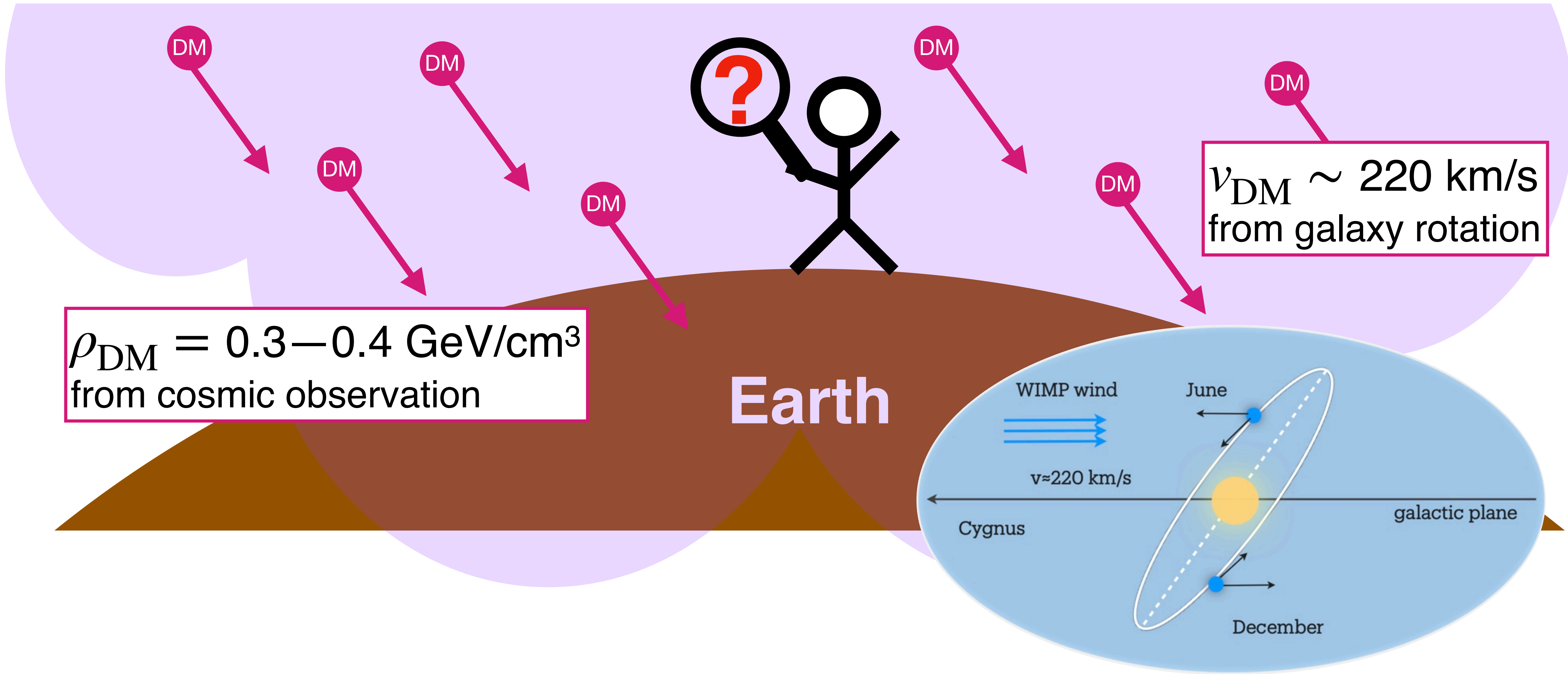
Exploring Dark Matter on Earth

—Overview of direct dark matter search from WIMP to ultra-light DM

Shunsuke Adachi (Okayama U)

2026.07.03 Challenges at the CMB Frontier, Suwa, Japan

We Aims to Detect it around Us!

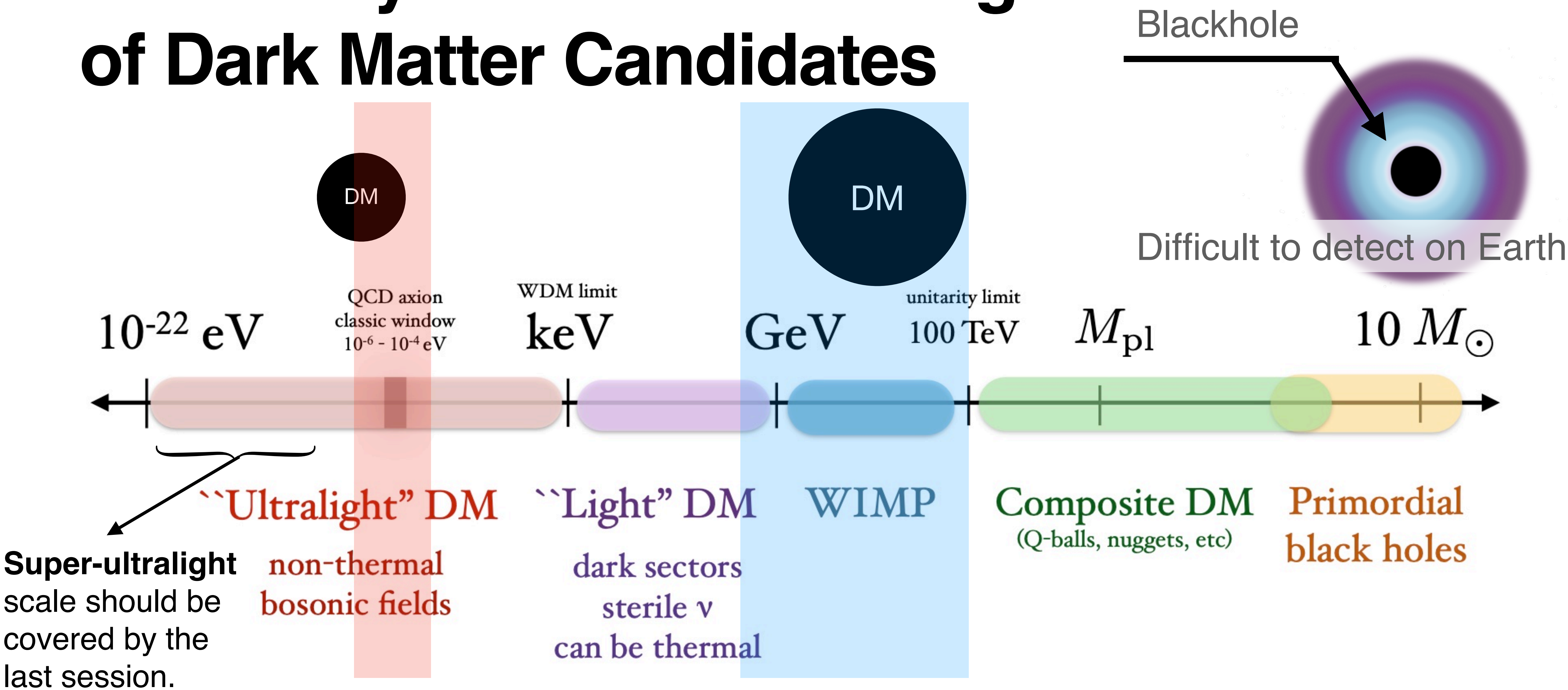


By detecting it, we want to reveal its particle properties.

- What is the **mass** of a DM particle?
- How **interact** with other particles?

Extremely Broad Mass Range of Dark Matter Candidates

T. Lin, arXiv:1904.07915v1



This review covers the dark matter mass regions where searches are advancing most rapidly — in the **WIMP** scale and **ultra-light** scale.

The WIMP searches are reviewed from DM conference (IDM 2026).

Wave-like v.s. Particle-like

Ultra-Light DM
Dark photon , Axion (ALP)

Dark matter mass m_{DM}

WIMP (Massive)

1 μeV — 1 meV — 1 eV — 1 keV — 1 MeV — 1 GeV

$\lambda \gtrsim 1$ **m**

de Broglie Wavelength

$$\lambda_{\text{de Broglie}} = \frac{h}{m_{\mathrm{DM}} v_{\mathrm{DM}}}$$

$\lambda \lesssim 10^{-9}$ **m**

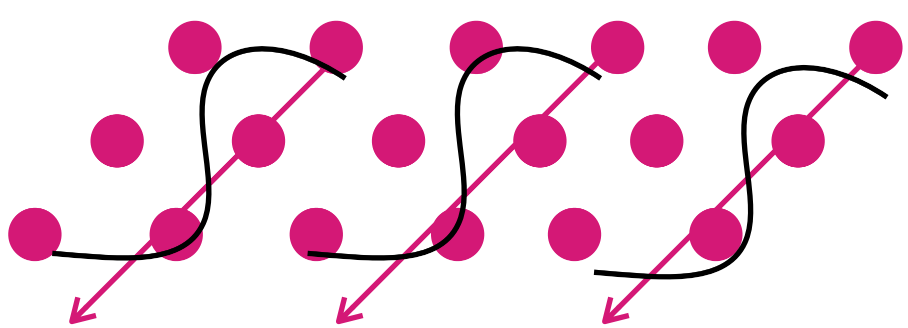
$\rho_{\mathrm{DM}} \sim 0.3\,\mathrm{GeV/cm^3}$

$v_{\mathrm{DM}} \sim 220\,\mathrm{km/s}$

- Many DMs on Earth (> 10^{12} DMs/cm^3)
- Coherent like a wave.

Its field has phase like a plane wave.

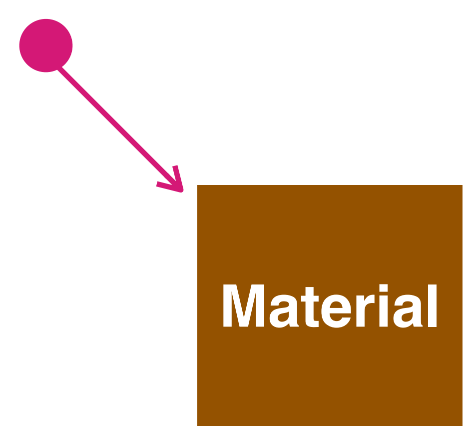
Wavy DM



Like gas

- A few DMs on Earth (≈ 1 DMs/cm^3)
- No coherence

Particle-like DM



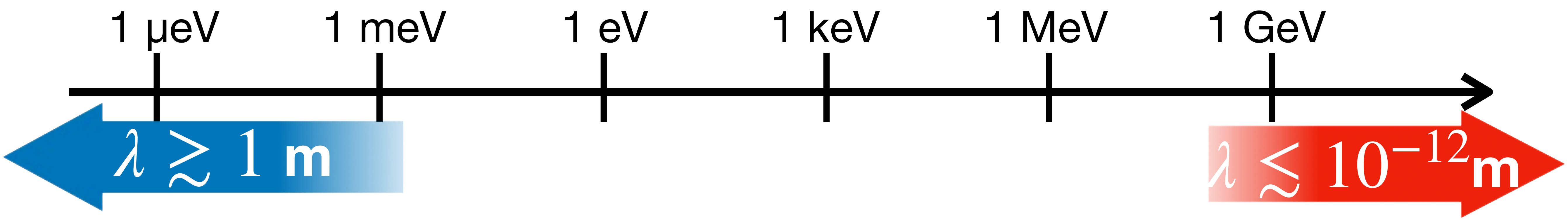
The interactions are very rare. (Stochastic event)

Wave-like v.s. Particle-like

Ultra-Light DM
Dark photon , Axion (ALP)

Dark matter mass m_{DM}

WIMP (Massive)



Wavy DM

Dark photon

- Motivated by **high-scale inflation model**, and **string theory models**
- **Couples to electromagnetic field** through kinetic mixing χ.
  (Value of χ is unknown.)

Axion (QCD axion)

- Well-motivated to solve the **strong CP-problem**
- Couples to various SM particles (gluons**, photons**, fermions)
- Mass-coupling relation is fixed: $g_{a\gamma\gamma} \propto m_a$

Axion-like particle (**ALP**)

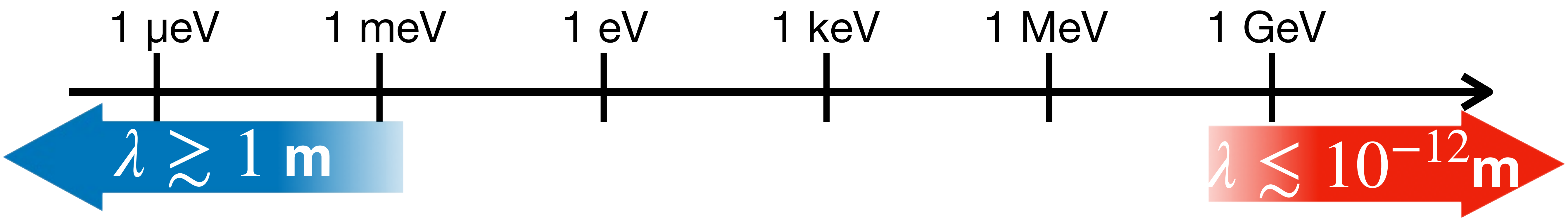
- Predicted in string theory models
- It has the **same couplings as in Axion**, but the mass-coupling relation is free.

Wave-like v.s. Particle-like

Ultra-Light DM
Dark photon , Axion (ALP)

Dark matter mass m_{DM}

WIMP (Massive)



Particle-like DM

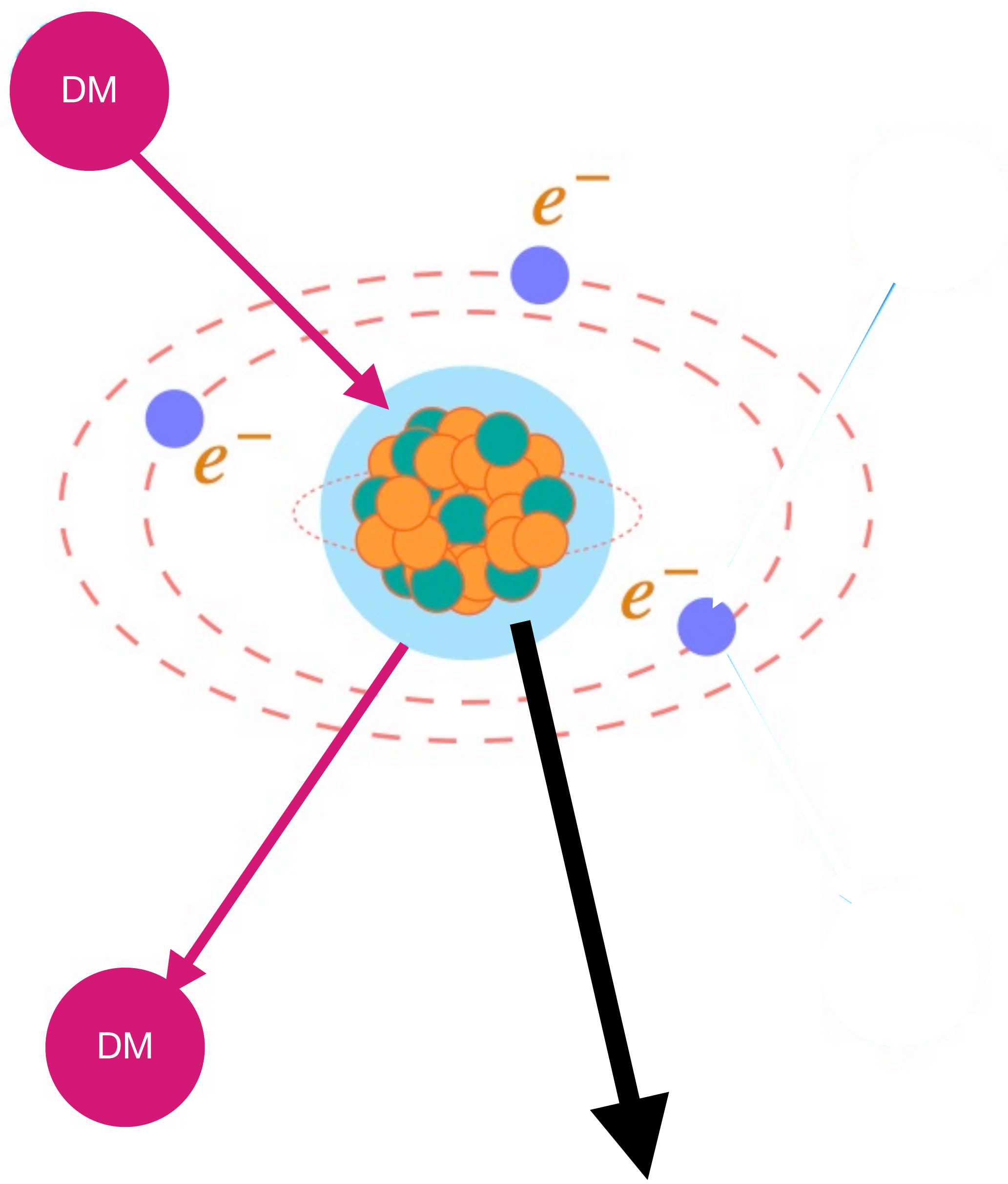
WIMP (Weakly Interacting Massive Particle)

- WIMP miracle:
  a thermal production (freeze-out) with a weak-scale annihilation cross-section automatically **reproduces the observed DM abundance** $\Omega h^2 \approx 0.12$ at present.
- Motivated also by **beyond standard model** (e.g. SUSY) in particle physics which independently predicts new particles, which can be the DM
  - ex) Lightest neutralino (LSP) in SUSY

WIMP Search

Signal

Figures from L. Baudis
in UK HEP Forum 2025



- Elastic DM collisions with **atomic nuclei (nuclear recoil)**

* There is another interaction of collision with electrons (electron recoil). However, today I will skip it due to time limitation.

Recoil E~10—100 keV
for Xenon

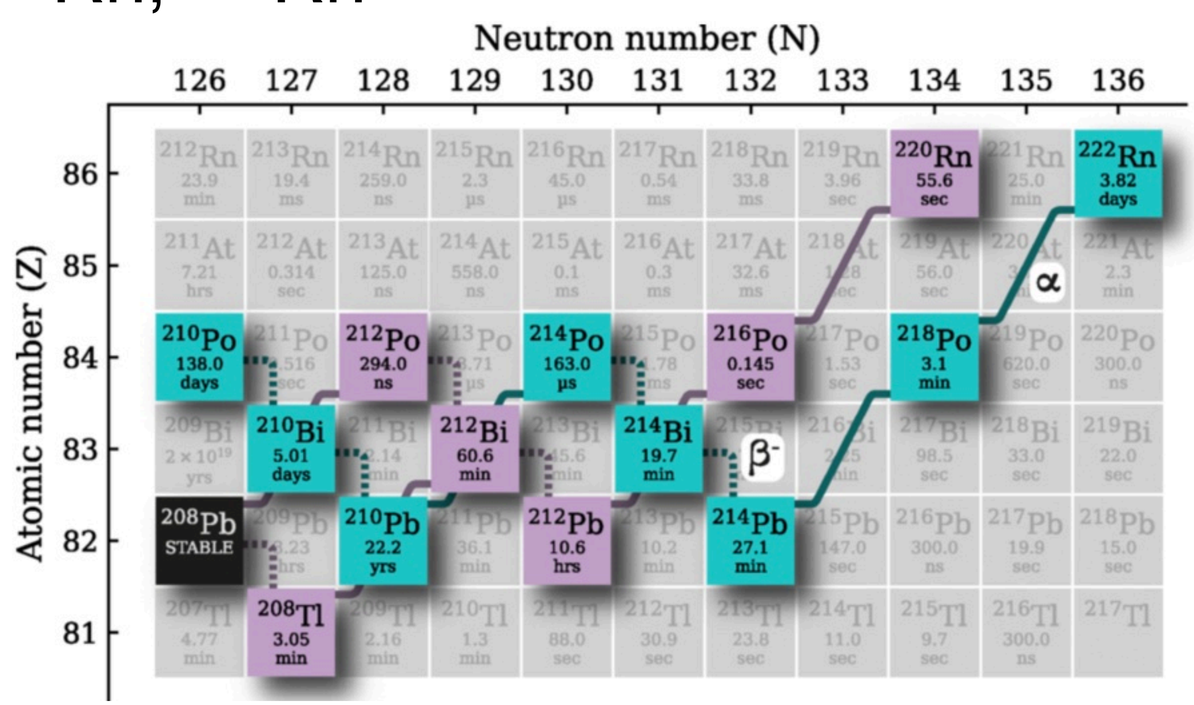
Scintillation light (178 nm)

Ionized electrons (charge signal)

Background

- Cosmic Rays
  - Need underground & large shields

- Radioactivity
  - Need to use ultra-low-radioactivity materials
  - ex) ^{222}Rn, ^{220}Rn

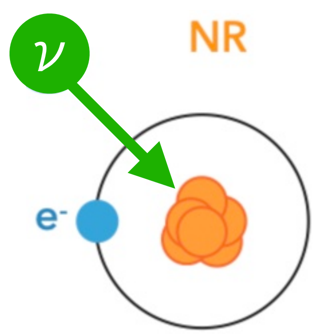


- Neutrinos
  - They are **irreducible background**.

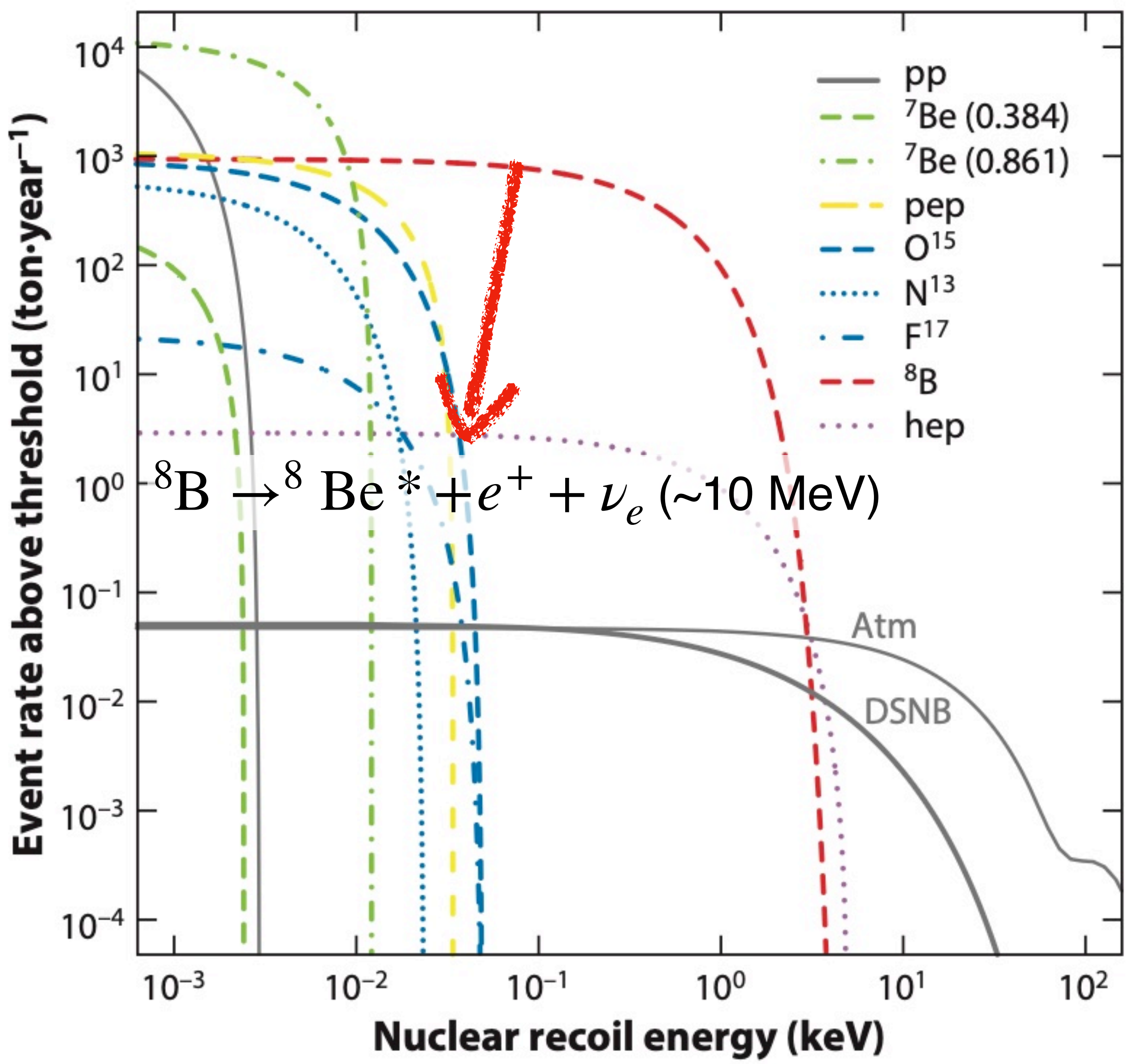
Neutrino Background

Main Neutrino source: Solar neutrinos

Collision with nuclei: “CEνNS” (Coherent Elastic Neutrino-Nucleus Scattering)

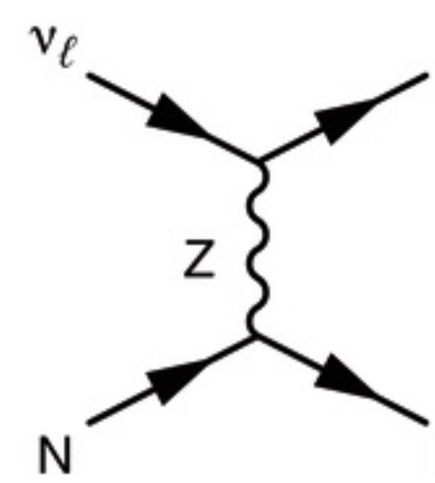


Solar reactions for neutrino production
v.s. event rates of CEνNS in Xenon detector



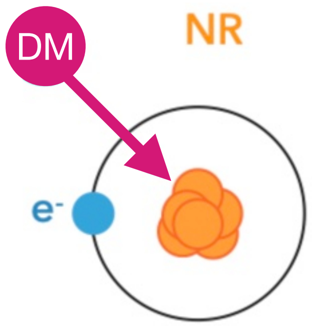
Ann.Rev.Nucl.Part.Sci. 69 (2019) 137-161

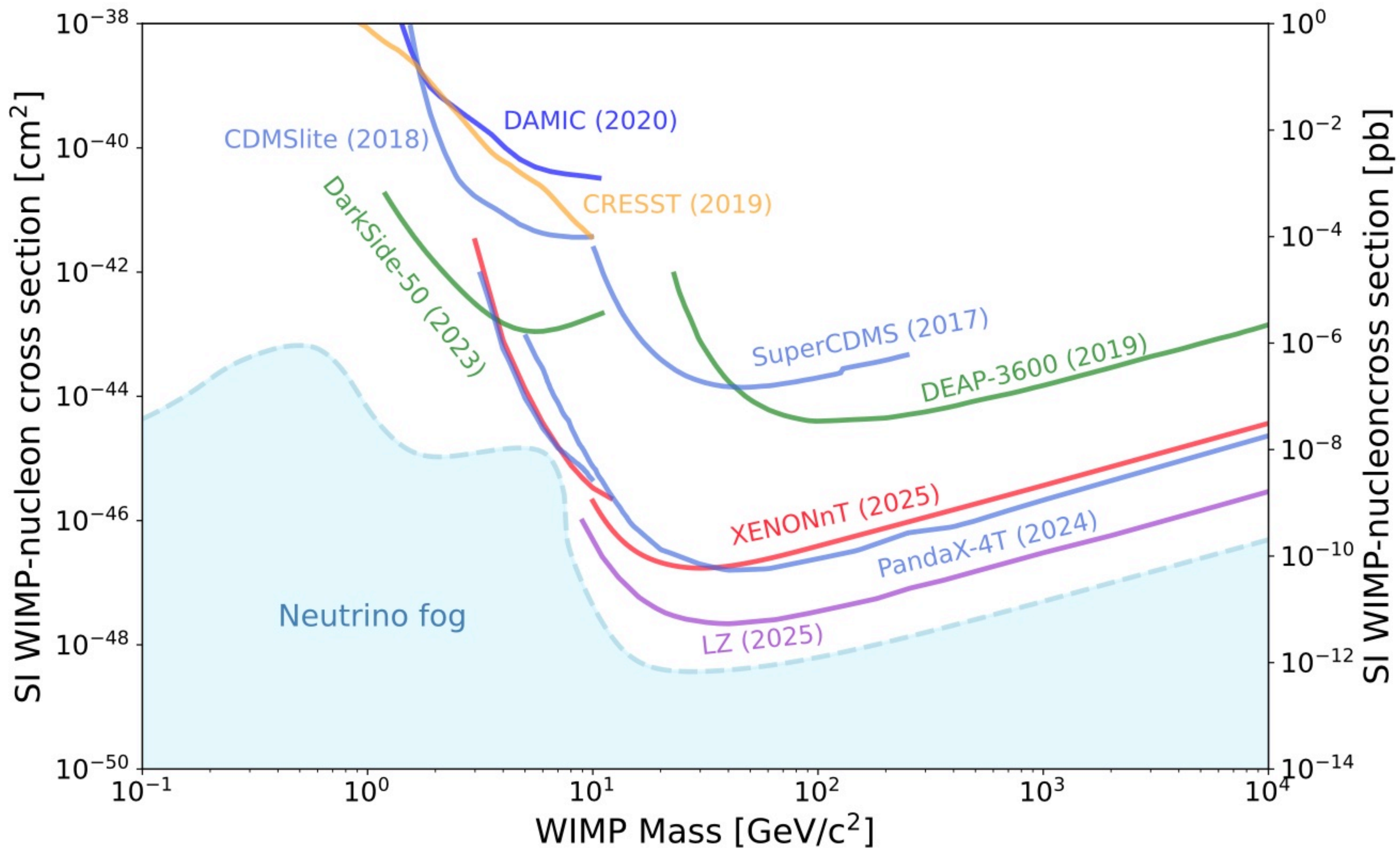
NC interaction (neutral-current)



WIMP Search to date

Particle Data Group 2026



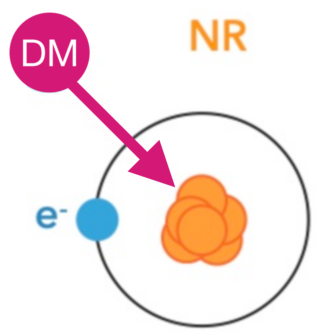


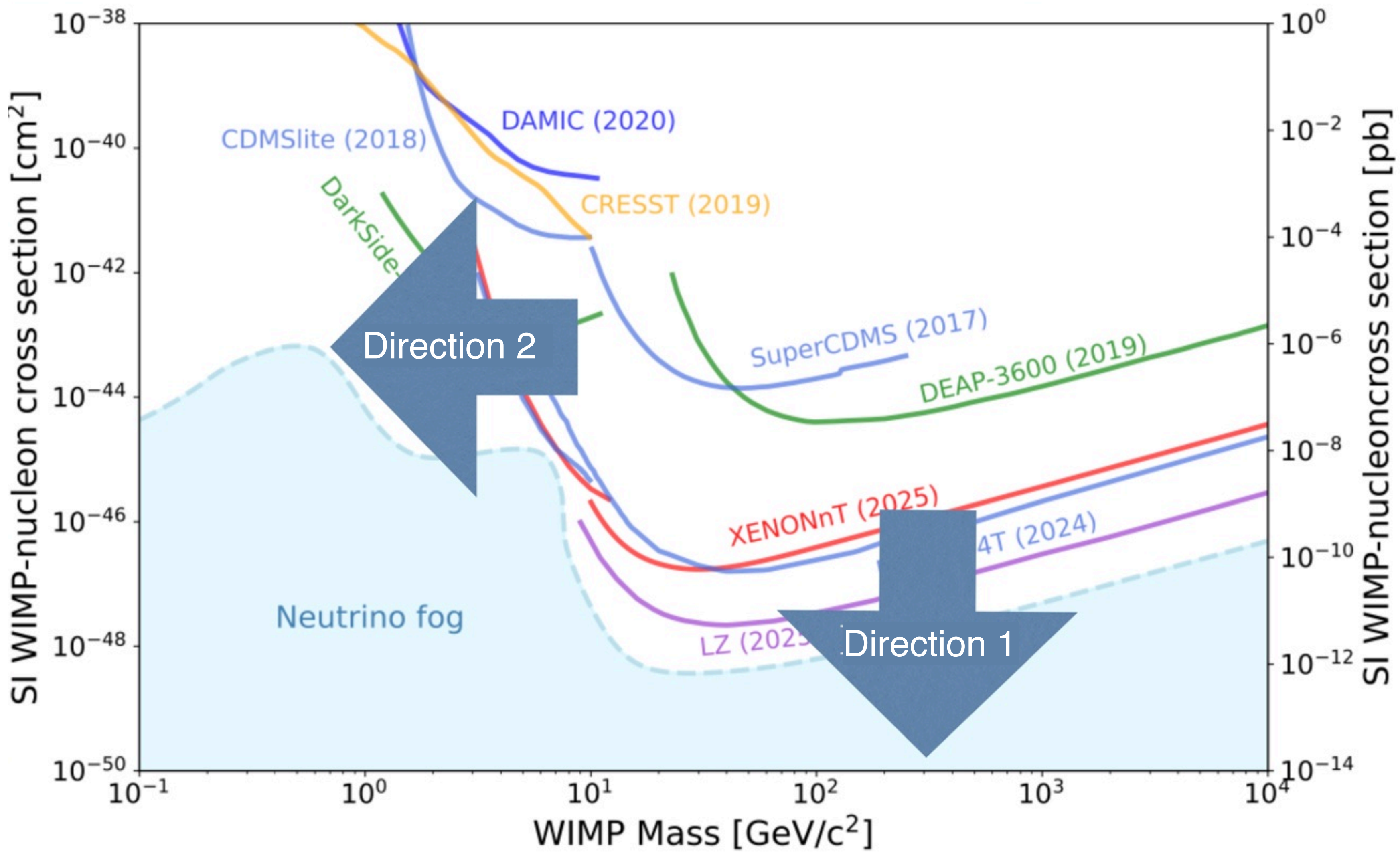
Neutrino fog is where the irreducible neutrino background appears.
(It was called “neutrino floor” years ago.)

We are almost reaching it now in the nuclear recoil!!

WIMP Search Direction

Particle Data Group 2026





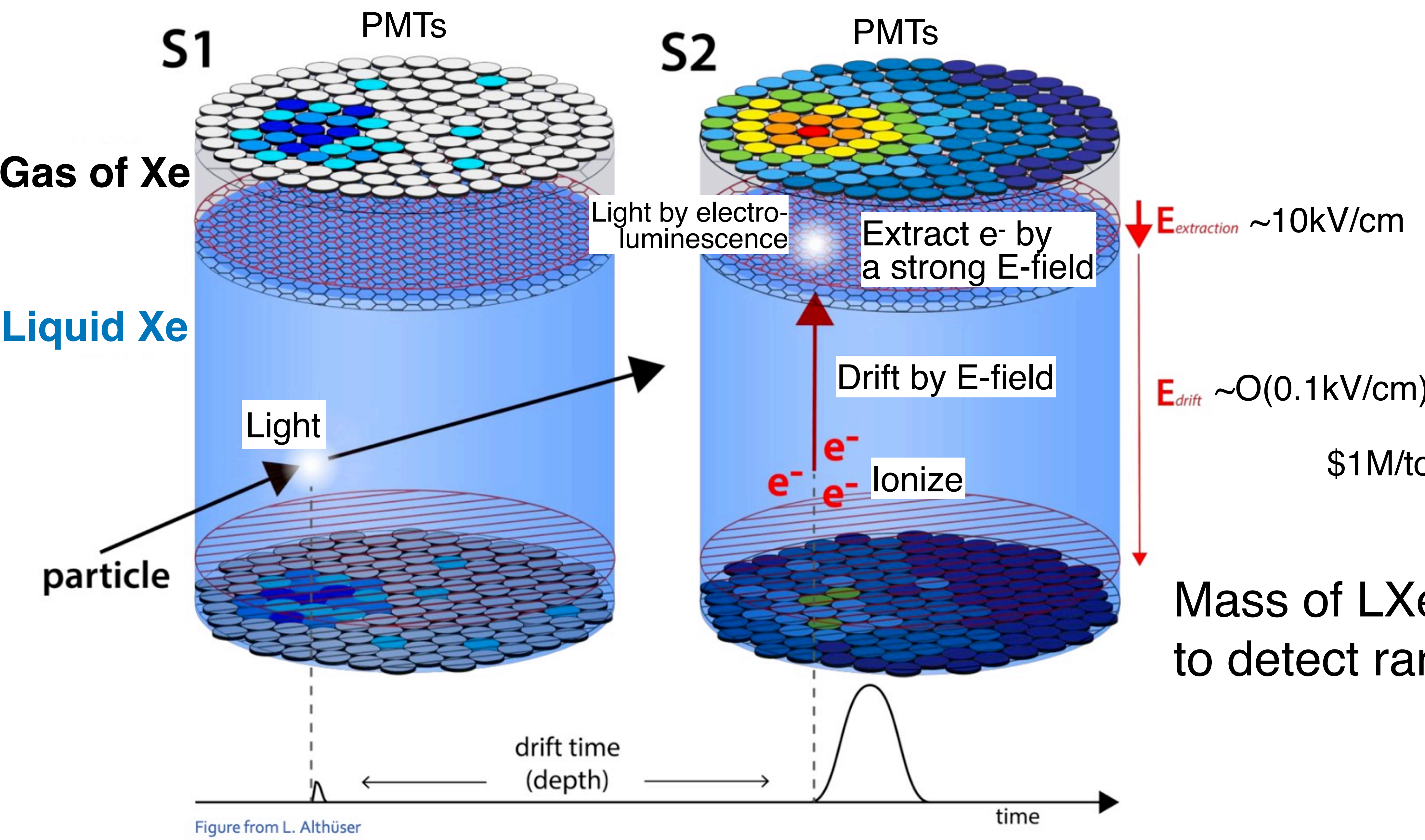
Direction 1: Deeper in the high mass range with **large liquid Xe**

Direction 2: Lower mass range with various tech. (cryogenic detectors, silicon…)

Direction 1 (High Mass)
Liquid Xe

Dual-phase TPC detector with LXe

Time Proportional Chamber



$1M/tonne

Mass of LXe is important to detect rare events of DM.

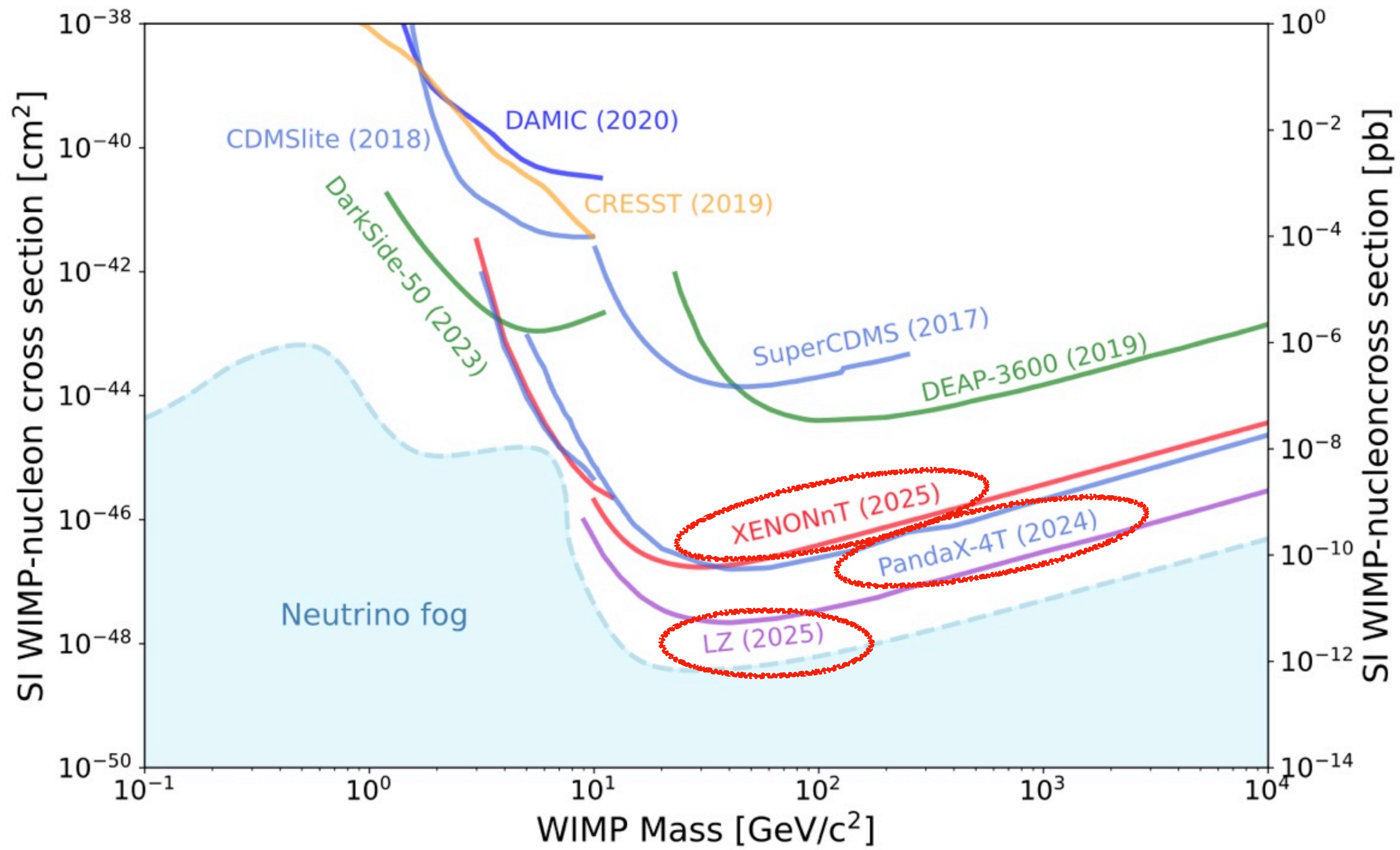
Two signals

- S1: primary scintillation light
- S2: delayed ionization signal (from electroluminescence)

By combining the signals, there is almost **no background**.

Current Ongoing Experiments

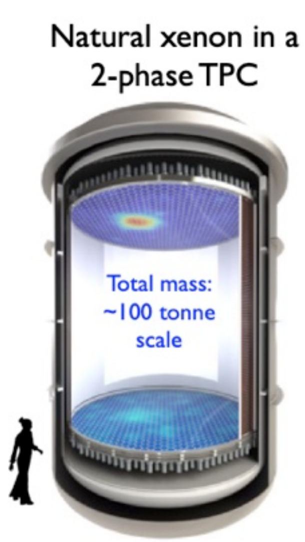
LZ (LUX-ZEPLIN)	XENONnT	PandaX
		
7t 2021—	5.9t 2021—	3.7t 2020—2026



Future Experiments

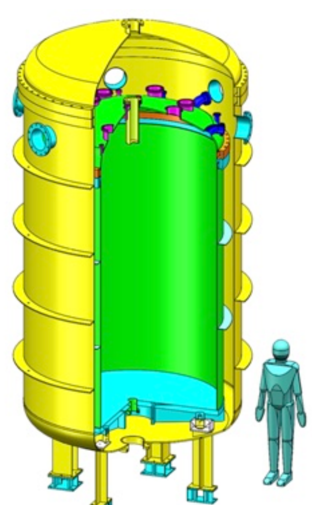
LZ (LUX-ZEPLIN)	XENONnT	PandaX-4T
		
7t 2021—	5.9t 2021—	3.7t 2020—2026

XLZD (60—80t)

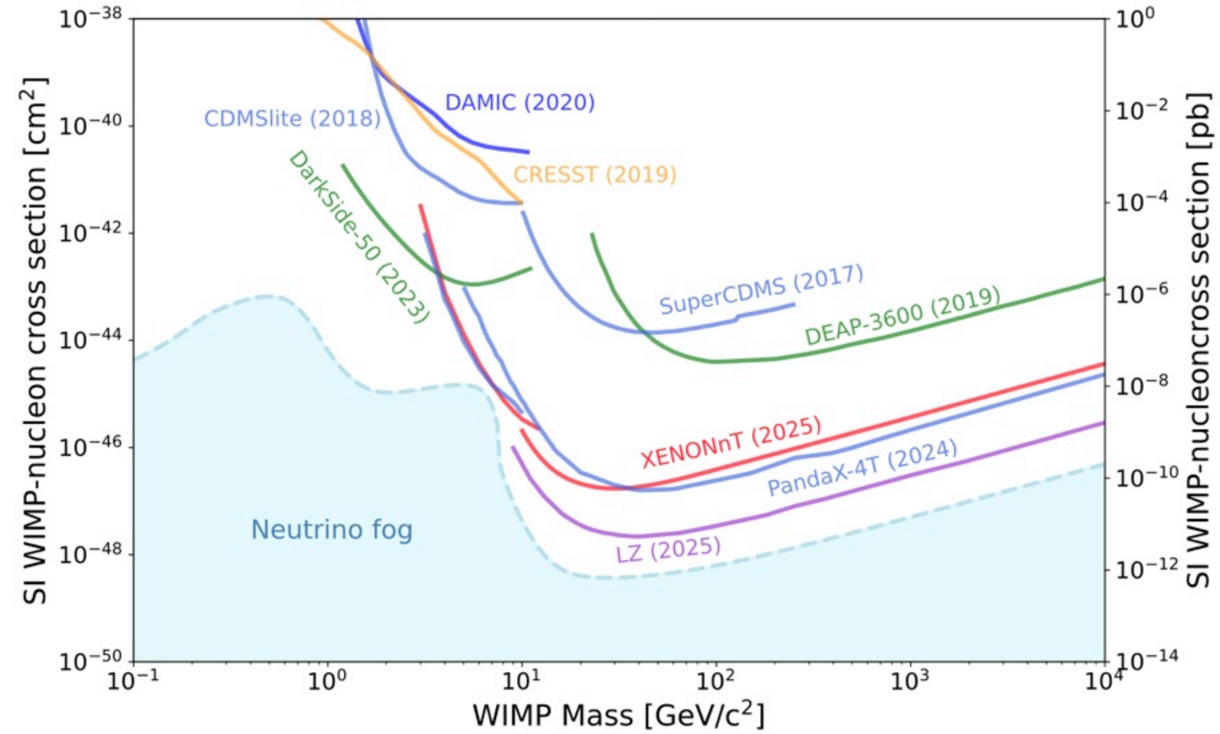


???—
(Not funded?)

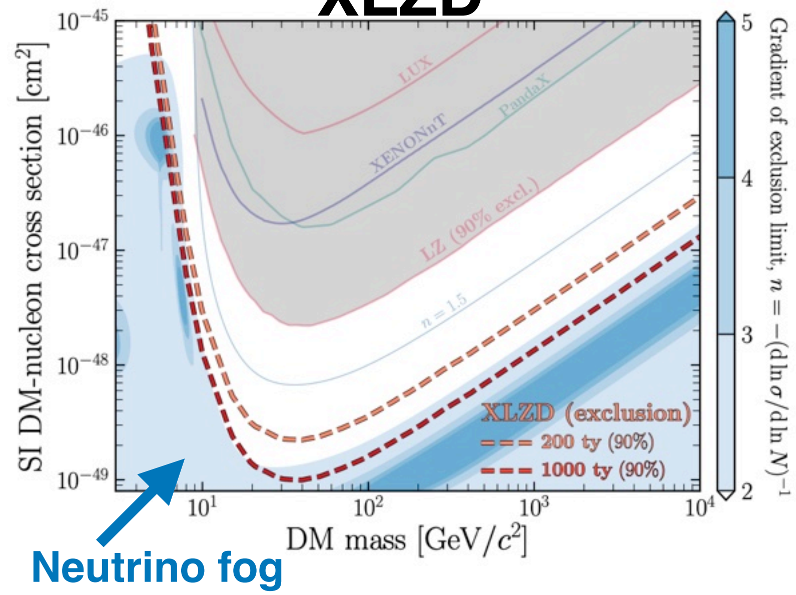
PandaX-xT (20—47t)



2028—
(20t is funded.)

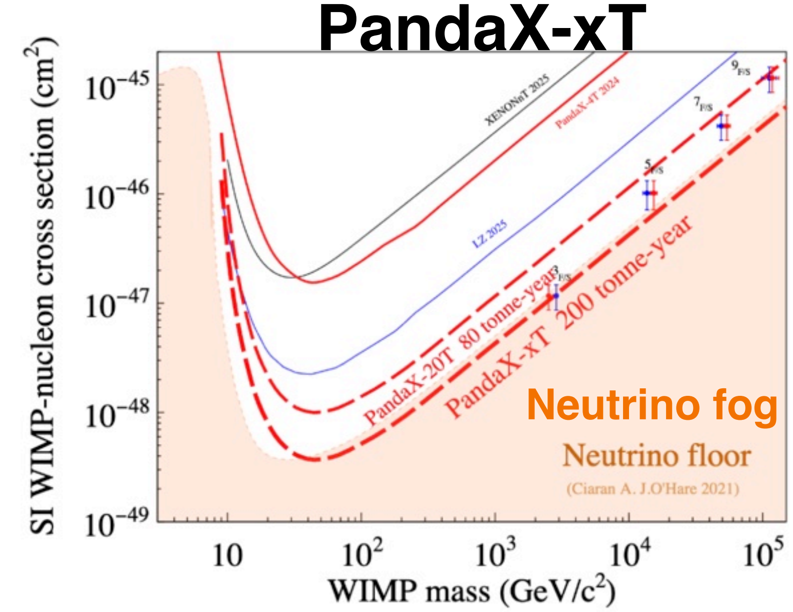


XLZD



Eur. Phys. J. C 85, 1192 (2025)

PandaX-xT

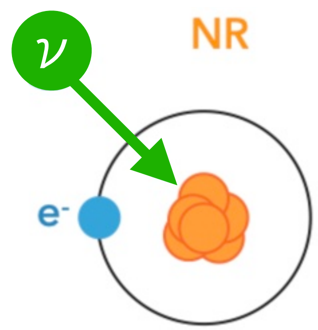


Slides from X. Xiao in IDM 2026

Entering the neutrino fog!!

Solar Neutrino already Detected!

There are dedicated analyses to measure Solar neutrino **as signal**.



Neutrino creation process in the Sun: $^{8}\mathrm{B} \rightarrow ^{8}\mathrm{Be}* + e^{+} + \nu_e$ (~10 MeV)

Solar neutrino from ^{8}B was detected (**CE ν NS**).

LZ
(LUX-ZEPLIN)

Components	Expectation	Fit Results
^{8}B CEνNS	-	$12.3^{+7.0}_{-5.4}$
Accidental coincidences	6.6 ± 0.3	6.6 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$
Total	6.6 ± 0.3	$18.9^{+7.0}_{-5.5}$

Background-only model rejected with **4.5σ** significance

arxiv:2512.08065 (2025)

XENONnT

Component	Expectation	Best fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	

Significance: **2.7 σ**

PhysRevLett 133, 191002 (2024)

PandaX

Fitted ^{8}B events: 75±28 events

Significance: **2.6 σ**

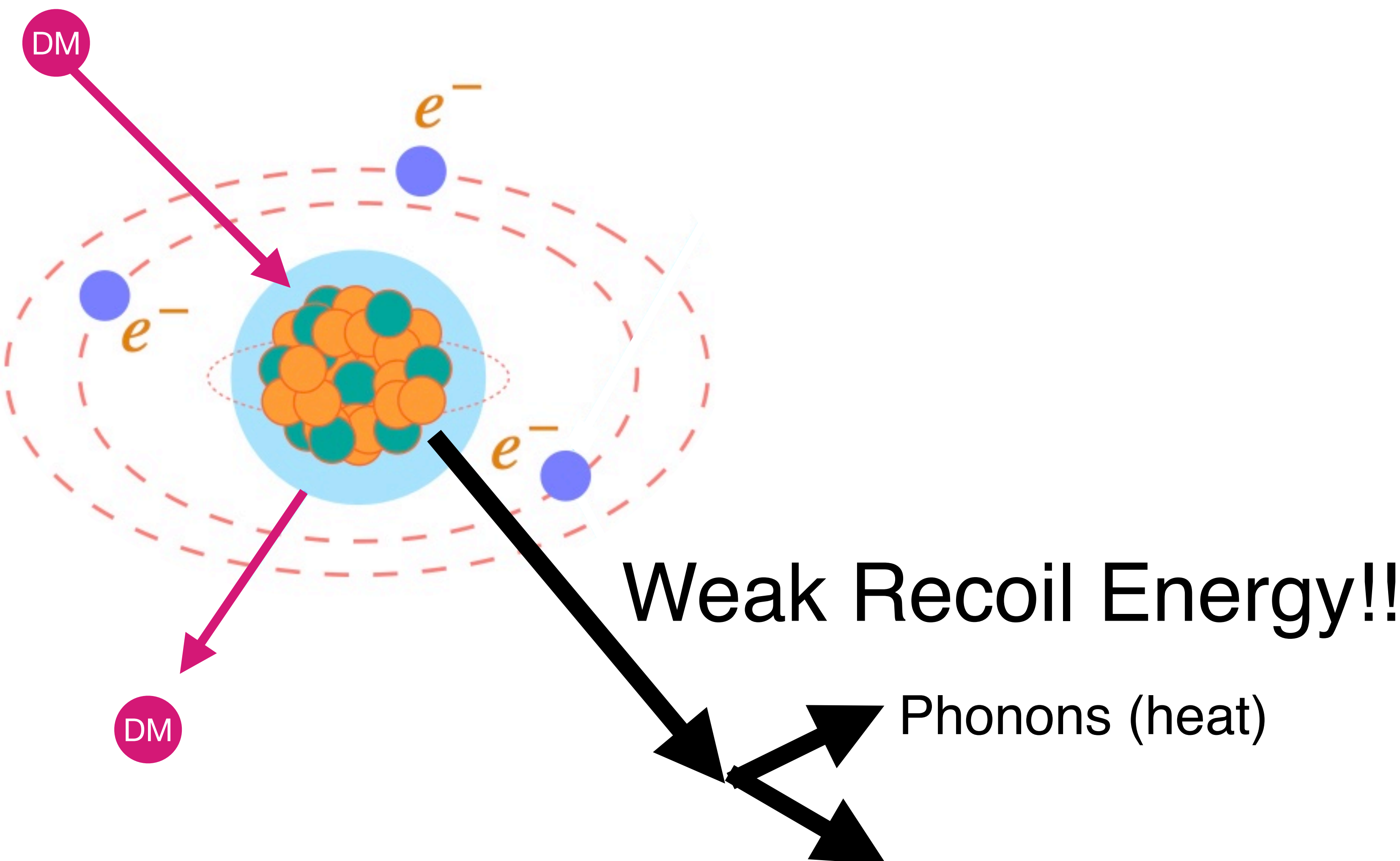
PhysRevLett 133, 191001(2024)

All of three experiments have the indications, and LZ has "detected" (> 3σ)!

Direction 2 (Low Mass)
Cryogenic Detectors

Signal (Low Mass DM)

Low mass $\lesssim 10\,\mathrm{GeV}$



Figures from L. Baudis
in UK HEP Forum 2025

Low mass needs
lower threshold of the detector.

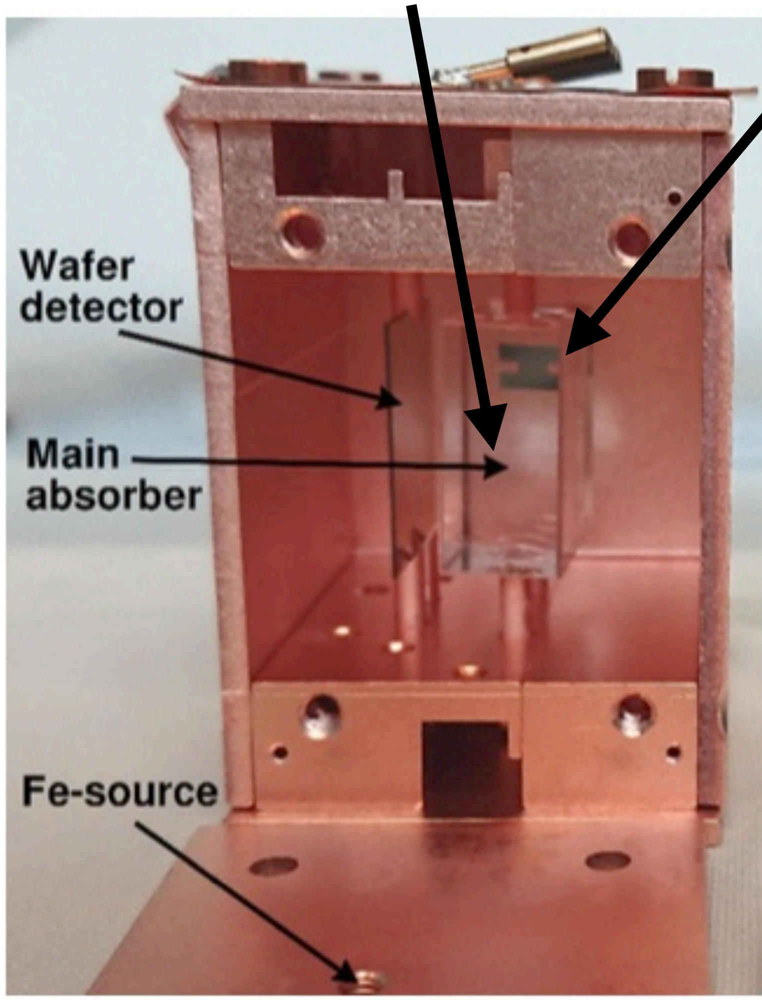
CRESST-III in Gran Sasso
(Italy)

Cryogenic Rare Event Search with Superconducting Thermometers

Cryogenic calorimeter (Phonons) wt TES + Scintillation Light Detection wt TES

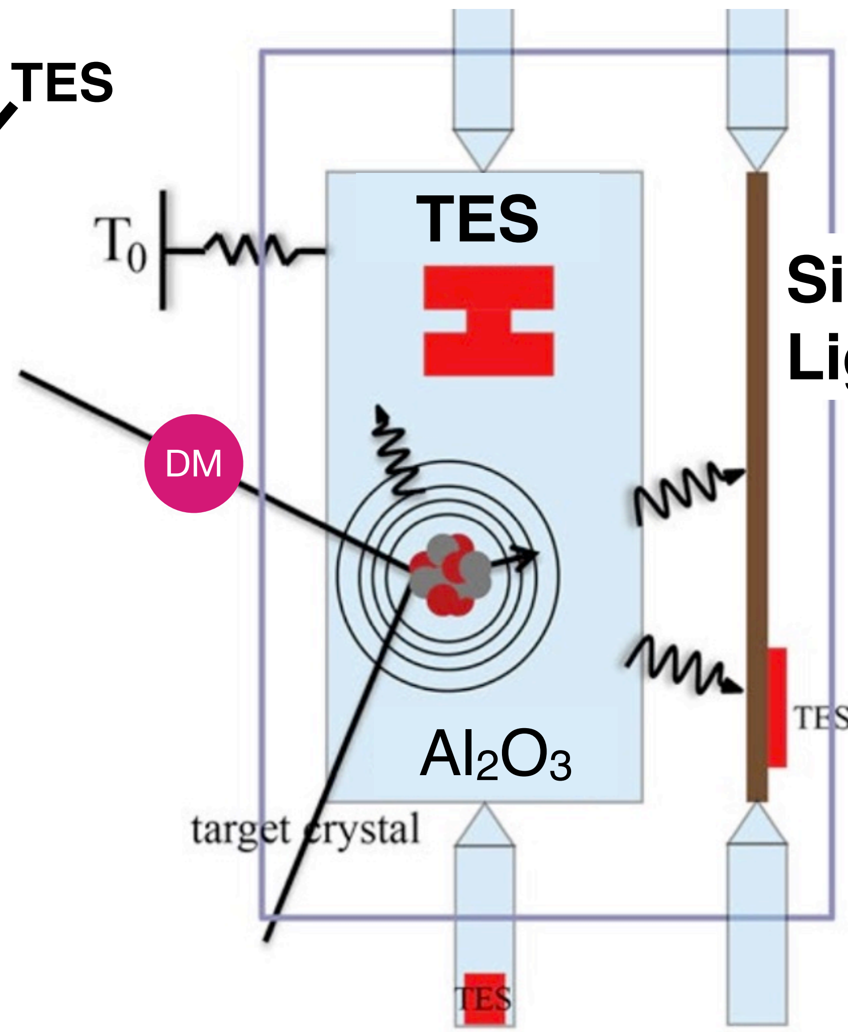
Main absorber (Al_2O_3 crystal)
2 x 2 x 1 cm³ (15.9g)

TES



PhysRevD 110, 083038 (2024)

Cool to 15 mK wt DR



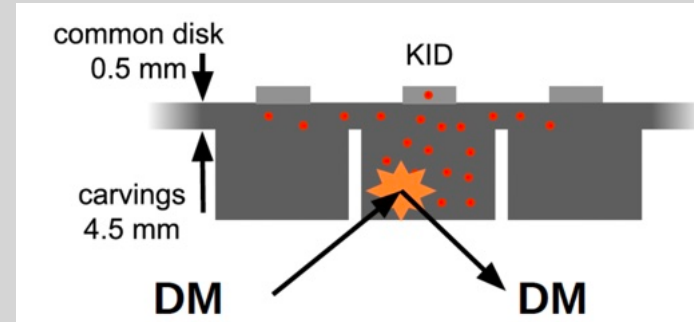
Silicone-on-Sapphire (SOS) Light Detector

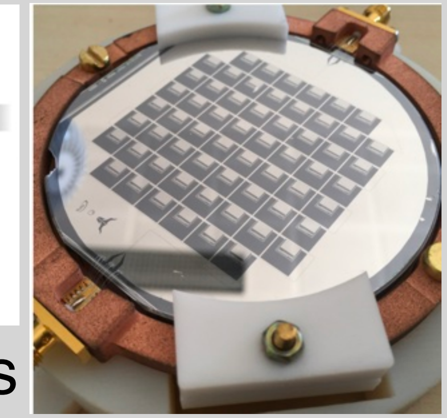
Si absorbs and turns light into heat; a TES reads it out.

LTD 199, 547 (2020)

- DM scatters with the Al_2O_3 to make phonons & scintillation light.
  - **Phonons** → Detected by **TES bolometer**
  - **Light** → Detected by **Silicone-on-Sapphire (SOS) Detector**
    - **Single scintillation light can be detected!**
- Threshold energy = **6.7 eV!!**

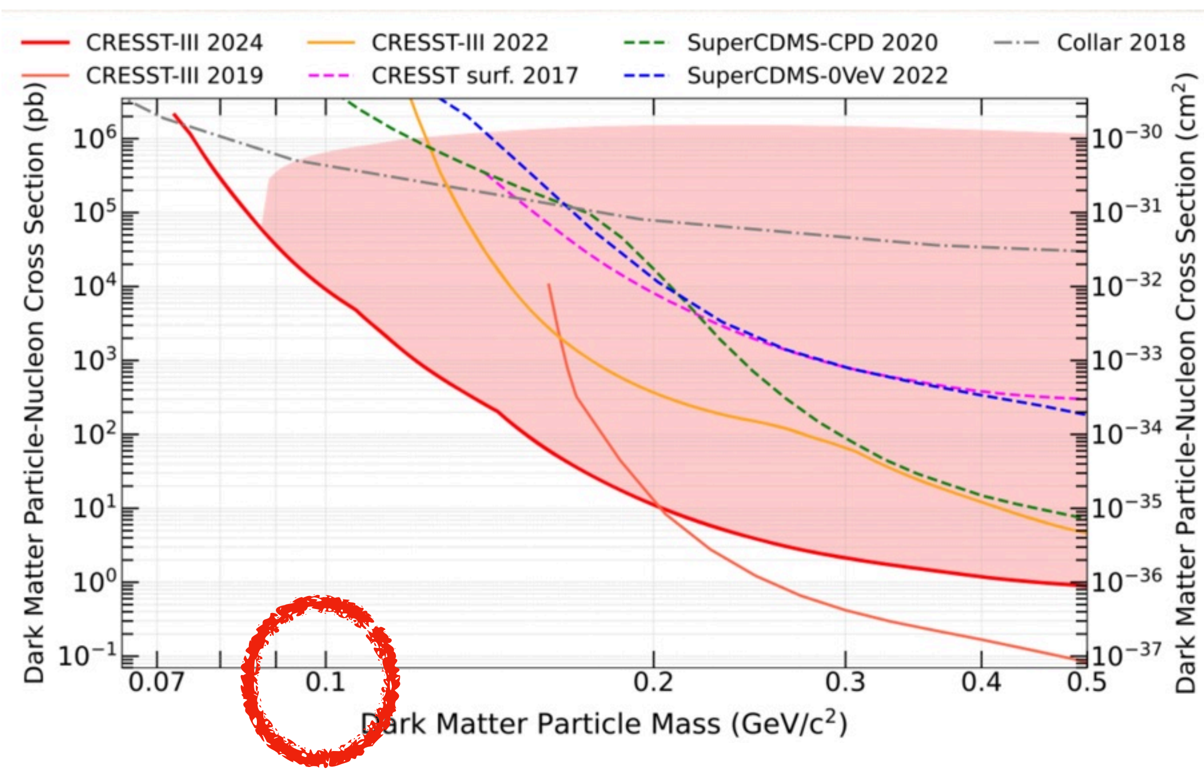
Sensitivity for Low Mass





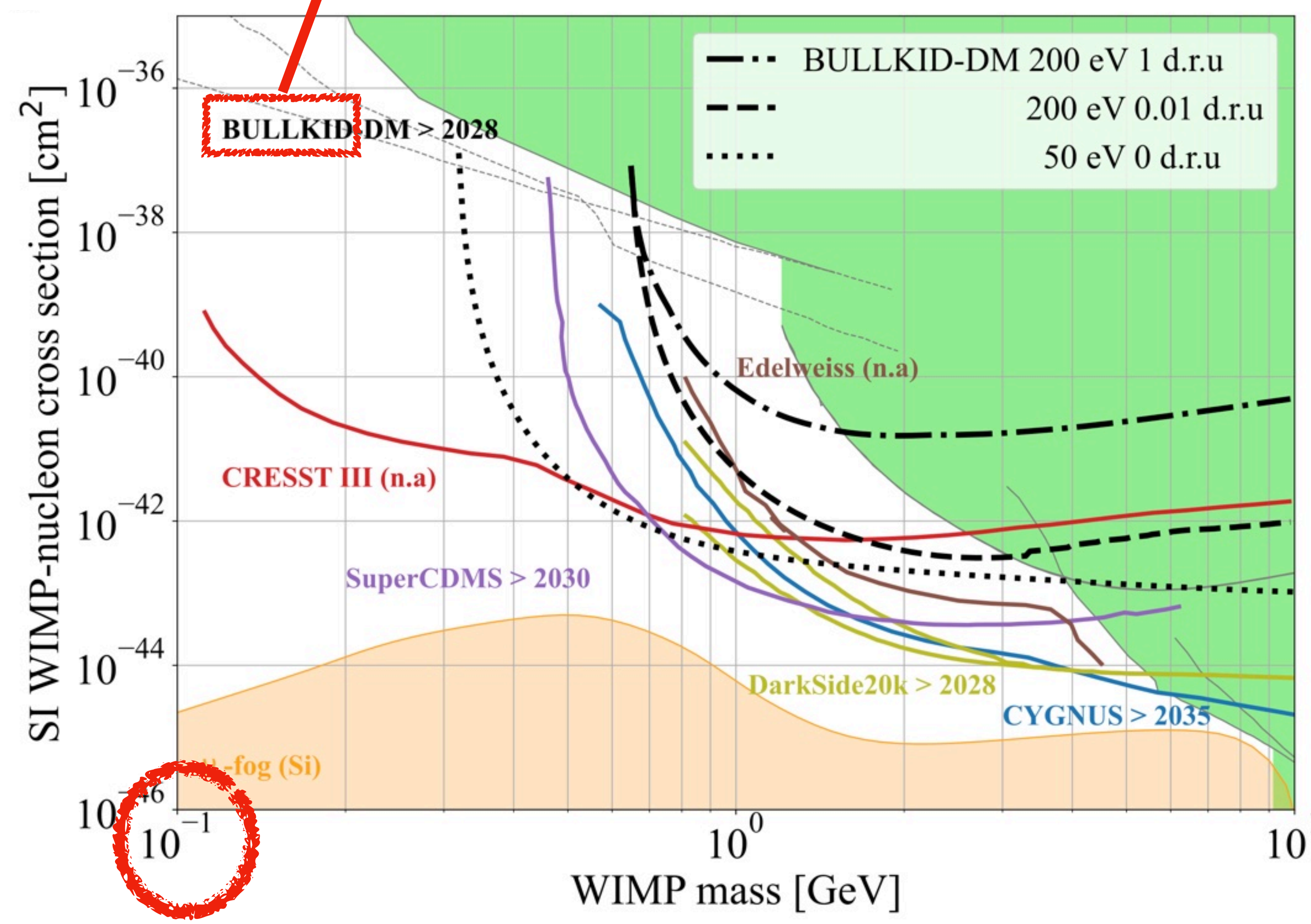
Experiment using MKIDs

CRESST results



PhysRevD 110, 083038 (2024)

Expected limits



Slides from B. v. Krosigkp in IDM 2026

WIMP searches are expanding into the sub-GeV range using cryogenic detectors.

Wavy Dark Matter Search

Axion, ALP, Dark Photon

Wave-like v.s. Particle-like

Ultra-Light DM

Dark photon , Axion (ALP)

Dark matter mass m_{DM}

WIMP (Massive)

1 μeV 1 meV 1 eV 1 keV 1 MeV 1 GeV

$\lambda \gtrsim 1$ **m**

de Broglie Wavelength

$$\lambda_{\text{de Broglie}} = \frac{h}{m_{\mathrm{DM}} \underbrace{v_{\mathrm{DM}}}_{\sim 220\,\mathrm{km/s}}}$$

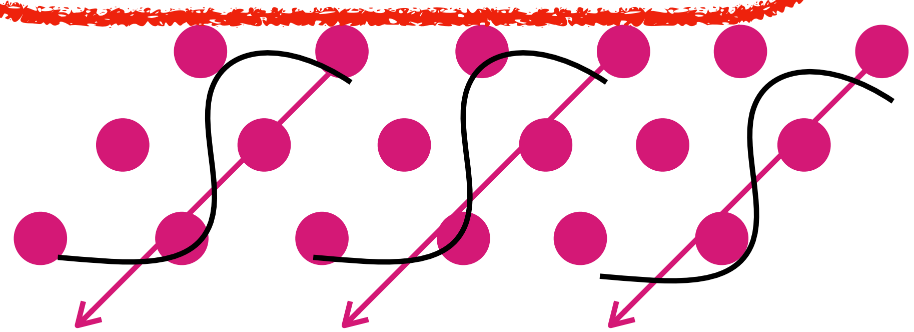
$\lambda \lesssim 10^{-9}$ **m**

$\rho_{\mathrm{DM}} \sim 0.3\,\mathrm{GeV/cm^3}$

- Many DMs on Earth (> 10^{12} DMs/cm³)
- Coherent like a wave.

Its field has phase like a plane wave.

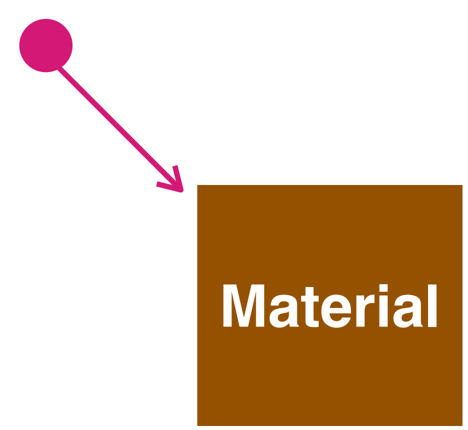
Wavy DM



Like gas

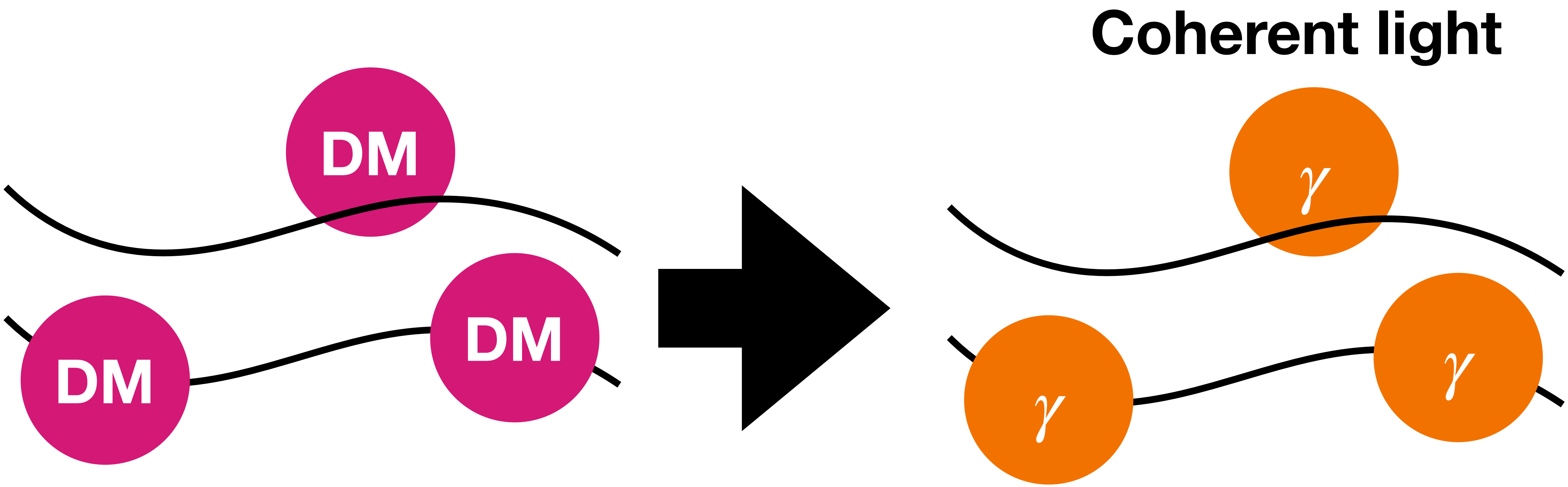
- A few DMs on Earth (≈ 1 DMs/cm³)
- No coherence

Particle-like DM



The interactions are very rare. (Stochastic event)

If it can be converted to photons...



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

*Considering CDM with a low momentum

Frequency is matched to the DM mass.

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

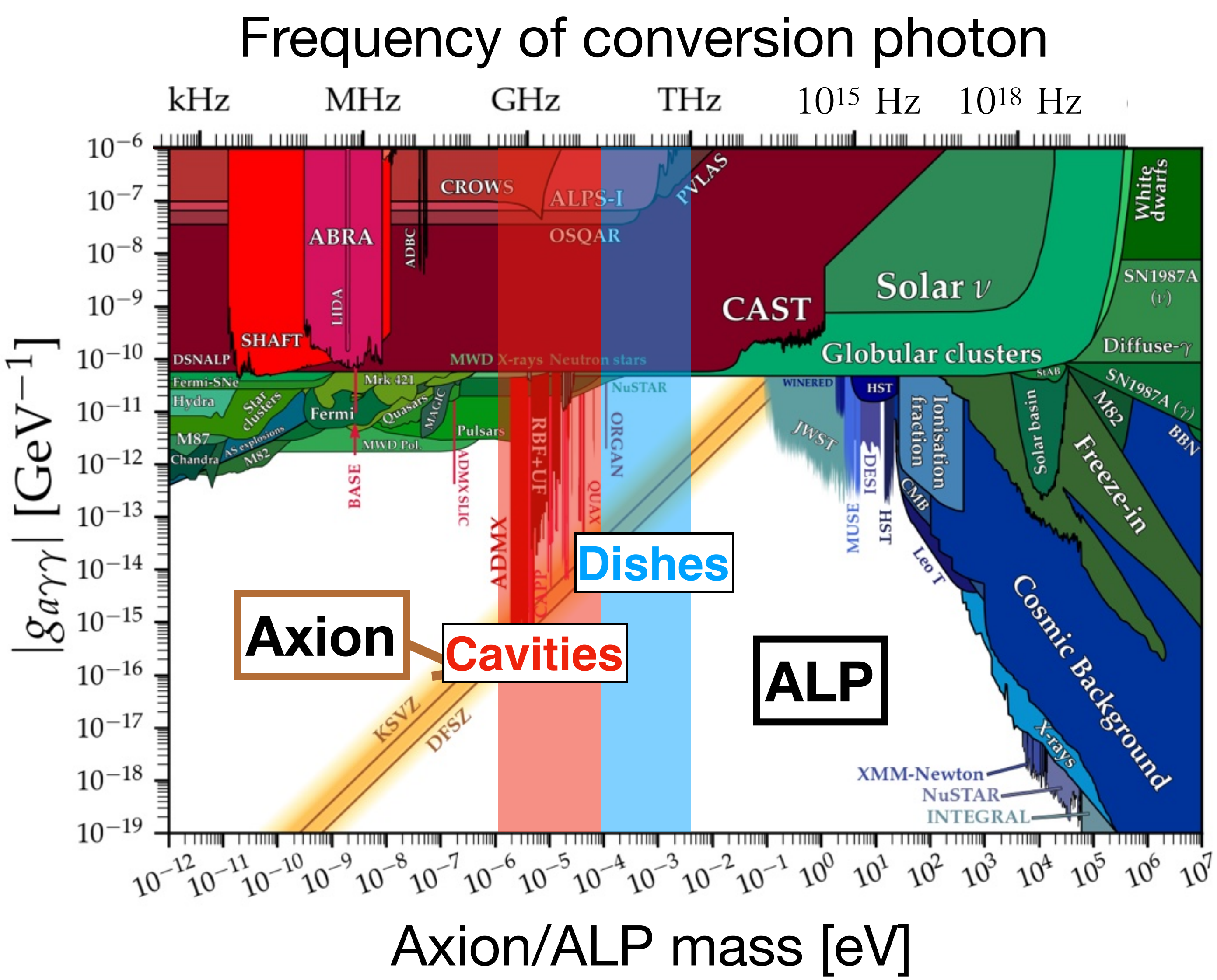
Frequency and mass are in one-to-one correspondence.

Coupling & Parameters

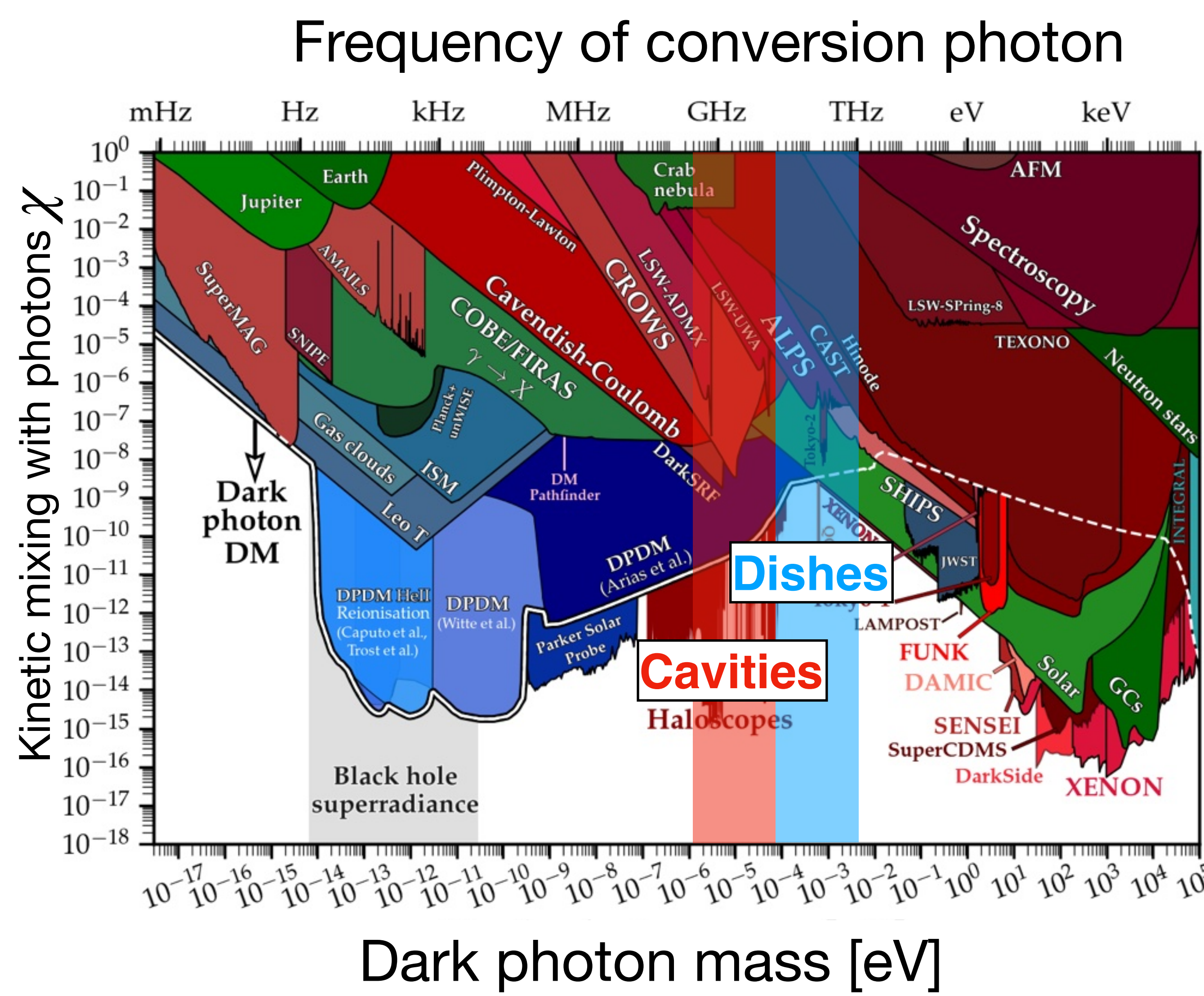
	Axion or Axion-like particle (ALP)	Dark photon
Motivation, Prediction	• Axion: Solve the strong CP problem • ALP: Models of string theory PRD 93 103520 (2016), JCAP 1206, 013 (2012)	High-scale inflation models PRD 81 123530 (2010)
Interaction with photons	$g_{a\gamma\gamma} \; a \, \vec{E} \cdot \vec{B}$ a: Axion field $\vec{E}, \vec{B}$: Electric field, magnetic field	$\frac{\chi}{2} F_{\mu\nu} \tilde{X}^{\mu\nu}$ $F_{\mu\nu}$: Field strength of EM field $\tilde{X}_{\mu\nu}$: Field strength of dark photon
Parameters	m_a : Mass $g_{a\gamma\gamma}\,[\mathrm{GeV}^{-1}]$: Coupling to photons *Axion: $g_{a\gamma\gamma} = \left(0.2\frac{E}{N} - 0.4\right)\frac{m_a}{\mathrm{GeV}^2}$ • DFSZ model $E/N = 3/8$ • KSVZ model $E/N = 0$	m_χ: Mass χ : Kinetic mixing (Strength of interaction)

Current status for axion / dark photon search

Axion + ALP
(photon coupling only)



Dark photon



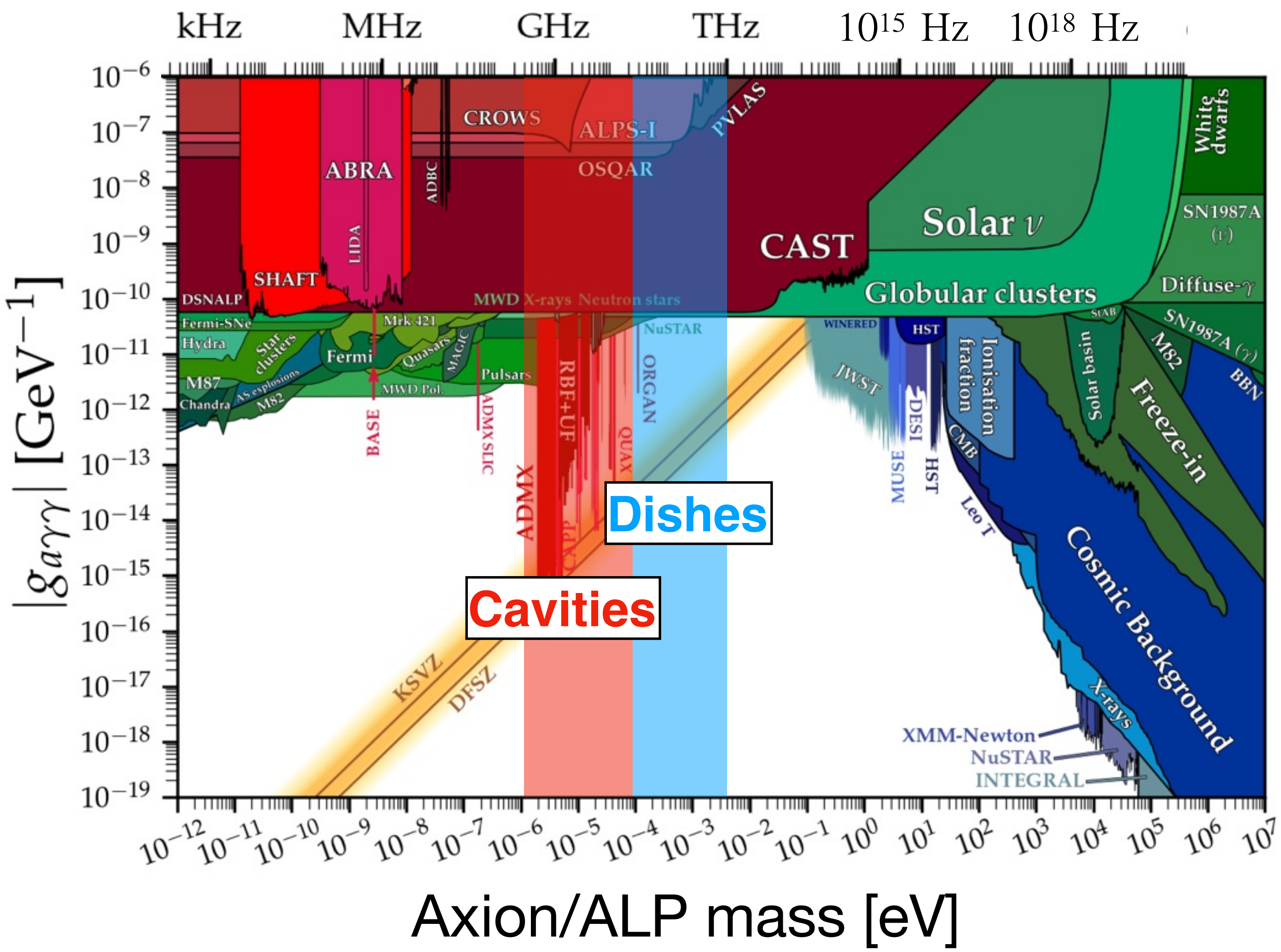
- Top / bottom axes are corresponding with $h\nu = m_{\mathrm{DM}}c^2$.
- Experimental approach is different between low and high frequency ranges.

Cite: https://github.com/cajohare/AxionLimits

Current status for axion / dark photon search

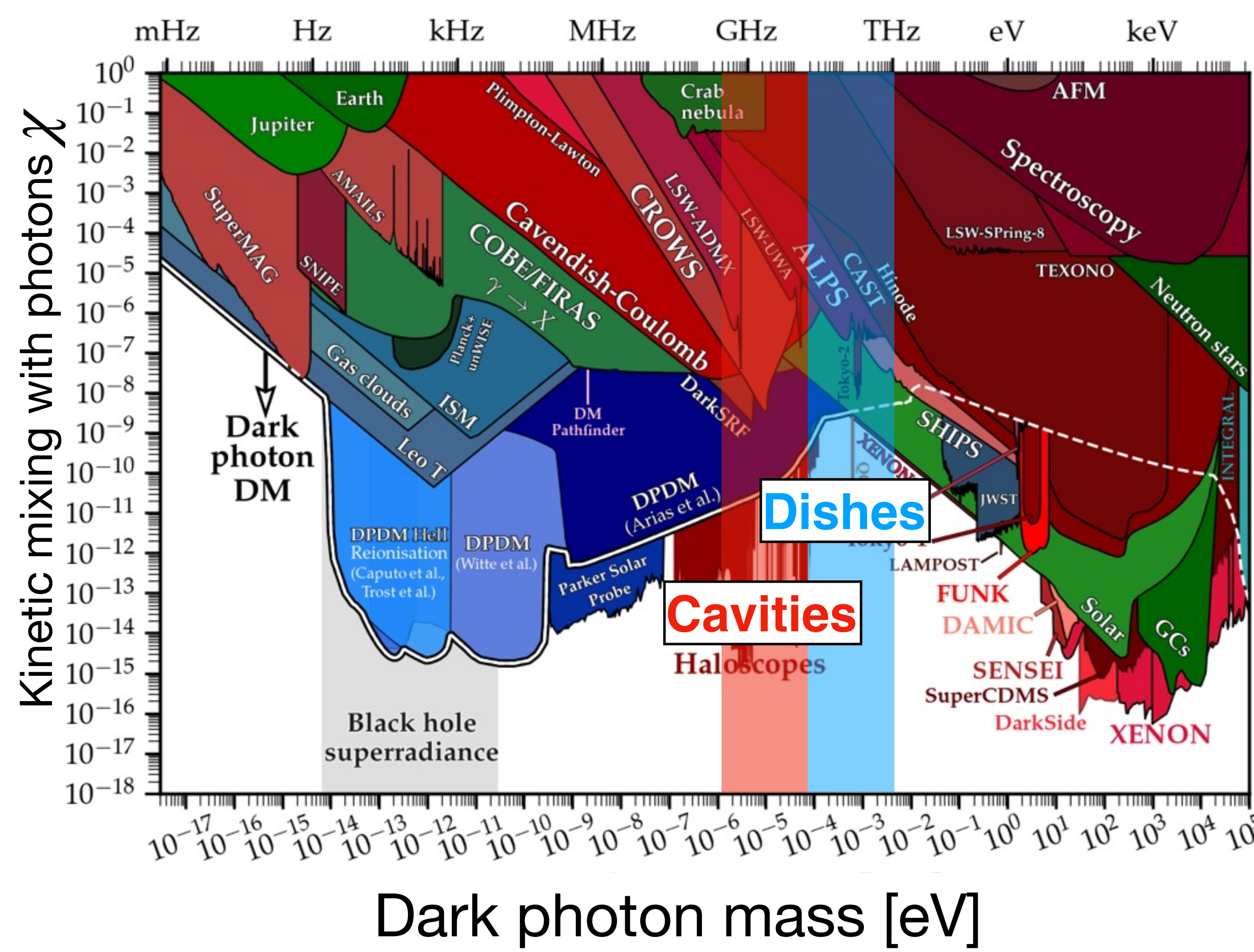
Axion + ALP
(photon coupling only)

Frequency of conversion photon



Dark photon

Frequency of conversion photon



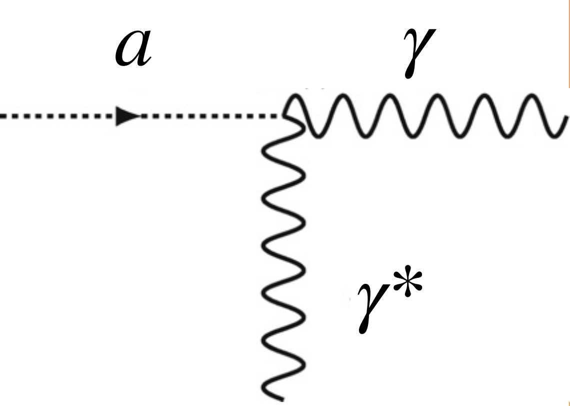
Experiments

Cavities: **ADMX, CAPP, HAYSTACK…**
Dishes: **DOSUE-RR, BREAD, MADMAX…**

Cavity Method

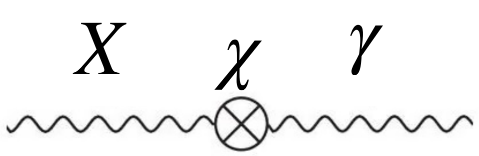
Successful Method: Resonant Cavity

Axion

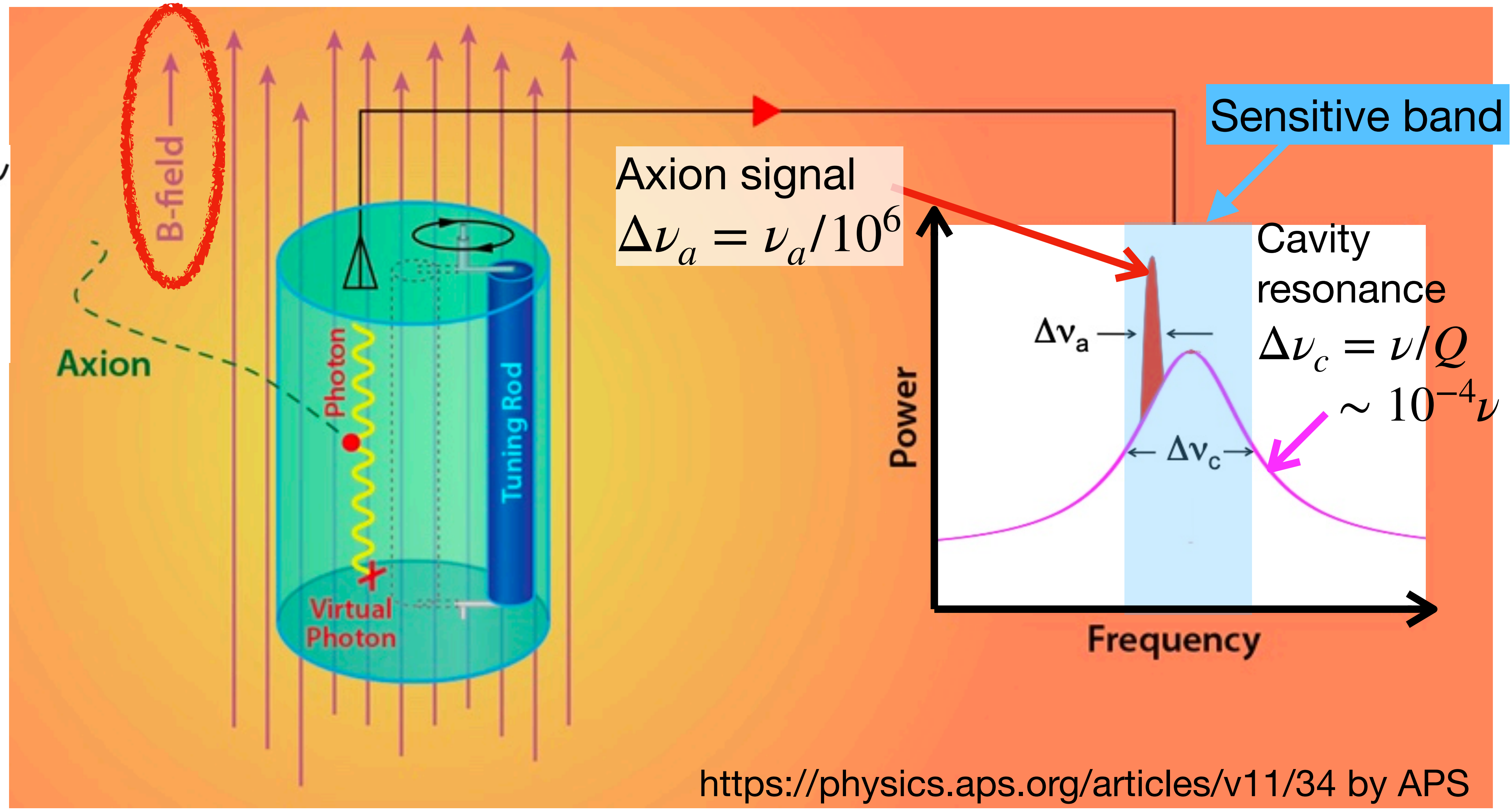


$$\mathscr{L} = \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$
$$= - g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

Dark photon



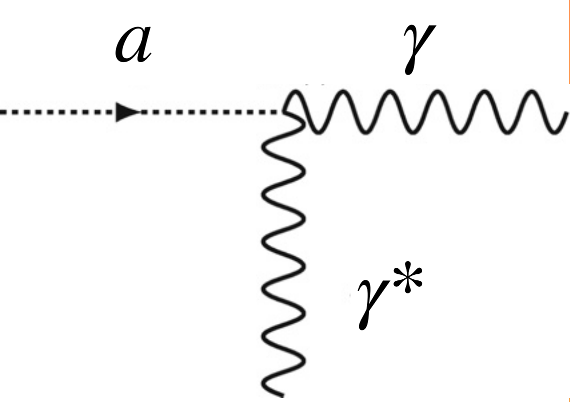
$$\mathscr{L}_{\text{int}} = - \chi F_{\mu\nu} X^{\mu\nu}$$



- Axions convert into photons in a cavity in a strong B-field.
- (Dark photon can converts without B-field.)
- The cavity enhances the signal when tuned to the photon freq.: $\nu = m_a c^2/h$.
  - Quality factor (Enhancement factor) $Q \sim 10^4$
- Need to scan the resonant frequency to cover wider axion mass range.
  - e.g. A rotating rod can change the resonant frequency.

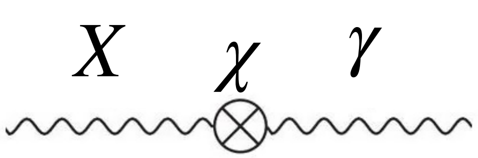
Successful Method: Resonant Cavity

Axion

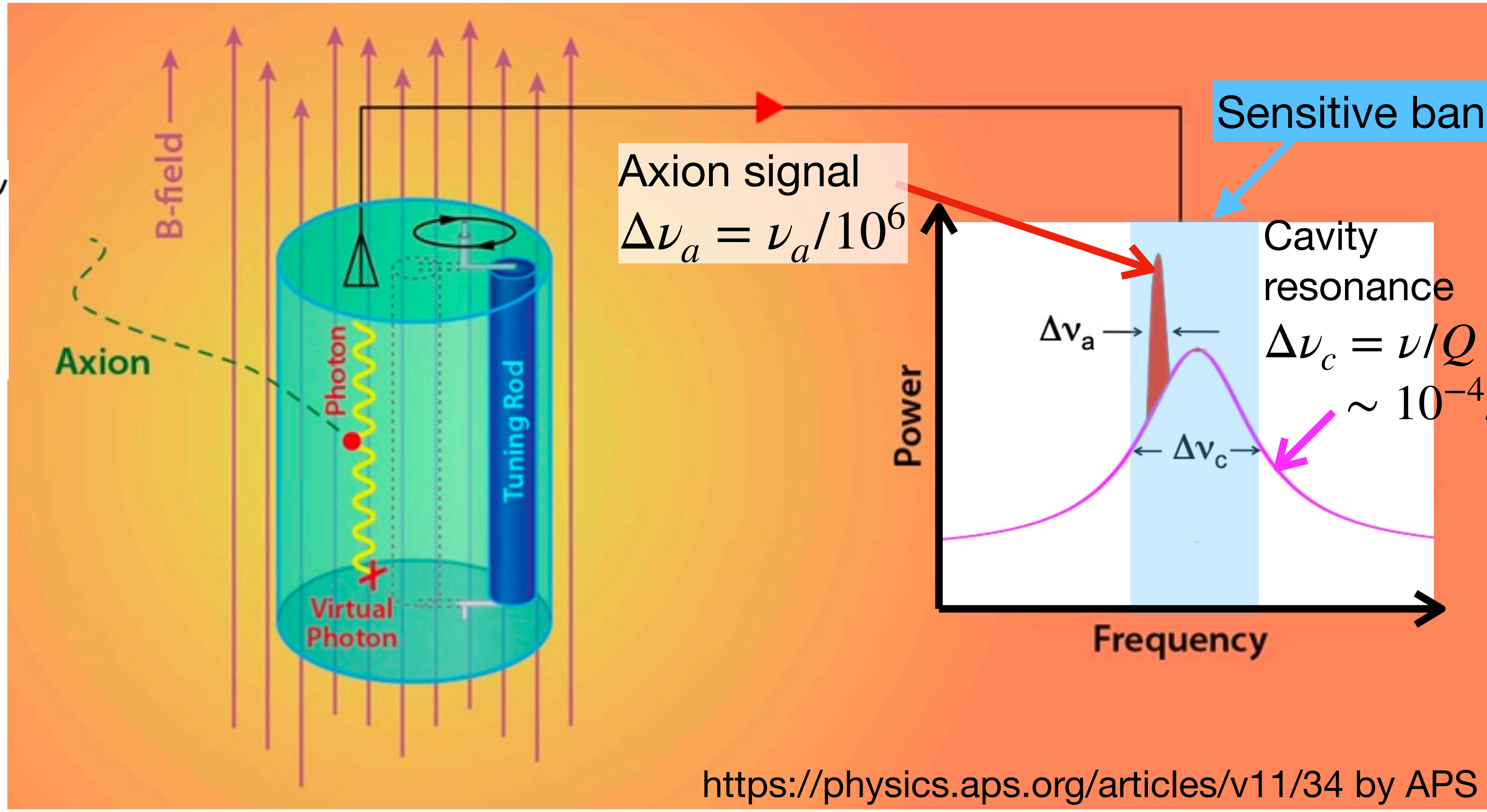


$$\mathscr{L} = \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$
$$= -g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

Dark photon



$$\mathscr{L}_{\text{int}} = -\chi F_{\mu\nu} X^{\mu\nu}$$

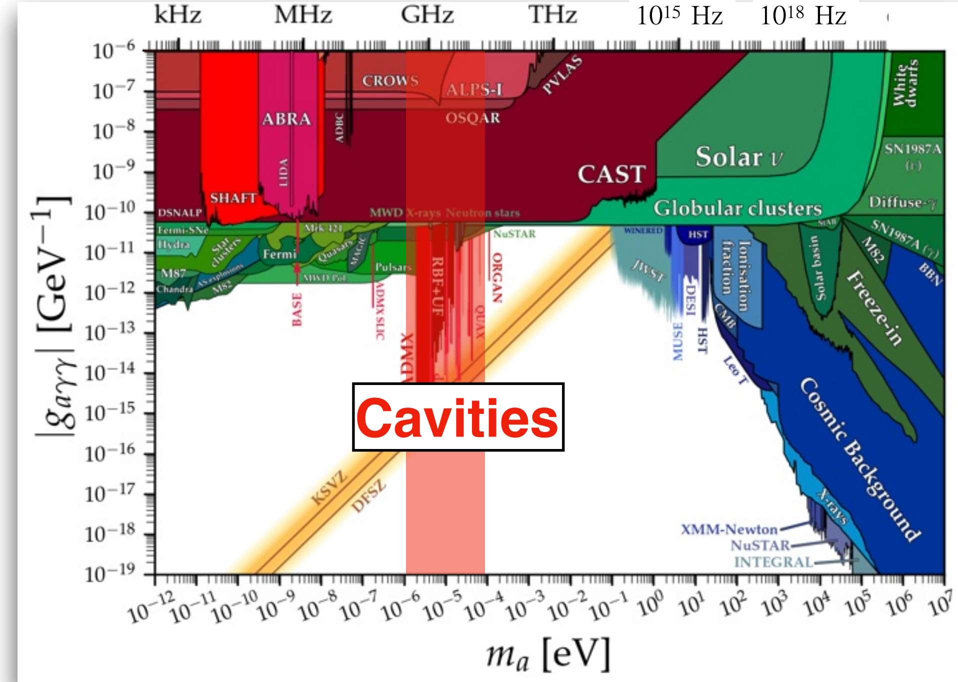


- Signal power $P_{\text{sig}} \propto g_{a\gamma\gamma} Q B^2 V C$
  - Q: Resonance quality factor, B: Magnetic field, V: Cavity volume, C: Form factor of cavity mode
- For **higher frequency** ($\gtrsim$10 GHz), this method is not good.
  - Making resonance needs fine structures due to shorter wavelength (<λ~1 cm)
  - Volume V should be decreased scaled by the wavelength.
  - This method is suitable for around 0.1 GHz—10 GHz.

ADMX

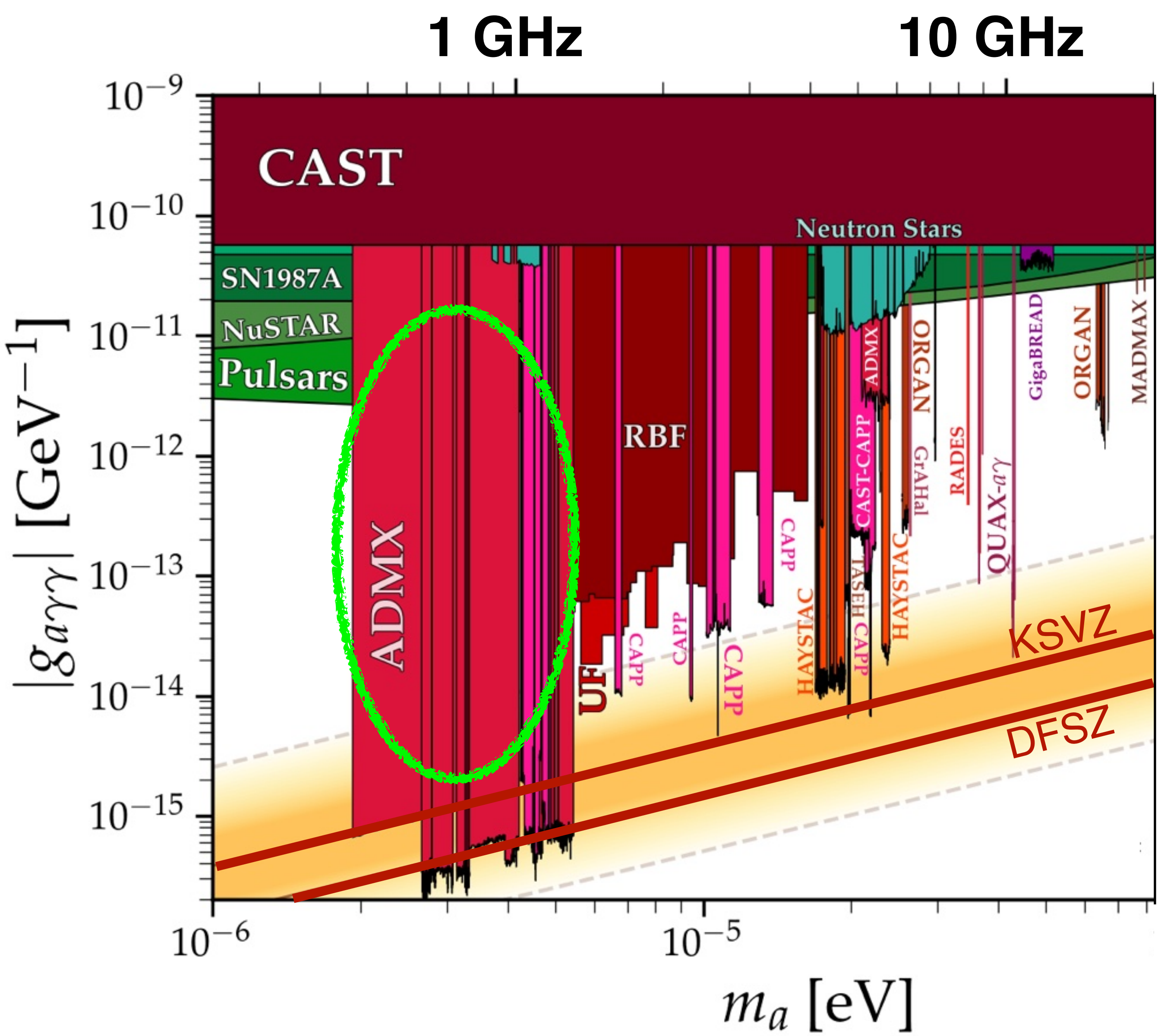
Phys. Rev. Lett. 135, 191001 (2025)

The most successful cavity-based experiment to date



- V = 100 L, B=8 T
- **Quantum amplifier** is used (JPA, Josephson Parametric Amplifier) to achieve low noise $T_{\rm sys} \sim 0.6\,\mathrm{K}$.

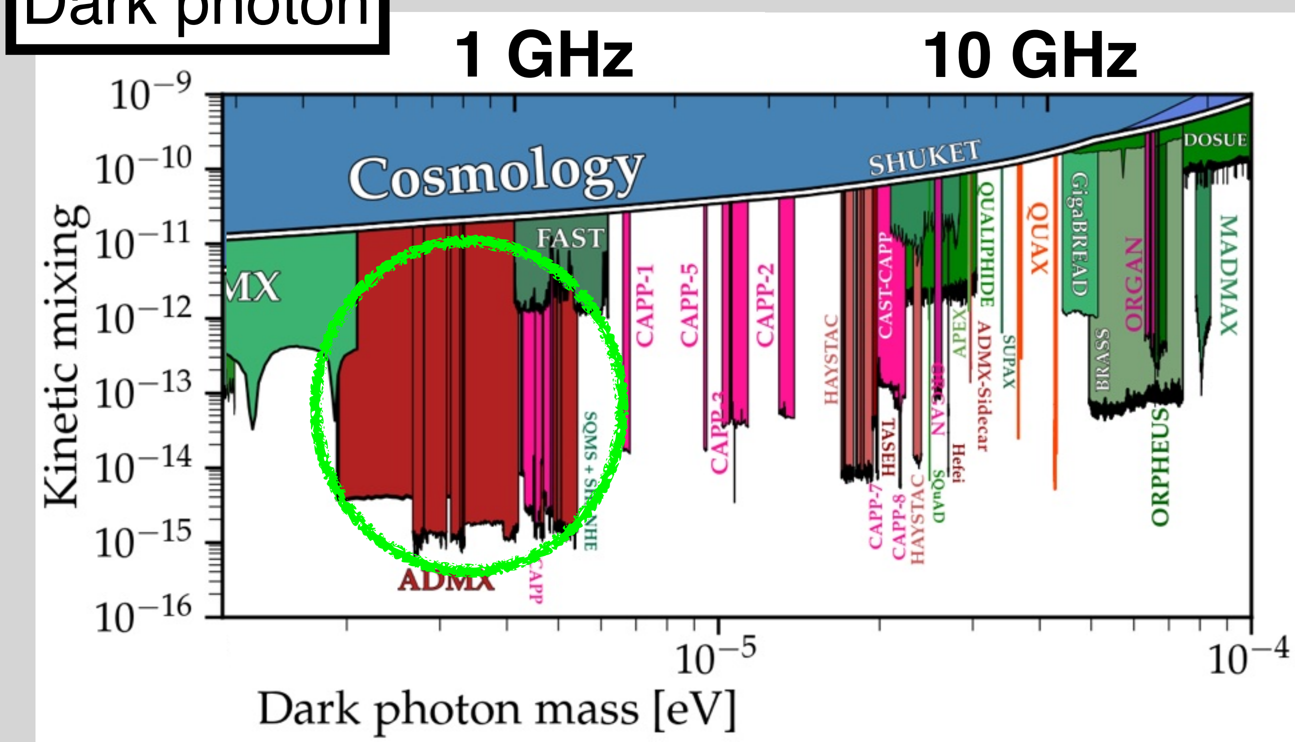
Axion



Reached QCD axion

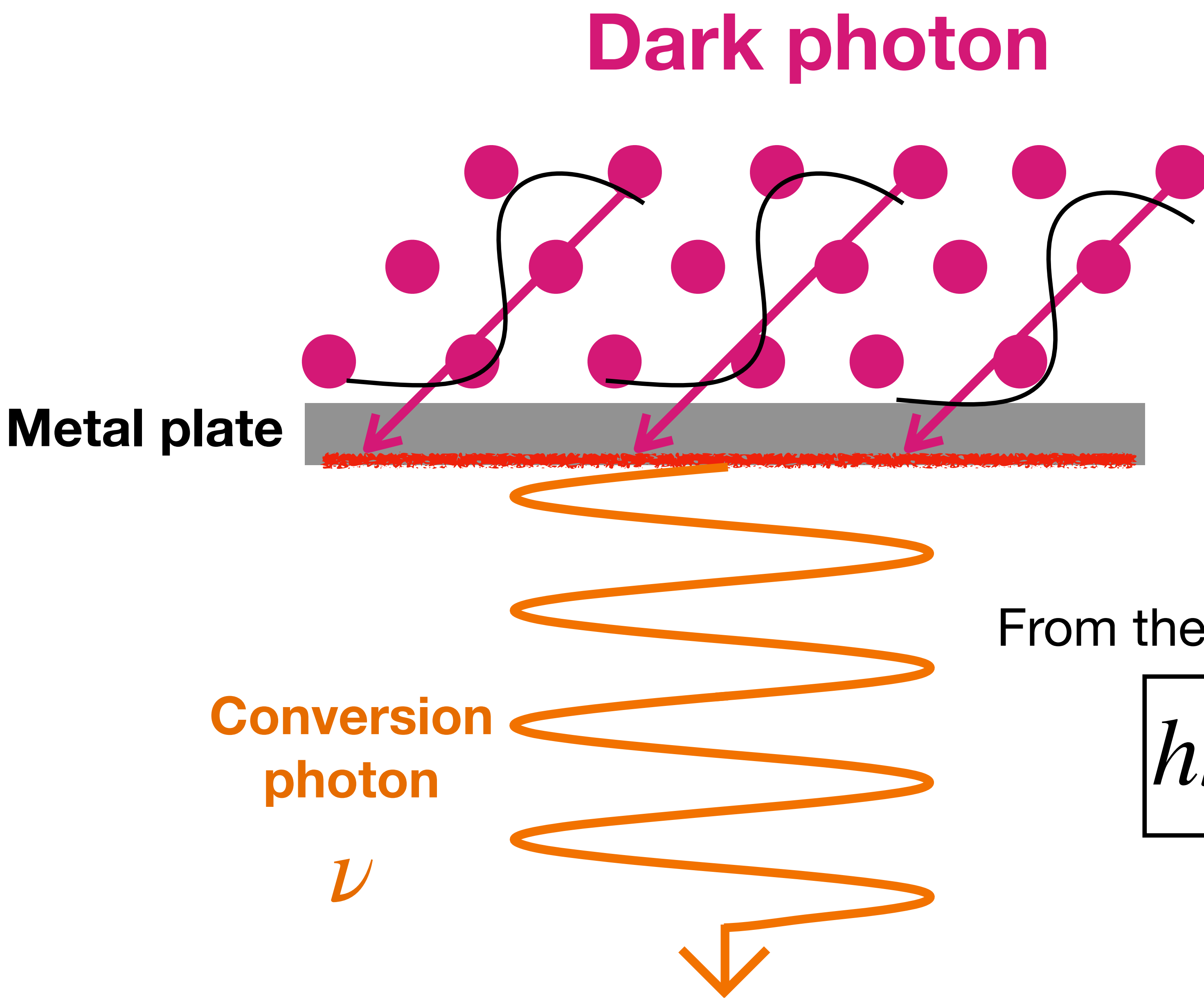
in 0.65~1.3 GHz (⇔ 2.7~5.4 μeV)

Dark photon



Dish Antenna Method

DP conversion to photon



$$\frac{\chi}{2} F_{\mu\nu} \tilde{X}^{\mu\nu}$$

$\tilde{\chi}_{\mu\nu}$: Field strength of dark photon

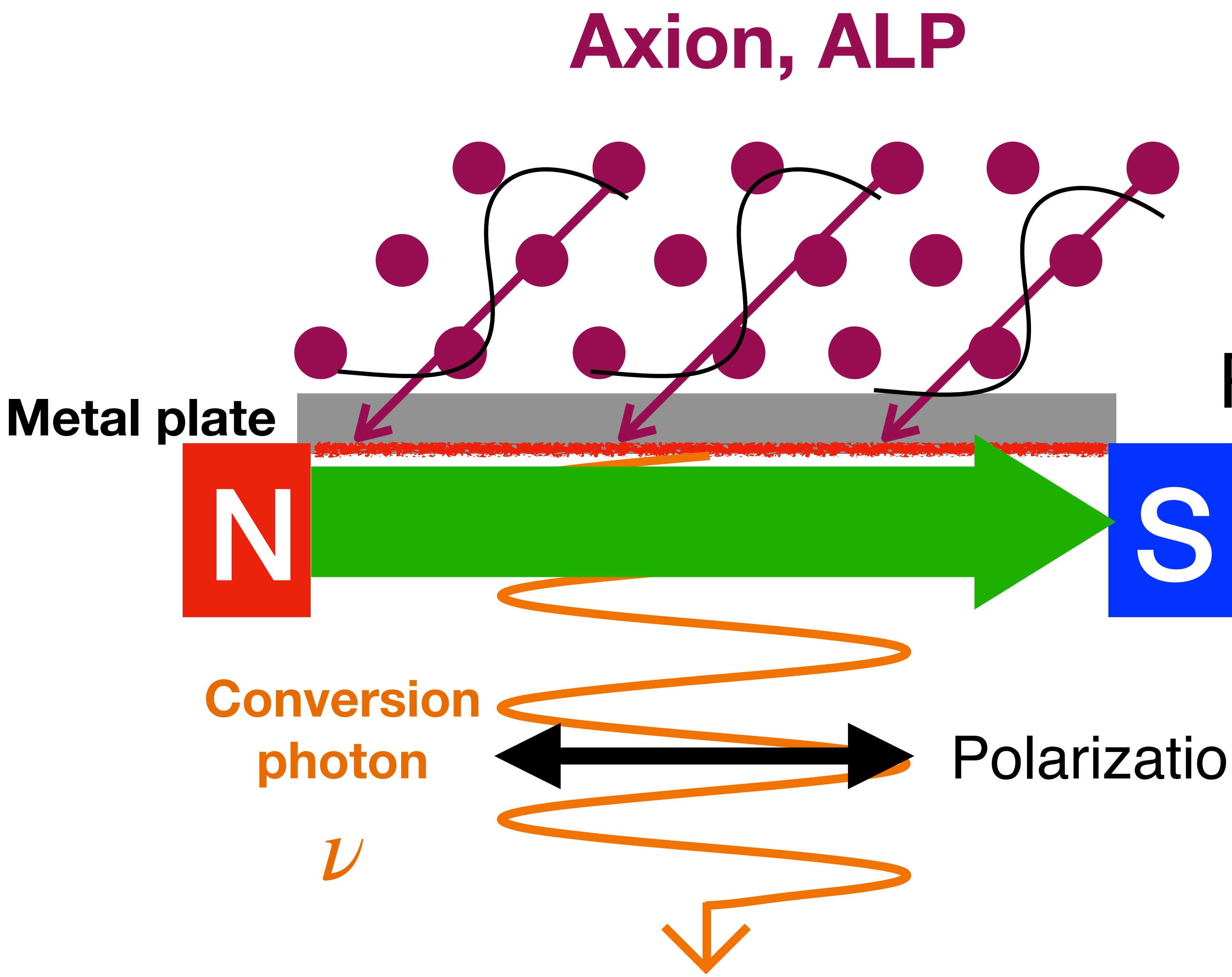
$F_{\mu\nu}$: Field strength of EM field

From the energy conservation:

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

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

Axion conversion to photon



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

Require a **magnetic field**

Polarization is parallel to the B-field.

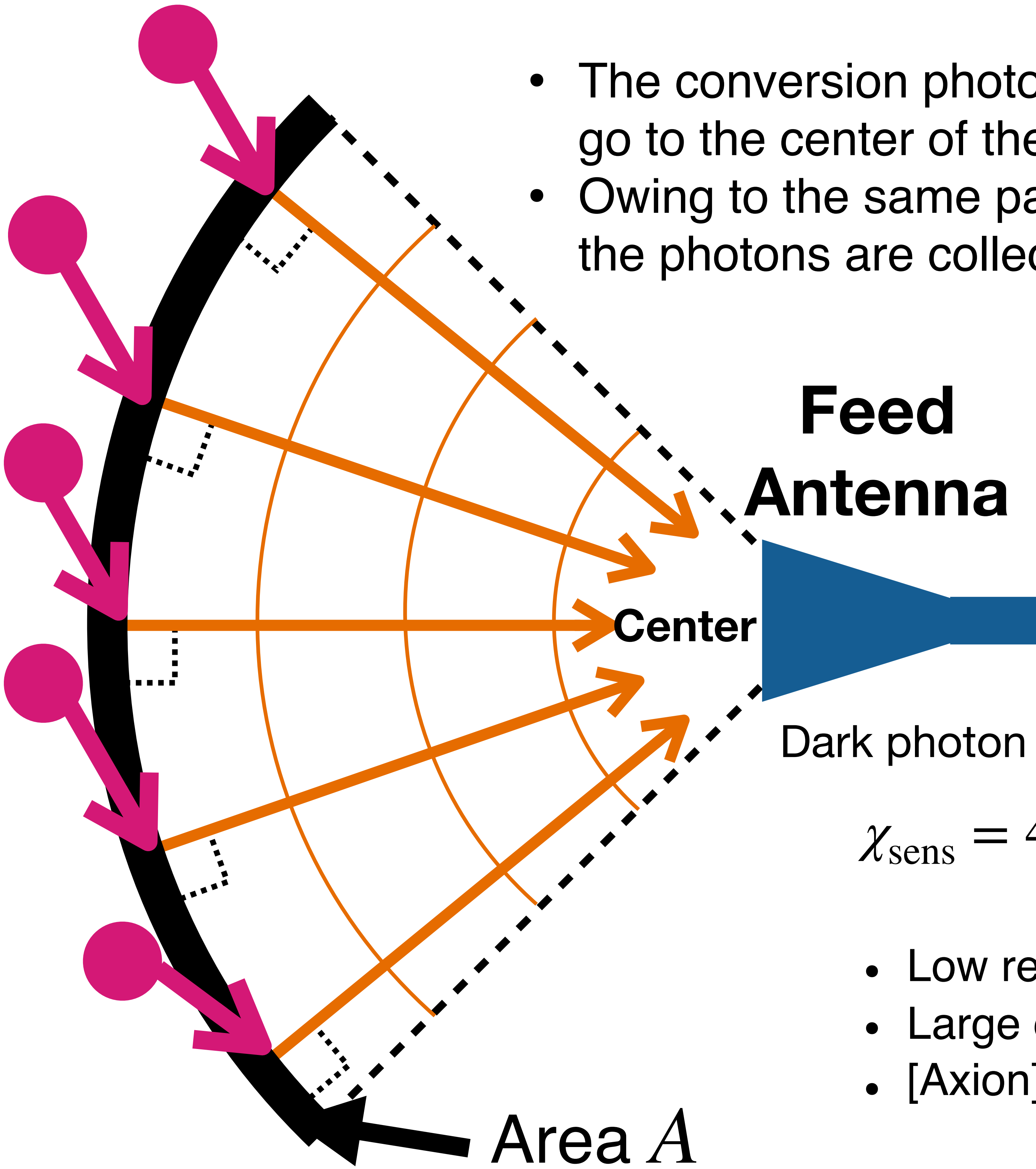
Same as in DP case

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

(Spherical) Dish Antenna Search

D. Horns et al, JCAP04 (2013) 016

- The conversion photons emitted on the spherical surface go to the center of the sphere.
- Owing to the same path length,
  the photons are collected coherently, giving a stronger signal.



Dark photon sensitivity:

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

- Low receiver noise ($P_{\rm noise}$)
- Large conversion area (A)
- [Axion] Stronger magnetic field B ($g_{a\gamma\gamma} \propto 1/B_{||}$)

Experiments & Approaches

1. DOSUE-RR

The simplest experiment for dark photon

2. BREAD

Increase conversion area A

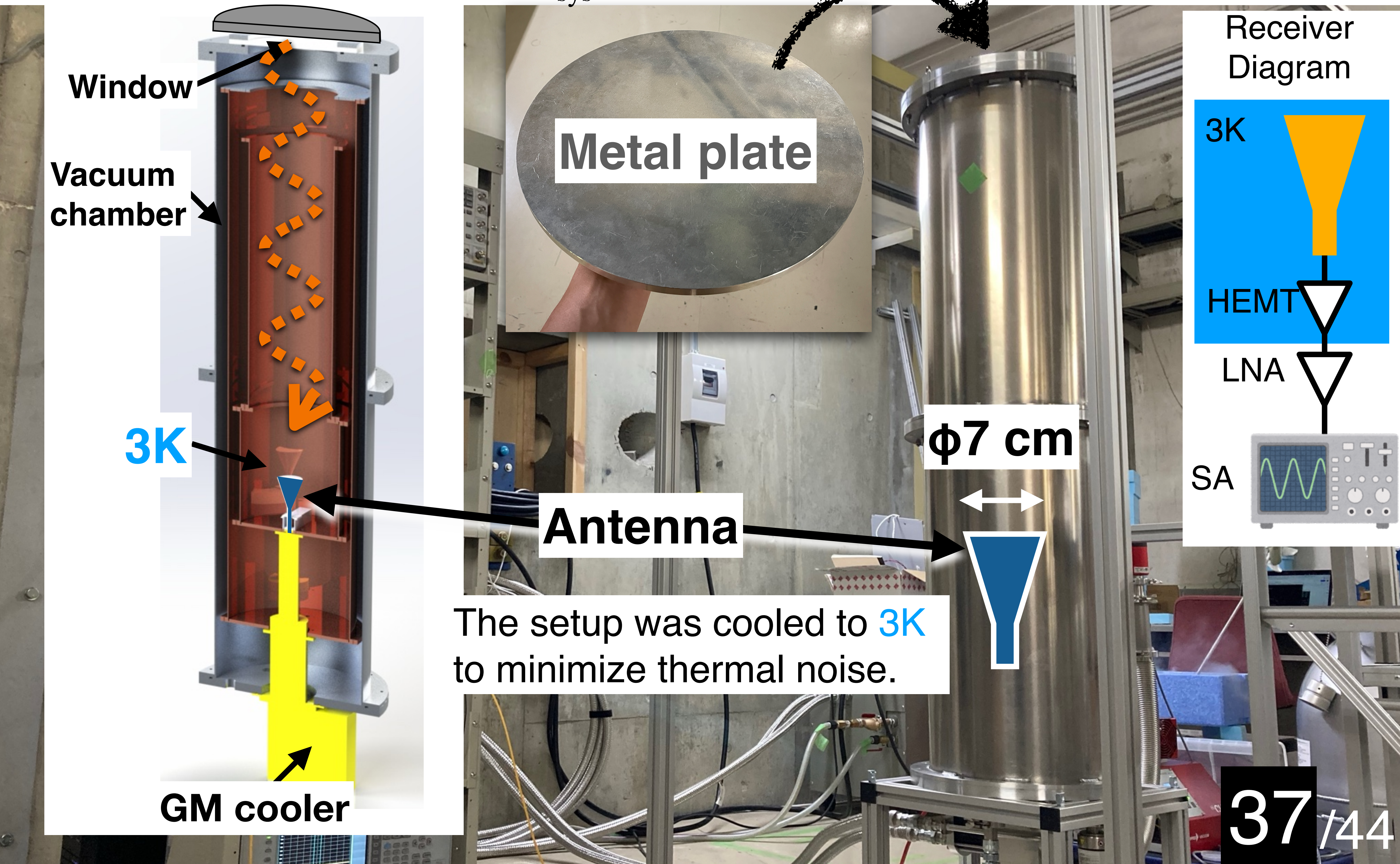
3. MADMAX

Get signal enhancement as in cavity method
(get an enhancement like Q-factor in cavity method.)

DOSUE-RR in Japan

The simplest search in dish antenna method only for ***dark photon***

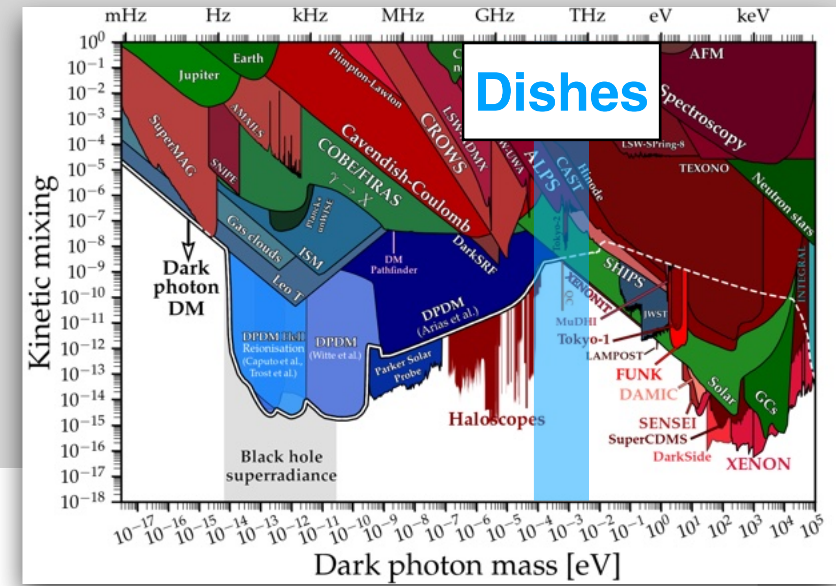
Uses a cryogenic HEMT amplifier ($T_{\rm sys} \approx 70\,{\rm K}$)

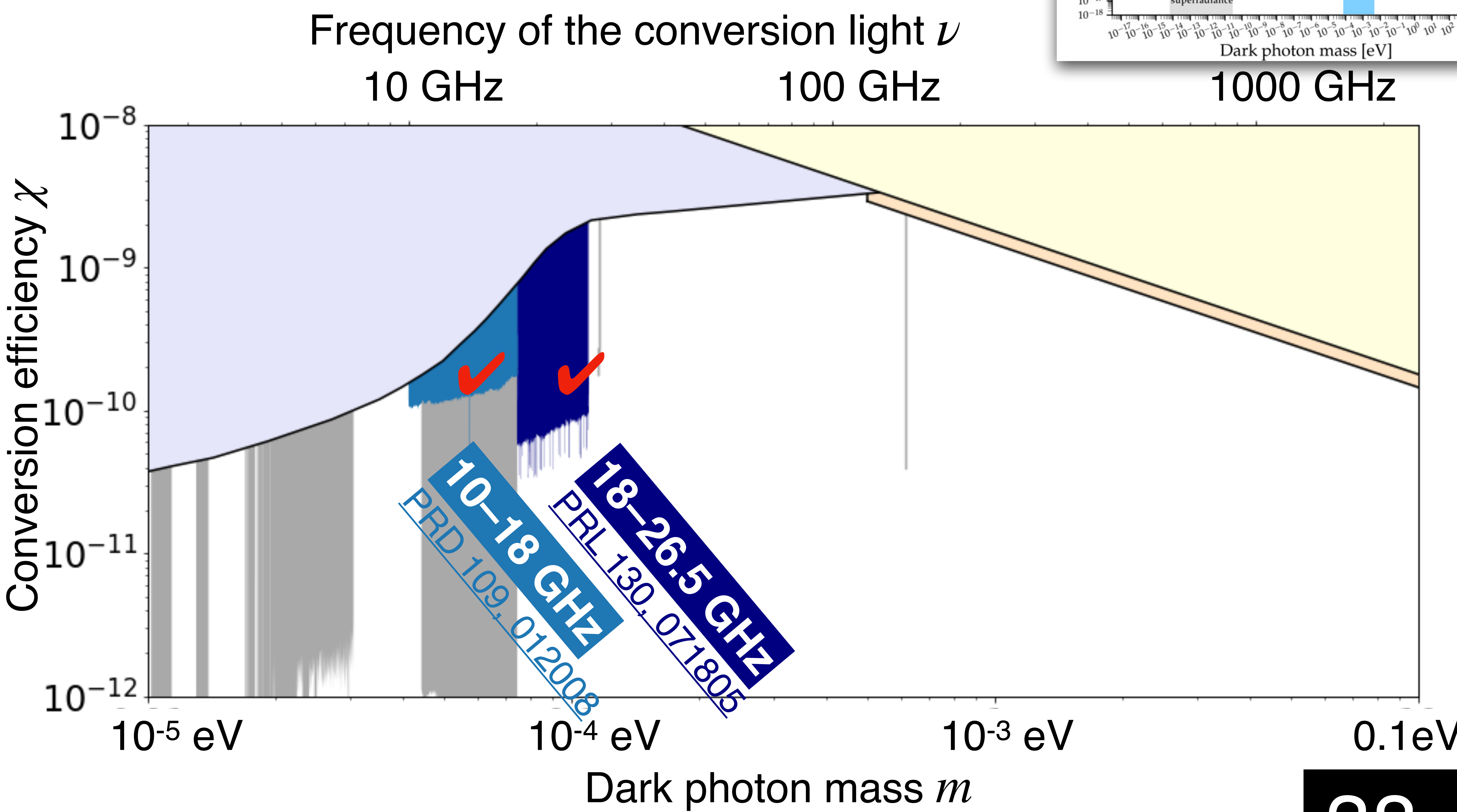


DOSUE-RR in Japan

Dark photon

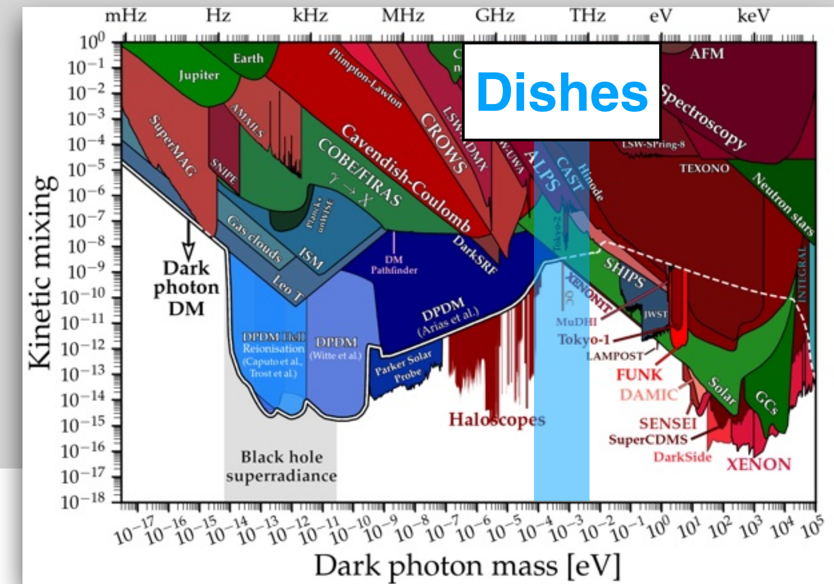
We are focusing on only dark photon now.

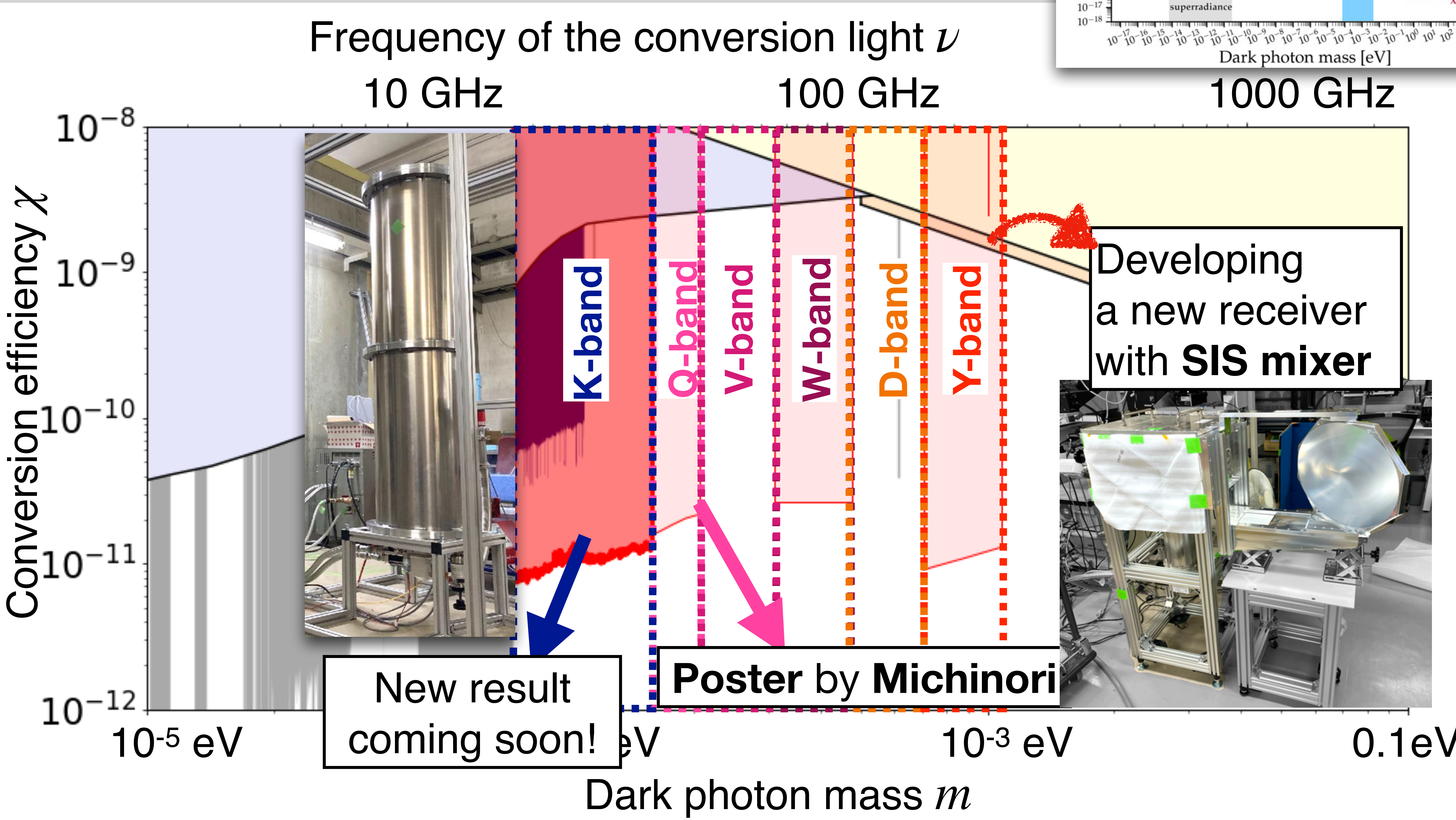




DOSUE-RR in Japan

Dark photon We are focusing on only dark photon now.





Now expanding to wider mass range!!

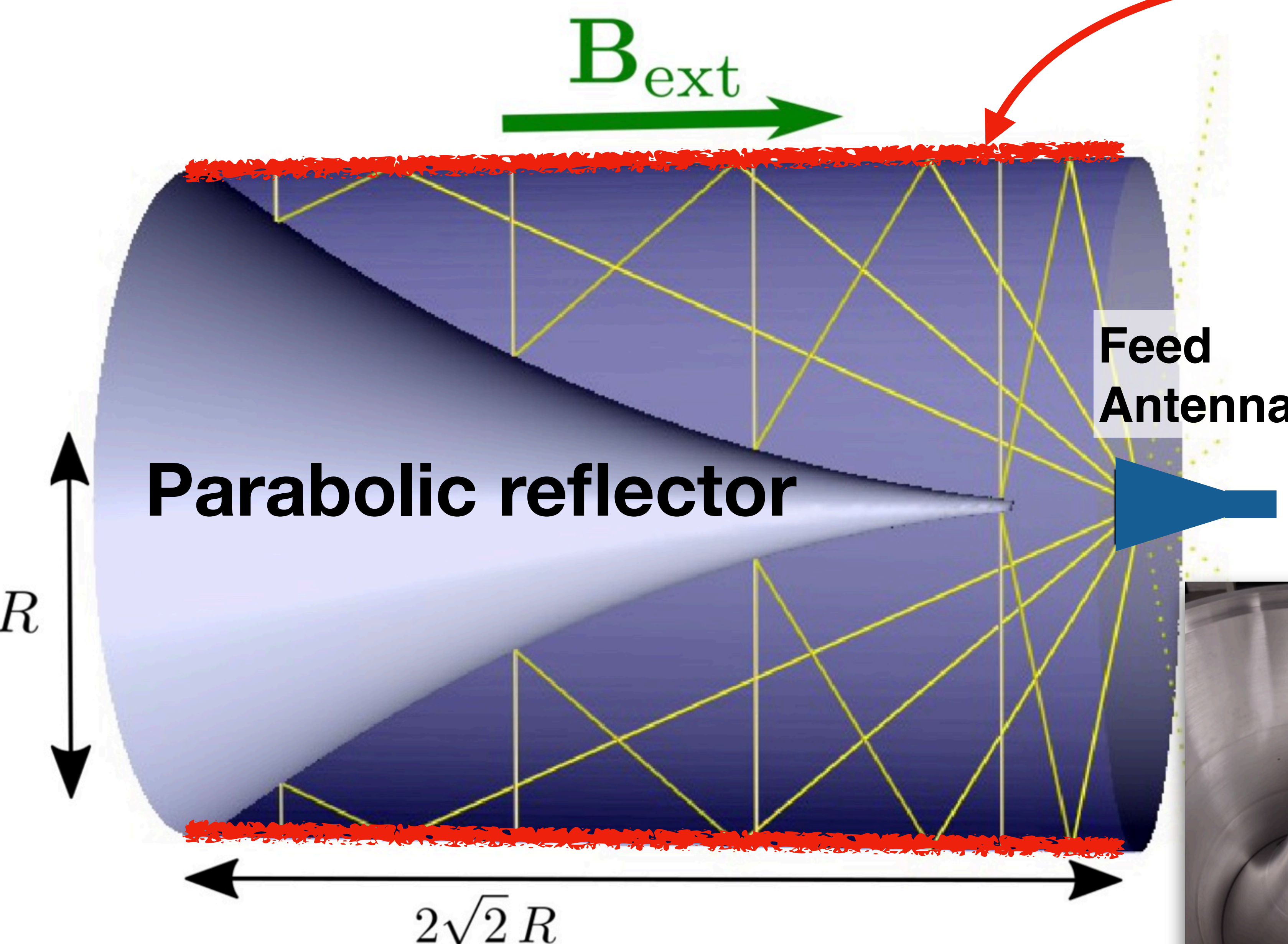
BREAD

BREAD COLLABORATION

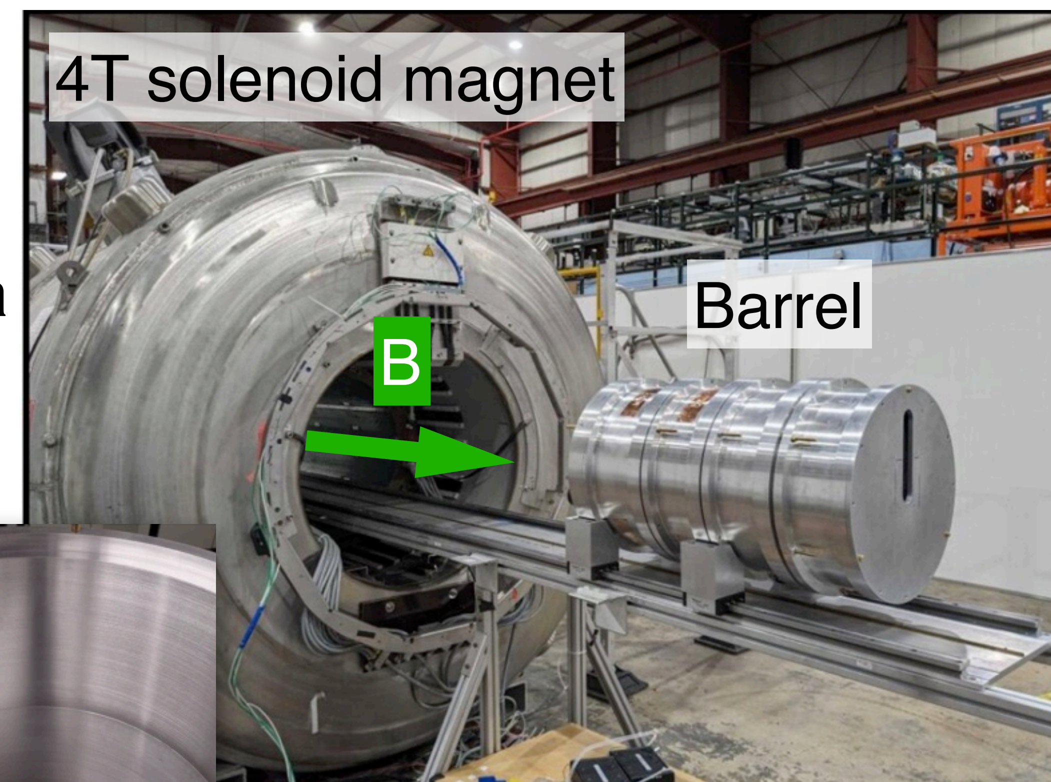
How can we increase the surface area? → Parabolic reflector

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

Cylindrical barrel



With solenoid magnet, it can search for axion.



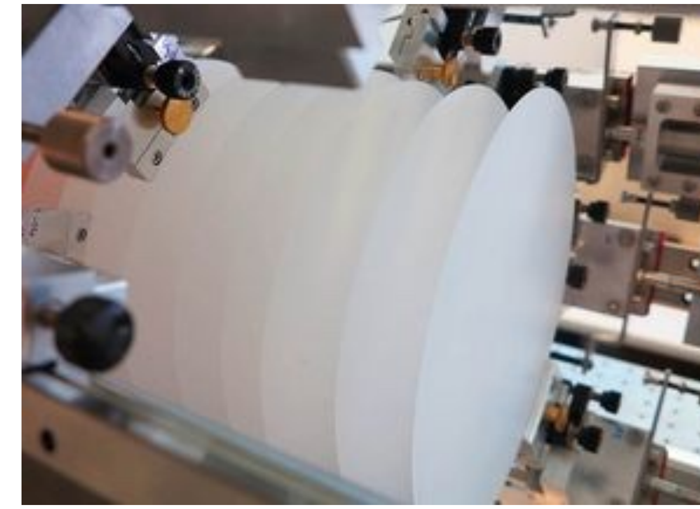
MADMAX

How can we enhance the signal like a cavity? → Dielectric mirrors

Conversion surface: Surfaces of dielectric disks

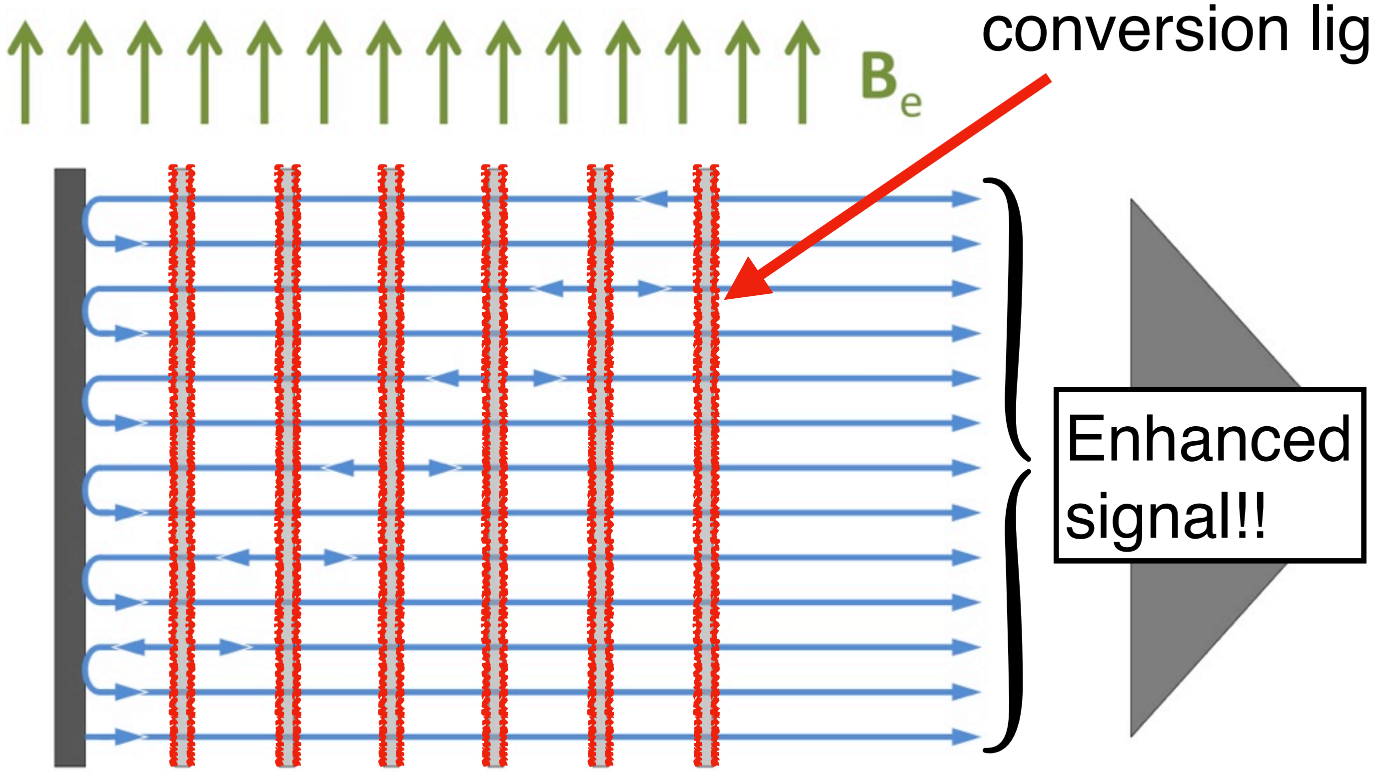
Signal enhancement principle:

If set the space properly,
all of the emission phases are matched,
and the signals from all surfaces add coherently.



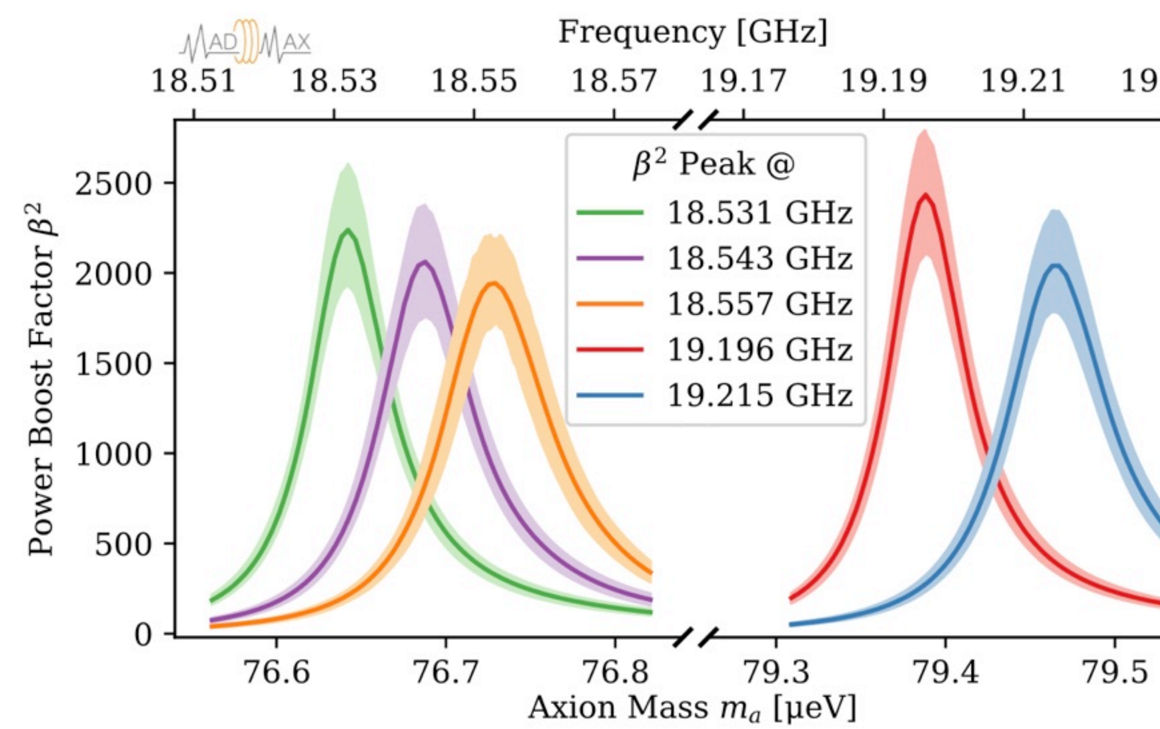
Dielectric disks

All surfaces emits
conversion lights from axion/dark photon.



Phys. Rev. Lett. 118, 091801 (2017)

Signal enhancement factor ~ 2000



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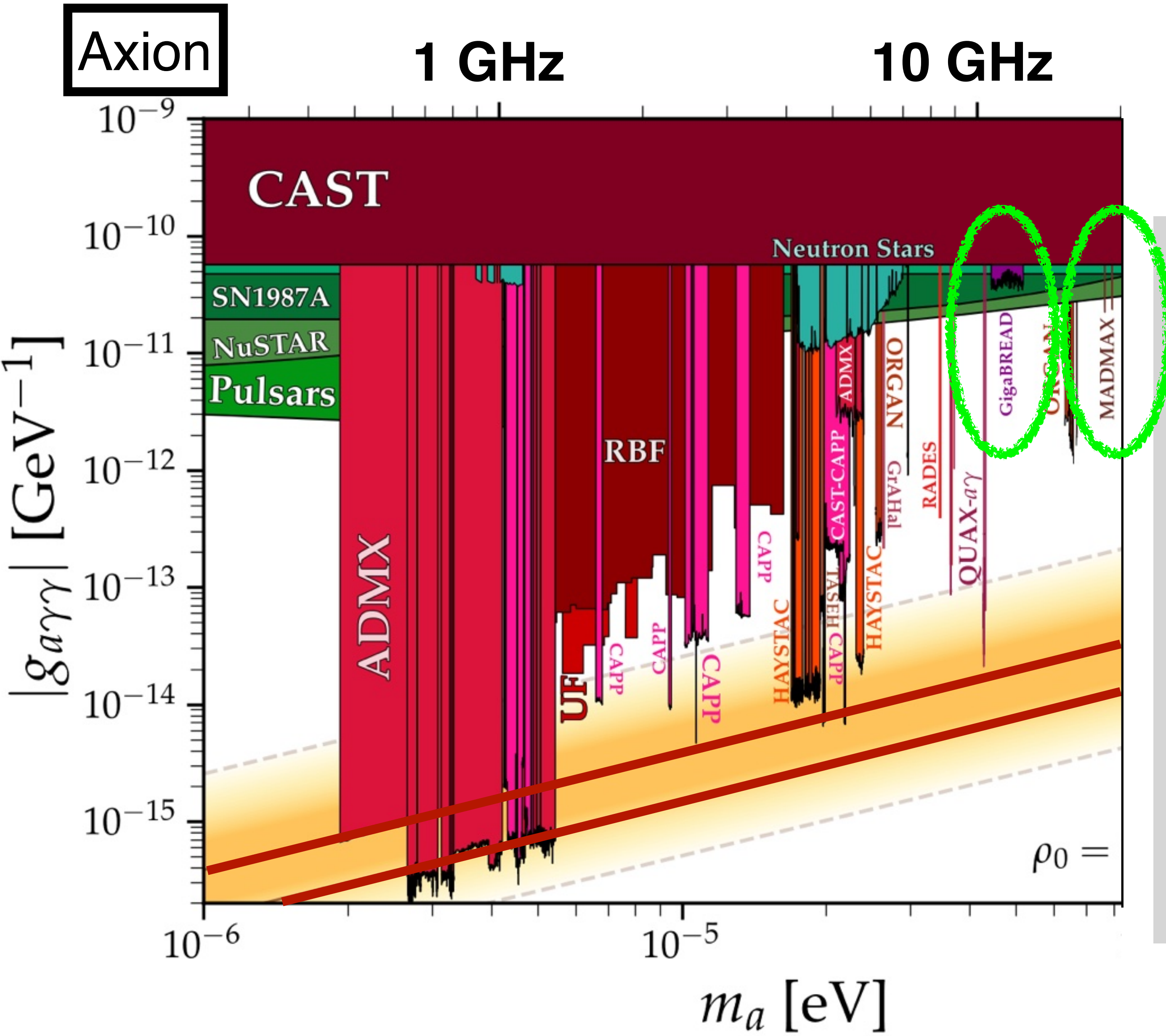
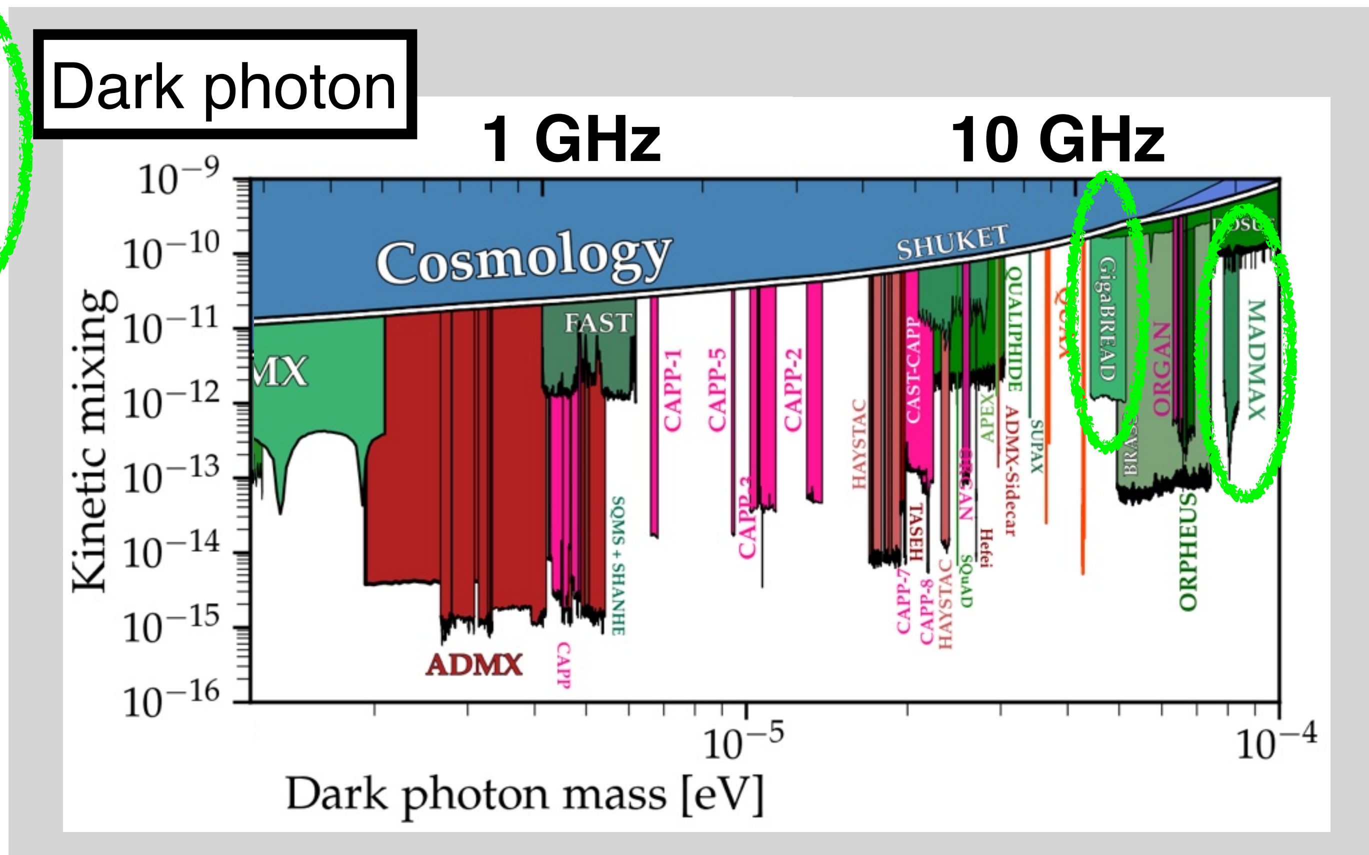
BREAD & MADMAX first results

- Both use room temperature receivers.

- MADMAX:
  - Axion: high enhancement factor
    → narrow sensitive band
  - Dark photon: mild enhancement factor
    → wider sensitive band



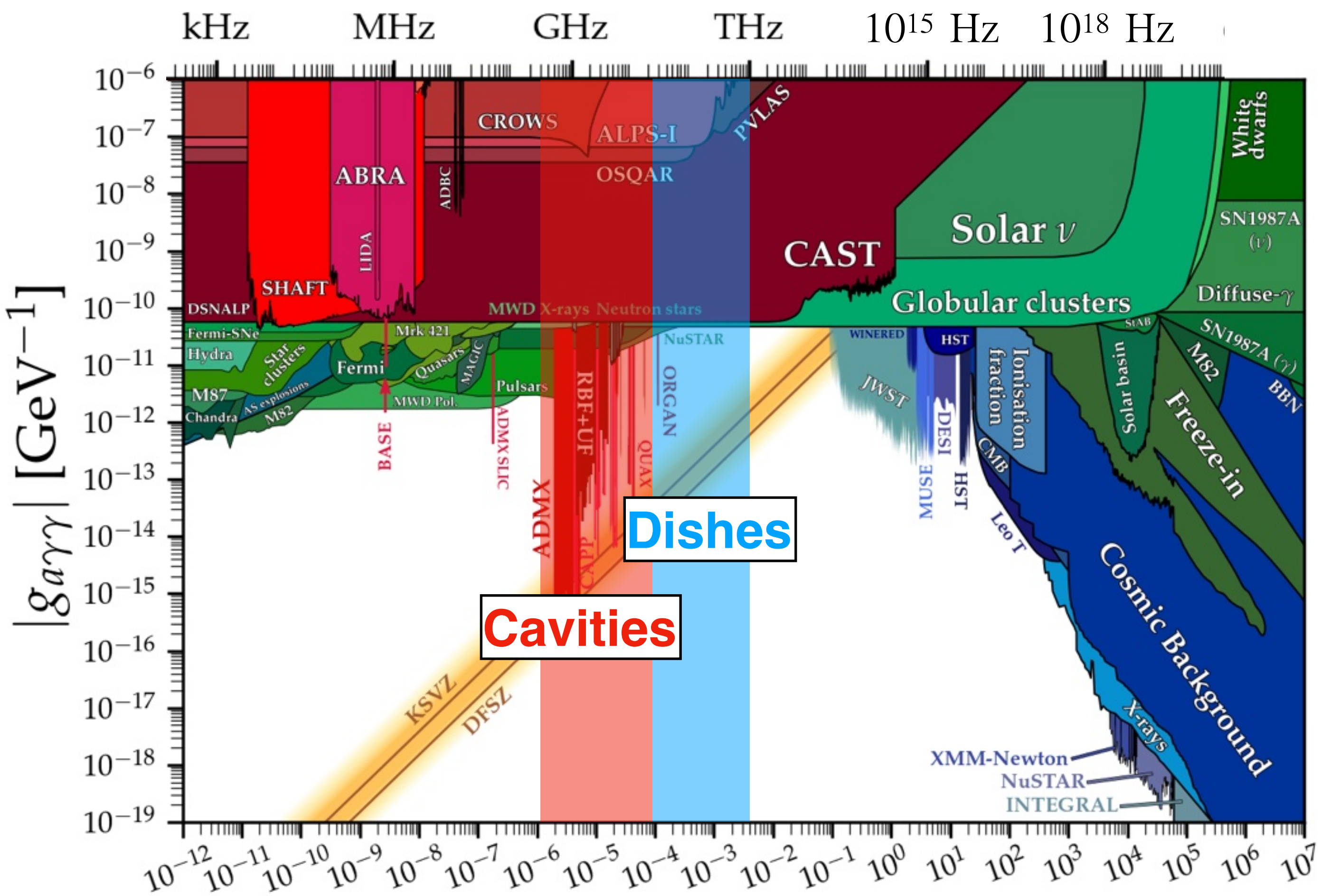


- BREAD will upgrade with 9 T magnet (from 4T) & a quantum amplifier.
- MADMAX will upgrade with 9T magnet (from 1T), larger disks, cryogenic receiver.

Current status for axion / dark photon search

Axion + ALP
(photon coupling only)

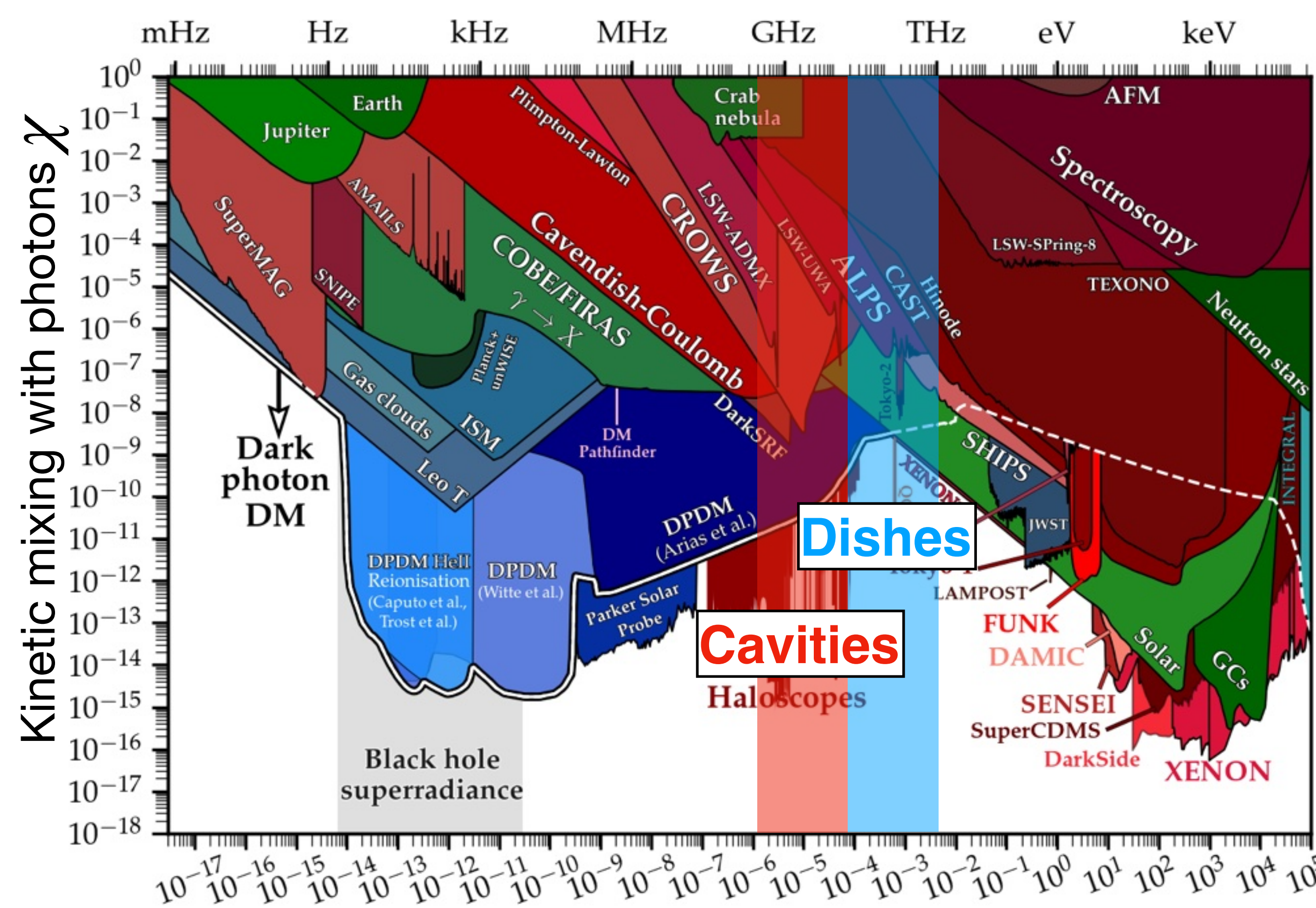
Frequency of conversion photon



Axion/ALP mass [eV]

Dark photon

Frequency of conversion photon

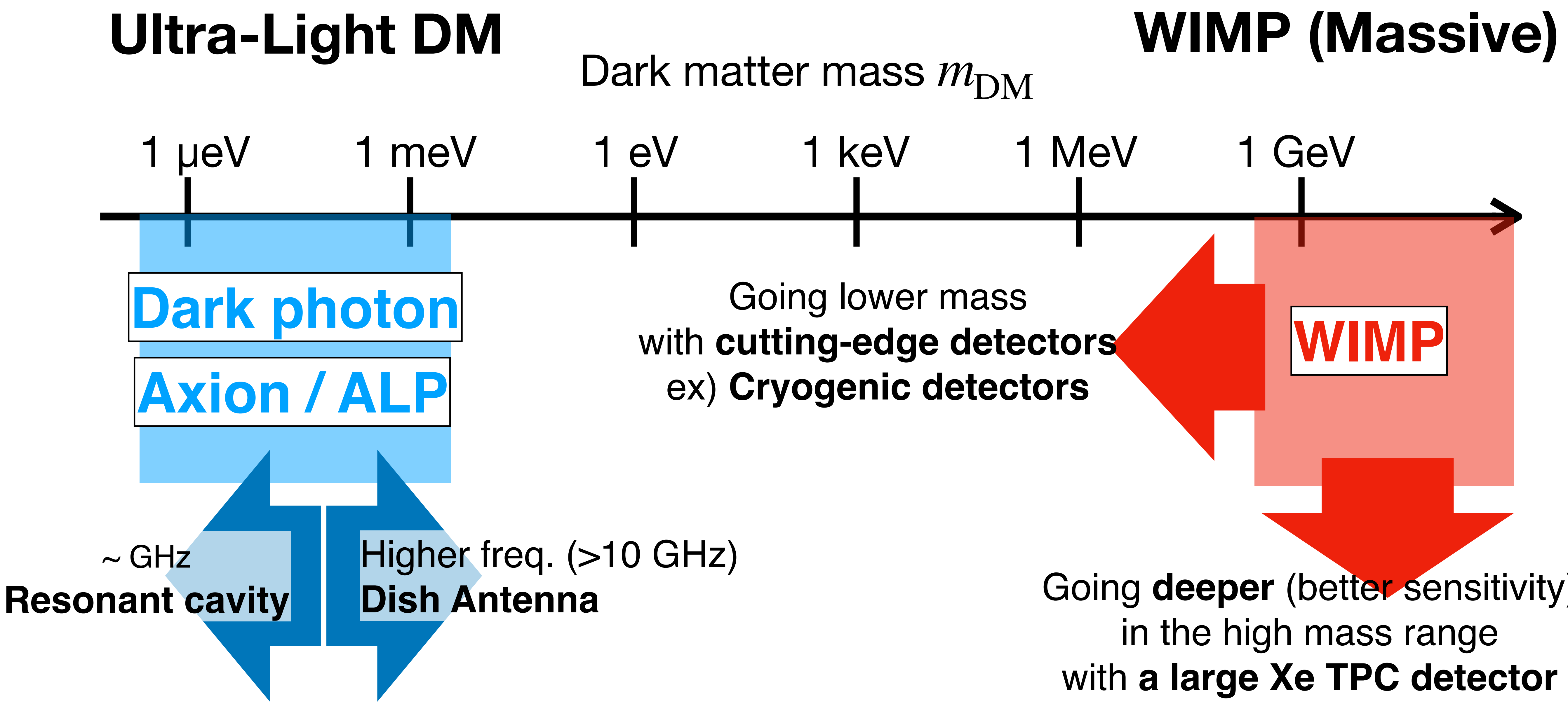


Dark photon mass [eV]

Experiments

Cavities: **ADMX, CAPP, HAYSTACK…**
Dishes: **DOSUE-RR, BREAD, MADMAX…**

Wave-like v.s. Particle-like



Which approach would you bet on?

Finally, several techniques are shared with CMB experiment.
There are potential for technology synergy between DM search and CMB.