Wave-like dark matter

UGAP conference in Sendai on March 5th, 2024

Y. Kishimoto

RCNS, Tohoku University

科研費 KAKENHI

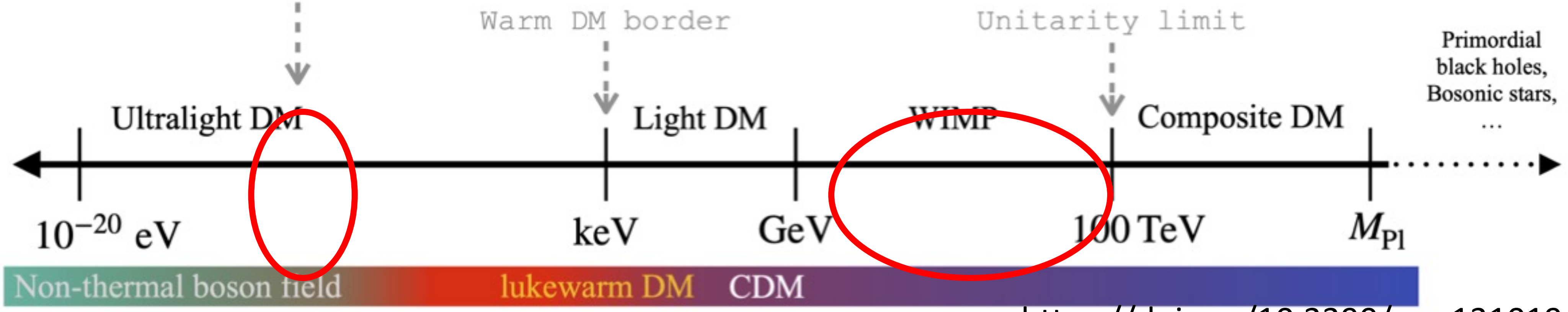
地下から解き明かす宇宙の歴史と物質の進化

Unraveling the History of the Universe and Matter Evolution with Underground Physics

DM exists, but what it is?

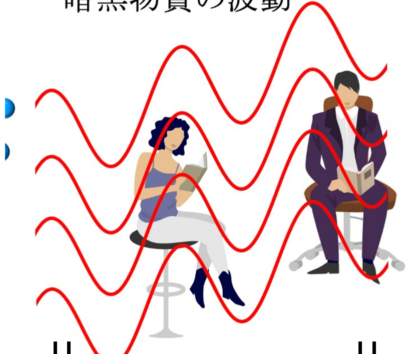
There are huge variety of candidates.

Axion, ALP and hidden photon

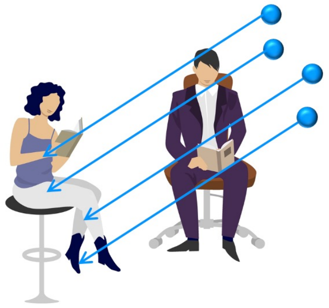


https://doi.org/10.3390/sym13101945

暗黒物質の波動



暗黒物質の粒子

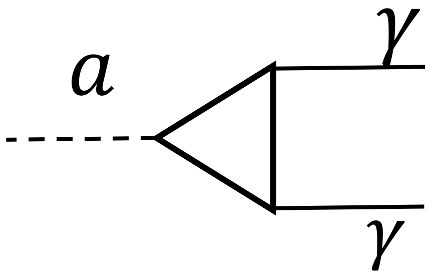


Considering small mass, small velocity, and high number, it should treat as a classical wave.

Wave-like DM

- Axion
  - Introduced to solve the strong CP problem
- Axion-like particle
  - Motivated by string theory.
- Hidden photon
  - Motivated by string theory.

Interaction of Axion and ALP



- $L = -\frac{1}{4} g_{agg} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

$$- \frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma N F^{\mu\nu}$$

$$+ g_{aNN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma^5 N$$

$$+ g_{eaa} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e$$

Coupling to **two** photons (the g_{agg} term)

- This exists in any model.
- Intensive experimental studies in wide mass range.

Coupling to nucleon (the g_d and g_{aNN} terms)

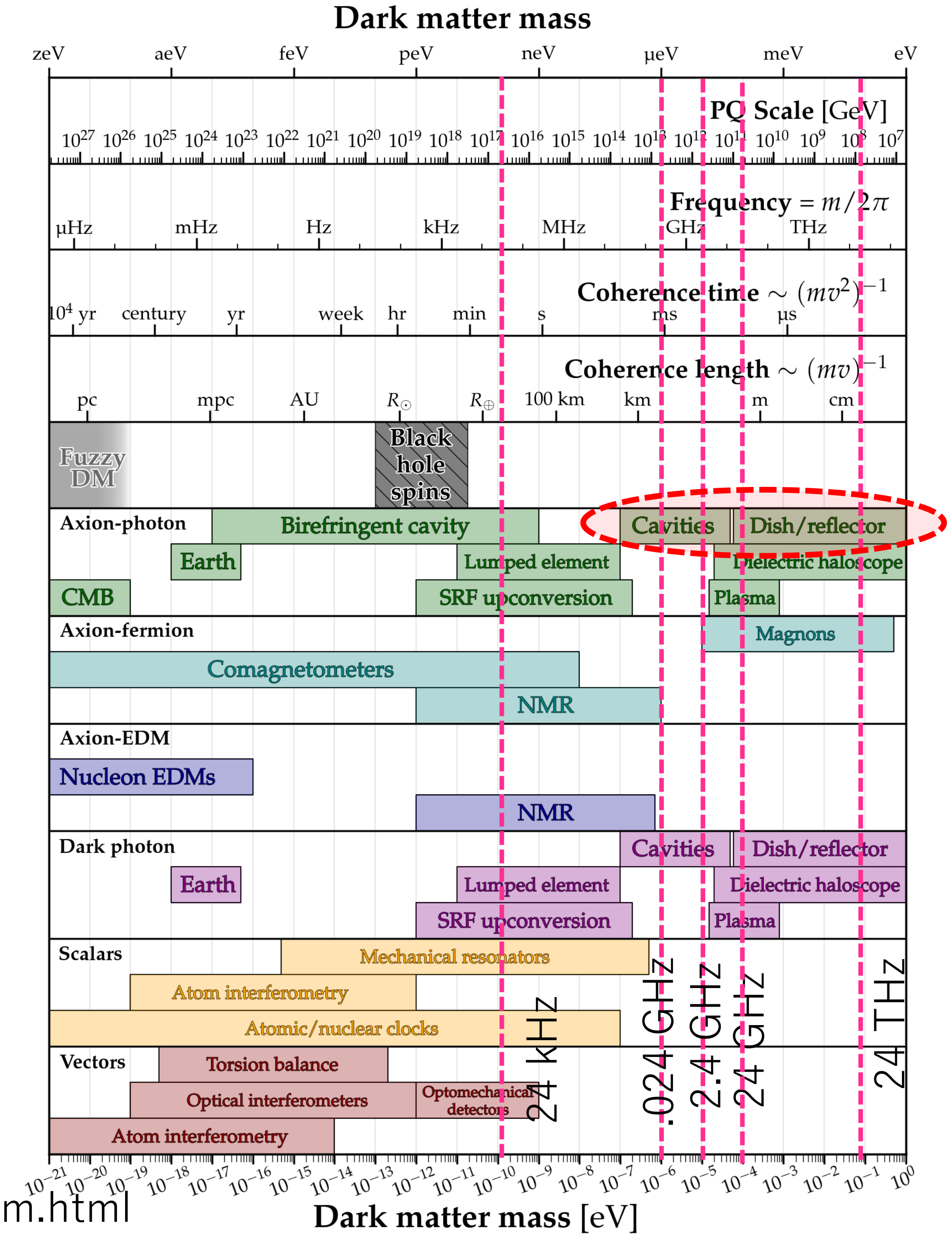
- Good at lower mass region.

Coupling electron (the g_{eaa} term)

- This does not exist in some axion model. (Eg. KSVZ)

DOI: 10.1103/PhysRevD.88.035023

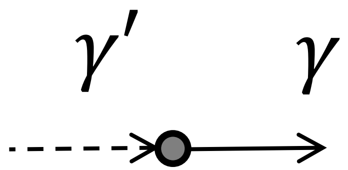
Detection methods for DM axion



https://cajohare.github.io/AxionLimits/docs/am.html

Interaction of Dark photon

- $L = -\frac{1}{2}\chi F_{\mu\nu}X^{\mu\nu}$ ⟵ Coupling to one photon



Experimental scheme for axion can be used for DP.

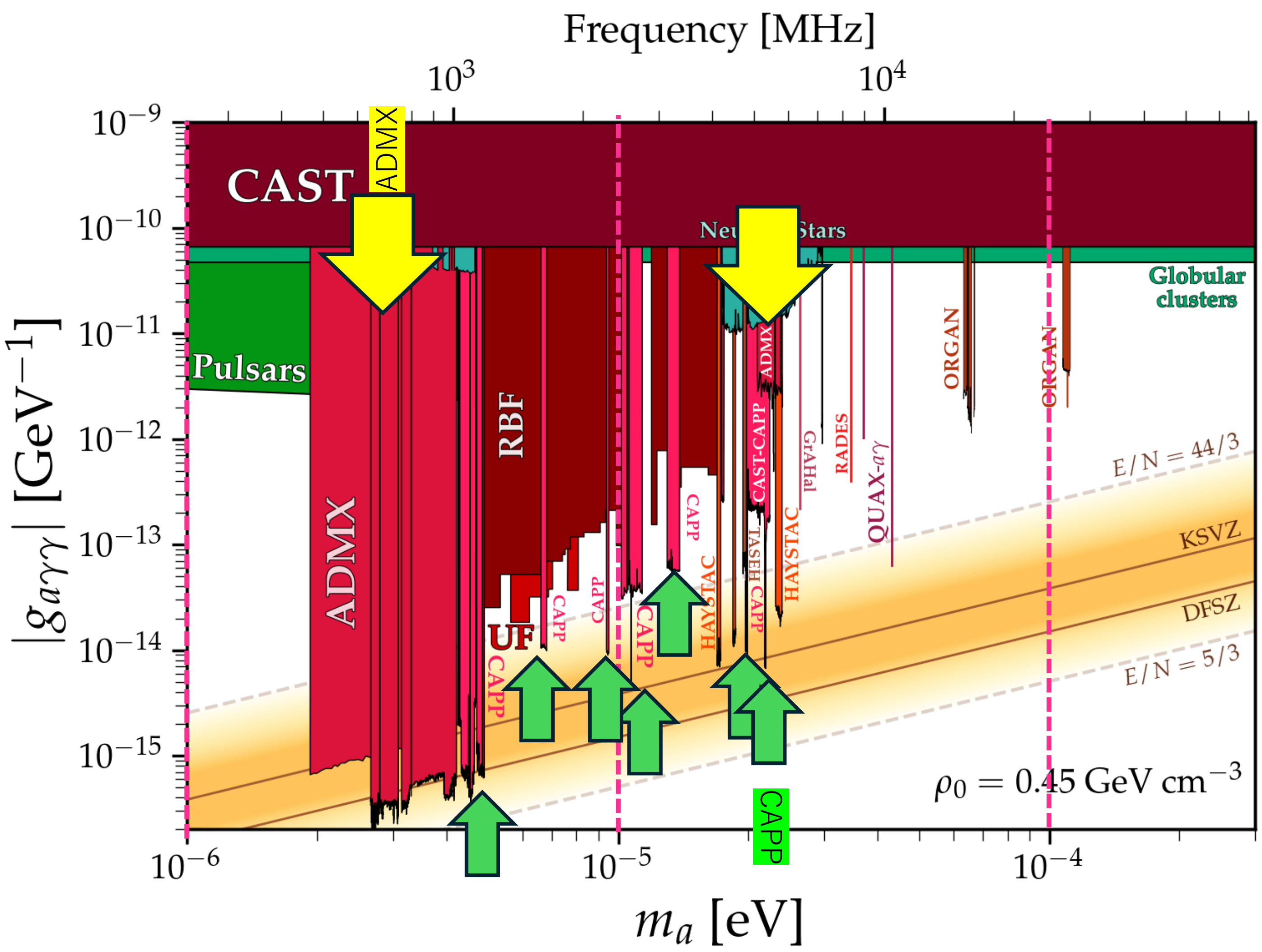
⇩

No magnet experiment: DP search

With magnet experiment: Axion/ALP

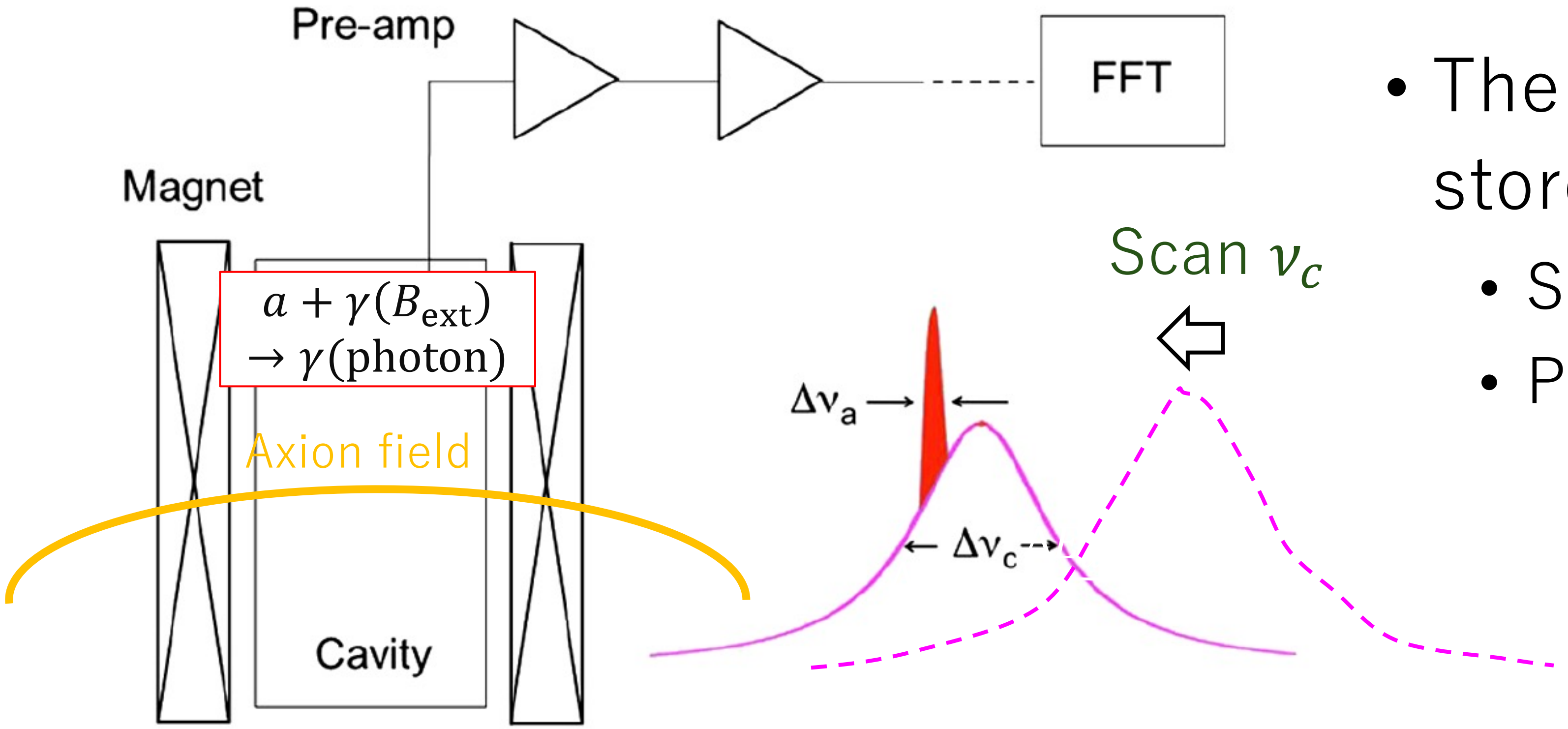
Axion searches

ADMX and CAPP lead the competition with cavity haloscopes.



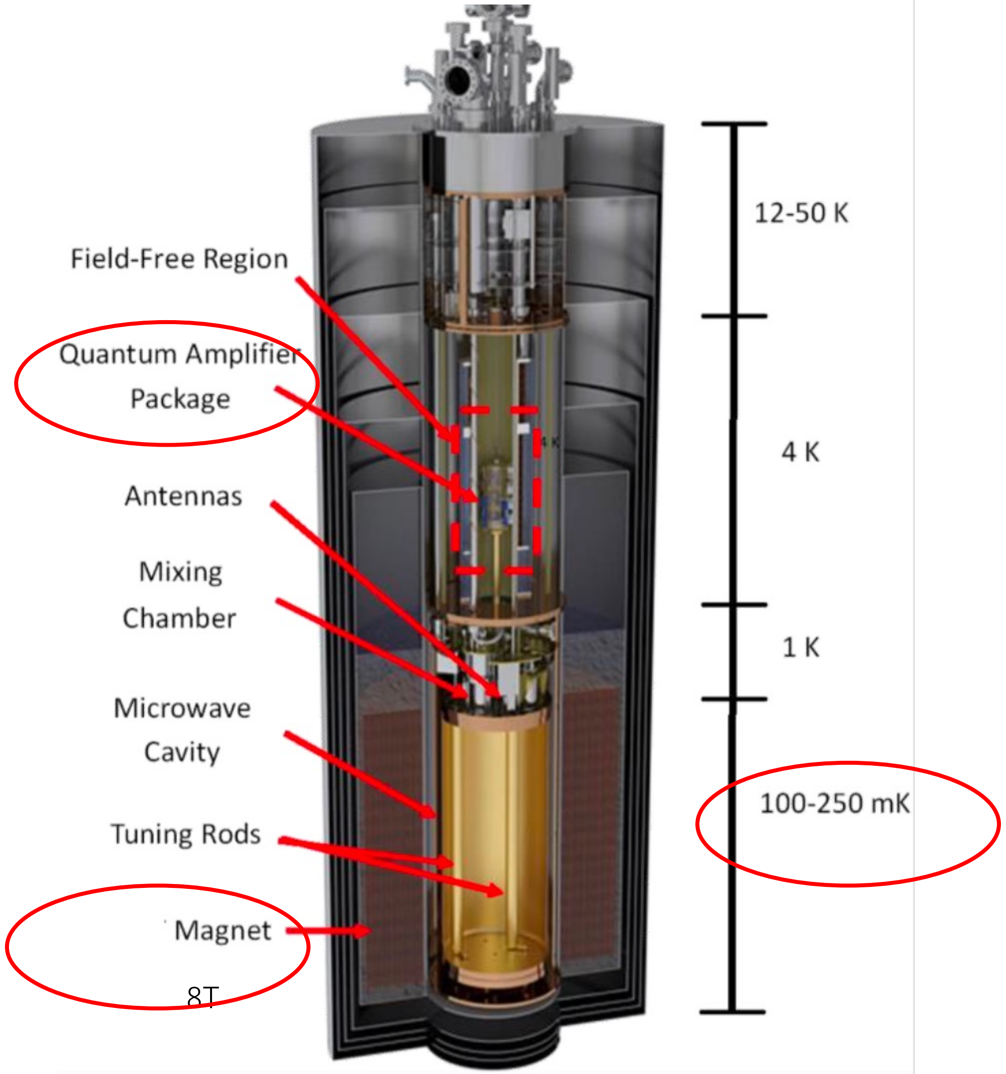
Principal of the cavity haloscope

$$P = \kappa g^2 V B_0^2 \rho_0 G_{lmn} \frac{1}{m_a} Q_c,\ G_{lmn} = \frac{\left(\int dV\, \vec{E}\cdot\vec{B_0}\right)^2}{|B^2| V \int dV\, E^2}$$



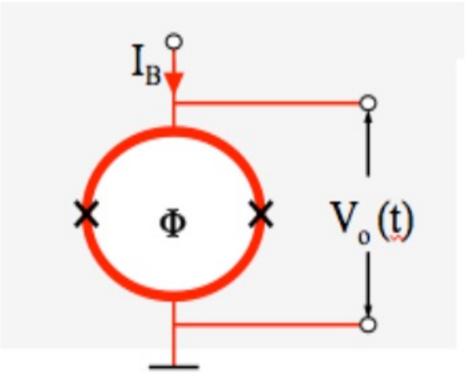
- Axion converts into RF photon in magnetic field.
- The converted photon is stored and enhanced by cavity.
  - Signal width = $\sim m_a \beta^2$
  - Peak search experiment

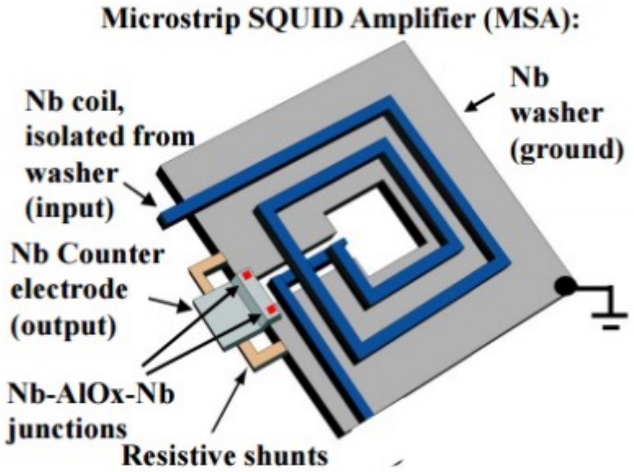
ADMX

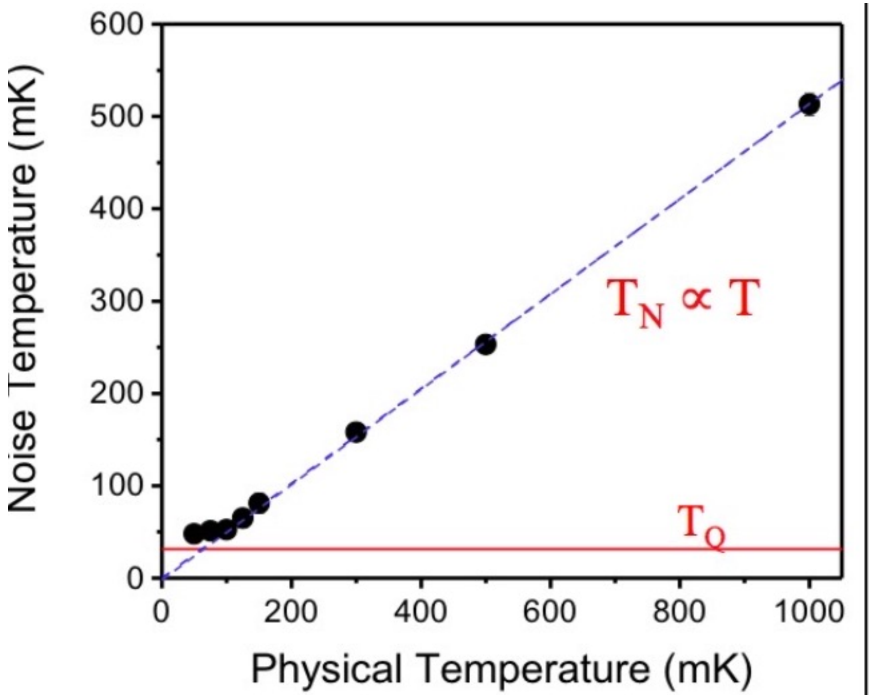


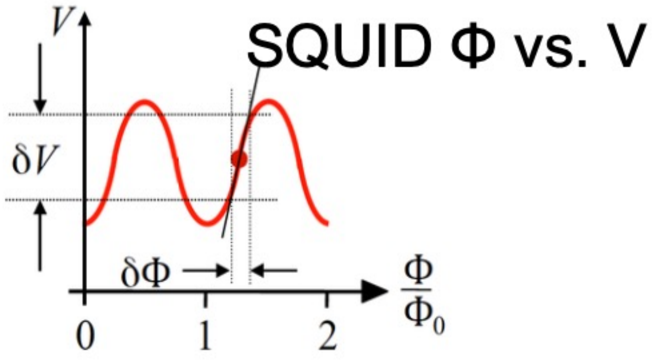
Slide from Rybka's talk in Kashiwa DM conference 2023

Microstrip SQUID Amplifier (MSA)





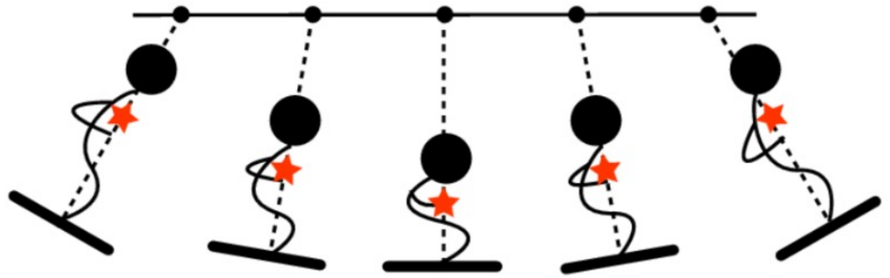




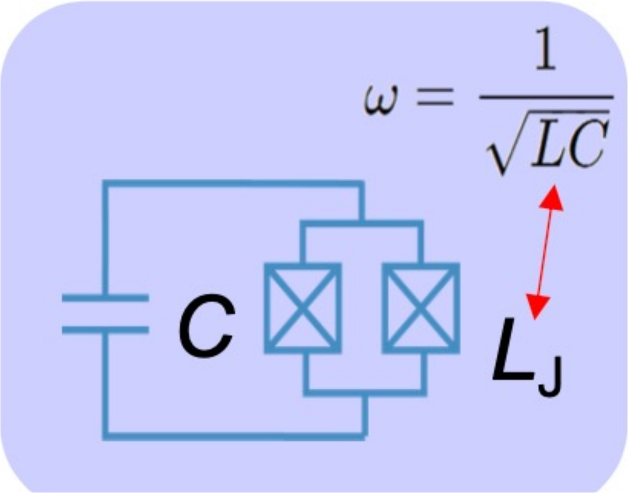
- Very low noise temperature $T_N \sim 50\ \mathrm{mK}$

From G. Carosi's slides at Axions Beyond Boundaries Workshop 2023

Josephson Parametric Amplifier (JPA)

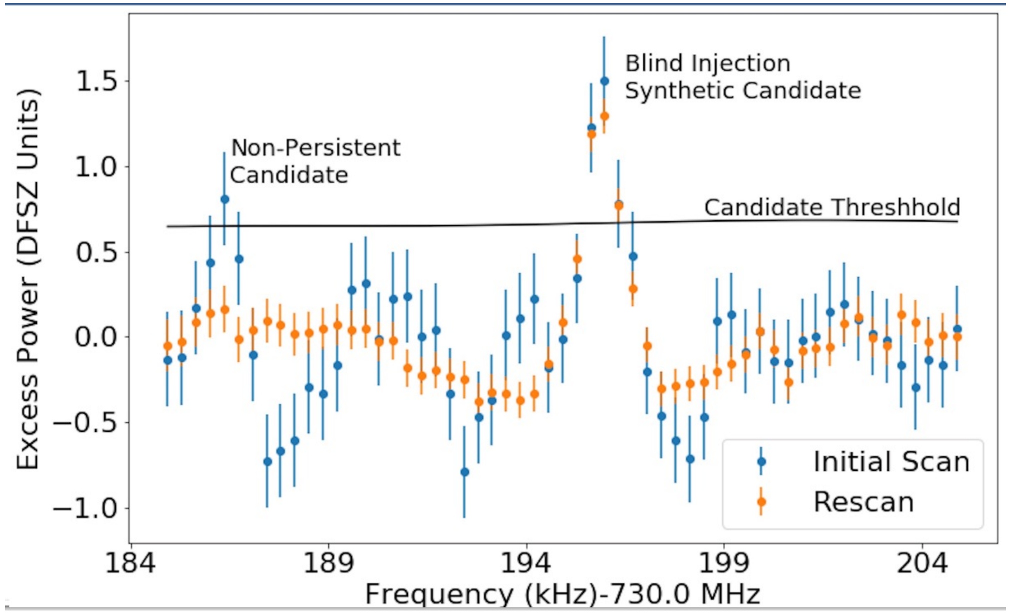


Classic example of parametric amplification is a child on a swing



Inductance in Josephson junction, L_J

- High gain and low noise at GHz range



- DFSZ signal can be clearly detected.
- → **Low noise amplifier is the key.**

CAPP(CAPP-8TB)

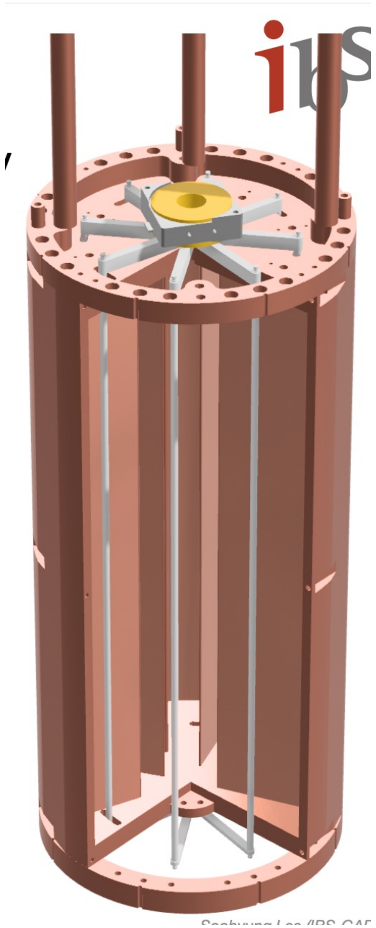
Axion Haloscope at IBS-CAPP (8T/165mm)

- CAPP-8TB experiment
  - Physics run 1
    - Conventional cavity + HEMTs
    - 1600 - 1650 MHz @ $g_\gamma \simeq 4 \times g_\gamma^{\mathrm{KSVZ}}$
    - PRL 124, 101802 (2020)
    - NIMA 1013, 165667 (2021)
  - Physics run 2
    - 8-cell cavity + JPA
    - 5830 - 5940 MHz @ $g_\gamma \simeq g_\gamma^{\mathrm{KSVZ}}$
- Superconducting cavity test @ $B = 8\,\mathrm{T}$
  - D. Ahn's talk on Thursday
- Axion quark nugget search
  - J. Kim's talk on Thursday

From S. Lee's slide in Patras 2023

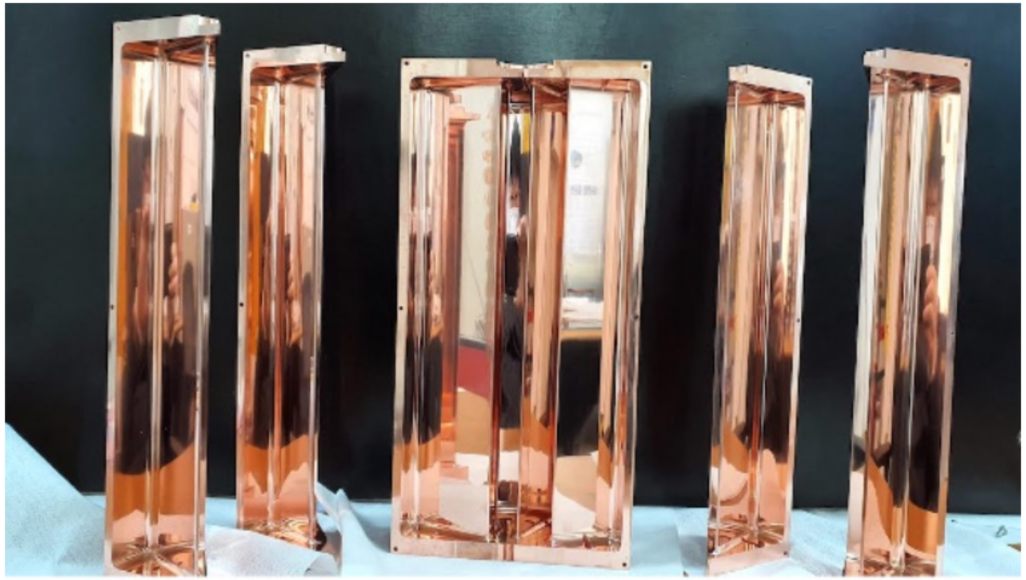
- In run 2, they addressed 5.83-5.9 GHz.
  - Dilution refrigerator
  - 8 –ell cavity
  - JPA
  - B=8 T

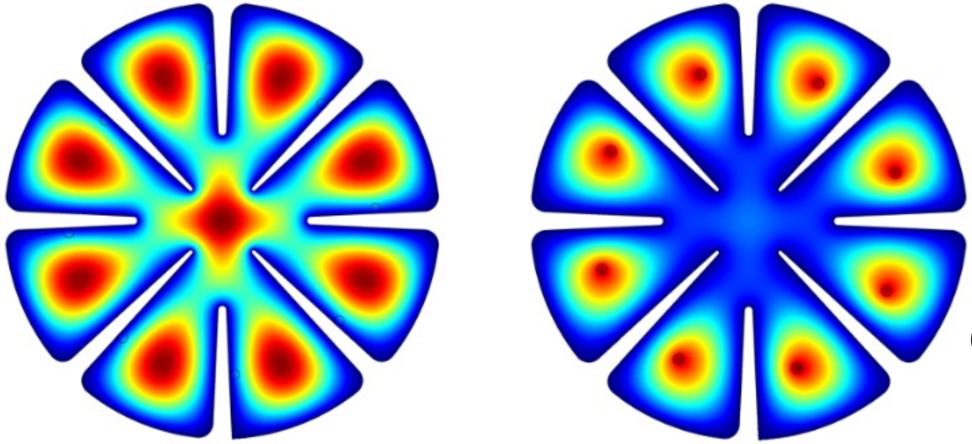
8 cell cavity



V=3.1L

Housed in D=165mm

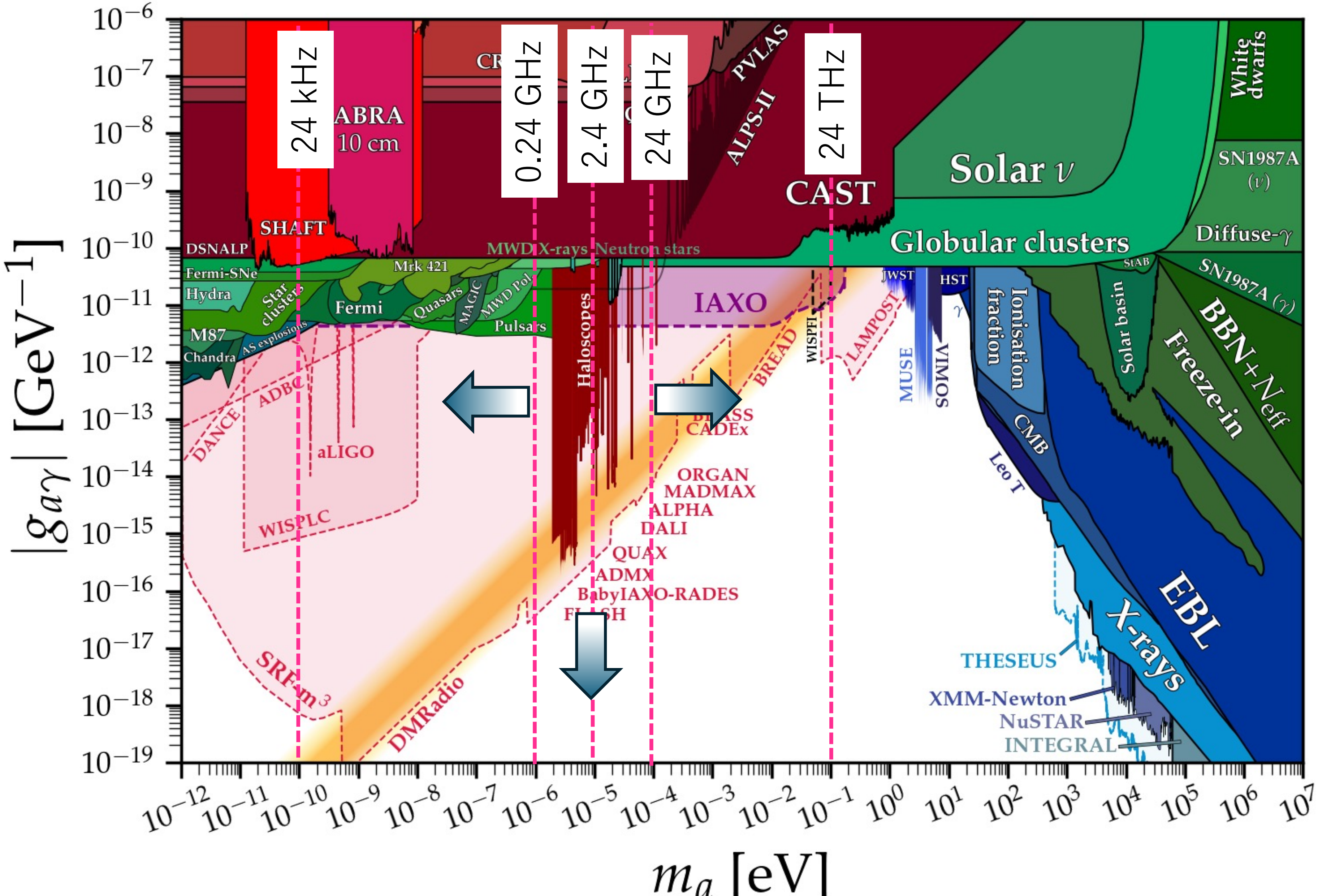




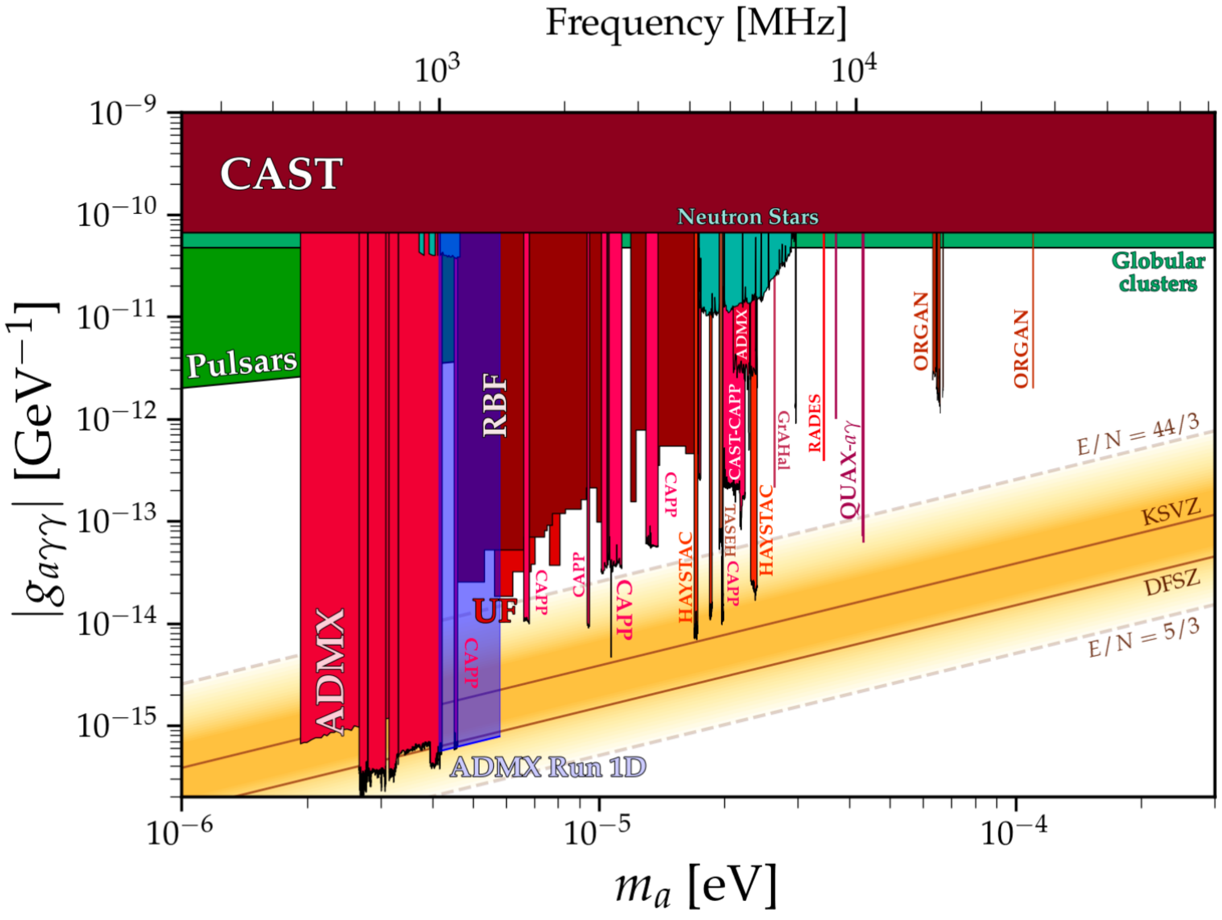
Cavity electric field structur
(Left dielectric rod is set at
edge, right at the center)

Cavity is important factor for higher frequency regime.

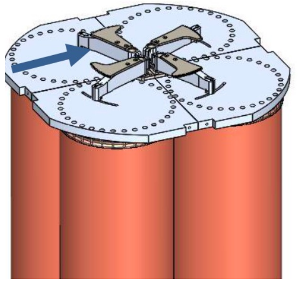
Various future projects !



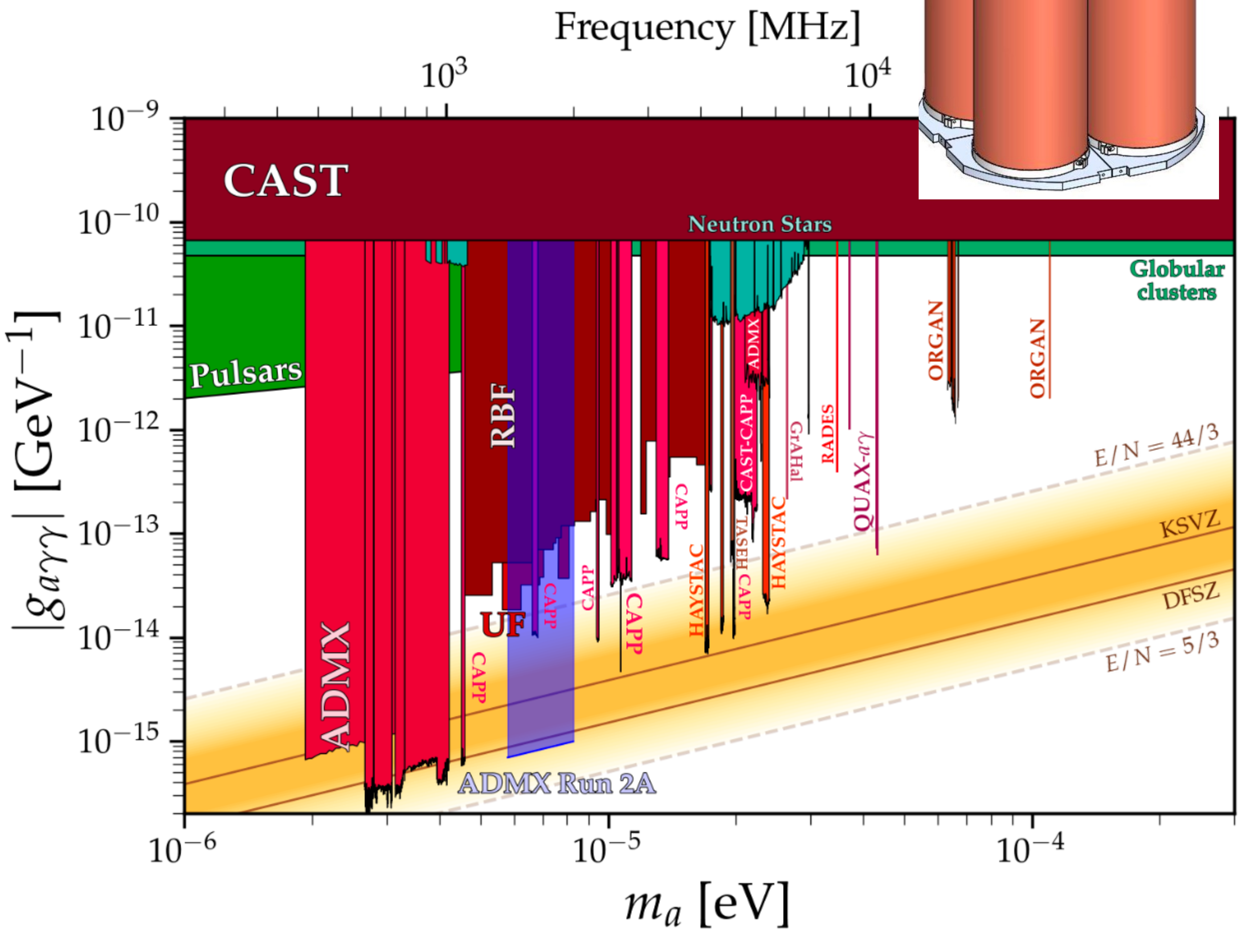
ADMX Run 1D and 2A



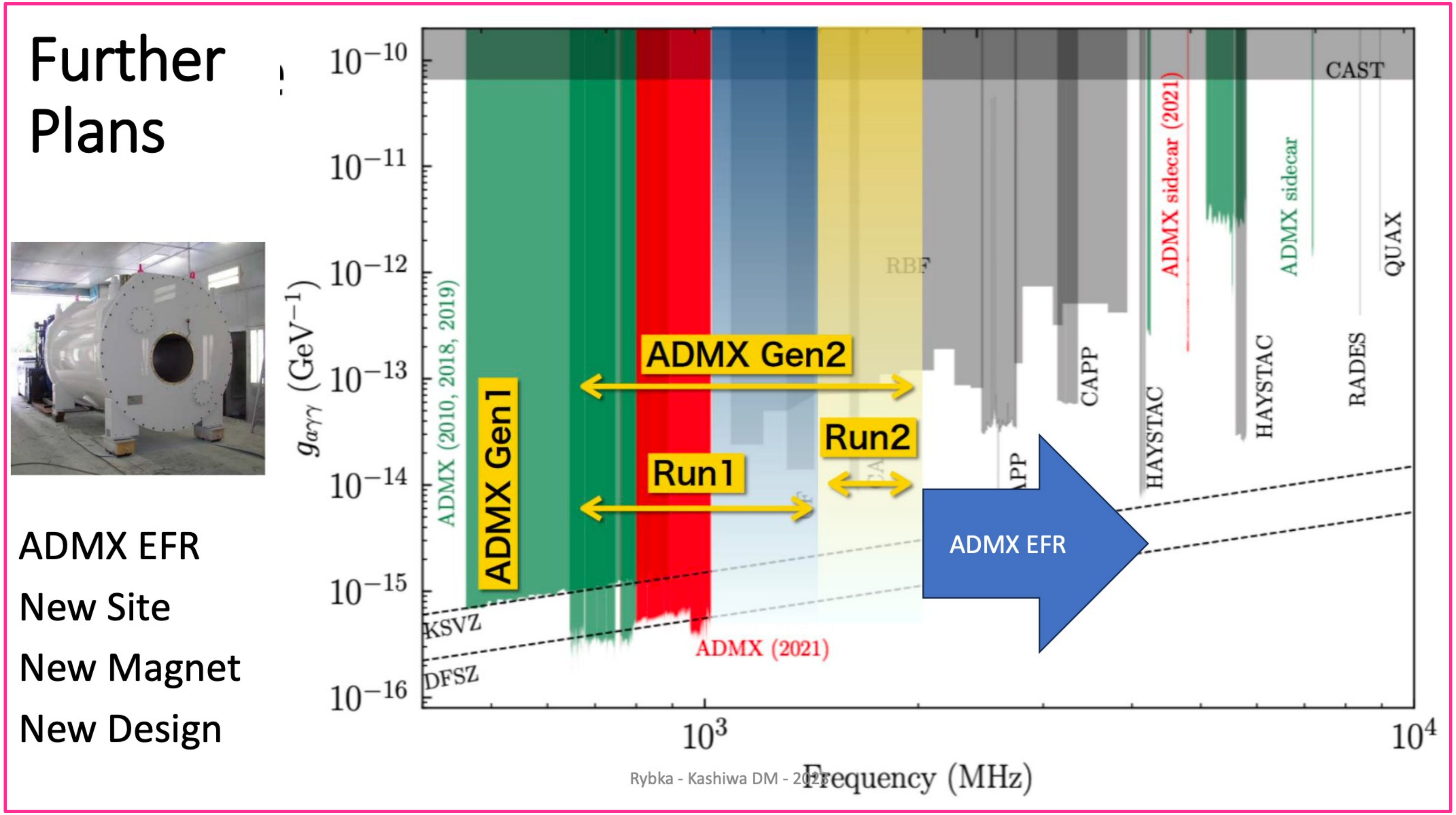
Running from summer 2023



Four individual cavities tuned by rotors



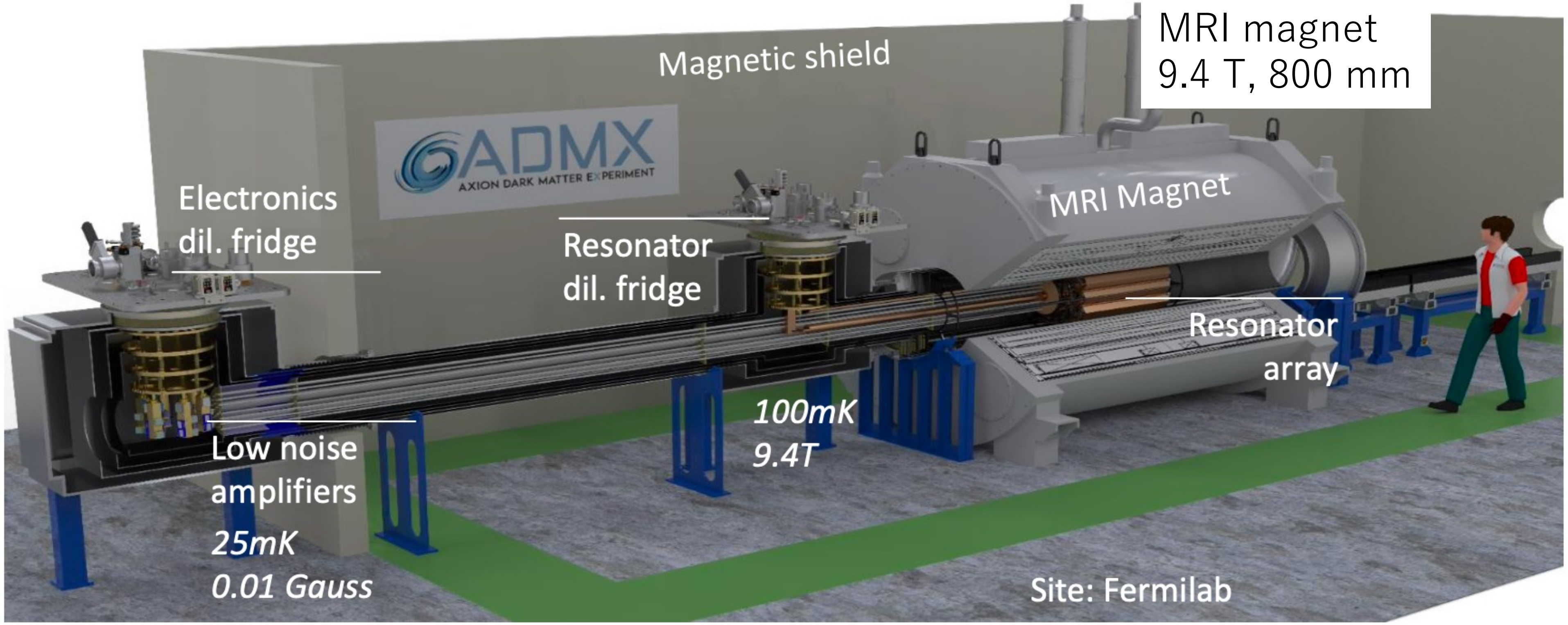
ADMX-EFR



Slide from Rybka’s talk in Kashiwa DM conference 2023

ADMX-EFR

- Incorporate technologies as they mature for a continuous scan sensitive to DFSZ axions at 2GHz and up

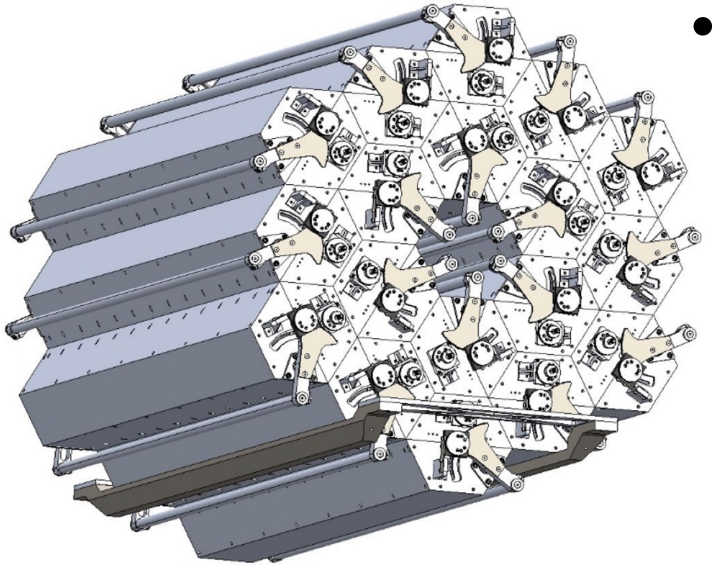


Rybka - Kashiwa DM - 2023

Slide from Rybka’s talk in Kashiwa DM conference 2023

Run 1A-C

Run 2



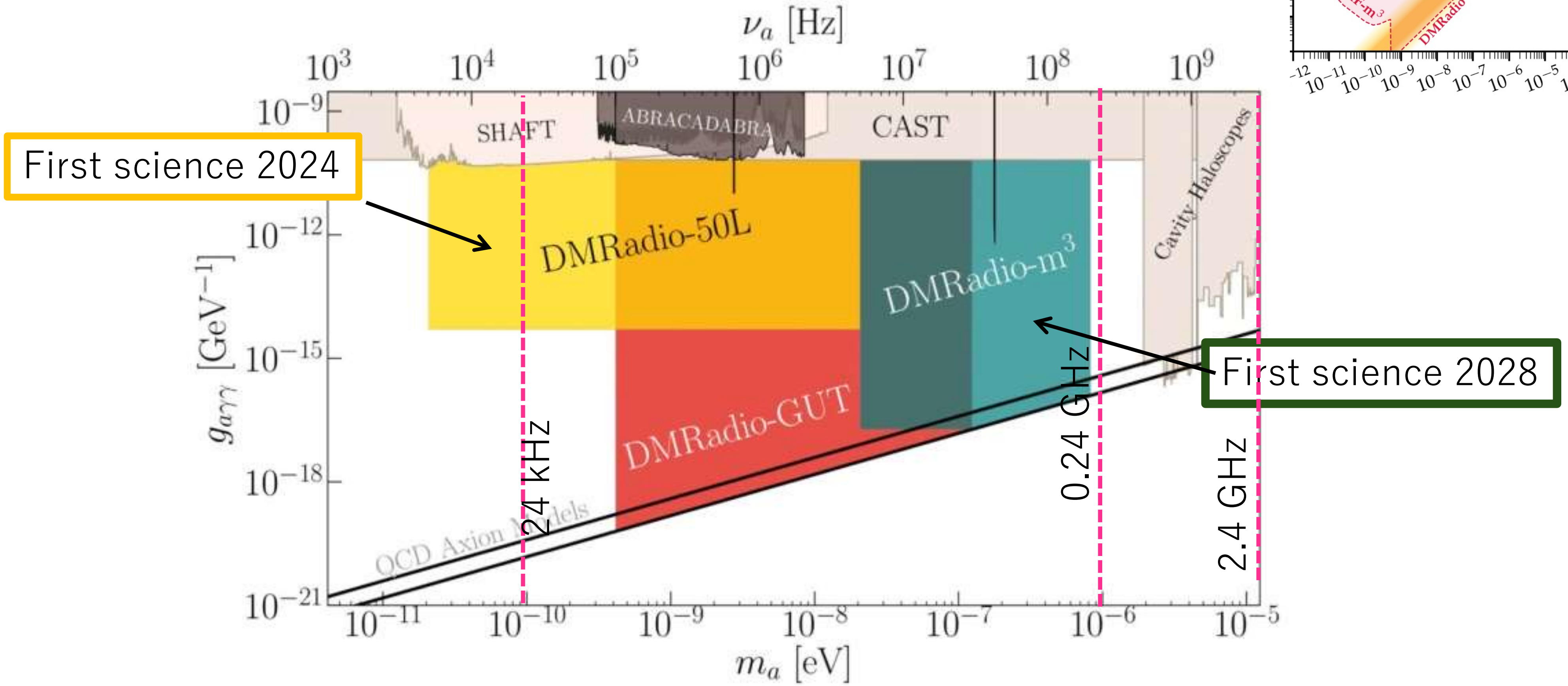
EFR

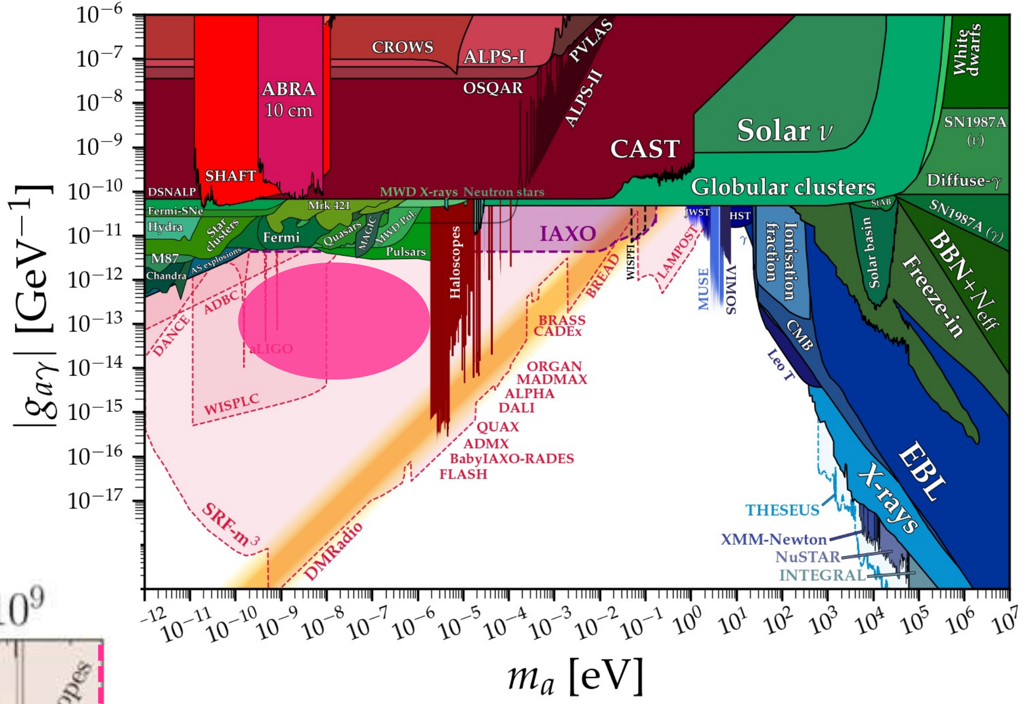
- Multi-cavities with multi-DAQ
  - Faster scan by simultaneous runs.
  - In-phase detection after the digitizing.
    - Axion signal is expected to be coherent, but the noise is in-coherent.

	Run 1A-D	Run 2A	EFR
Frequency Range	650–1390 MHz	2–4 GHz	2–4 GHz
Number of Cavities	1	4	18
Volume	106–136 ℓ	85 ℓ	80 ℓ
Q	58,000 (avg)	60,000	90,000
B Field	7.7 T (A: 6.85 T)	7.7 T	9.6 T
Avg Form Factor	0.45 (D: 0.35)	0.45	0.4
Noise Temperature	300–350 mK (A: 700 mK)	350 mK	325 mK
Operations Days	1000	300	1000

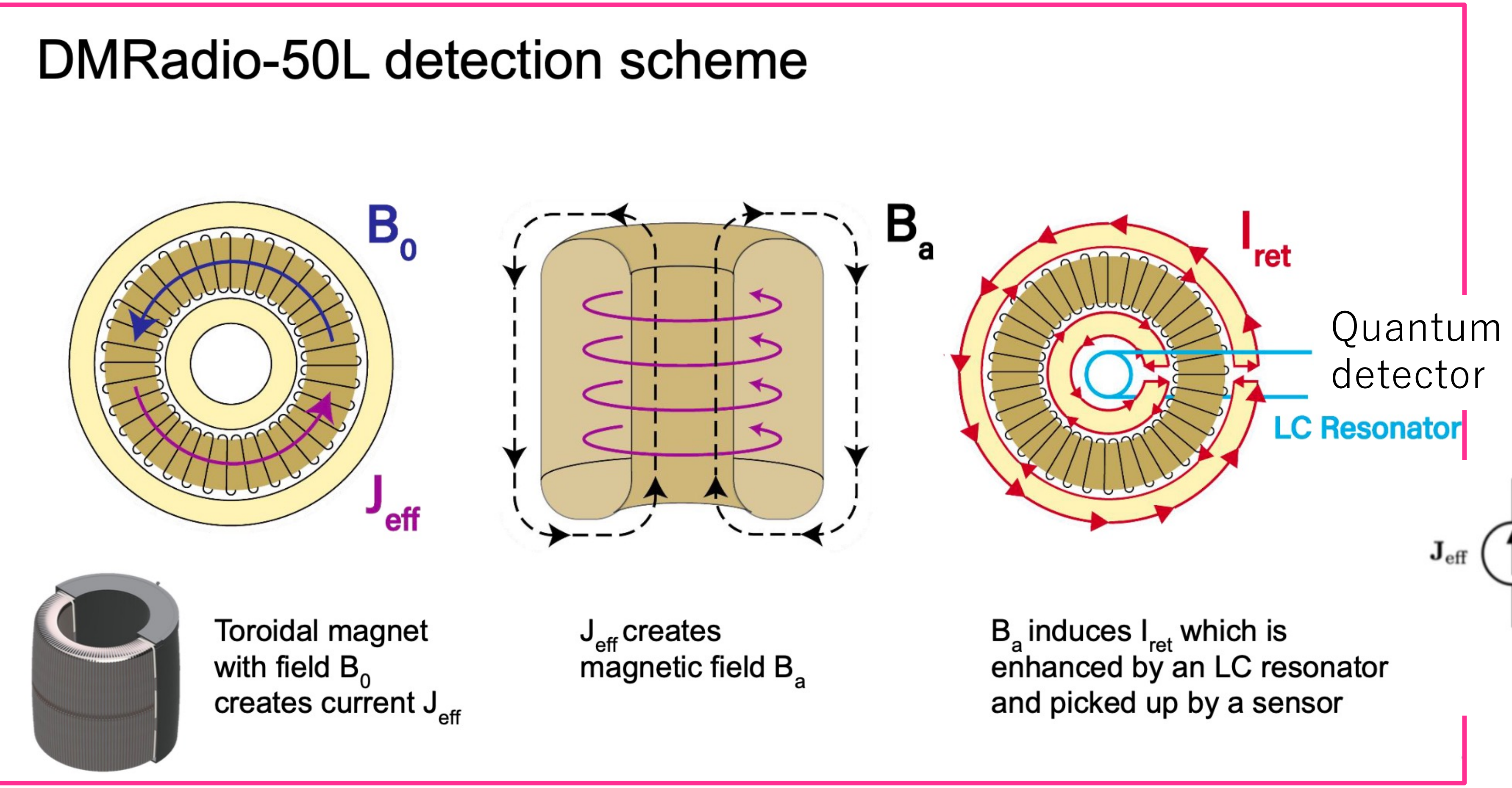
DM Radio

- Challenges at lower frequency side
  - Magnet size limitation
  - Coupling constant get lower in QCD axion

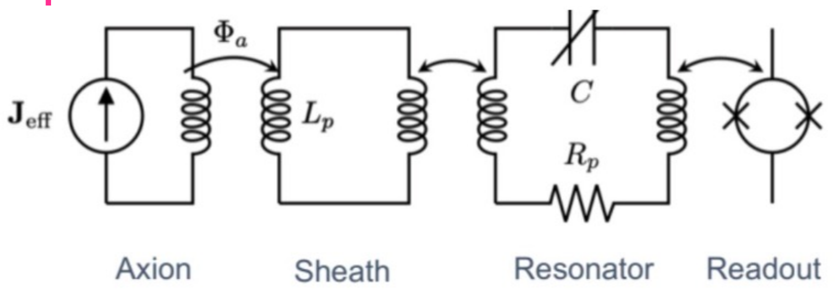




DMRadio 50L

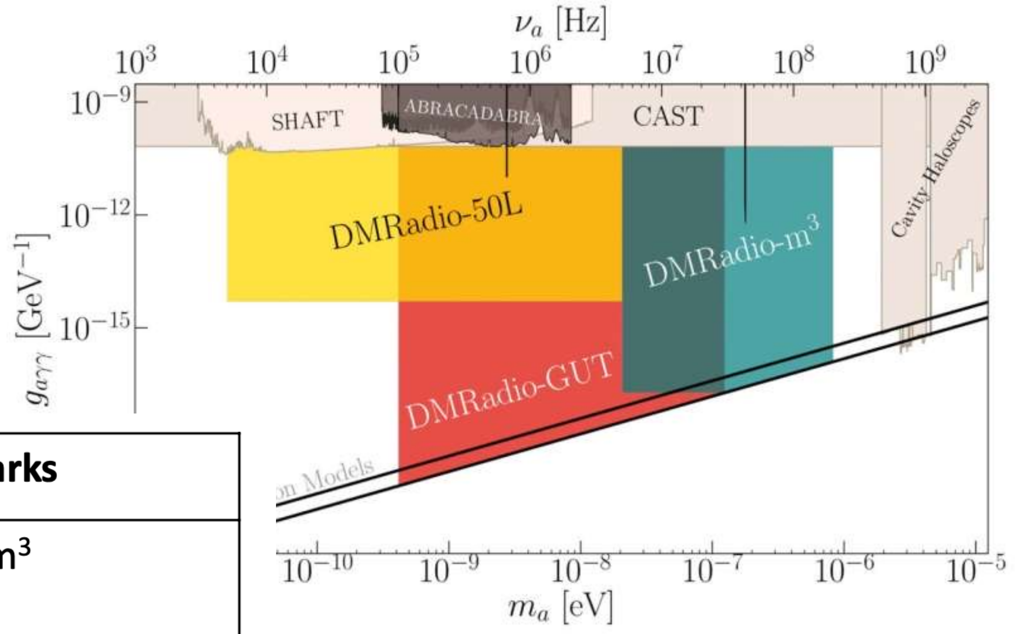


- Toridal magnet
- Inductive couplings and LC resonator



From M. Simanovskaia's slide at Patras 2023

DMRadio-GUT

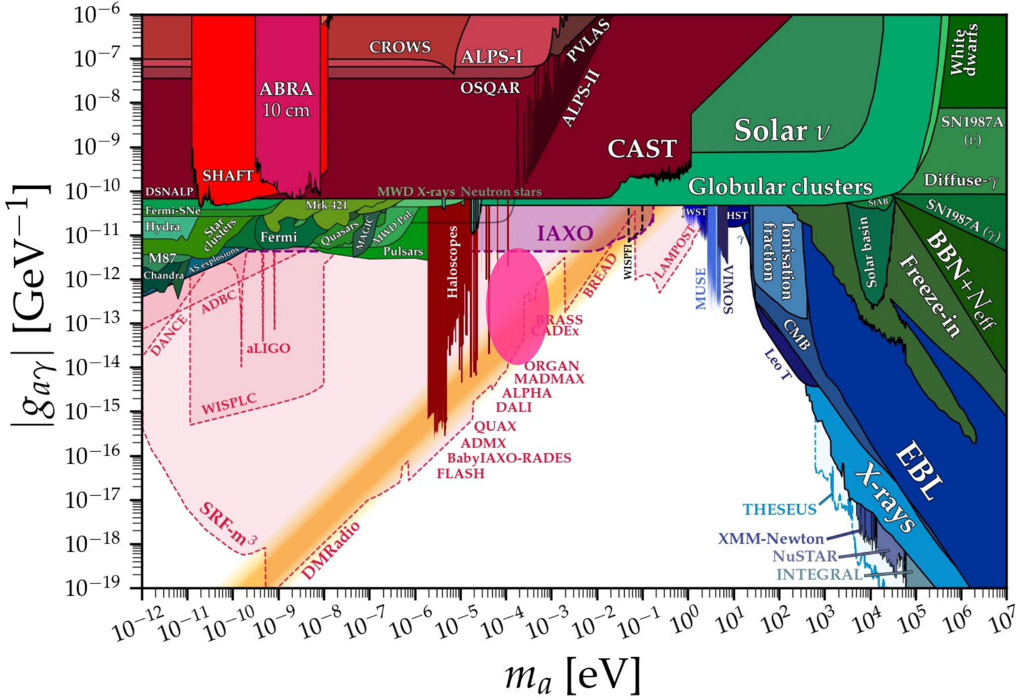


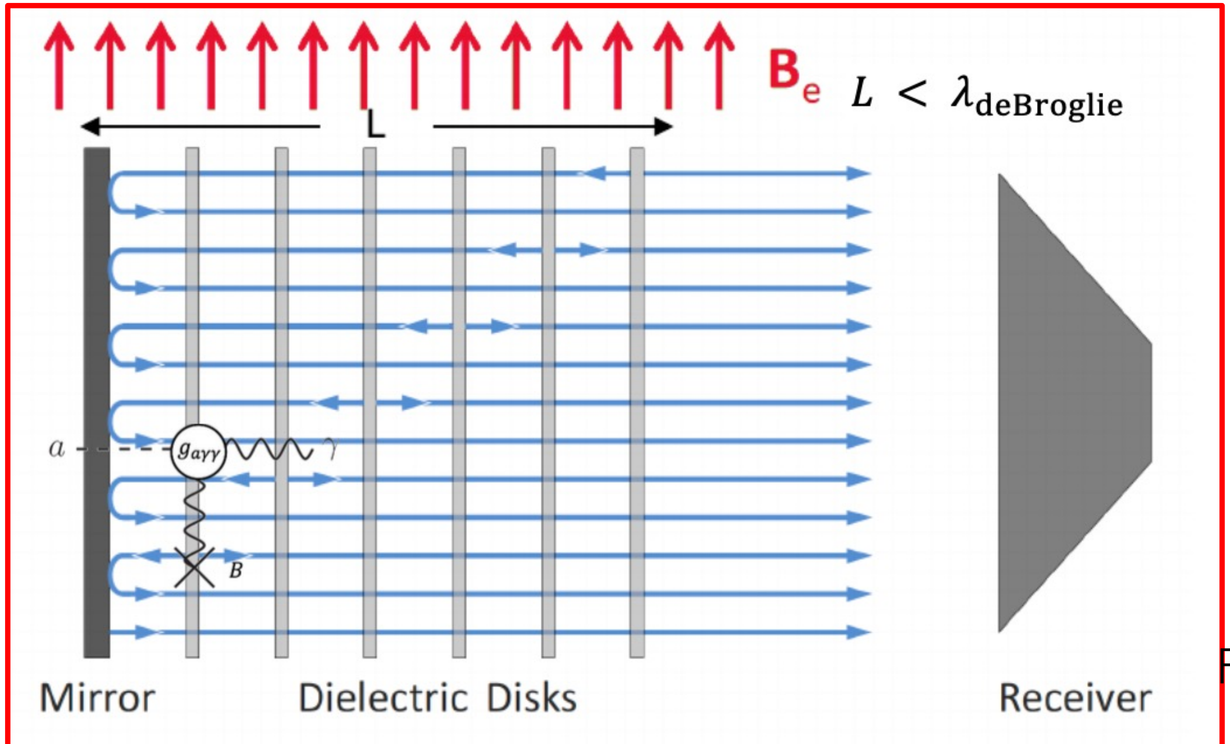
Parameter	Target Value	DMRadio benchmarks
Magnetic field	16 T	>4 T for DMRadio-m^3
Volume	10 m^3	~2 m^3 magnet for DMRadio-m^3
Quality factor	2 x 10^7	State-of-the-art ~10^6
Temperature	10 mK	20 mK for DMRadio-m^3
Amplifier noise	-20 dB of backaction noise reduction below SQL	RF Quantum Upconverters (RQUs)
Integration time	6.2 years	

https://arxiv.org/pdf/2203.11246.pdf

MADMAX

- Challenges at higher frequency side
  - Limitation on $G_{lmn}V$
  - Q-value gets lower, $Q \propto \nu^{-\frac{1}{2}}$



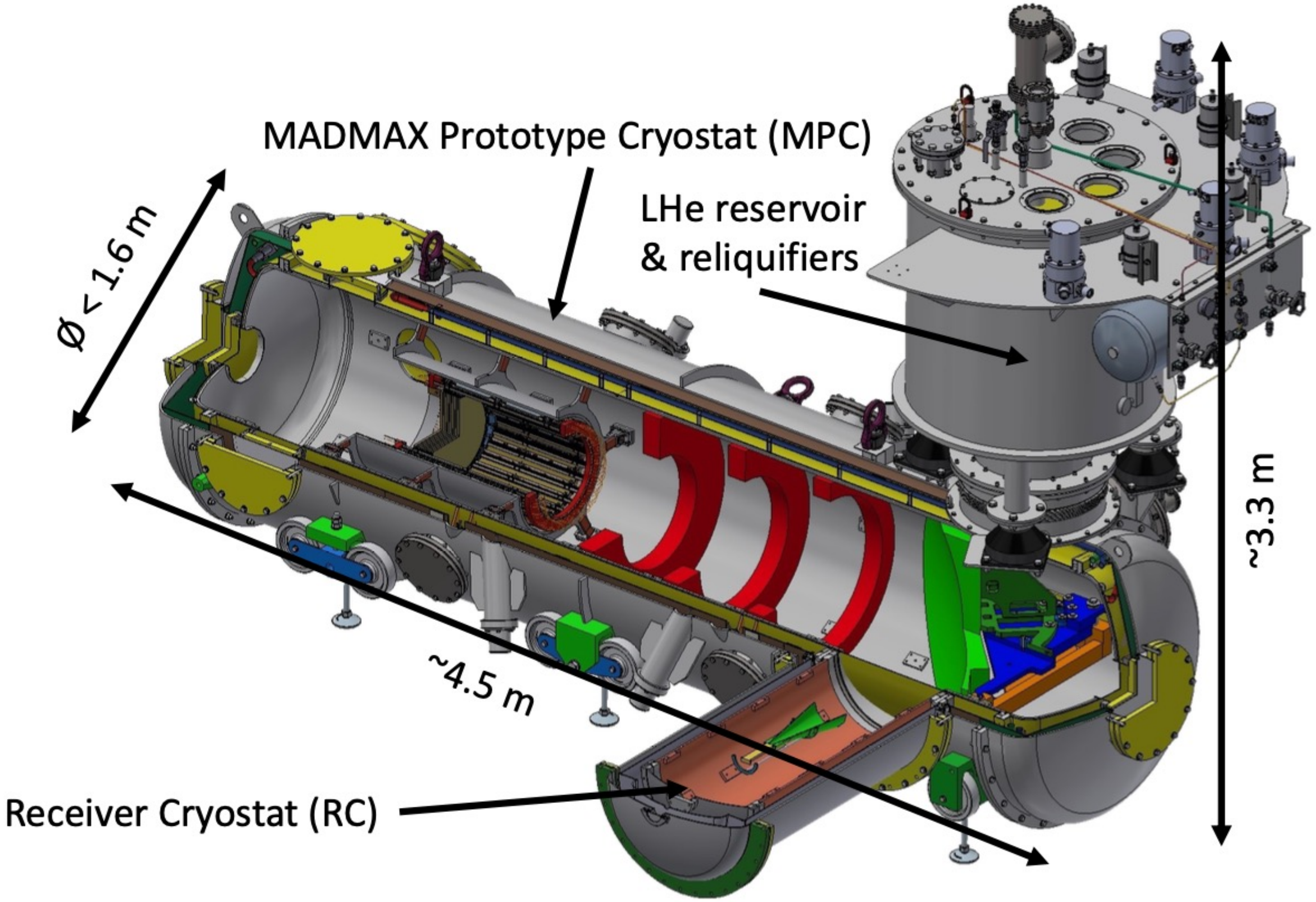


Axion is produced at surface parallel to B.

- Dielectric disk
  - Transparent to RF
  - Large index
- One receiver corrects coherent signals from the disks.

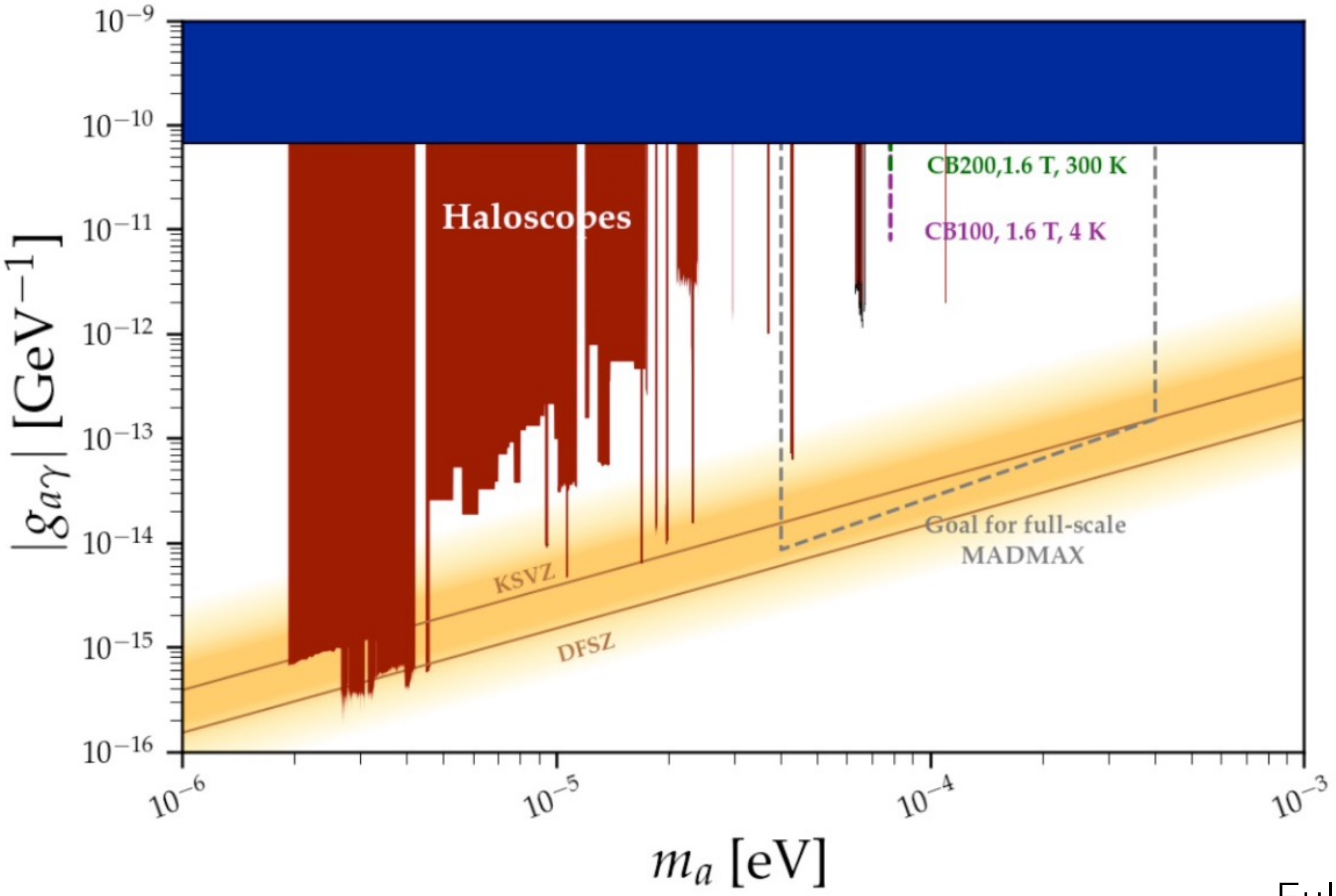
From E. Garutti's slides at patras 2023

MADMAX Prototype

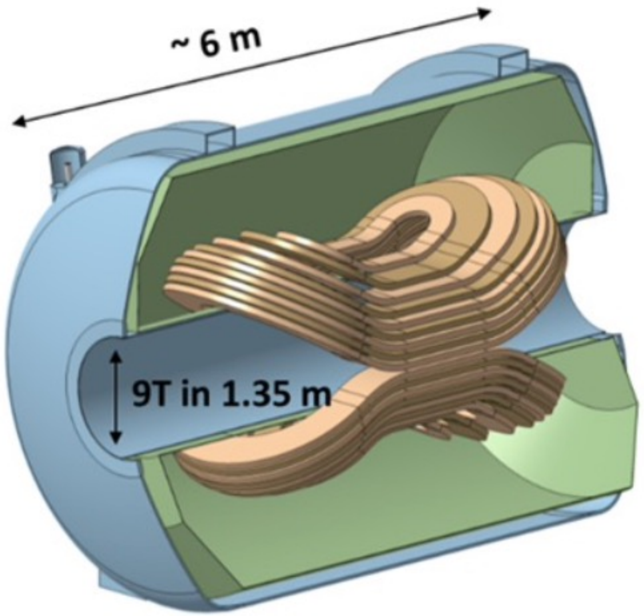


- Manufactured by Bilfinger Noell GmbH
- Two vacuum vessels:
  - inner (4 K) cooled via LHe circulating through double-wall
  - outer (isolation vacuum)
- Closed-loop system with 4 cryocoolers fo reliquification of LHe
  ➔ during operation: 50 l LHe
- Delivery expected begining of 2024
- Commissioning with OB300 in Hamburg mid 2024

From E. Garutti's slides at patras 2023

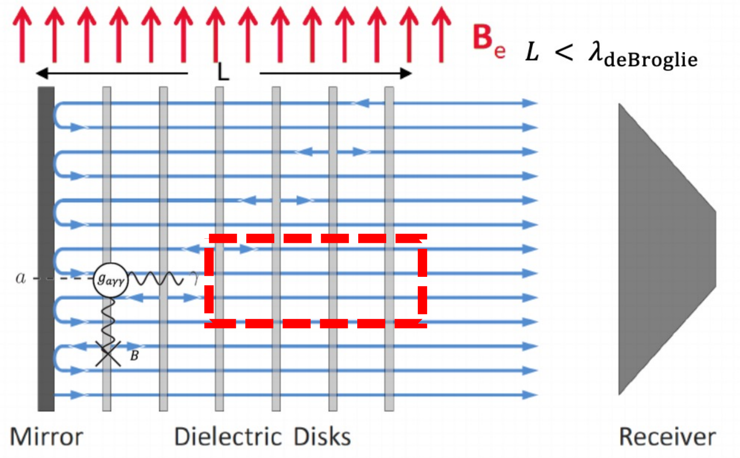


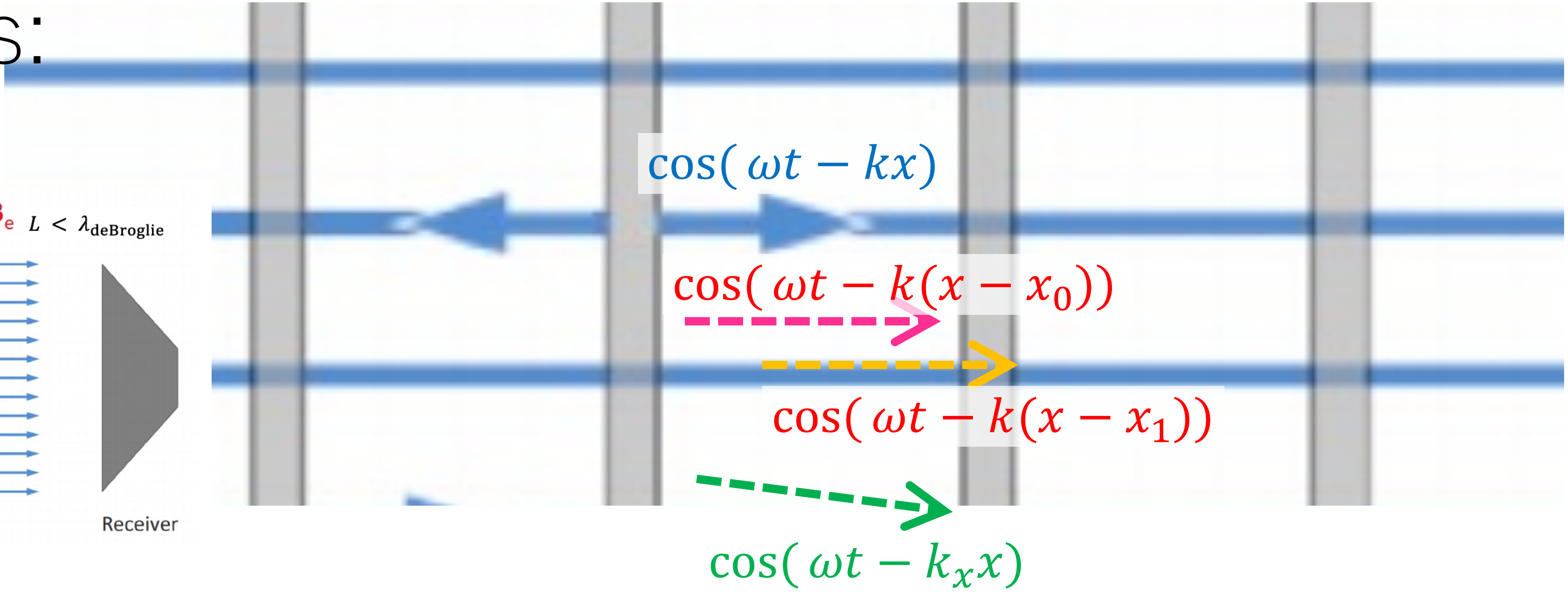
Huge magnet !



Full size commissioning from 2028(?).

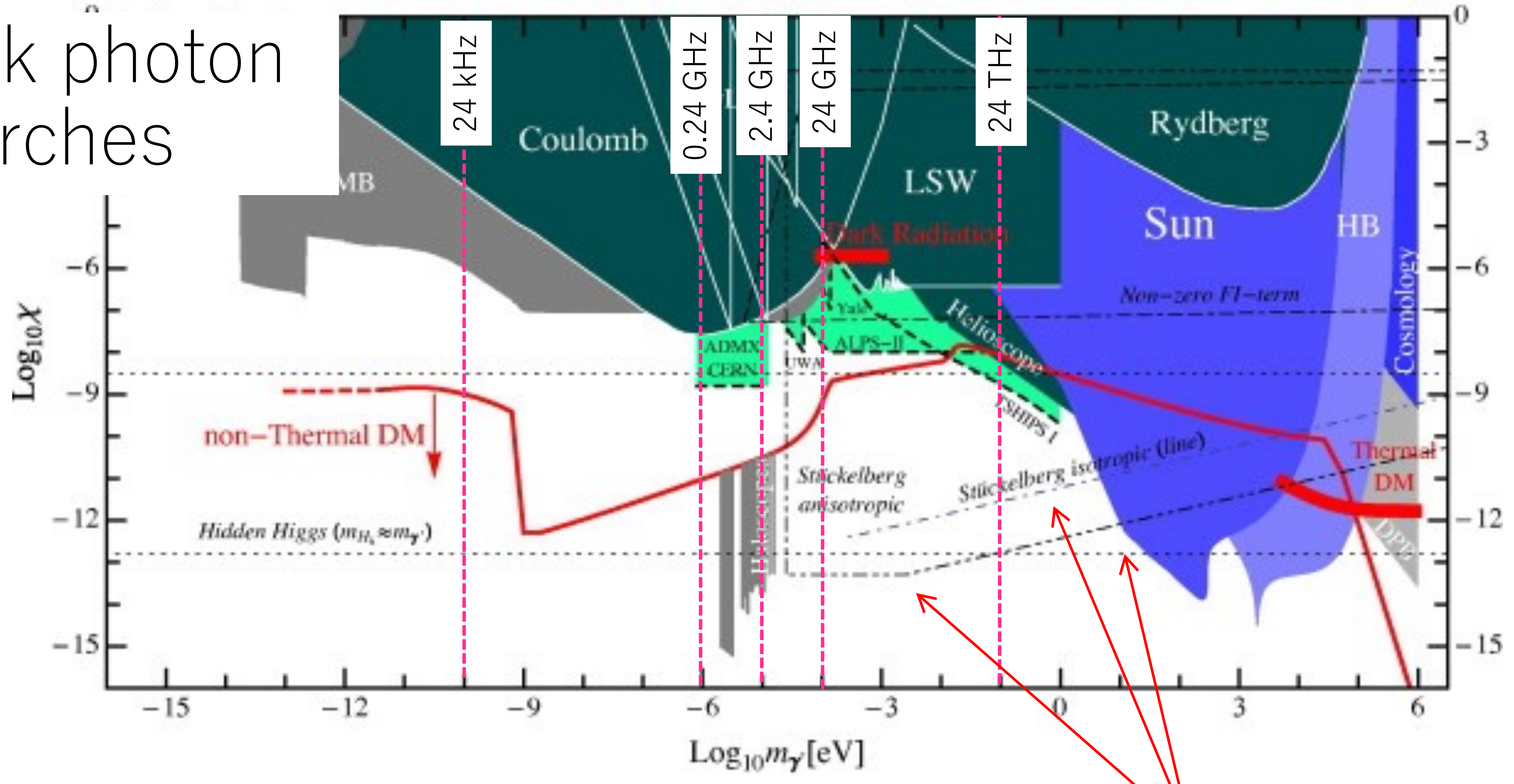
Questions:





- Axion induced photons, which have same phase ϕ, are also produced in every space where B field is applied.
- This means more signal?
- This leads more complicated interference pattern and makes physics interpretation difficult ?

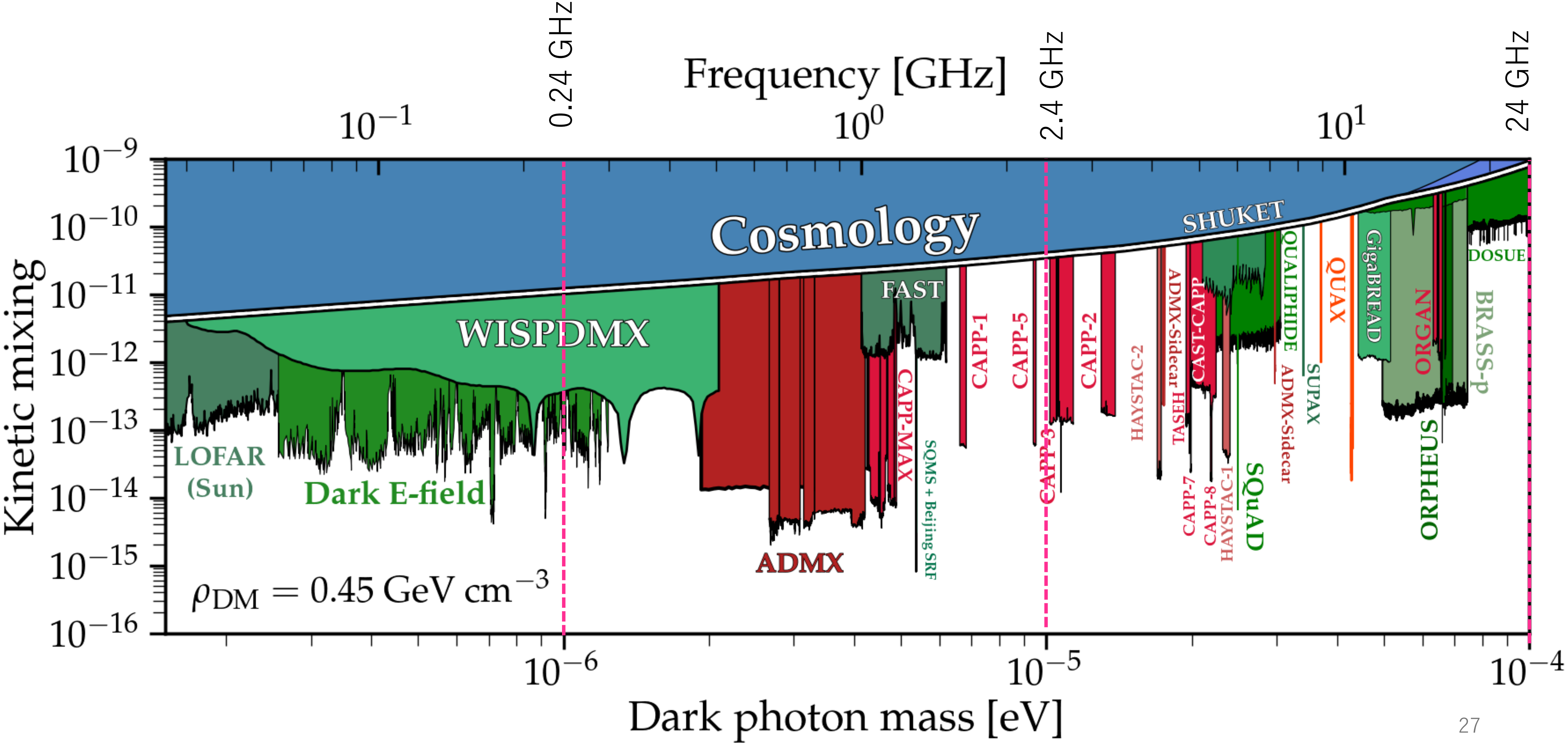
Dark photon searches



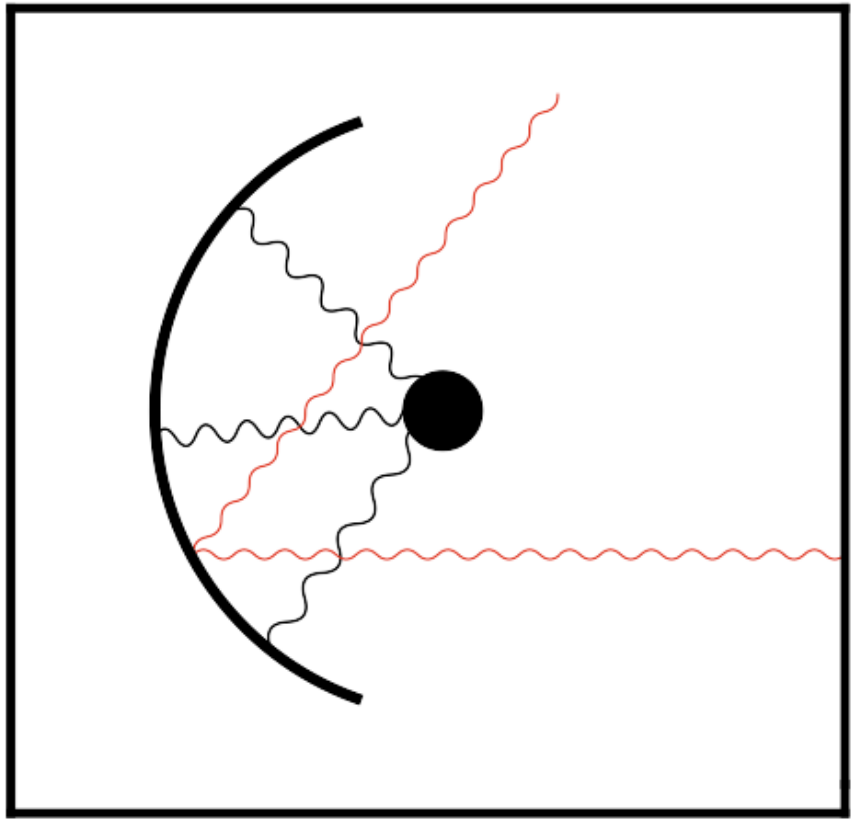
Wider open space than axion !

DOI: 10.1016/j.dark.2012.10.008 (2012)

Dark photon searches (Closeup around haloscope)



Wave-like DM with Dish antenna



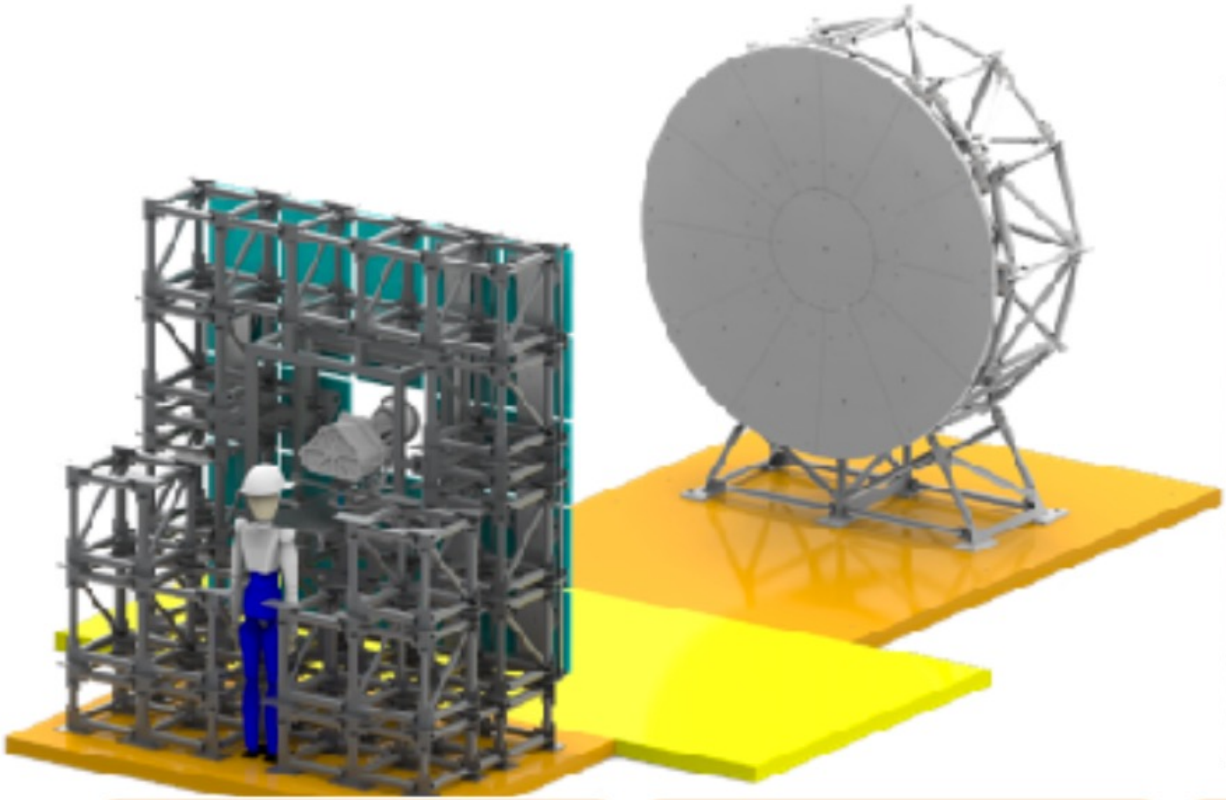
- To meet the boundary condition on surface, DM induced photons are emitted.
- The photon goes perpendicular to the surface.
- Thermal photon noise: $n = \epsilon kT$.
  - Al: $\epsilon = 0.04$
  - Electropolished Cu: $\epsilon = 0.03$
  - spreads to all direction (Red line)
-

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

BRASS-p Setup

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

[arxiv:2306.05934]

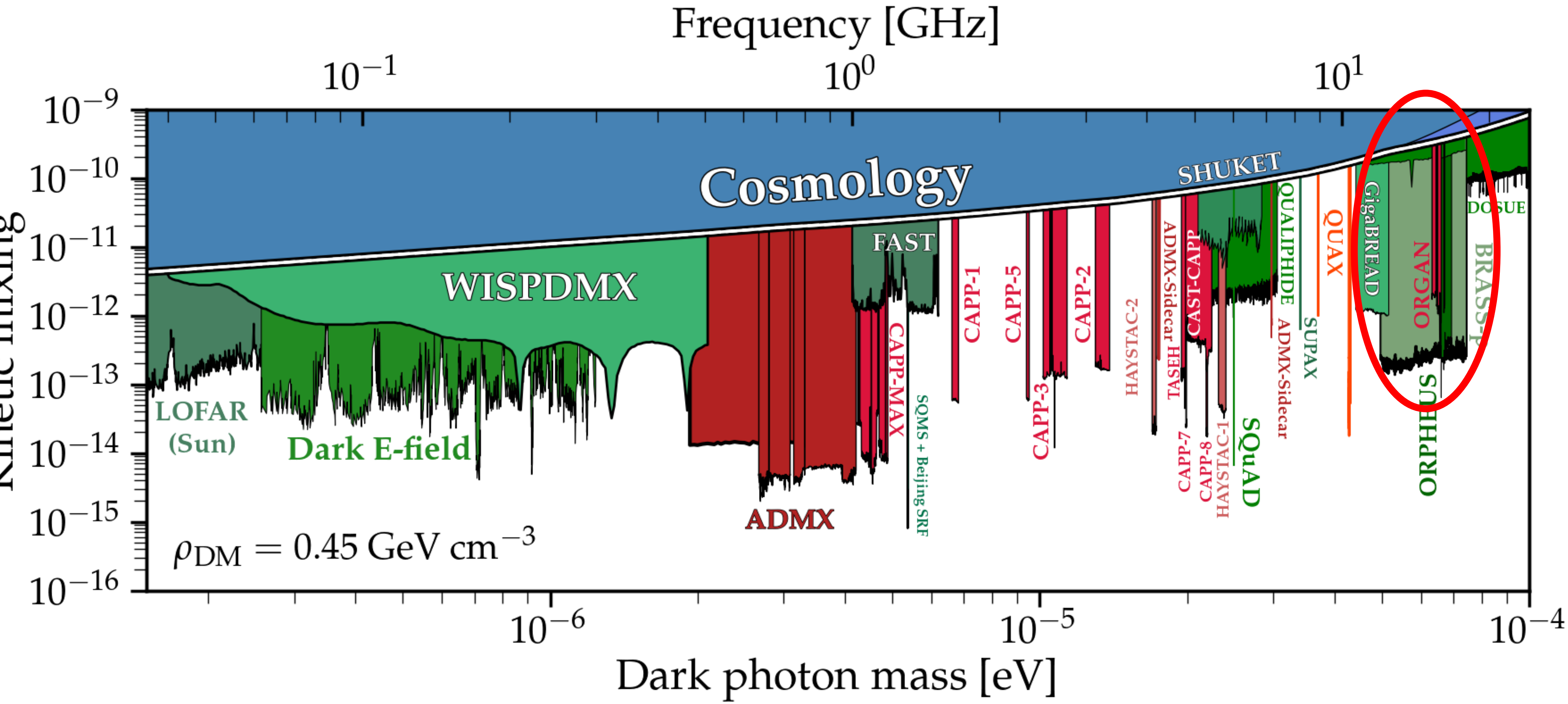


Illuminated Area: $A = 4.44\ m^2$	Parabolic mirror: D = 2.5m, f = 4.8m	Broadband Receiver: 12-18 GHz	IF Bandwidth: 4 GHz $\Delta f = 5 - 125Hz$

5

On T=15 K Stage

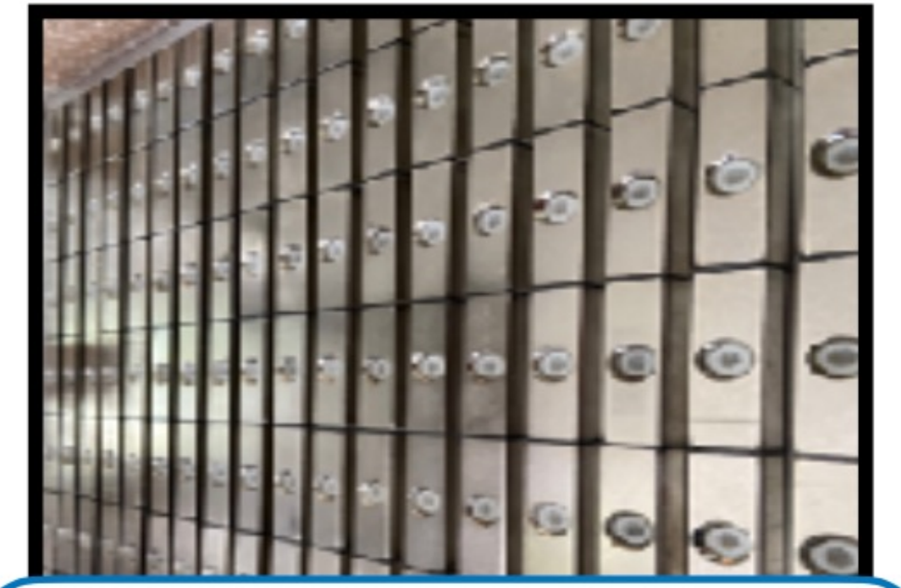
Result



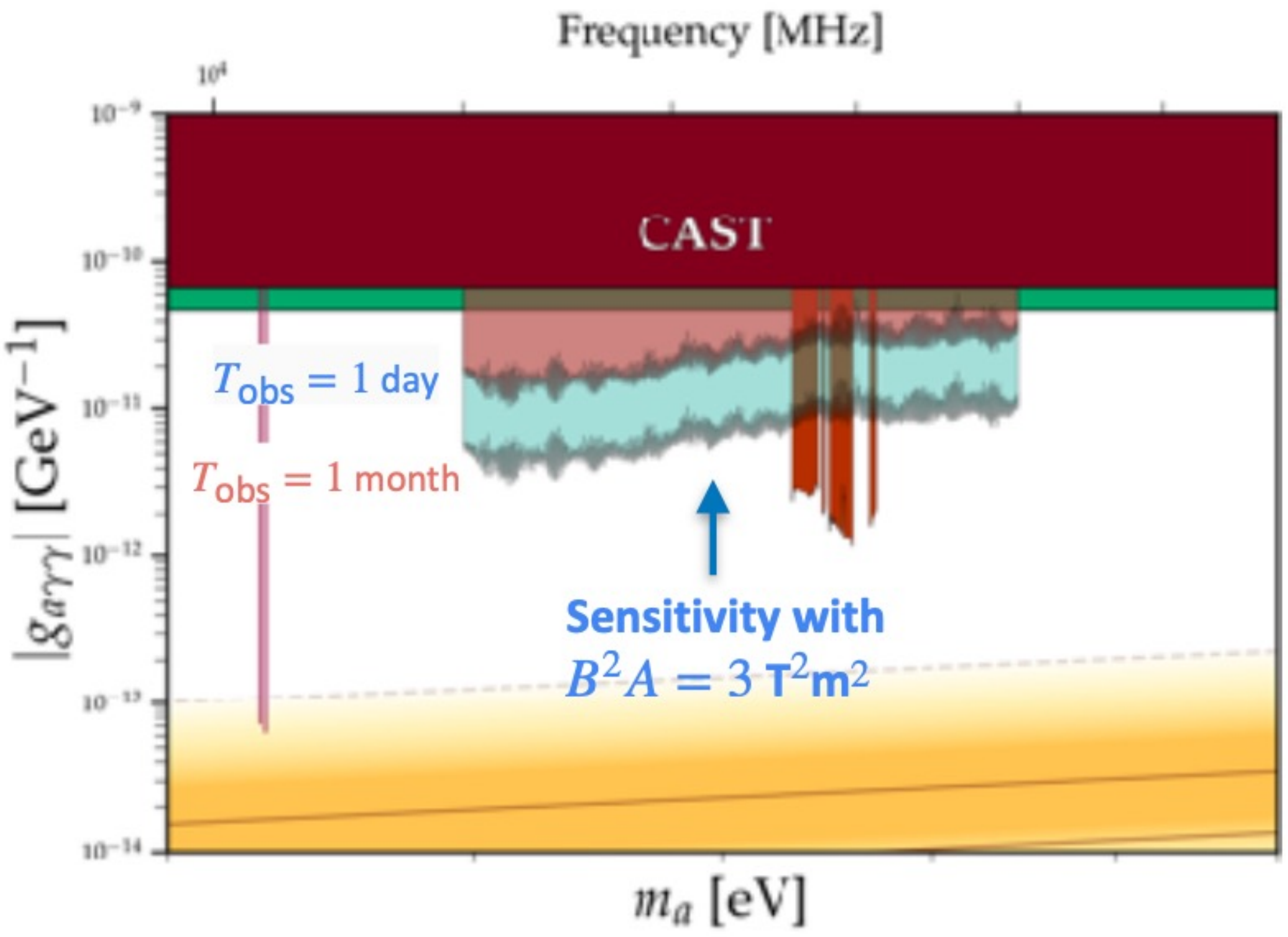
Frequency [GHz]
10^{-1}
10^{0}
10^{1}
Kinetic mixing
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Cosmology
SHUKET
WISPDMX
FAST
LOFAR (Sun)
Dark E-field
ADMX
CAPP-MAX
SQMS + Beijing SRF
CAPP-1
CAPP-5
CAPP-3
CAPP-2
HAYSTAC-2
ADMX-Sidecar HF
TASEH
CAST-CAPP
CAPP-7
CAPP-8
HAYSTAC-1
SQuAD
QUALIPHIDE
ADMX-Sidecar
SUPAX
QUAX
GigaBREAD
ORGAN
ORPHEUS
DOSUE
BRASS-p
$\rho_{DM} = 0.45$ GeV cm^{-3}
10^{-6}
10^{-5}
10^{-4}
Dark photon mass [eV]

BRASS extension to Axion/ALP

$$g_{a\gamma\gamma} = \frac{3.6\times 10^{-8}}{\text{GeV}}\left(\frac{\sigma_{\text{det}}(\nu)N_{\text{ch}}(\nu)^{-1/2}}{10^{-23}\ \text{W}}\right)^{\frac{1}{2}}\left(\frac{5\ \text{Tesla}}{B_{\text{ex}}}\right) \times\left(\frac{m_a}{\text{eV}}\right)\left(\frac{0.3\ \text{GeV/cm}^3}{\rho_{\text{DM}}}\right)^{\frac{1}{2}}\left(\frac{1\ \text{m}^2}{A_{\text{eff}}}\right)^{\frac{1}{2}}$$



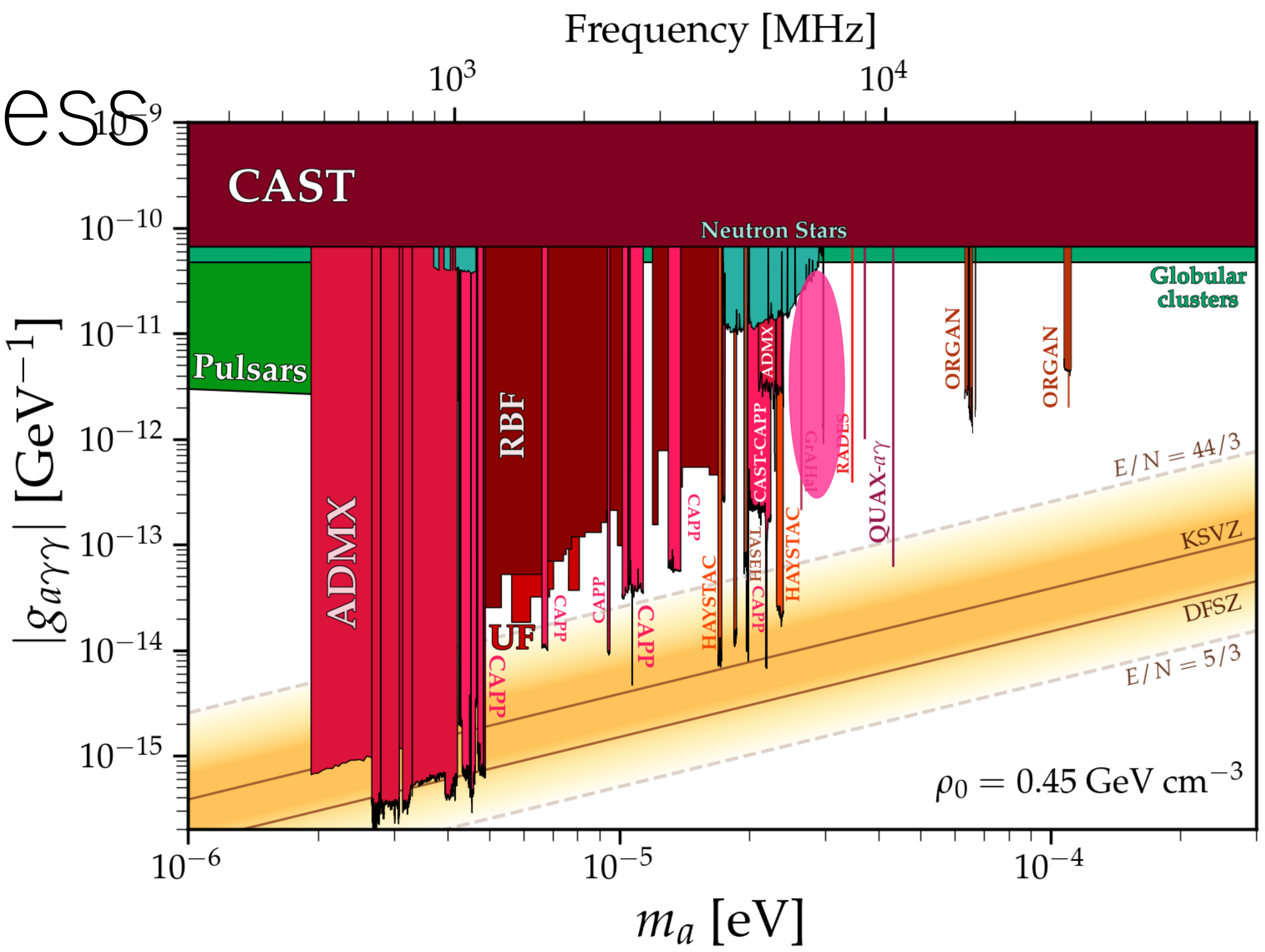
Averaged horizontal field strength is approx 0.9 Tesla



Data taking this year!

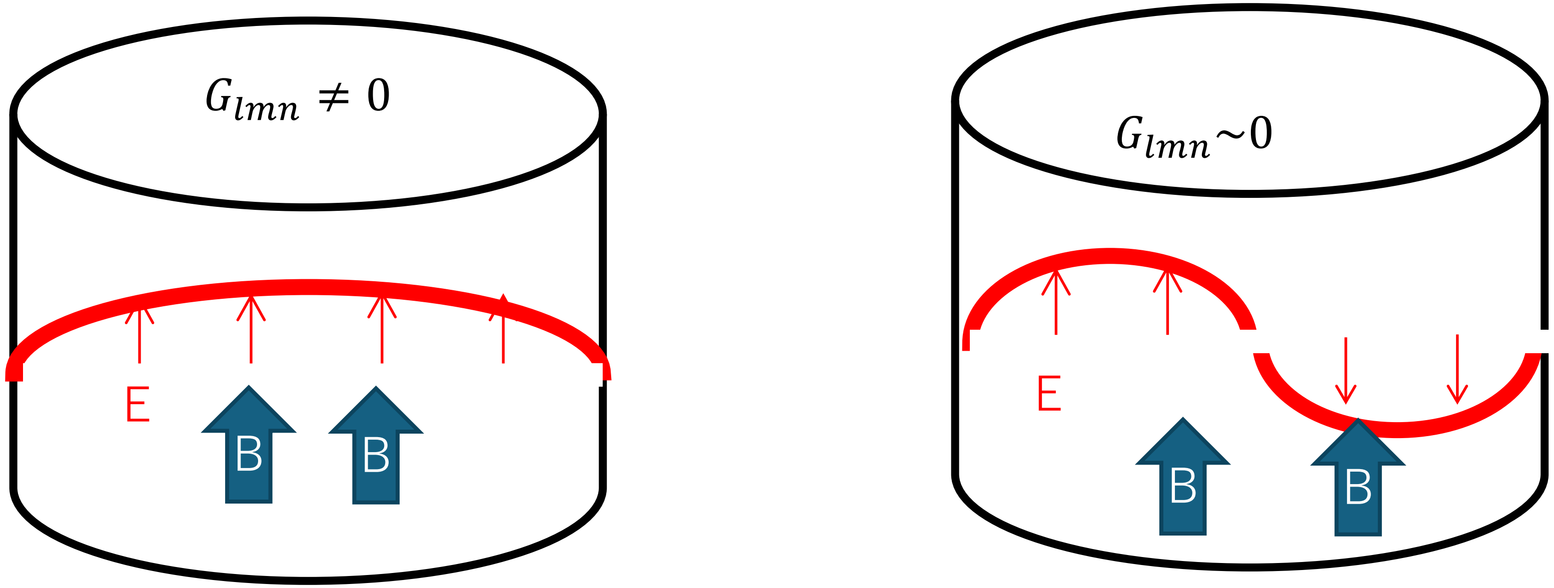
Tohoku efforts to address the wave-like DMs

- Method:
  - Haloscope
- Target mass:
  - Higher frequency
  - ~8 GHz and then more)
- R&D items
  - Cavity for high frequency
    - High Q and large volume even in higher frequency.
  - Cryogenic DAQ
    - RF technology



Studies on cavity

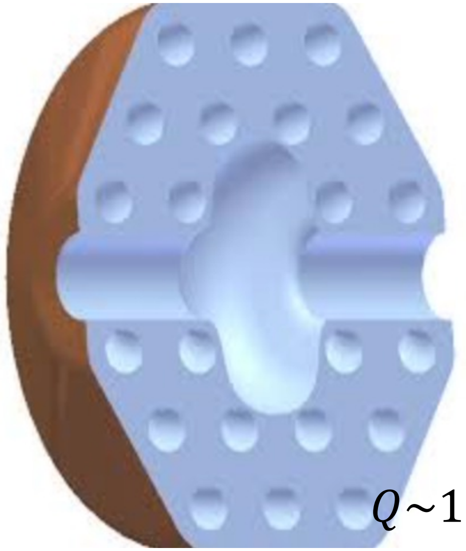
- Axion Signal:
  - $P = \kappa g^2 V B_0^2 \rho_0 G_{lmn} \frac{1}{m_a} Q_c,\ G_{lmn} = \frac{\left(\int dV\, \vec{E}\cdot\overrightarrow{B_0}\right)^2}{|B^2| V \int dV\, E^2}$
- Enlarging $G_{lmn}VQ$ is essential for higher frequency regime.



G_{lmn} is suppressed in higher eigen mode.

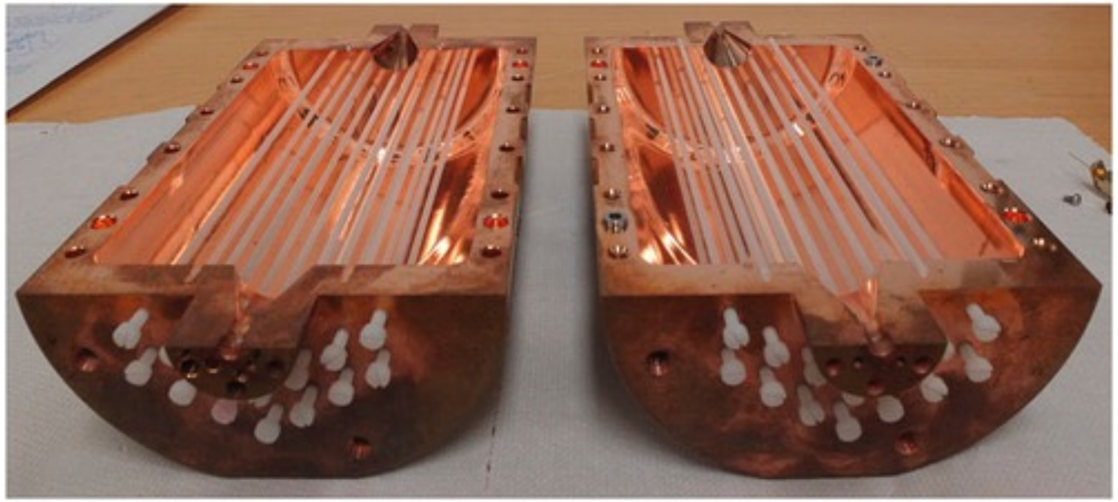
Photonic assist cavity

- RF reflects ~100% by forbidden zone with photonic crystal structure.
- In cryogenic condition, there are dielectric materials with very low dielectric loss ($\tan\delta$)
  - Saphiere： $\tan\delta$ ~10^{-4} at RT,　~10^{-7} at LN_2, ~10^{-9} at LHe



$Q{\sim}10^6$

An application to the accelerator
（KEK H. Yoshida）

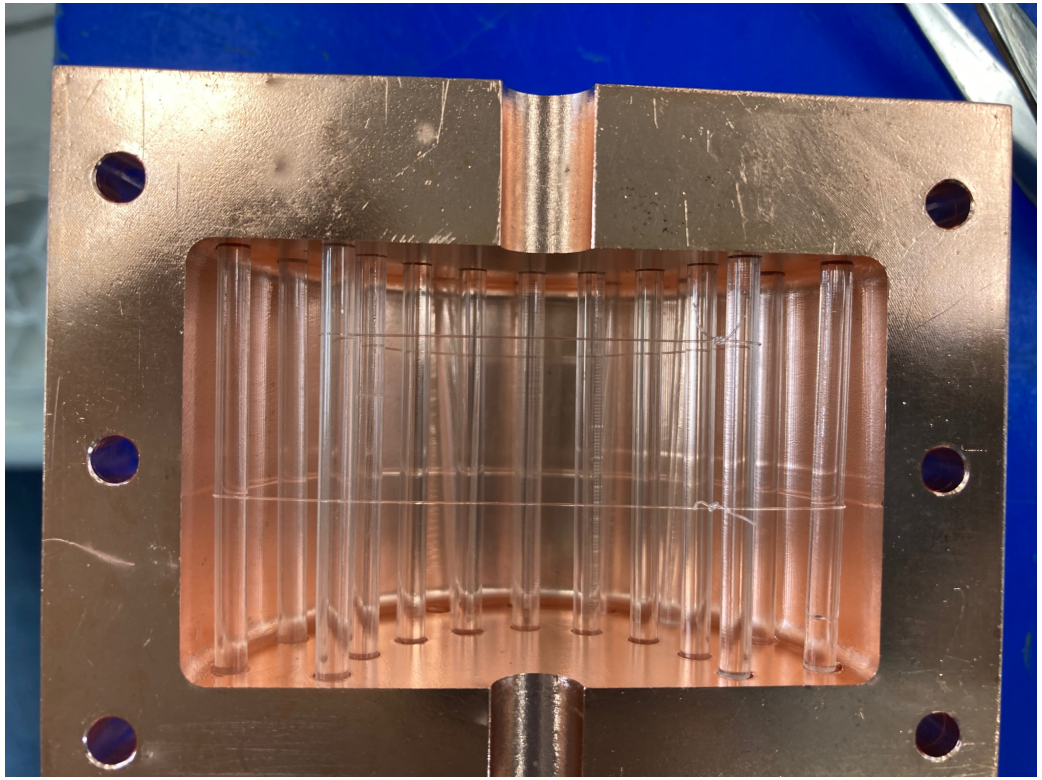


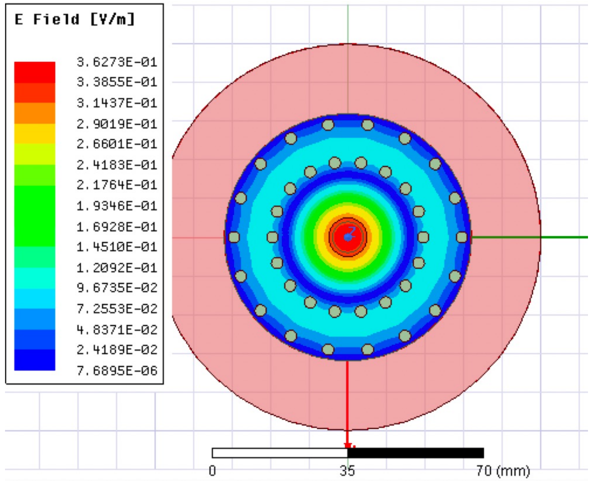
Example of QUAX Collaboration

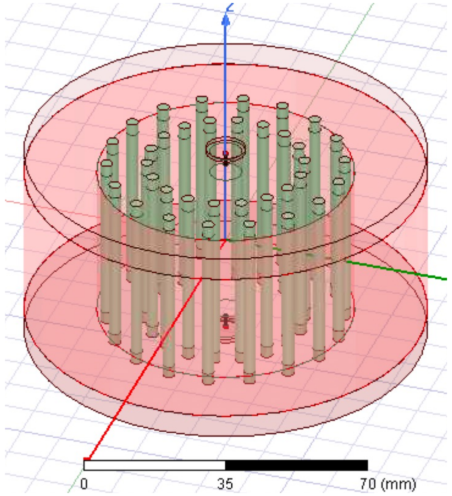
$Q_0 = 1.6{\times}10^5$ at RT
$Q_0 = 2.9{\times}10^5$ at 4.2 K

Photonic assist cavity with sapphire

$Q_0 = 1.2\times10^5$ at T=4 K, B=0 T



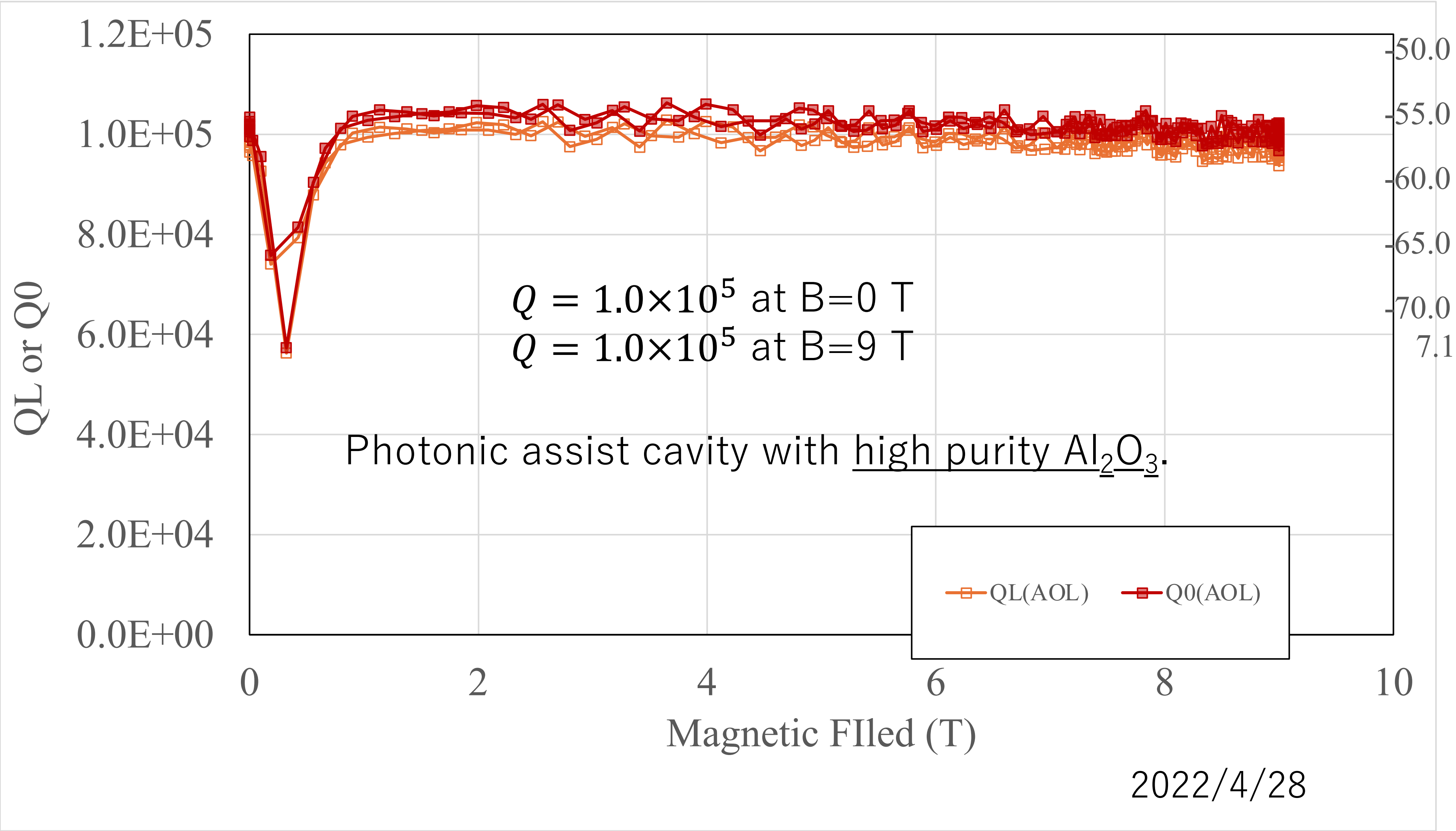


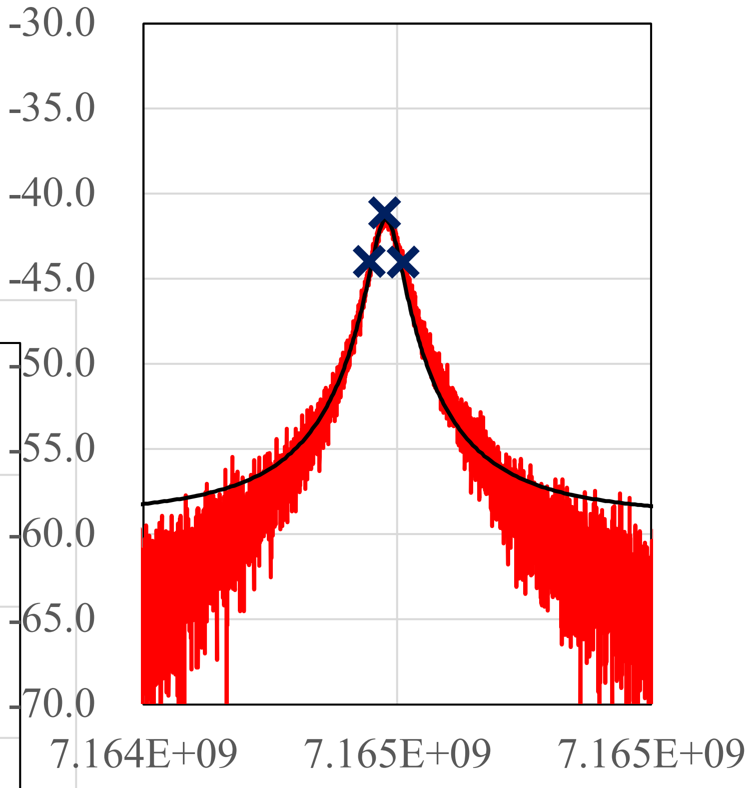


2022/7/28

- According to the dielectric loss measurements by ourselves, higher Q could be achieved potentially.
- Drawback is non-negligible dead volume and high expense for sapphire.

In the magnetic field.





Q_0=1.23 × 10^5 at 4.3 K

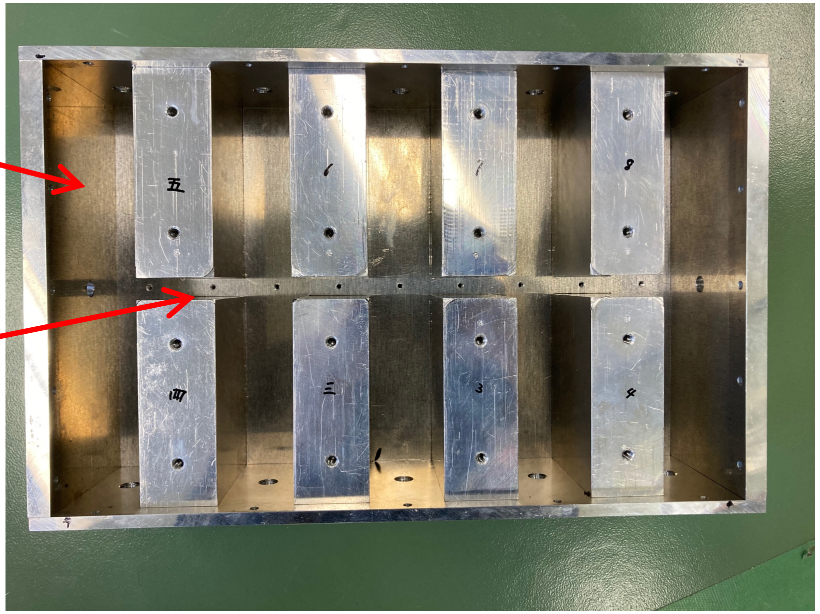
Q_0=1.4 × 10^4 at RT

(2022/2/18)

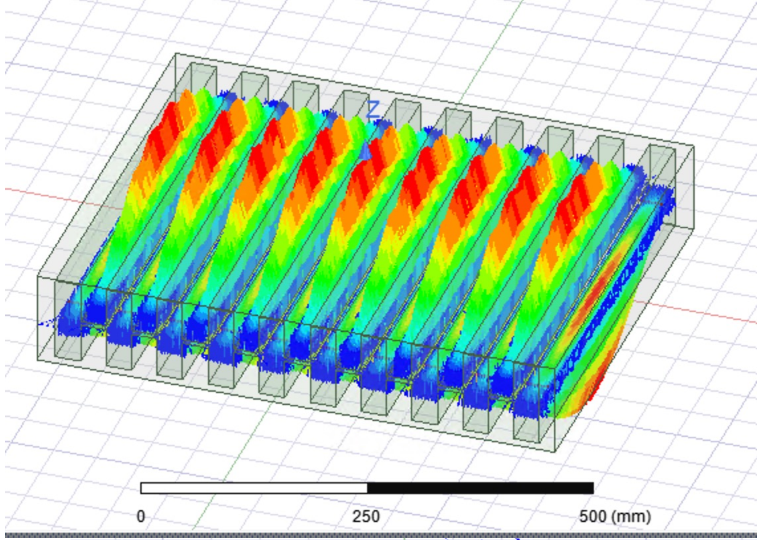
New ideas in the cavity

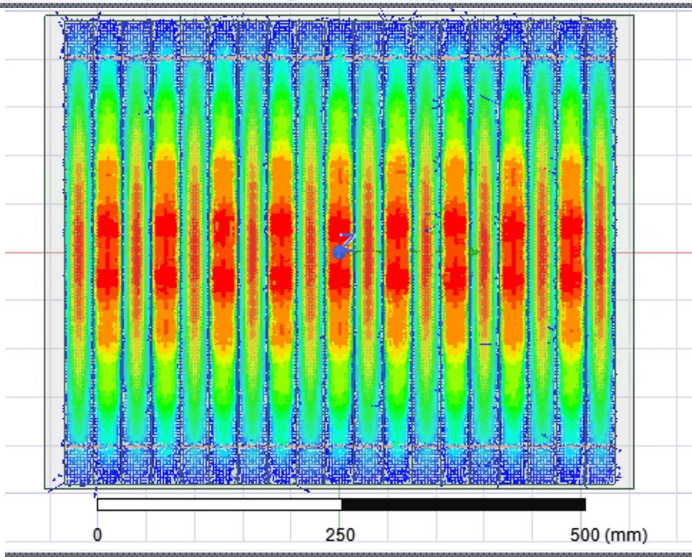
- When we look $G_{lmn} = \frac{\left(\int dV\, \vec{E}\cdot\overrightarrow{B_0}\right)^2}{|B^2| V \int dV\, E^2}$ carefully, the negative interference can avoid by dV in numerator.

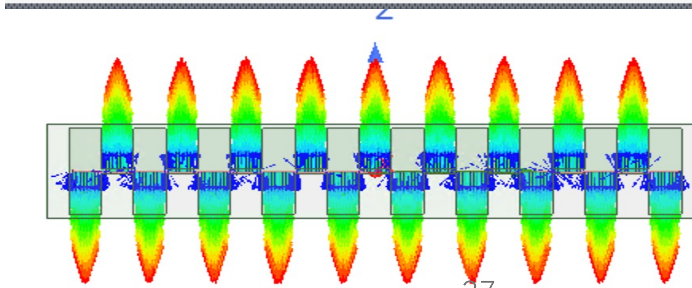
Large volume
(H=100mm)



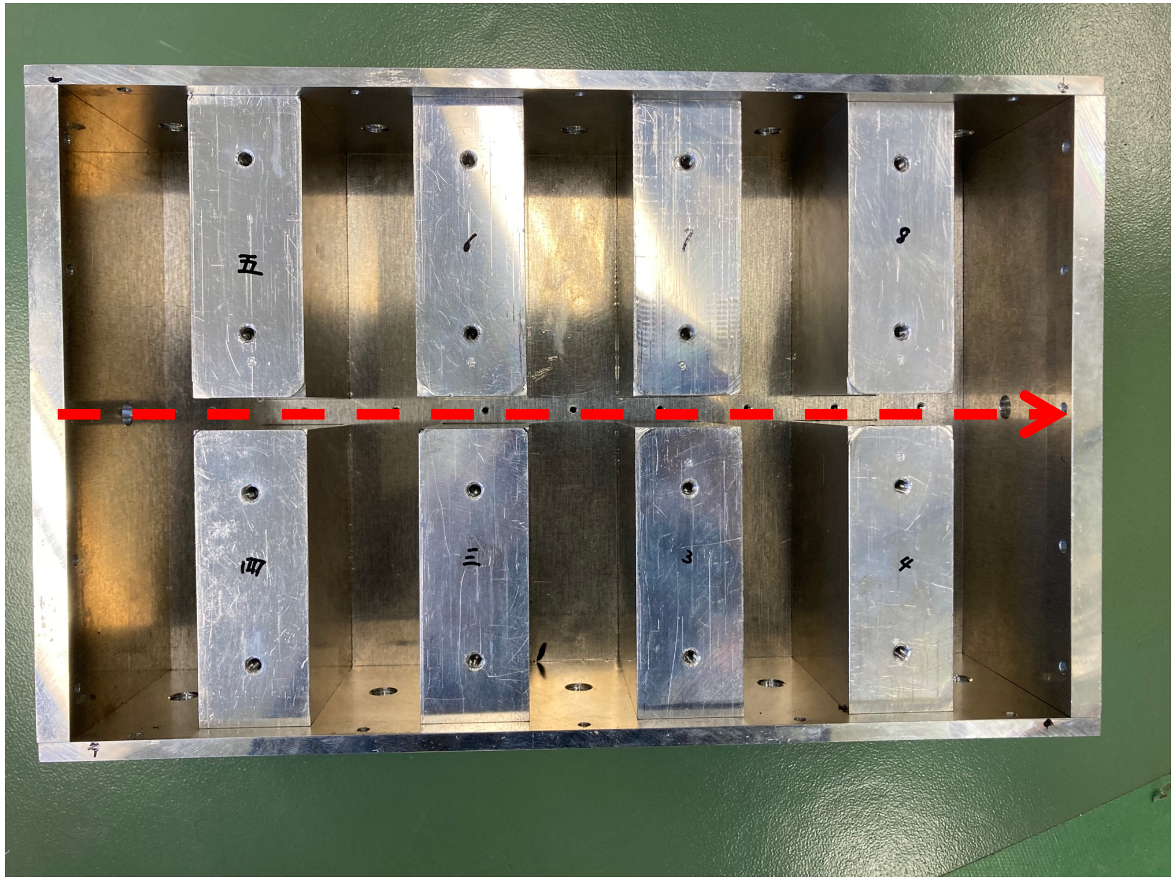
Smaller volume
(H=10 mm)

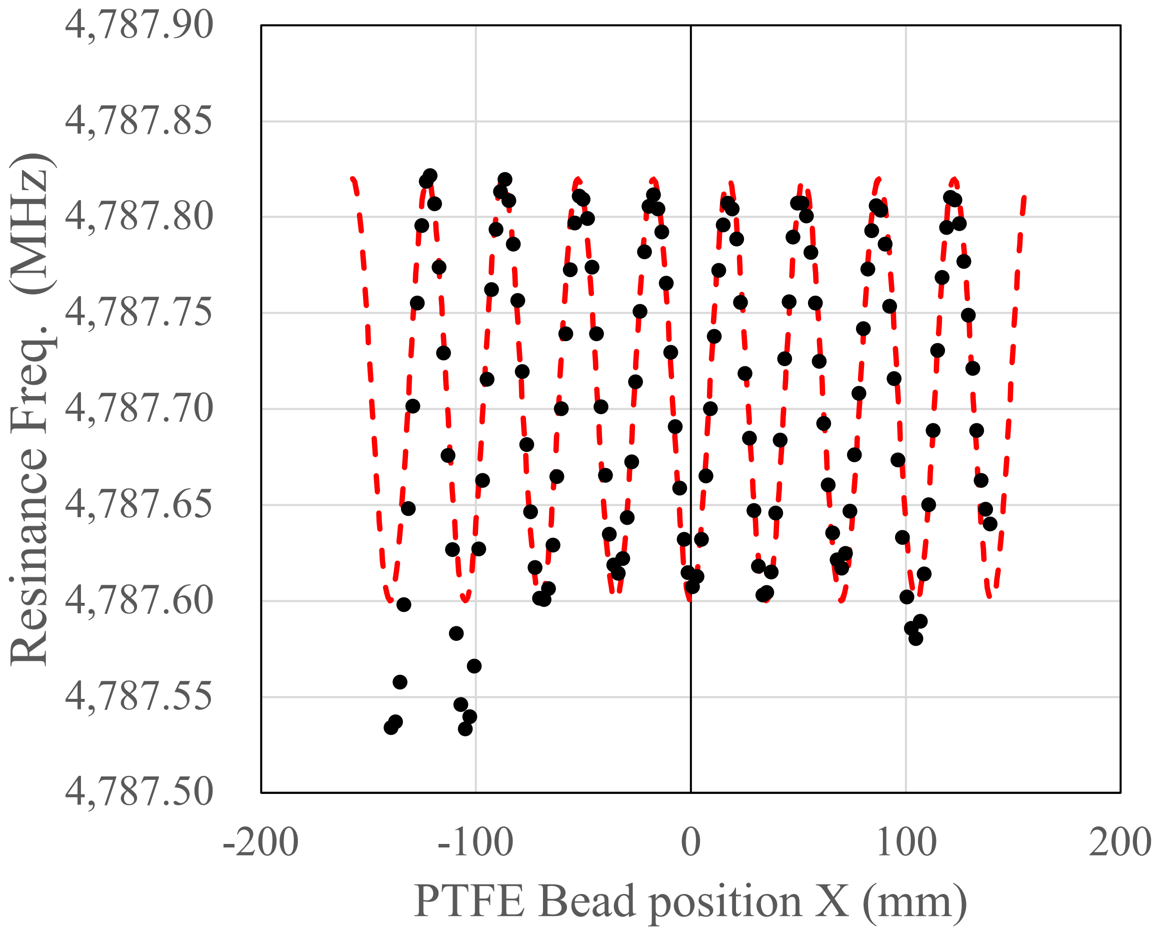




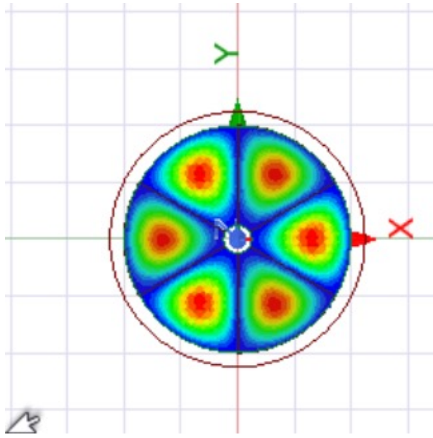


E field profile measurement (x direction) by beads method

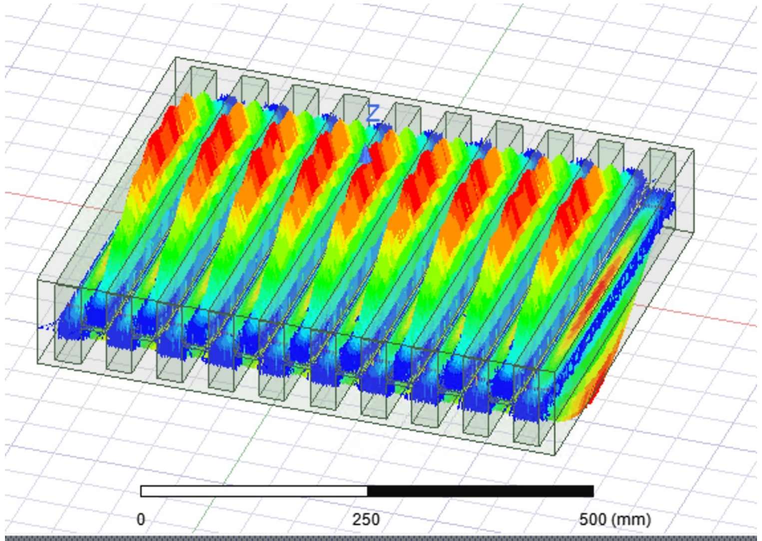


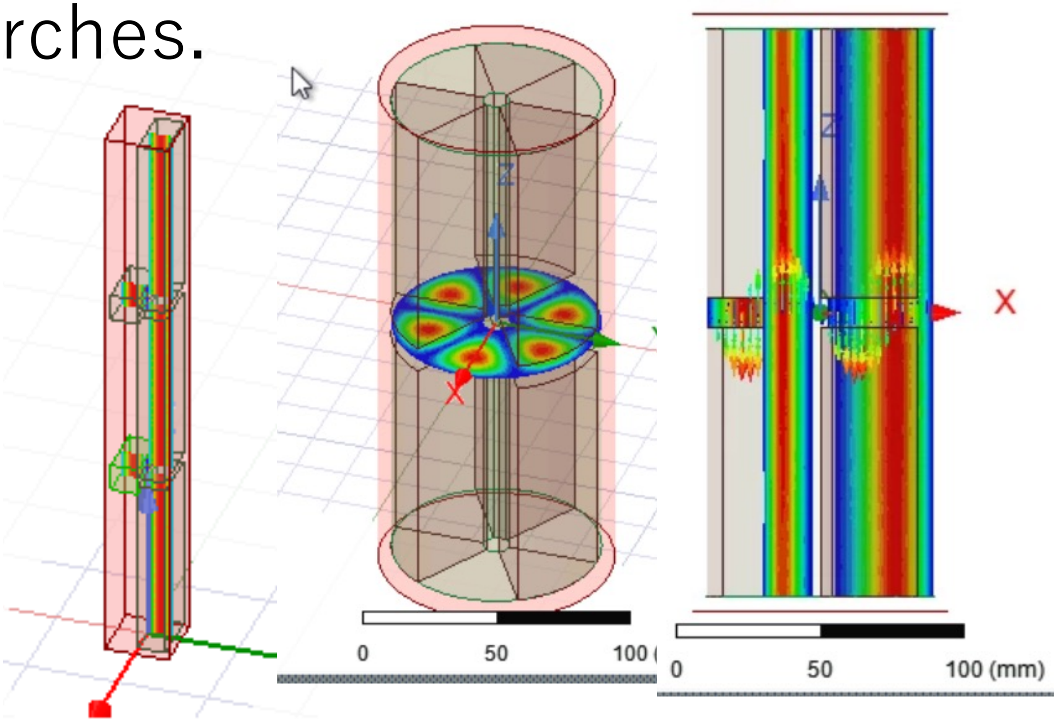


- E field distribution is not matched to calculation, but the basic idea is proven
- This cavity volume is about 5 times larger.



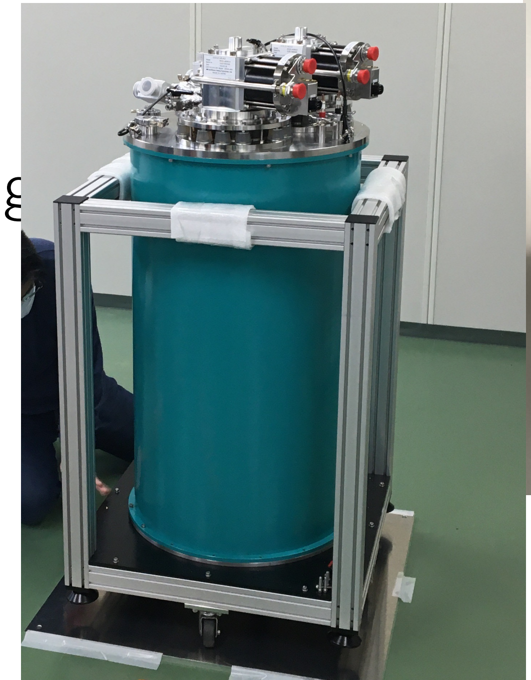
- Acceding to simulation results, we can connect more to enhance the volume.
- This fits to HP searches, especially for high frequency.
- The idea can be adopted to axion searches.
  - We will conduct a mock-up tests soon.

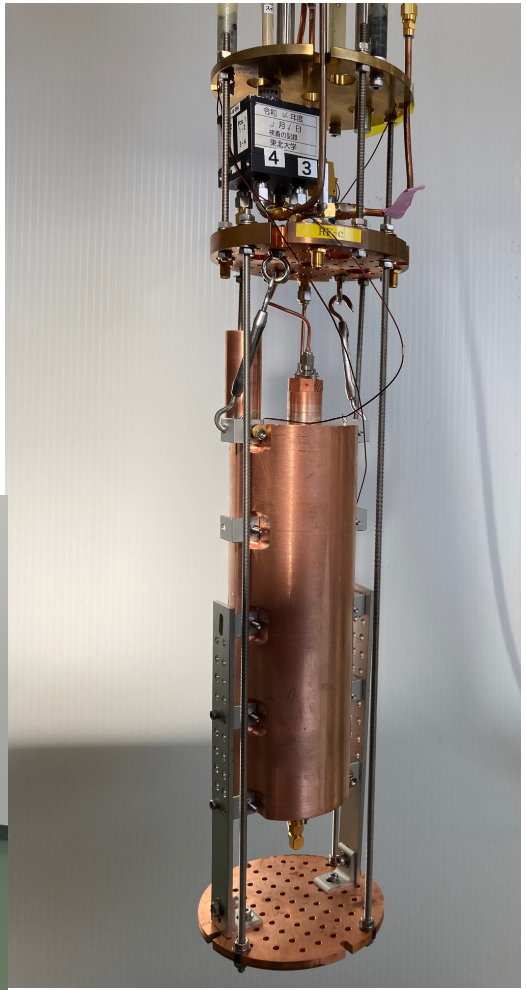


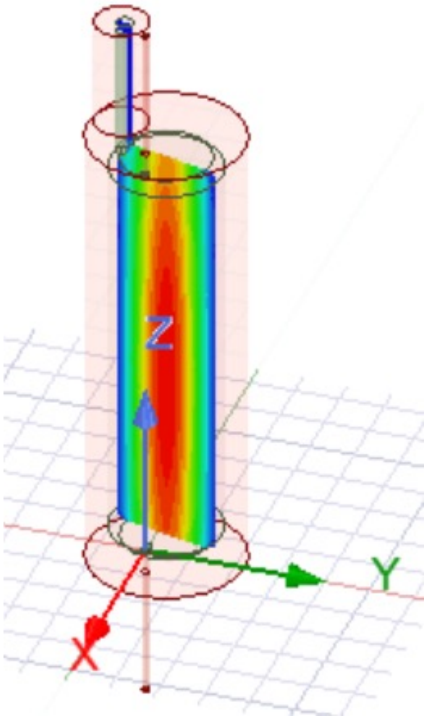


Polit run system for axion search in Tohoku

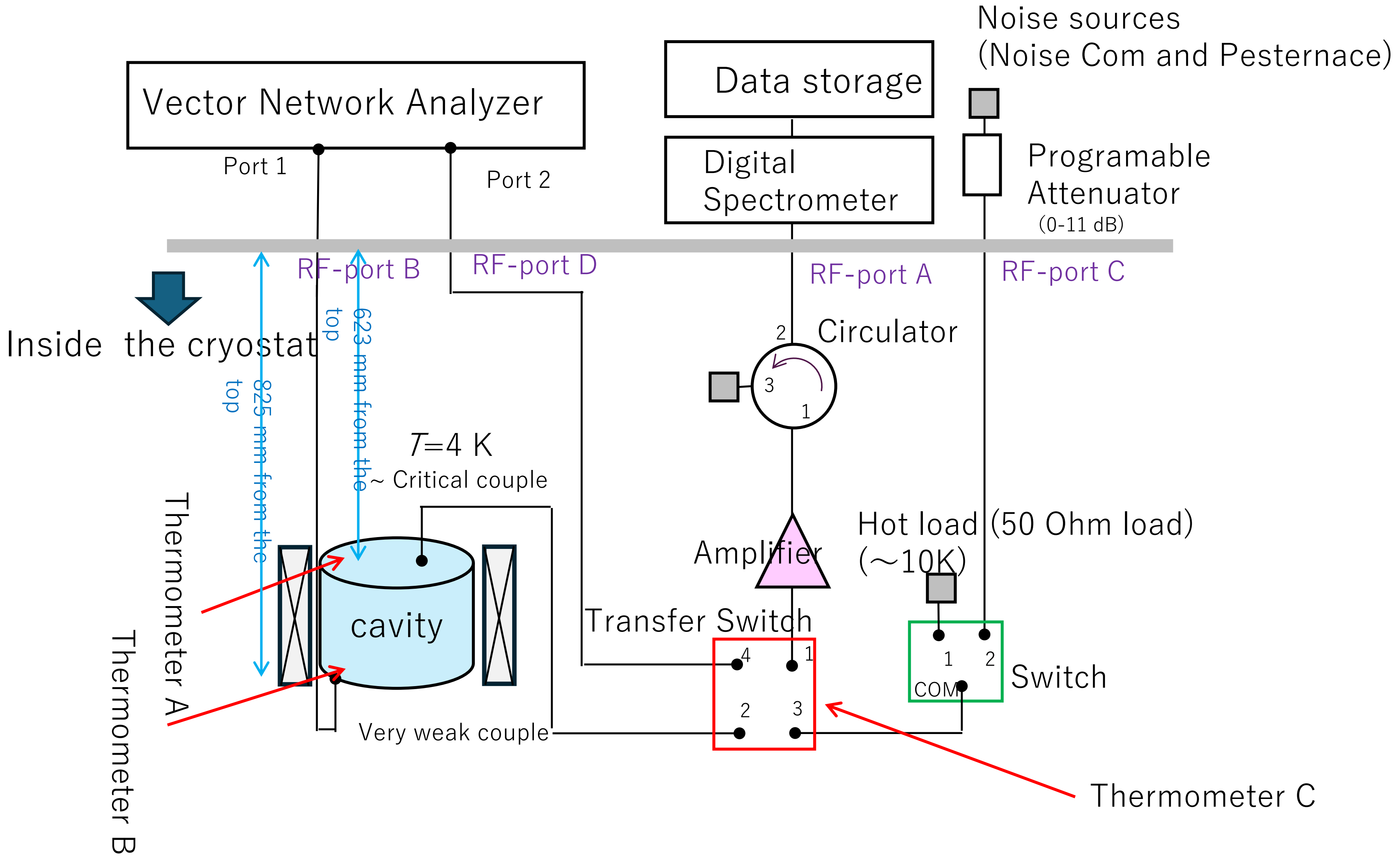
- Magnet
  - Sample volume D=110mm, L=220 mm
  - Max B=9.1 T (2% unifomity)
- Simple cavity
  - $G = 0.686$
  - $V = 373\ \text{cm}^3$
  - $Q_L = 1.84\times10^4$
  - $f_R = 4{,}614.54\ \text{MHz}$ (No tuning
  - Antenna coupling $\beta = 2.04$
- Temperature
  - $T = 8.85\ \text{K}$
    - No load min. $T = 3.8\ \text{K}$

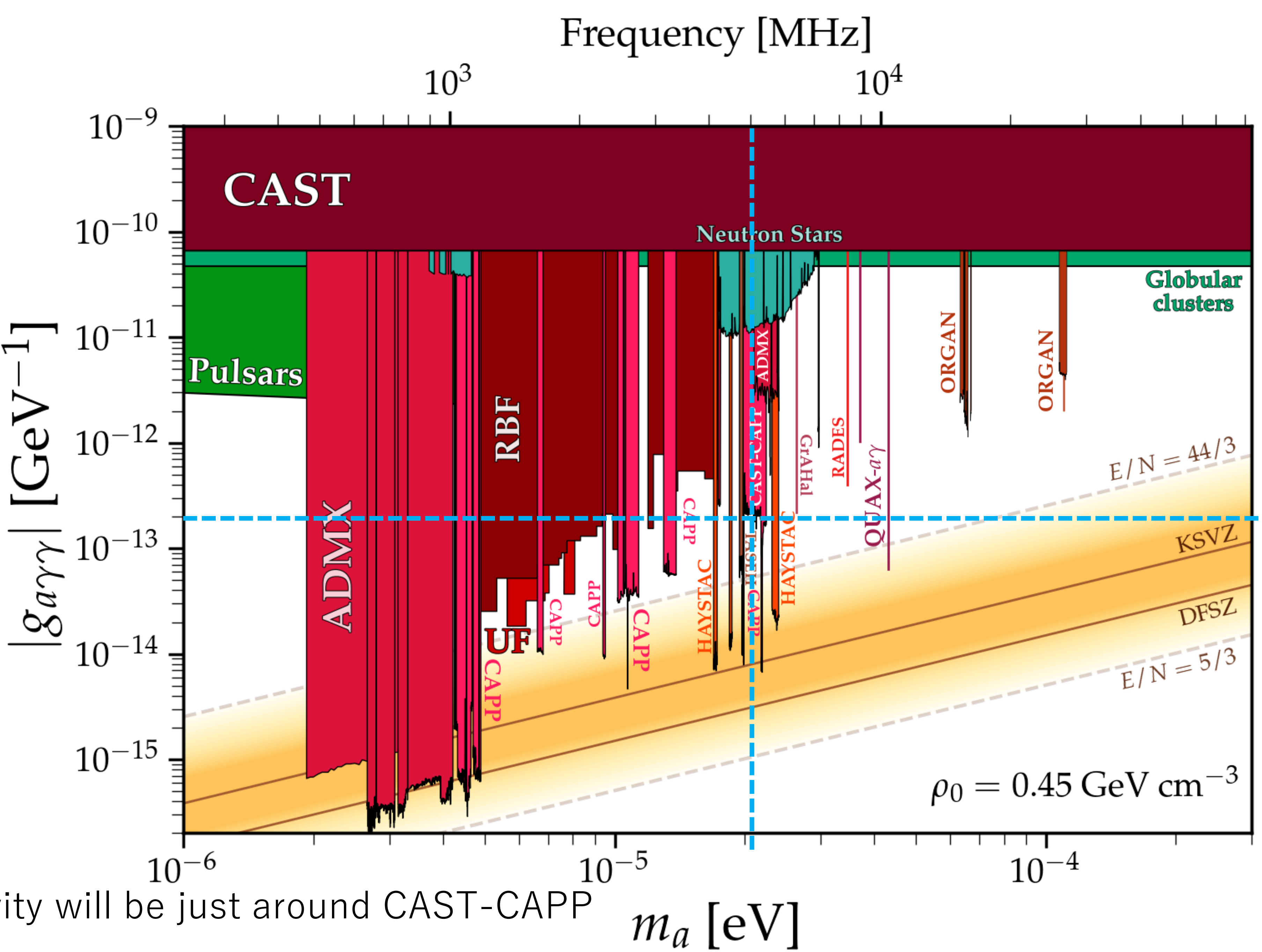






DAQ at Polit run (2024 Jan.)





Expected sensitivity will be just around CAST-CAPP

Future

<u>Physics search with current apparatus</u> (FY 2024-26)

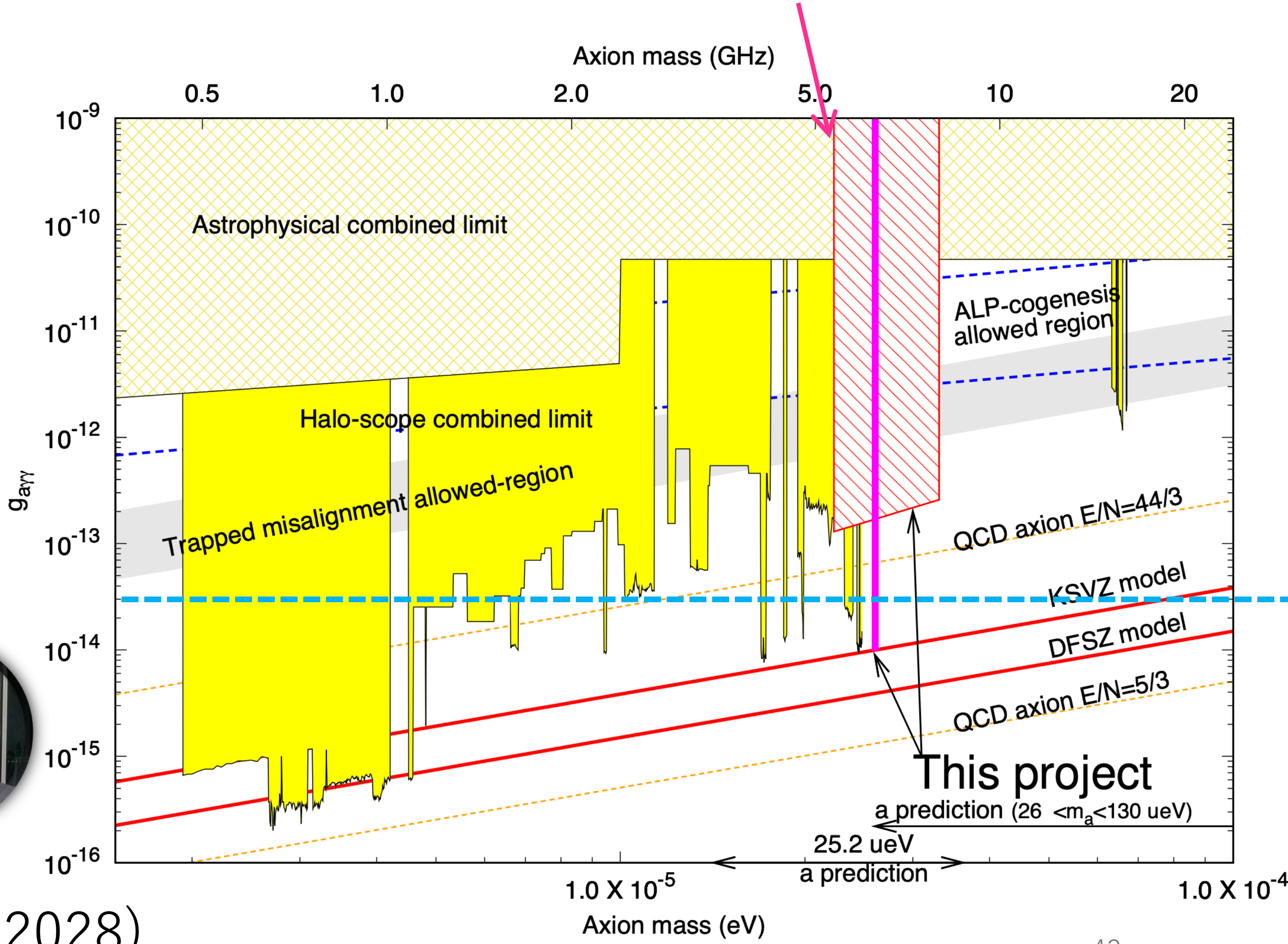
$$g_{a\gamma\gamma} = 2\times10^{-13}\ (\mathrm{GeV}^{-1}),\ f = 5.4\sim7.8\ \mathrm{GHz}$$

<u>Current cavity technology +</u>

<u>New apparatus</u> (FY 2027-28)

- Large $G_{lmn}VQ$ cavity
- New cryostat: $T = 1.8$ K
- New magnet and B free region
- Kinetic Inductance Parametric Amp. ($T_N = 2$ K)

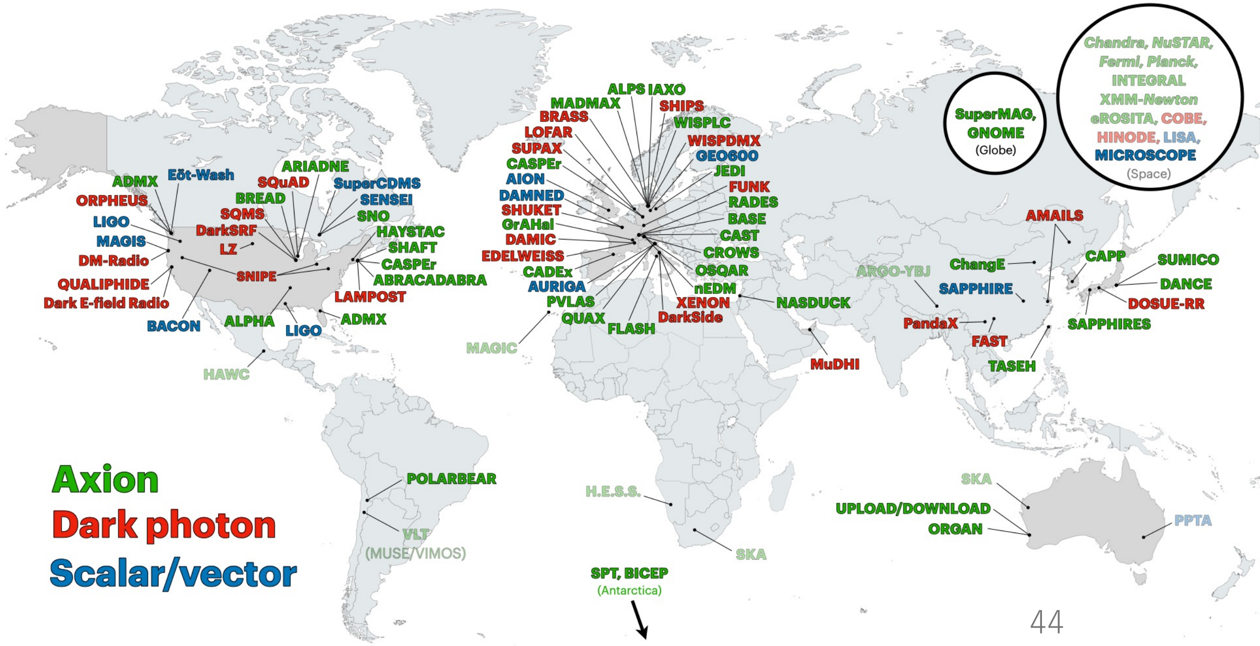
Tough KSVZ



New budget is approved (FY 2024-2028)

Summary

- The wave-like DMs are well motivated.
- It is not yet discovered even though a lot of efforts.
- Wide parameter spaces are unexplored. (mass and coupling)
- Many projects in worldwide with variety of methods.
- DM is waiting to be discovered.



Acknowledgement

- Thanks to our collaborators and those who provide advises and comments.

- This study is supported by JSPS KAKENHI (Grand number 19H05809, 21K18621, 21H05446, 22K18716, and 23H03999), NIFS collaboration research (NIFS-3-1), and the Cooperative Research Project Program of REIC.