doe-su-é double-R

First results of DOSUE-RR experiment — the most stringent constraint for dark-photon CDM at the mass range of 74—110 μeV

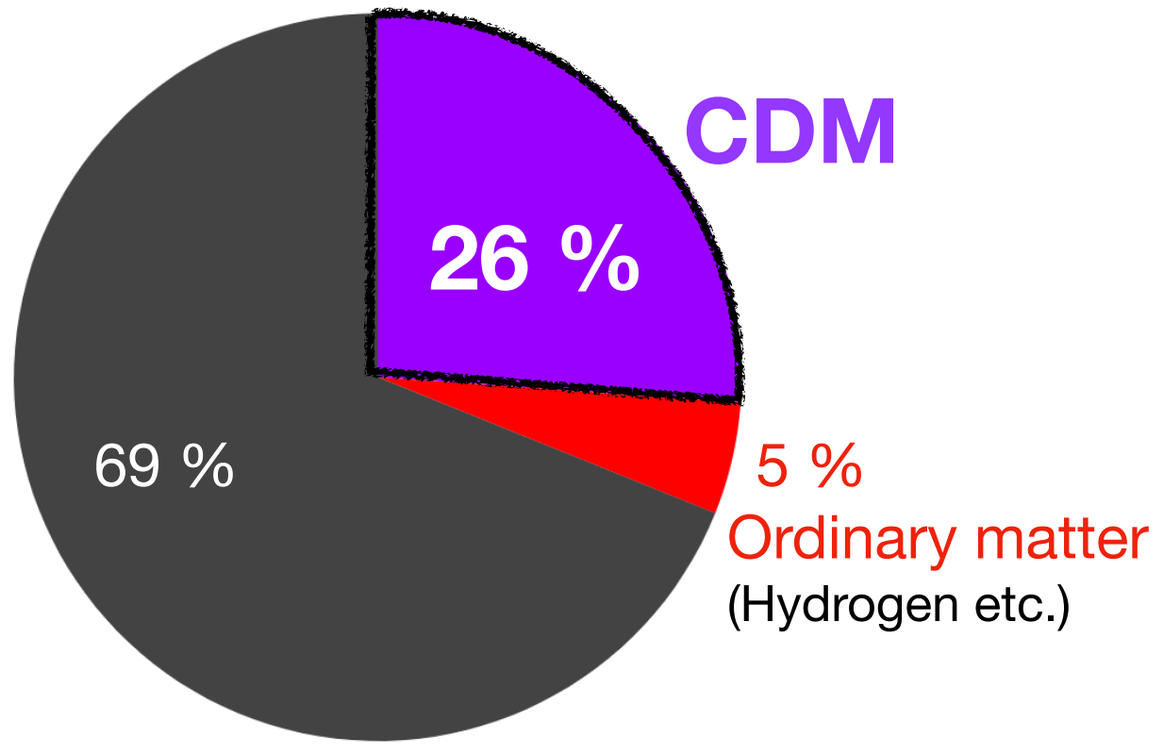
Shunsuke Adachi (Kyoto Univ.)
for the DOSUE-RR collaboration

ICHEP 2022 Jul. 8, 2022, Bologna (Italy)

Cold dark matter (CDM)

- CDM is one of main components in the universe!

Energy fractions of the universe

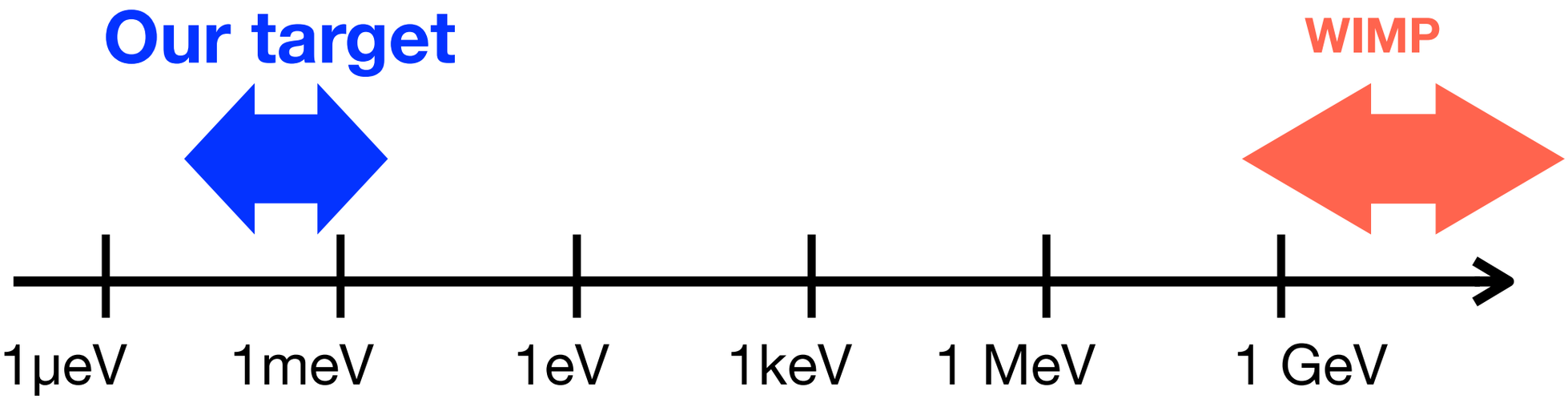


- Still unknown for the **mass** and **interactions** with SM particles. *except for gravity
- **WIMP** has been conventional candidate.
  - No conclusive result yet
- We consider **another candidate**.

Our target: Light dark photon CDM

"DP-CDM"

1. Ultra low mass



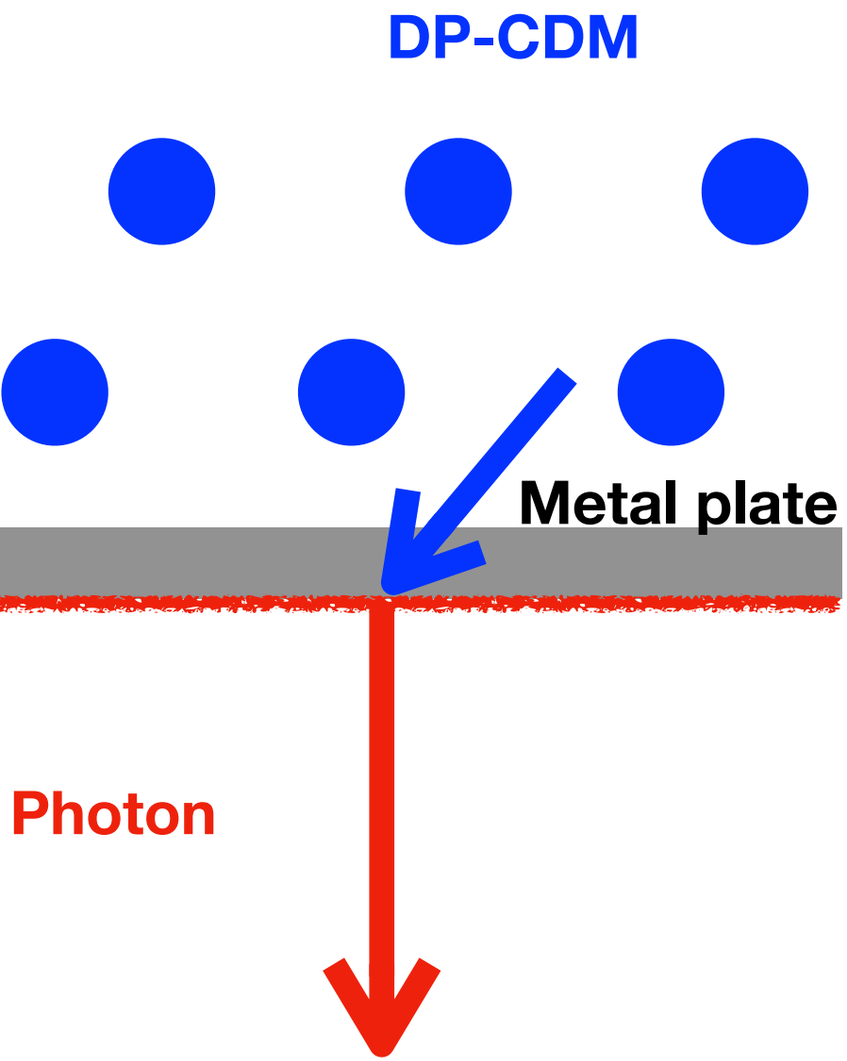
2. Interaction with photon
   via a kinetic mixing
   (A small coupling constant χ)

P Arias et al, JCAP06 (2012) 013

WIMP
Interact with
nucleons

Photon conversion of DP-CDM

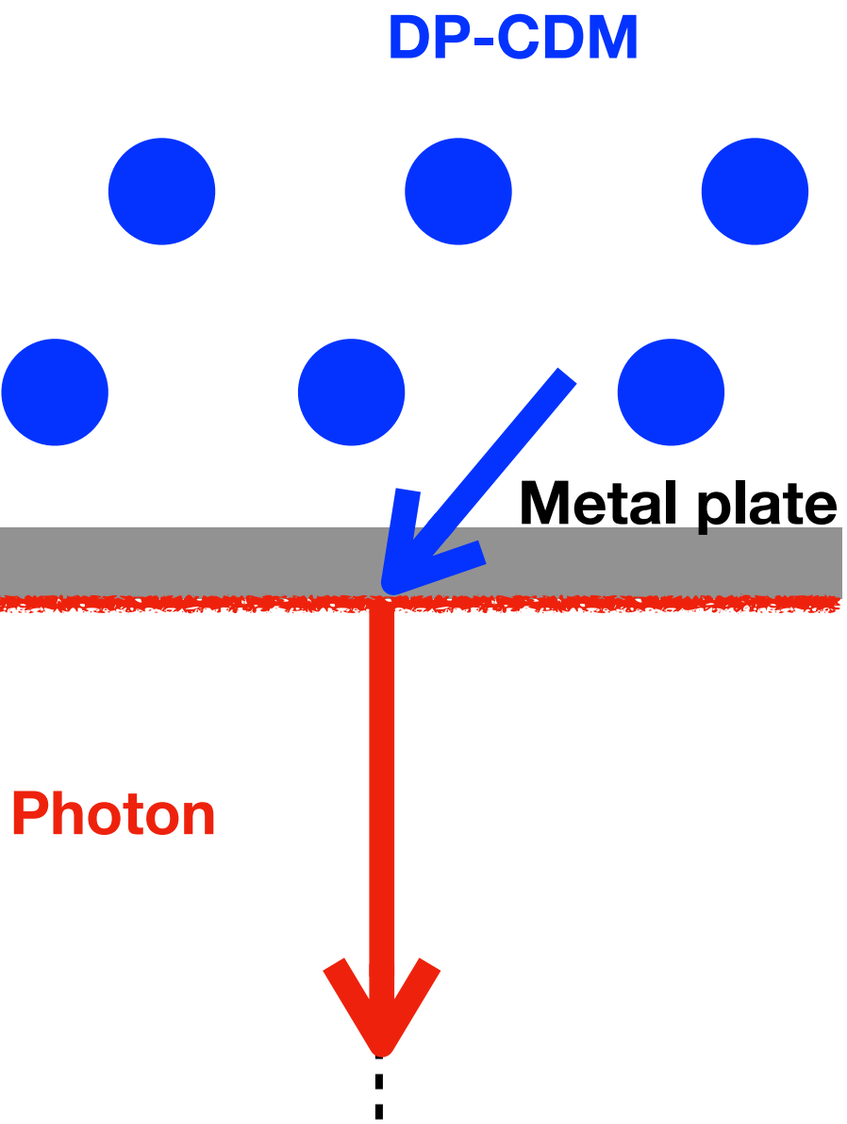
D. Horns et al, JCAP04 (2013) 016



If the CDM has a interaction with **EM**-field
electromagnetic
via the kinetic mixing,
photon is emitted from **a EM boundary**!
i.e., **a metal surface**

Photon conversion of DP-CDM

D. Horns et al, JCAP04 (2013) 016



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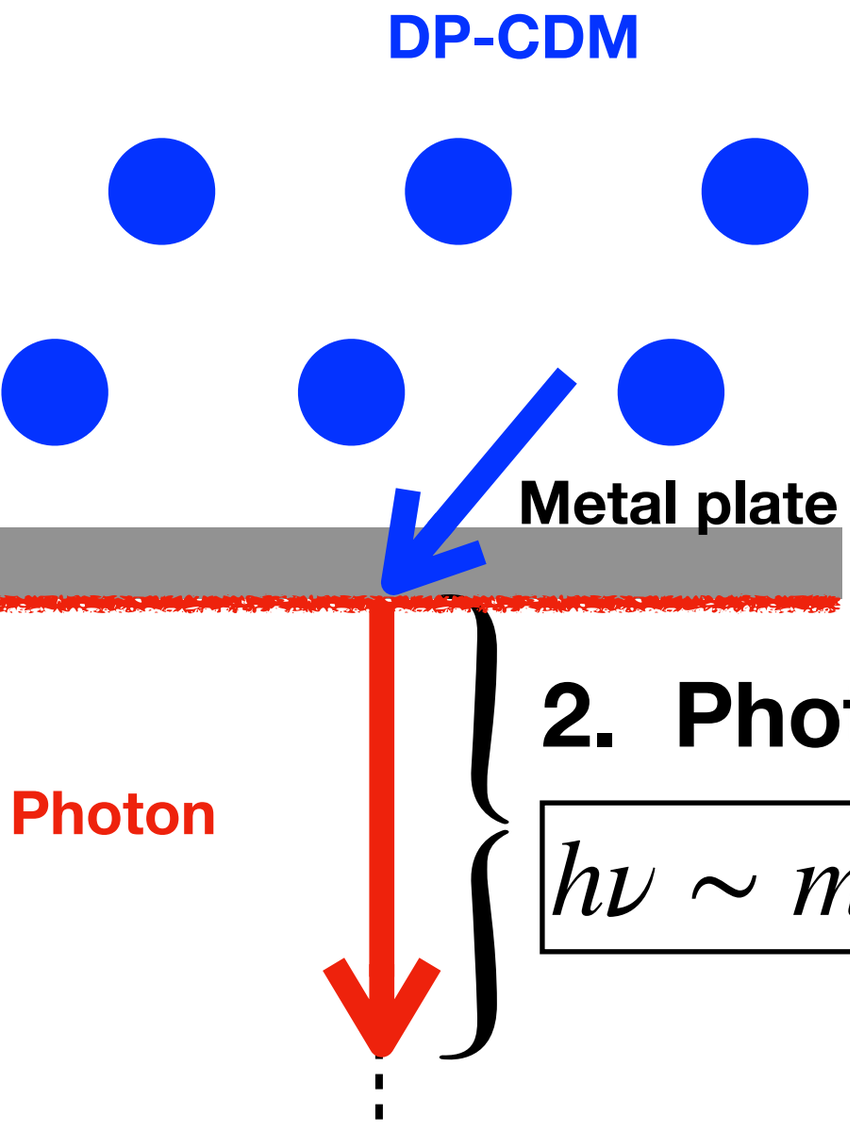
1. **Conversion photons are perpendicularly emitted!** (<0.06°)

Photon conversion of DP-CDM

D. Horns et al, JCAP04 (2013) 016



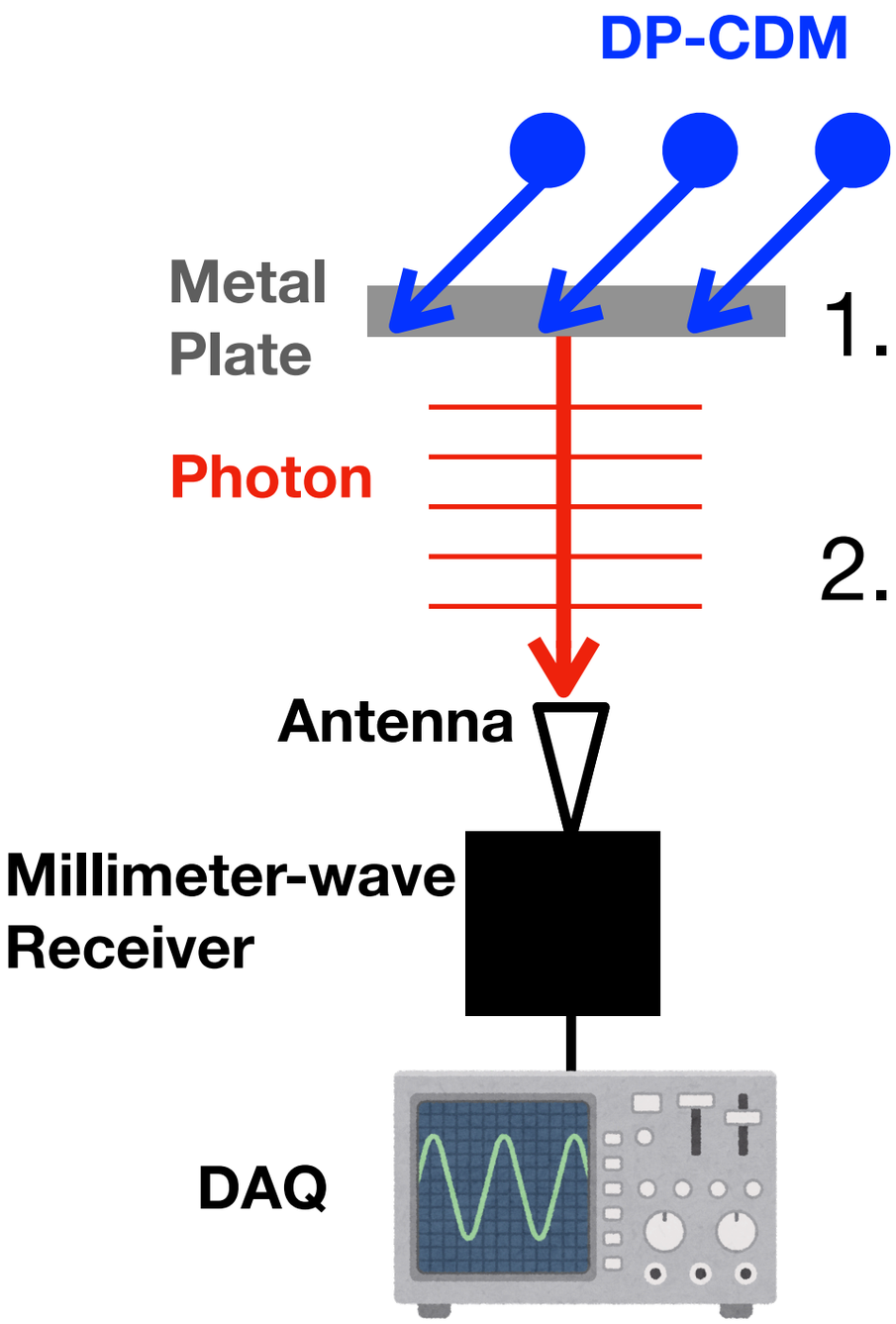
If the CDM has a interaction with **EM**-field
electromagnetic
via the kinetic mixing,
photon is emitted from **a EM boundary**!
i.e., **a metal surface**

2. **Photon frequency $\nu \propto m_{\mathrm{DP}}$!**

$$h\nu \sim m_{\mathrm{DP}}c^2$$

1. **Conversion photons are perpendicularly emitted!** (<0.06°)

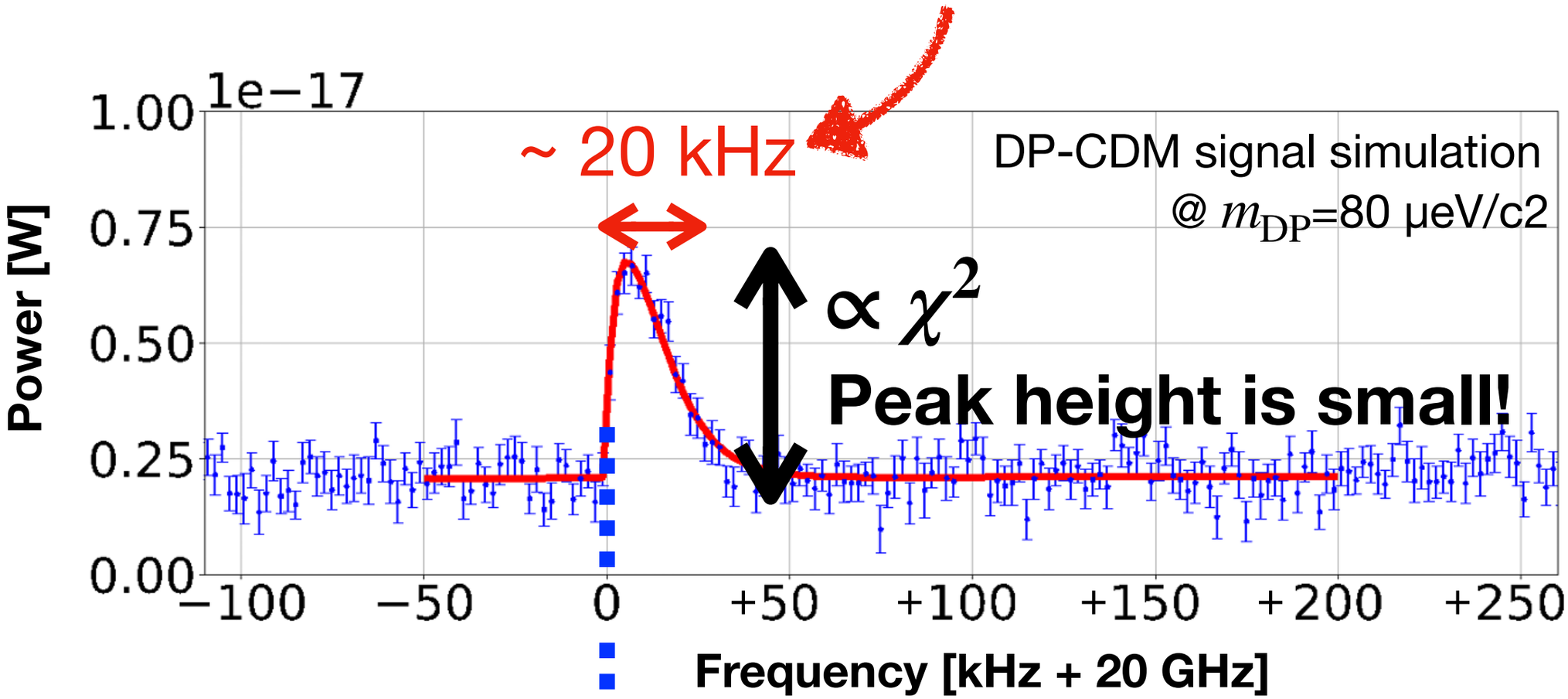
Detection principle



1. Easy to detect the signal photon using a millimeter-wave receiver
2. Frequency is specified by the DP mass.
    1. $h\nu \sim m_{\mathrm{DP}}c^2$

Signal frequency spectrum

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



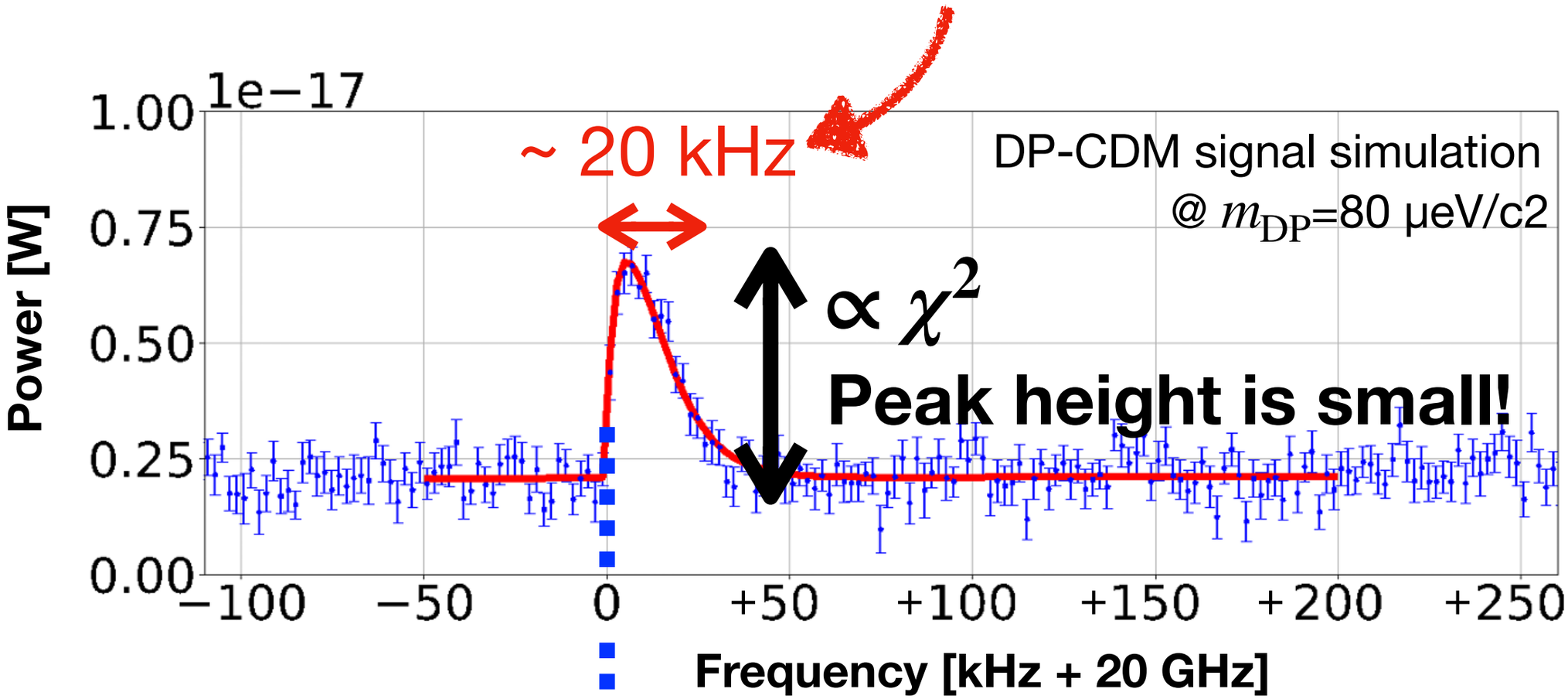
$\nu_0 = 20$ GHz

$\Leftrightarrow m_{\mathrm{DP}} = 80$ μeV/c²

Small peak search in a frequency spectrum

Signal frequency spectrum

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

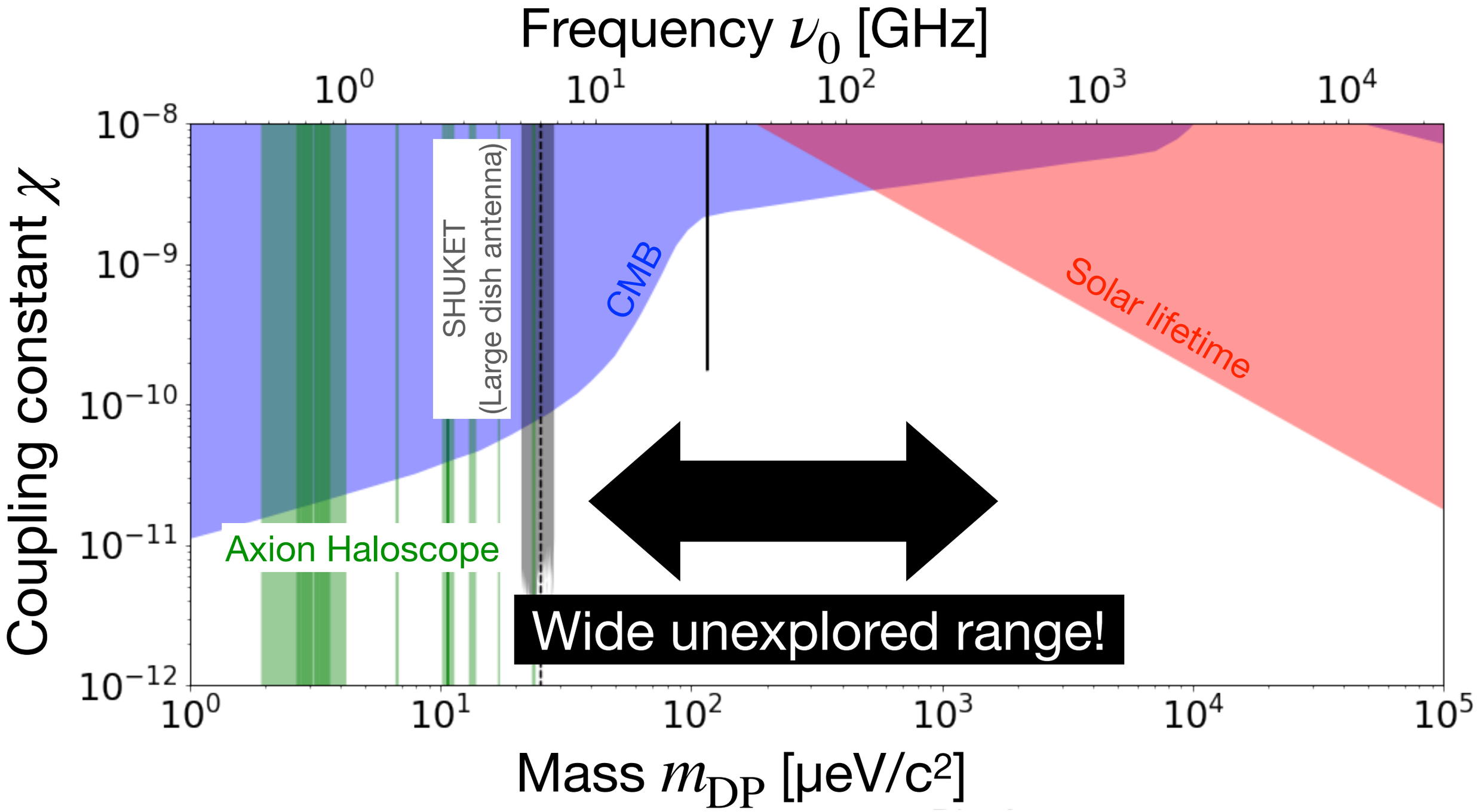


$\nu_0 = 20$ GHz

$\Leftrightarrow m_{\mathrm{DP}} = 80$ μeV/c²

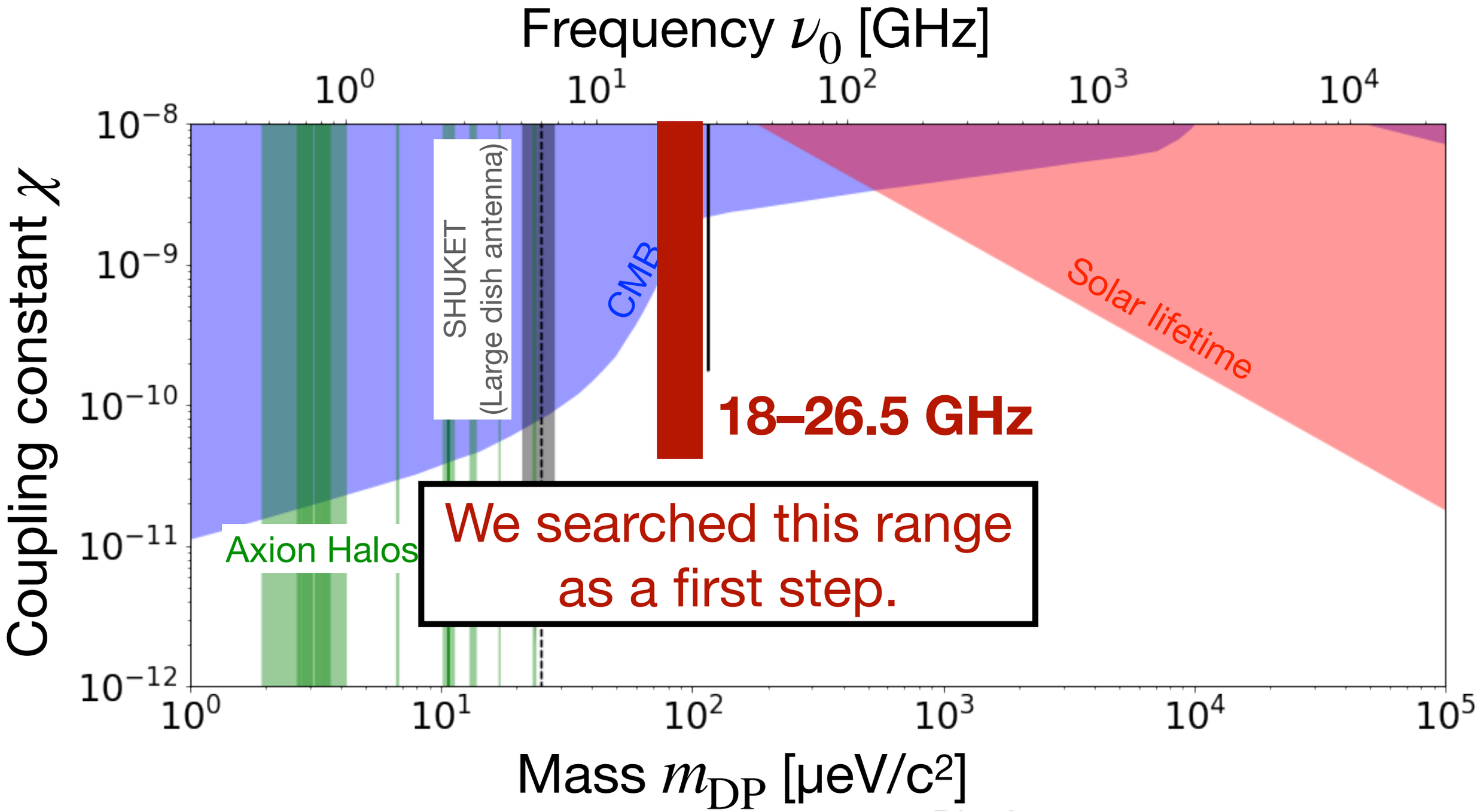
Peak position ⇔ CDM mass m_{DP}
Peak height ⇔ Coupling constant χ

Constraints on DP-CDM



DOSUE-RR aims to cover 10 GHz—a few 100 GHz !

Constraints on DP-CDM



Signal power P_{DP}

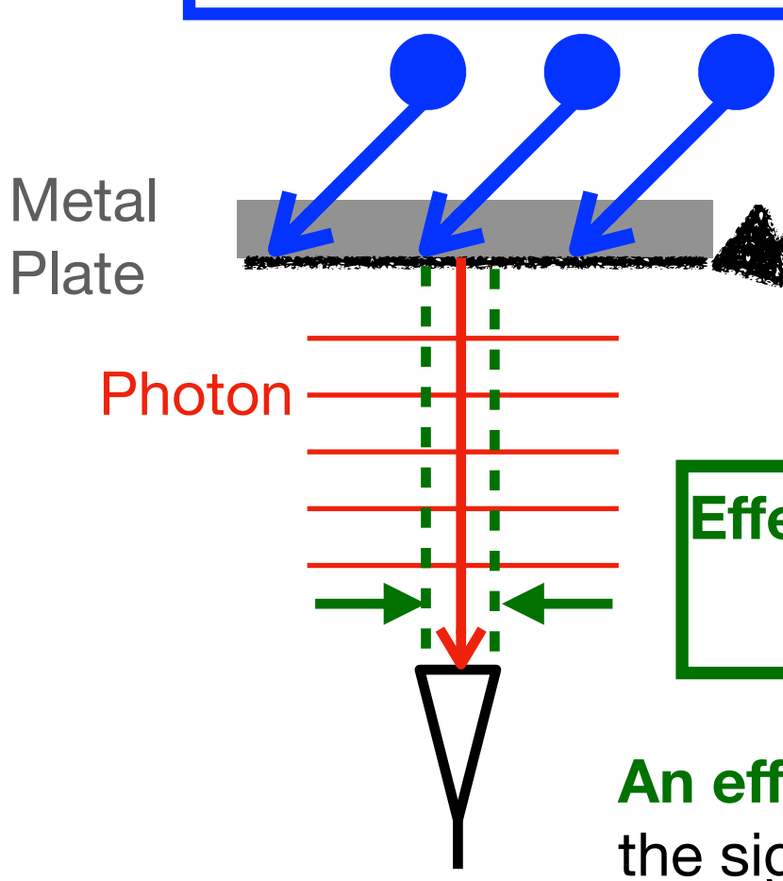
Ref. D. Horns et al, JCAP04 (2013) 016

$$\frac{P_{DP}}{10^{-19}\,\mathrm{W}} = 1.1 \times \left(\frac{\chi}{10^{-10}}\right)^2 \left(\frac{A_{\mathrm{eff}}}{17.3\,\mathrm{cm}^2}\,\frac{\rho_{\mathrm{CDM}}}{0.39\,\mathrm{GeV/cm}^3}\right)$$

DP-CDM

$\rho_{\mathrm{CDM}} = 0.39 \pm 0.03\,\mathrm{GeV/cm}^3$

R Catena and P. Ullio, JCAP08 (2010) 004



Conversion eff.
$\propto \chi^2$

Effective aperture area
$A_{\mathrm{eff}} = \eta_{\mathrm{eff}} A_{\mathrm{horn}}$

Aperture: ϕ 6 cm
$A_{\mathrm{horn}} = 28\,\mathrm{cm}^2$

An efficiency to collect the signal photons
$\eta_{\mathrm{eff}} = 0.63$

Horn antenna

Signal power P_{DP}

Ref. D. Horns et al, JCAP04 (2013) 016

Our target **~10^{-10}**

From simulation **17.3 cm²**

From cosmic observation **0.39 GeV/cm³**

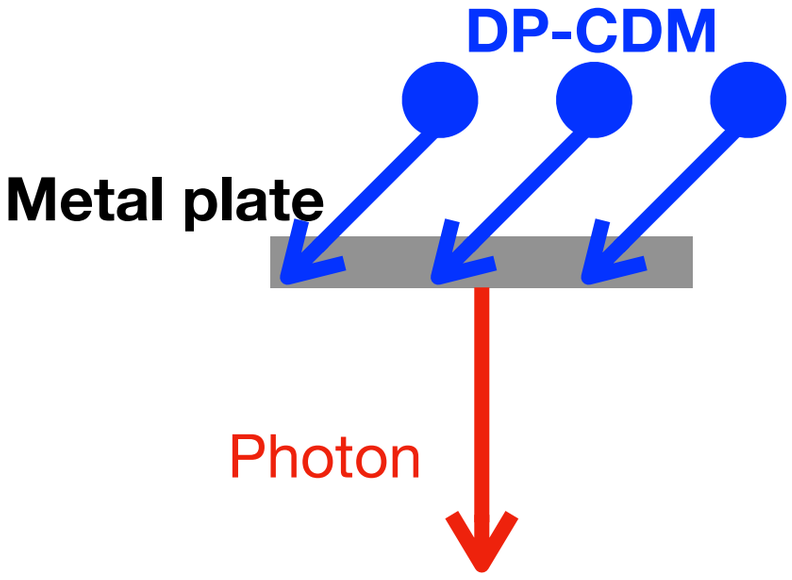
$$\frac{P_{DP}}{10^{-19}\,\mathrm{W}} = 1.1 \times \left(\frac{\chi}{10^{-10}}\right)^2 \left(\frac{A_{\mathrm{eff}}}{17.3\,\mathrm{cm}^2}\,\frac{\rho_{\mathrm{CDM}}}{0.39\,\mathrm{GeV/cm}^3}\right)$$

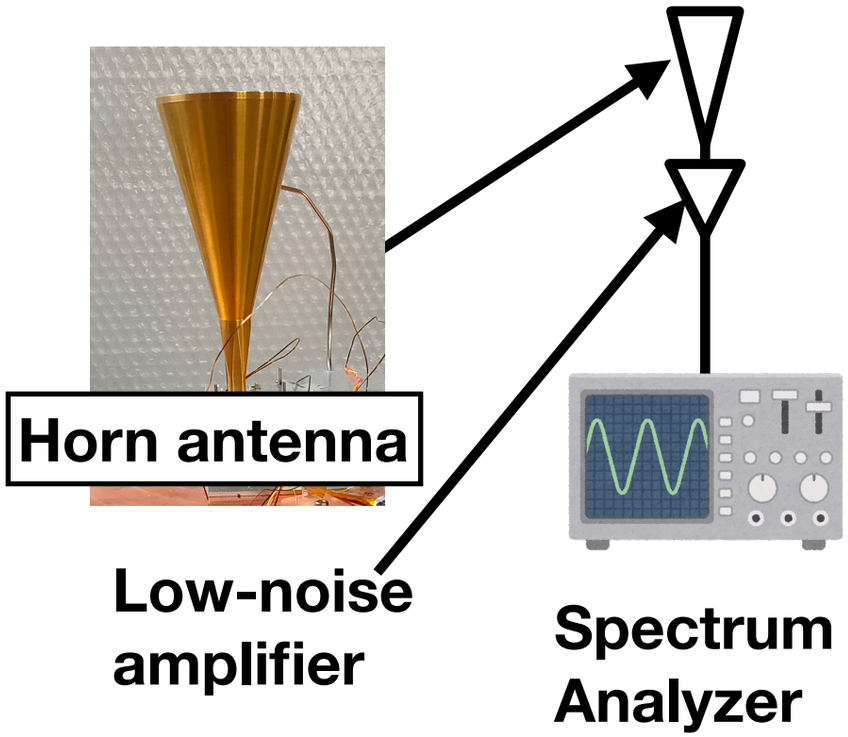
Signal power P_{PD} is $\sim 10^{-19}\,\mathrm{W}$ @ $\chi = 10^{-10}$.

Need to find a faint signal !

Need a low noise measurement!

Experimental setup





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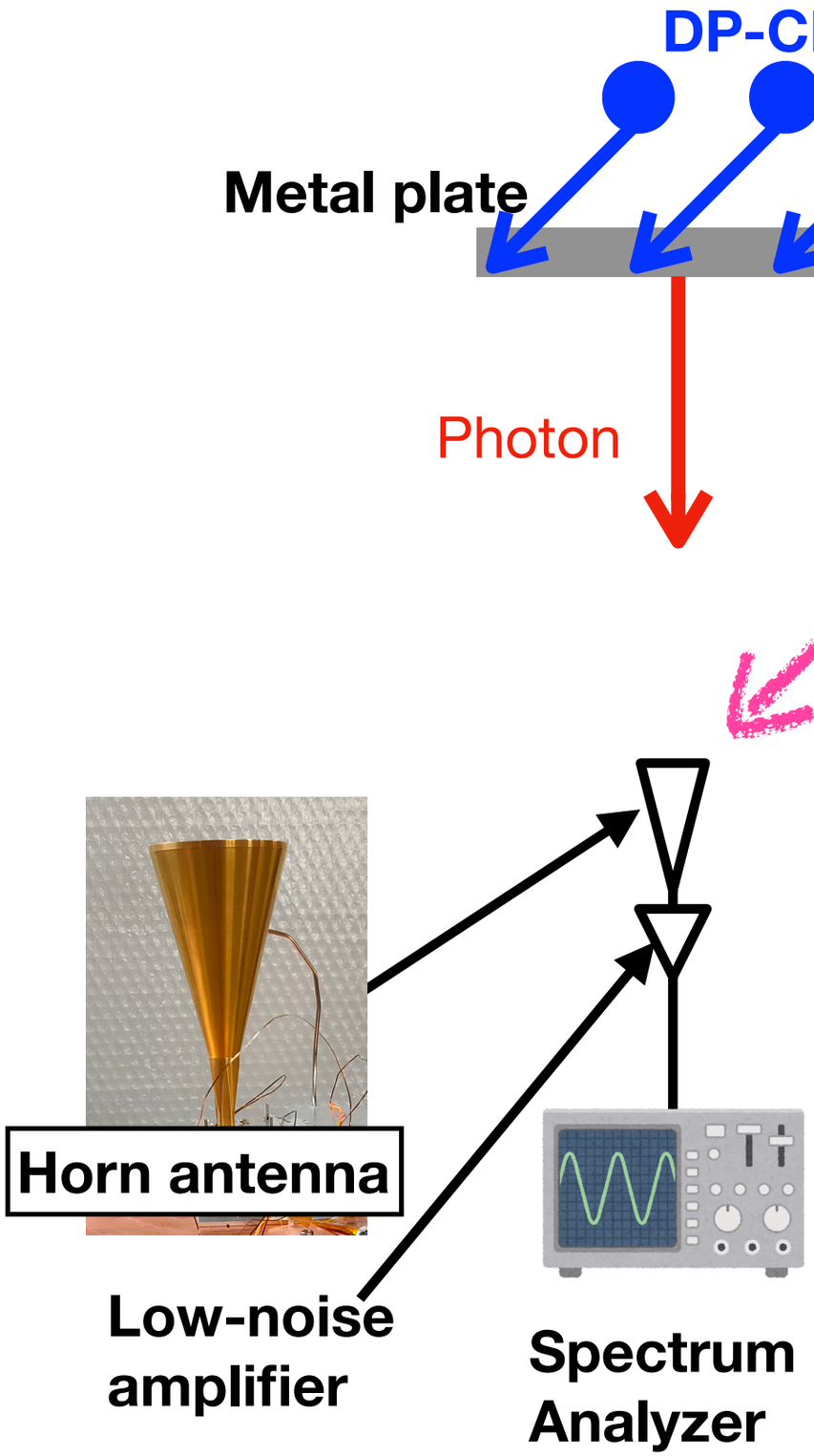


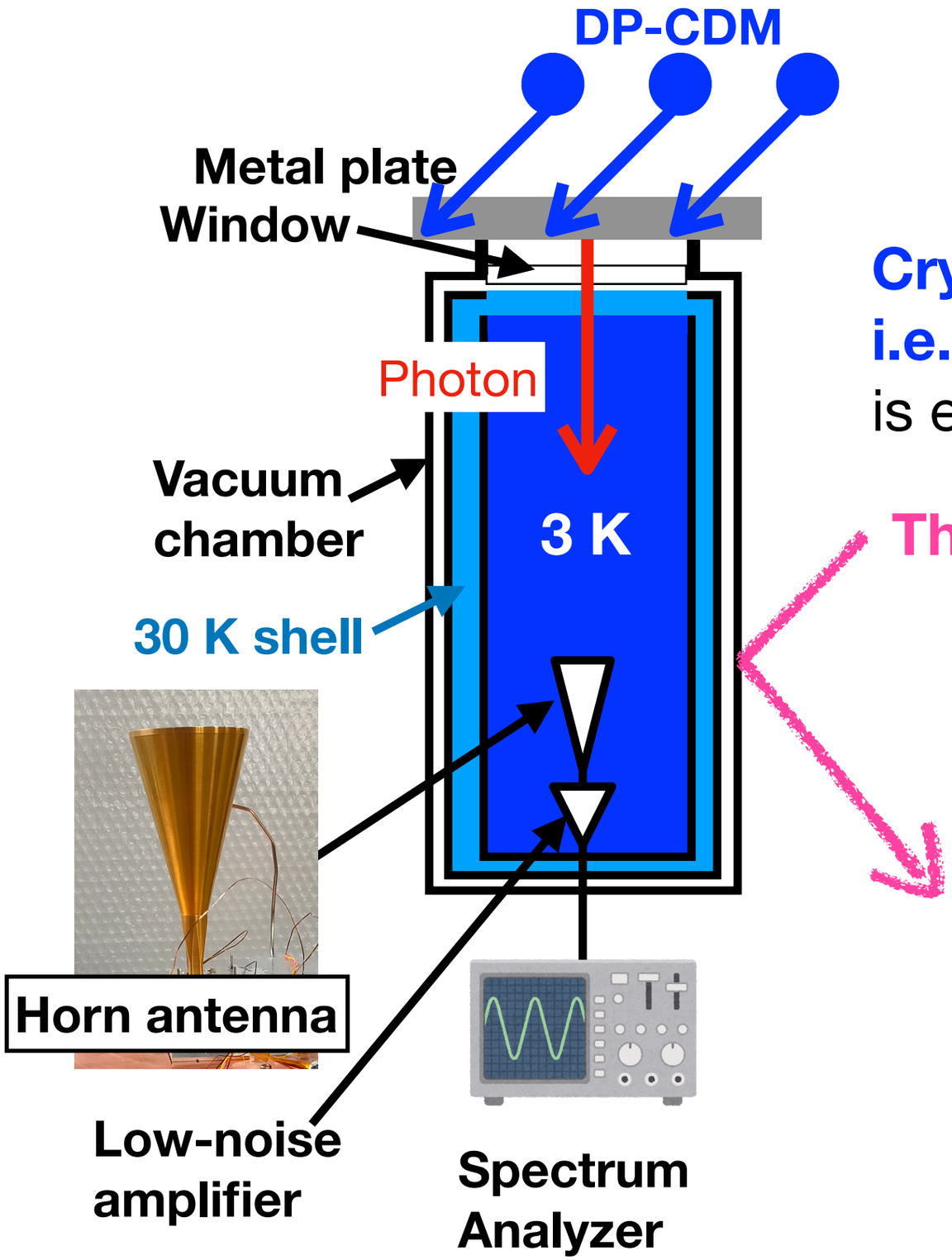
Main noise source:

Thermal radiation

from the surrounded materials (~300K)

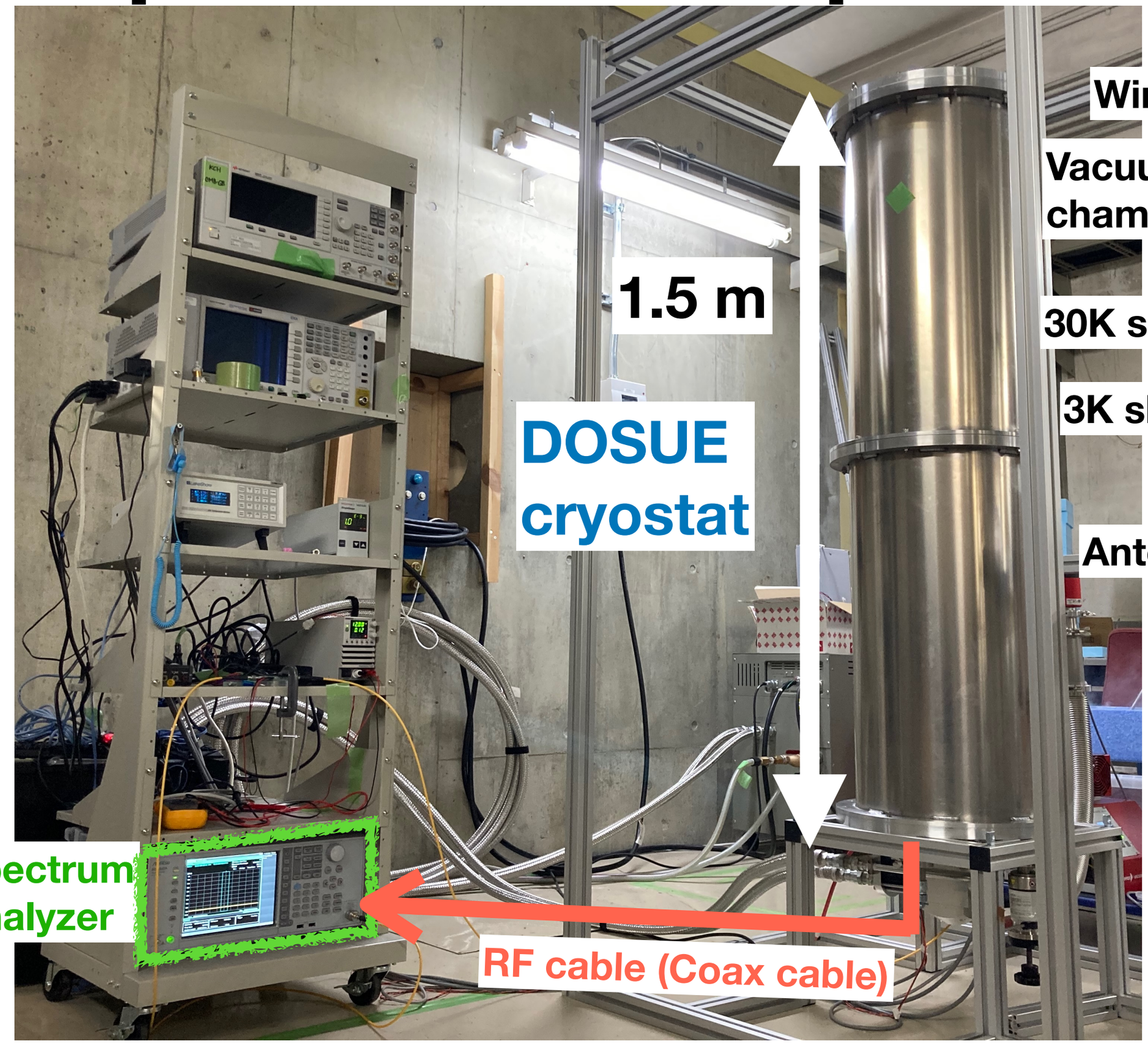
- Noise power P [W] ∝ Temperature T [K]

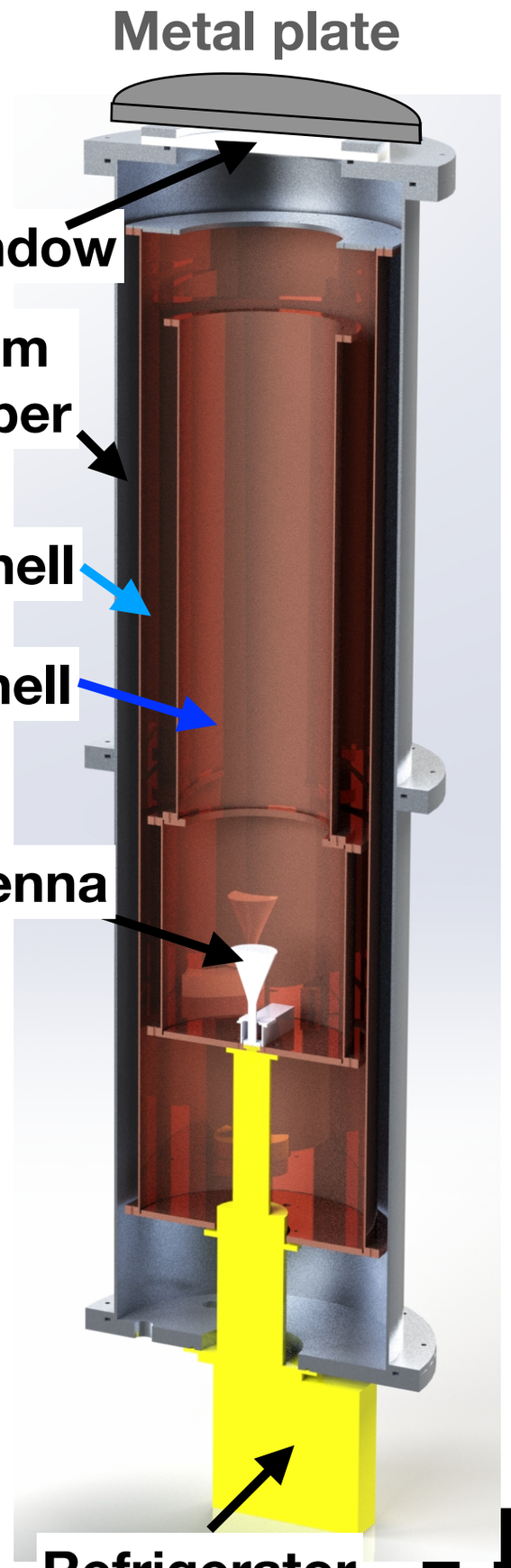
Experimental setup



Cryogenically cooled optical path,
i.e. a long cryostat,
is employed for the thermal noise reduction.

Experimental setup





Input power P_{in} & measured power P_{measure}

Gain: G — Input signal power: P_{in} — Receiver intrinsic noise: $k_{\mathrm{B}} T_{\mathrm{rx}} \Delta\nu$

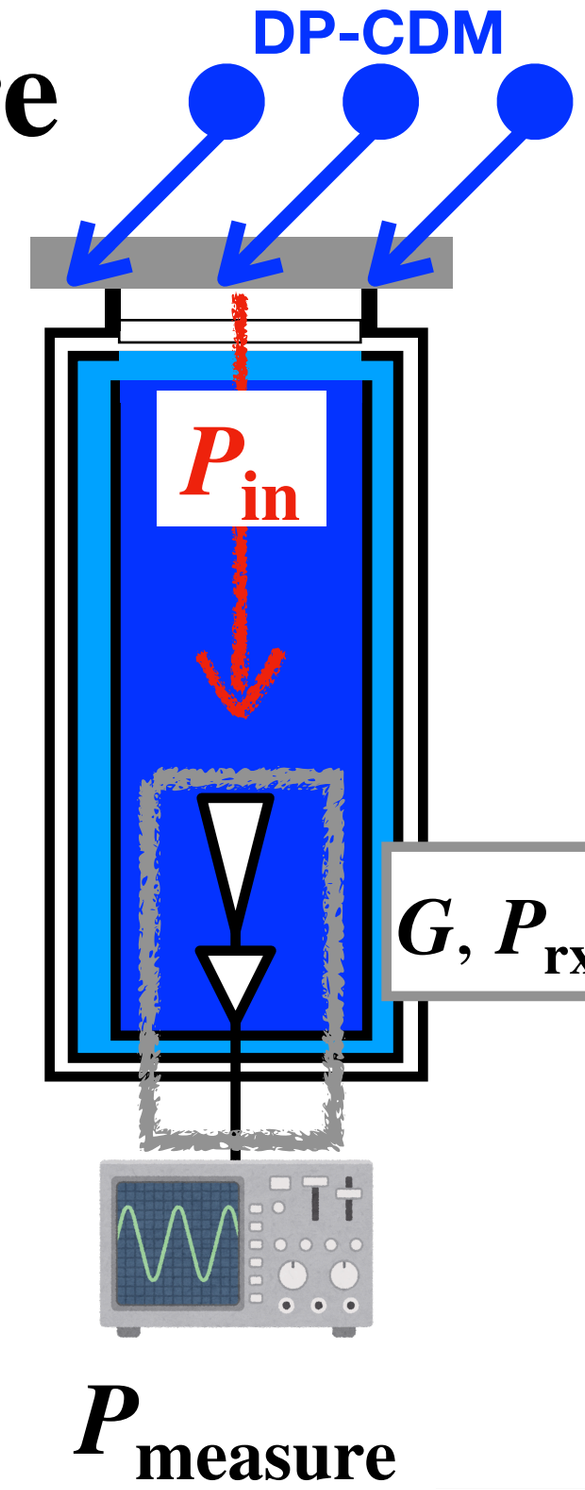
$$P_{\mathrm{measure}} = G \left(P_{\mathrm{in}} + k_{\mathrm{B}} T_{\mathrm{rx}} \Delta\nu \right)$$

- k_{B}: Boltzmann const.
- $\Delta\nu$: Frequency resolution, $\Delta\nu$ = 0.3 kHz

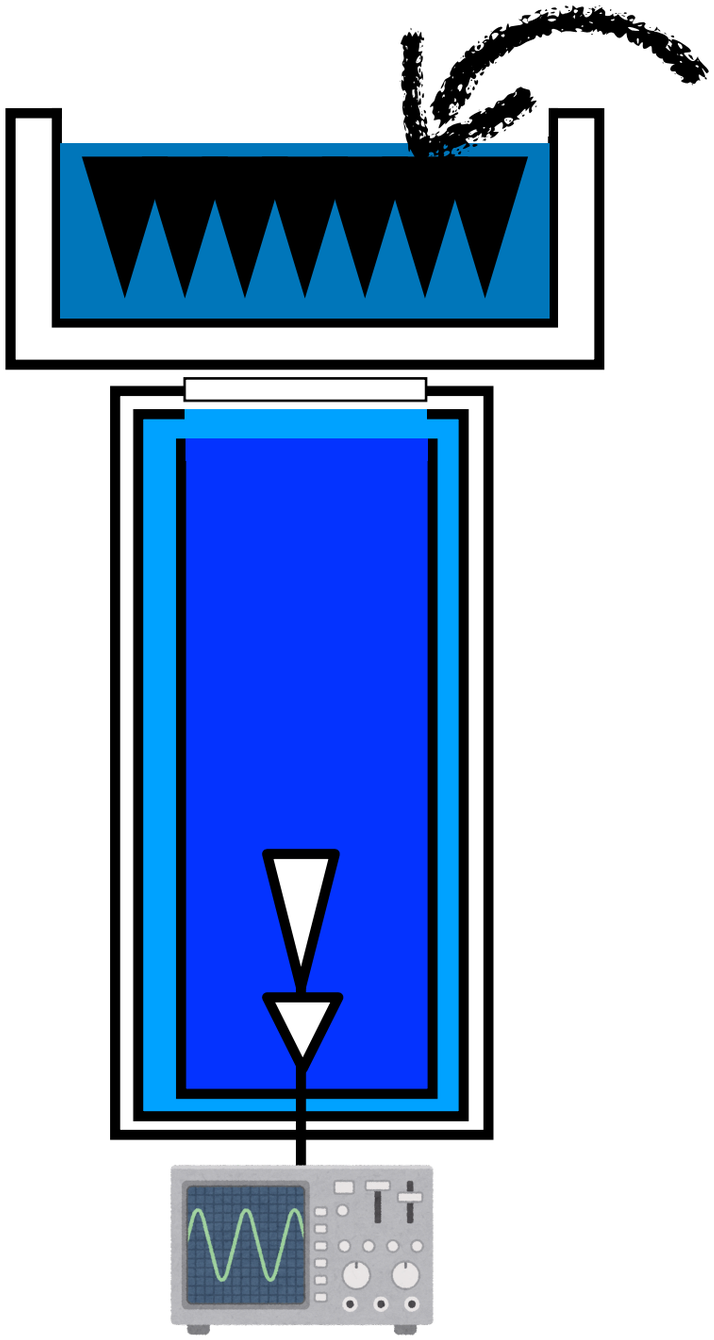
* $k_{\mathrm{B}} T_{\mathrm{rx}} \Delta\nu = P_{\mathrm{rx}}$ [W]

We need to know

- Gain G [dB],
- Receiver noise temperature T_{rx} [K]

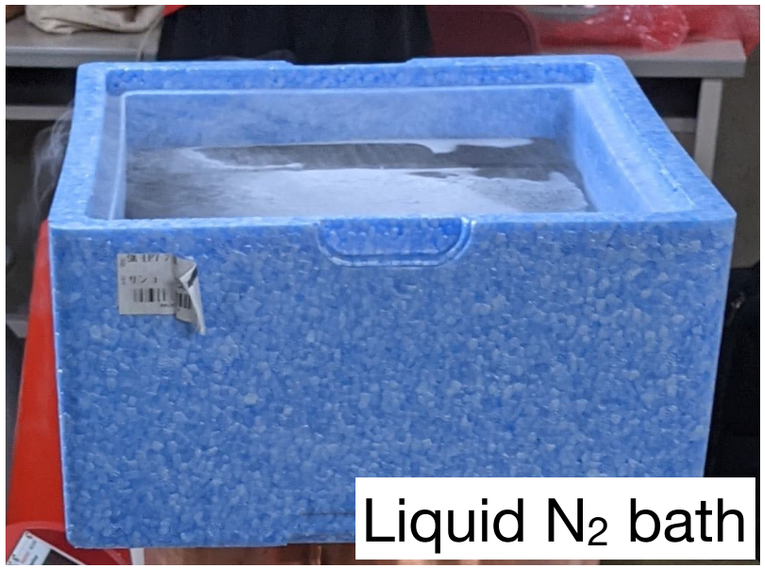


Hot & cold calibration

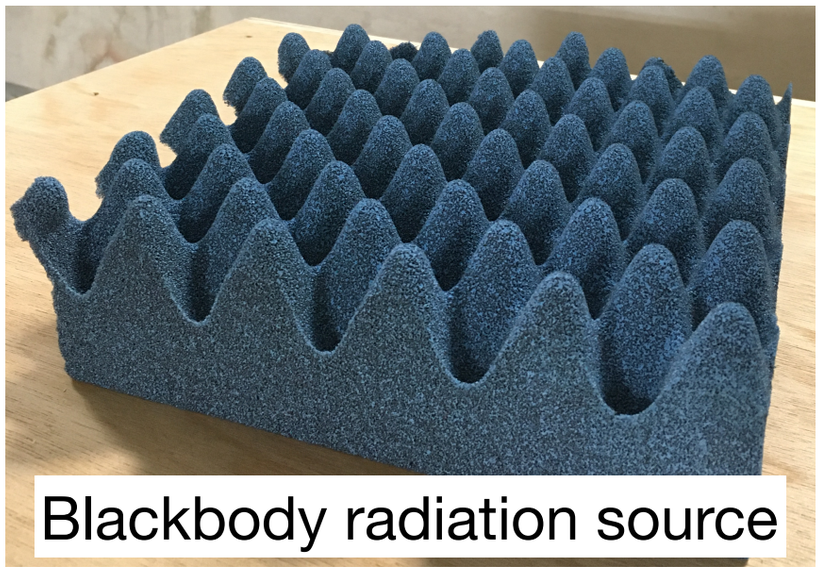


Two blackbody radiation sources

1. in liquid N_2 (77K)
2. at room temp.(300K)



Liquid N_2 bath

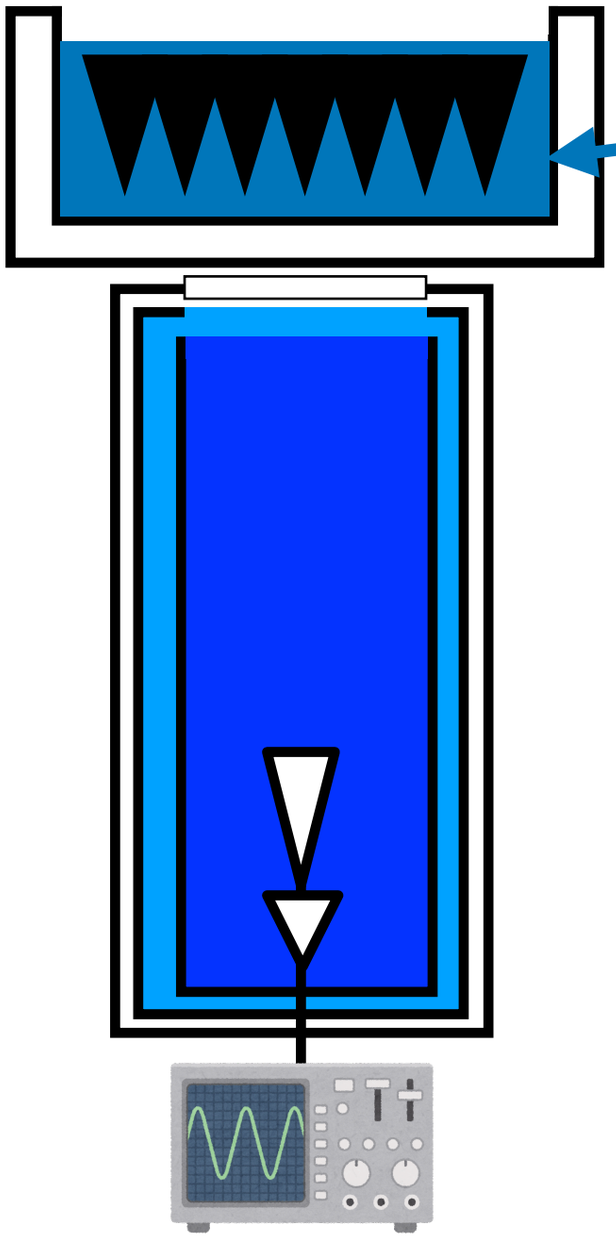


Blackbody radiation source

Radiation power P_{in} [W] $= k_{\mathrm{B}} T_{\mathrm{BB}} \Delta\nu$

- $T_{\mathrm{BB}} =$ Blackbody temp. (77K or 300K)
- $\Delta\nu =$ 300 Hz (Frequency resolution)

Hot & cold calibration



Liquid N_2 (77K) or room temp.(300K)

$$P_{\mathrm{measure,\,77K}} = G k_{\mathrm{B}} \left(77\,\mathrm{K} + T_{\mathrm{rx}}\right) \Delta\nu$$

$$P_{\mathrm{measure,\,300K}} = G k_{\mathrm{B}} \left(300\,\mathrm{K} + T_{\mathrm{rx}}\right) \Delta\nu$$

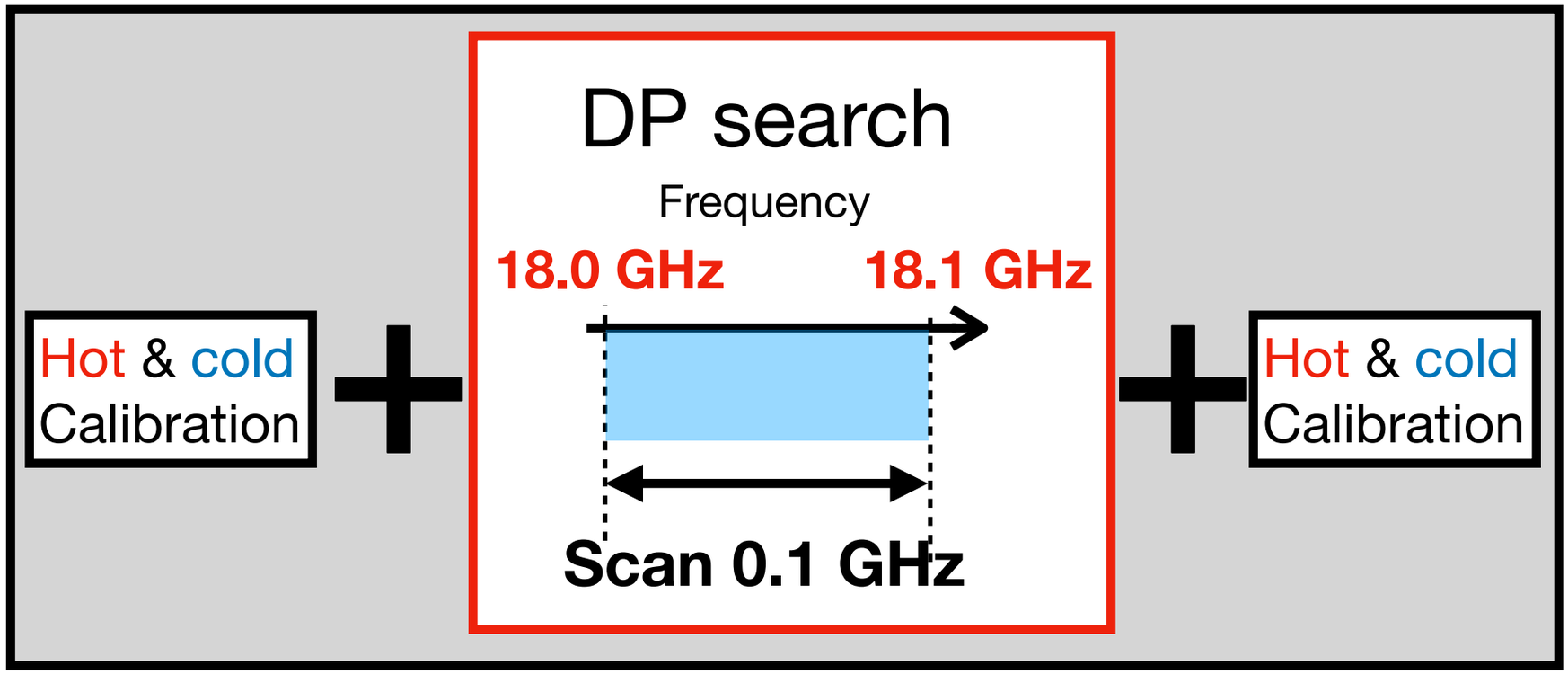
G : ~ +62 dB

T_{rx} : ~ 40 K $\ll$ 300K

Frequency scan

- Frequency: **18.0–26.5 GHz**
  - Capability of the spectrum analyzer:
    Frequency span of 2.5 MHz for each measurement at each center frequency
- Resolution (RBW): **300 Hz** ≪ **20 kHz** (signal peak width)

One measurement cycle (~40 min)



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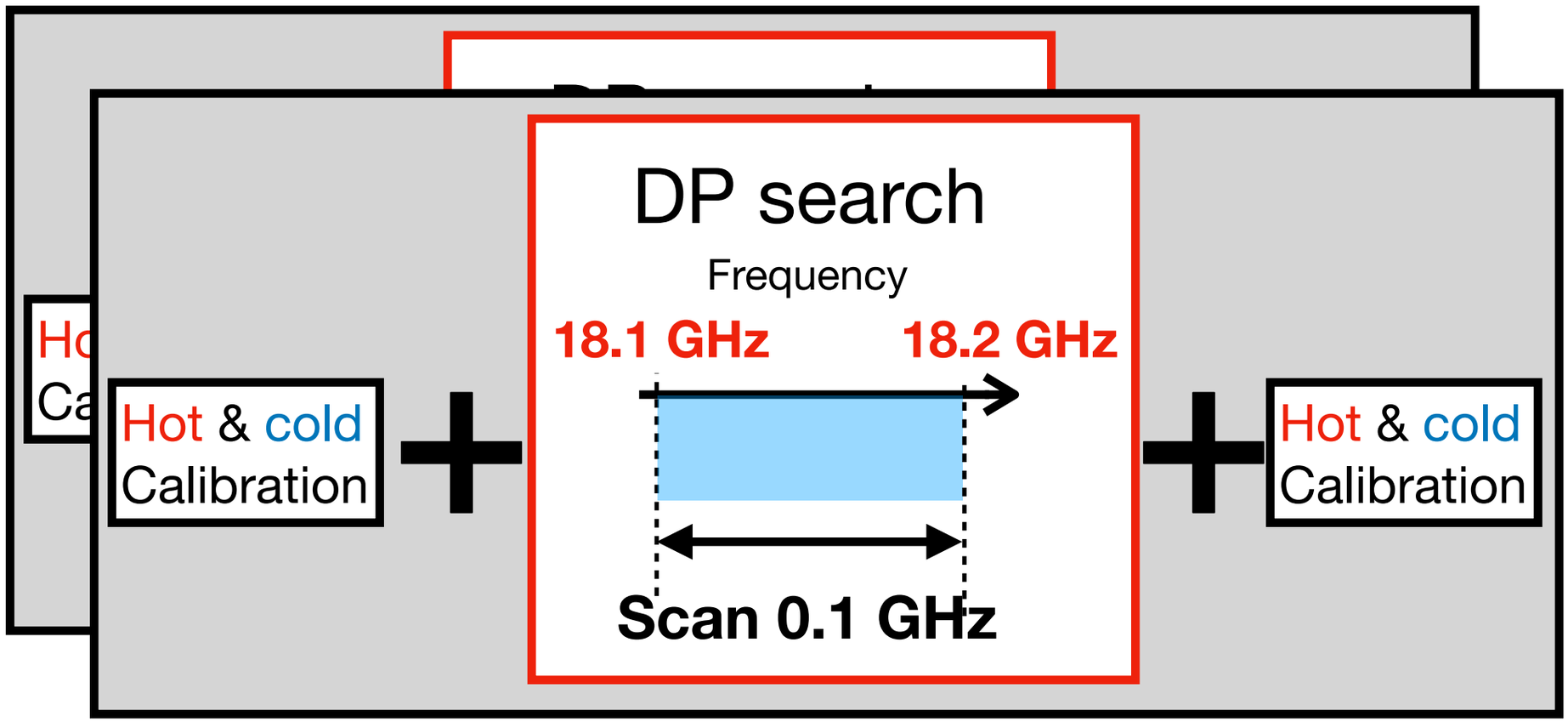

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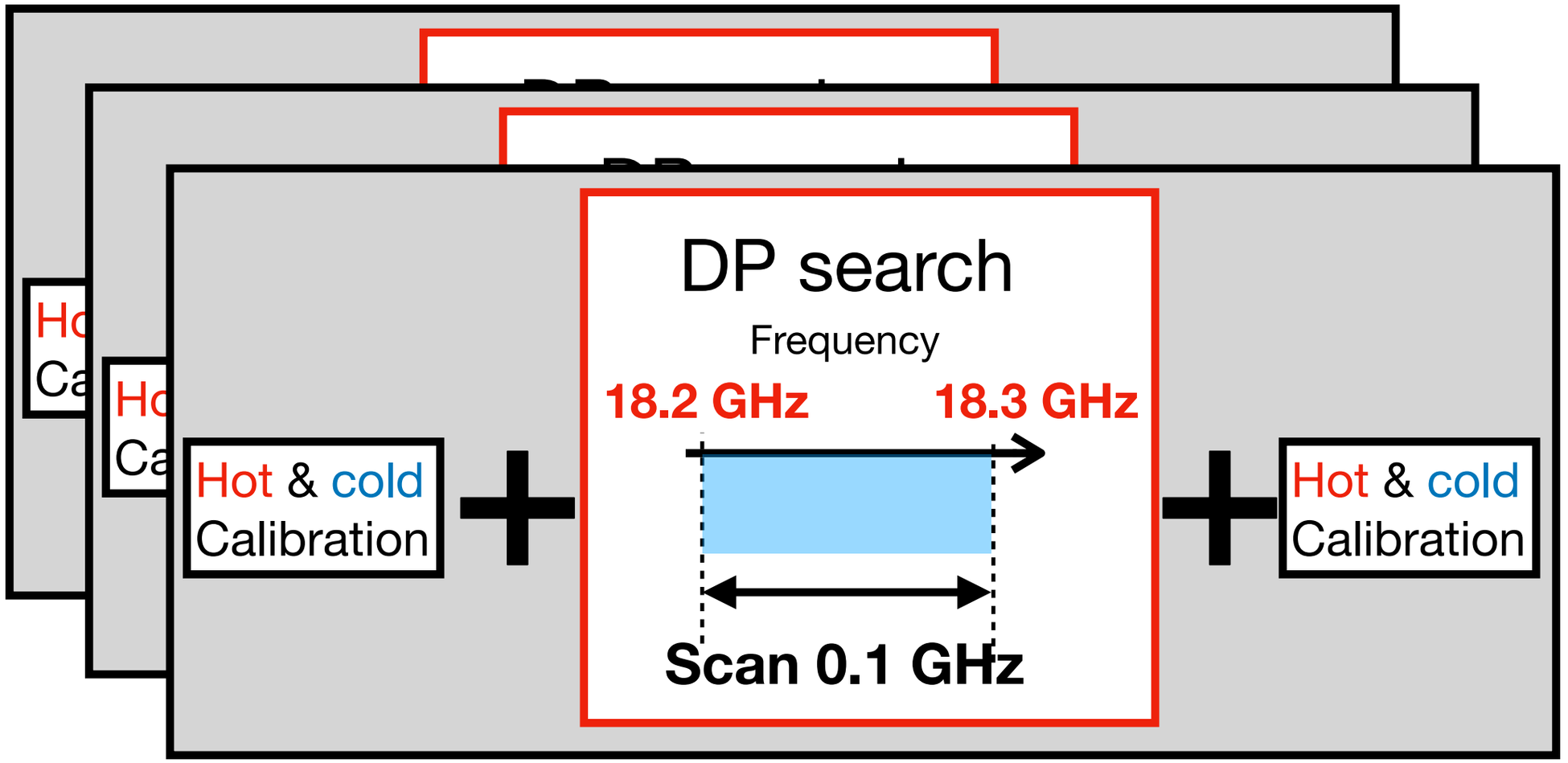

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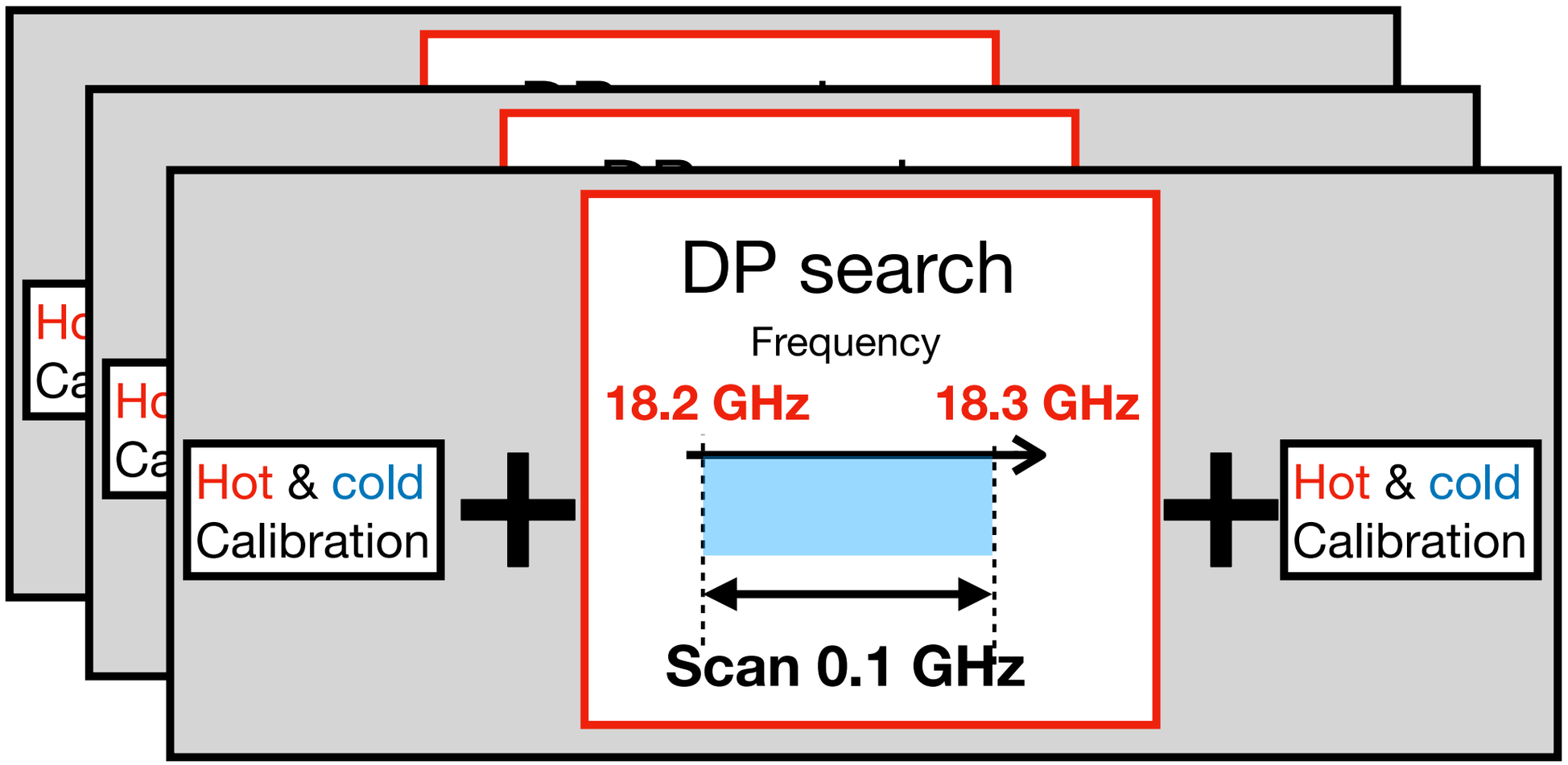


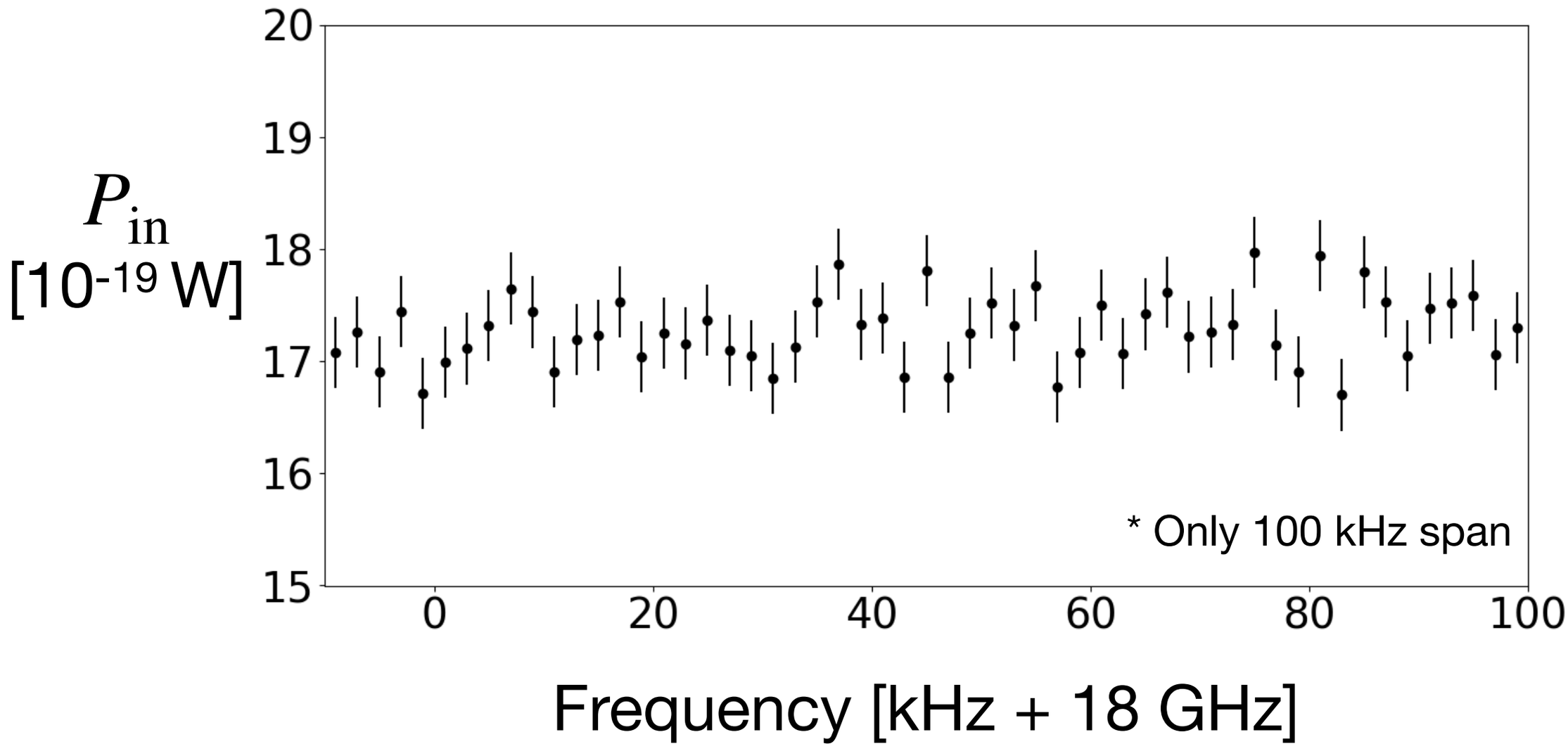
× **85 times**

To cover
18—26.5 GHz

Date: Nov. 29—Dec. 10 in 2021 ~ **2 weeks**

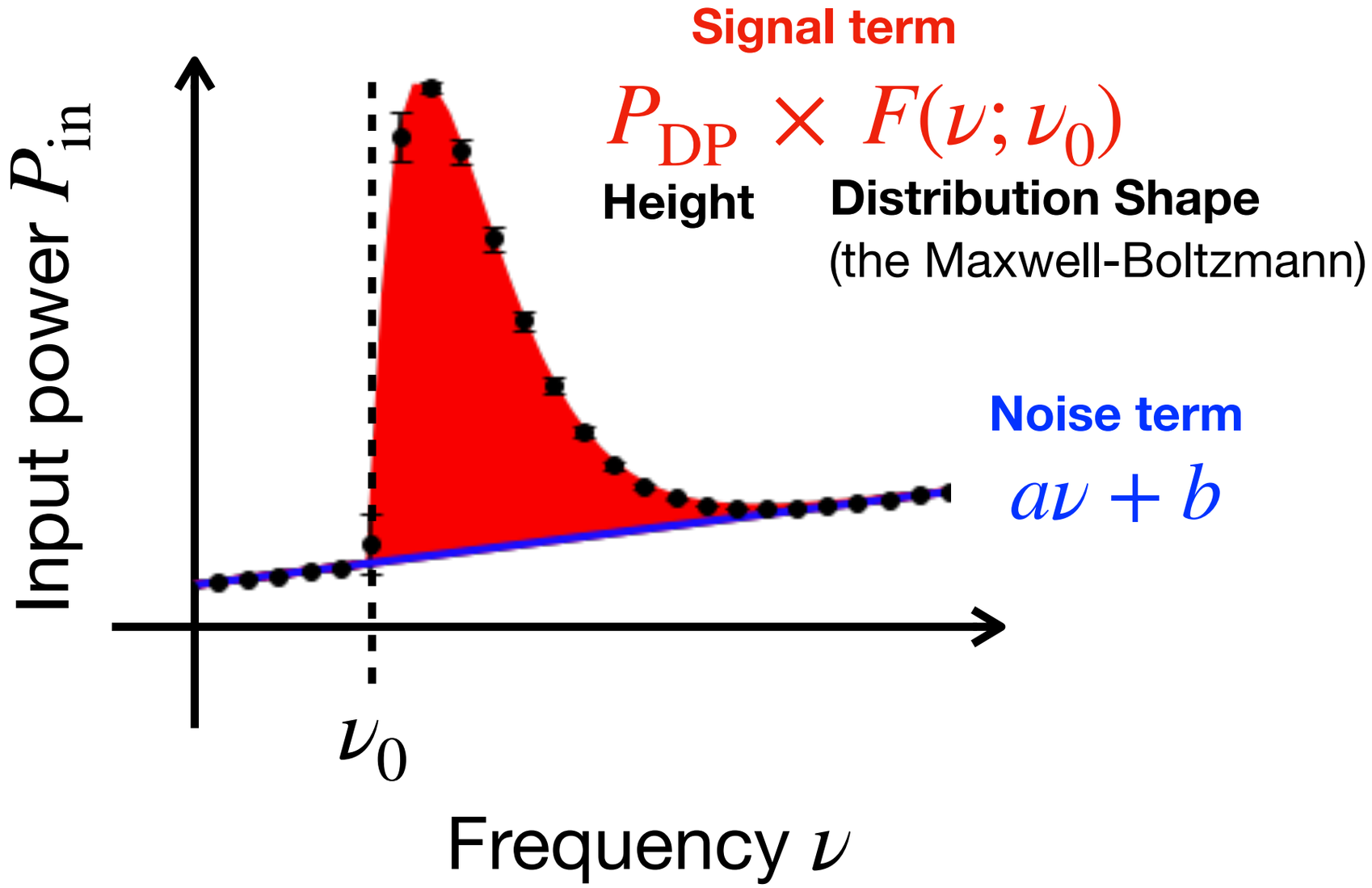
Calculated input power: $P_{\mathrm{in}}(\nu)$

- $P_{\mathrm{measure}} = G\left(\boldsymbol{P_{\mathrm{in}}} + k_{\mathrm{B}} T_{\mathrm{rx}} \Delta\nu \right)$
- $(G,\ T_{\mathrm{rx}})$ from hot & cold calibration



Signal extraction

- 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



Signal term

$$P_{\mathrm{DP}} \times F(\nu;\nu_0)$$

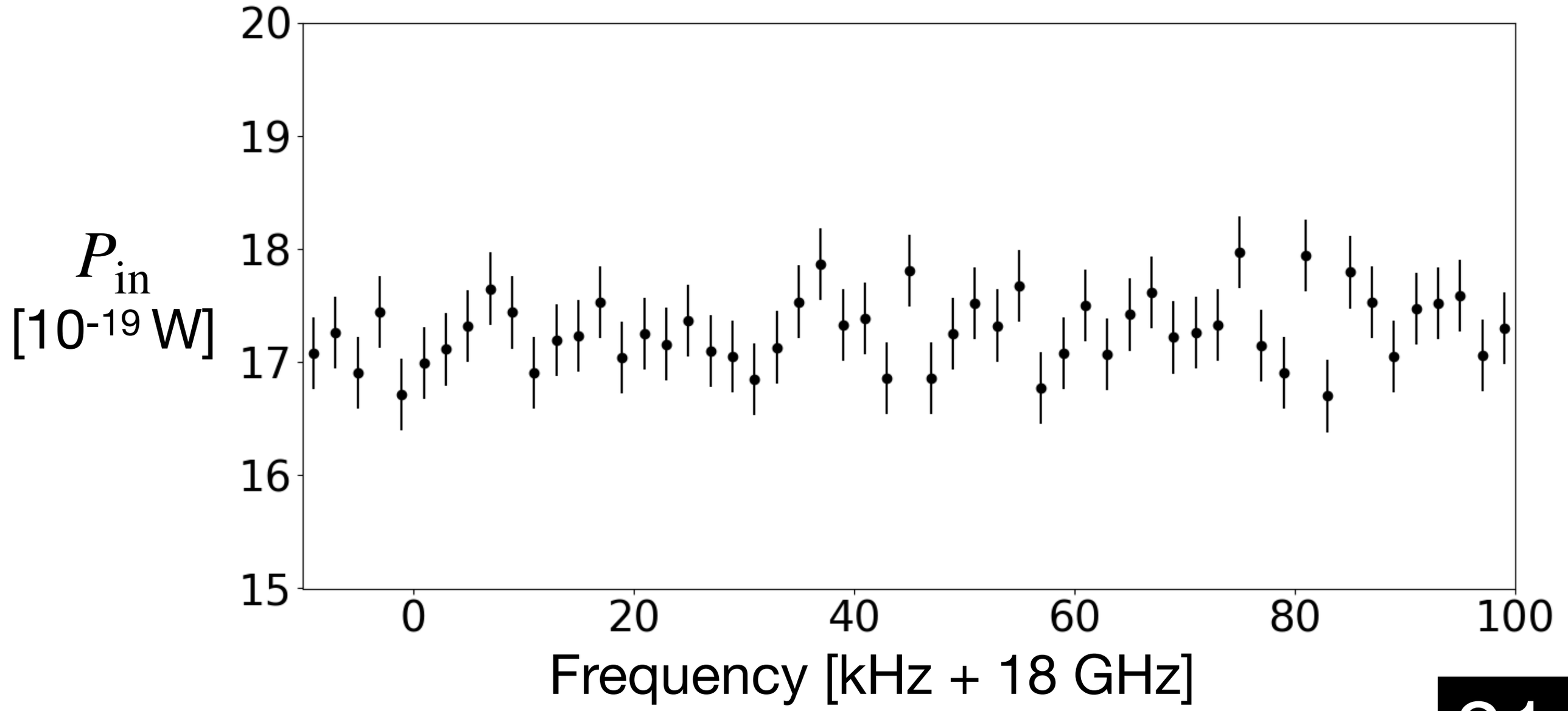
Height **Distribution Shape**
(the Maxwell-Boltzmann)

Noise term

$$a\nu + b$$

Repeat signal extraction with shifting ν_0 (i.e. m_{DP})

- $\nu_0 \equiv m_{\mathrm{DP}}c^2/h$ is unknown.
- It is shifted by **+2kHz** steps from 18 GHz to 26.5 GHz



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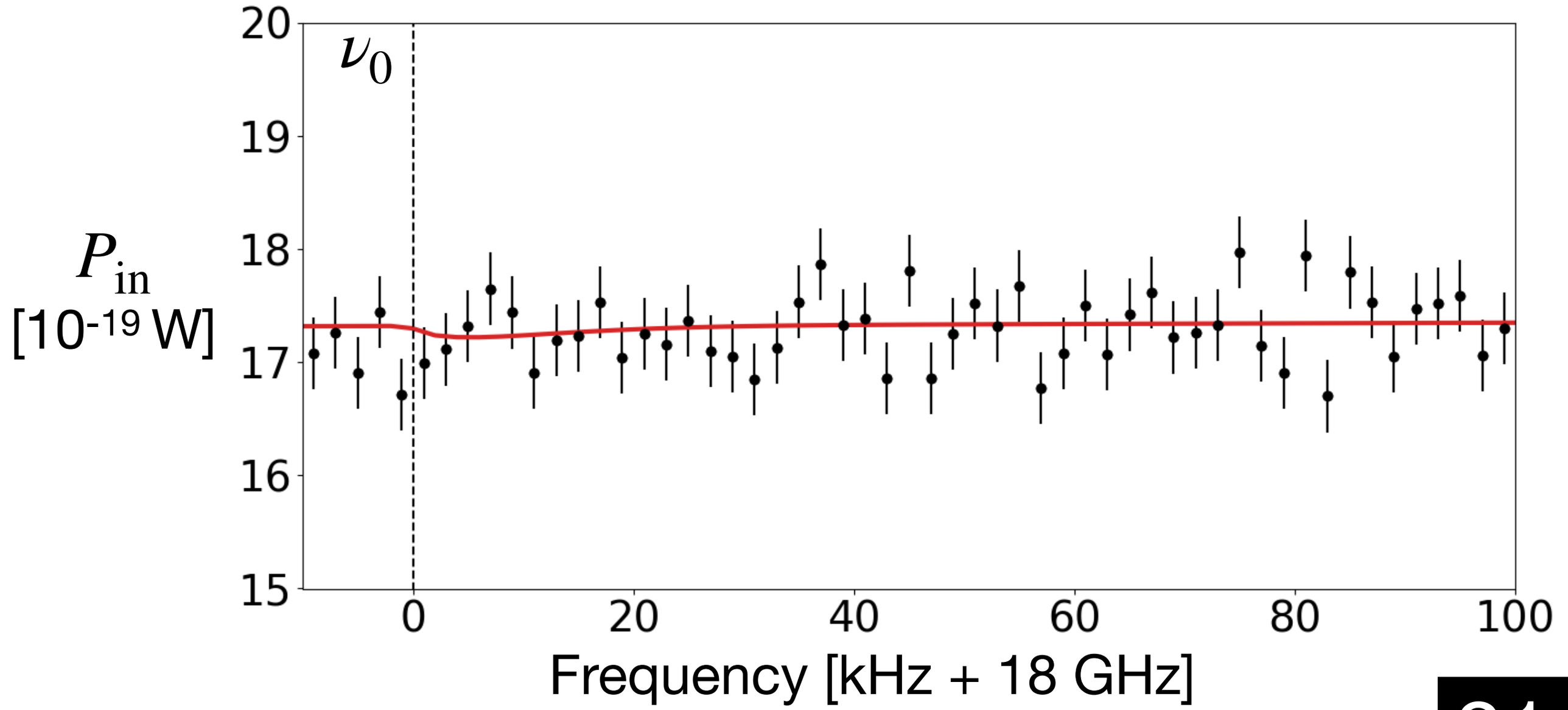

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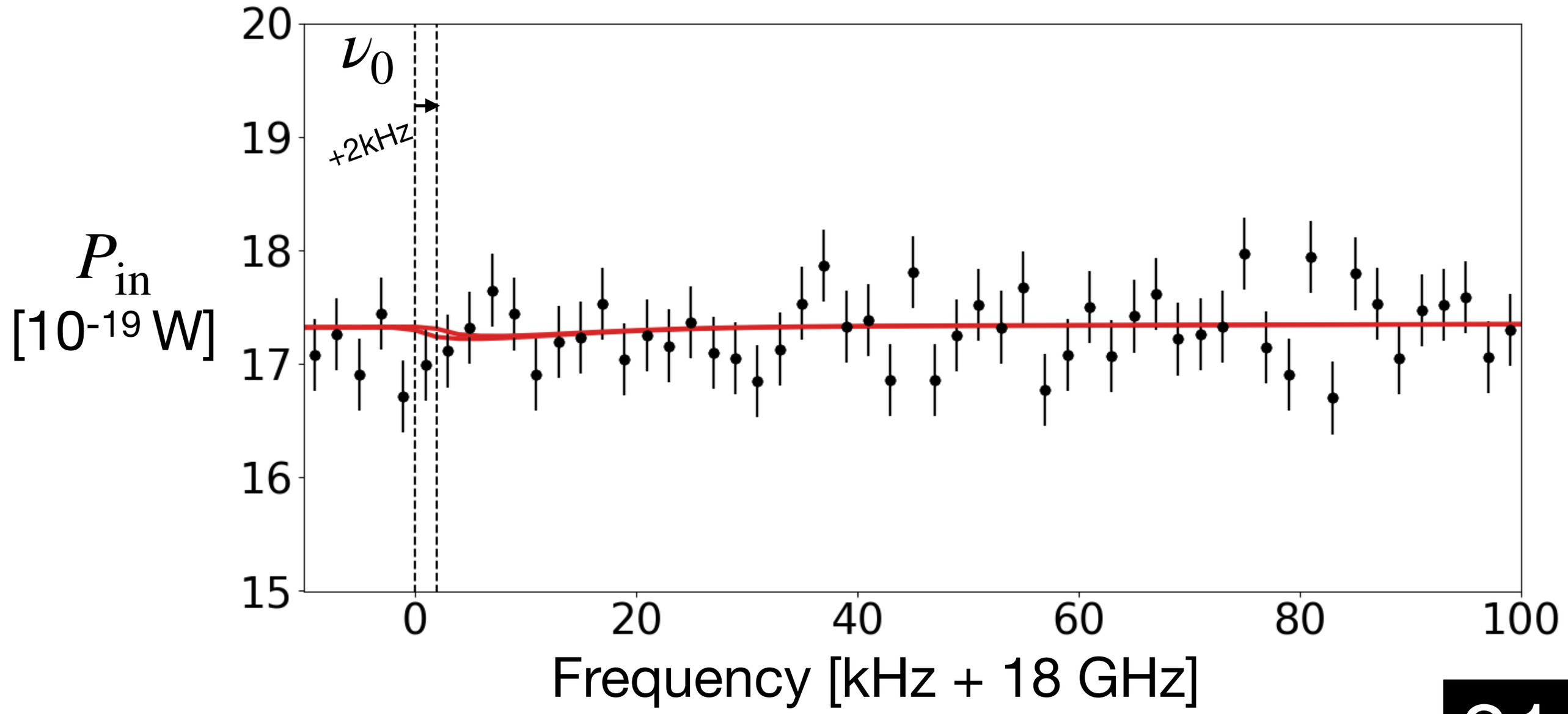

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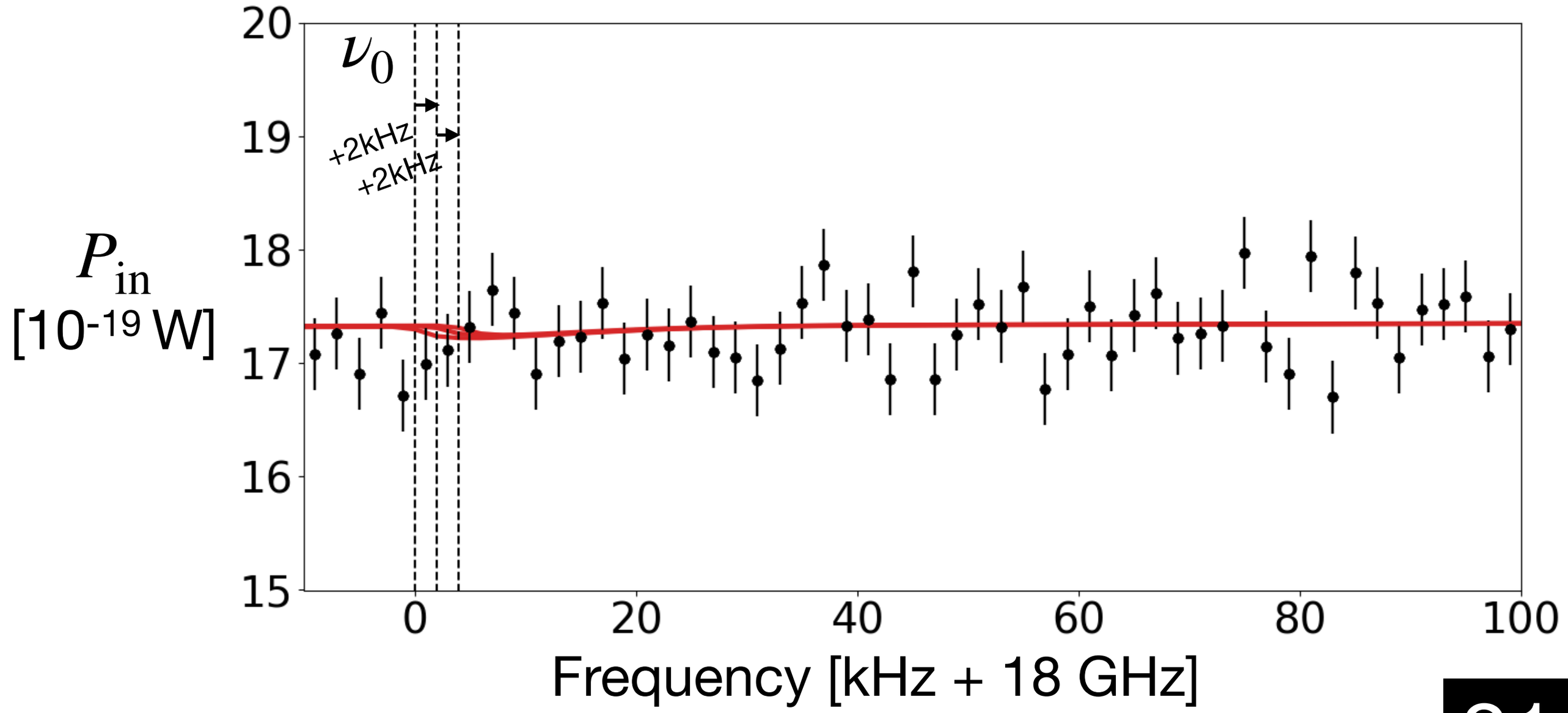

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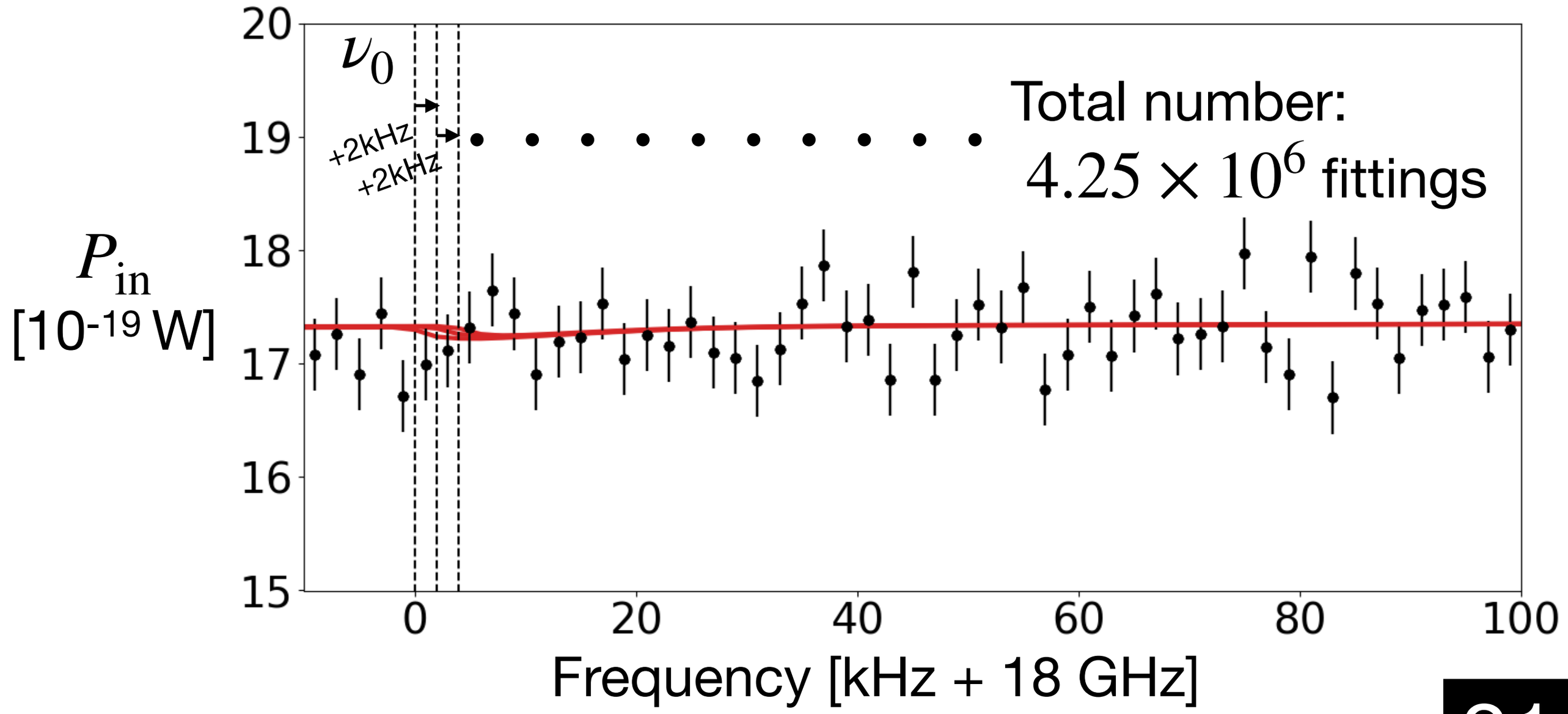
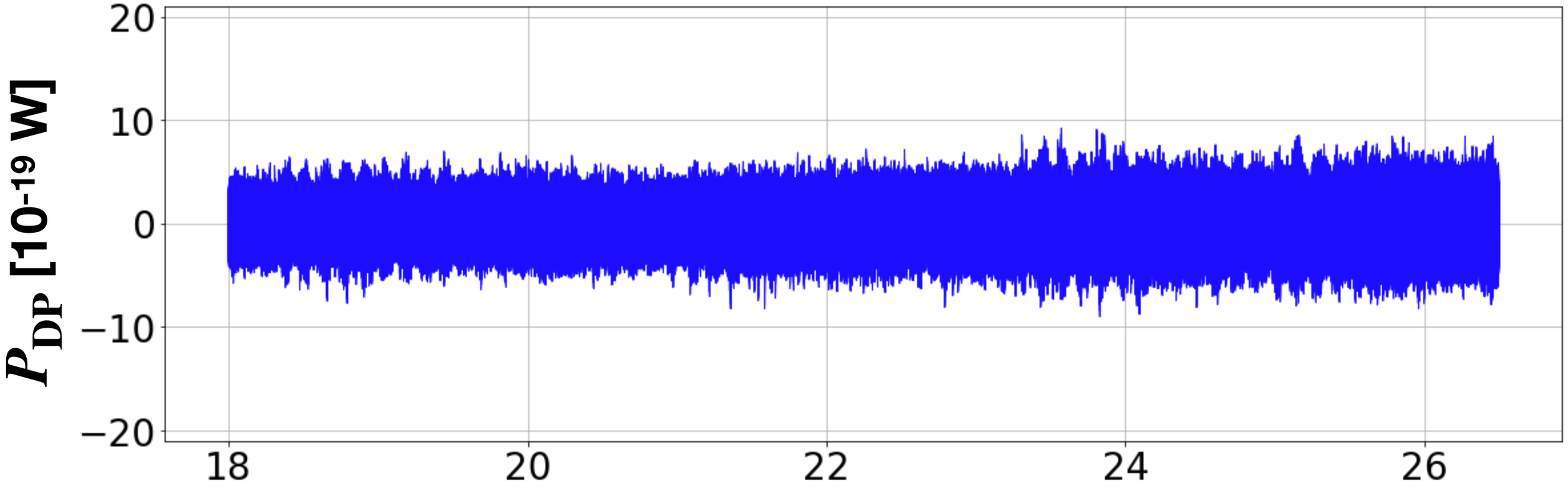


Fitted results: P_{DP}

All range: 18.0—26.5 GHz (4.25×10^6 fittings)



Zero-consistent with precision of $\approx 10^{-19}\,\mathrm{W}$

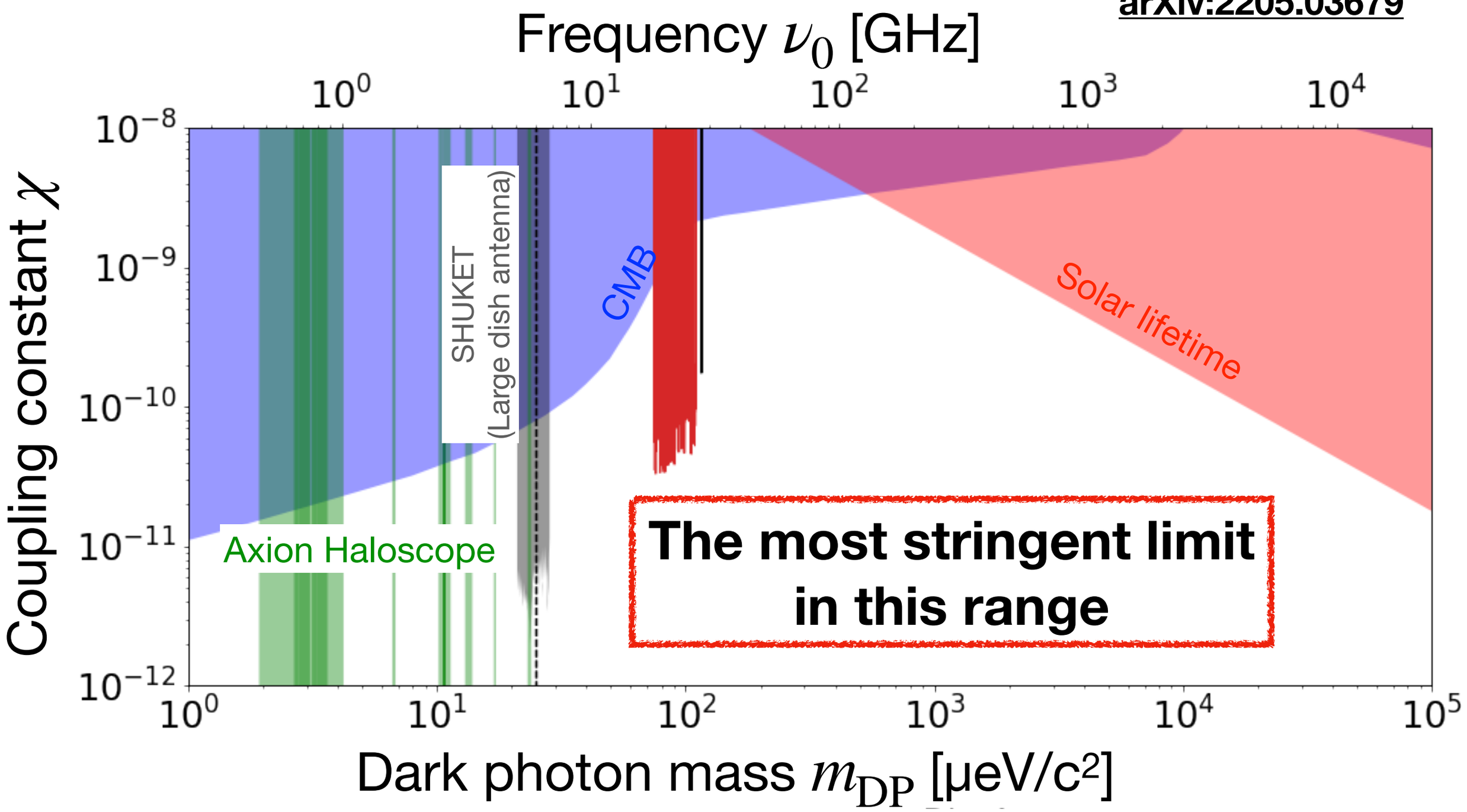
Global p-value under null-signal hypothesis = **68 %**

(considering look-elsewhere effect)

➡ **No significant signal excess** was found.

Upper limit on χ by DOSUE-RR

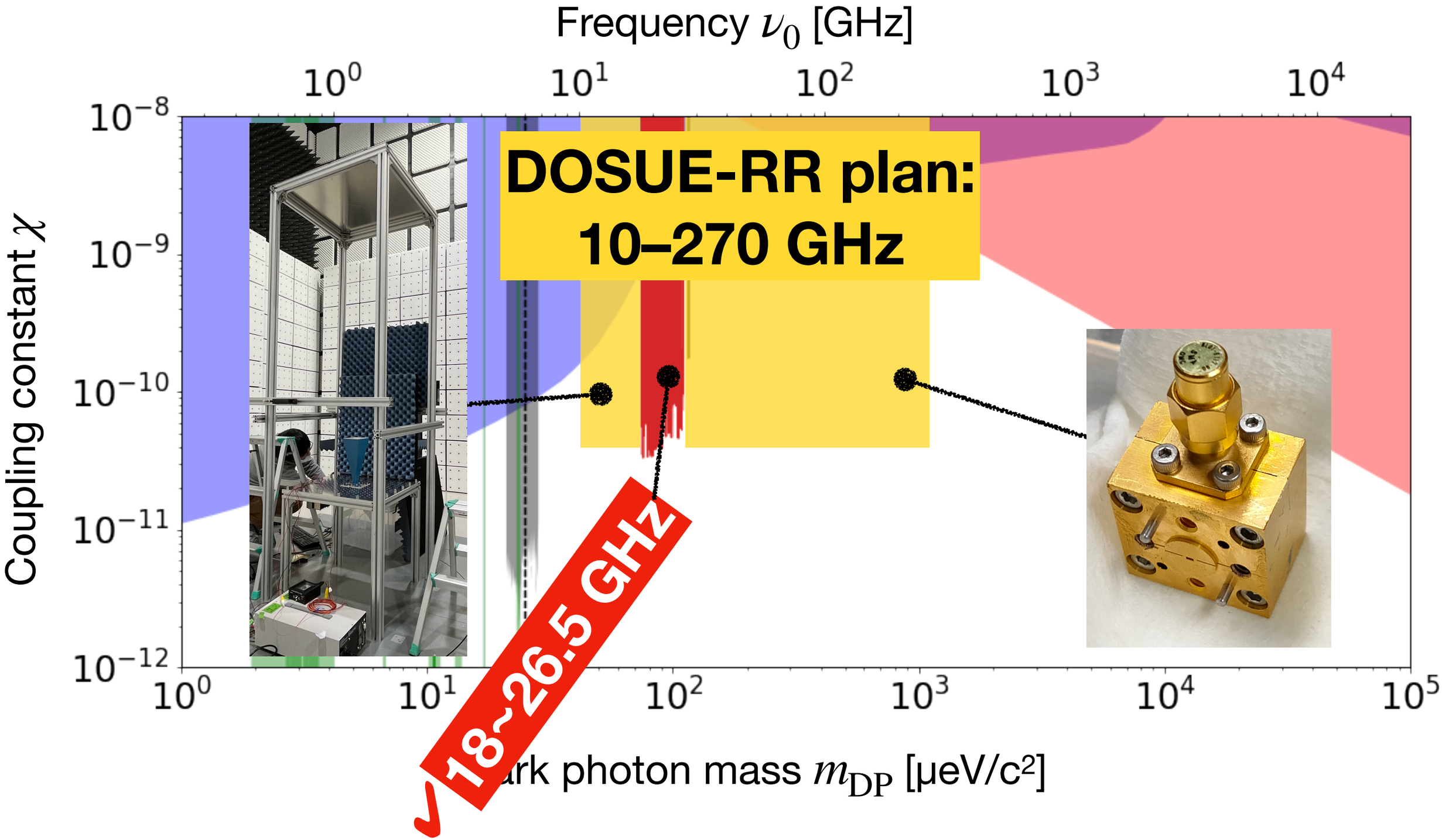
arXiv:2205.03679



Summary

- We performed our first search for DP-CDM using the cryogenically cooled system.
- Search range: 18—26.5 GHz (m_{DP}=74—110 μeV/c²)
- No significant signal excess was found.
- Set the most stringent constraint to date!

  $\chi < (0.3—2.0) \times 10^{-10}$ @ 95 % C.L.

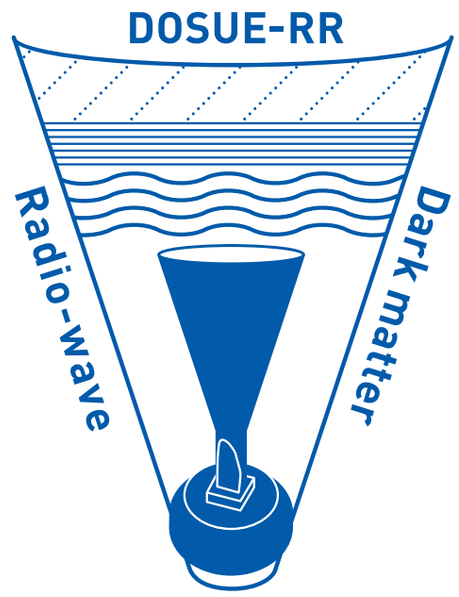

Frequency ν_0 [GHz]
10^0
10^1
10^2
10^3
10^4
Coupling constant χ
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
DOSUE-RR plan:
10–270 GHz
✓18~26.5 GHz
10^0
10^1
10^2
10^3
10^4
10^5
rk photon mass m_{DP} [μeV/c²]

Stay Tuned!

Backup

dou-sue-é double-R

DOSUE-RR experiment



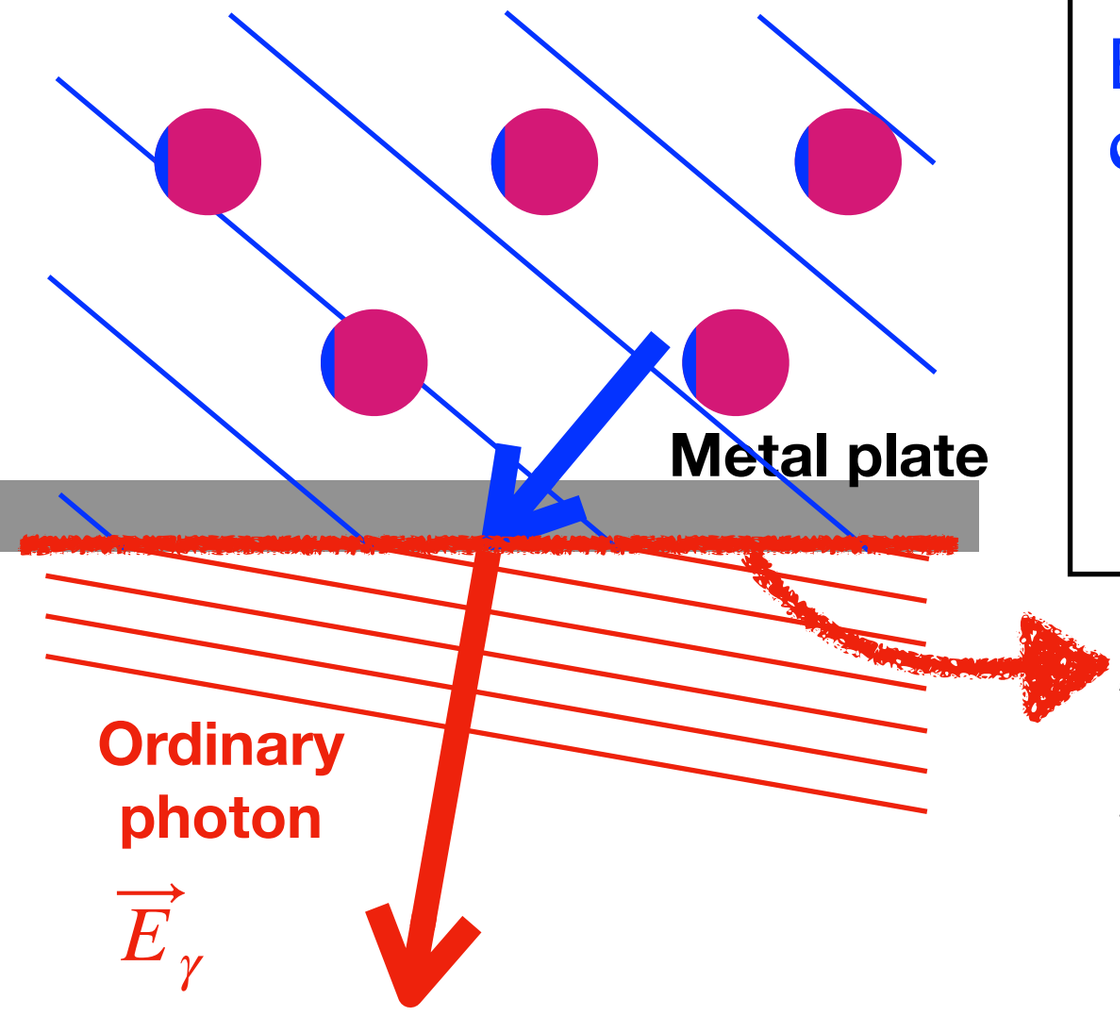
“ Dark-photon Observing System for Un-Explored Radio-Range”

O(GHz)—a few 100 GHz

Same frequency range
as in the CMB observation

Dark photon (DP) at metal surface

DP-CDM with a small EM-field



DP: A mixing state (χ: coupling constant)

EM-field
$\propto \chi \ll 1$

Dark photon

DP-field
(No interaction)

DP has a **small ($\propto \chi$)** electric field.

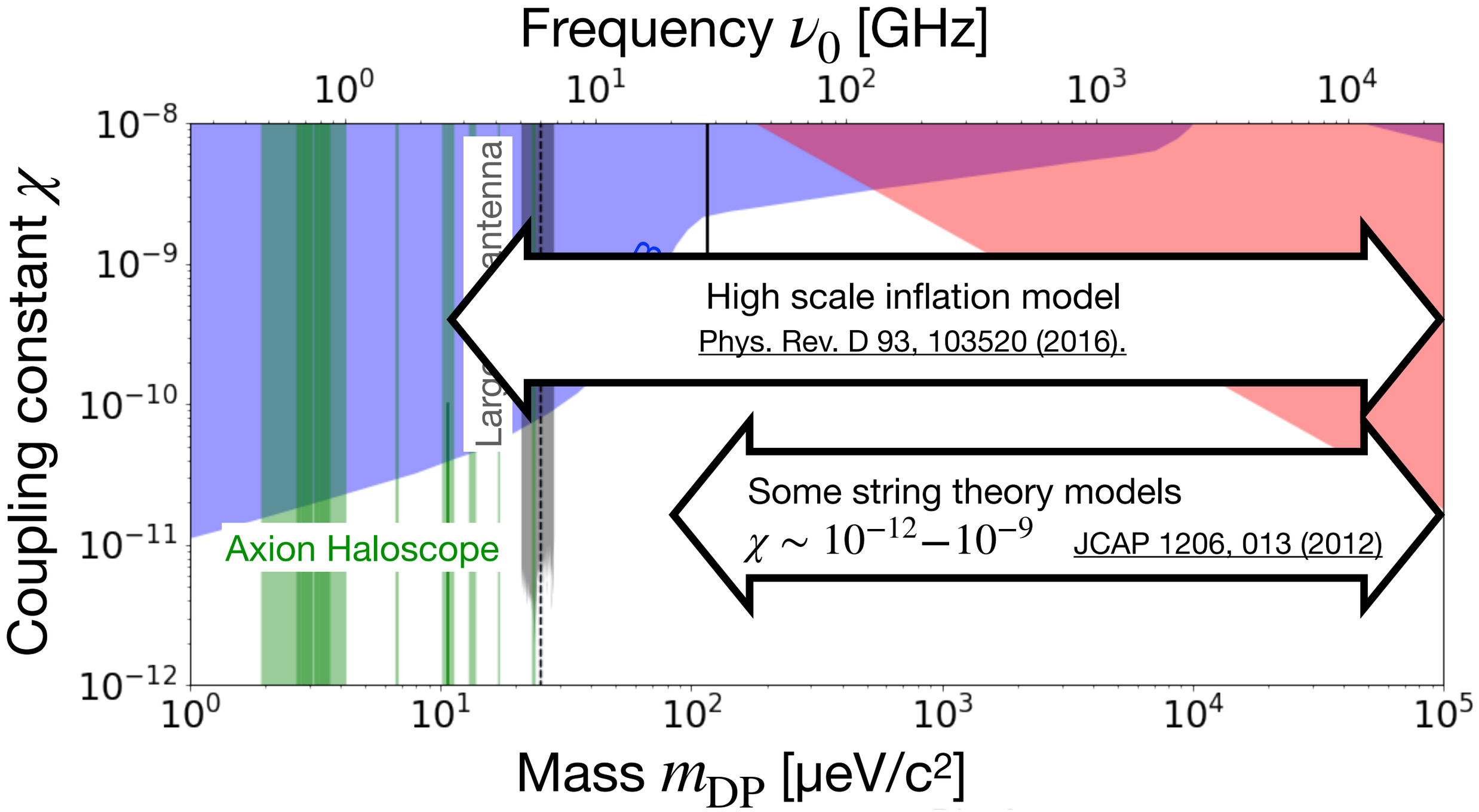
At the electromagnetic boundary,

$E_{||} = 0$ is required!

$$E_{||} = E_{\mathrm{DP},||} + E_{\gamma,||} = 0$$

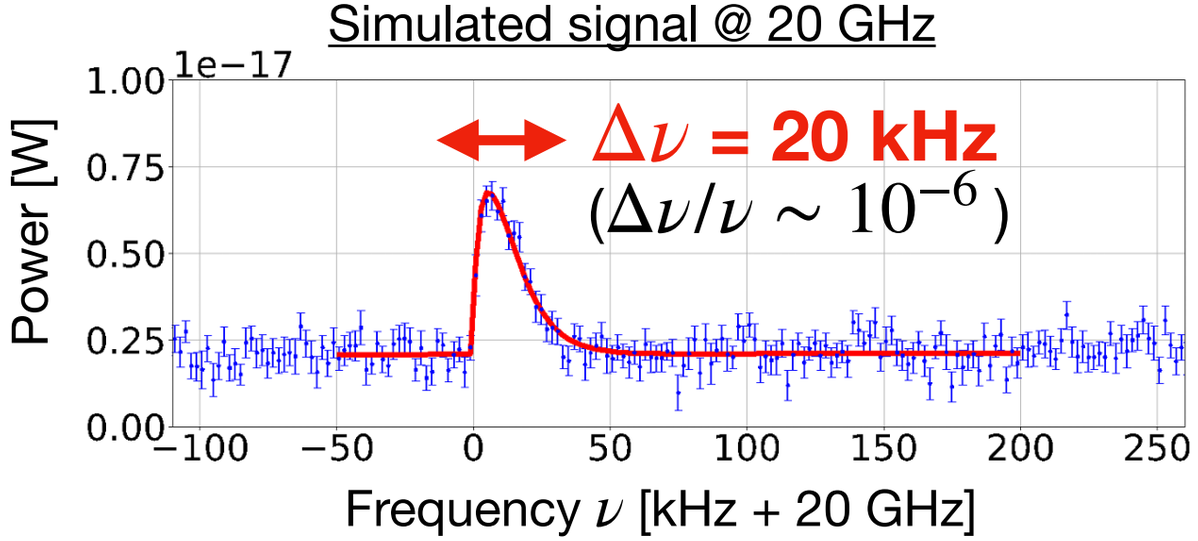
Ordinary photon $\vec{E}_\gamma$ is appeared to meet the requirement.

Constraints on DP-CDM

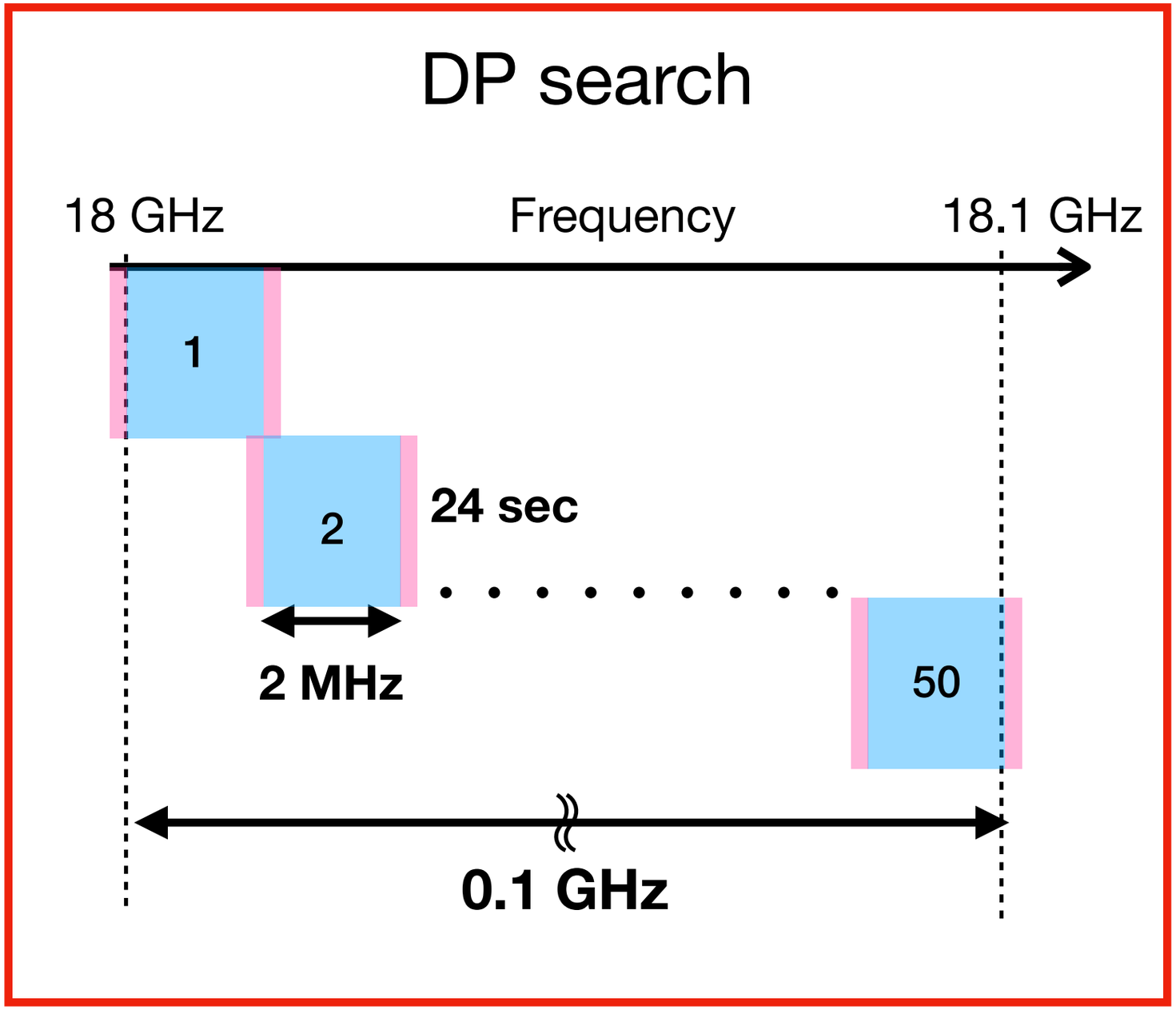


Frequency scan

- Frequency: **18.0–26.5 GHz**
- Resolution (RBW): **300 Hz** ≪ **20 kHz**
- Frequency span in one measurement:
  2.5 MHz (due to the spectrum analyzer)



One search cycle
(~20 min)



Conversion from P_{DP} to χ

$$\chi = 1.0 \times 10^{-10} \left(\frac{P_{\mathrm{DP}}}{10^{-19}\,\mathrm{W}} \frac{17.3\,\mathrm{cm}^2}{A_{\mathrm{eff}}} \frac{0.39\,\mathrm{GeV/cm}^3}{\rho_{\mathrm{CDM}}} \right)^{1/2}$$

Systematics errors were applied here:

Source	Systematics [%]	
Gain G	4.0	Calibration or simulation uncertainties
A_{eff}	4.2	
ρ_{CDM}	3.9	← Theory model
Frequency binning	0.6	
Alignment of metal	<0.1	
Direction of conversion	<0.1	
Total	7.0	