Search for the Cosmic Axion Background with ADMX

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Tatsumi Nitta (The University of Tokyo, ICEPP)

18th Patras Workshop on Axions, WIMPs and WISPs

~~@ University of Rijeka, Croatia~~ @ University of Trieste, Italy

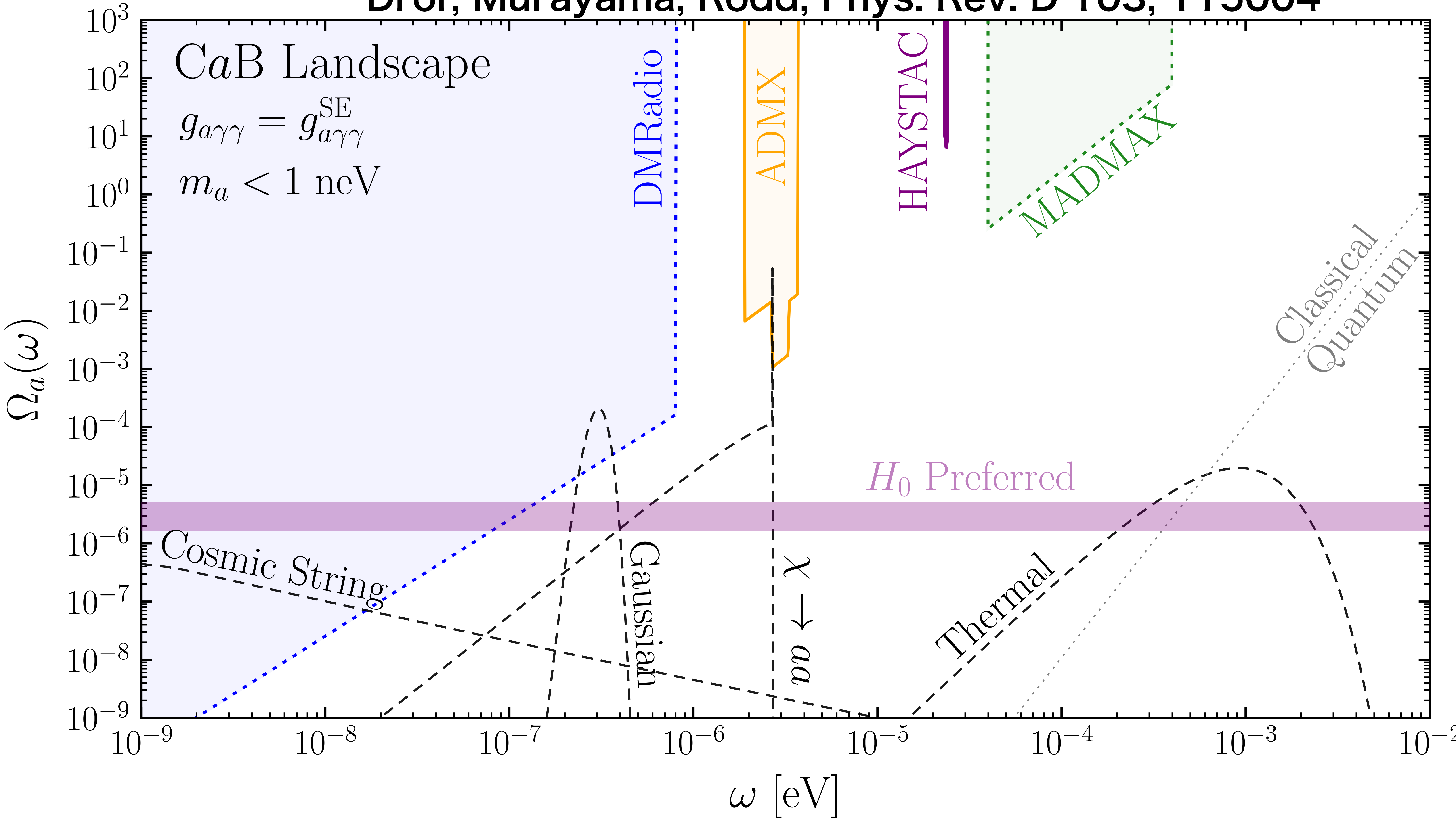
Cosmic axion Background (CaB)

CaB: relativistic species of axions in Universe

<u>CaB sources</u>

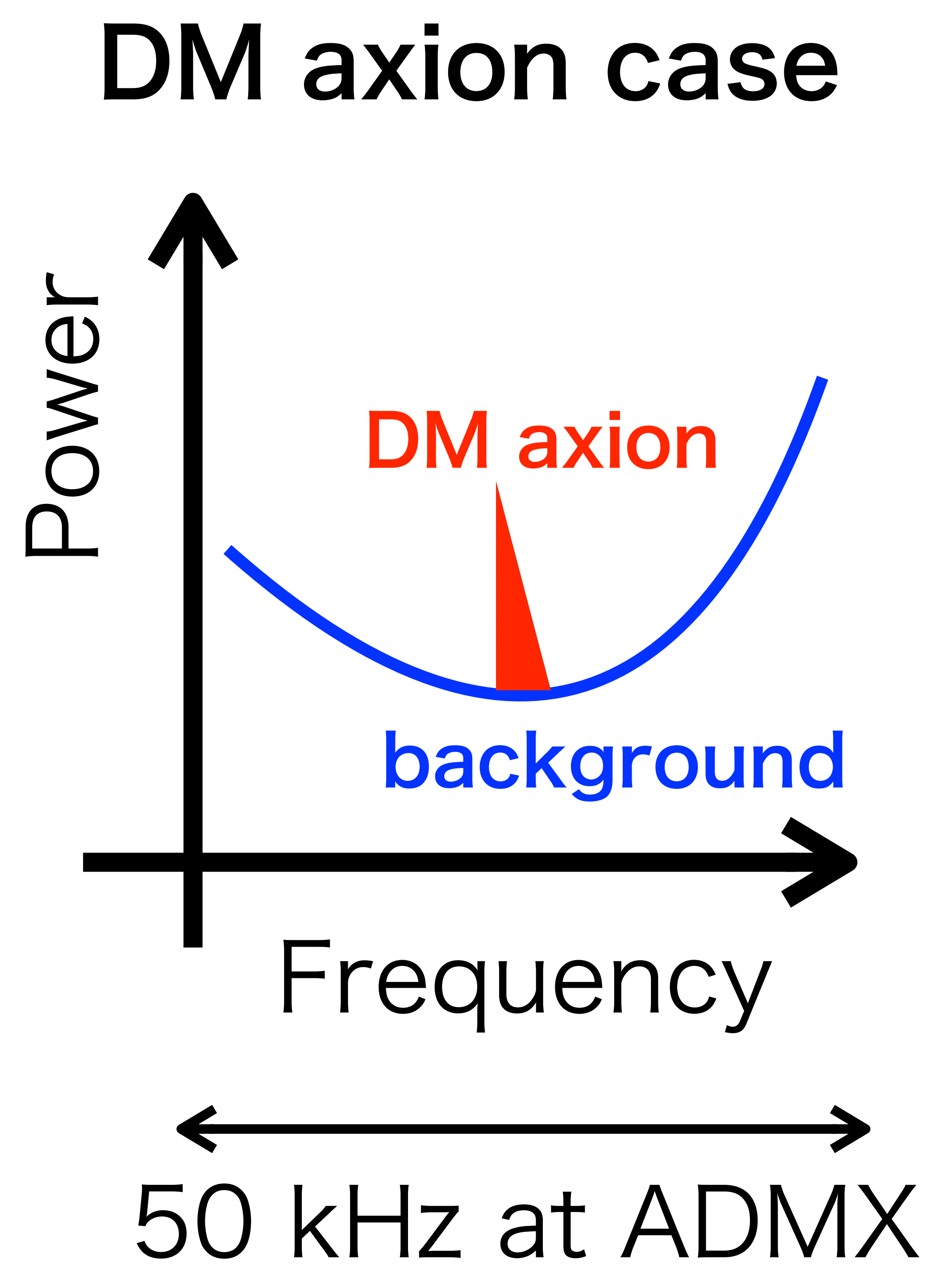
- Thermal production
- Decay of cosmic string
- Dark matter decay
- …

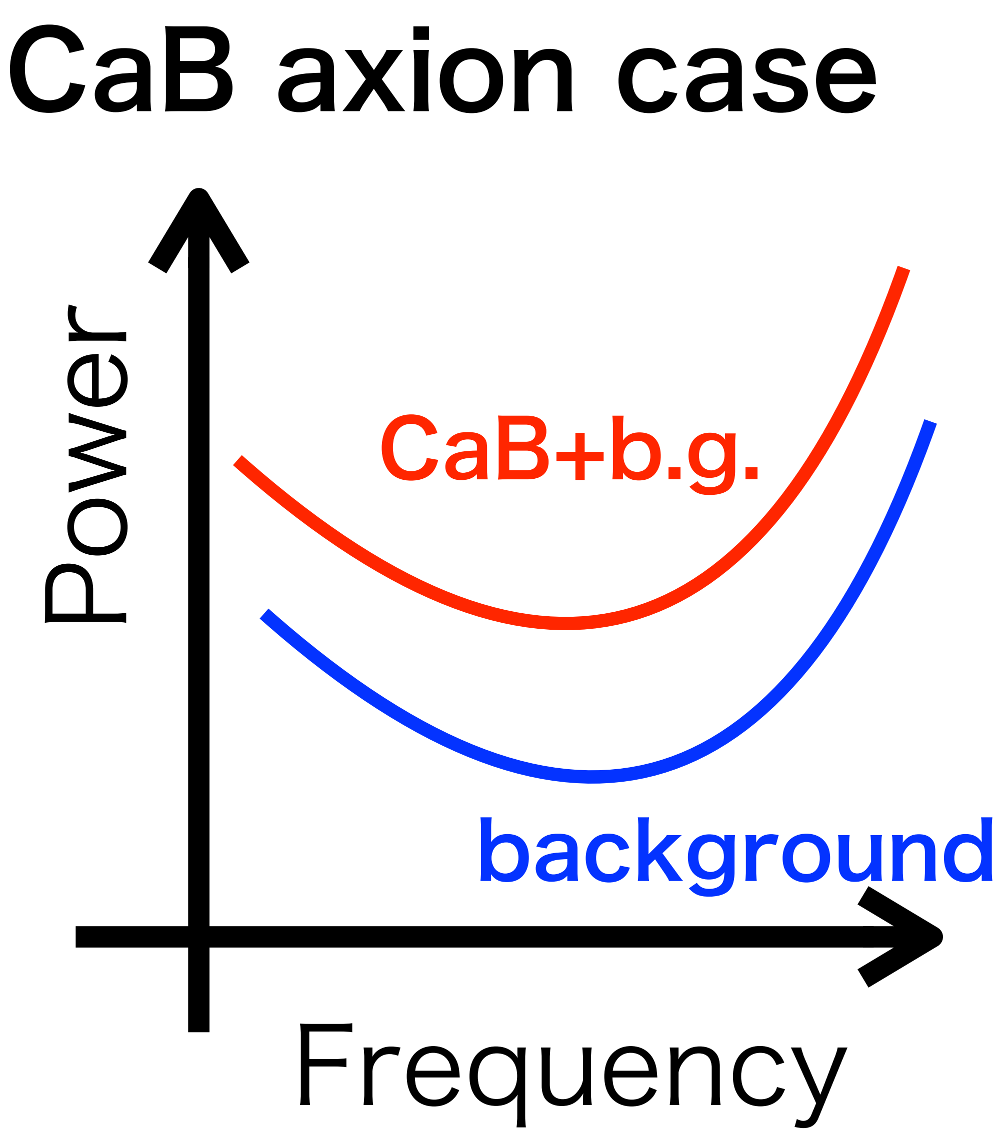
Dror, Murayama, Rodd, Phys. Rev. D 103, 115004



No dedicated CaB search was performed ever
→ Plenty possibility of discovery of new physics

CaB is broad

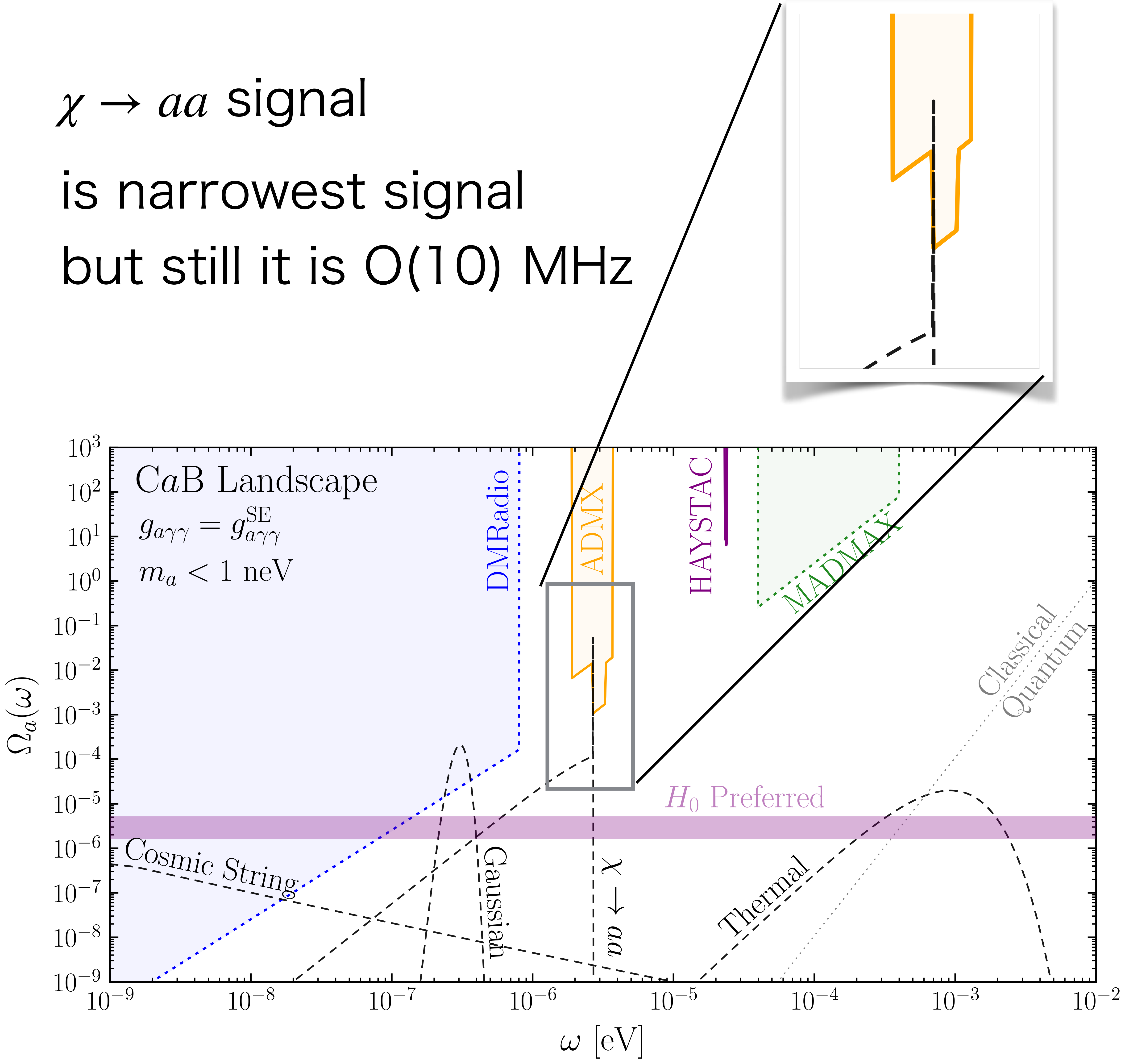




$\chi \to aa$ signal

is narrowest signal

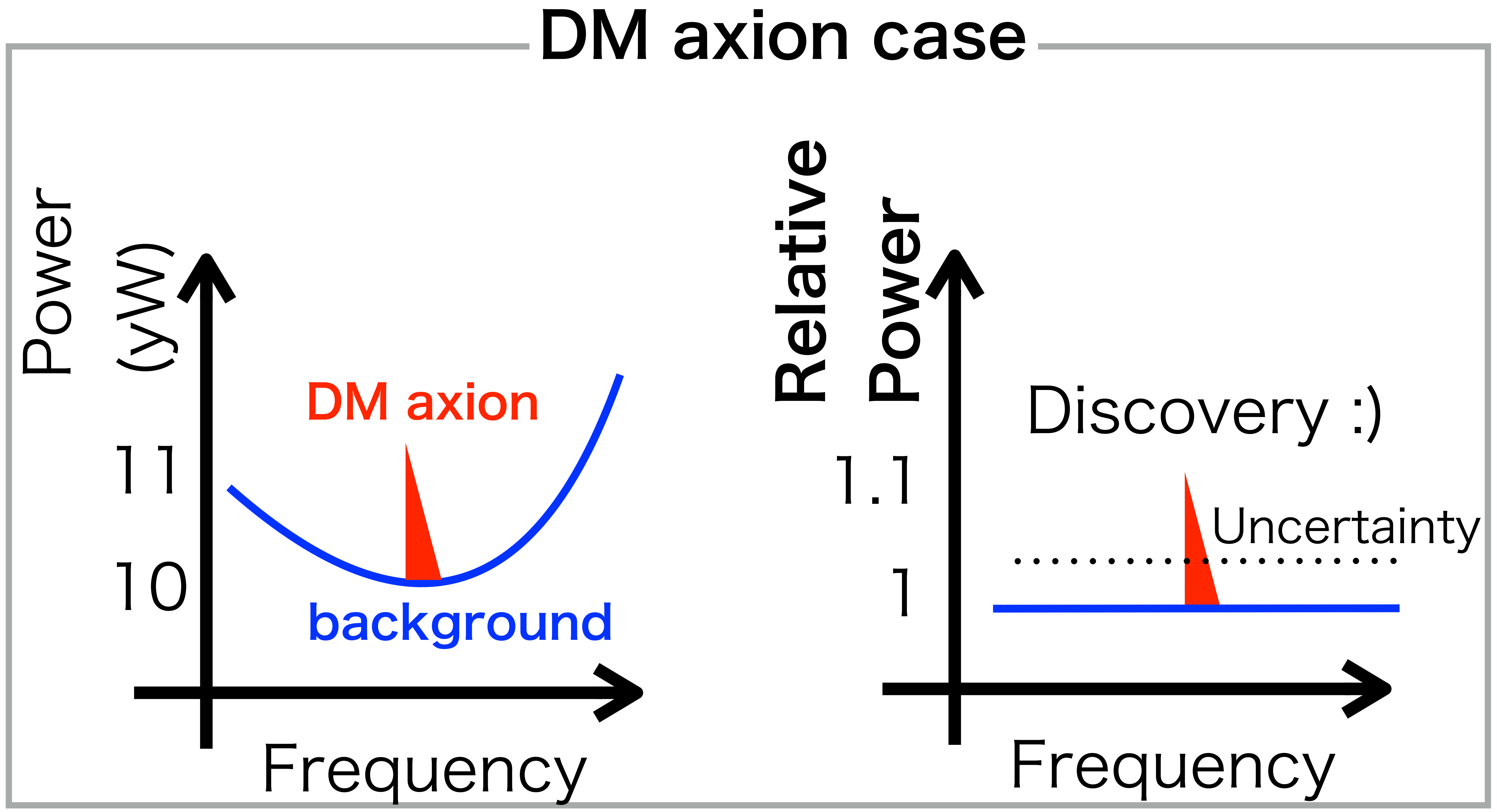
but still it is O(10) MHz

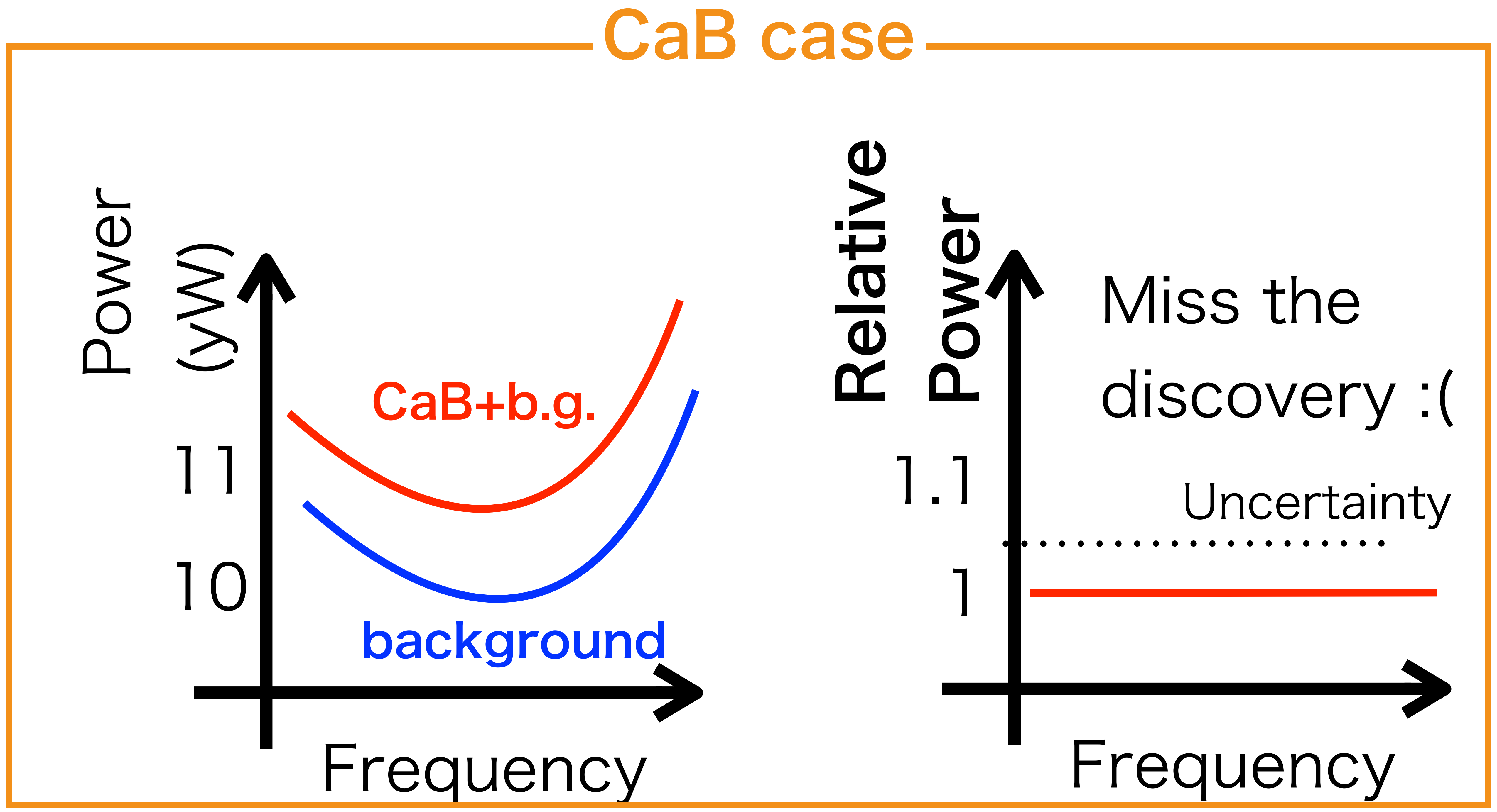


Broadband signal in standard analysis

ADMX doesn't monitor absolute power level

→ Only sensitive to signals much narrower than the digitization window





Standard analysis completely level off the CaB signal

→ **Need new analysis technique** (or new absolute power detector)

Equation of Motion

maxwell's equation

$$\nabla \cdot \mathbf{E} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J}$$

including axion

$$\nabla \cdot \mathbf{E} = \rho - \boxed{g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a}$$

CaB can induce this term

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} + \boxed{g_{a\gamma\gamma}(\mathbf{B}\partial_t a} - \mathbf{E} \times \nabla a)$$

For detecting DM axion

$g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$ **is a key to explore CaB**

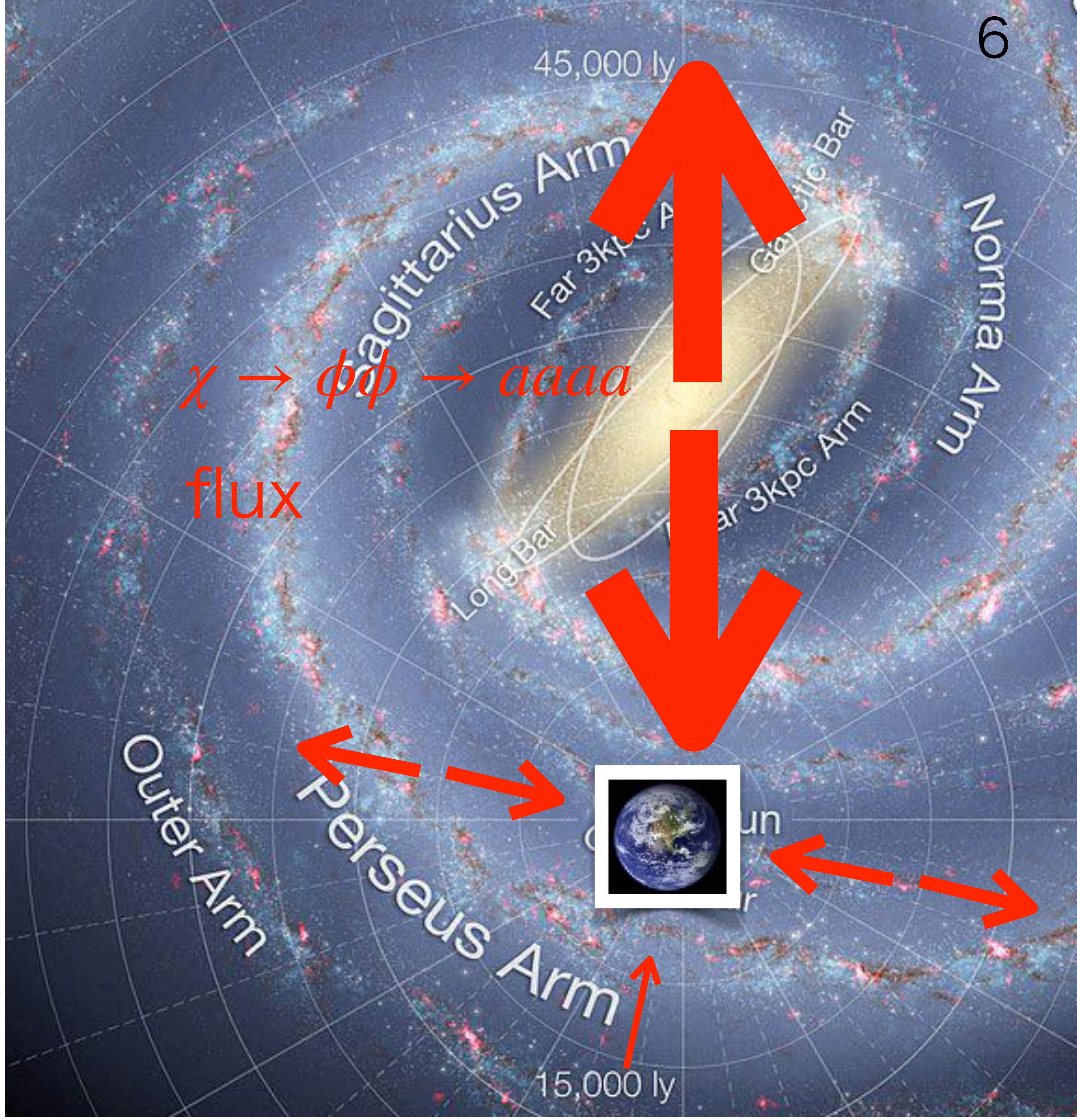
Anisotropy

Production mechanism of CaB:

- Thermal production
- Decay of cosmic string
- X -> aa where X is dark matter
  - X -> ΦΦ -> aaaa at anywhere
  - **X -> ΦΦ -> aaaa from galaxy**

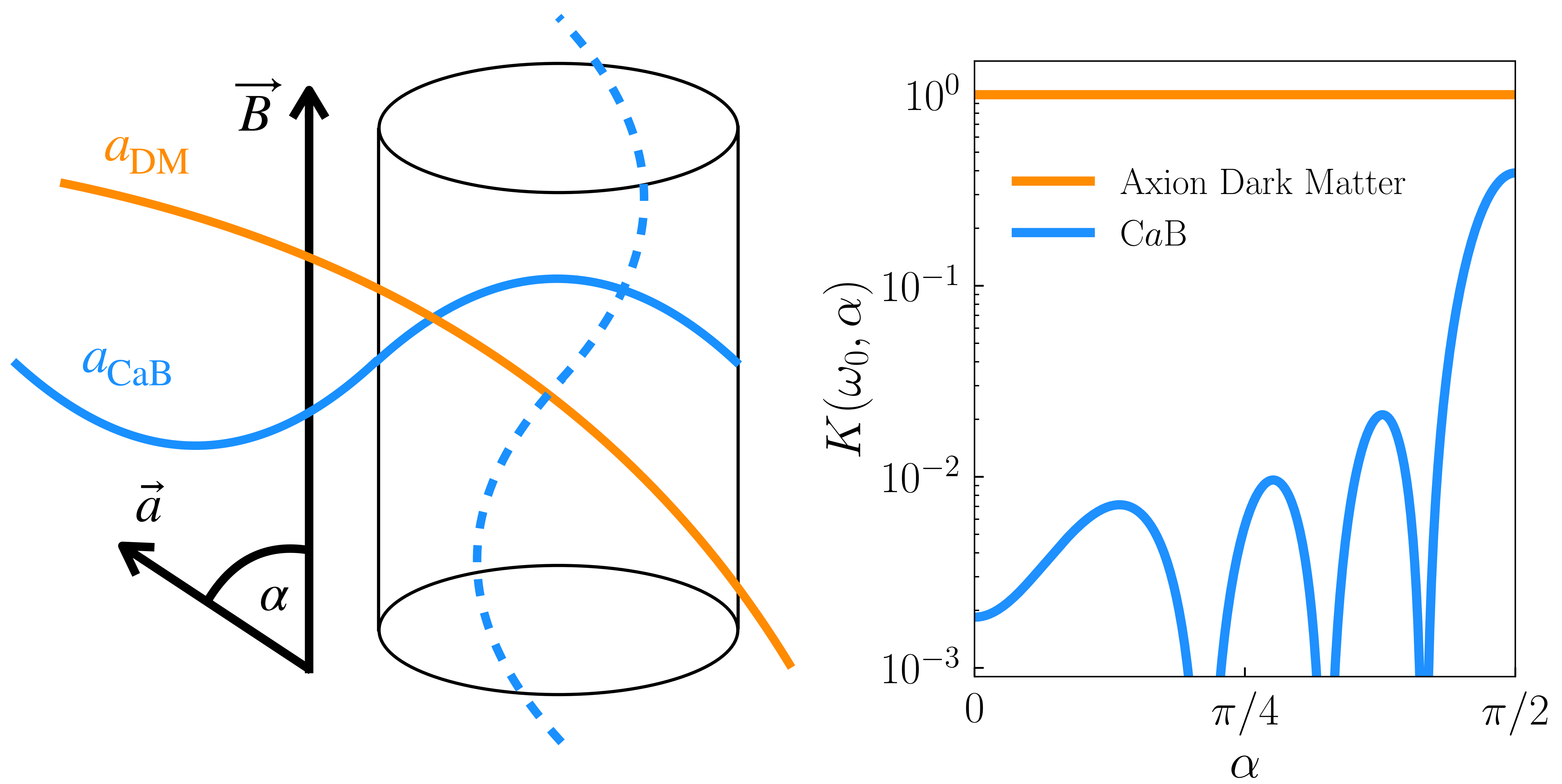
isotropic

anisotropic



Anisotropic signals varies signal amplitude as the Earth rotate (detector fixed on ground)

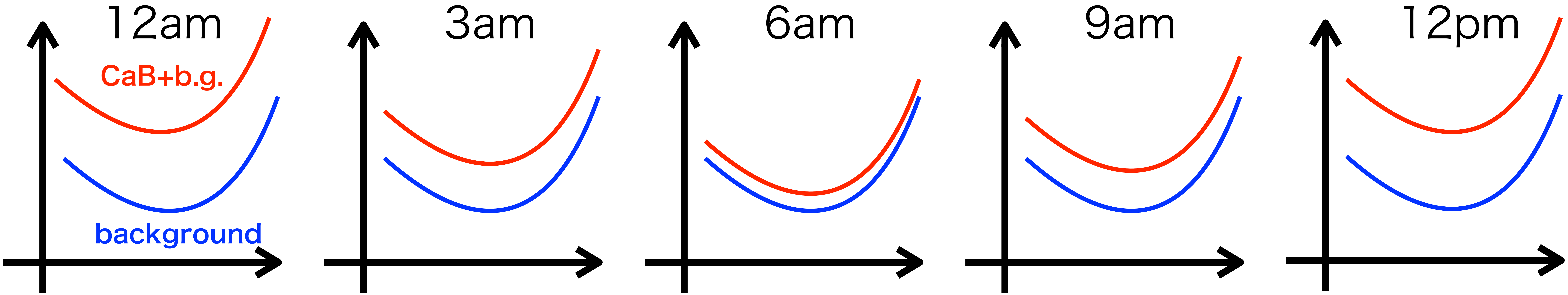
Daily modulation



$\alpha = \pi/2$: Signal maximized

→Daily modulation

Monitoring relative power level is enough to detect CaB



CaB power at ADMX

CaB case (differential power)

$$\frac{dP_a}{d\omega}(\omega,\alpha) = \frac{\rho_c g_{a\gamma\gamma}^2 B^2 V C \beta}{8Q((\omega-\omega_0)^2+(\omega_0/2Q)^2)}\frac{\omega_0^3}{\omega^3} \times \left[\Omega_a^{\mathrm{MW}}(\omega)\int dz d\phi \mathcal{D}_\nu(-z) K(\omega,\alpha) + \frac{1}{2}\Omega_a^{\mathrm{EG}}(\omega)\int dz d\phi K(\omega,\alpha)\right].$$

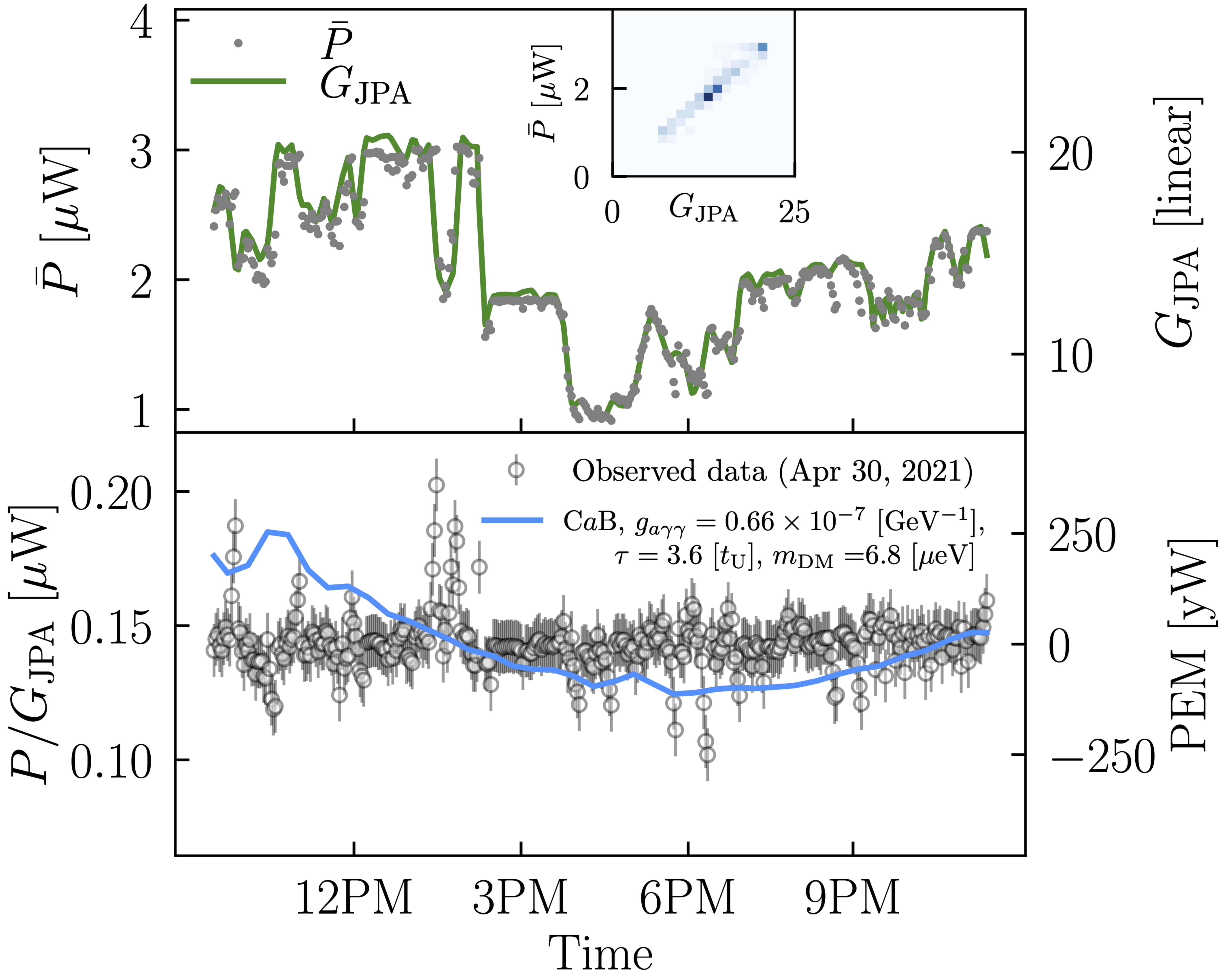
c.f. dark matter axion at ADMX

$$P_{\mathrm{axion}} = 7.7\times 10^{-23}\ \mathrm{W}\left(\frac{V}{136\ell}\right)\left(\frac{B}{7.5\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right) \times \left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.45\ \mathrm{GeV/cc}}\right)\left(\frac{f}{1\ \mathrm{GHz}}\right)\left(\frac{Q_L}{80\,000}\right)$$

Source of daily modulation

$$K(\omega,\alpha) = \left[\frac{\sin(\omega L\cos\alpha)}{\omega L\cos\alpha}\frac{J_0(\omega R\sin\alpha)}{1-(\omega R\sin\alpha/j_{01})^2}\right]^2$$

Power Excess Modulation (PEM)

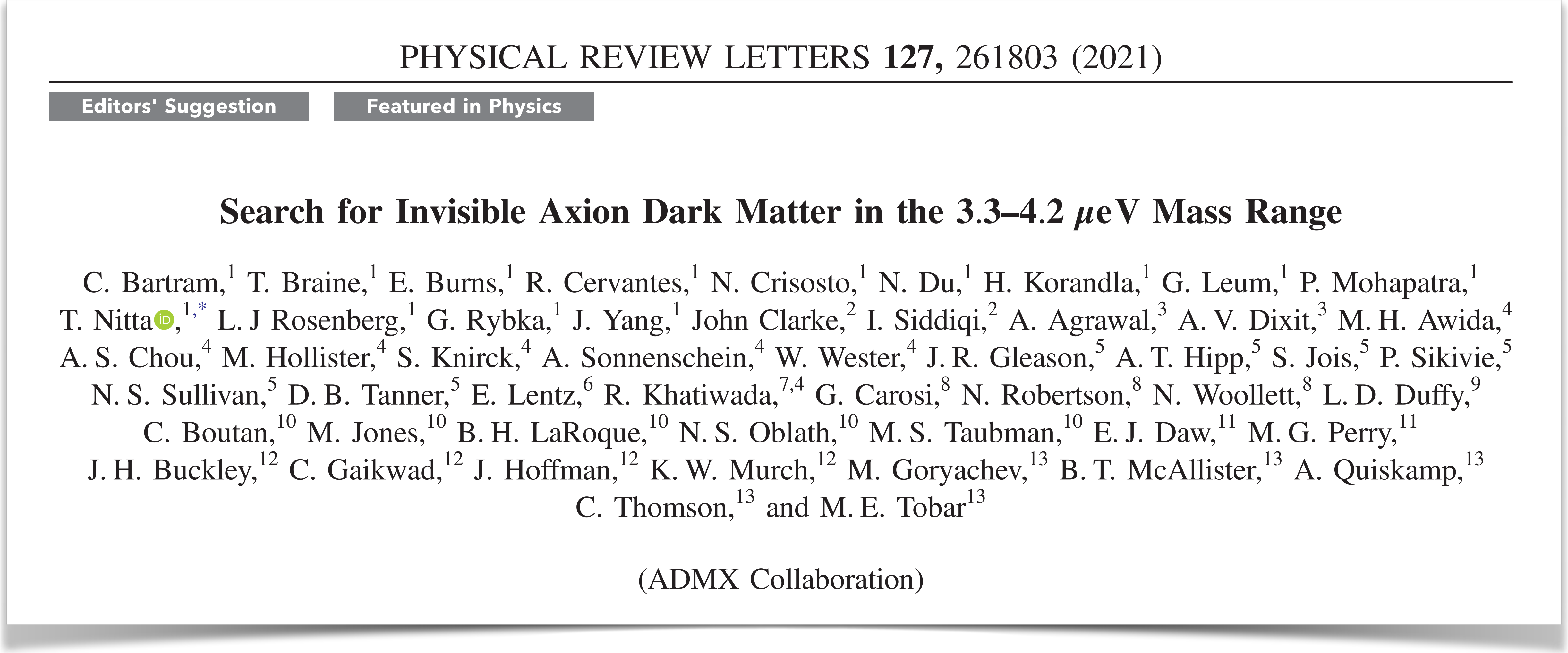


JPA gain varies to get highest SNR

$$\mathrm{PEM} = \frac{\overline{P}(t)/G_{\mathrm{JPA}}(t) - \langle \overline{P}(t)/G_{\mathrm{JPA}}(t)\rangle}{\langle \sigma_P(t)/G_{\mathrm{JPA}}(t)\rangle} k_{\mathrm{B}} T_{\mathrm{sys}} \sqrt{\frac{b}{T}}.$$

PEM clears JPA fluctuations
→ better sensitivity to the modulation signals

Dataset



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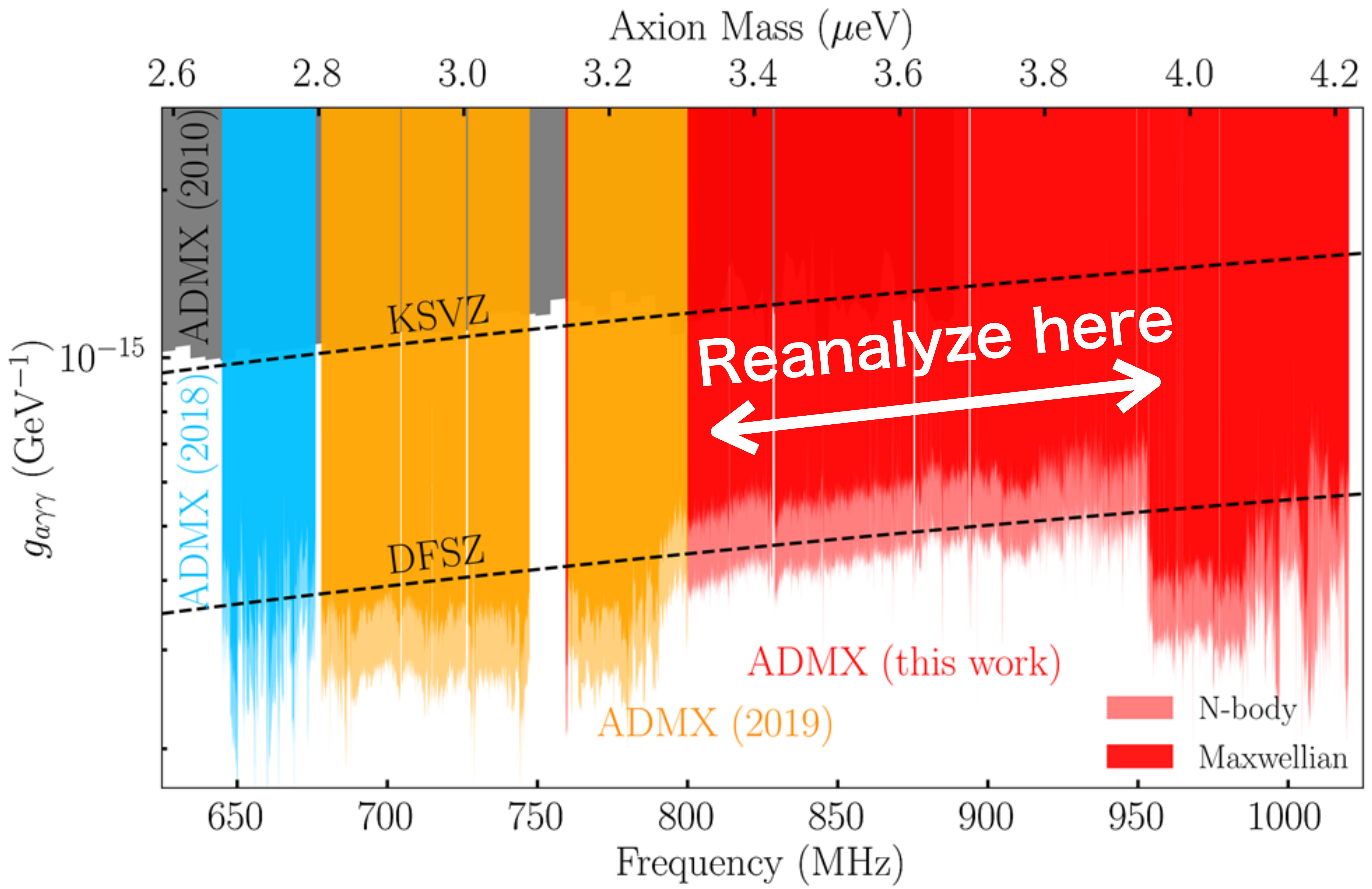
Editors' Suggestion | Featured in Physics

Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range

C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1,*] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A. T. Hipp,[5] S. Jois,[5] P. Sikivie,[5] N. S. Sullivan,[5] D. B. Tanner,[5] E. Lentz,[6] R. Khatiwada,[7,4] G. Carosi,[8] N. Robertson,[8] N. Woollett,[8] L. D. Duffy,[9] C. Boutan,[10] M. Jones,[10] B. H. LaRoque,[10] N. S. Oblath,[10] M. S. Taubman,[10] E. J. Daw,[11] M. G. Perry,[11] J. H. Buckley,[12] C. Gaikwad,[12] J. Hoffman,[12] K. W. Murch,[12] M. Goryachev,[13] B. T. McAllister,[13] A. Quiskamp,[13] C. Thomson,[13] and M. E. Tobar[13]

(ADMX Collaboration)



Reanalyze run1C-part1 dataset with special selection for CaB search

Discard 950-1020 MHz where JPA gain significantly fluctuates

Uncertainties

Four sources of uncertainties:

1. Standard haloscope uncertainties (Q, β, SNRI, $T_{\rm off}/\epsilon, B^2VC$)
2. Short timescale (about 5 minutes) fluctuation
3. Daily fluctuation
4. Uncertainty on $K(\omega, \alpha)$

1. Standard Uncertainties on ADMX

We just use the same uncertainties related to the axion halo scope

TABLE II. Summary of uncertainties associated with the observed power.

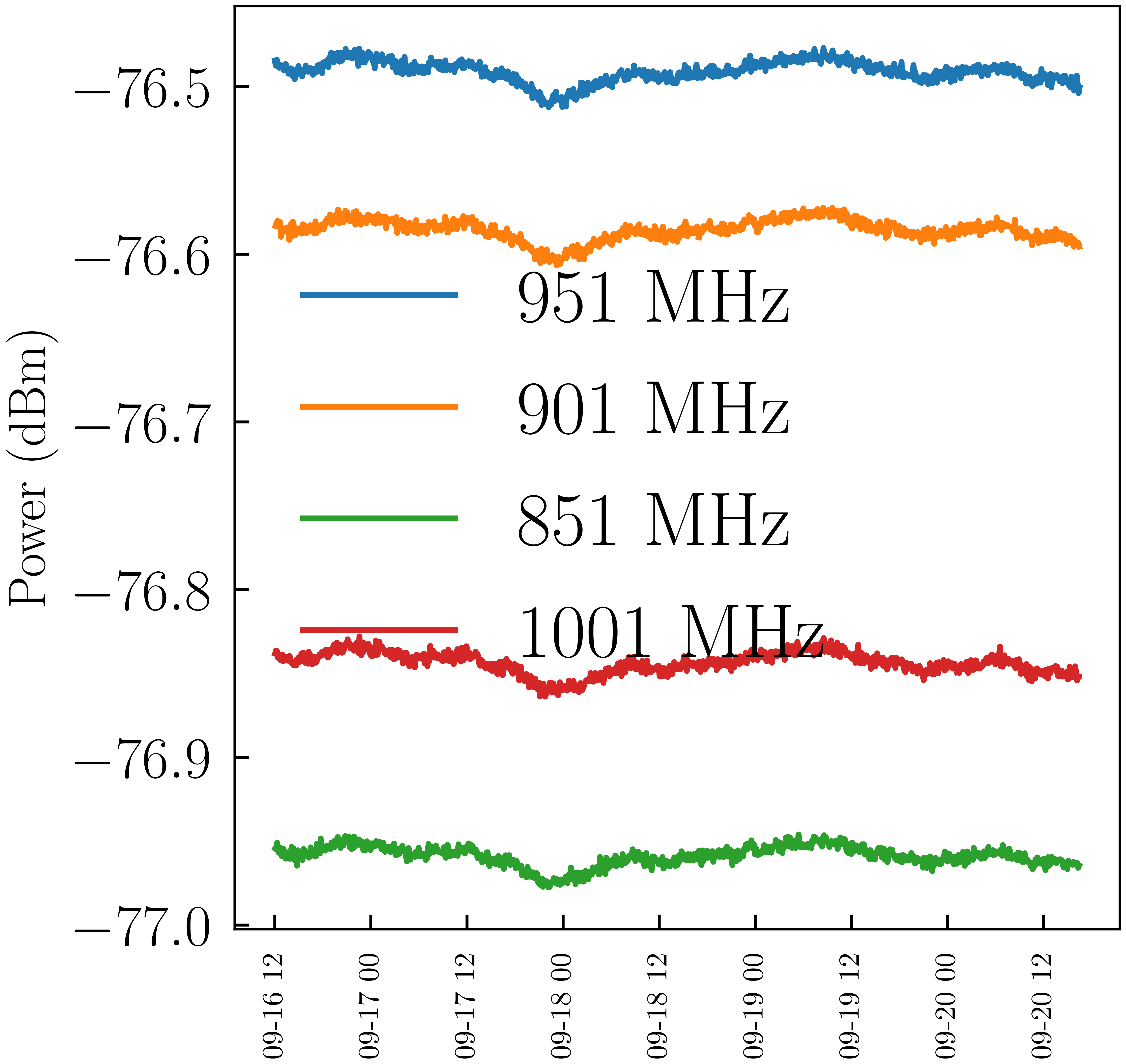
Source	Fractional uncertainty on $P_{\rm axion}$
Cavity Q factor	2%
Antenna coupling	2%
JPA SNRI	0.8%
$T_{\rm off}/\epsilon$	4.3%
B^2VC	3%
Total	6%

2. Daily power fluctuation

Receiver chain:
Digitizer + HFET amps + cables
is not perfectly stable
ex.) temperature change, vibration…

Dedicated 1-week power monitoring performed to extract potential uncertainty

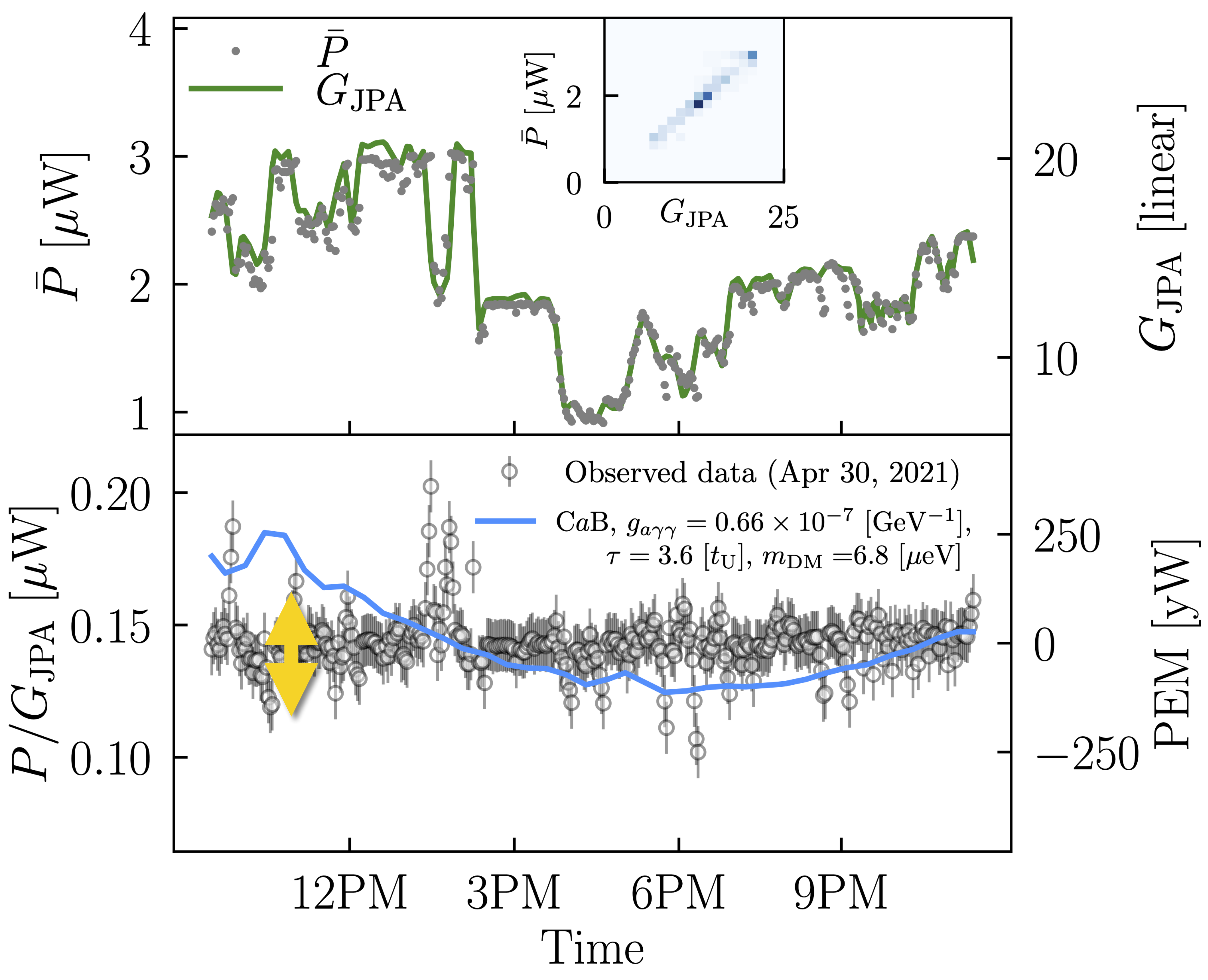
Estimated as 2.8%
(not the dominant uncertainty)



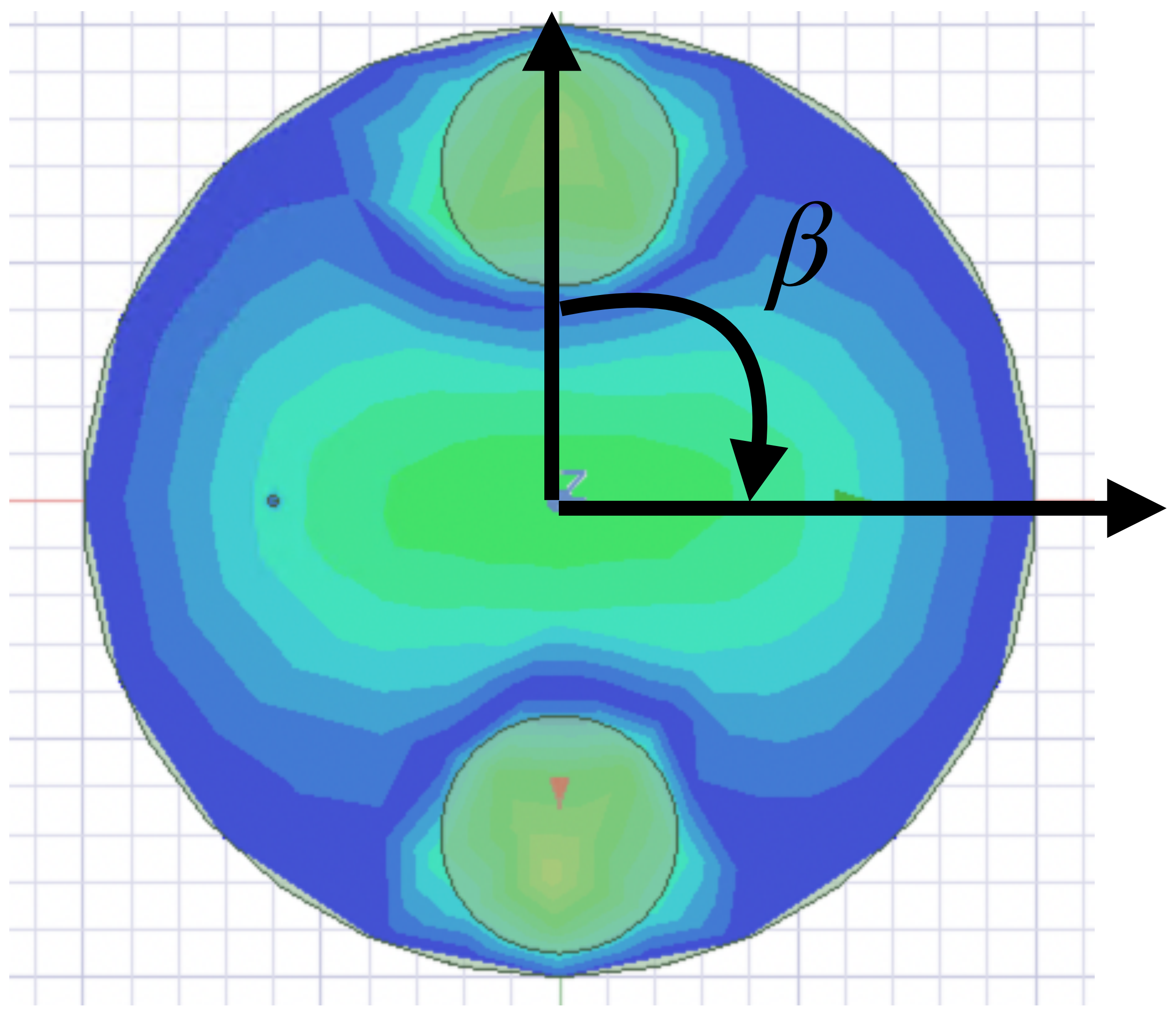
3. Short timescale fluctuation

Residual JPA gain fluctuation is the dominant uncertainty

This is calculated from the RMS of the PEM spectrum



4. Uncertainty on $K(\omega, \alpha)$



Assuming $\vec{E} \cdot \vec{B} = 1$

	empty	rods (f~780 MHz)	rods (f~1 GHz)
C	0.69	0.62	0.54
$CK(\omega_0, 0)$ $\beta = 0$	0.47	0.47	0.42
$CK(\omega_0, 0)$ $\beta = \pi/2$	0.47	0.38	0.26

$K(\omega, \alpha)$ is determined each timestamp, assuming vacant cylinder **without rod** for simplicity

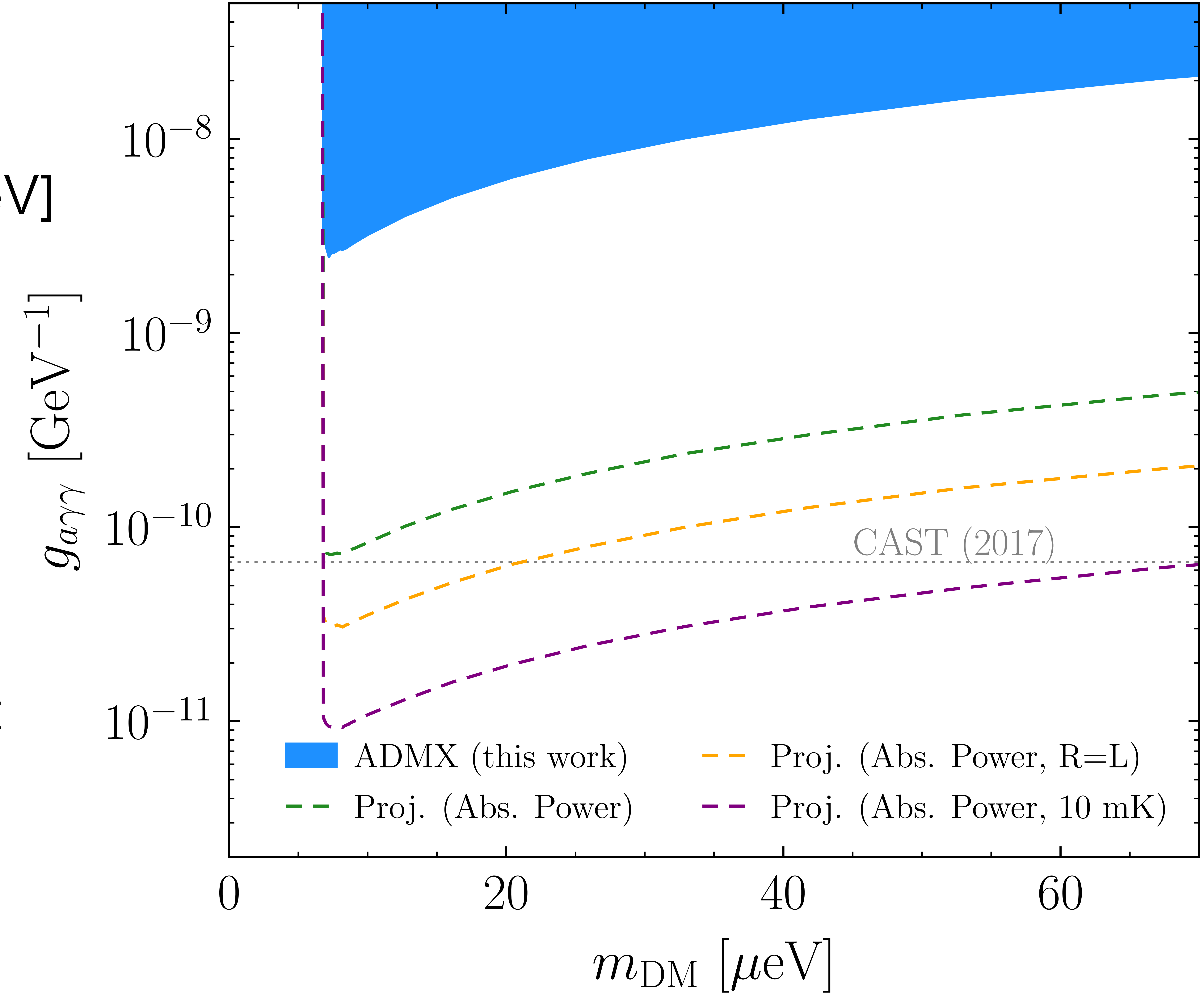
We estimated how $K(\omega, \alpha)$ changes by the existence of the tuning rod ~ 30% uncertainty

Result

Best sensitivity ~ 2e-9 [/GeV]
at lower mass
(due to kinematics)

CAST bound is strong
but ADMX did good job

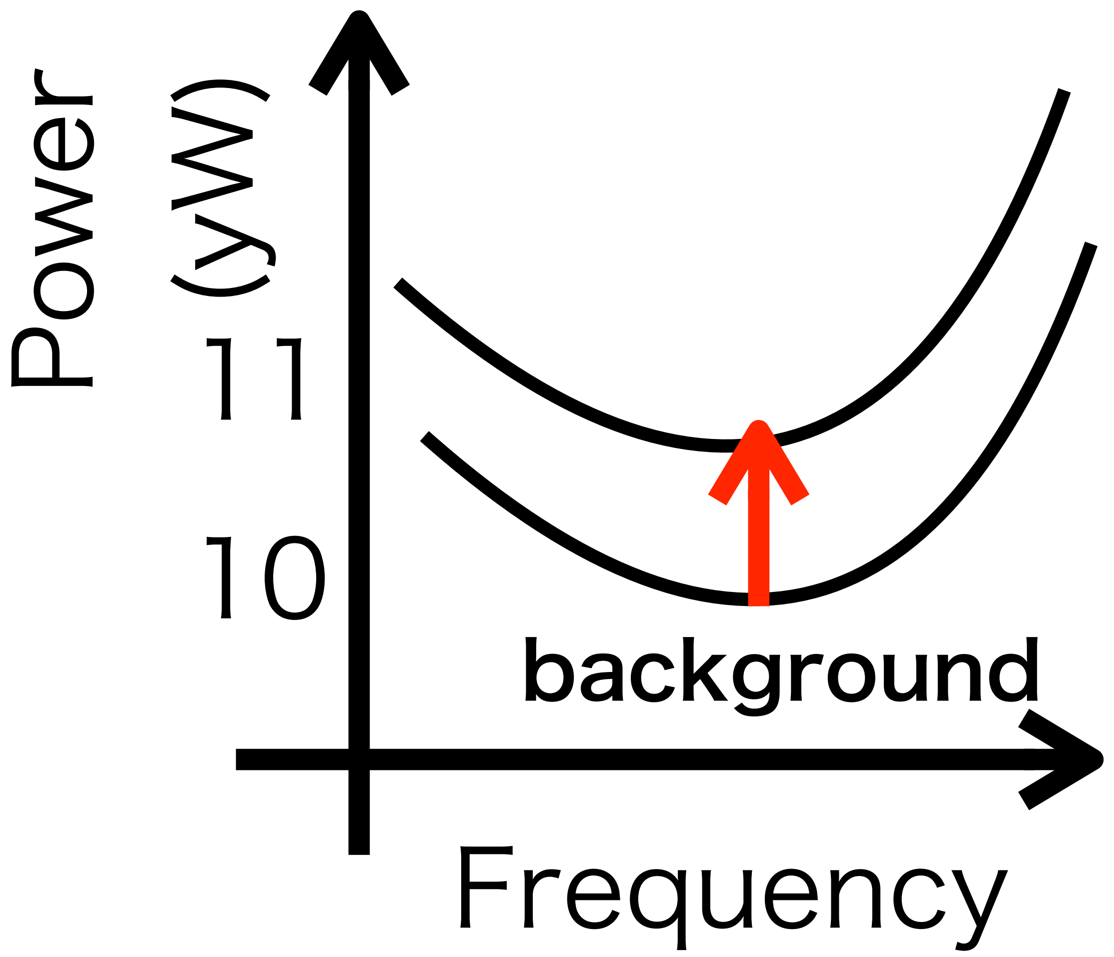
There might be able to get
better sensitivity by a few
improvements

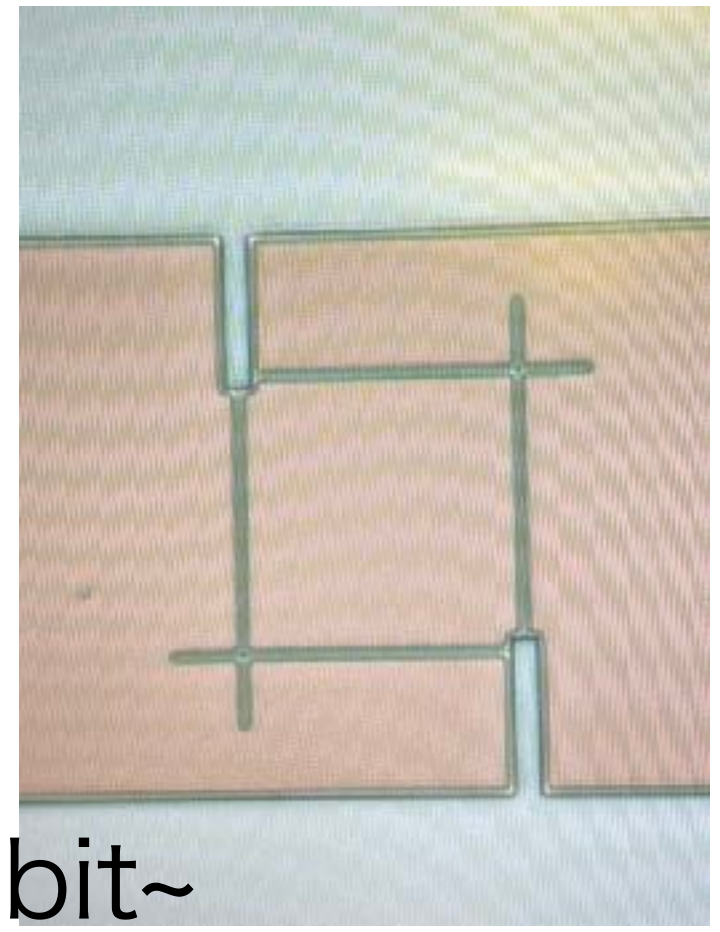


Future prospects

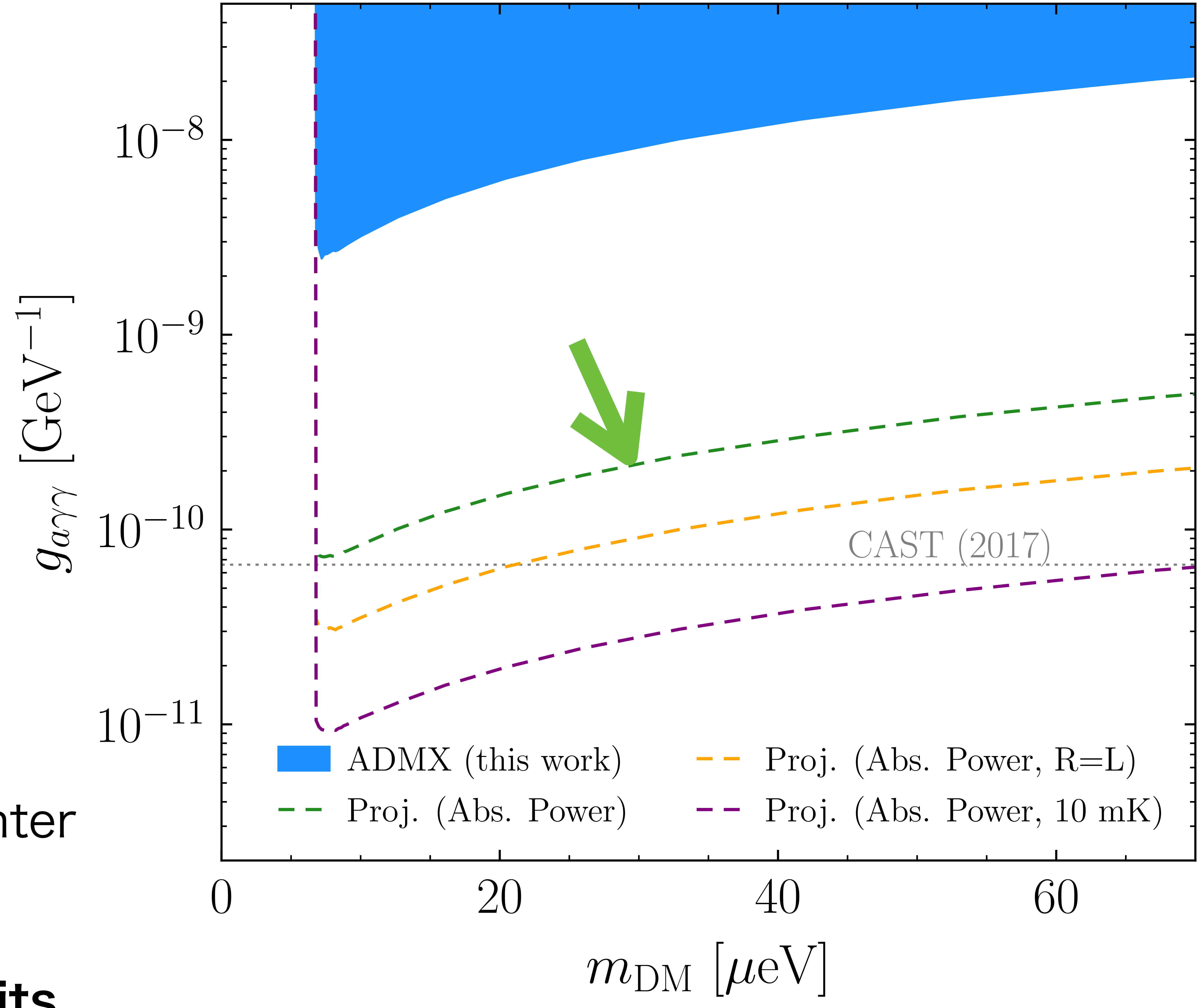
Abs. Power:

Absolute power measurement evades broadband signal issue





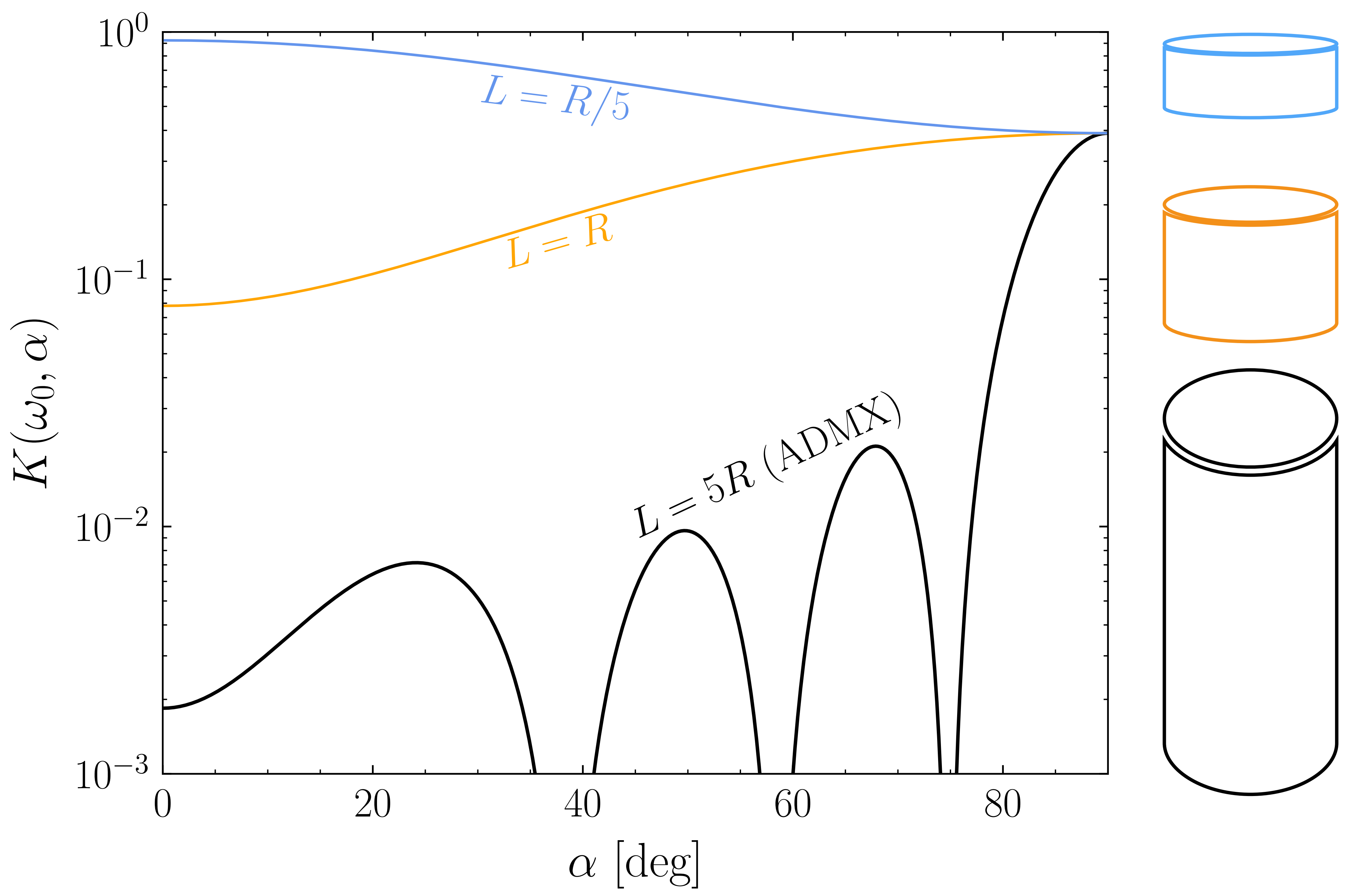
qubit~
single photon counter

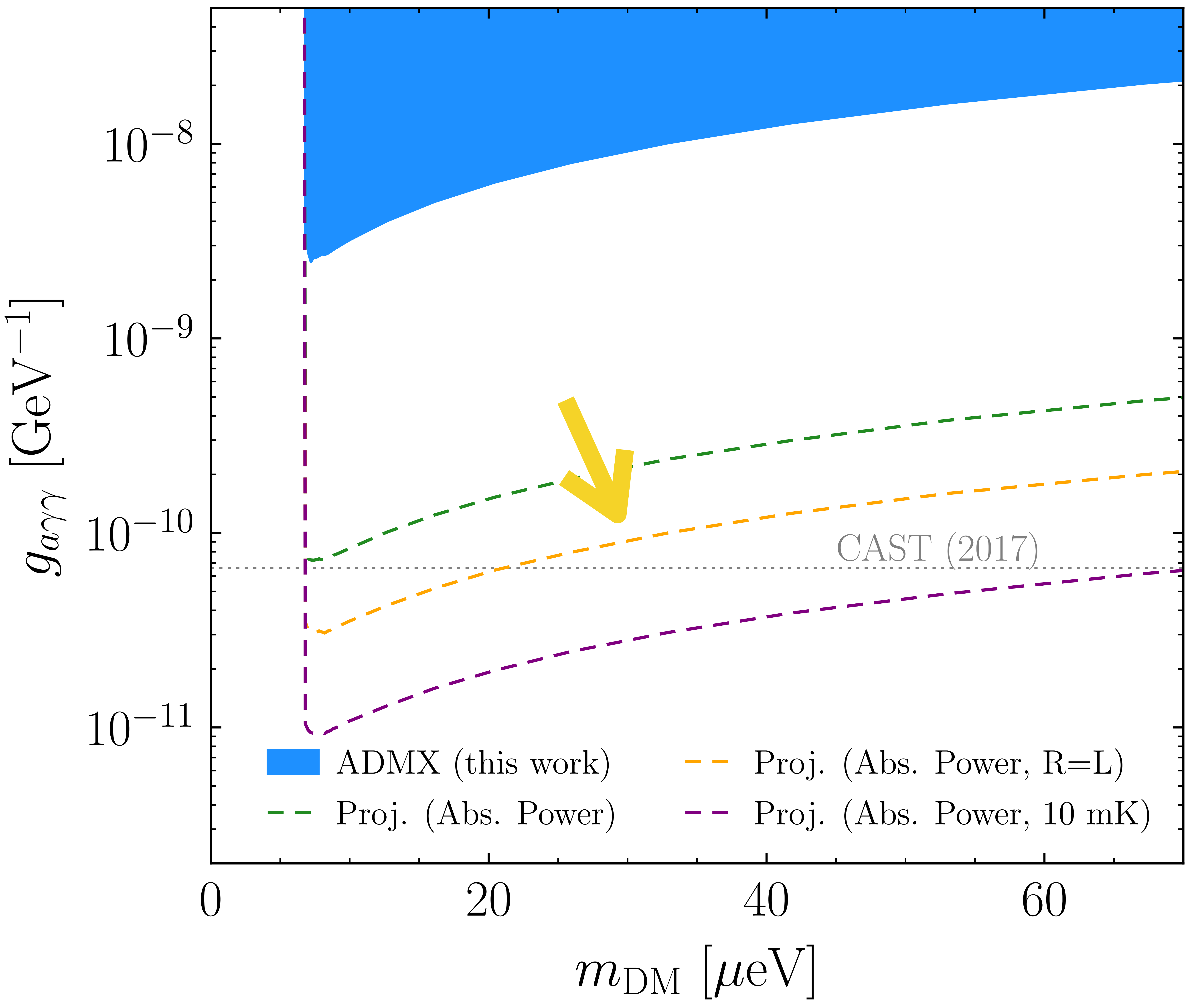


Please check Shion Chen's poster about U Tokyo activity related to qubits

Future prospects

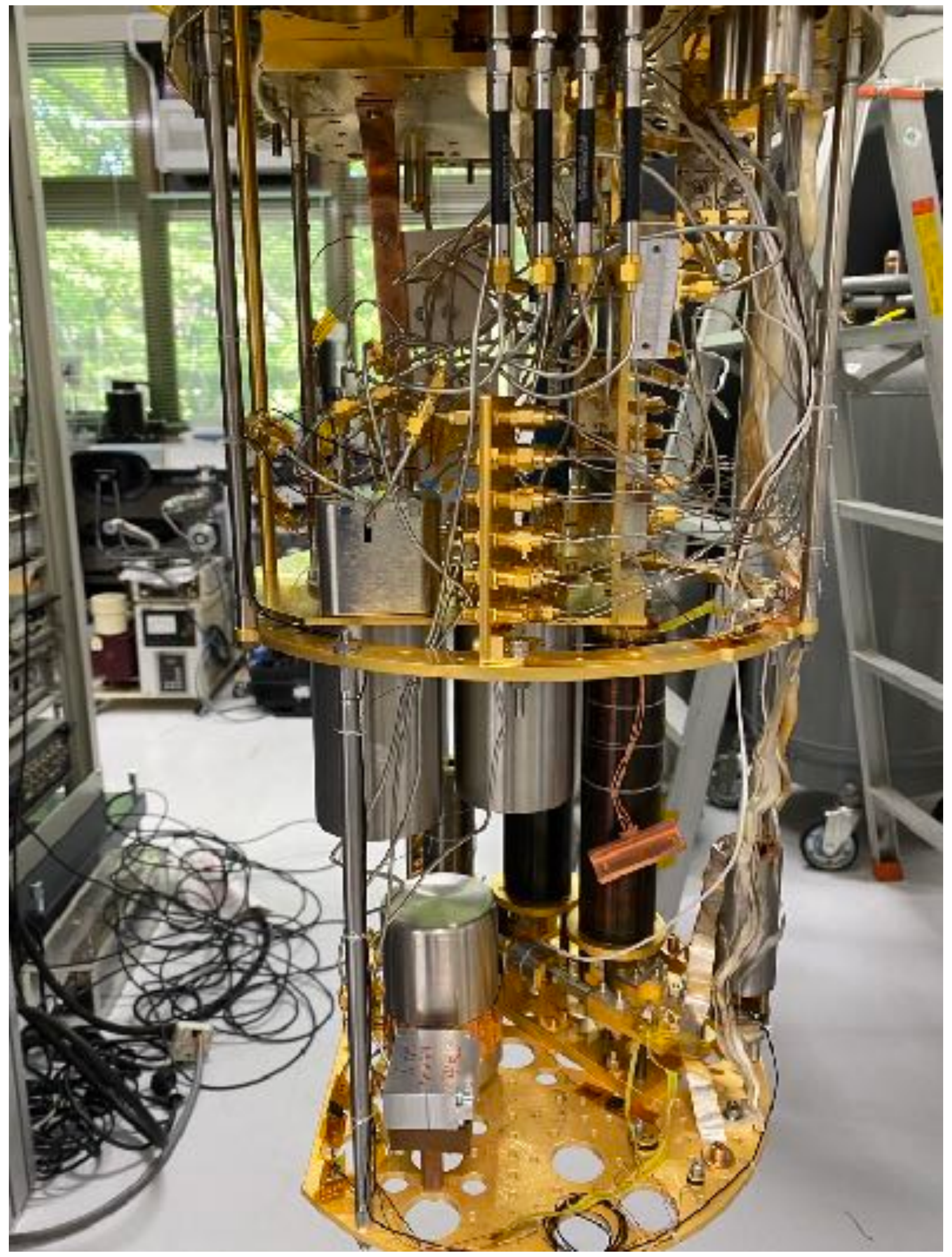
R=L: Pancake-like cavity greatly enhances signal parallel to the cavity z-axis



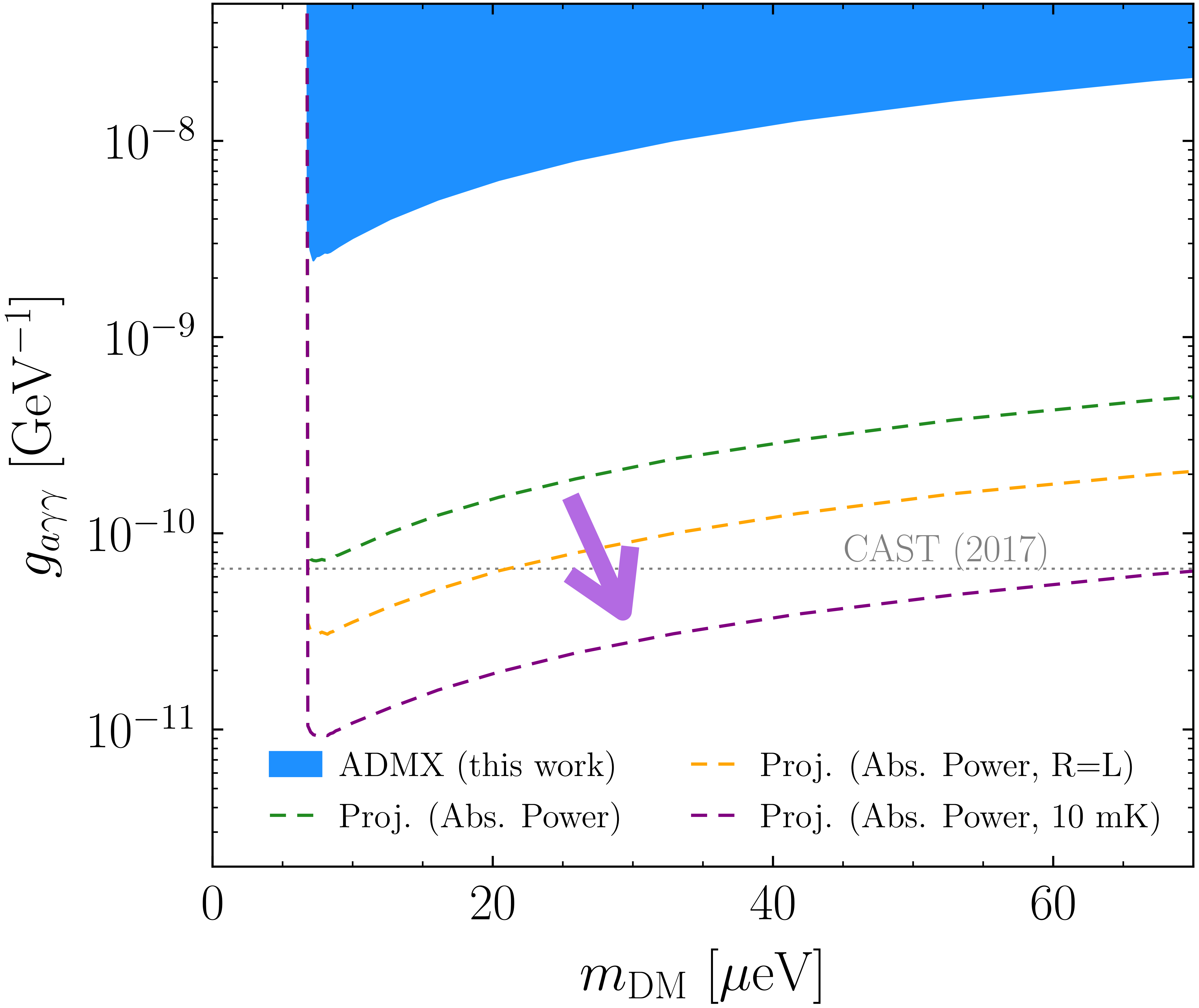


Future prospects

10 mK: Superconducting qubits are cool



Achievable lower noise



Summary

- The first direct CaB search with the ADMX dataset
- Achieved by the new analysis to search daily modulation signals

  → Any daily modulation signal can be detected by this analysis
- No signal found but limit on $g_{a\gamma\gamma}$ in a particular CaB model

  → Further improvements might open searches for deeper parameter space

The paper is on arxiv 2303.06282 submitted to PRL

APS/123-QED, CERN-TH-2023-041

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(ADMX Collaboration)

J. A. Dror,[15] H. Murayama,[3,16,17] and N. L. Rodd[18]

Backup

∇a makes Daily modulation

$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a \qquad \mathbf{B} \cdot \nabla a \sim \mathbf{B} \cdot \mathbf{k}$

The effective charge density will be changed by axion spatial gradients

~ inner product of magnetic field and momentum changed effective charge

axion induced electric field becomes like this

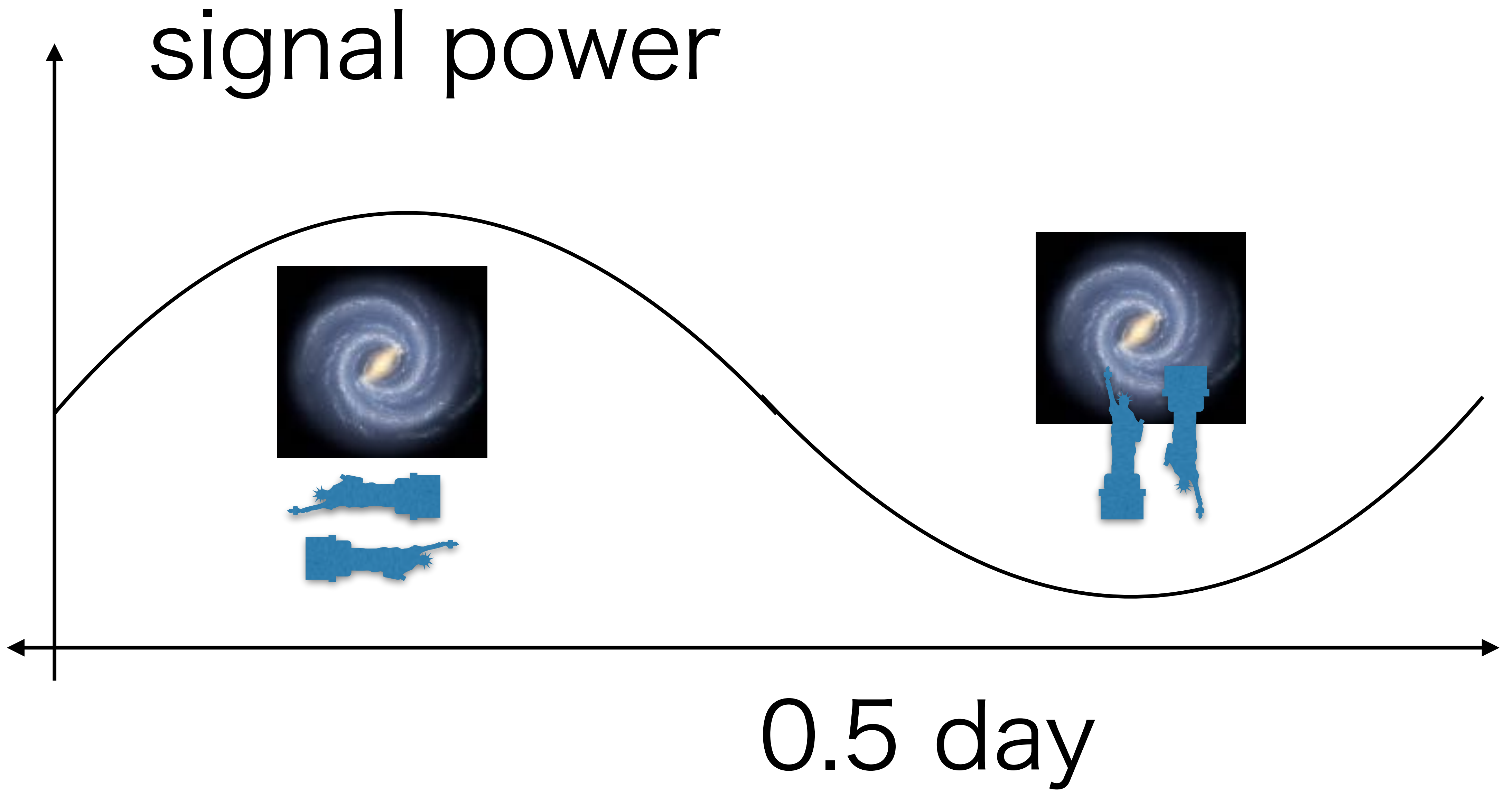
$$(\nabla^2 - \partial_t^2)\mathbf{E}_a = g_{a\gamma\gamma}\mathbf{B}_0\partial_t^2 a - g_{a\gamma\gamma}(\mathbf{B}_0 \cdot \nabla)\nabla a$$

signal is proportion to

$\hat{\mathbf{z}} - (\hat{\mathbf{n}} \cdot \hat{\mathbf{z}})\hat{\mathbf{n}}$ where $\mathbf{B}_0 = B_0\hat{\mathbf{z}} \quad \mathbf{k} = \omega\hat{\mathbf{n}}$

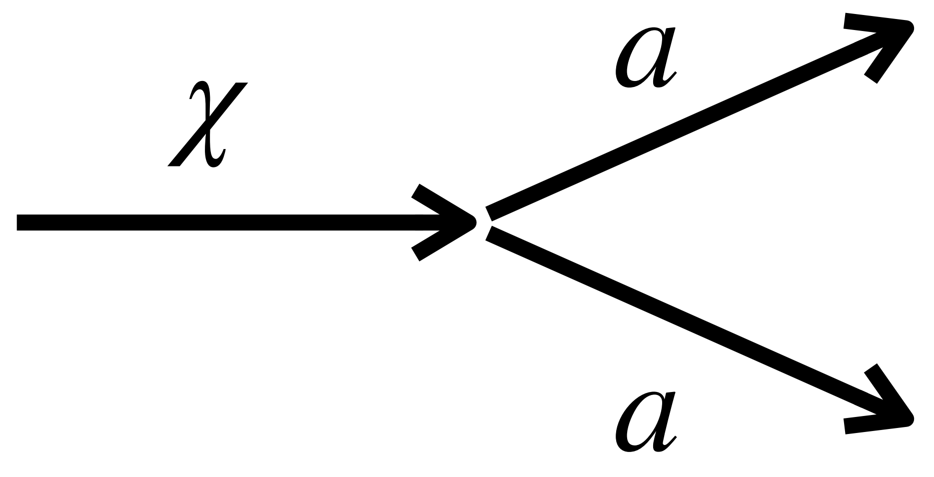
if it is TM modes, signal is proportion to

$\sin^2\alpha$, where $\alpha = \arccos(\hat{\mathbf{n}} \cdot \hat{\mathbf{z}})$



Why we need cascade decay?

Simplest case

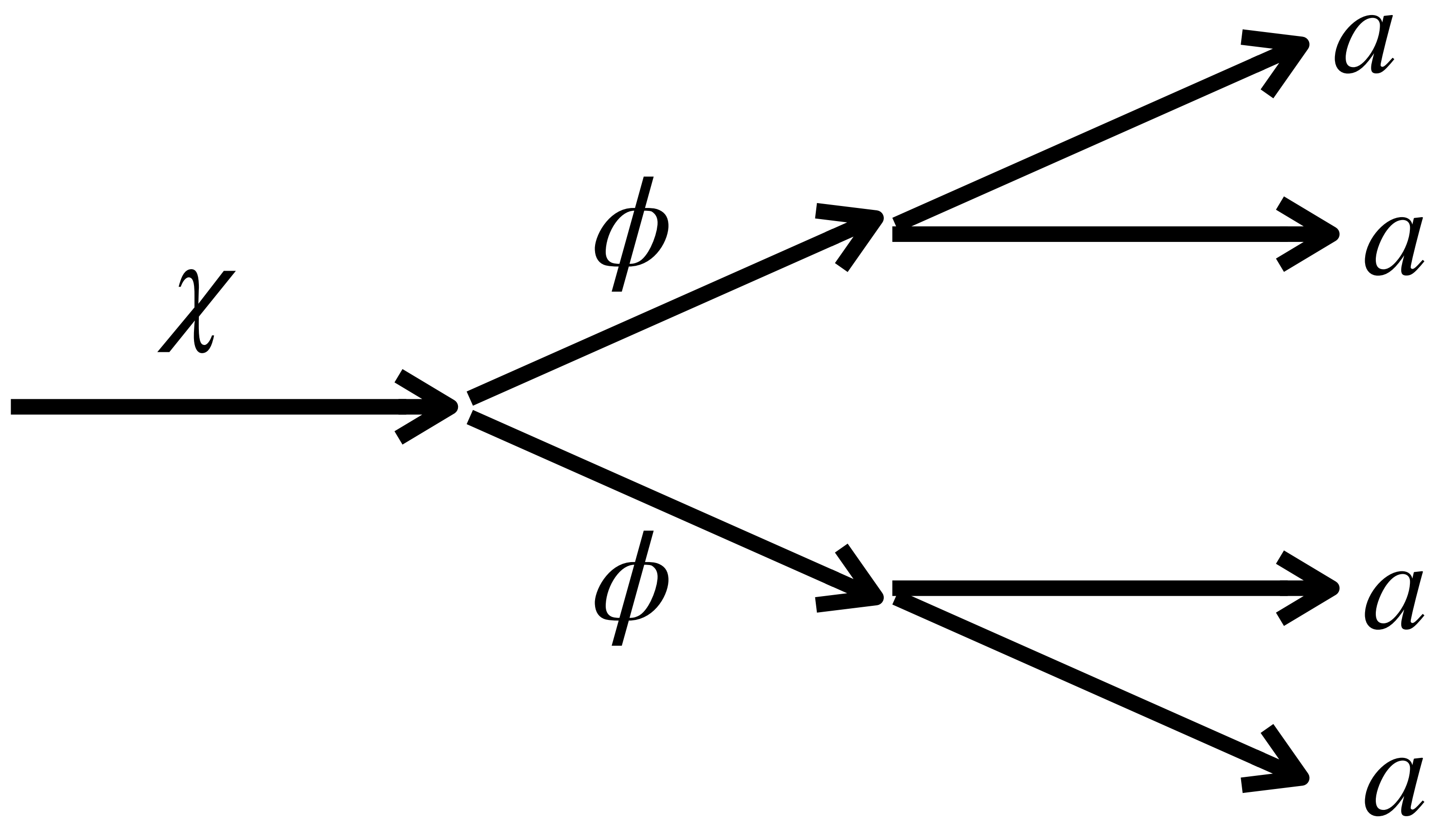


χ is any dark matter

assuming having coupling only with axions

$\rightarrow \chi$ decays too fast by Bose enhancement (interference with environmental axions and the diagram)

Cascade decay



Cascade decay can evade the problem.
(χ decay rate is independent with the existence of environmental axions)