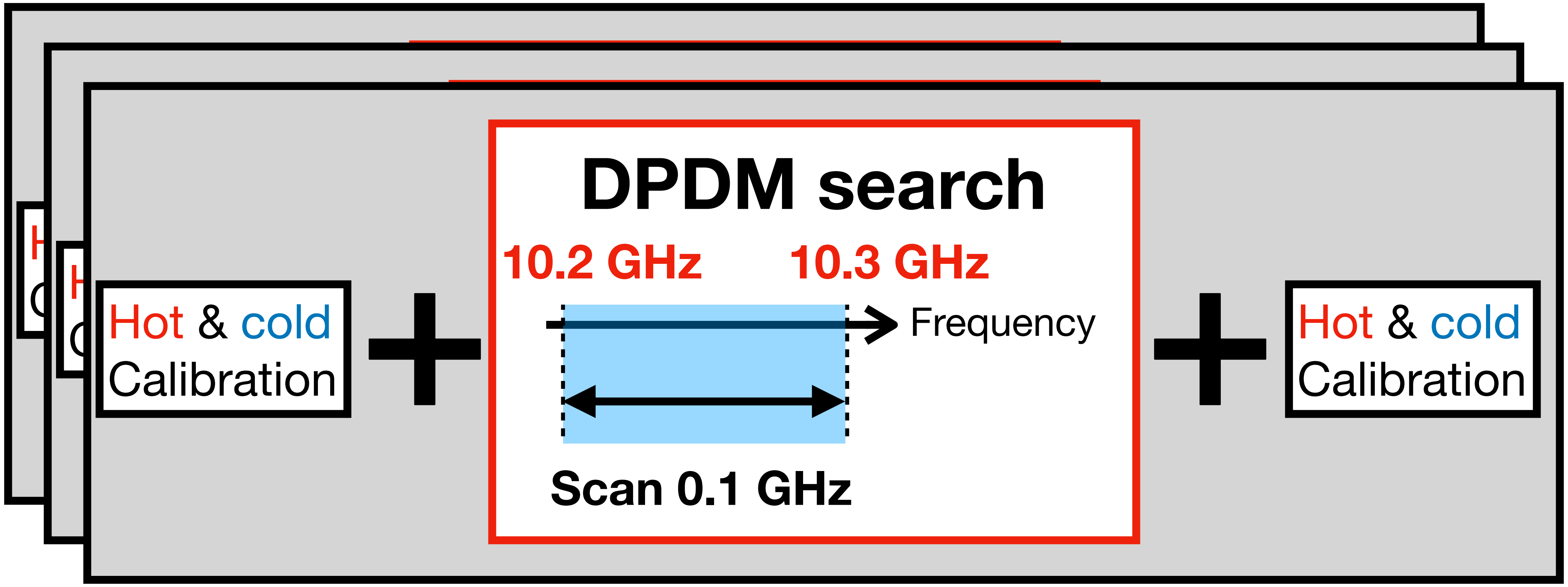

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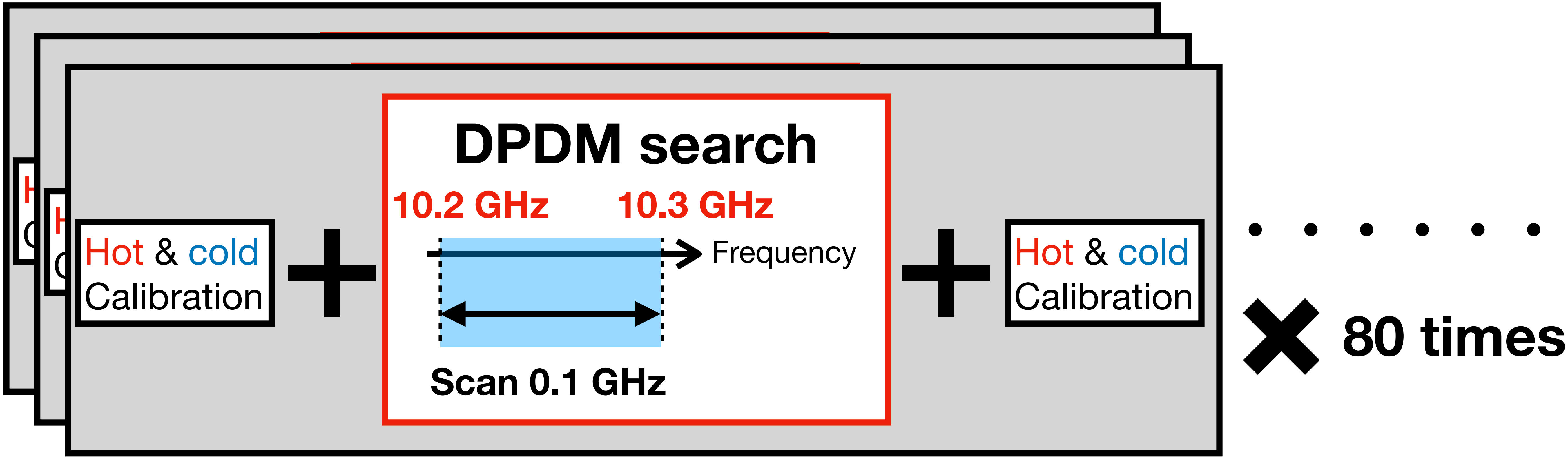

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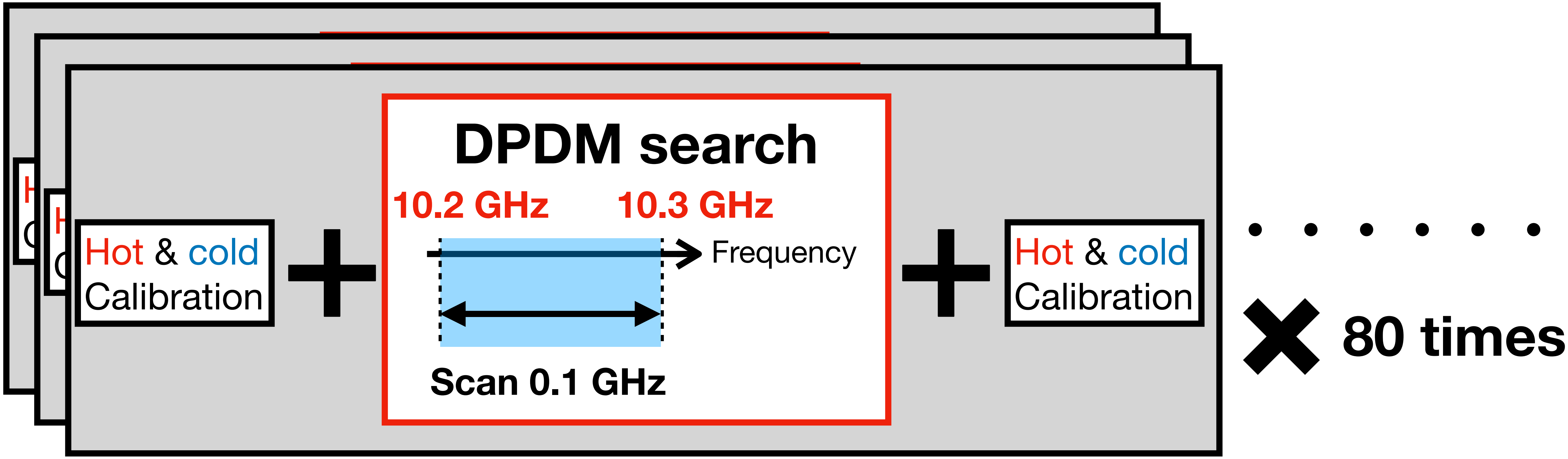
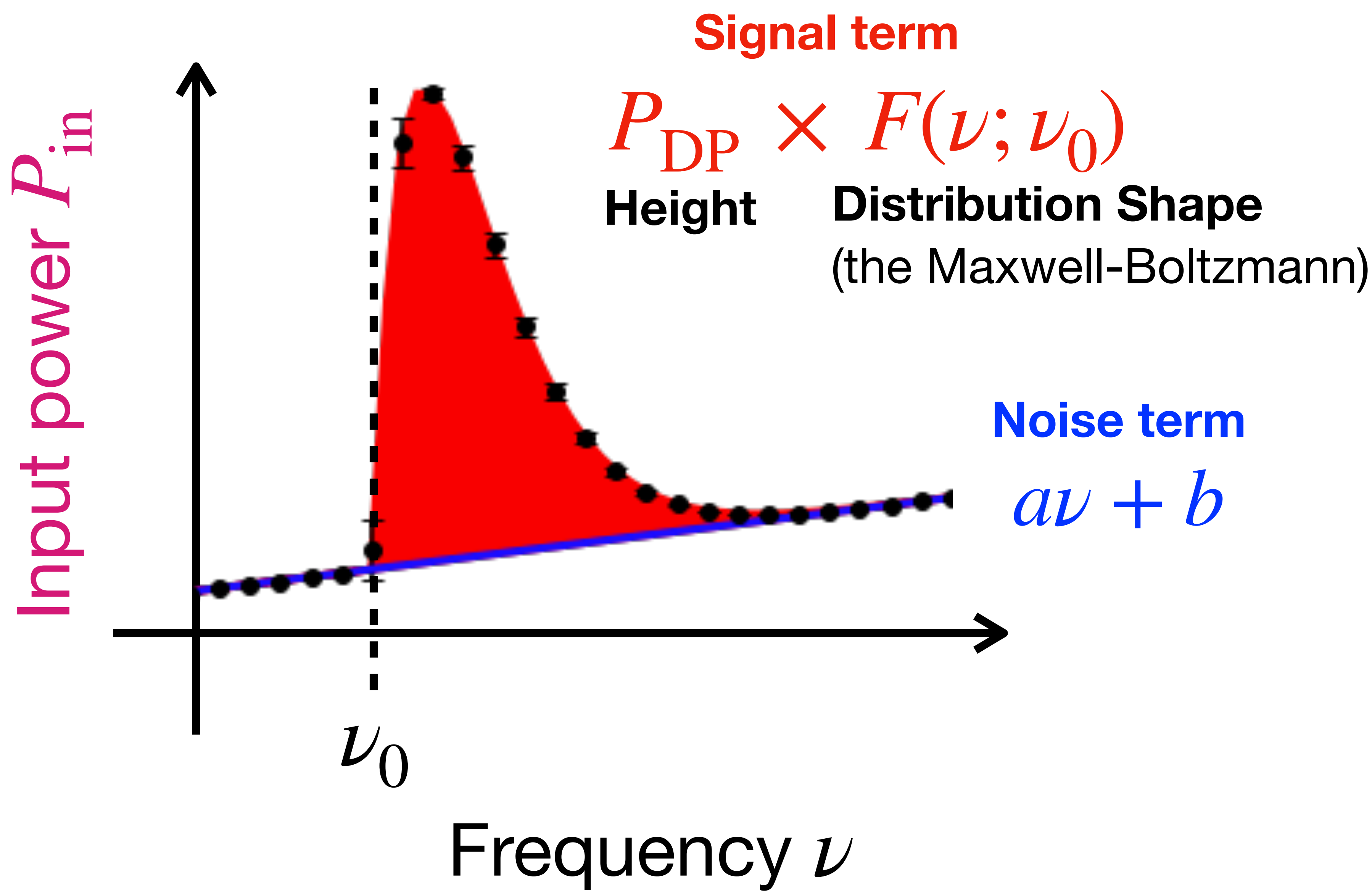


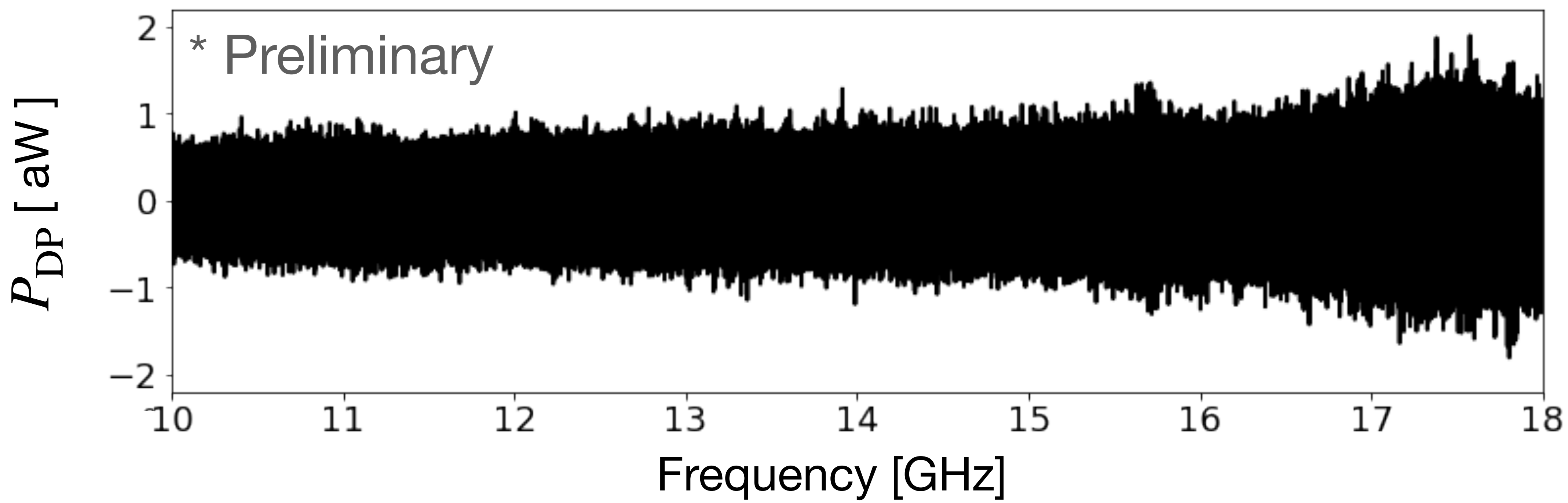
Date: 6–17 March in 2023 **(Observed for 9 days)**

Signal Extraction (Fitting)

- Fit to $P_{\mathrm{in}}(\nu)$ by the formula: $P_{\mathrm{DP}} \times F(\nu;\nu_0) + a\nu + b$
- Three free parameters: P_{DP}, a, b



Extracted signal powers: P_{DP}



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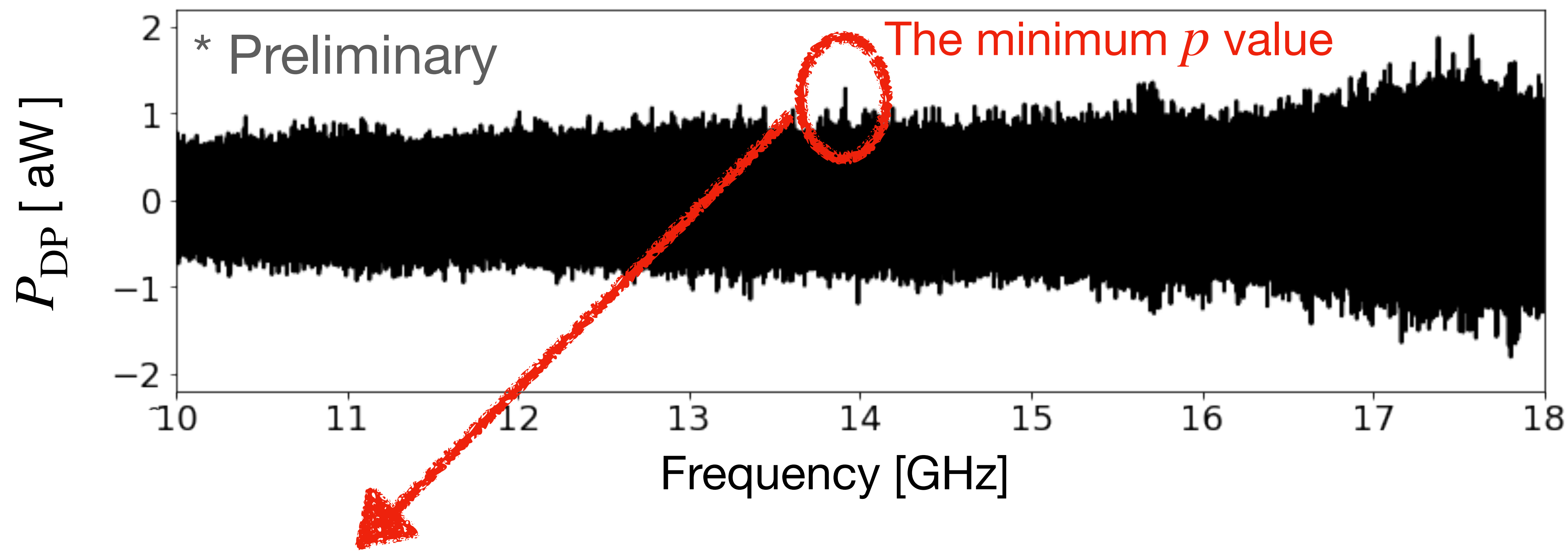
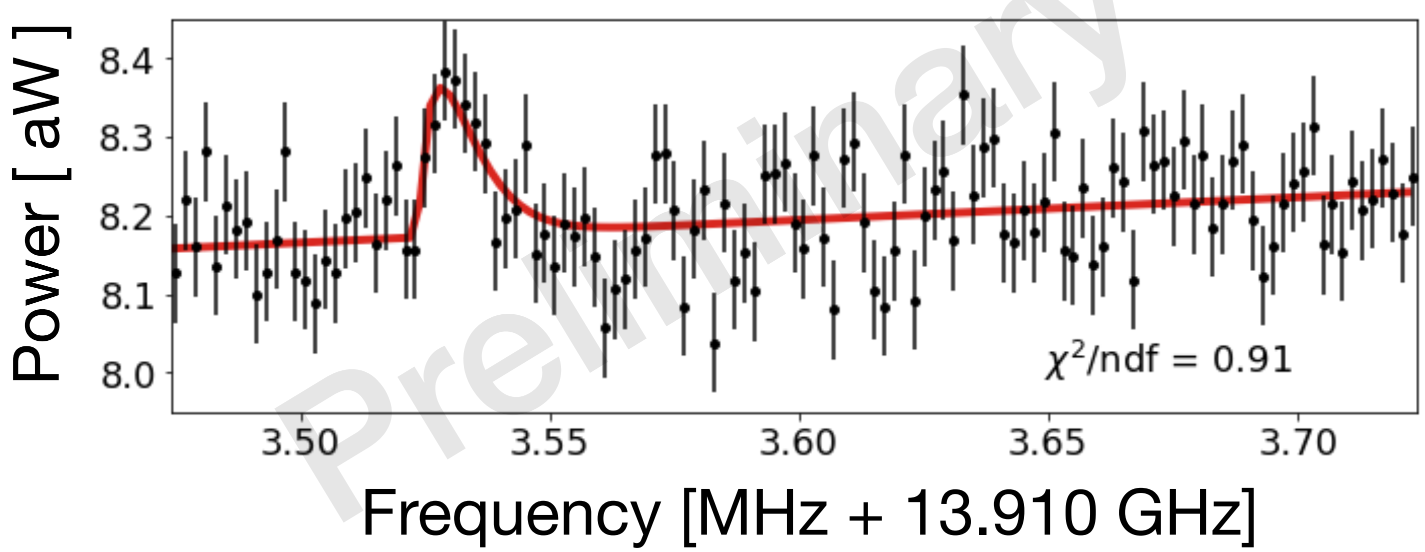


Fitting at 13.91352 GHz



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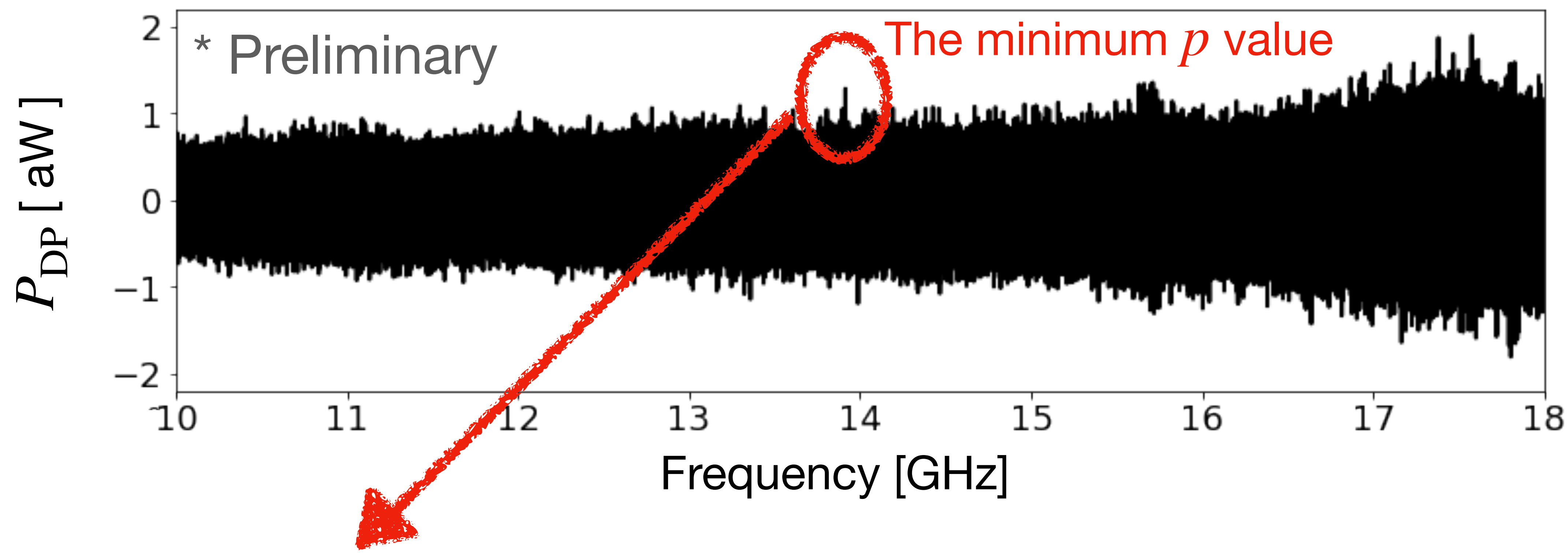

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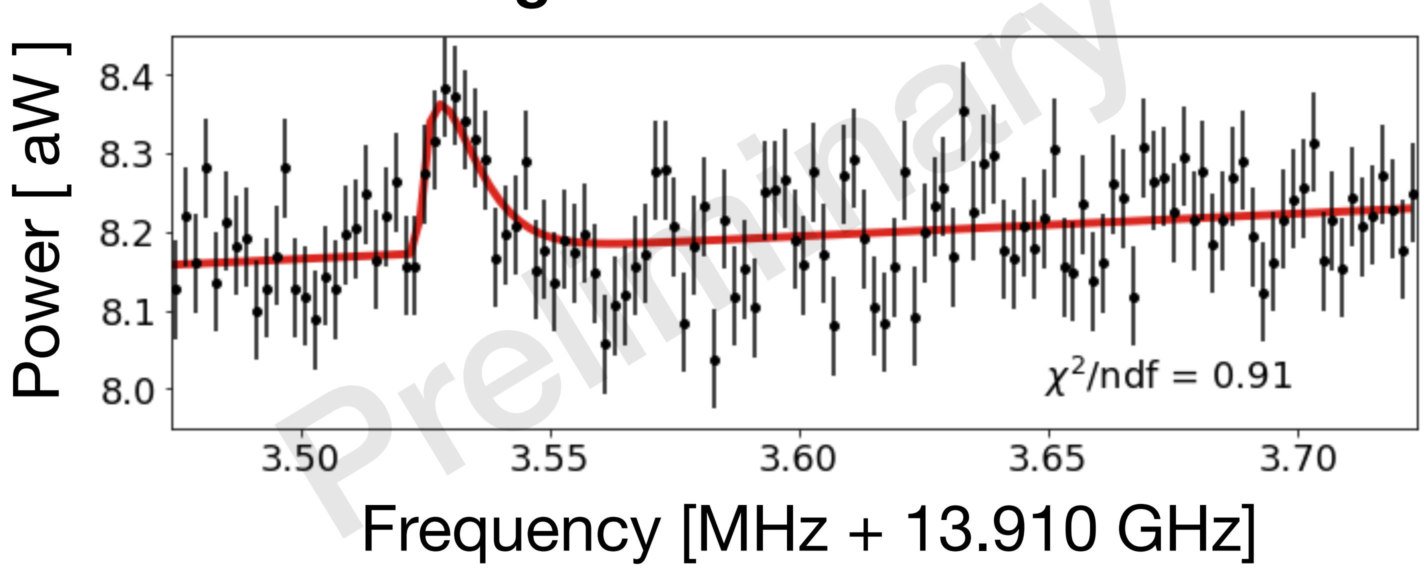
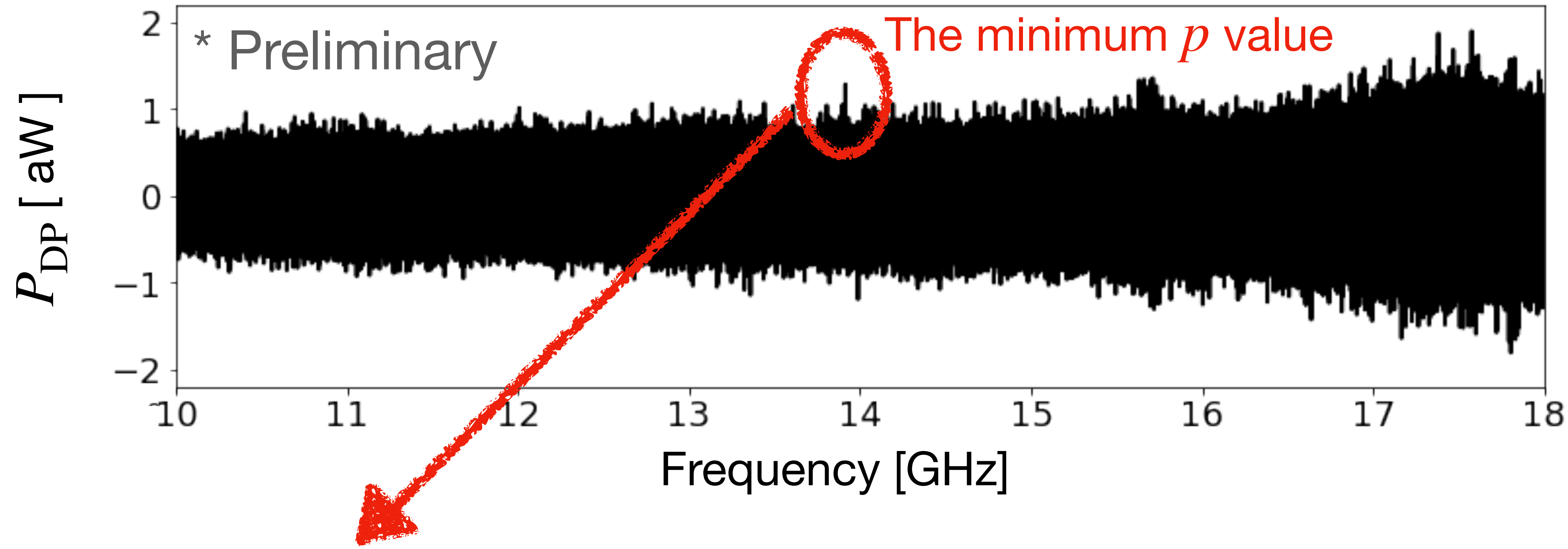


Global p value = **2%**

- Null-hypothesis over 10–18 GHz
- Considering look-else-where effect

Extracted signal powers: P_{DP}



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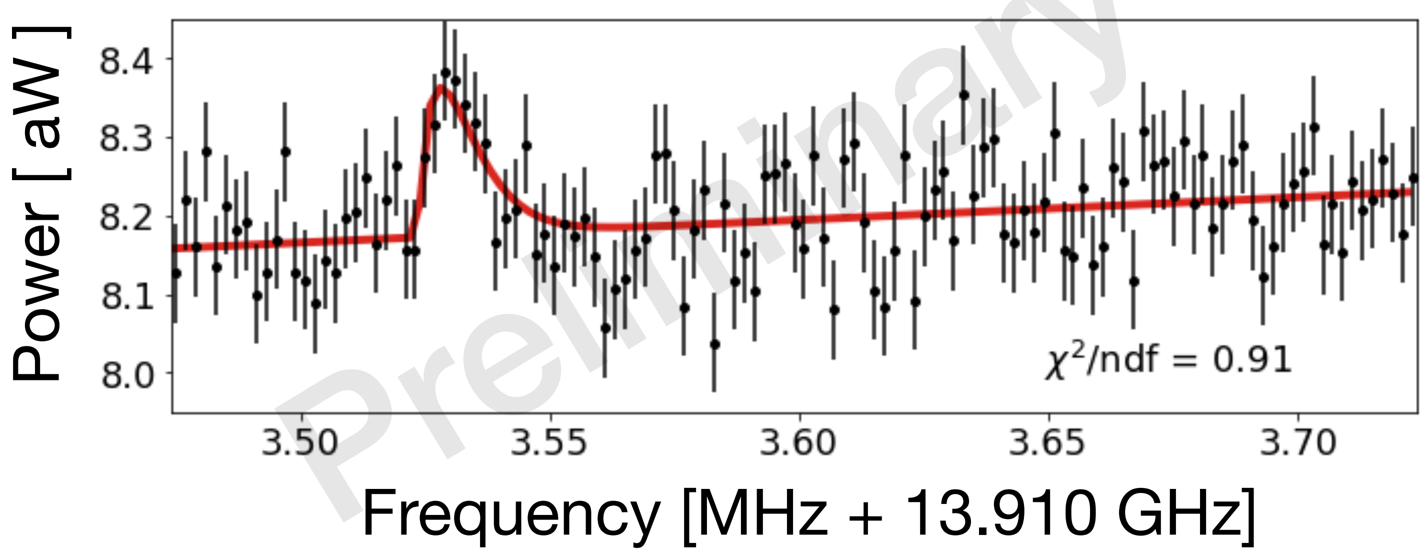
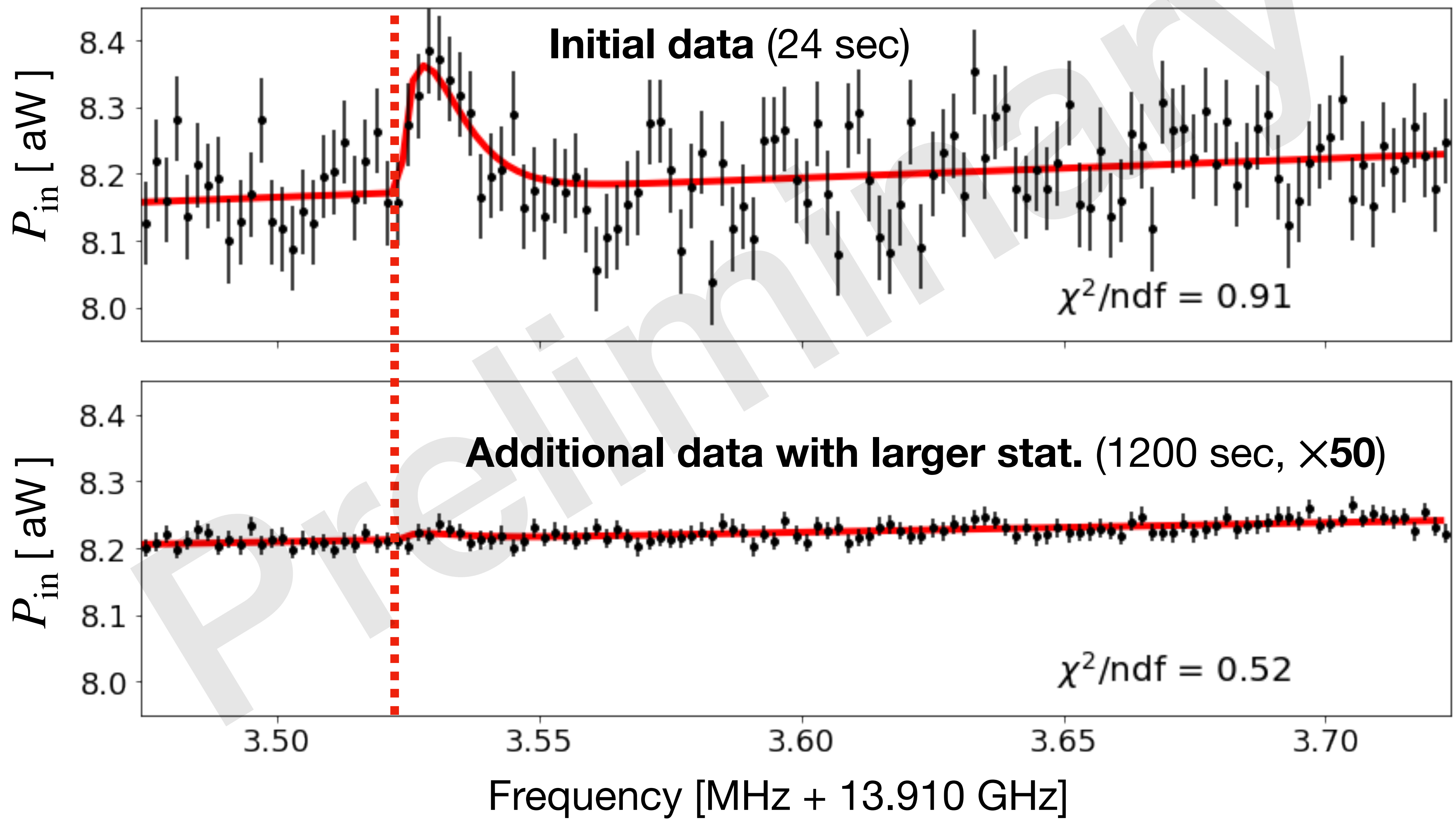


Global p value = **2%**

- Null-hypothesis over 10–18 GHz
- Considering look-else-where effect

Additional data taking (stat. x50) for further check

Revising the minimum p value region



No signal was confirmed with larger statistics(×50).

Conversion from P_{DP} to χ

$$\chi = 1.2 \times 10^{-10} \left(\frac{P_{\mathrm{DP}}}{1\,\mathrm{aW}} \frac{100\,\mathrm{cm}^2}{A_{\mathrm{eff}}} \frac{0.4\,\mathrm{GeV/cm^3}}{\rho_{\mathrm{DM}}} \right)^{1/2}$$

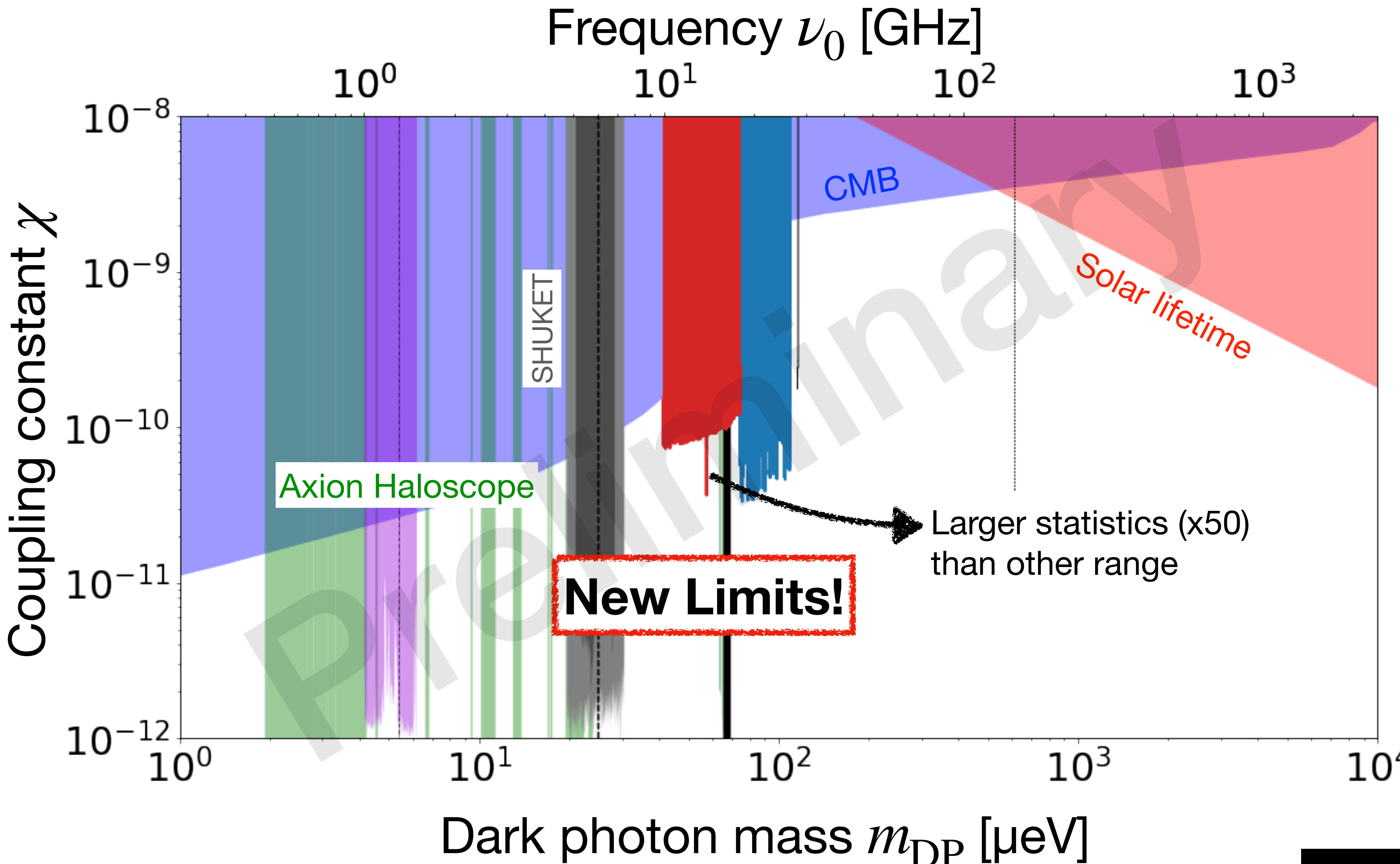
Systematics errors were applied here: * Preliminary

Source	Systematics on χ [%]
Antenna calibration	3.1–8.4
DM density ρ_{CDM}	3.9
DM velocity	2.3
Frequency binning	1.3
Gain calibration	1.0
Alignment	<0.1
Total	5.7–9.7

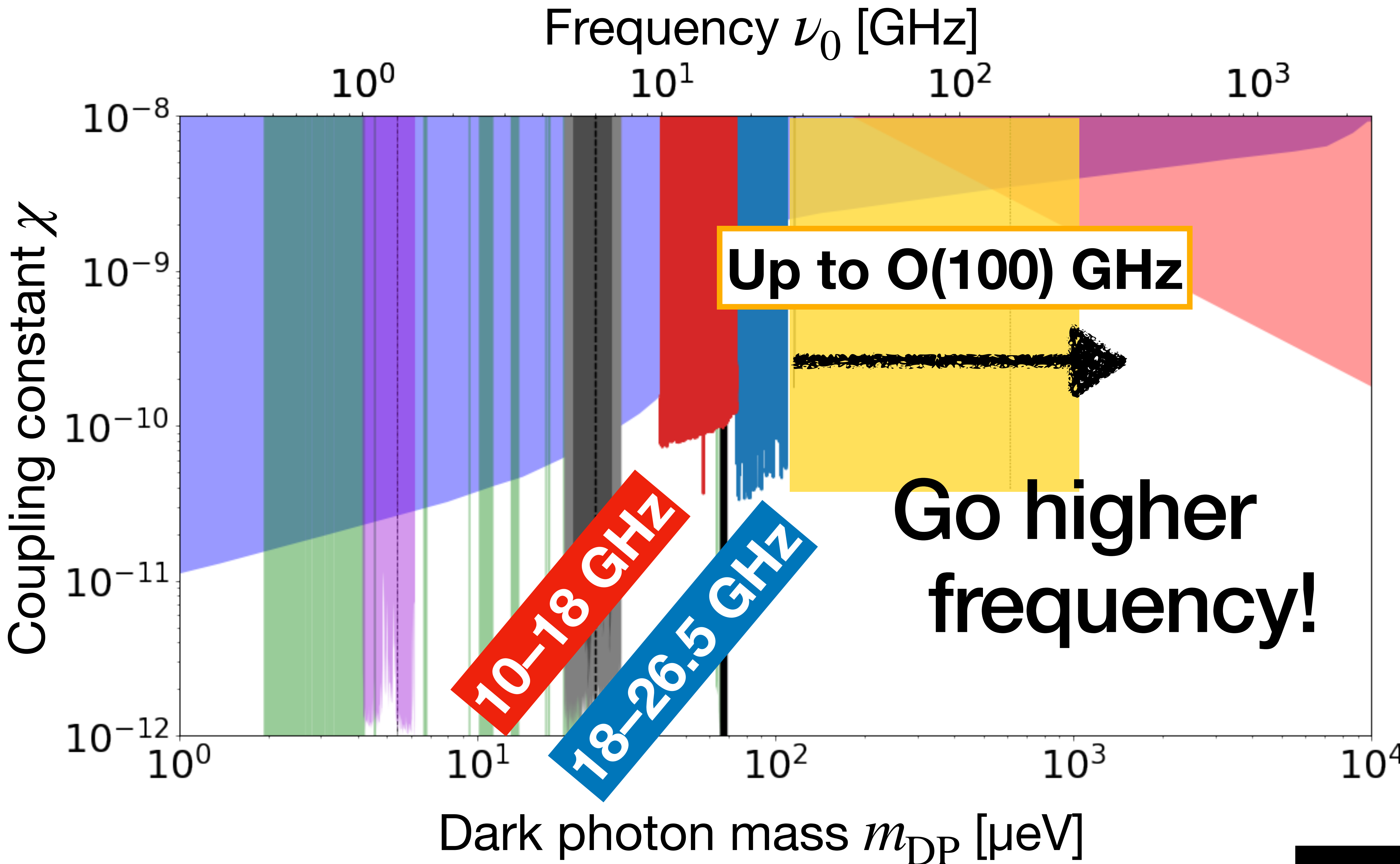
Theory model

Uncertainties on the fit shape $F(\nu; \nu_0)$

Upper Limits on χ by DOSUE-RR

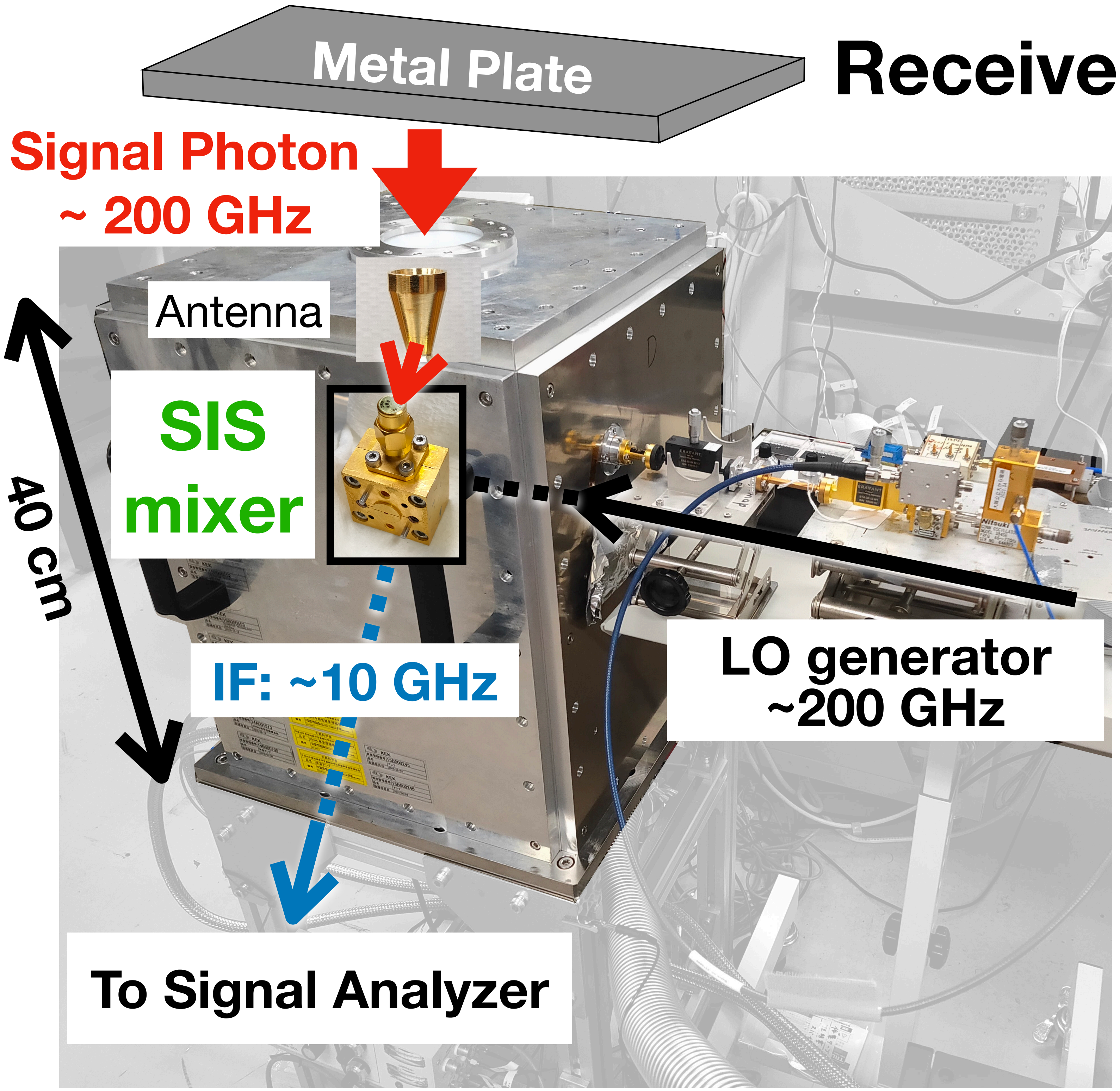


Next Steps



Frequency ν_0 [GHz]
10^0
10^1
10^2
10^3
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Coupling constant χ
Up to O(100) GHz
Go higher frequency!
10–18 GHz
18–26.5 GHz
10^0
10^1
10^2
10^3
10^4
Dark photon mass m_{DP} [μeV]

200 GHz Receiver in Preparation



Receiver with SIS mixer

- Superconducting down-converter
- Base technology for ALMA

- Collaborating with experts for radio telescopes
  - Osaka Metro. U.
  - Nagoya U.

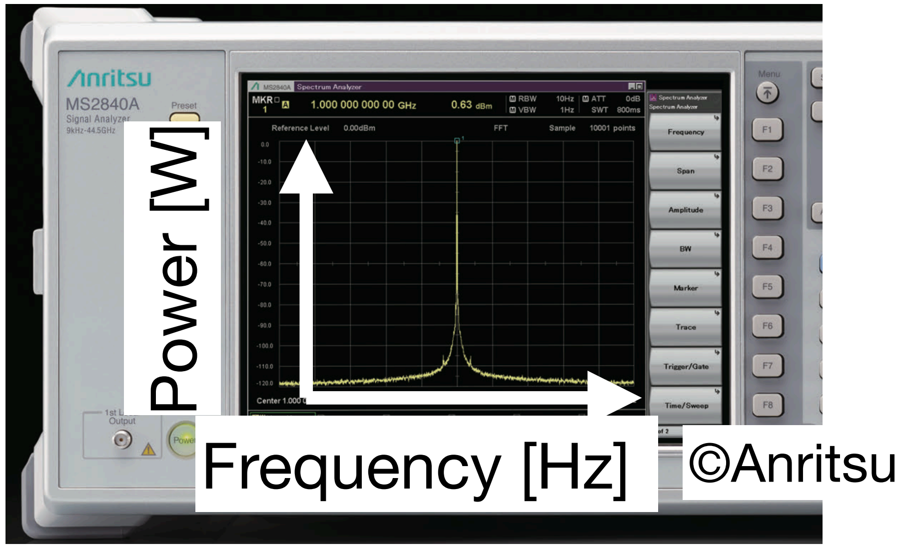
Another Activity for Improvement

For more efficient measurement,
we are developing a new spectrometer with an RFSoC.

Poster (Hiroki Takeuchi)

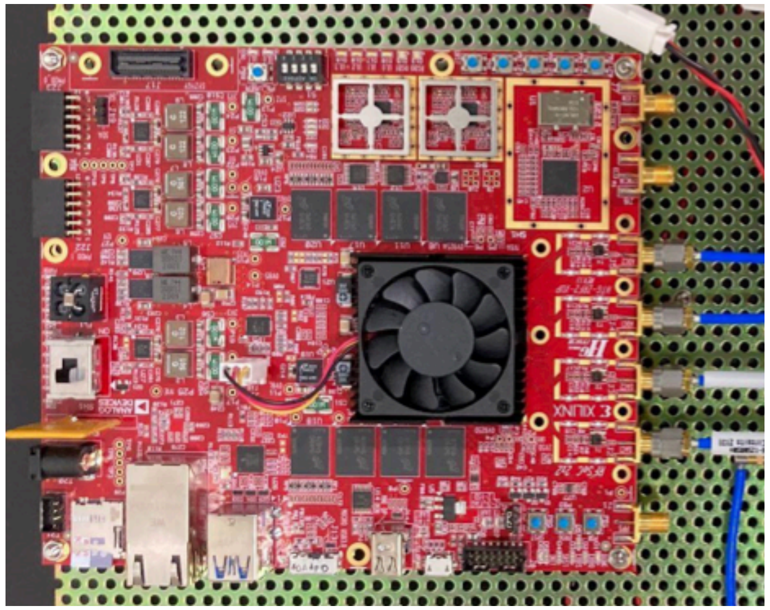
"dSpec, dead-time free spectrometer for WISP searches using 5G telecommunication technologies"

Commercial Signal Analyzer
(Anritsu MS2840A)



2 MHz bandwidth

New Spectrometer "*dSpec*"



4 GHz bandwidth

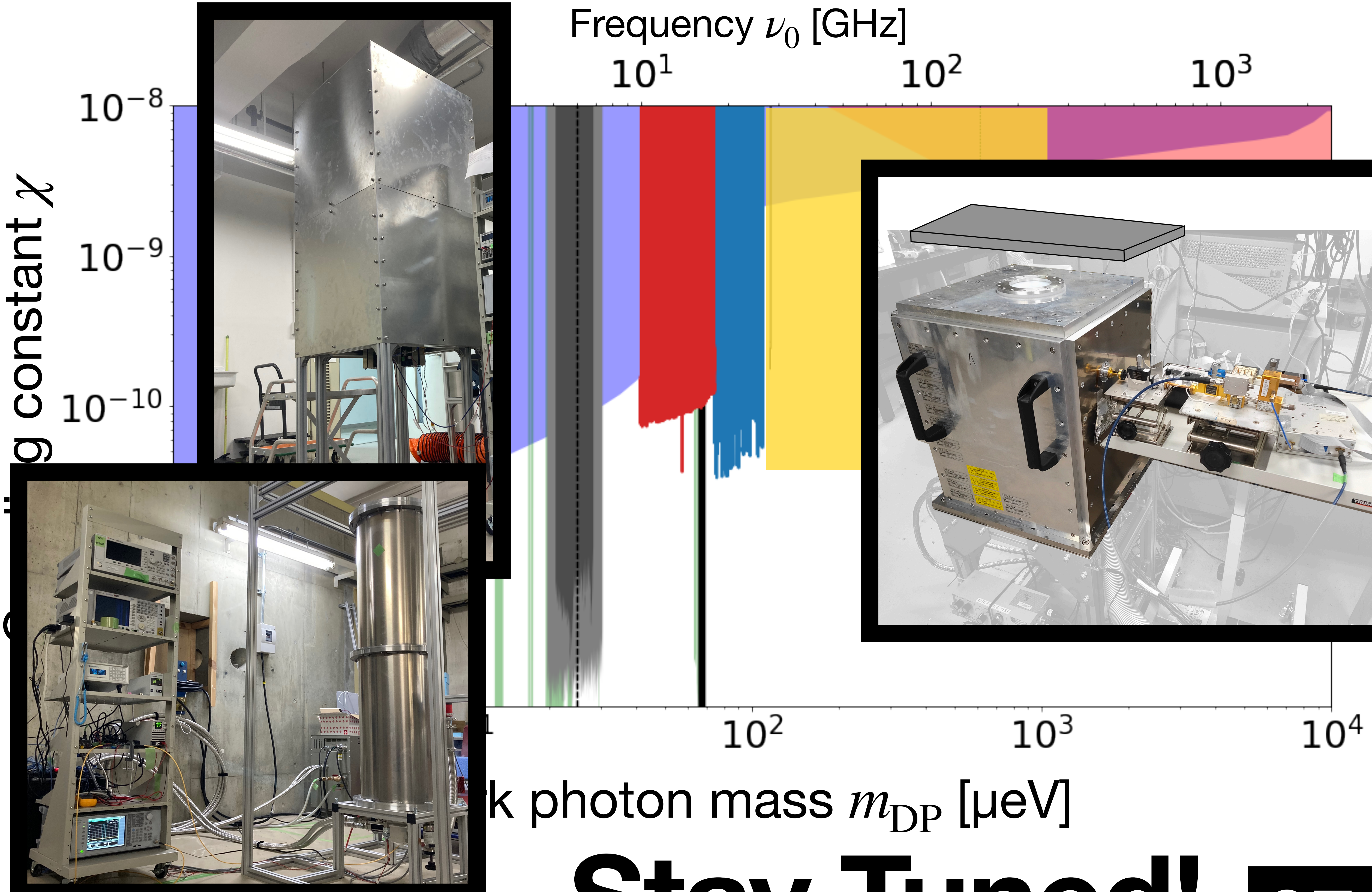
× 2000 wider!!

Summary

- DOSUE-RR is a series of searches for DP-DM using millimeter-wave receivers.
- 1st results: 18–26.5 GHz in 2022 (PRL 130, 071805)
- 2nd results: 10–18 GHz in March 2023
- Next steps
  - Go higher frequency using SIS mixer
  - Improve the bandwidth by a new spectrometer (***dSpec***)
    → Poster by Hiroki Takeuchi

    "dSpec, dead-time free spectrometer for WISP searches using 5G telecommunication technologies"

Thank you for your attention!



Stay Tuned!