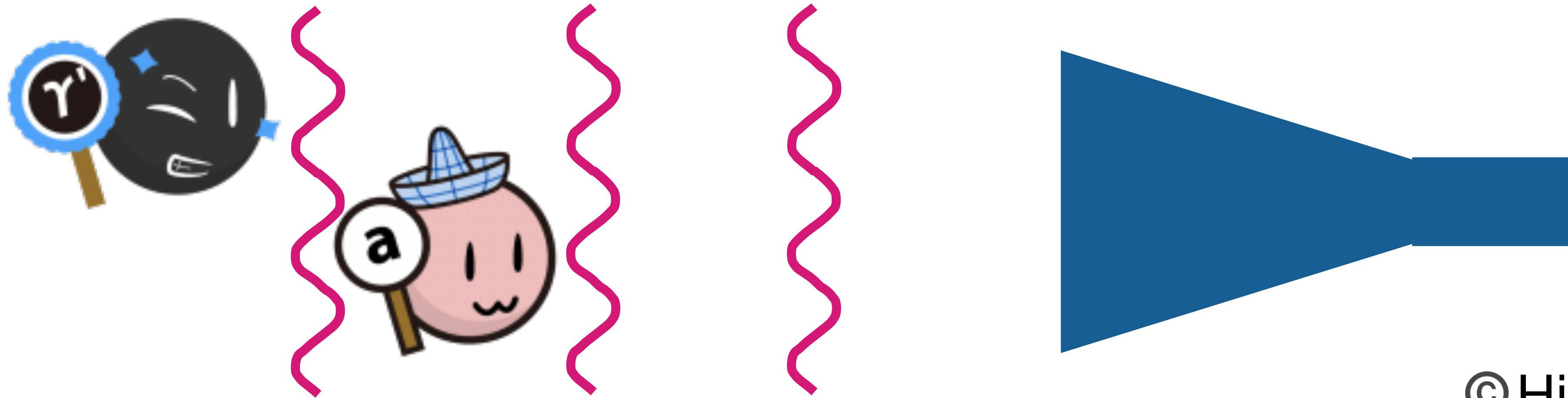


Broadband search for wavy dark matter using antenna in the millimeter-wave range

Shunsuke Adachi (Kyoto University, Japan)

Nov. 30 2023, International Workshop on Multi-probe approach to wavy dark matters @ Seoul, Korea

Wavy dark matter

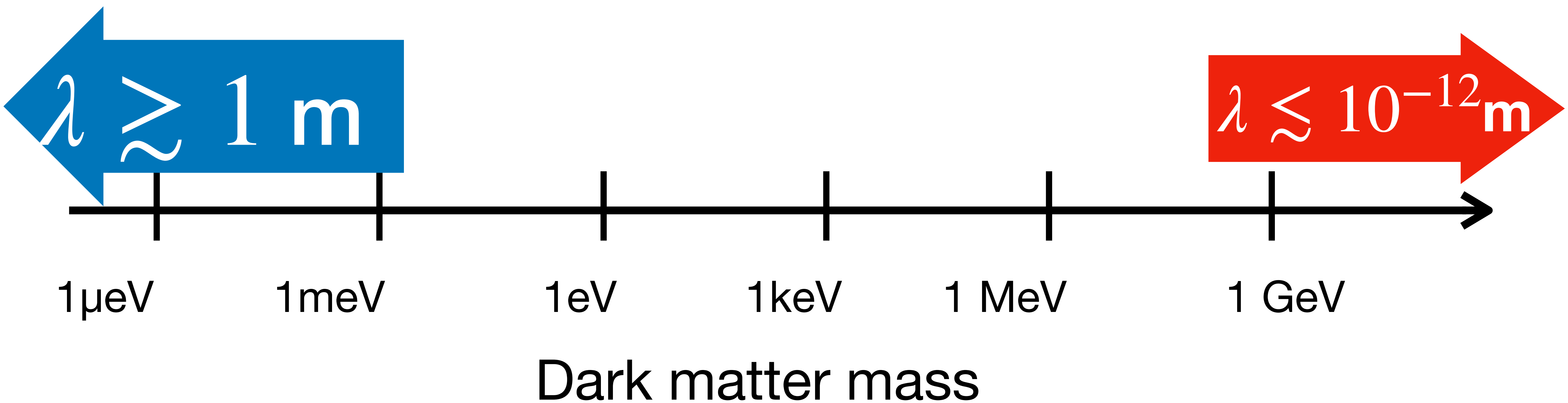
For non-relativistic particles: $\lambda_{\text{de Broglie}} = \dfrac{h}{m v_{\text{DM}}}$

“Ultra Light" DM

||

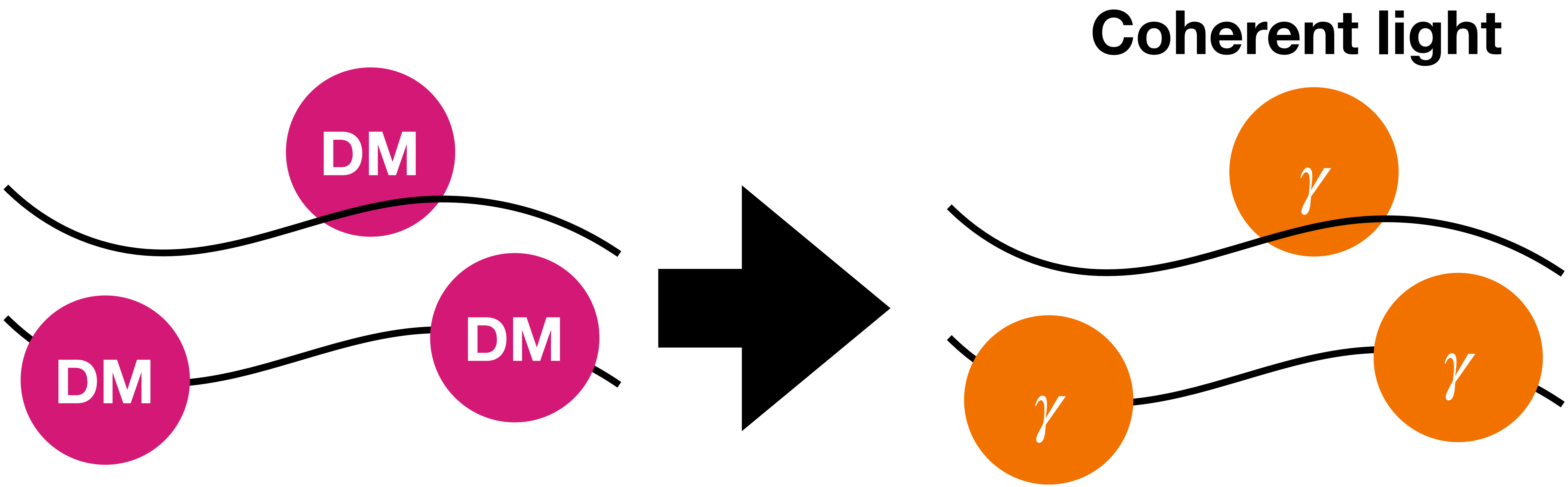
“Wavy" DM

WIMP



Wavy DM field has **coherency** in the human size or more.

If it can be converted to photons...



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

*Considering CDM with a low momentum

Measuring frequency spectrum by FFT (**Spectroscopy**) is a good method to search for it in **wide mass range**.

The wavy DM candidates having a coupling with photons

Dark photon

$F_{\mu\nu}$: Ordinary photon

$\tilde{\chi}_{\mu\nu}$: Dark photon

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m_{\mathrm{DP}}^2}{2}\tilde{X}_\mu\tilde{X}^\mu + J^\mu A_\mu$$

PRD 93 103520 (2016), JCAP 1206, 013 (2012)

- Kinematic mixing with photon: χ
- High-scale inflation model or some string theory models

Axion or Axion-like particle (ALP)

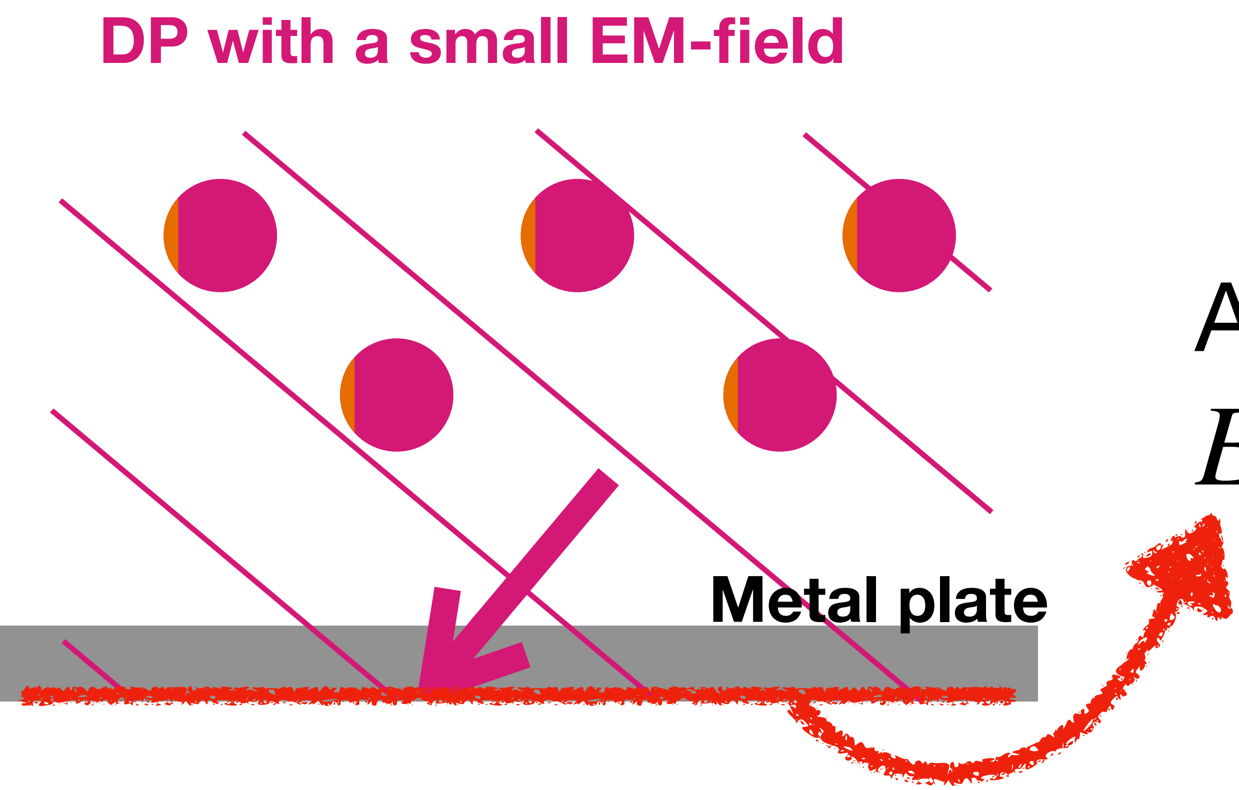
$$\mathscr{L}_{a\gamma\gamma} = -\frac{1}{4}g_{a\gamma\gamma}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\,a\,\vec{E}\cdot\vec{B}$$

$F_{\mu\nu}, \tilde{F}^{\mu\nu}$: Ordinary photon

a : Axion, ALP

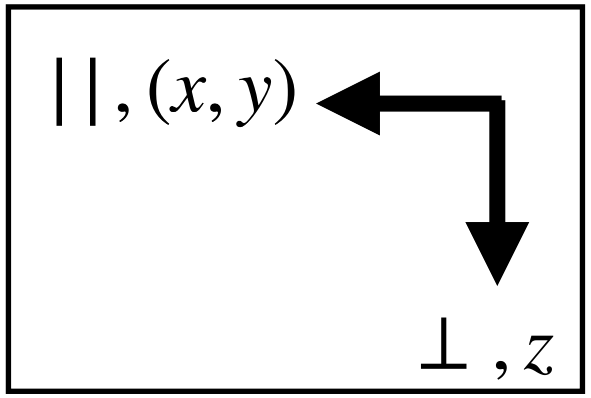
- Coupling with photon and magnetic field: $g_{a\gamma\gamma}$
- Axion (Solving Strong CP problem): $g_{a\gamma\gamma} = \left(0.2\frac{E}{N} - 0.4\right)\frac{m_a}{\mathrm{GeV}^2}$ DFSZ E/N=8/3, KSVZ E/N=0
- ALP: No relationship

Dark photon at EM boundary



At the electromagnetic boundary,
$E_{||} = 0$ is required!

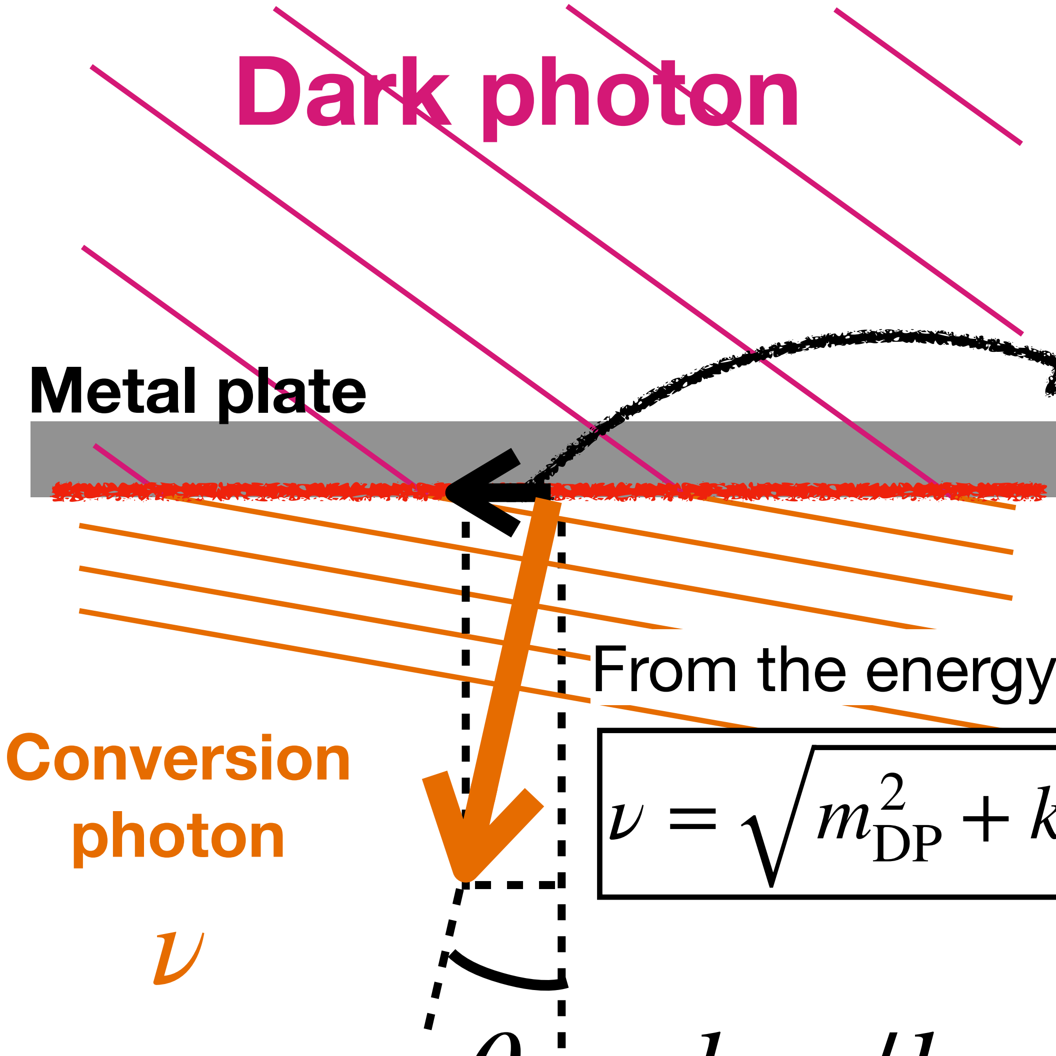
$$E_{||} = E_{\mathrm{DP},\,||} + E_{\gamma,\,||} = 0 \quad \begin{cases} z = 0 \\ \text{any } x, y \end{cases}$$



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

DP conversion to photon

We know that the velocity is small: $\beta_{\mathrm{DM}} \equiv v_{\mathrm{DM}}/c \sim 10^{-3}$



From the boundary condition:

$$k_{\gamma,\parallel} \lesssim \beta_{\mathrm{DM}} m_{\mathrm{DP}}$$

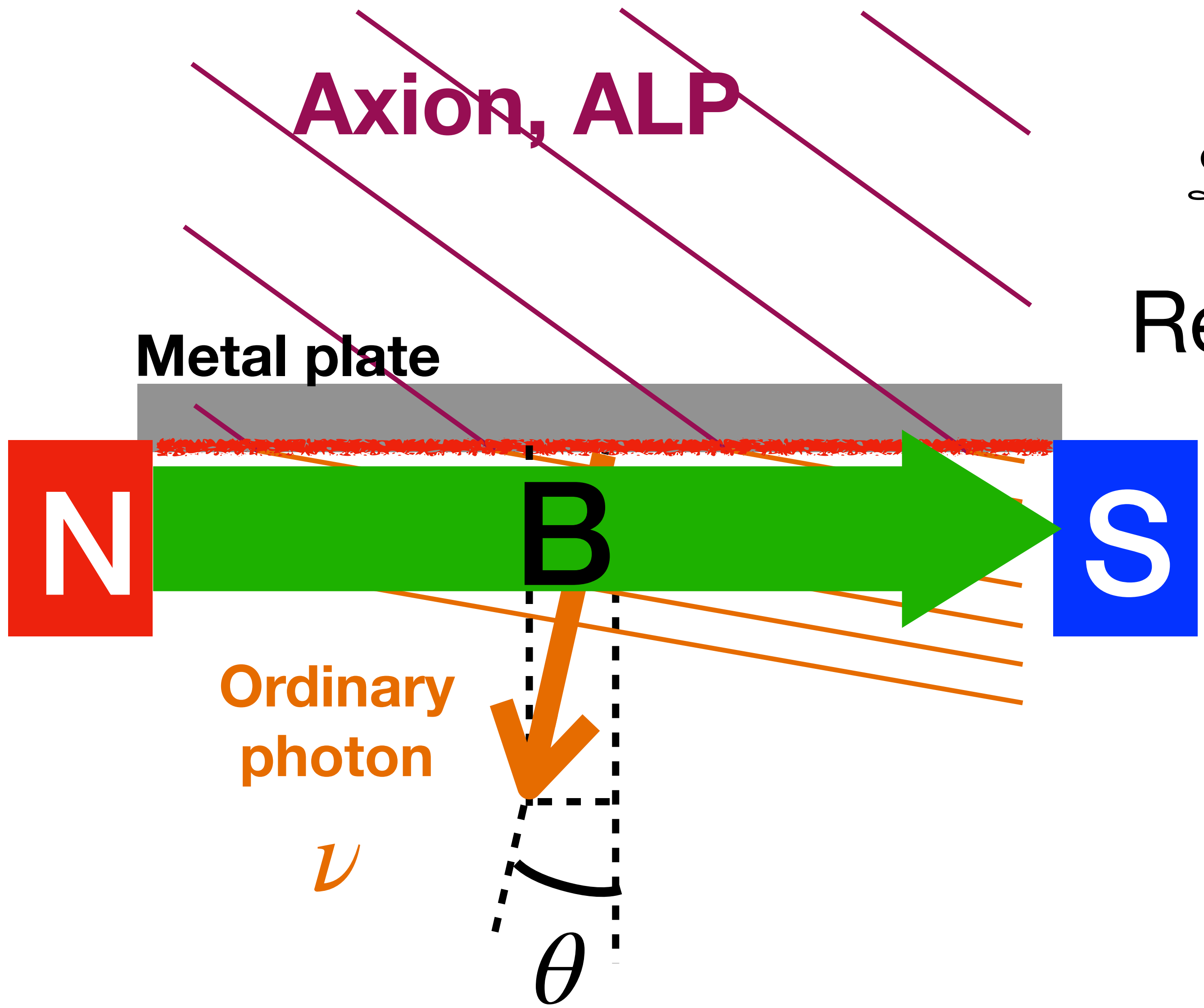
From the energy conservation:

$$\nu = \sqrt{m_{\mathrm{DP}}^2 + k_{\mathrm{DP}}^2} \sim m_{\mathrm{DP}}$$

$$\theta \sim k_{\gamma,||}/k_{\gamma,\perp} \lesssim \beta_{\mathrm{DM}} \sim 0.06^\circ$$

- Photon Direction : perpendicular to the plate
- Photon Frequency ν: ~ Mass m_{DP}

Axion conversion



$$\mathscr{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\, a\, \vec{E} \cdot \vec{B}$$

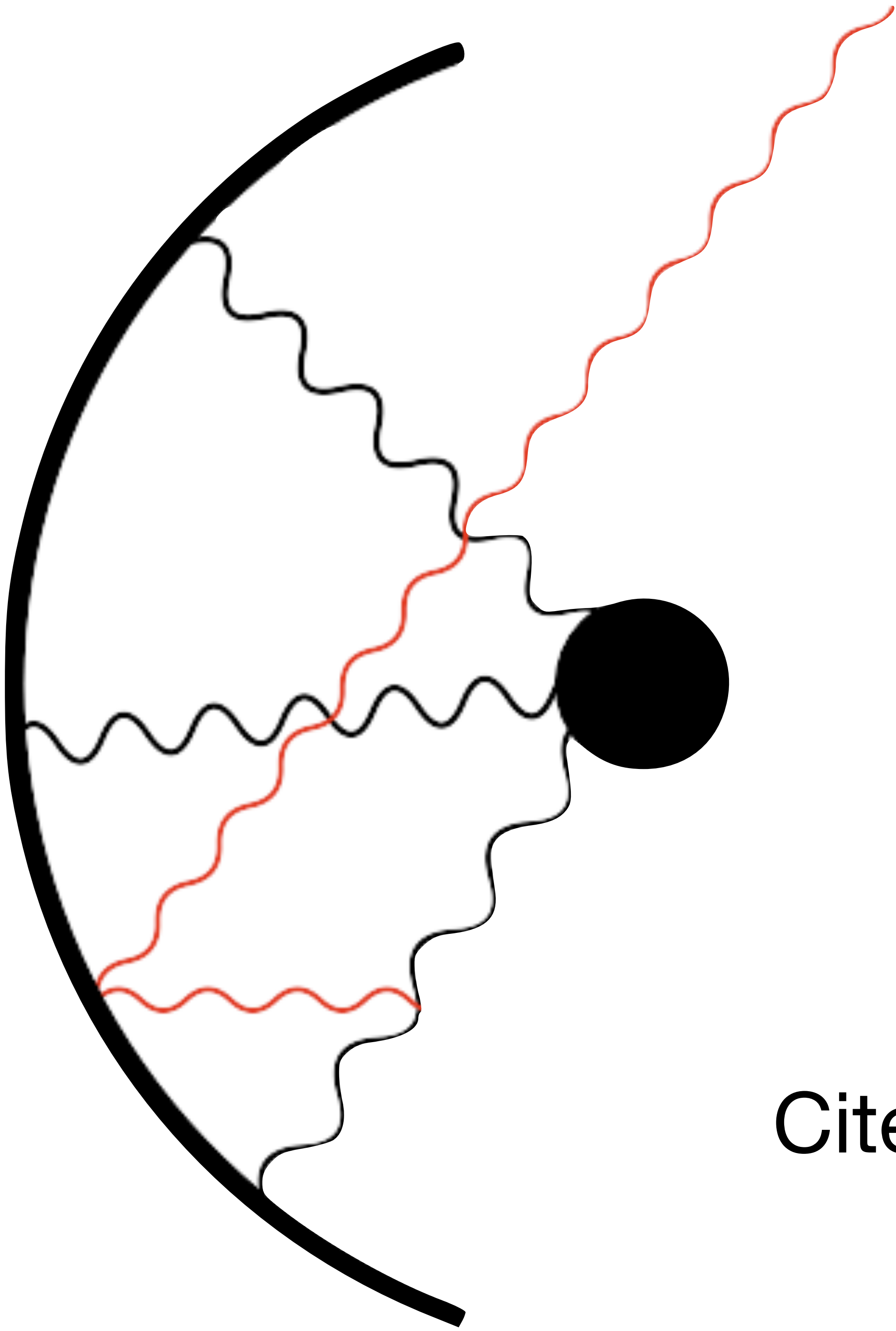
Require a **magnetic field**

Same as in DP case

- Photon Direction : perpendicular to the plate
- Photon Frequency ν: ~ Mass m_{DP}

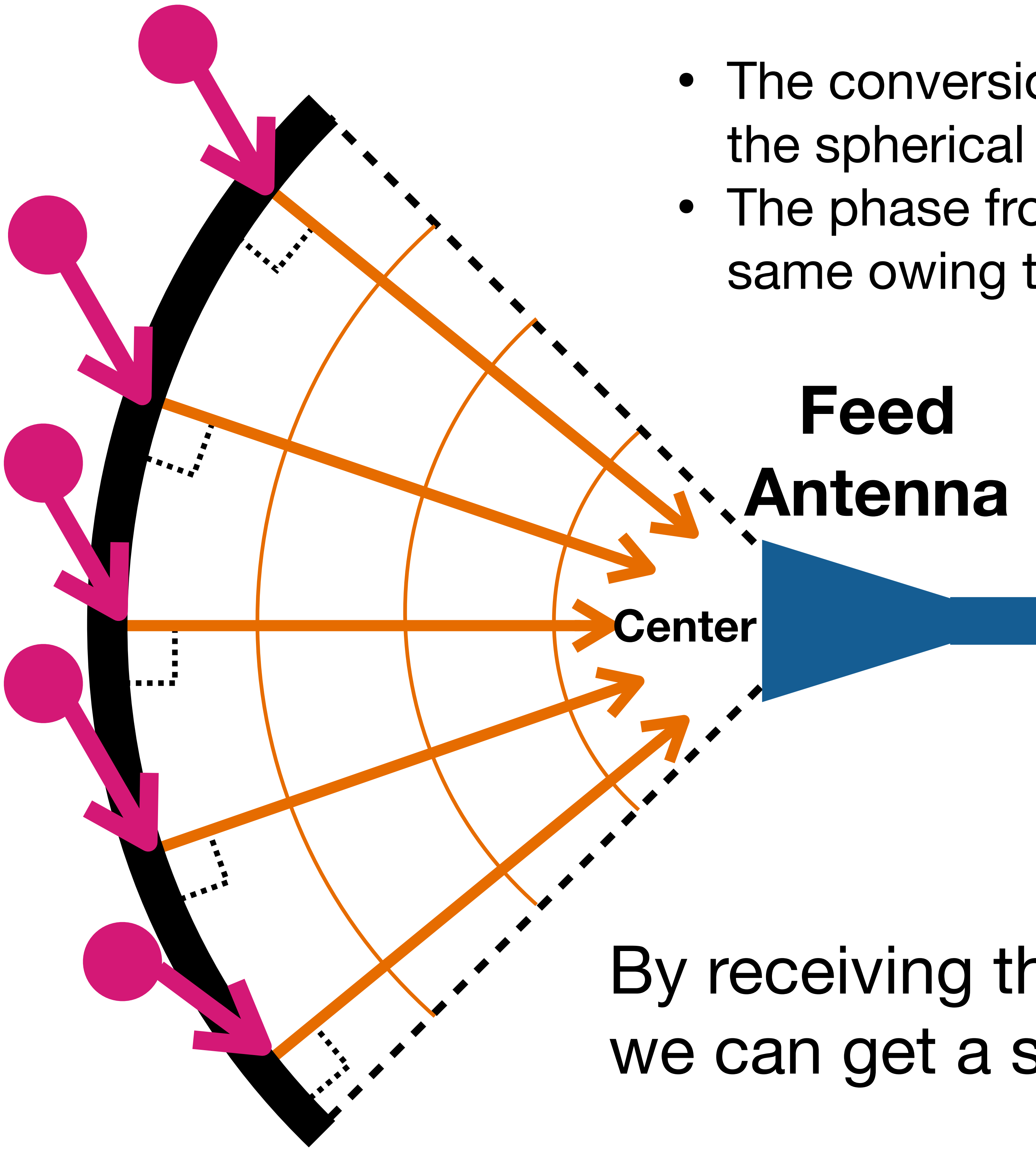
(Spherical) Dish Antenna Search

Proposed by D. Horns et al. (2013)



Cited from JCAP04(2013)016

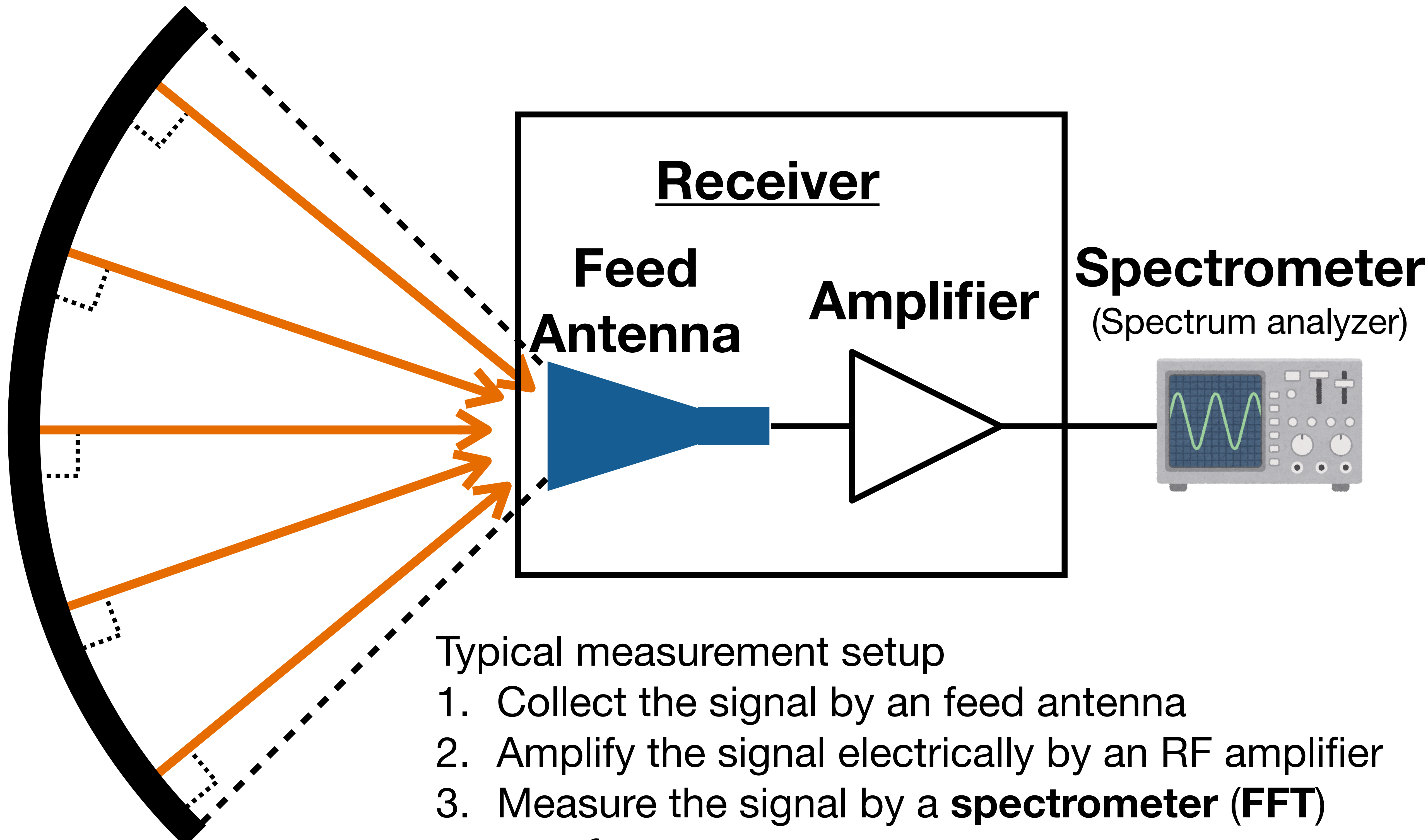
(Spherical) Dish Antenna Search



- The conversion photons from the spherical surface are focused at the center!
- The phase from any position on the dish is the same owing to the coherency.

By receiving the signal at the center, we can get a strong signal.

(Spherical) Dish Antenna Search



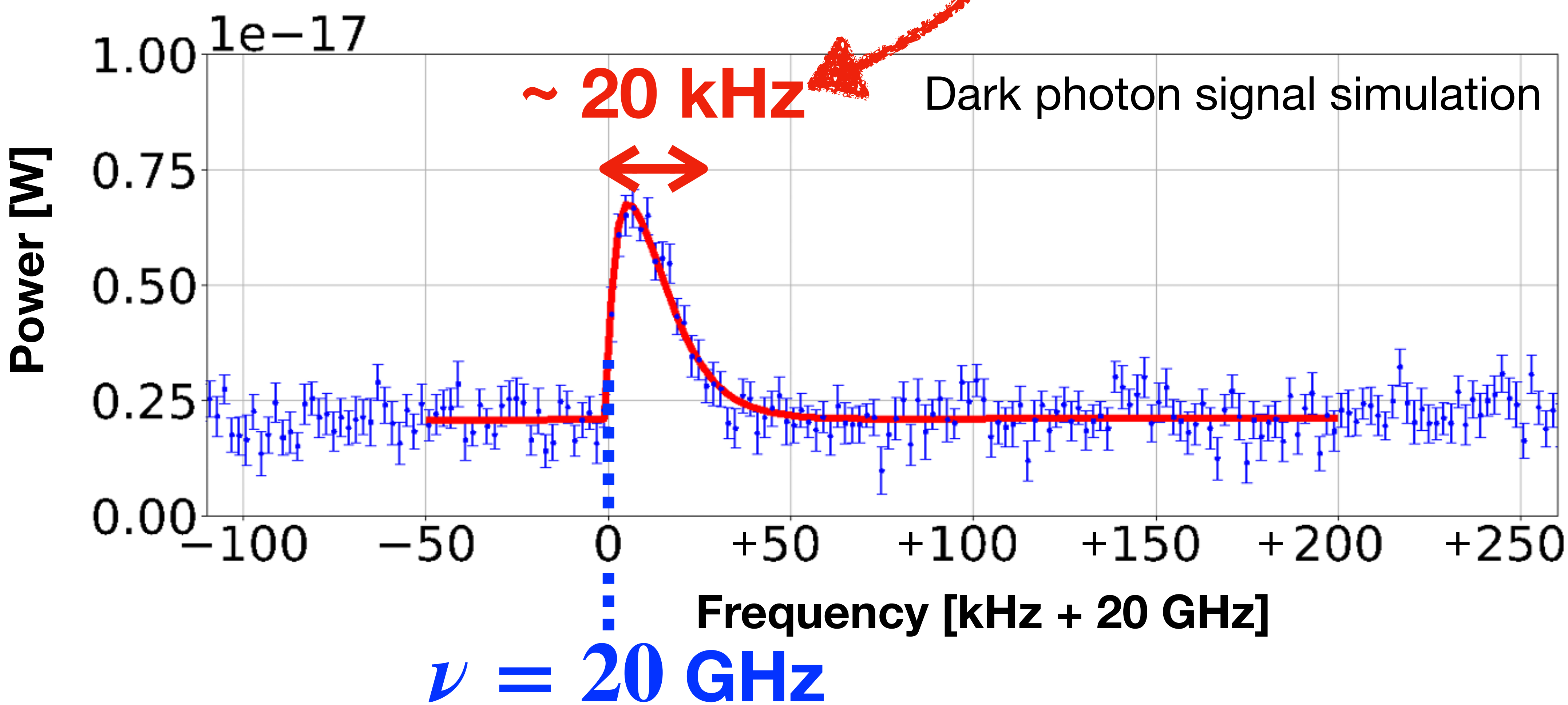
Typical measurement setup

1. Collect the signal by an feed antenna
2. Amplify the signal electrically by an RF amplifier
3. Measure the signal by a **spectrometer** (**FFT**) as a **frequency spectrum**

Expected signal if $m = 80\,\mu\mathrm{eV}$

Signal is a narrow frequency peak.

$\Delta\nu/\nu \sim 10^{-6}$ under assumption of the Maxwell-Boltzmann distribution with $\beta_{\mathrm{DM}} \sim 10^{-3}$

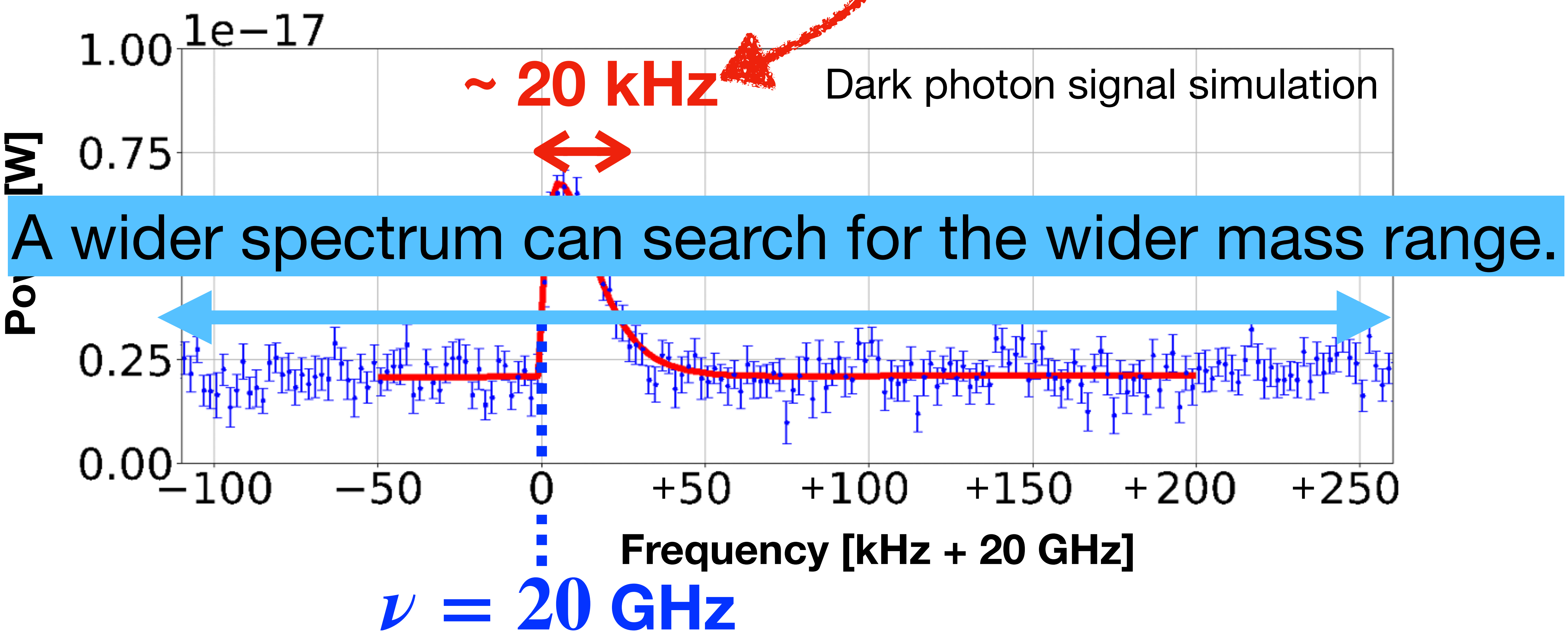


- Need a high frequency resolution: $\Delta\nu/\nu \lesssim 10^{-6}$

Expected signal if $m = 80\,\mu\mathrm{eV}$

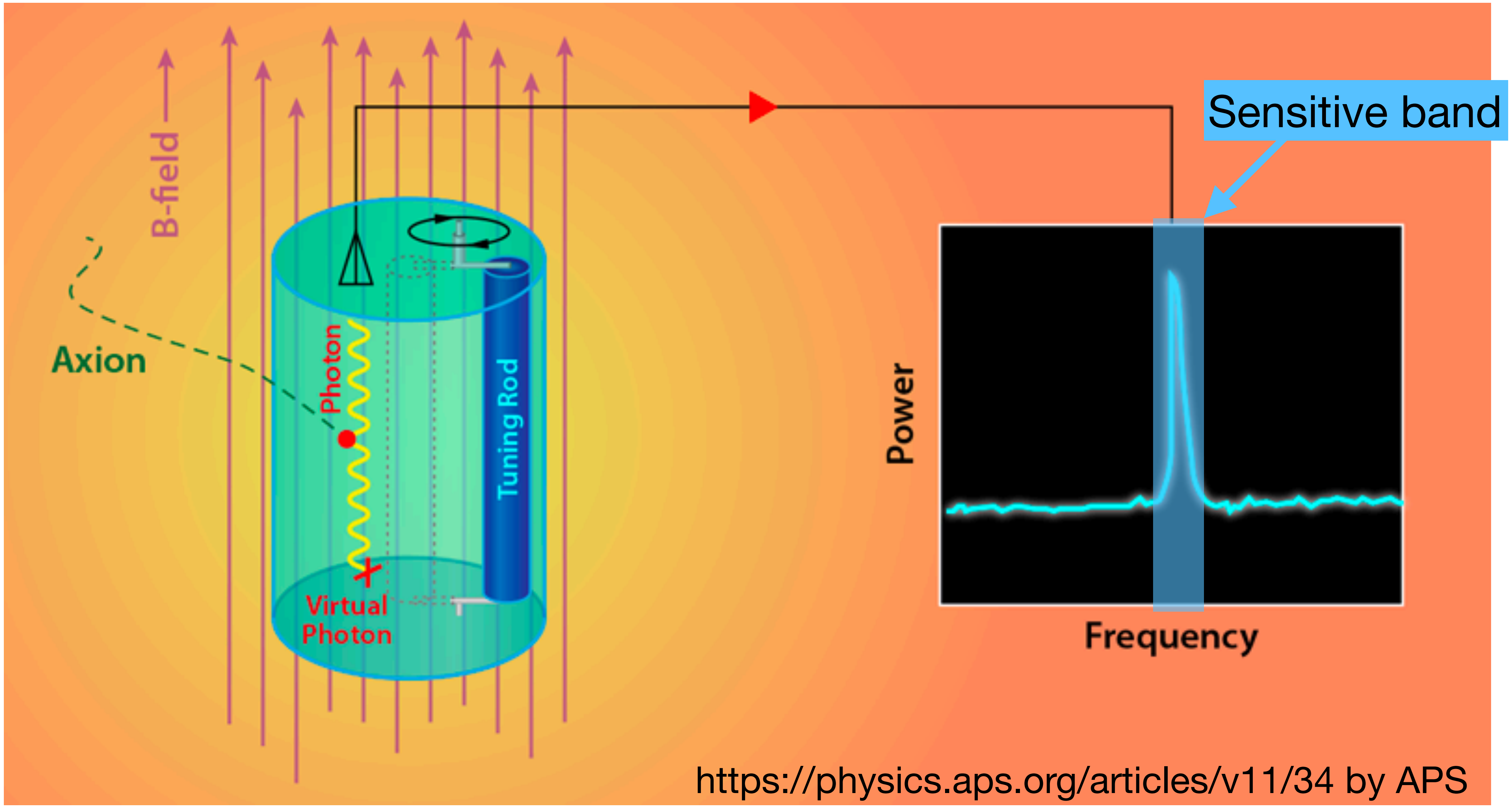
Signal is a narrow frequency peak.

$\Delta\nu/\nu \sim 10^{-6}$ under assumption of
the Maxwell-Boltzmann distribution with $\beta_{\mathrm{DM}} \sim 10^{-3}$



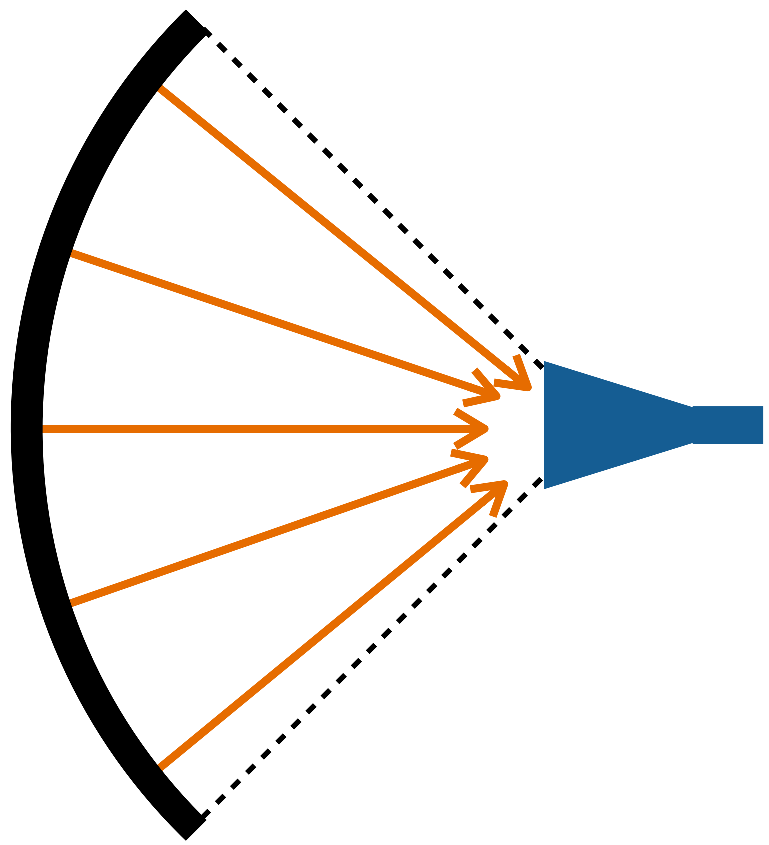
- Need a high frequency resolution: $\Delta\nu/\nu \lesssim 10^{-6}$

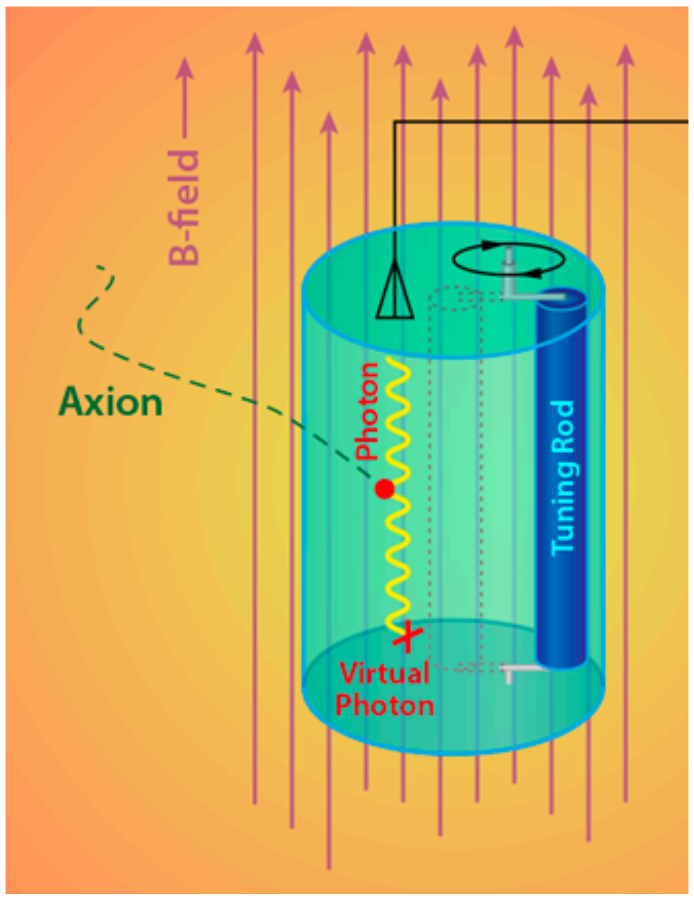
Resonant Cavity Search



- Good enhancement of the signal by the resonance
- Needs scan of the resonance frequency (**Narrow band**)
- **Difficult** to make a cavity for **higher frequency** ($\gtrsim$10 GHz)
  - Need fine structures around the wavelength (<λ~1 cm) to create resonance

Advantages of Dish Antenna Search





- Narrow band
- Difficult for higher frequency

- Wide bandwidth with one setup:
  - Bandwidth/$\nu \approx 50\,\%$

    ex) 10—20 GHz

- No limitation on the frequency
  - Applicable for higher frequency (e.g. $\gtrsim$ 10 GHz)

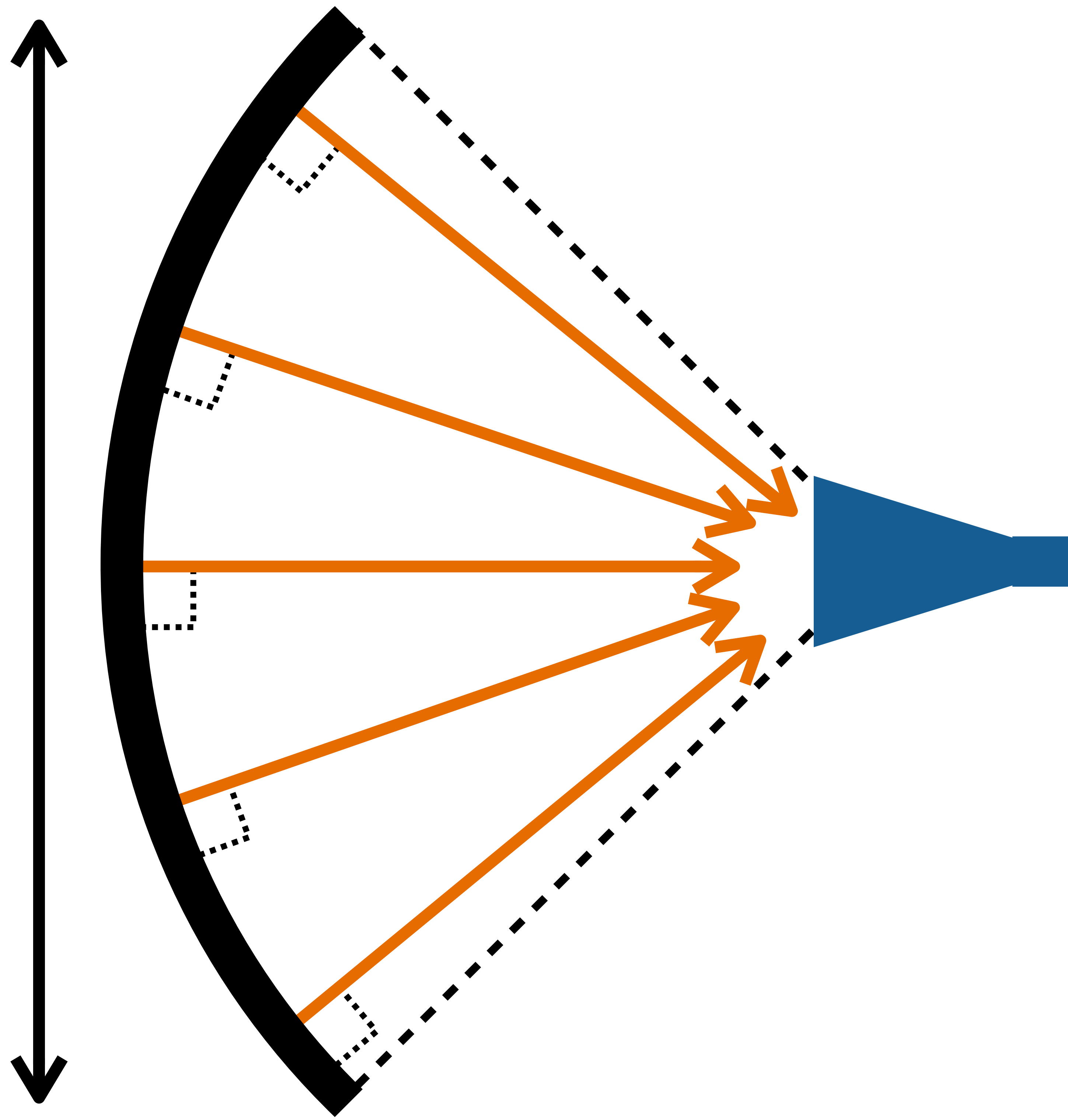
Limitation of the Dish Antenna Search

The dish size < $\lambda_{\text{de Broglie}}$

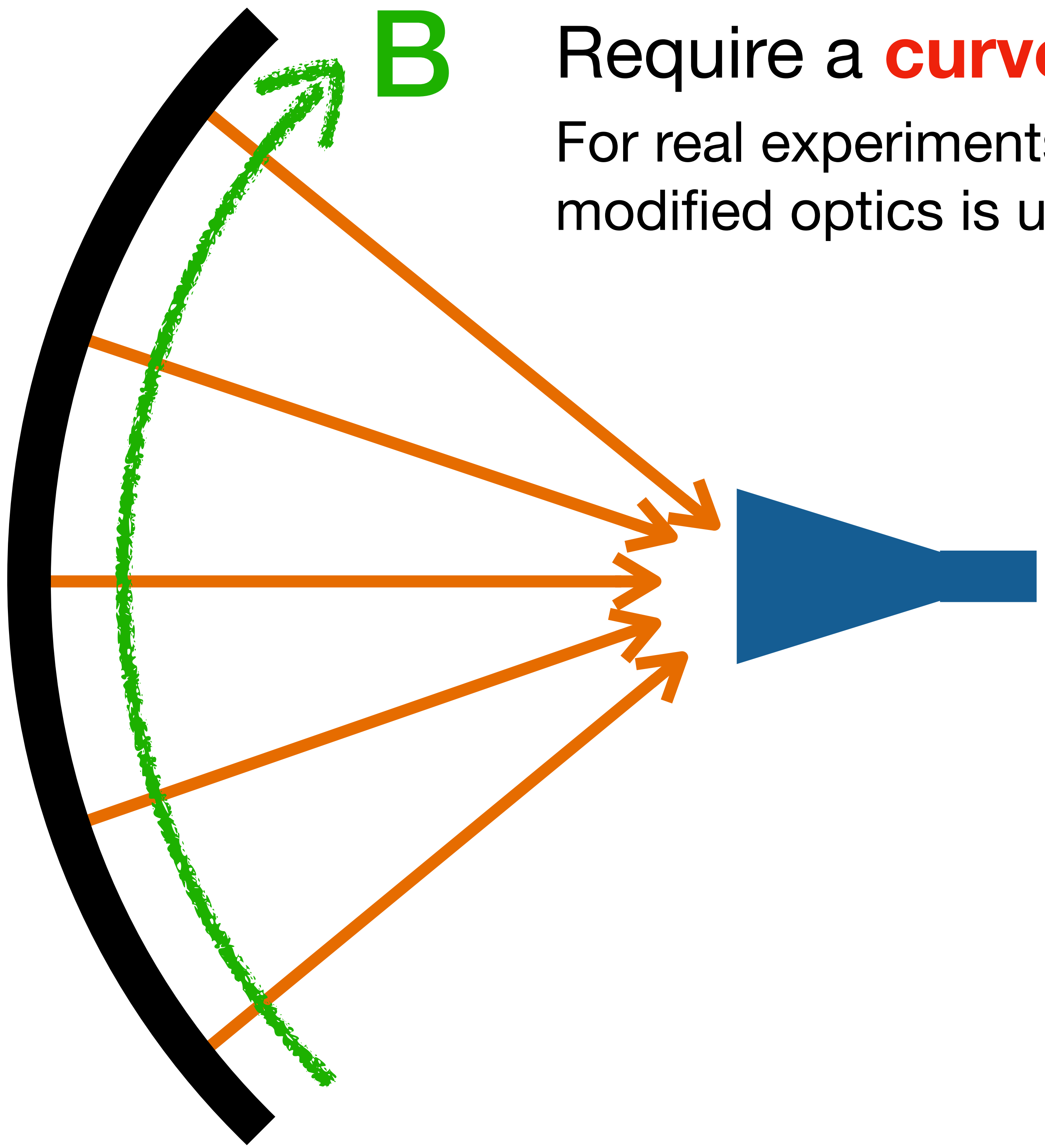
Limiting the signal gain

$$m = 1\,\mu\text{eV} \Leftrightarrow \lambda_{\text{de Broglie}} = 1700\,\text{m}$$

$$m = 1\,\text{meV} \Leftrightarrow \lambda_{\text{de Broglie}} = 1.7\,\text{m}$$



Difficulty in Axion Search



Require a **curved magnetic field**

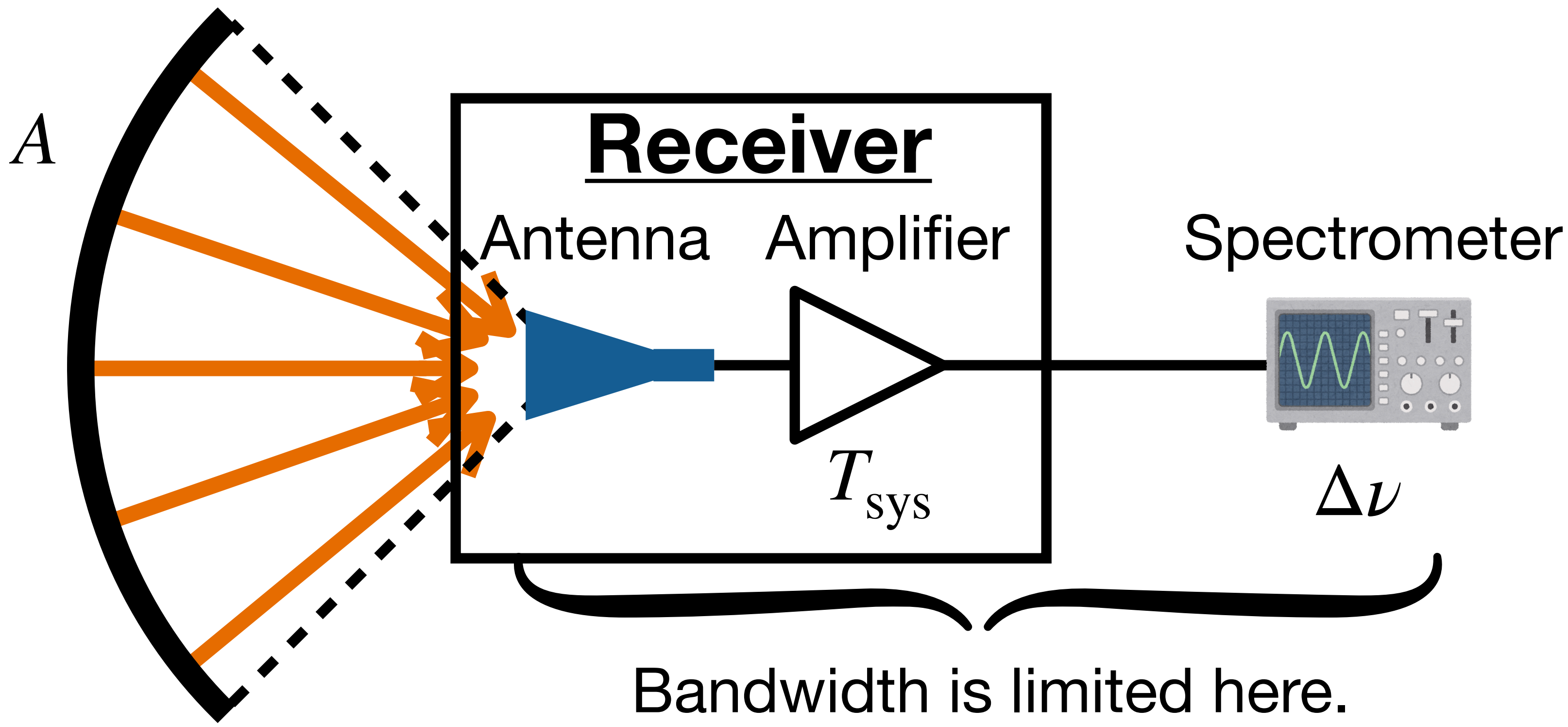
For real experiments,
modified optics is used instead of a dish antenna.

Sensitivity for experiment

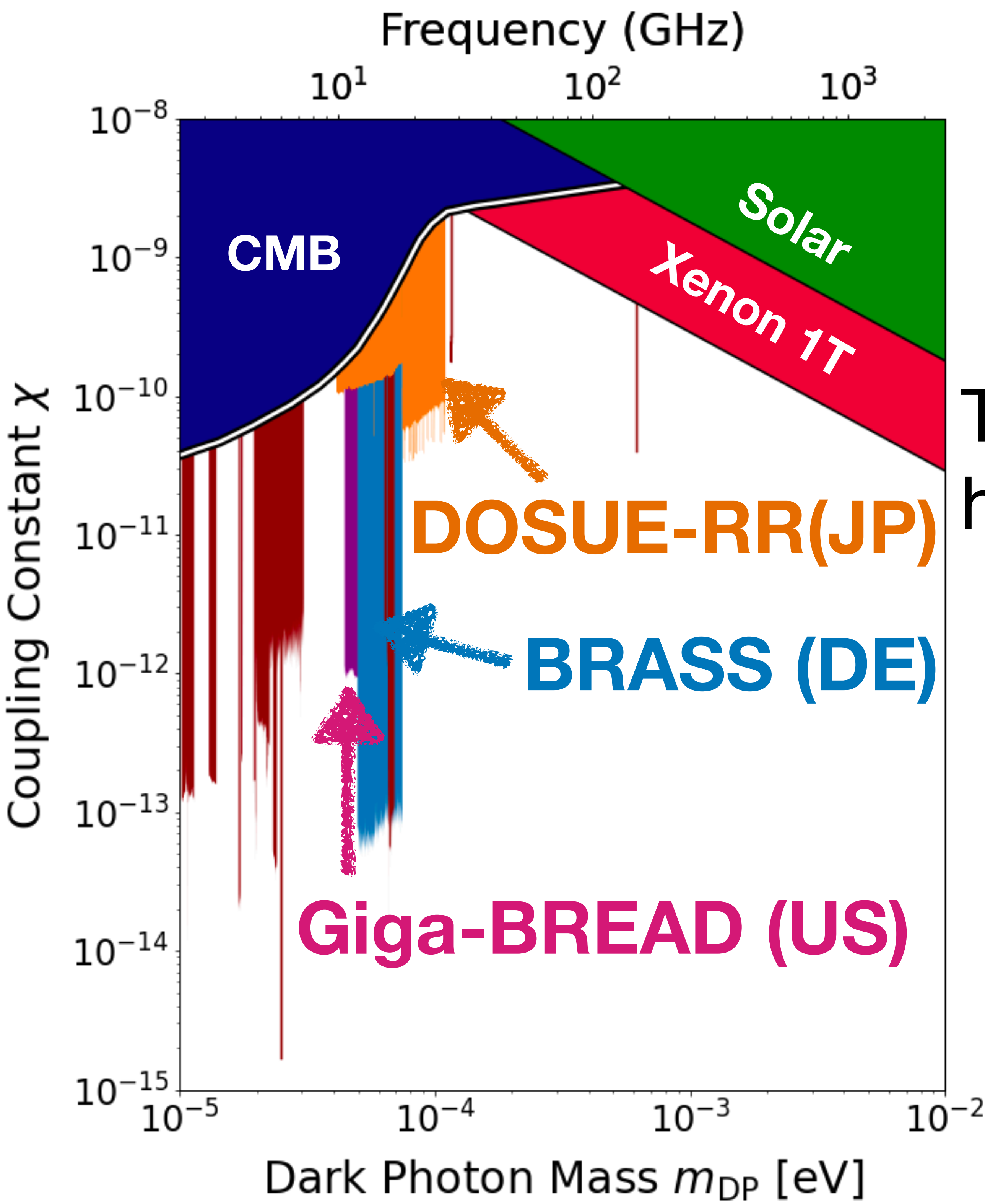
Dark photon case:

$$\chi_{\rm sens} = 4.5 \times 10^{-14} \left(\frac{P_{\rm noise}}{10^{-23}\,{\rm W}} \frac{1\,{\rm m}^2}{A} \frac{0.3\,{\rm GeV/cm}^3}{\rho_{\rm DM}} \right)^{1/2}$$

- Low noise ($P_{\rm noise}$) : Amplifier (System noise temperature $T_{\rm sys}$)
- Large conversion area (A) : Dish antenna
- Broad bandwidth : Receiver and spectrometer
- Frequency resolution $\Delta\nu$: Spectrometer (Requirement: $\Delta\nu/\nu \lesssim 10^{-6}$)
- (Magnetic field B for axion : Magnet ($g_{a\gamma\gamma} \propto 1/B_{||}$)



Dark photon searches using antenna



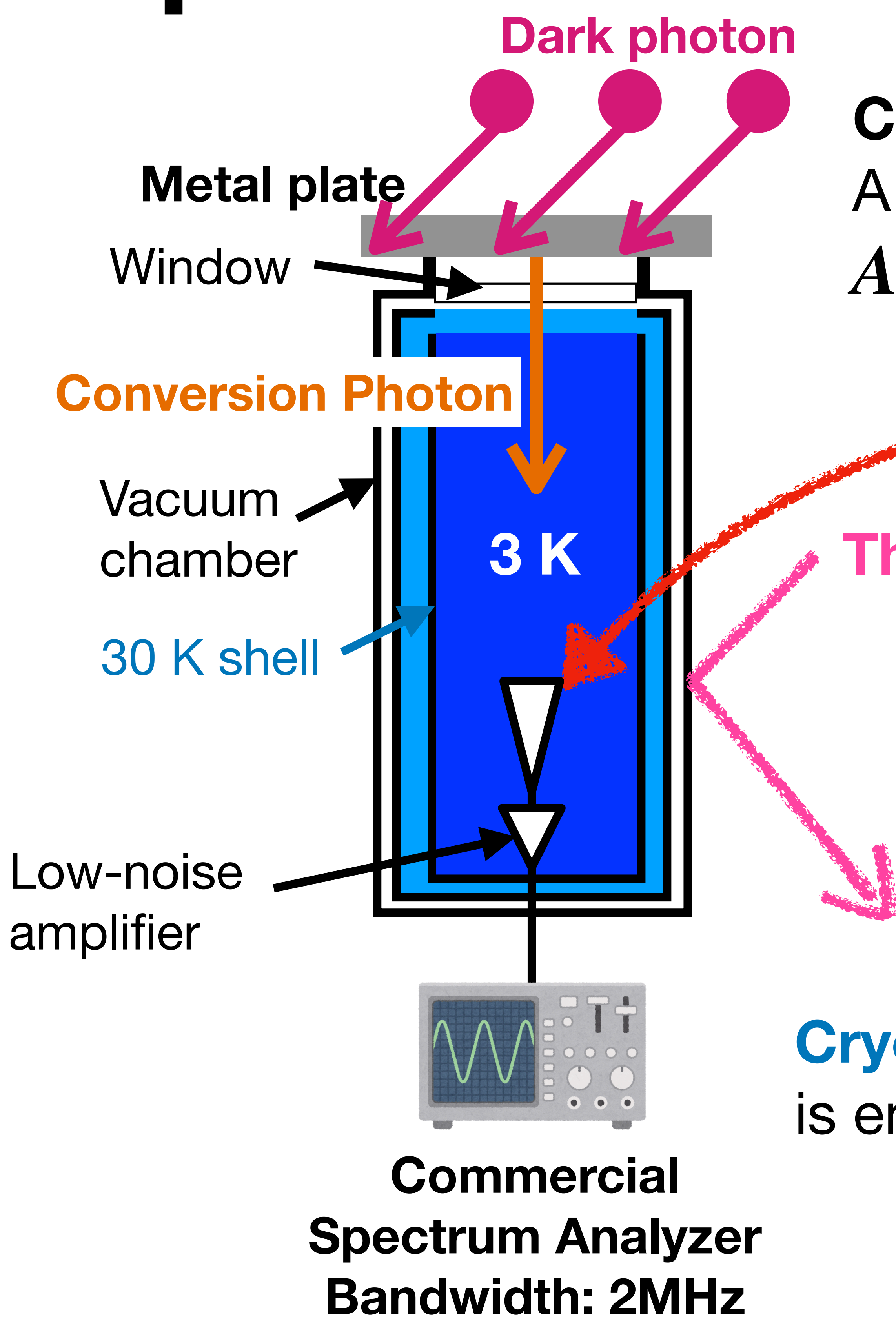
Three experiments with antenna have published their new results!

DOSUE-RR

My project @ Kyoto in Japan

cf. S. Kotaka et al, PRL 130, 071805 (2023)
S. Adachi et al, arXiv:2308.14656

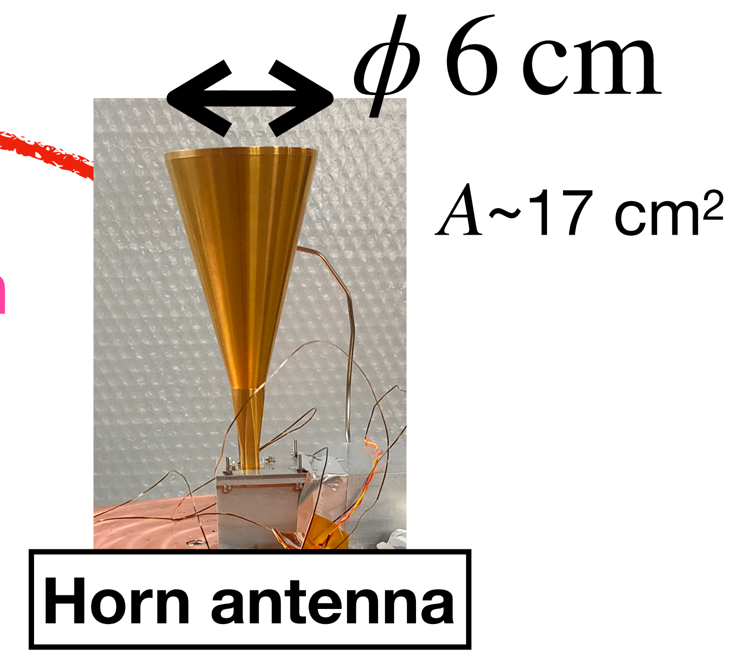
Setup: Plate + Horn antenna



Conversion: Flat plate (No dish)

A horn antenna directly sees a plate.

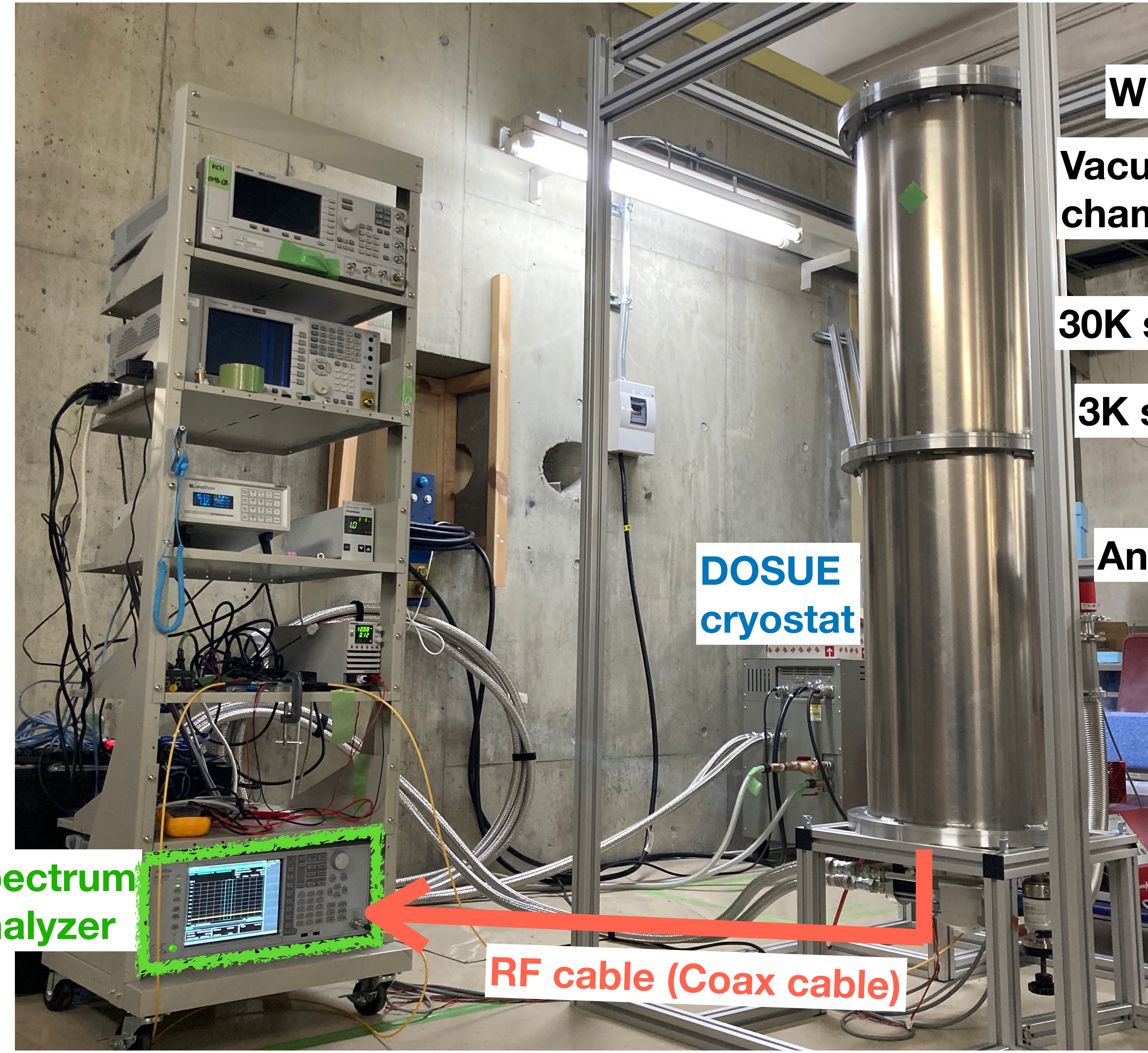
A **~ Horn Antenna aperture**

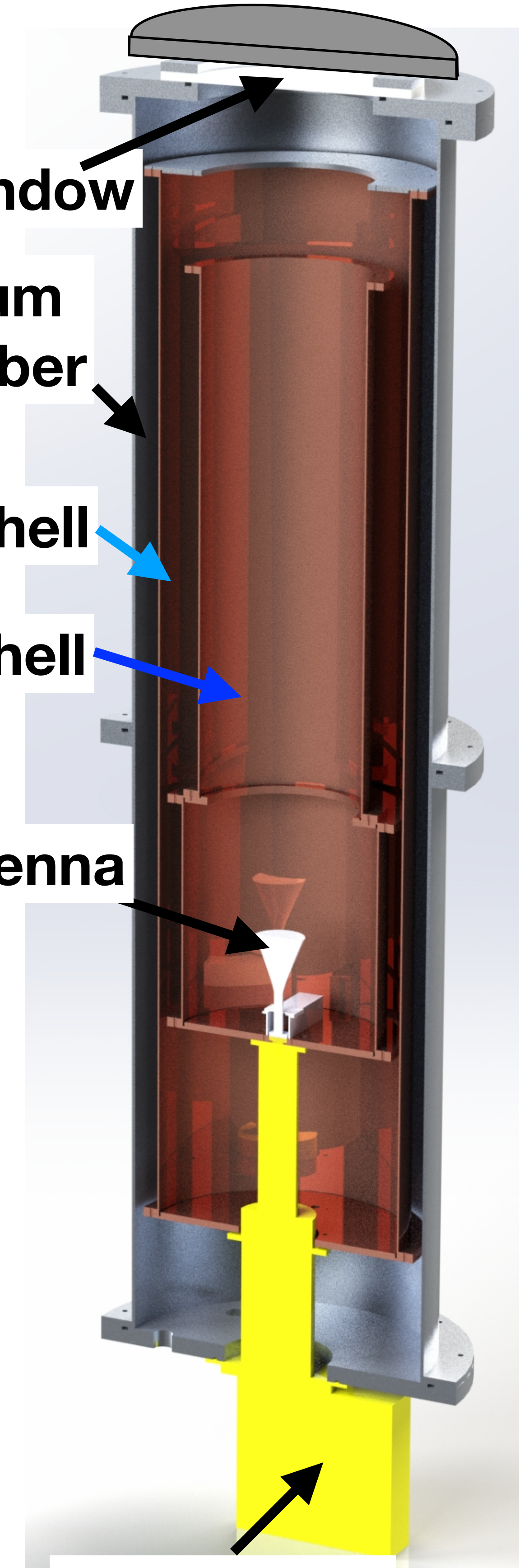


Cryogenically cooled optical path
is employed for the thermal noise reduction.

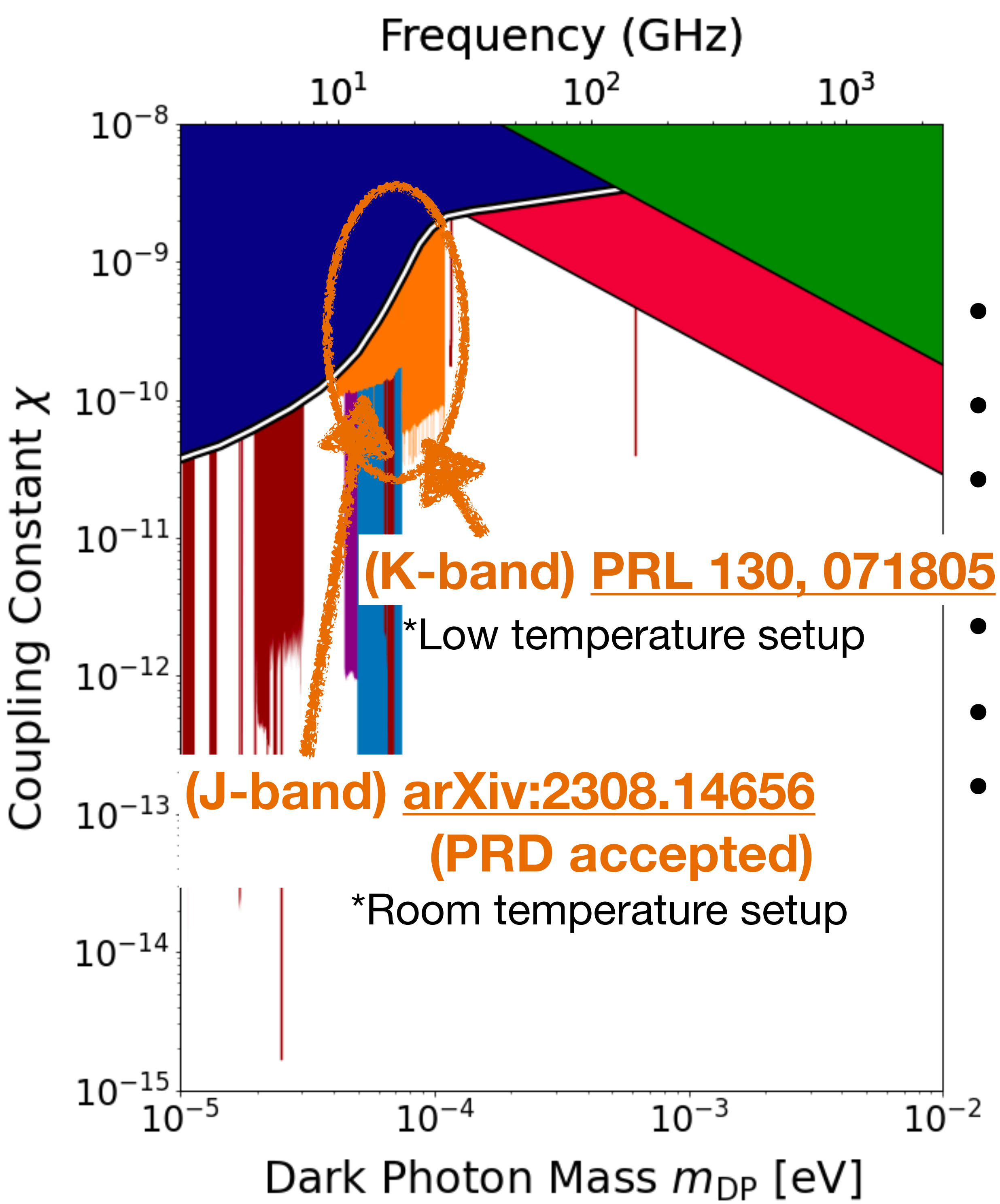
$$T_{\rm sys} \sim 70\,\mathrm{K}$$

Photo: Overview





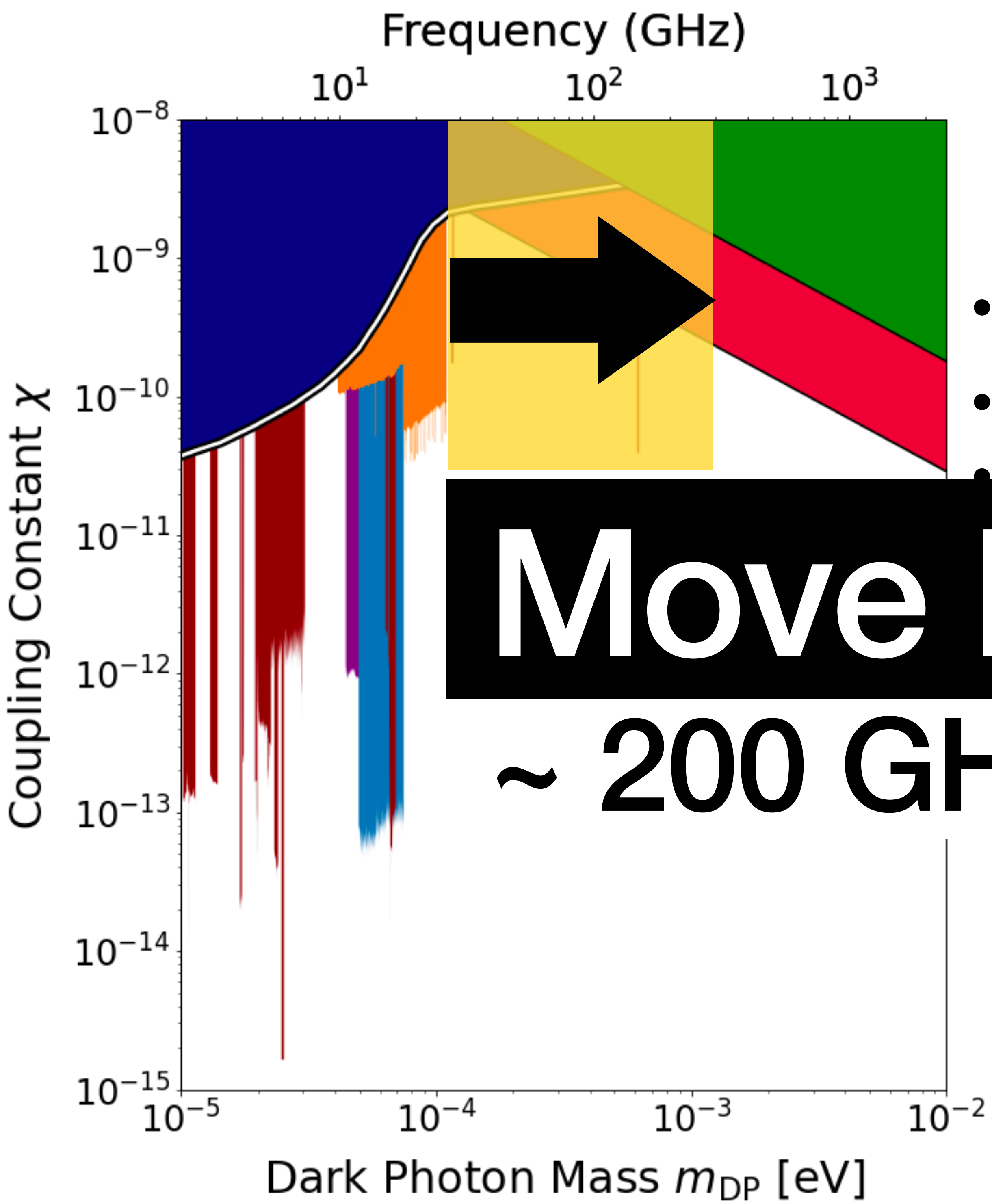
Results of DOSUE-RR



- T_{sys} ~ 70 K
- A ~ 17 cm²
- Frequency range: (J-band) 10–18 GHz
  (K-band) 18—26.5 GHz
- Bandwidth : 2 MHz
- Resolution $\Delta\nu$: 0.3 kHz
- Time : 24 sec x 8250 bands*

*To cover the entire frequency range, they scanned the frequency.

Plans of DOSUE-RR



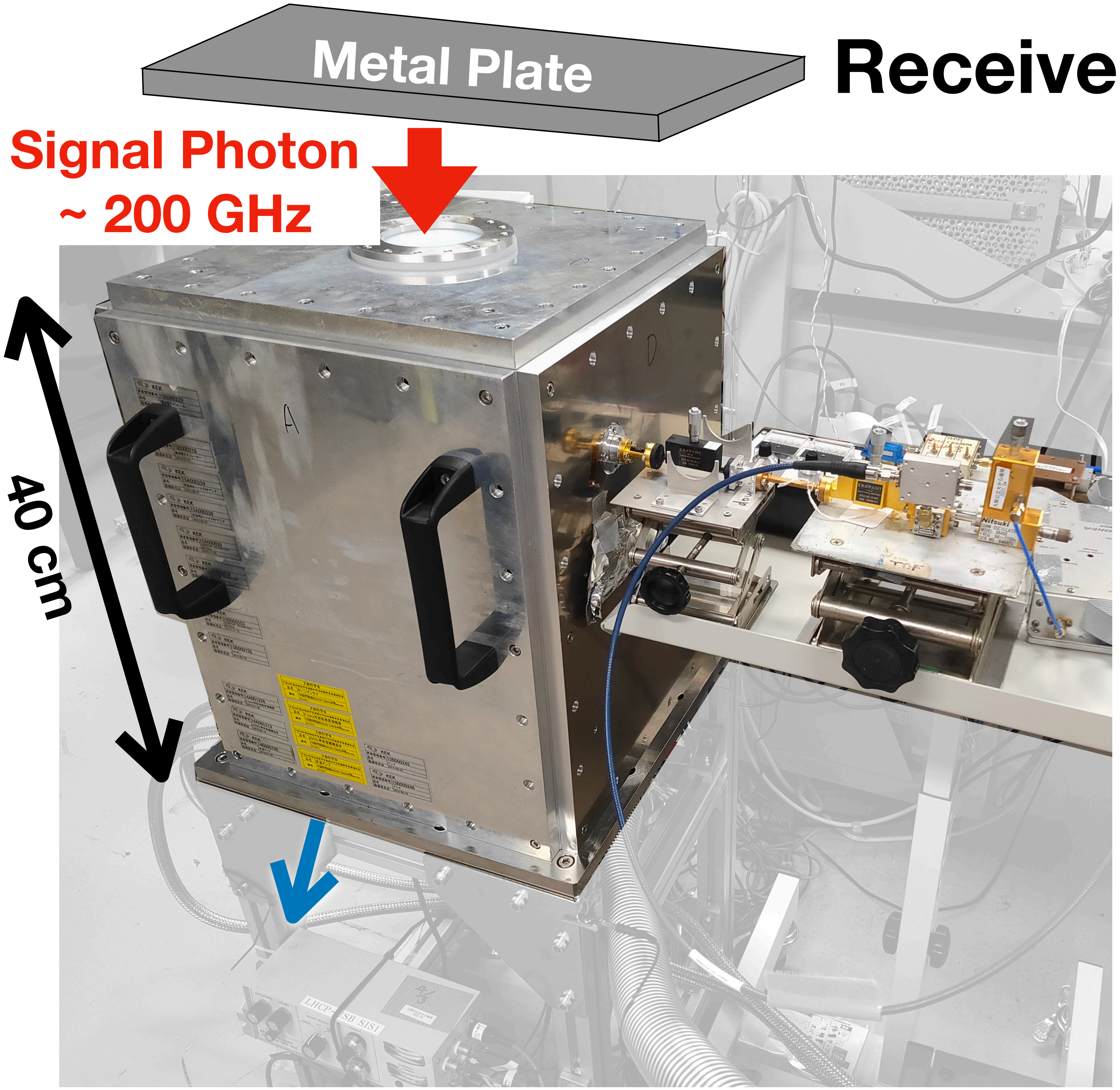
Move higher

~ 200 GHz

- T_{sys} ~ 70 K
- A ~ 17 cm^2
- Frequency range: (J-band) 10–18 GHz
  (K-band) 18—26.5 GHz
- 2 MHz
- esolution $\Delta\nu$: 0.3 kHz
- me : 24 sec x 8250 bands*

*To cover the entire frequency range, they scanned the frequency.

200 GHz Receiver in Preparation



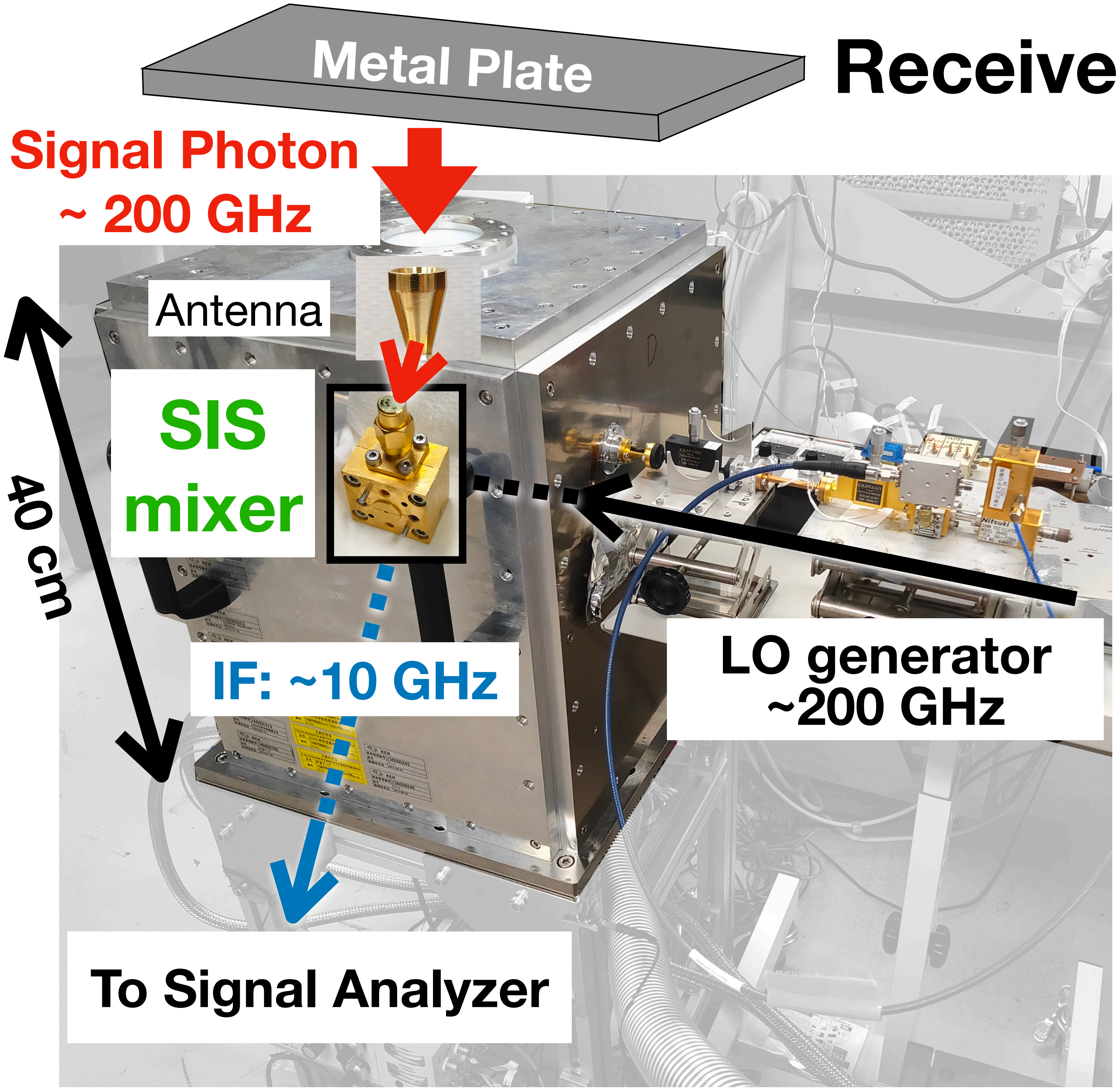
Receiver with SIS mixer

- Superconducting down-converter
- Base technology for ALMA

$$T_{sys} \sim 100\,\mathrm{K}$$

*Commercial semiconducting down-converter: ~500 K

200 GHz Receiver in Preparation



Receiver with SIS mixer

- Superconducting down-converter
- Base technology for ALMA

$$T_{sys} \sim 100\,\mathrm{K}$$

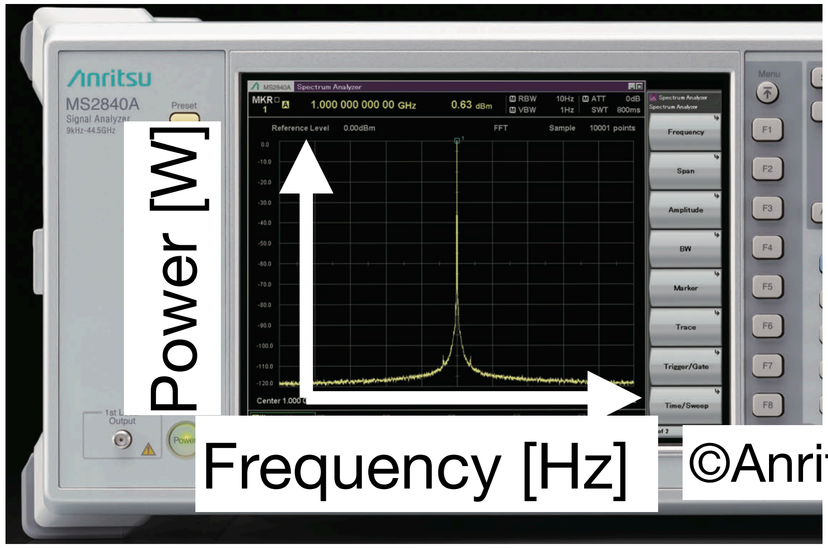
*Commercial semiconducting down-converter: ~500 K

Development of Spectrometer

For more efficient measurement,
we have developed a new spectrometer with an RFSoC.

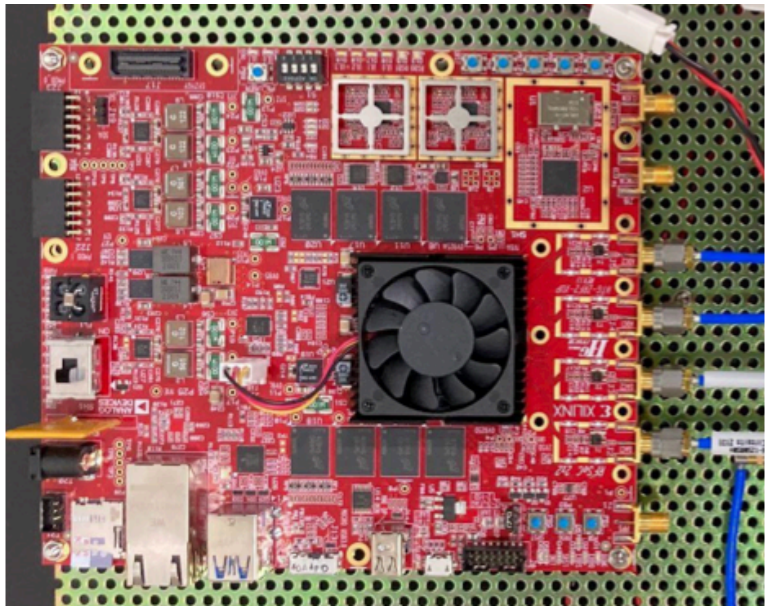
FPGA + 4Gsps ADC + CPU

Commercial Spectrum Analyzer
(Anritsu MS2840A)



2 MHz bandwidth

New Spectrometer "*dSpec*"



4 GHz bandwidth

× 2000 wider!!

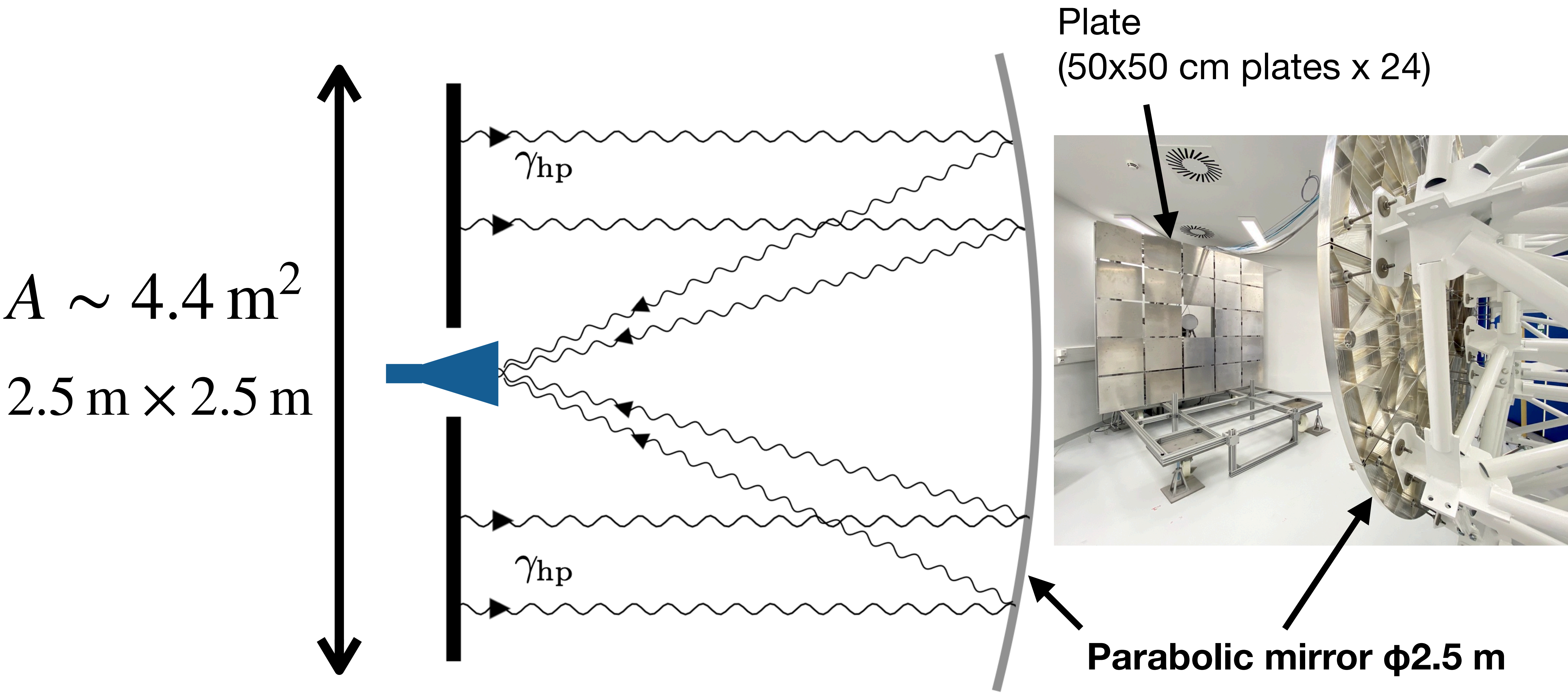
It will used from the next search.

BRASS
@ Hamburg in Germany

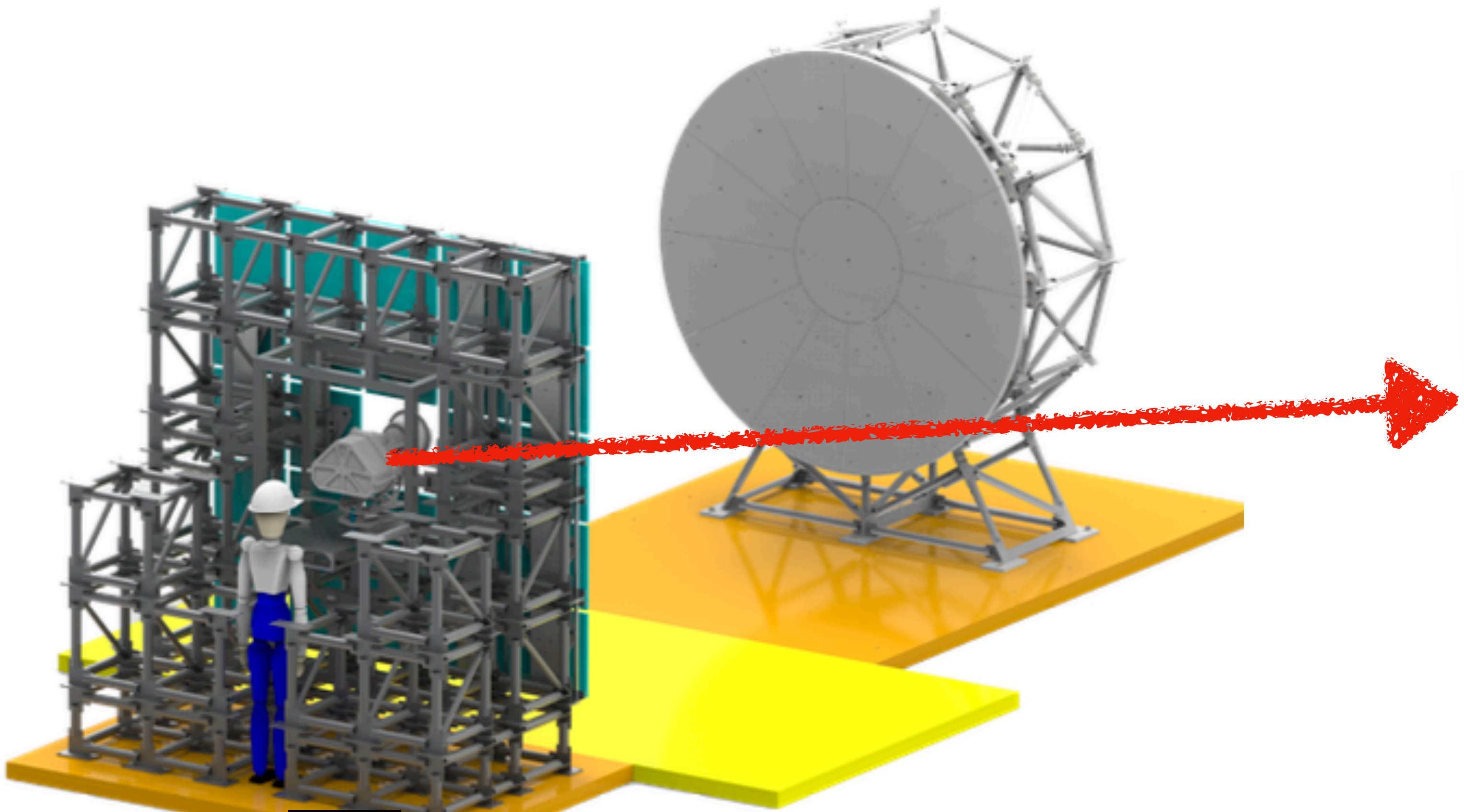
cf. Le Hoang, 18th patras workshop's slide
Fayez Bajjali et al JCAP08(2023)077

Setup: Parabolic mirror + Plate

Photons from the plate is corrected by a large parabolic mirror.

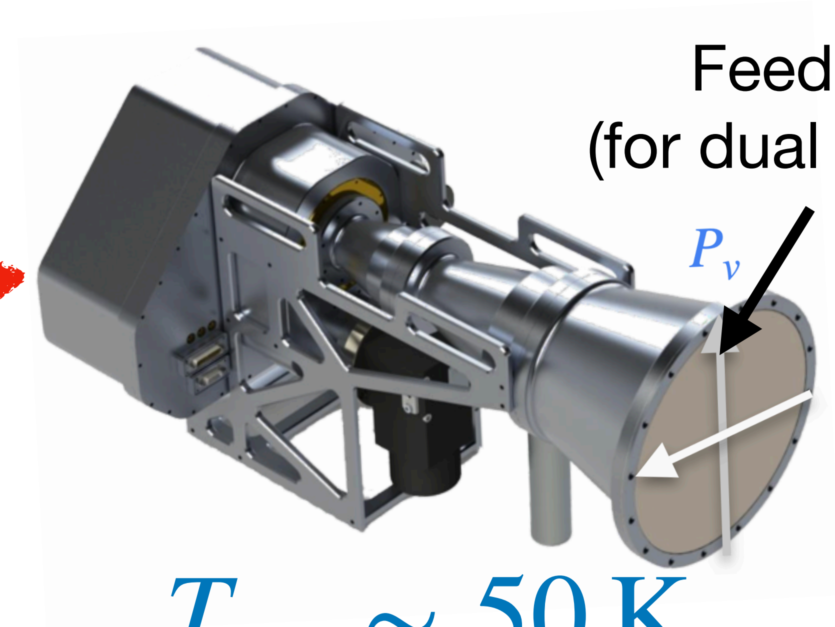


Setup: Receiver & Spectrometer



Cryogenic receiver (15 K)

Feed antenna
(for dual polarization)

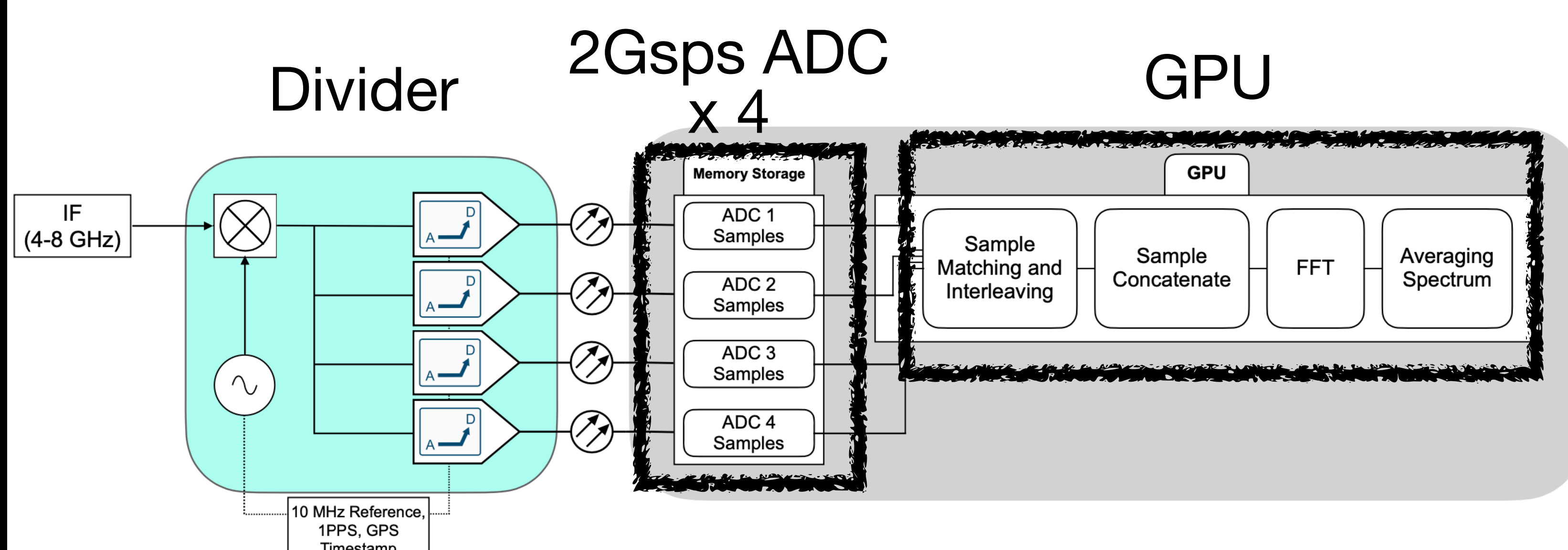


$T_{sys} \sim 50\,\mathrm{K}$

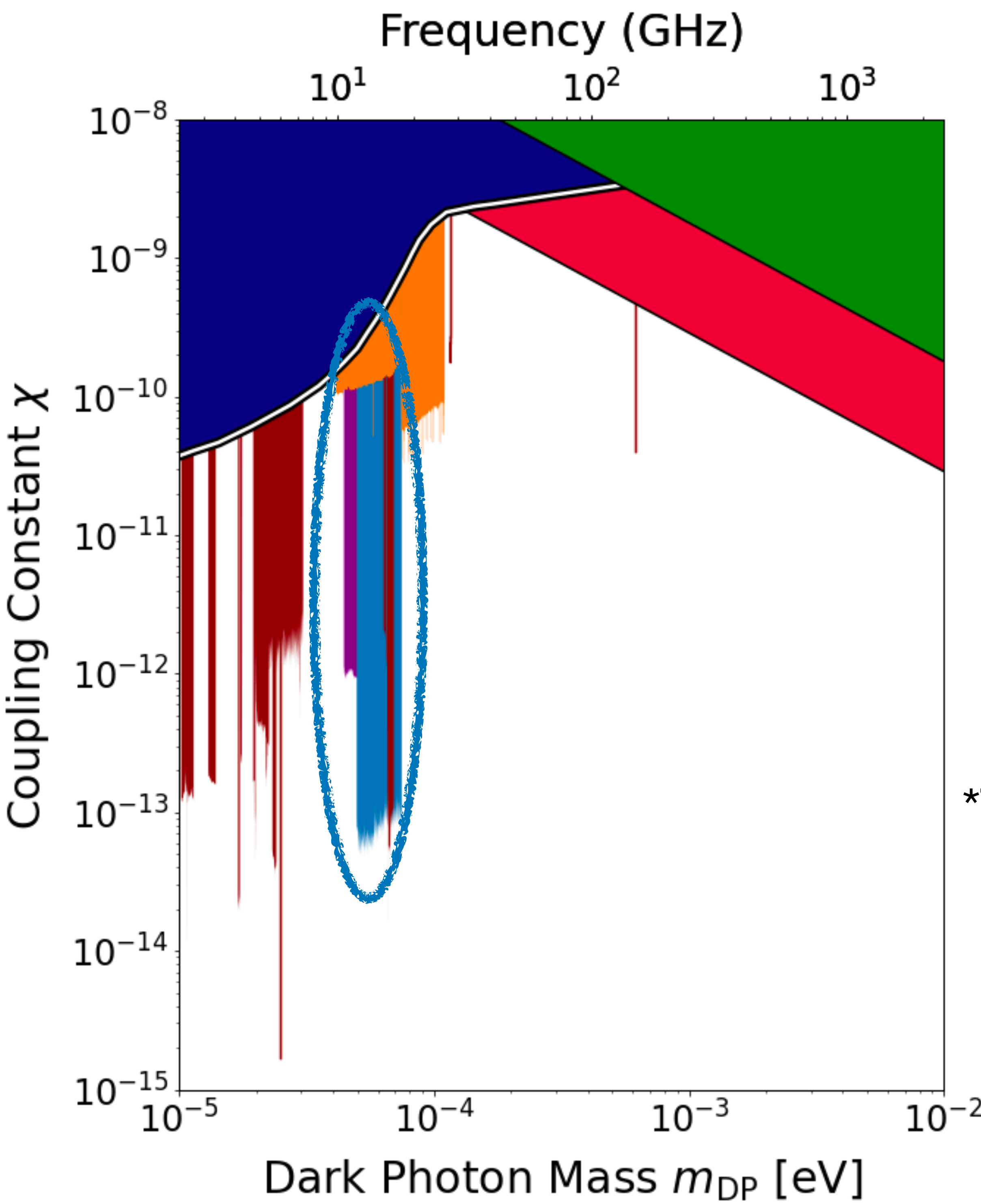
12—18 GHz signal

Original Spectrometer using GPU

4GHz bandwidth, $\Delta\nu$=125 Hz



Results of BRASS-p

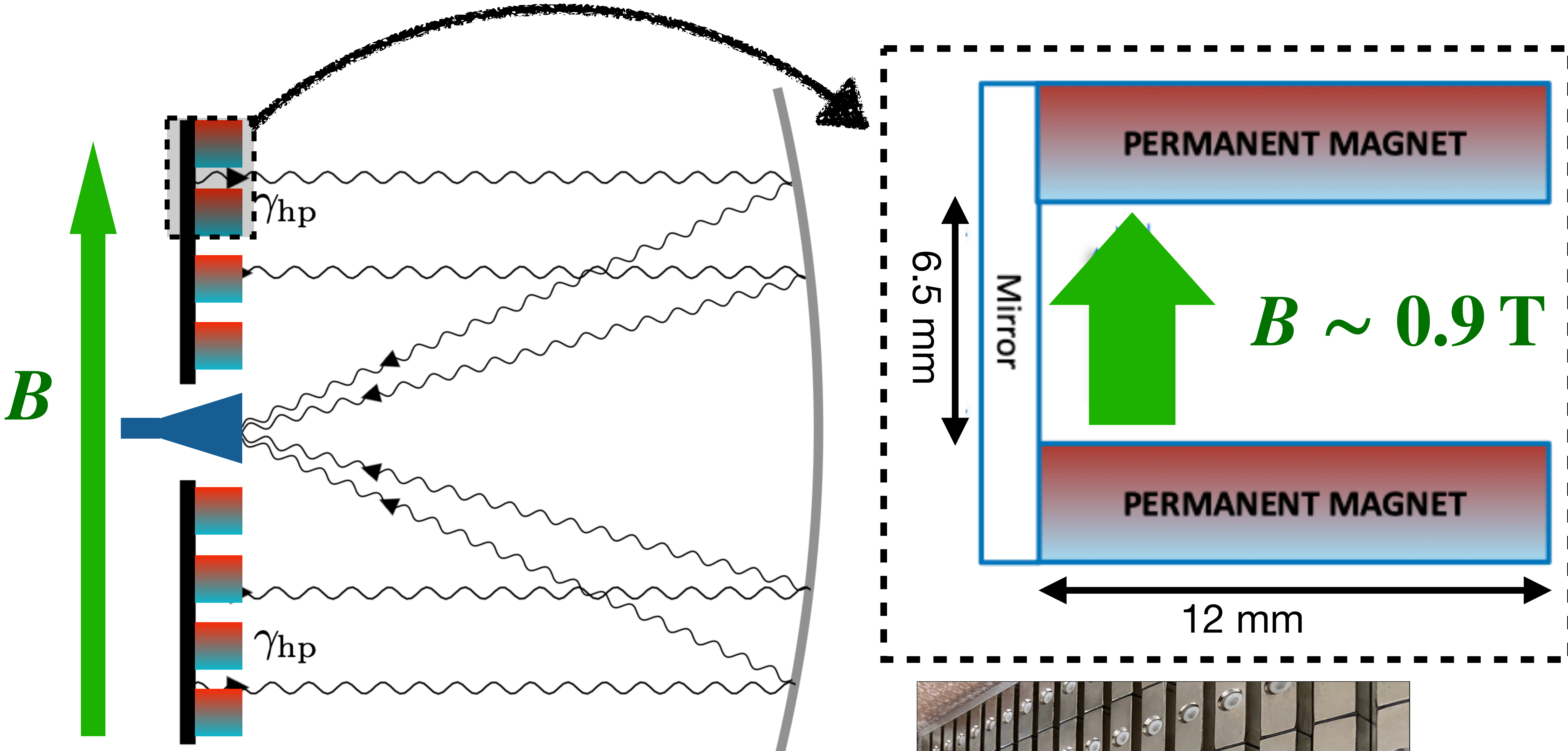


- T_{sys} ~ 50 K
- A ~ 4.4 m²
- Frequency range: 12–18 GHz
- Bandwidth : 4 GHz
- Resolution $\Delta\nu$: 125 kHz
- Time : 2.5 days x 2 bands*

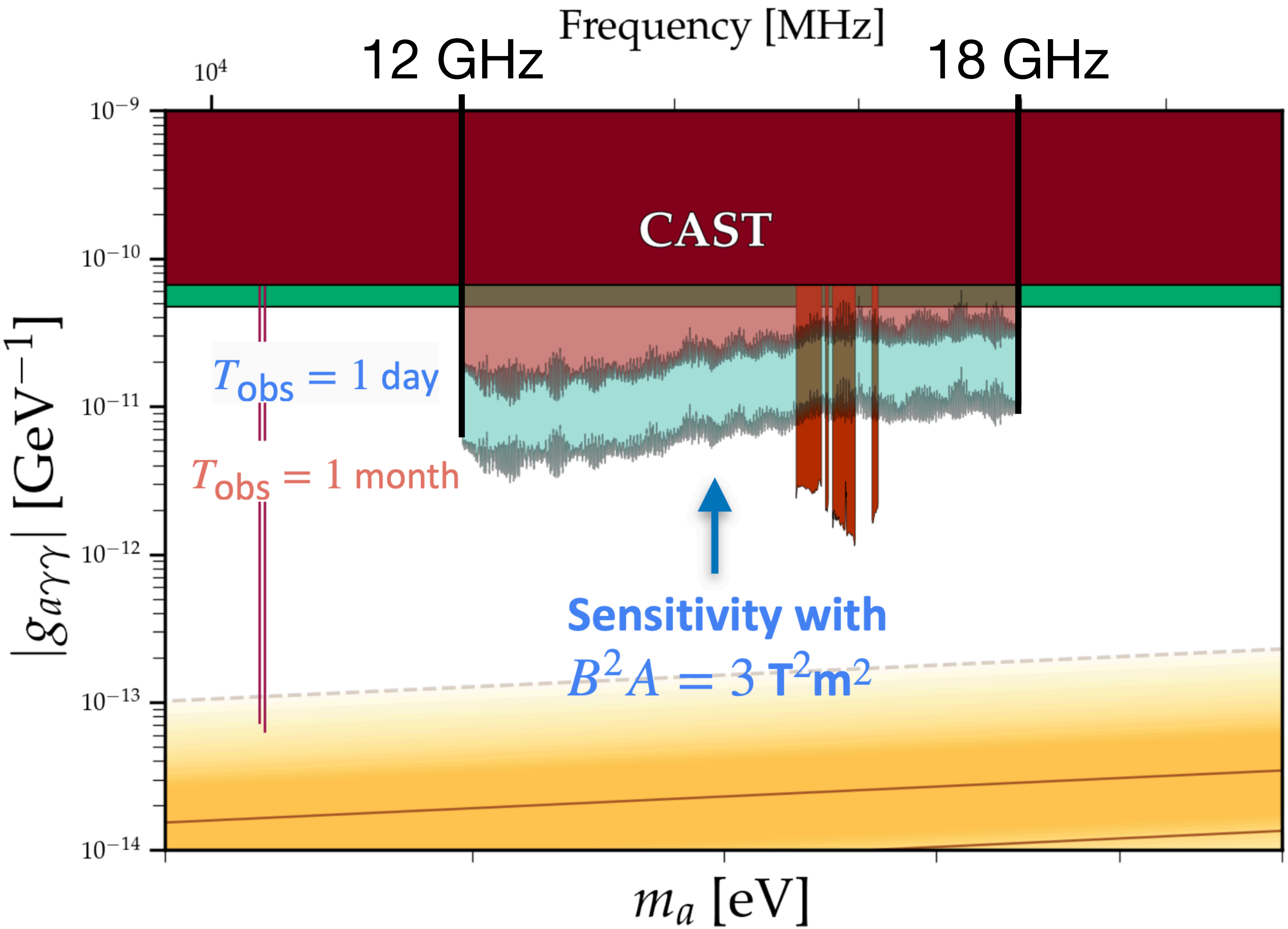
*To cover the entire frequency range, they had two bands of 12–16 GHz and 14–18 GHz.

Plans: Axion search

Add permanent magnet on the plate for axion search



Sensitivity for Axion

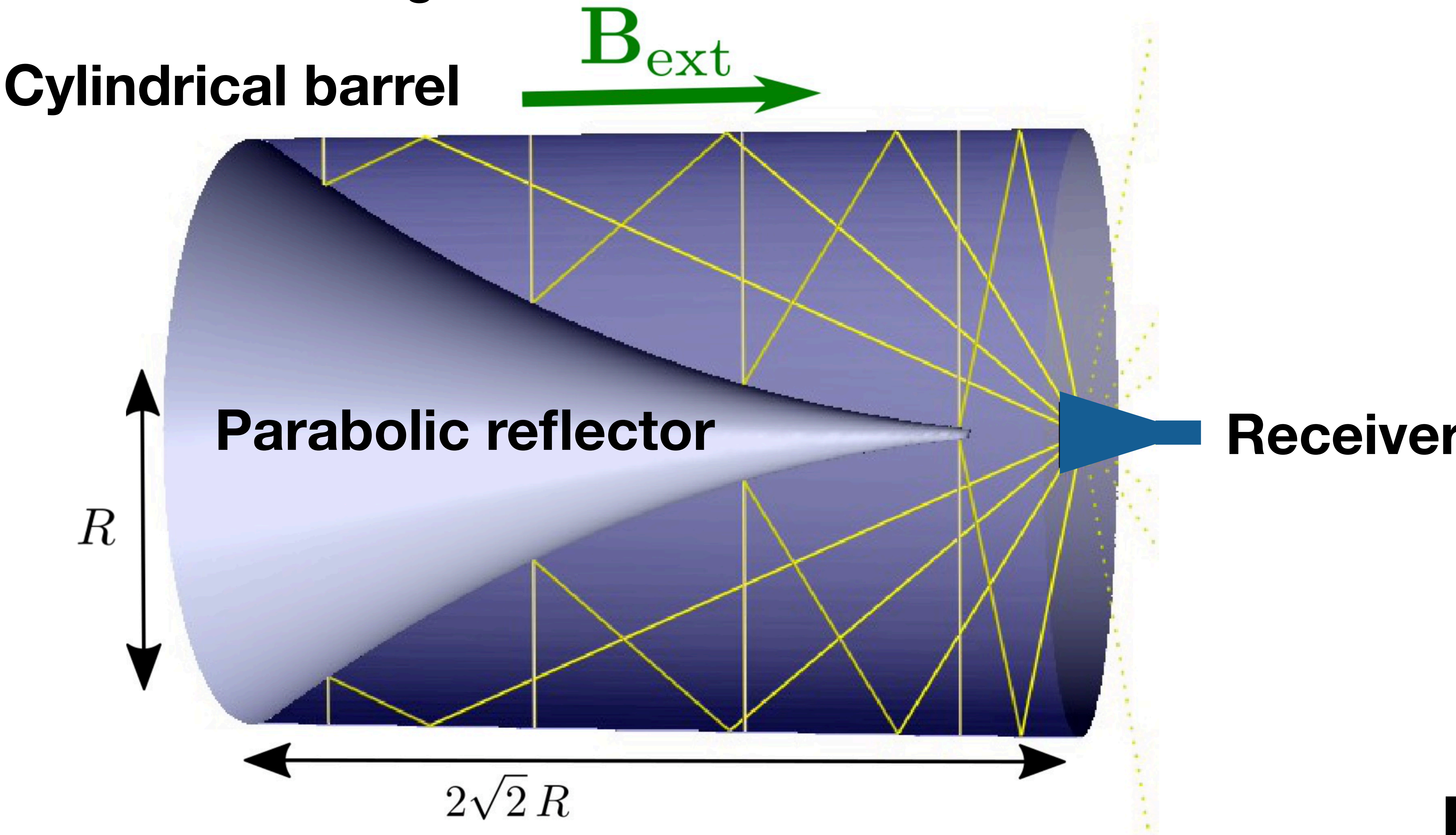


(Giga) BREAD in US

cf. S. Knirck, 18th patras workshop's slide
S. Knirck et al, arXiv:2310.13891

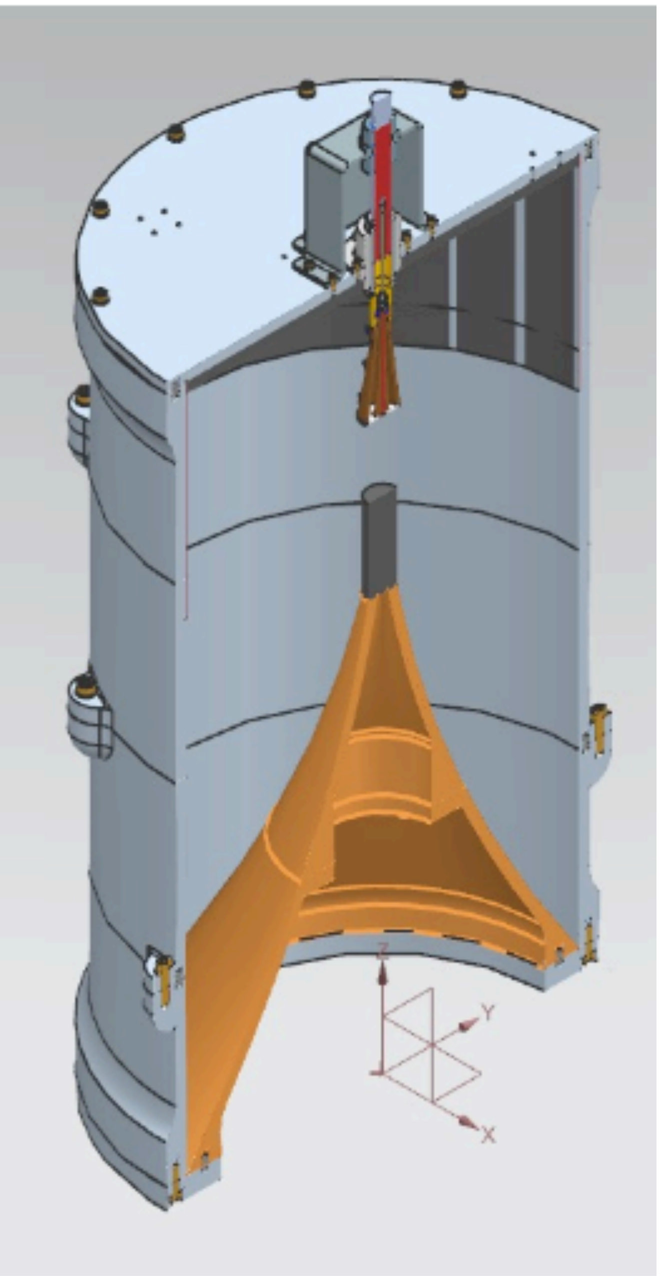
Setup: Coaxial dish antenna

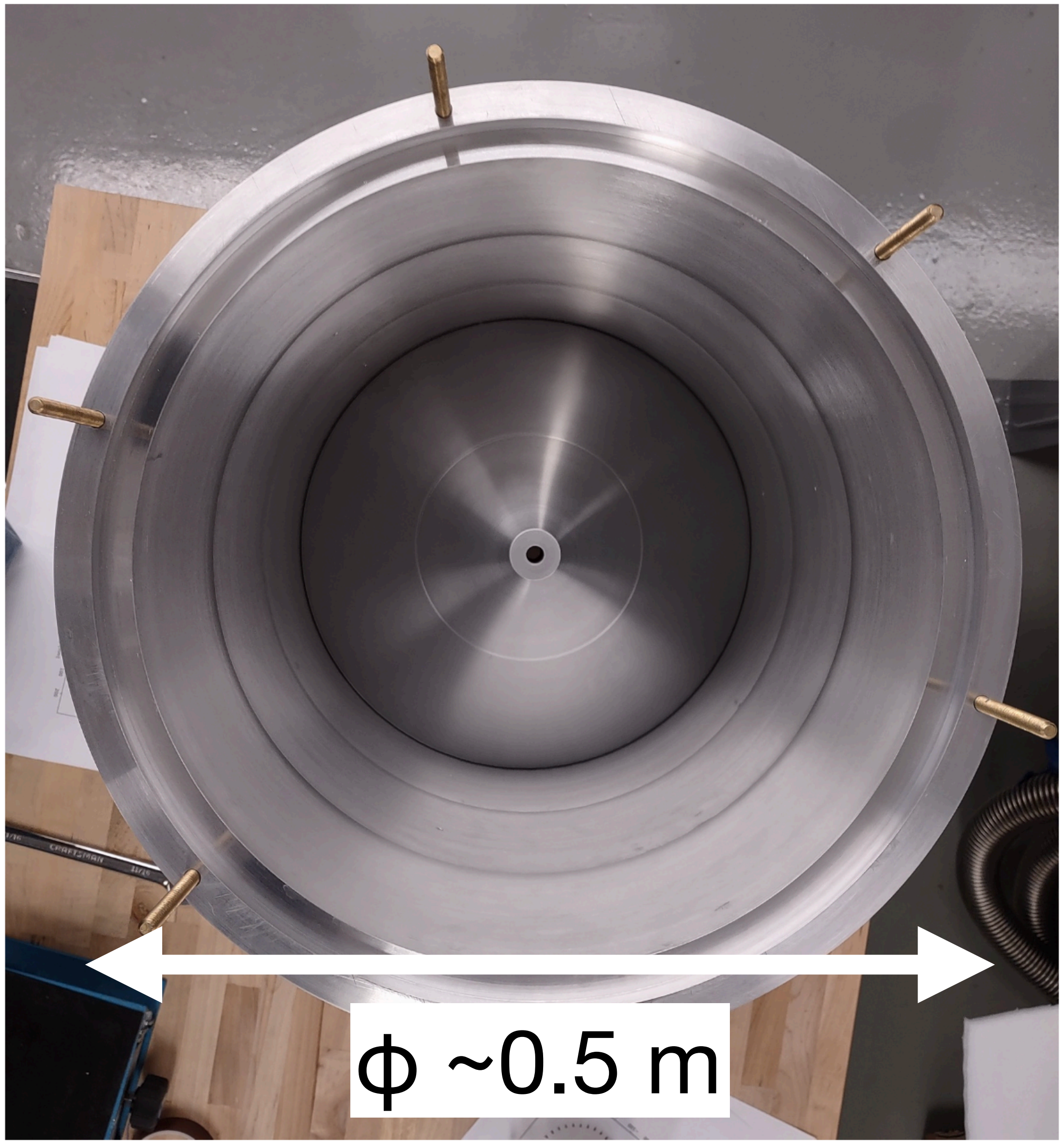
Conversion surface : Inner wall of the **cylindrical barrel**
Photon focusing method : **Parabolic reflector**



Pilot experiment: Giga BREAD

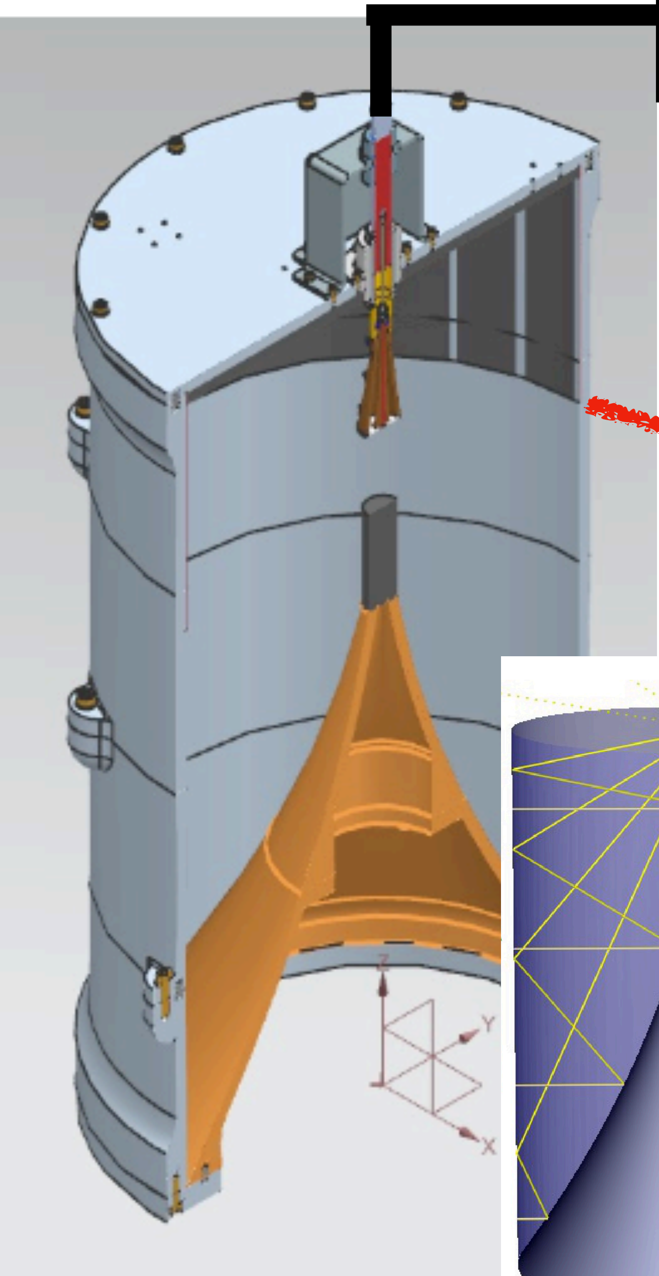
- No Magnetic Field (Dark photon search, 44−52μeV⇔10.7−12.5 GHz)
- At room temperature, $T_{\rm sys} \sim 400\,{\rm K}$
- $A \sim 0.5\,{\rm m}^2$



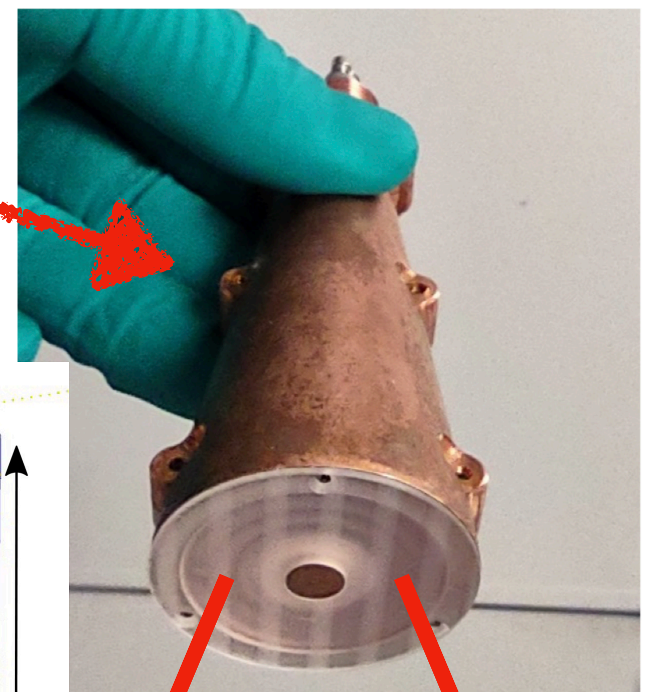


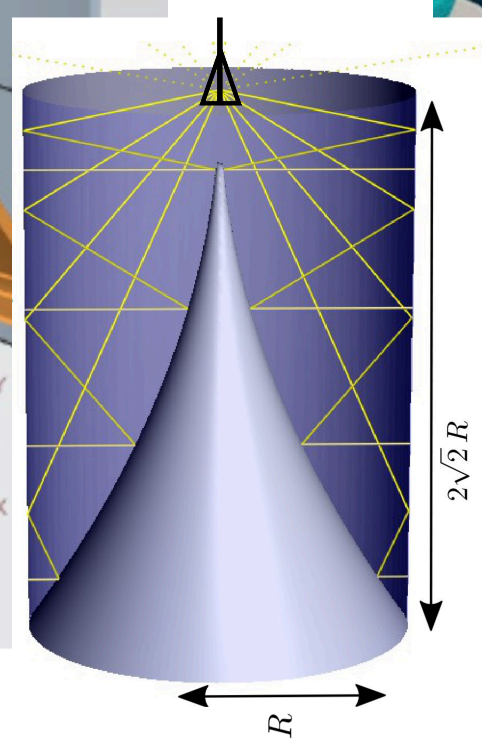
Receiver & Spectrometer

Amplifiers chain for 10.7—12.5 GHz



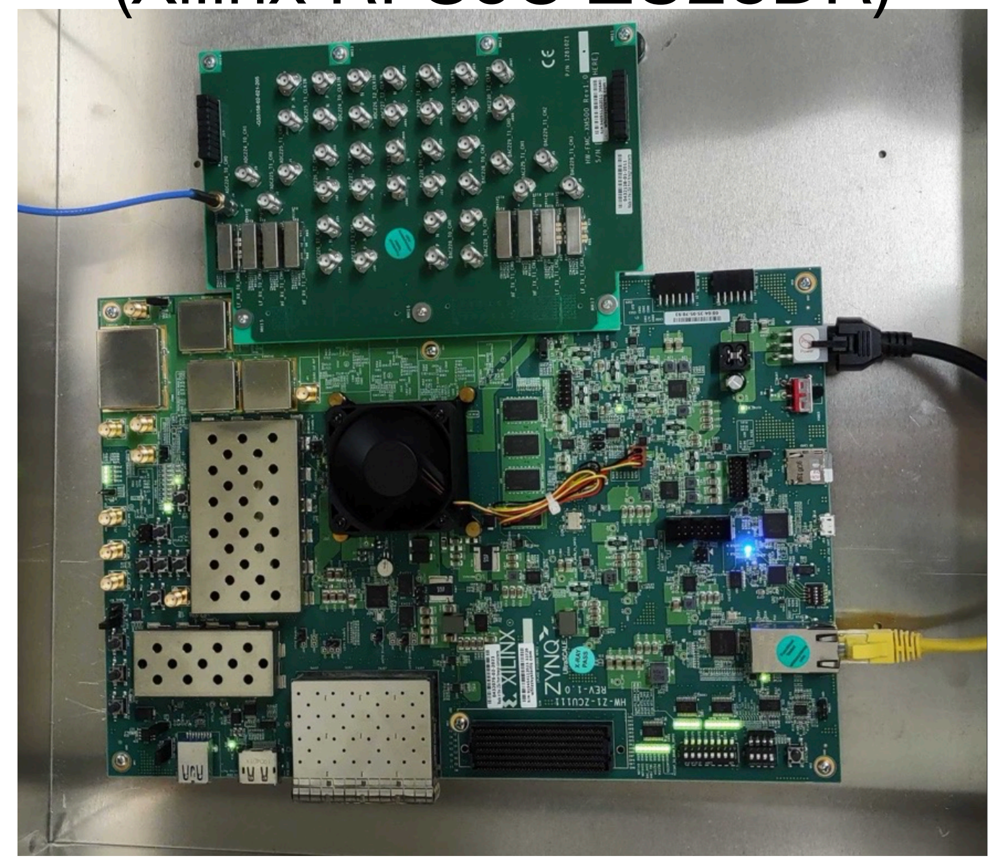
Coaxial Horn Antenna





Sensitive to off-center

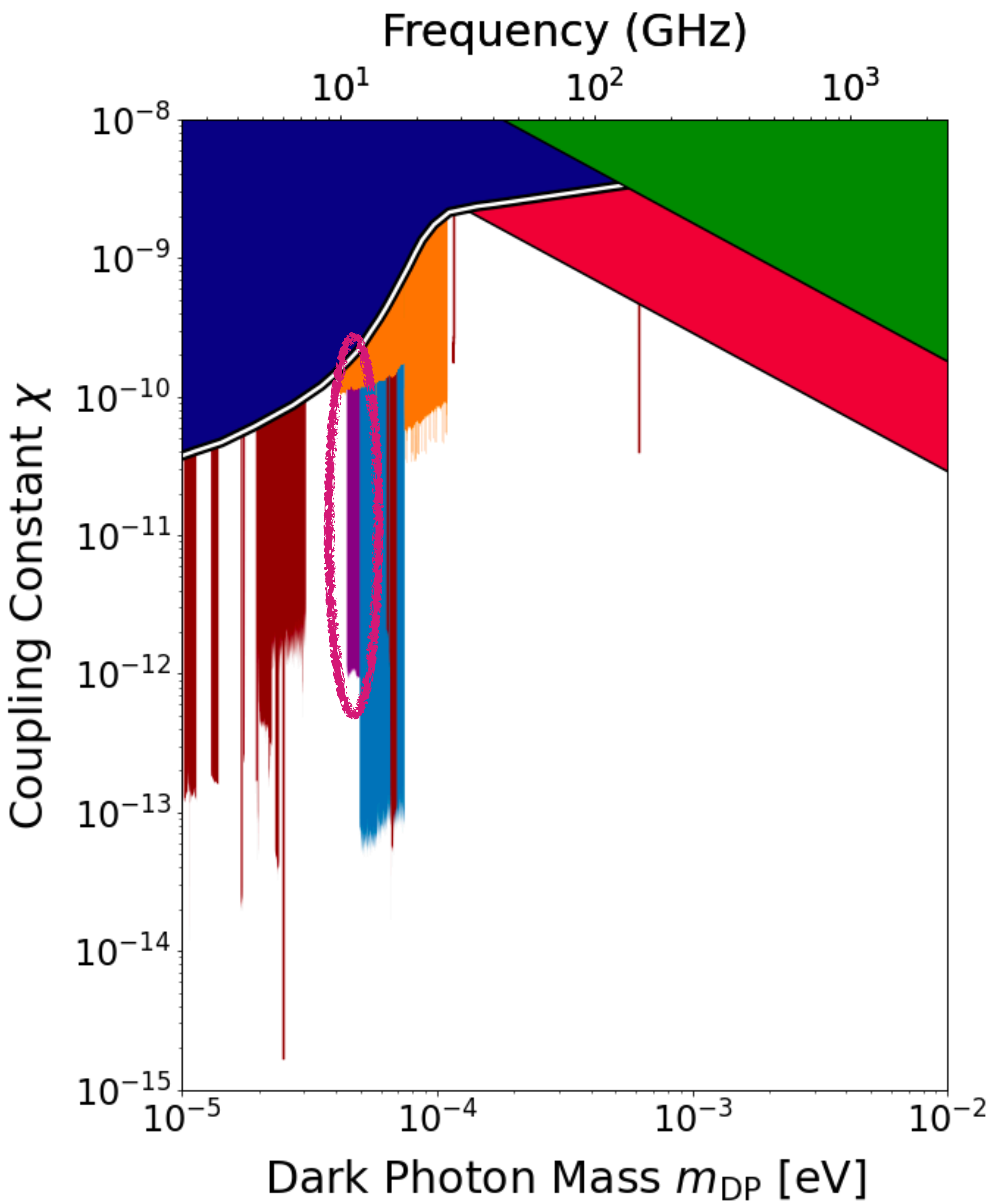
Spectroscopy (FPGA)
(Xilinx RFSoC ZU28DR)



- Sampling rate: 4Gsps
- Bandwidth: 2 GHz
- Resolution $\Delta\nu$: 7.8 kHz

e.g. Bykov et al, *Instrum Exp Tech* **51**, 724–728 (2008)
Barros et al, *IMOC*, 2013, pp. 1-4

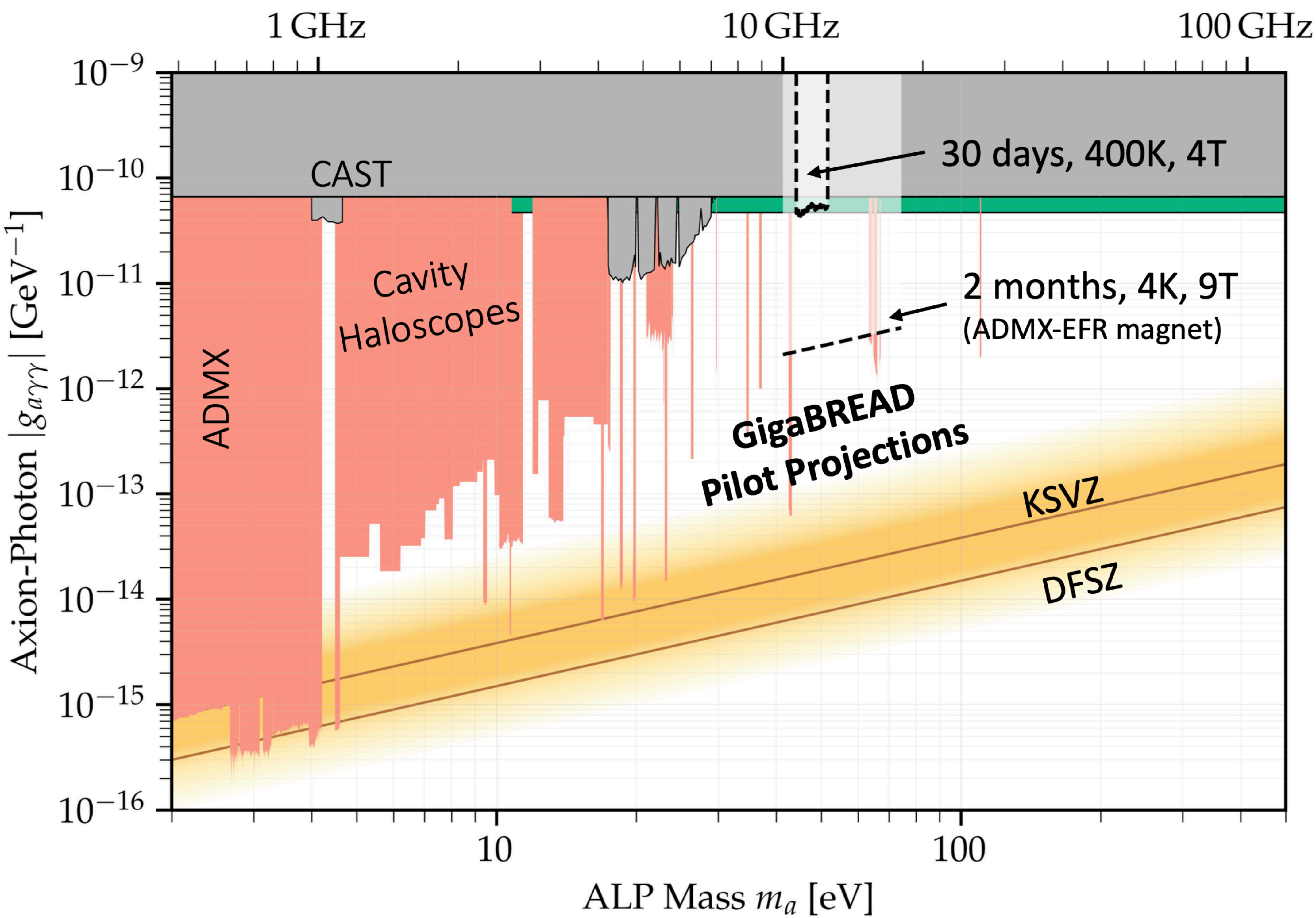
Results of Giga-BREAD



- T_{sys} ~ 400 K
- A ~ 0.5 m²
- Frequency range : 10.7—12.5 GHz
- Bandwidth : 2 GHz
- Resolution $\Delta\nu$: 7.8 kHz
- Time : 24 days

Next Plans: Axion search

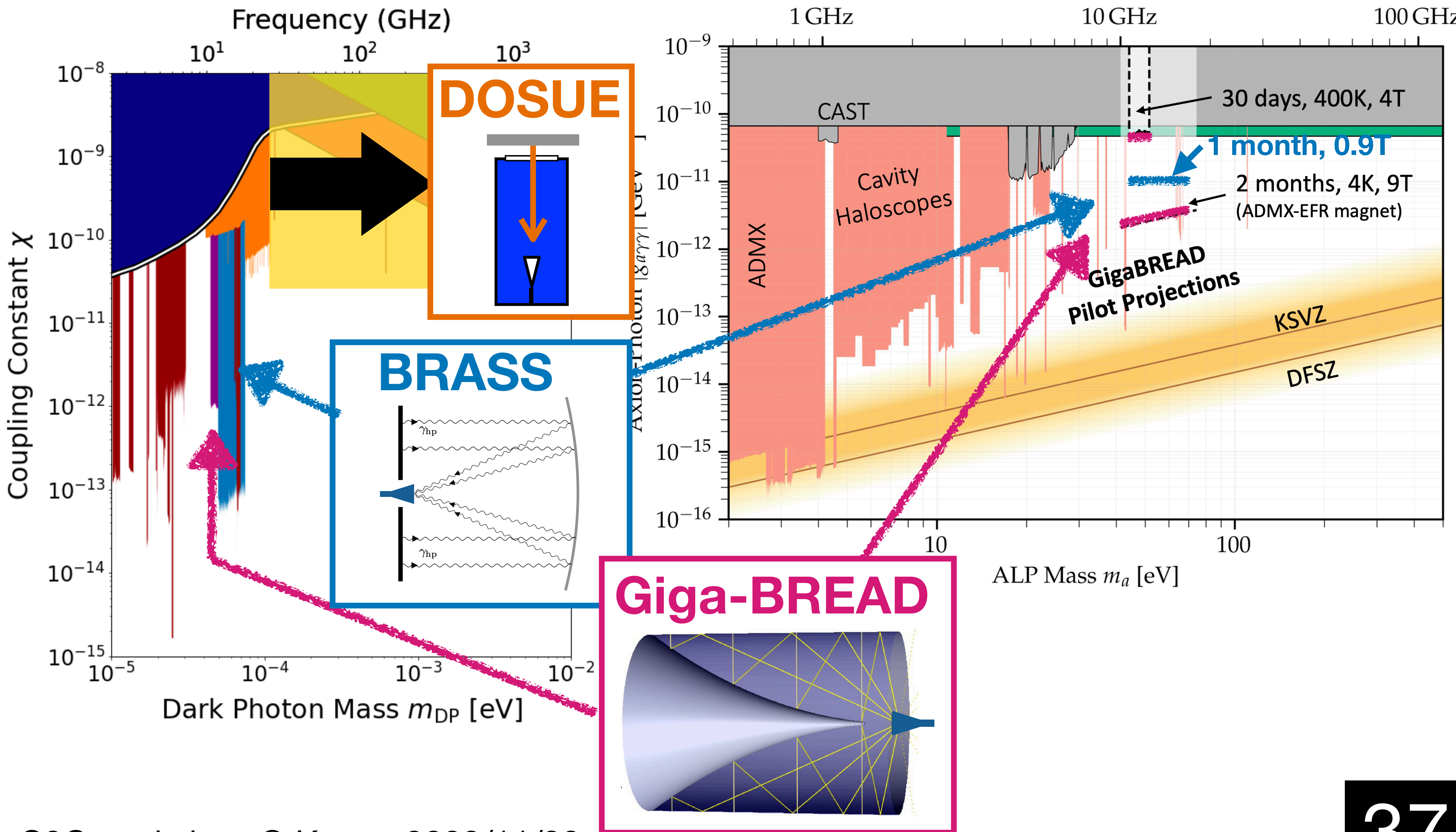
- Near-term : Install the setup into the 4T MRI magnet at Argonne
- Further plan : A stronger magnet & under cryogenic conditions



Summary of the experiments

Dark photon

Axion / ALPs



Summary

- Antenna gives us methods to search for wavy dark matter in broadband and high frequency ($\gtrsim$ 10 GHz).
- Several experiments (DOSUE, BRASS, BREAD) have published the results in dark photon search with various type of antennas or reflectors.
- They will proceed to another mass range or axion search.

Stay tuned for their outputs!

Dark photon (DP)

Dark photon can be introduced in the Lagrangian as a new U(1) symmetry.
It makes a mass eigenstate mixing with EM-field.

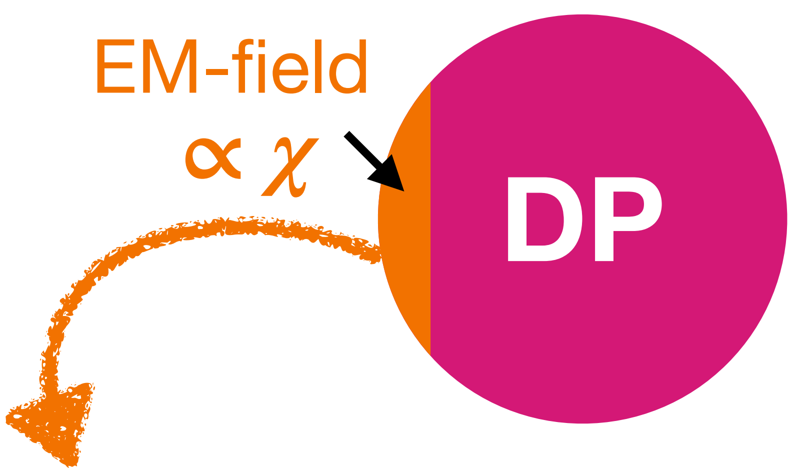
EM-field (interacting with SM)

Mass = m_{DP} state
(Dark photon)

$$\begin{pmatrix} \vec{A} \\ \vec{X} \end{pmatrix}_{\mathrm{DP}} = \vec{X}_0 \begin{pmatrix} \chi \\ 1 \end{pmatrix} \exp\{-i(\omega_{\mathrm{DP}} t - \vec{k} \cdot \vec{x})\}$$

DP-field (No interaction)

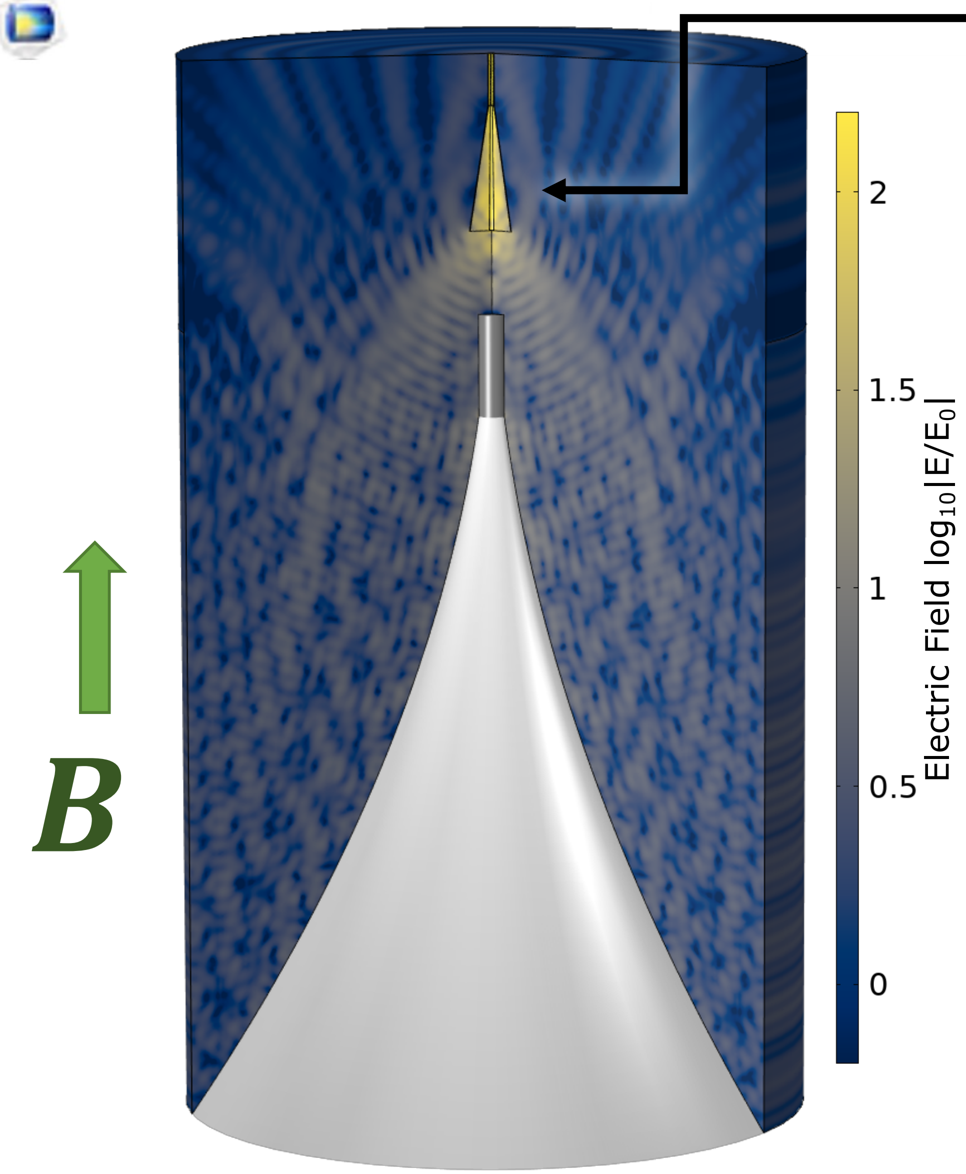
- Energy: $\omega_{\mathrm{DP}} = \sqrt{m_{\mathrm{DP}}^2 + \vec{k}^2}$
- χ : coupling constant (≪1)

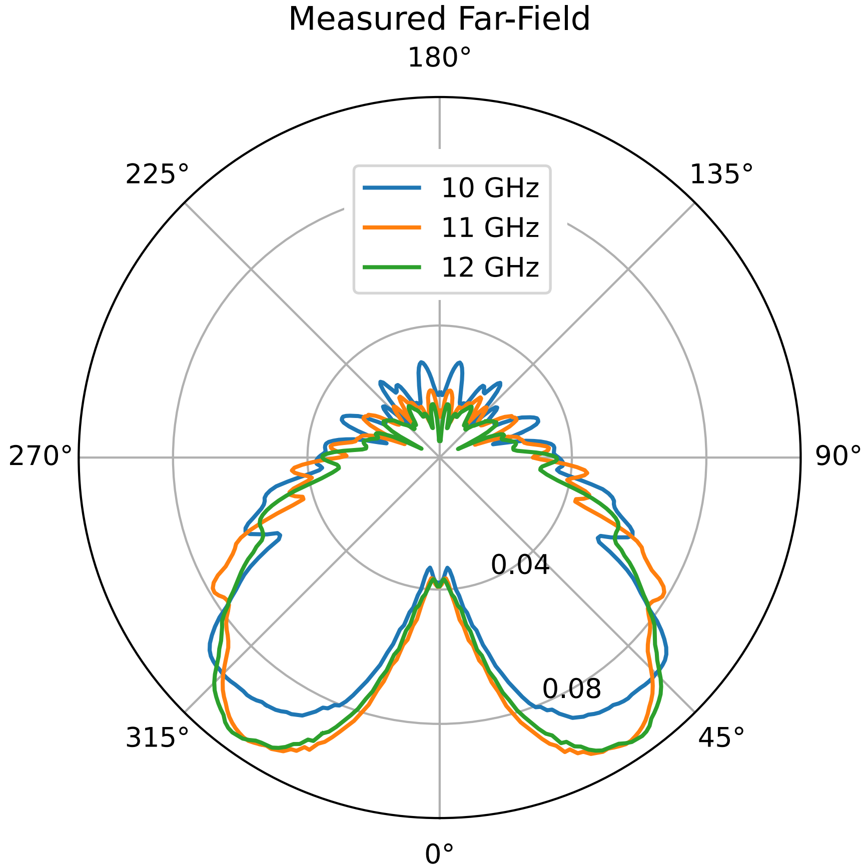


DP has a **small ($\propto \chi$)** electric field.

$$\vec{E}_{\mathrm{DP}} = -\partial_0 \vec{A}_{\mathrm{DP}} = i\chi\omega_{\mathrm{DP}} \vec{X}_0 \exp\{-i(\omega_{\mathrm{DP}} t - \vec{k} \cdot \vec{x})\}$$

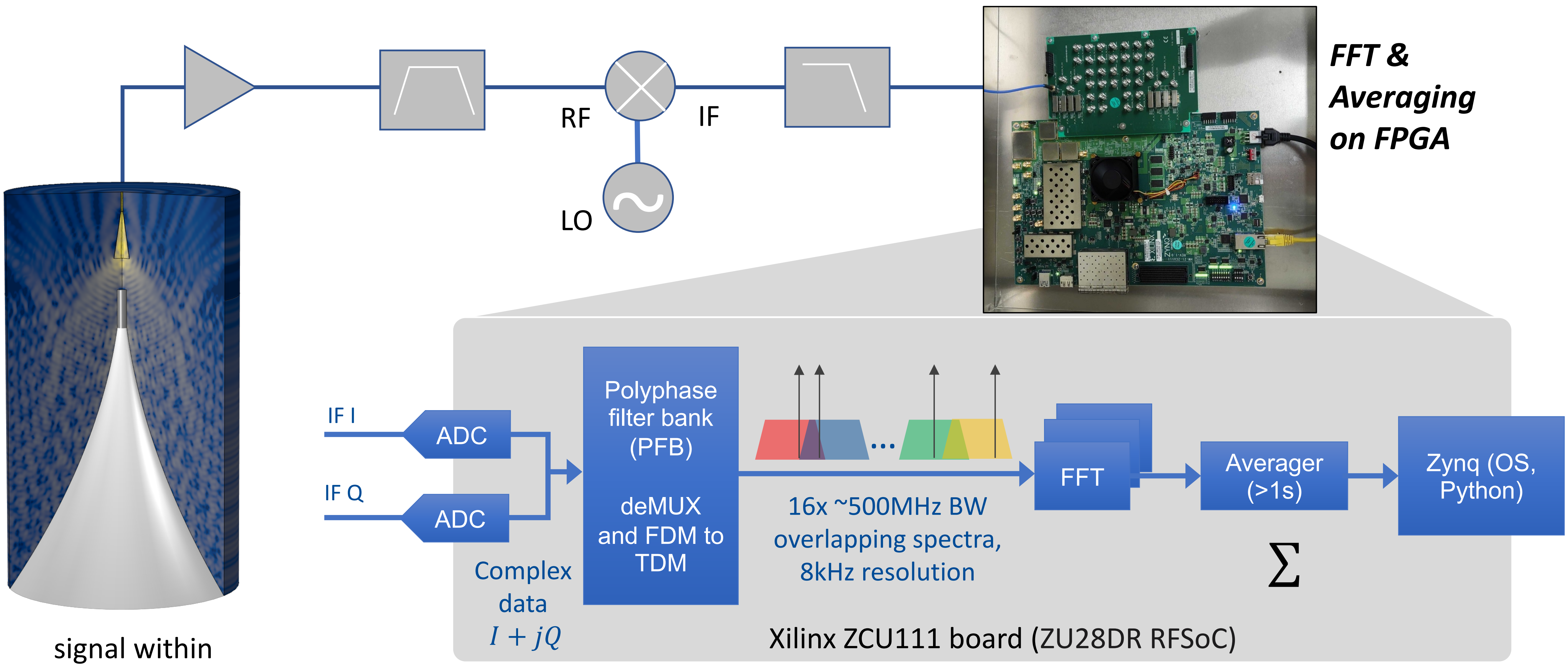
Receiver





e.g. [Bykov et al, DOI:10.1134/S0020441208050126]
[Barros et al, DOI:10.1109/IMOC.2013.6646569]

DAQ

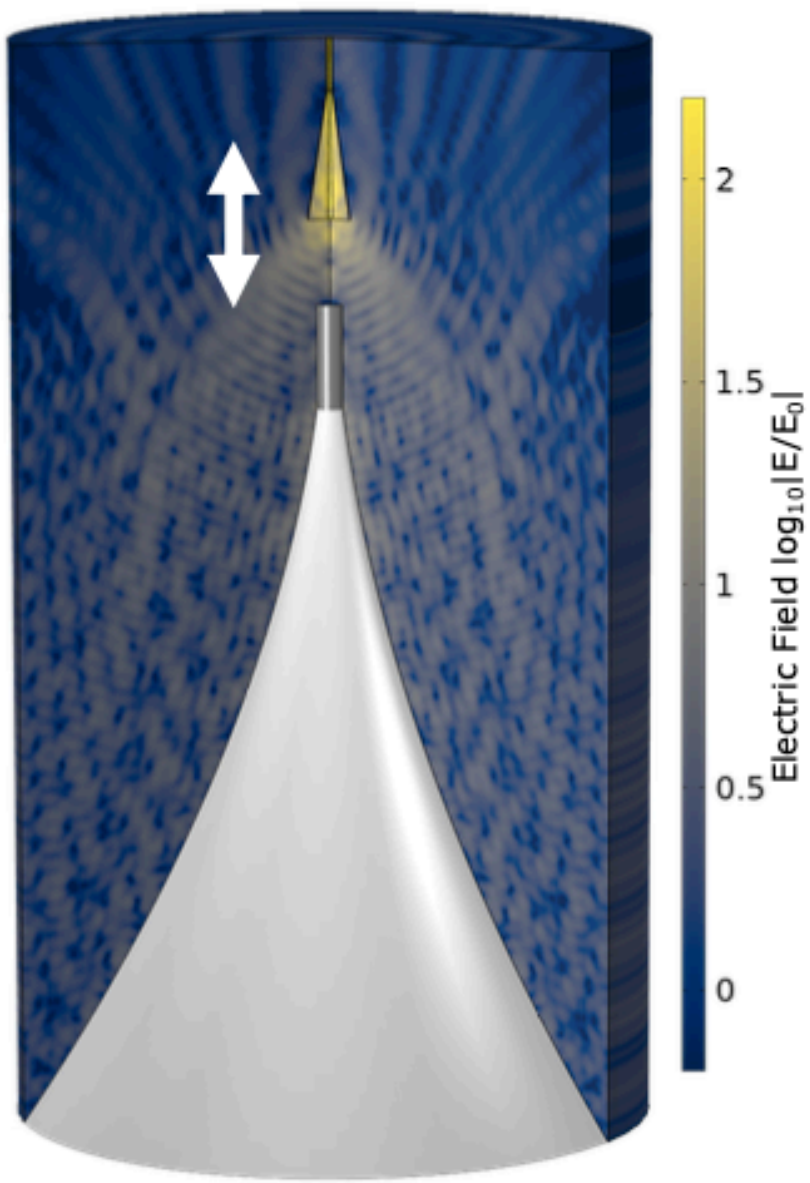


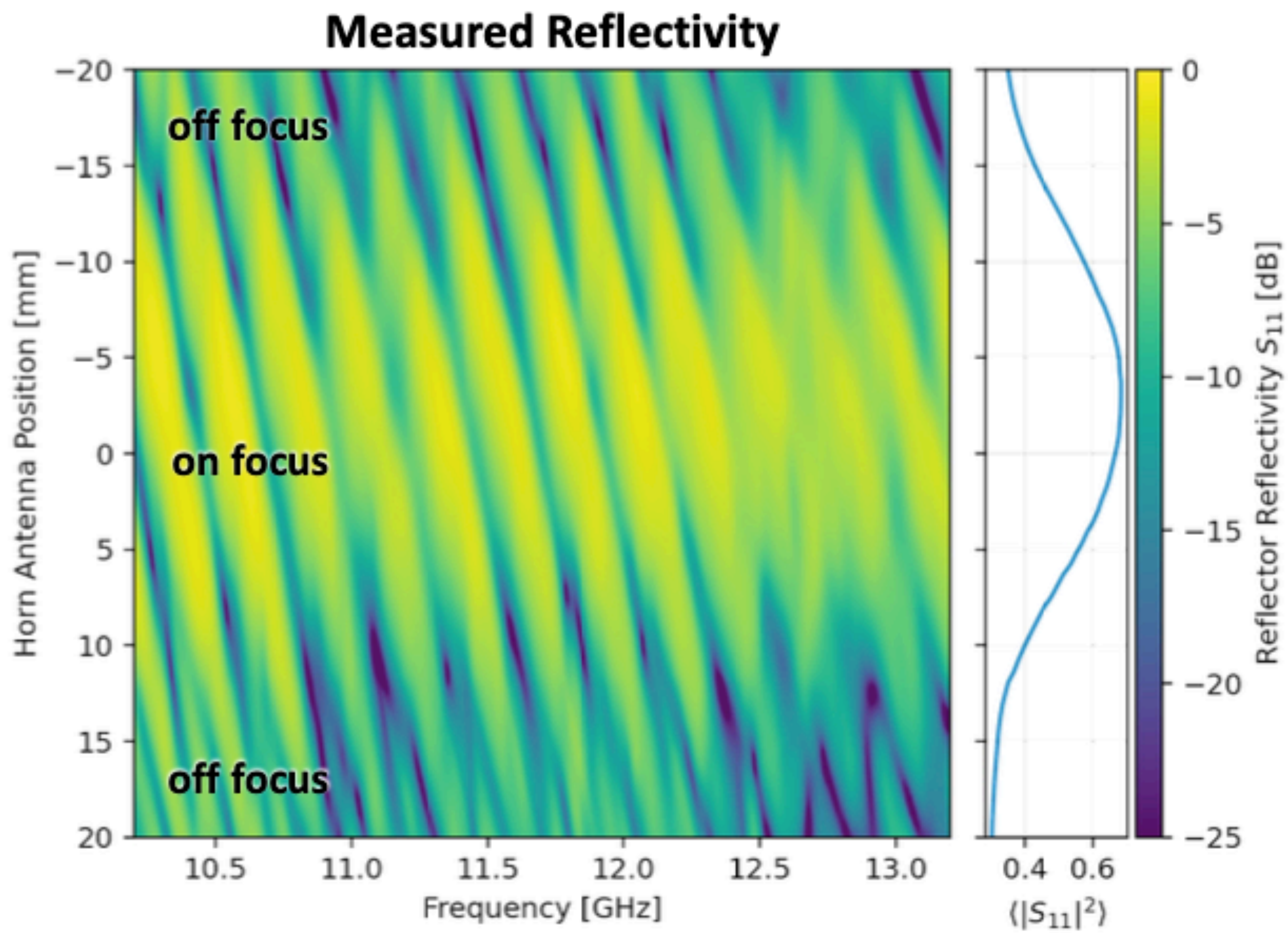
signal within
antenna bandwidth
(10.7 - 12.5) GHz

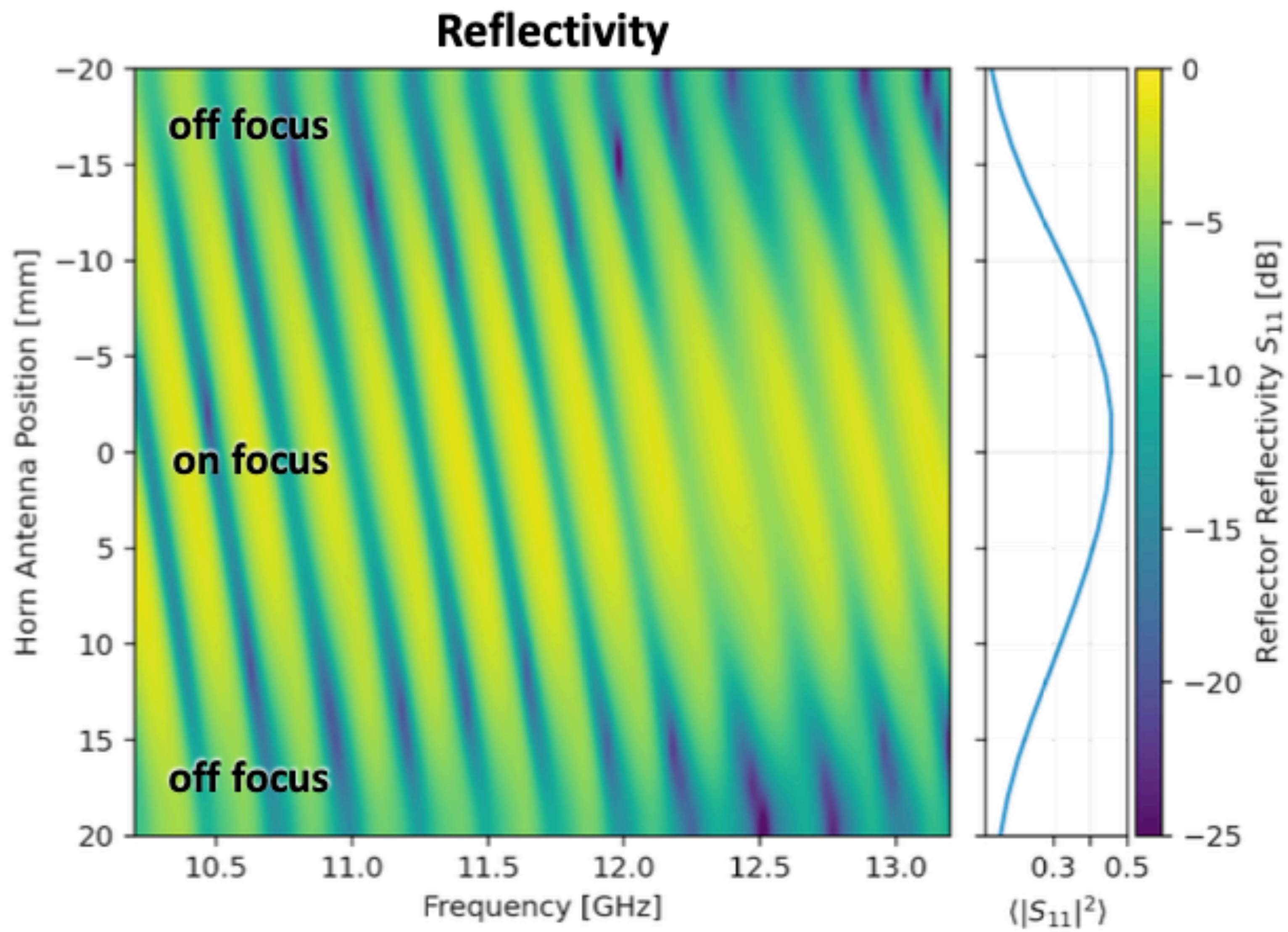
Negligible Dead Time after >1s on-board averaging

Focal spot

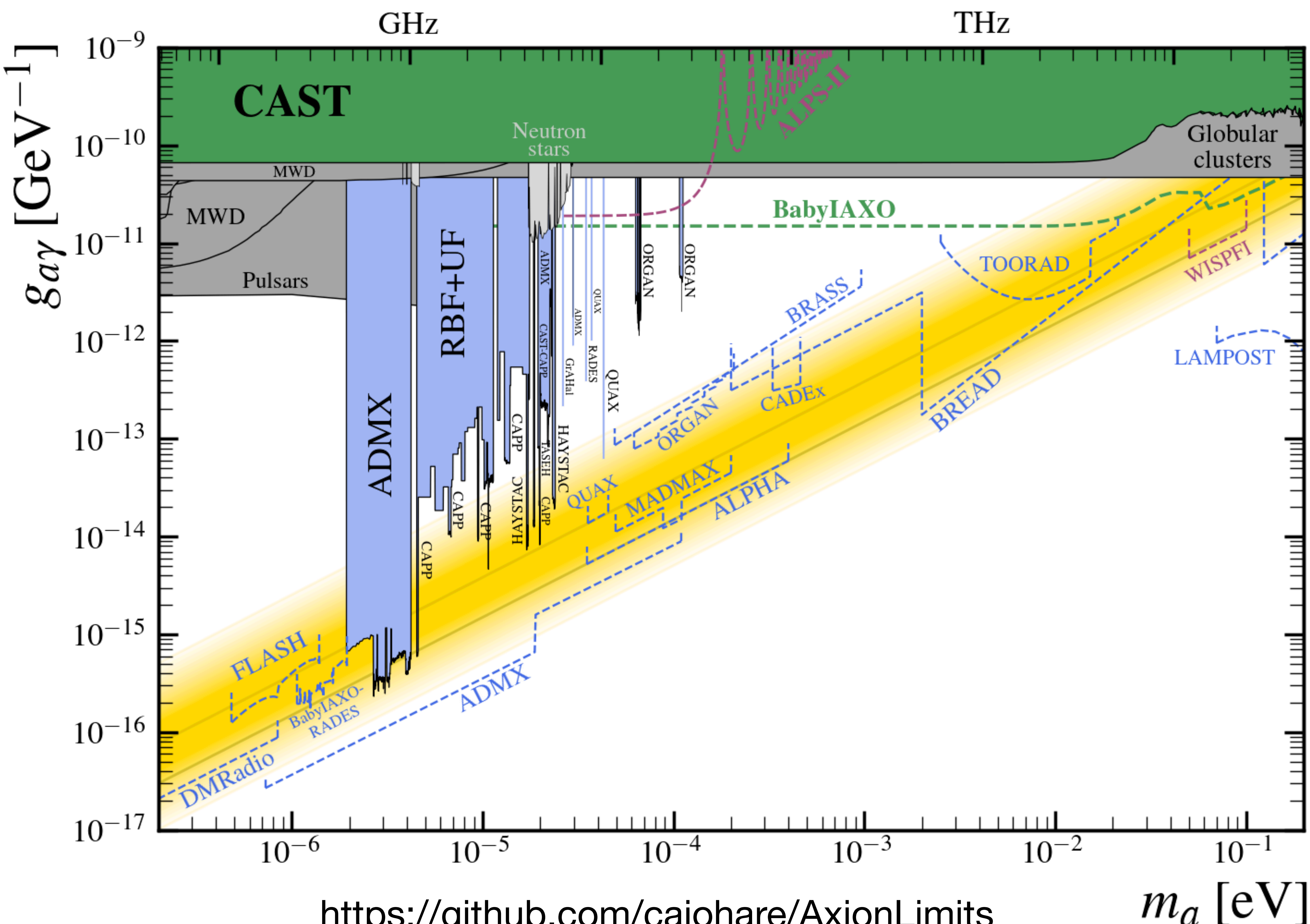
- The focal spot along the z-axis depends on the frequency.
- The receiver moves along the z-axis.
- The efficiency is evaluated
  by measuring the reflectivity (S11) of the barrel wall.






Reflectivity
off focus
on focus
off focus
Horn Antenna Position [mm]
Frequency [GHz]
⟨|S11|²⟩
Reflector Reflectivity S11 [dB]
−20
−15
−10
−5
0
5
10
15
20
10.5
11.0
11.5
12.0
12.5
13.0
0.3
0.5
0
−5
−10
−15
−20
−25

Future prospects for axion search



https://github.com/cajohare/AxionLimits

Sensitivity for Large BREAD