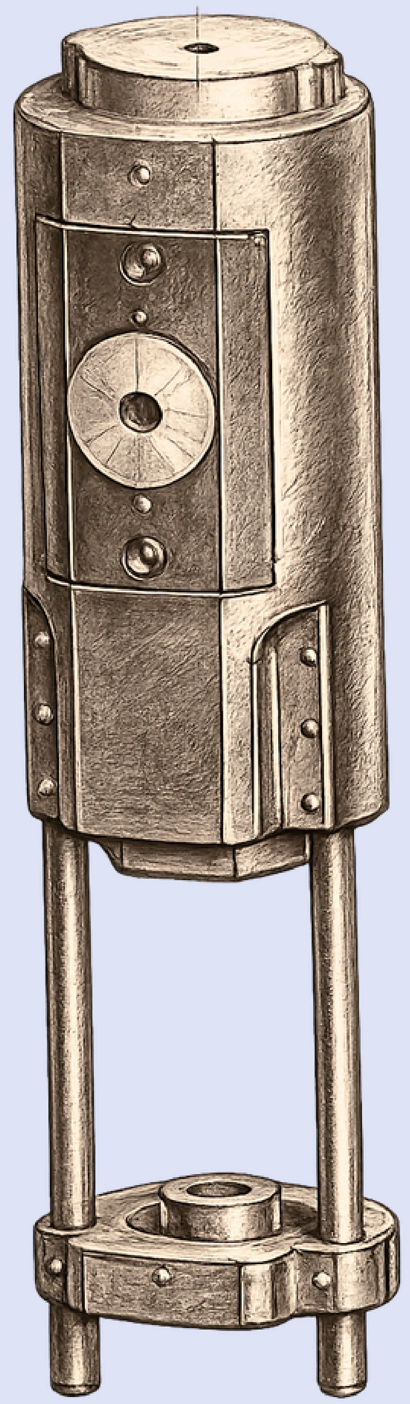
ASTROPARTICLE
PHYSICS LAB

جامعة نيويورك أبوظبي
NYU ABU DHABI

# A Dielectric Haloscope for Axions & HFGWs



**Alia Zino**

# Overview

**About the Lab**

→ Dark Matter Searches [ MuDHI ]

**DALIL**

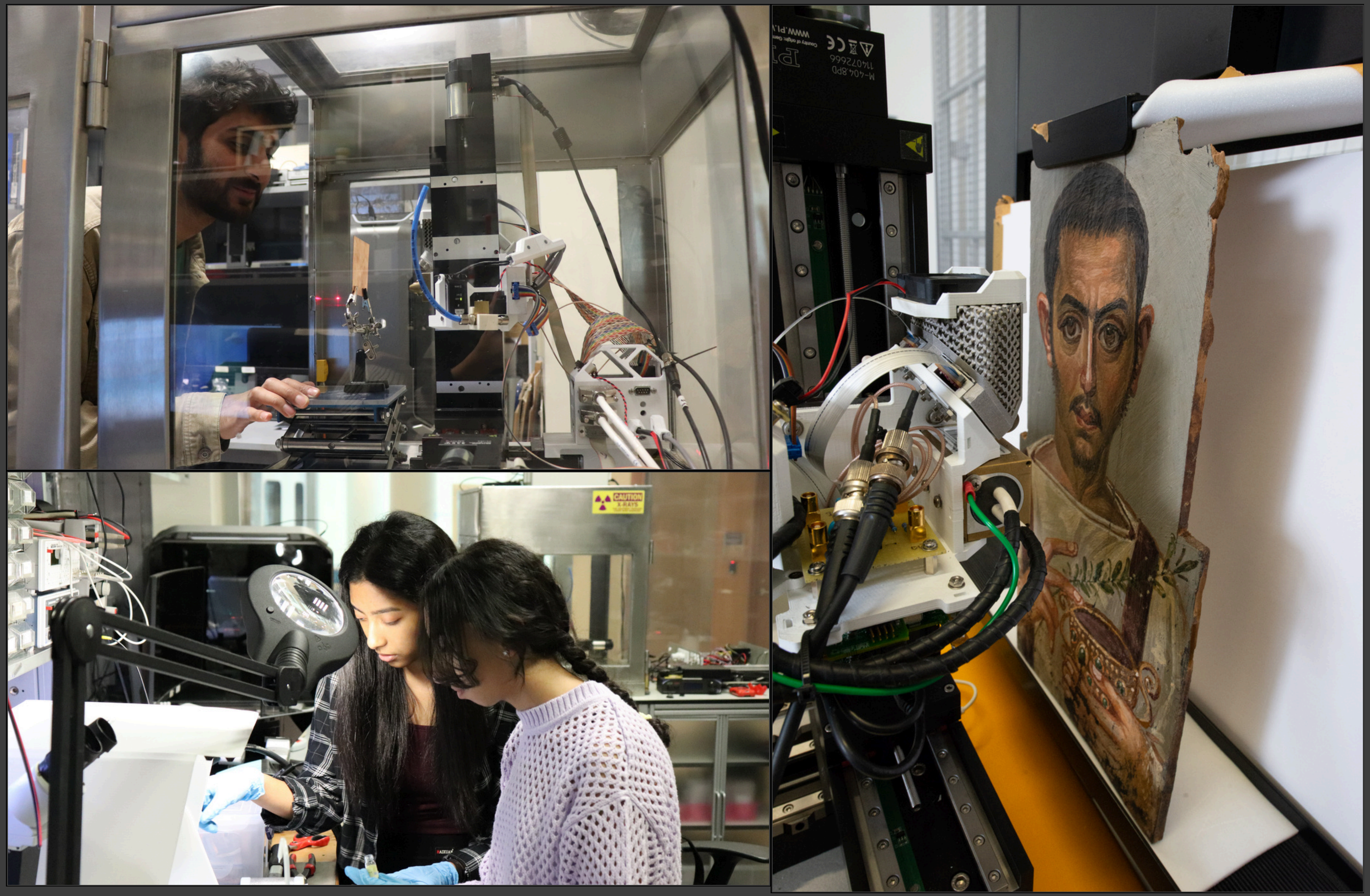
- Axion Search
- Gravitational Wave Search

**Next Steps**

# About the Astroparticle Physics Lab

experimental physics lab specializing in particle detection physics

- Dark Matter Search
- Space Study
- Cultural Heritage



# About the Astroparticle Physics Lab

where we are located

# About the Astroparticle Physics Lab

where we are located

# Dark Matter Search Using Haloscopes

## 1st Candidate

Dark Photon - MuDHI EXperiment

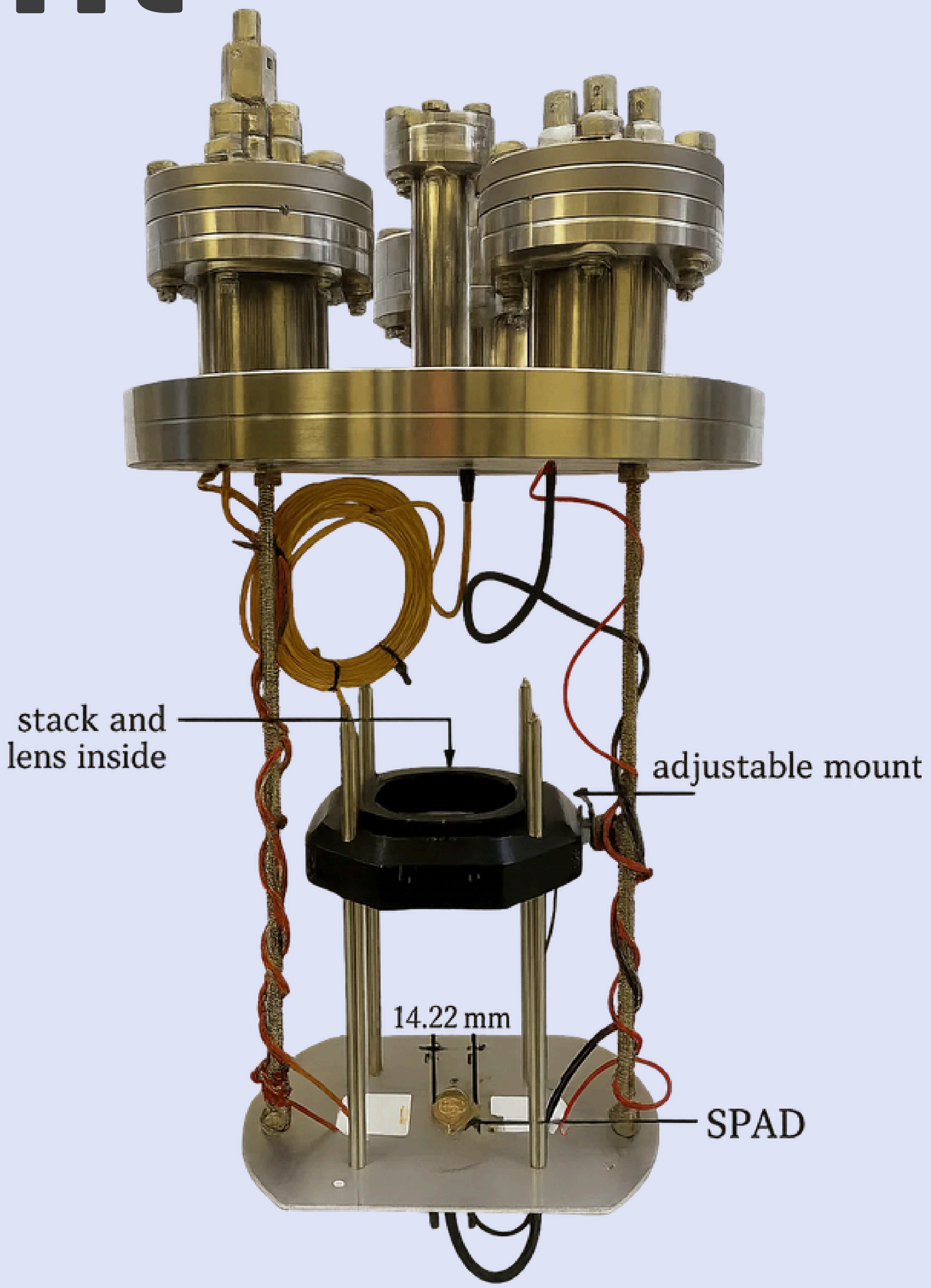
## 2nd Candidate

Axions - DALIL

# MuDHI Experiment

## Multilayer Dielectric Haloscope Investigation

- search for DP with mass 1.5 eV/$c^2$
- 23 dielectric layers, chirped configuration
- exploits kinetic mixing: DP → SM photons
- No excess signal, imposed 90% CL exclusion limits on the kinetic mixing parameter



# MuDHI Experiment

Published in:
L. Manenti et al., "*Search for dark photons using a multilayer dielectric haloscope equipped with a single-photon avalanche diode*", **Phys. Rev. D 105, 052010 (2022)**

- arXiv:2110.10497, DOI: 10.1103/PhysRevD.105.052010

NORDITA-2021-087

**Search for dark photons using a multilayer dielectric haloscope equipped with a single-photon avalanche diode**

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*Physics Department, Columbia University, New York, New York 10027, USA*

(Dated: January 10, 2023)

We report on the results of the search for dark photons with mass around 1.5 eV/c$^2$ using a multilayer dielectric haloscope equipped with an affordable and commercially available photosensor. The multilayer stack, which enables the conversion of dark photons (DP) to Standard Model photons, is made of 23 bilayers of alternating $SiO_2$ and $Si_3N_4$ thin films with linearly increasing thicknesses through the stack (a configuration known as a "chirped stack"). The thicknesses have been chosen according to an optimisation algorithm in order to maximise the DP-photon conversion in the energy region where the photosensor sensitivity peaks. This prototype experiment, baptised MuDHI مضيء (Multilayer Dielectric Haloscope Investigation) by the authors of this paper, has been designed, developed and run at the Astroparticle Laboratory of New York University Abu Dhabi, which marks the first time a dark matter experiment has been operated in the Middle East.

No significant signal excess is observed, and the method of maximum log-likelihood is used to set exclusion limits at 90% confidence level on the kinetic mixing coupling constant between dark photons and ordinary photons.

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

## A New Light Boson?

Steven Weinberg
*Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138*
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

One of the attractive features of quantum chromodynamics[1] (QCD) is that it offers an explanation of why $C$, $P$, $T$, and all quark flavors are conserved by strong interactions, and by order-$\alpha$ effects of weak interactions.[2] However, the discovery of quantum effects[3] associated with the "instanton" solution of QCD has raised a puzzle with regard to $P$ and $T$ conservation. Because of Adler-Bell-Jackiw anomalies, the chiral transformation which is needed in QCD to bring the quark-mass matrix to a real, diagonal, $\gamma_5$-free form will in general change the phase angle $\theta$ associated[3] with instanton effects, leaving $\bar{\theta} \equiv \theta + \arg\det m$ invariant. [Here $m$ is the coefficient of $\frac{1}{2}(1+\gamma_5)$ in a decomposition of the quark-mass matrix into $\frac{1}{2}(1\pm\gamma_5)$.] The condition for $P$ and $T$ conservation is that $\theta = 0$ when the quark fields are defined so that $m$ is real, or more generally, that $\bar{\theta} = 0$. But $\theta$ is a free parameter, and in QCD there is no reason why it should take $U(1)_{PQ}$], under which $\det m(\varphi)$ changes by a phase. The phase of $\det m(\varphi)$ at the minimum of $V(\varphi)$ is then undetermined in any finite order of perturbation theory, and is fixed only by instanton effects which break the $U(1)_{PQ}$ symmetry. However, the potential will then depend on $\bar{\theta}$, but not separately on $\theta$ and $\arg\det m$, so that it is not a miracle if the phase of $\det m(\varphi)$ at the minimum of $V(\varphi)$ happens to have the $P$- and $T$-conserving value $-\theta$. Peccei and Quinn[5] show in a number of examples that this is just what happens.

Now, the $U(1)_{PQ}$ symmetry of the Lagrangian is intrinsically broken by instantons, and so at first sight one might not expect that it would have any further physical consequences. Certainly it does not lead to the strongly interacting isoscalar pseudoscalar meson below $\sqrt{3}m_\pi$,[6] that was the bugbear of the old U(1) problem. However, the scalar fields $\varphi$ do not know about instantons, except through a semiweak ($\propto G_F^{1/2}$) coupling to

Semantic Scholar via Internet Archive, archived Feb. 24, 2019

# Axions


PamexFoods, accessed June 7, 2026

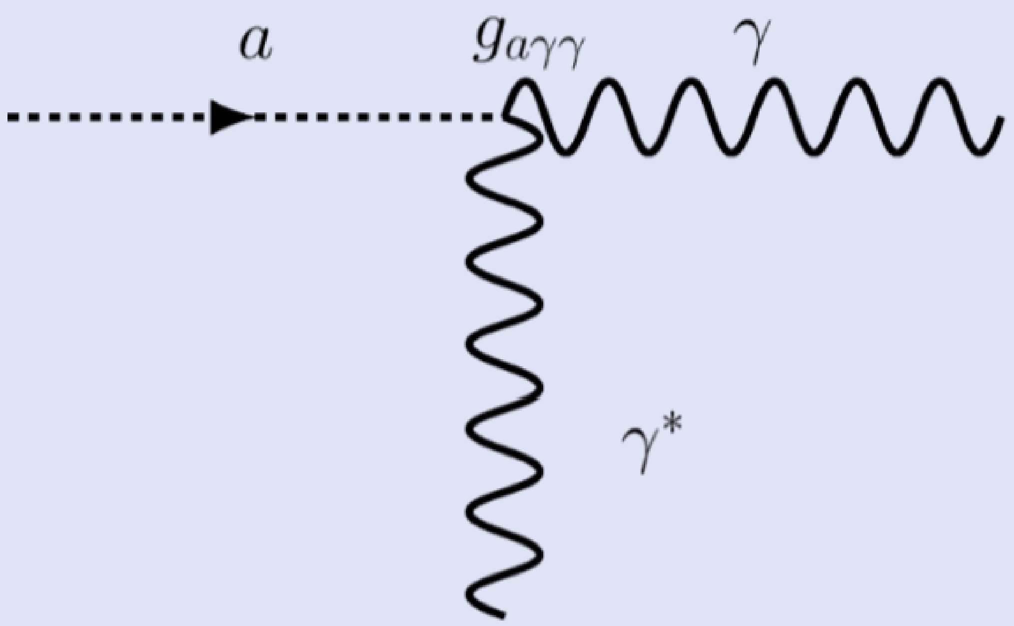
# Axions

# Theory

## Axions

- hypothetical, extremely light particles
- proposed to solve the strong CP problem [QCD axions]
- DM candidate [QCD, ALPs]
- Primakoff Effect: coupling of axion to product of B & E

$$L_{a\gamma\gamma} = g_{a\gamma\gamma}\, a(t)\, \mathbf{E} \cdot \mathbf{B}$$



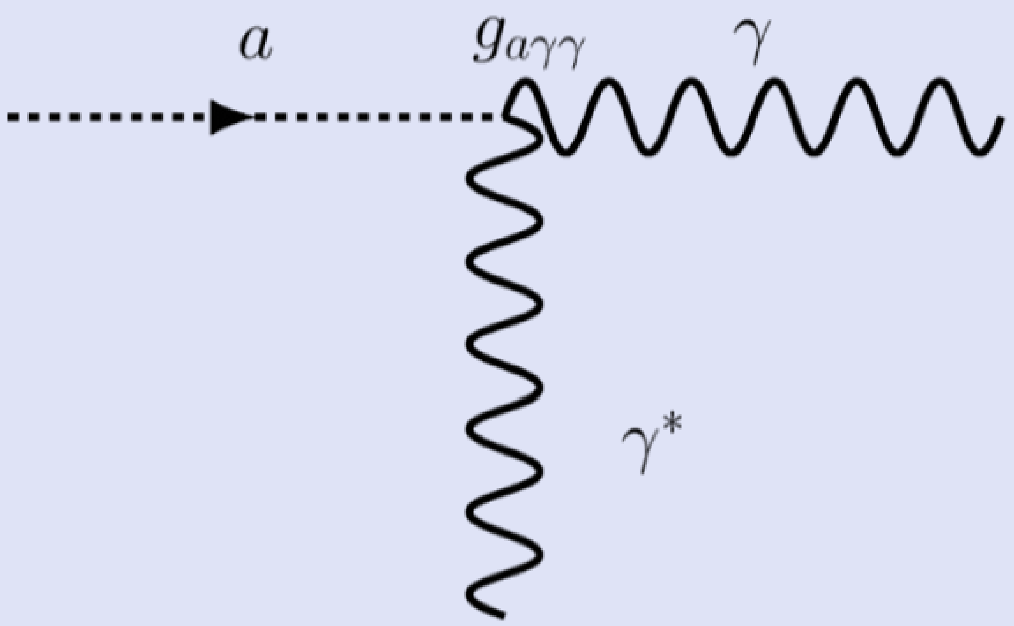
Inverse - Primakoff Effect

# Theory

## Axions

- magnetic field enables conversion
- more conditions to detect the signal

$$L_{a\gamma\gamma} = g_{a\gamma\gamma}\, a(t)\, \mathbf{E} \cdot \mathbf{B}$$

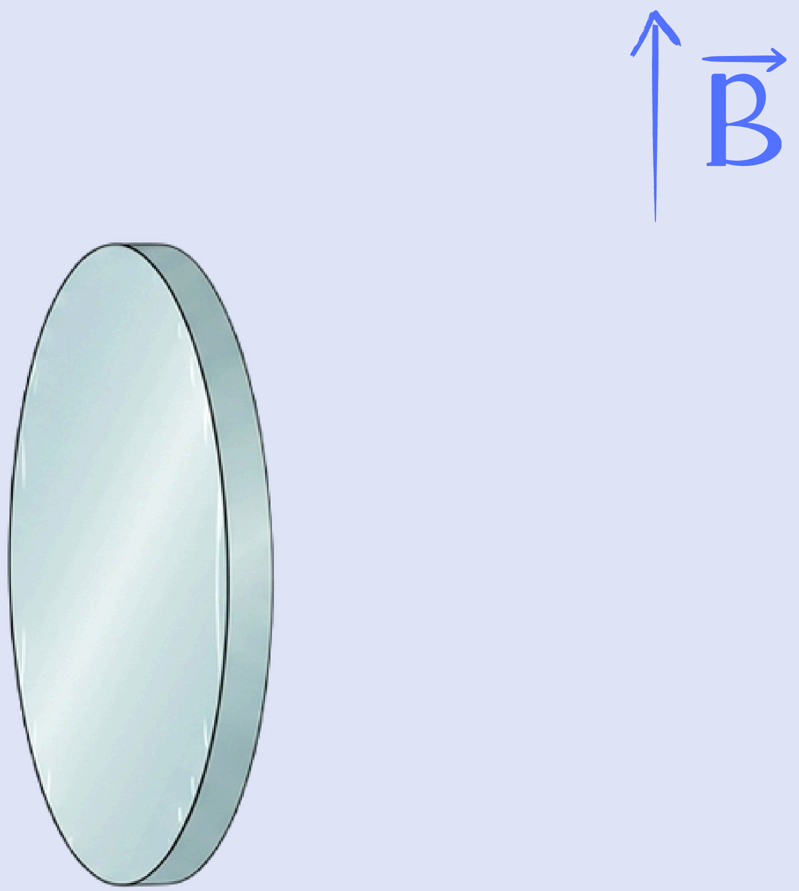



Inverse - Primakoff Effect

# Experiment

## Axions

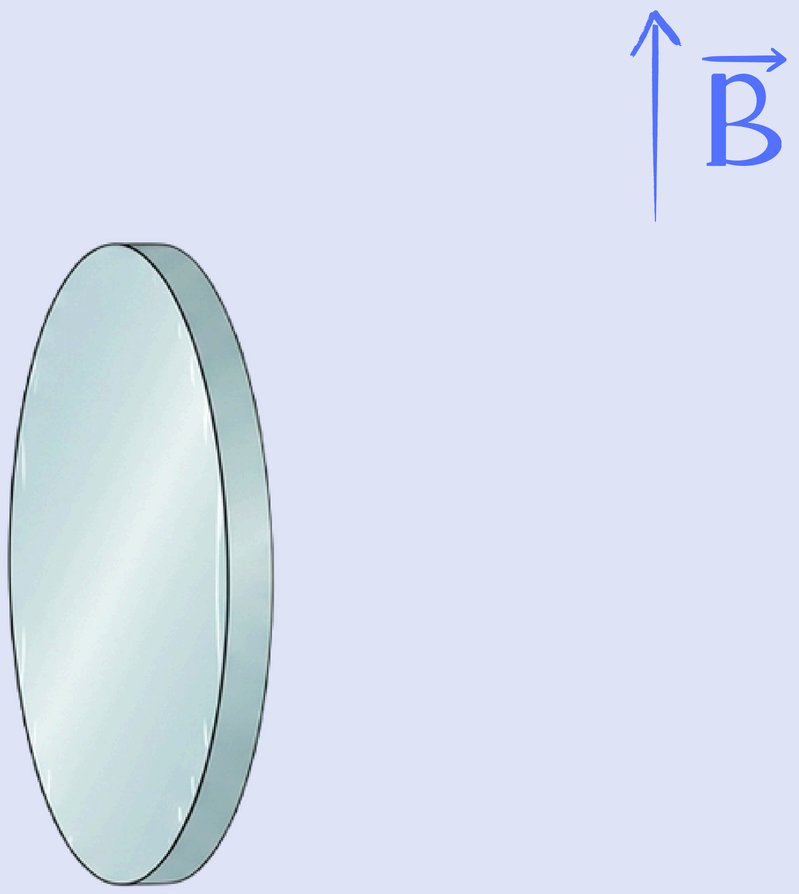
A dielectric interface will emit a tiny amount of EM radiation when placed in a magnetic field parallel to its surface.



# Experiment

## Axions

A single surface produces a very faint signal...



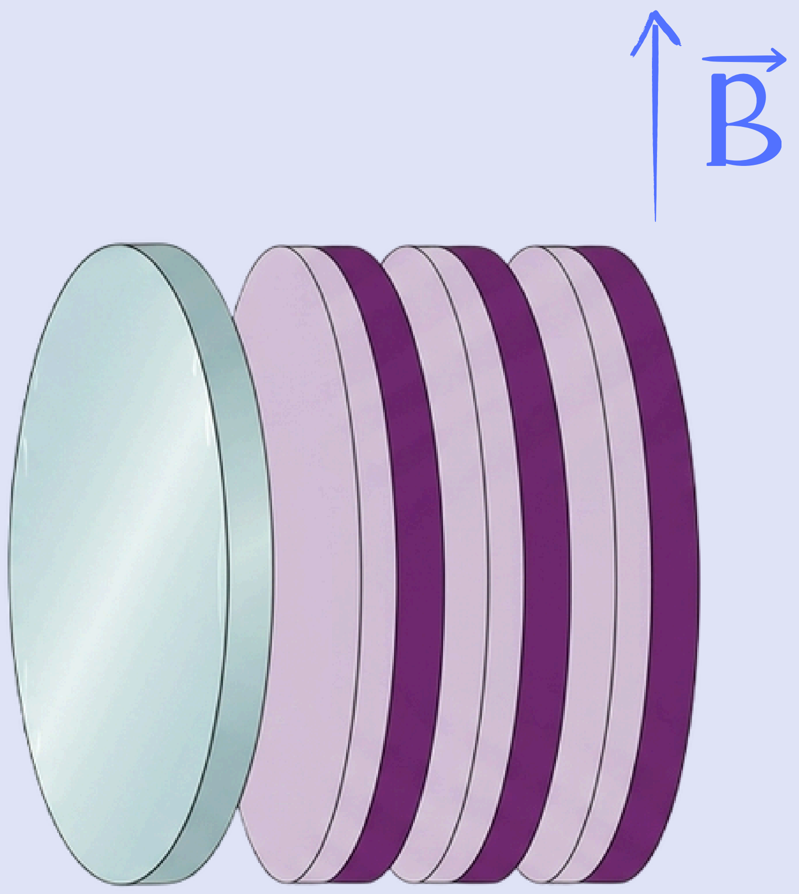
# Experiment

## Axions

A single surface produces a very faint signal...

A haloscope enhances this by:

- stacking multiple layers
- constructive interference



# DALIL

## Target

**“axion”**
a non-relativistic dark matter particle candidate

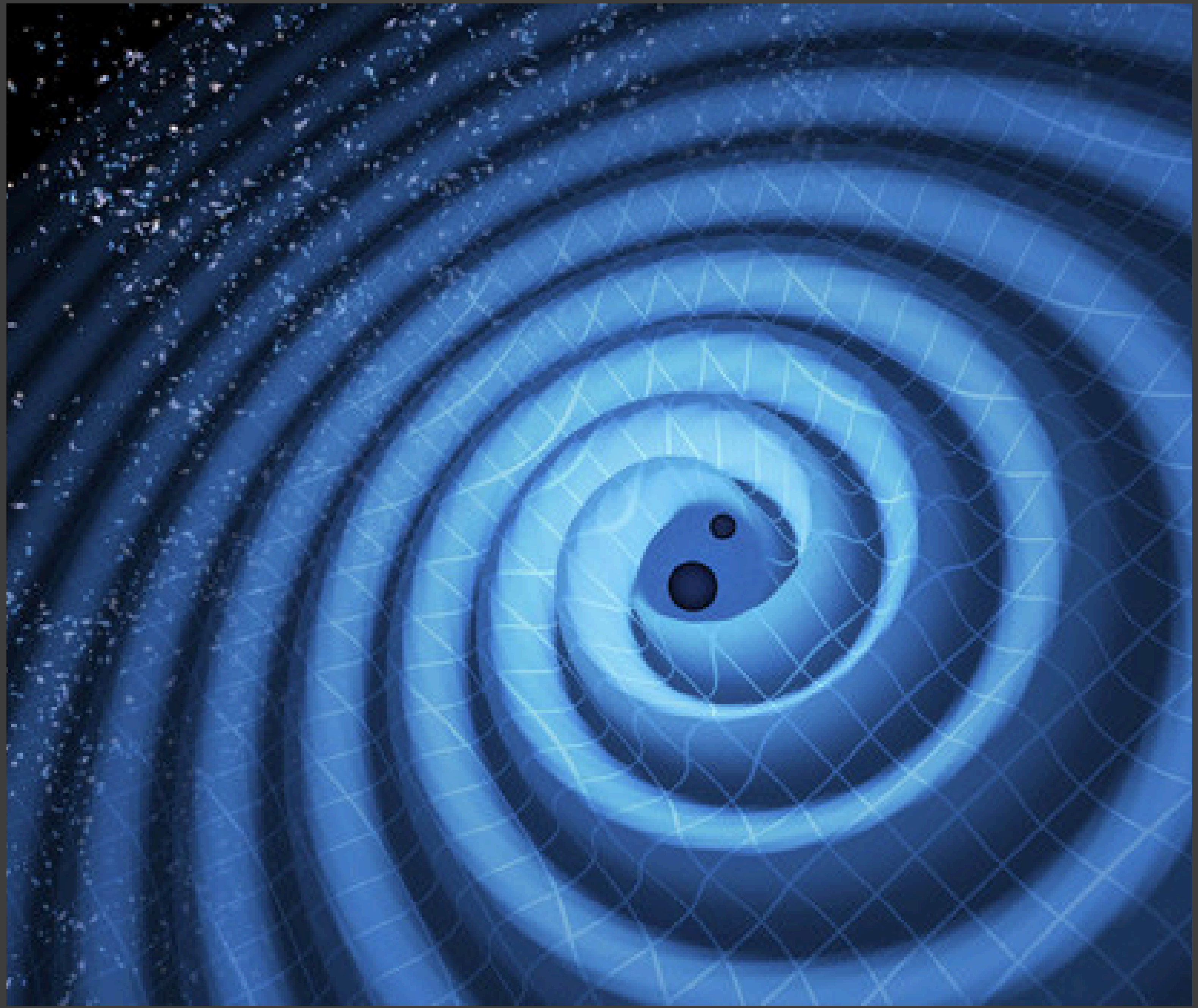
## Principle

axion field → EM waves directly at the surfaces of dielectric disks

## Detector

**dielectric haloscope**

- dielectric layers + static magnetic field for conversion
- photosensor for detecting converted photons



Adapted from LIGO Scientific Collaboration (2025)

# Gravitational Waves

## a new target for haloscopes

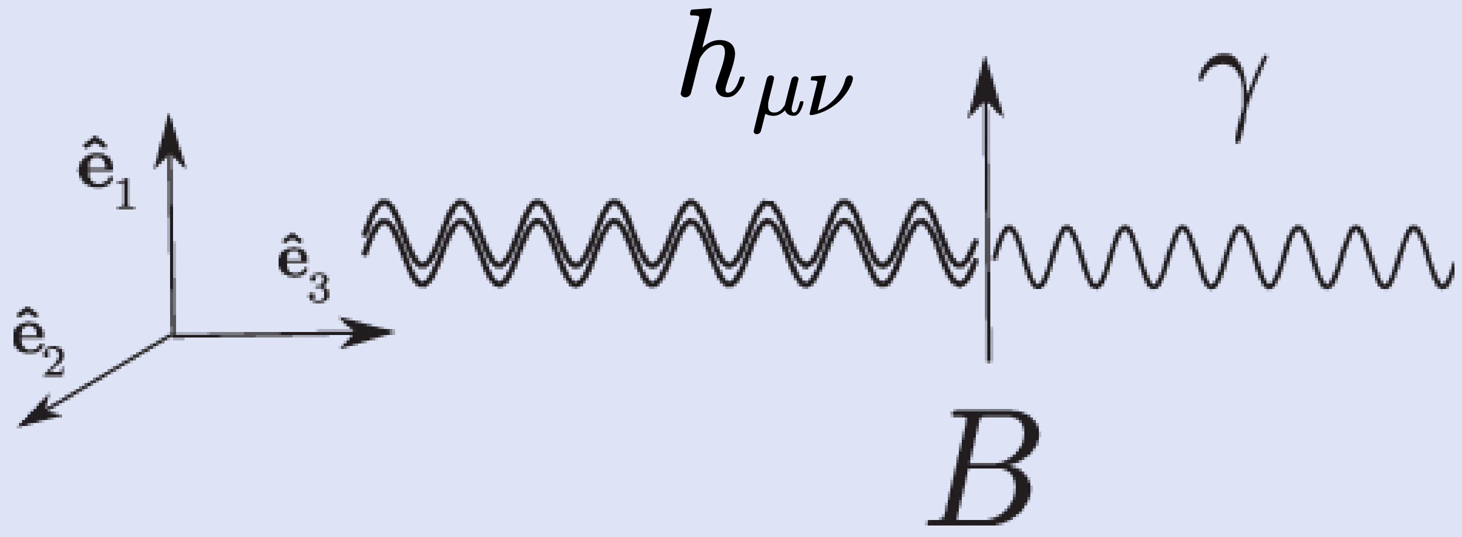
# Theory

## Gravitational Waves

- magnetic field enables conversion
- Inverse Gertsenshtein effect

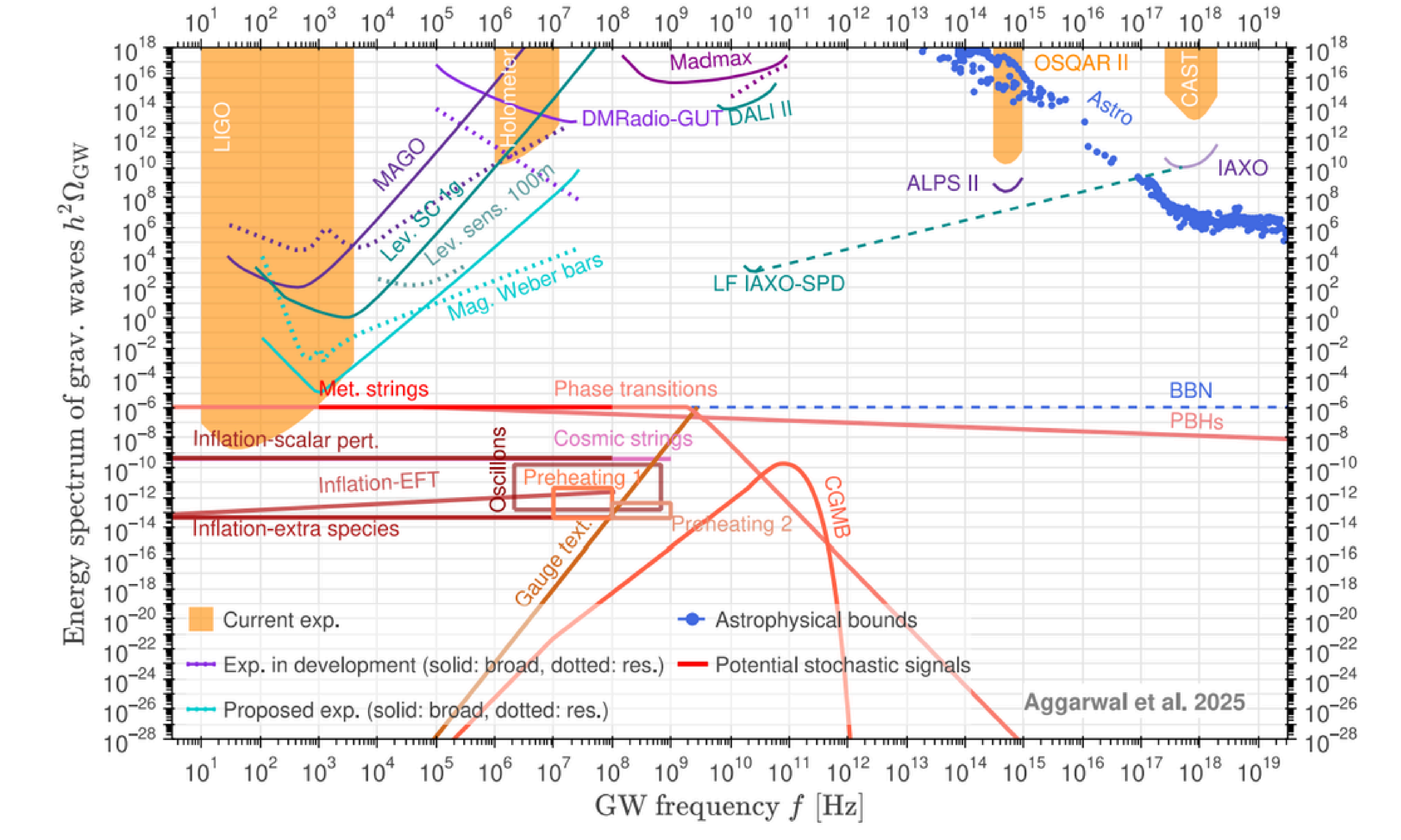
$$\mathcal{L} \supset \frac{1}{2} h_{\mu\nu} T^{\mu\nu}$$

$$\mathcal{L} \supset h_{\mu\nu} F_h{}^{\nu}{}_{\alpha} F_0^{\mu\alpha} + \ldots$$



# Detection

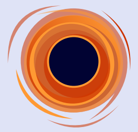
- ultra-high frequency range inaccessible by traditional experiments



# GW Detection

## GW Target

- for the same axion haloscope setup ~ $m_a$ 1-1.5 eV target:
  GW frequency ~300-400 THz

- possible sources in this frequency range
  - GW spectrum of the sun 
    - spans $10^{12}$ to $10^{19}$ Hz
  - evaporating primordial black holes 
    - peak between $10^{13}$ & $10^{22}$ Hz

# GW Detection

## GW Target

- for the same axion haloscope setup ~ $m_a$ 1-1.5 eV target:
  GW frequency ~250-360 THz

- possible sources in this frequency range
  - New Physics!

# DALIL - GW Detection

## Target

**“gravitational wave”**
ripples in spacetime
relativistic nature

## Principle

inverse Gertsenshtein effect:
incoming gravitational wave in the presence of a magnetic field sources an effective current

## Detector

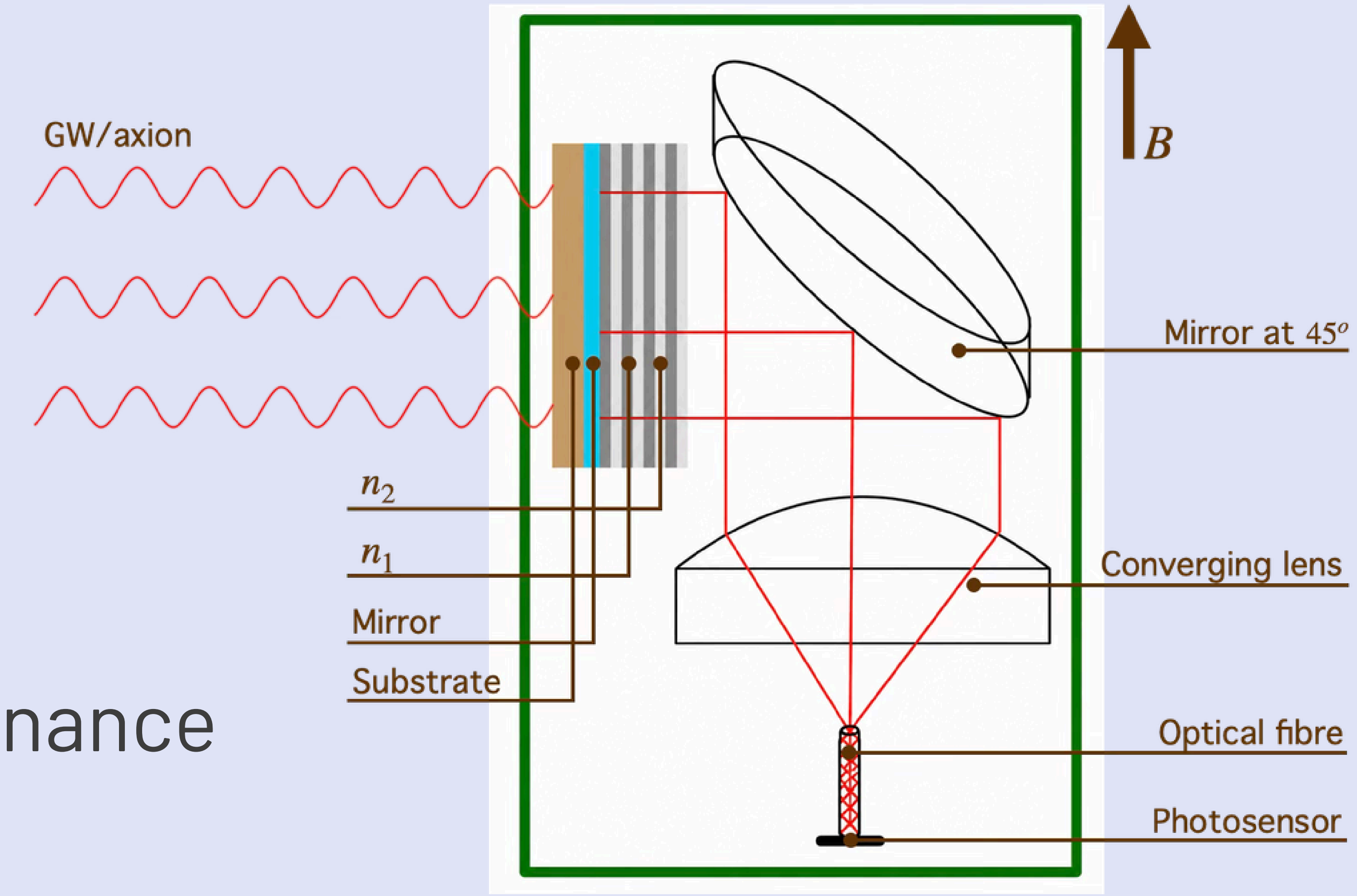
**dielectric haloscope**

- dielectric layers + static magnetic field for conversion
- photosensor for detecting converted photons

# DALIL

## Haloscope components:

- 25 dielectric layers of $Si_3N_4$ & $SiO_2$
- 2 mirrors
- converging lens
- SPAD
- set-up prepared for Nuclear Magnetic Resonance (NMR) machine ~ 14 T



# DALIL

**Haloscope components:**

- 25 dielectric layers of $Si_3N_4$ & $SiO_2$
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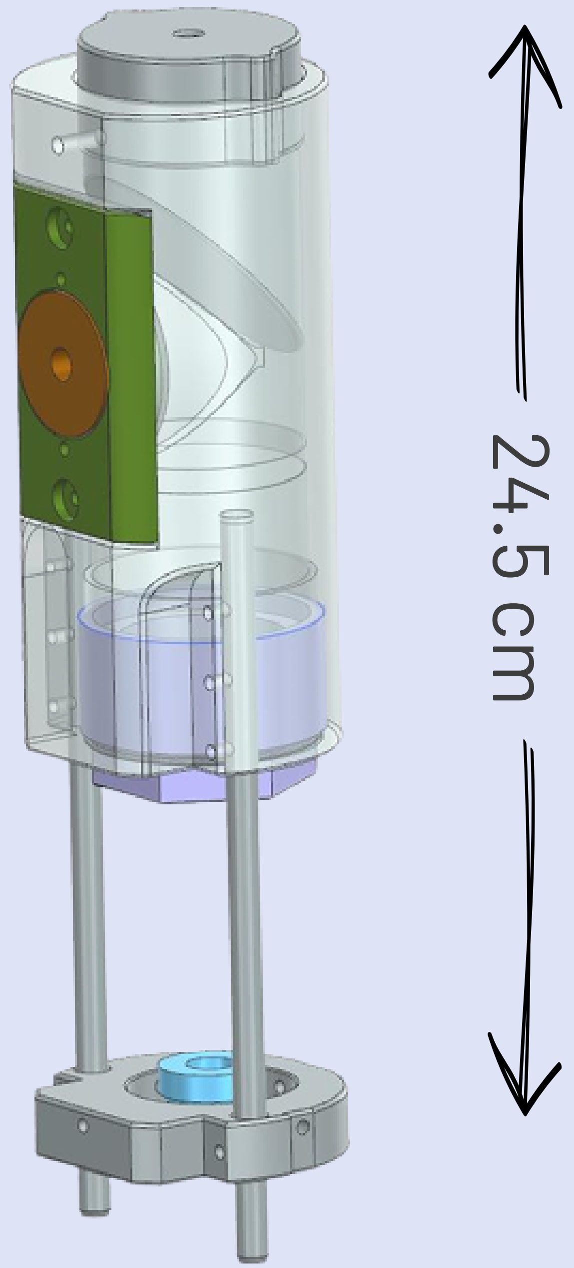


# GW Detection (repurposing)

***non-relativistic light particle → relativistic massless metric perturbations***

Vacuum interaction & massless resonance:

- GWs & photons both massless
- travel at the same speed in vacuum
- additional enhancement that is absent in axion case

# GW Detection (repurposing)

***non-relativistic light particle → relativistic massless metric perturbations***

Direction and phase inheritence

- phase factor
- propagation direction

# GW Detection - Sensitivity

Sensitivity estimation methodology

- strength of the expected signal from GW
- noise in the detector

$$(\boldsymbol{S}^{h}_{noise})^{1/2} \propto \frac{\text{Noise (Dark Counts)}^{1/4}}{\text{Stack Area} \times \text{Magnetic Field} \times \text{Boost Factor} \times \text{Frequency} \times \text{Length}}$$

# GW Detection - Sensitivity

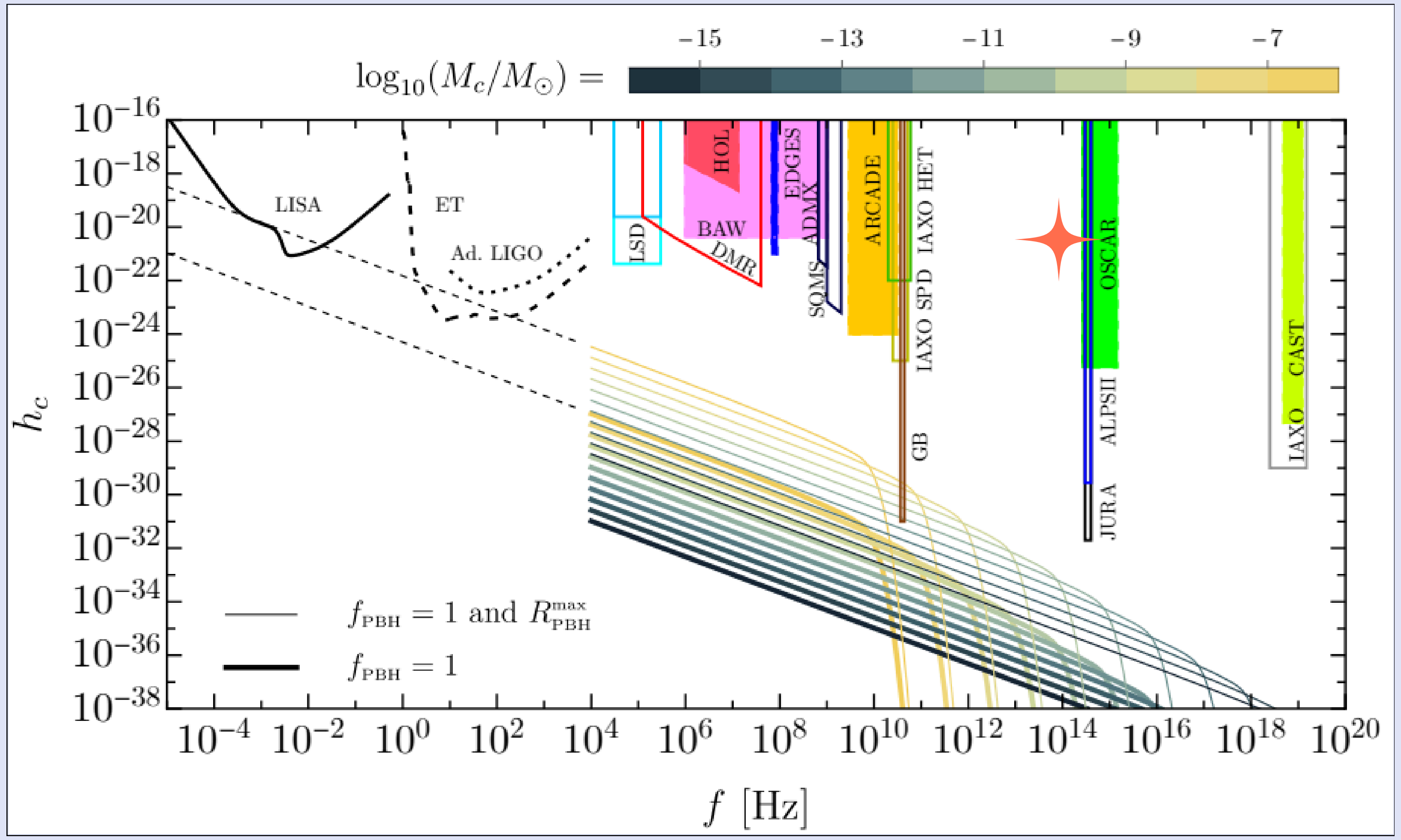
Sensitivity estimation methodology

- strength of the expected signal from GW
- noise in the detector

$$(S_h^{\text{noise}})^{1/2} \simeq 4 \times 10^{-21}\ \text{Hz}^{-1/2} \frac{1}{\beta} \left(\frac{1}{\eta}\right)^{1/2} \left(\frac{100\ \text{cm}^2}{A_{\text{eff}}}\right)^{1/2} \times \left(\frac{10\ \text{T}}{B}\right) \left(\frac{10\ \mu\text{m}}{\ell}\right) \left(\frac{3.7 \times 10^{14}\ \text{Hz}}{f}\right) \times \left(\frac{\dot{N}_{\text{dc}}}{1\ \text{Hz}}\right)^{1/4} \left(\frac{\Delta f}{10^{13}\ \text{Hz}}\right)^{1/4}$$

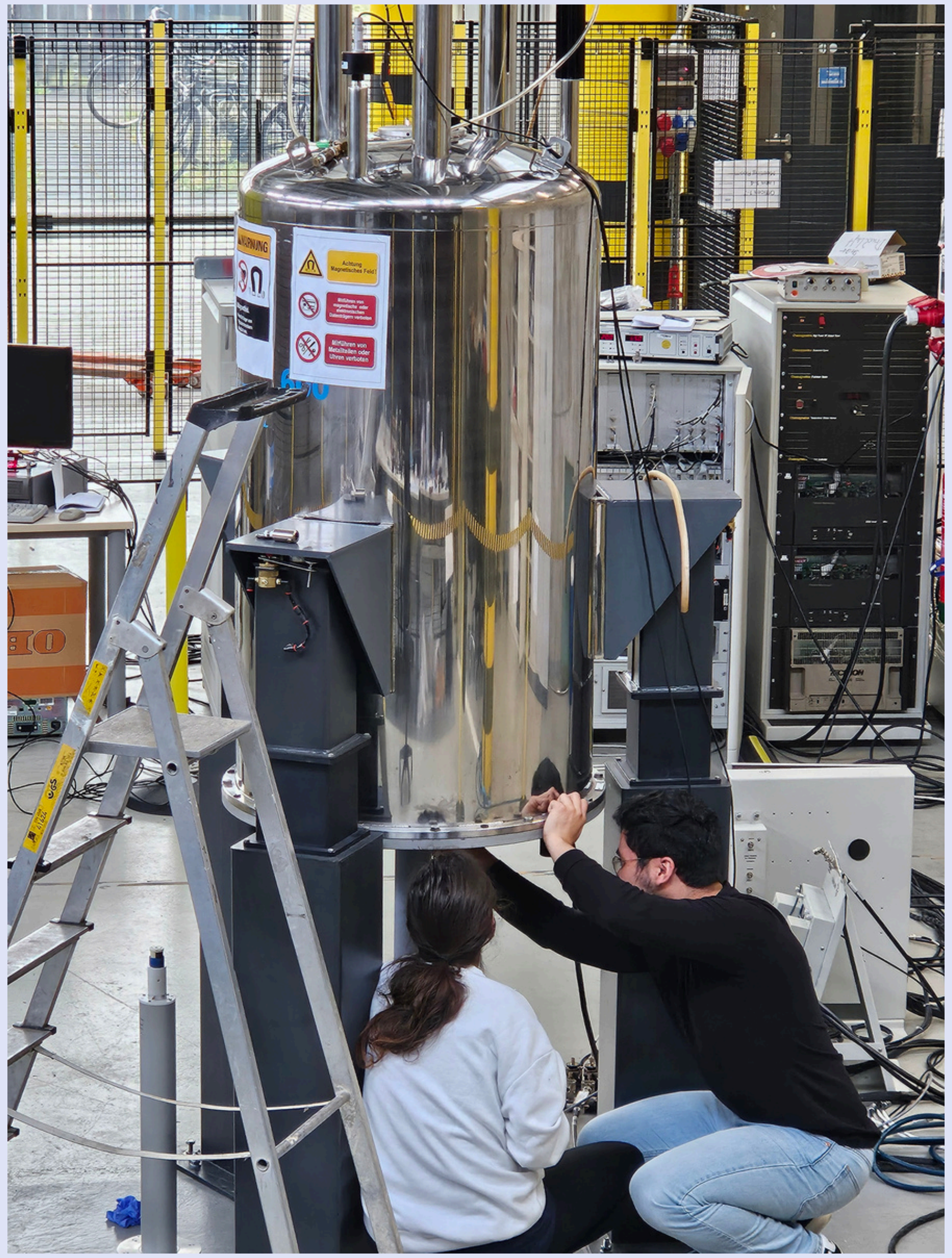
# GW Detection - Sensitivity

sensitivity ~ $10^{-20}\ Hz^{-1/2}$



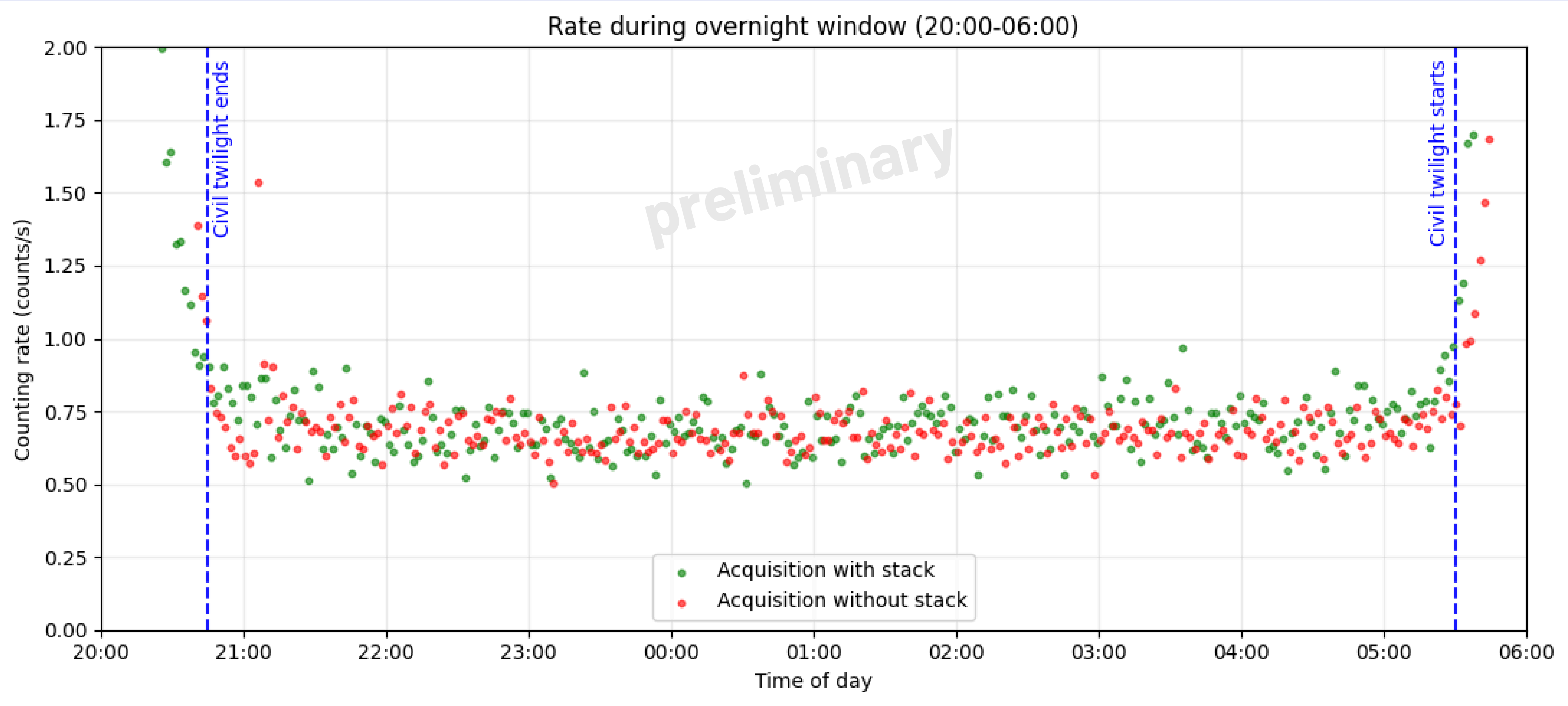

Adapted from Franciolini et al. (2022)

# First Run

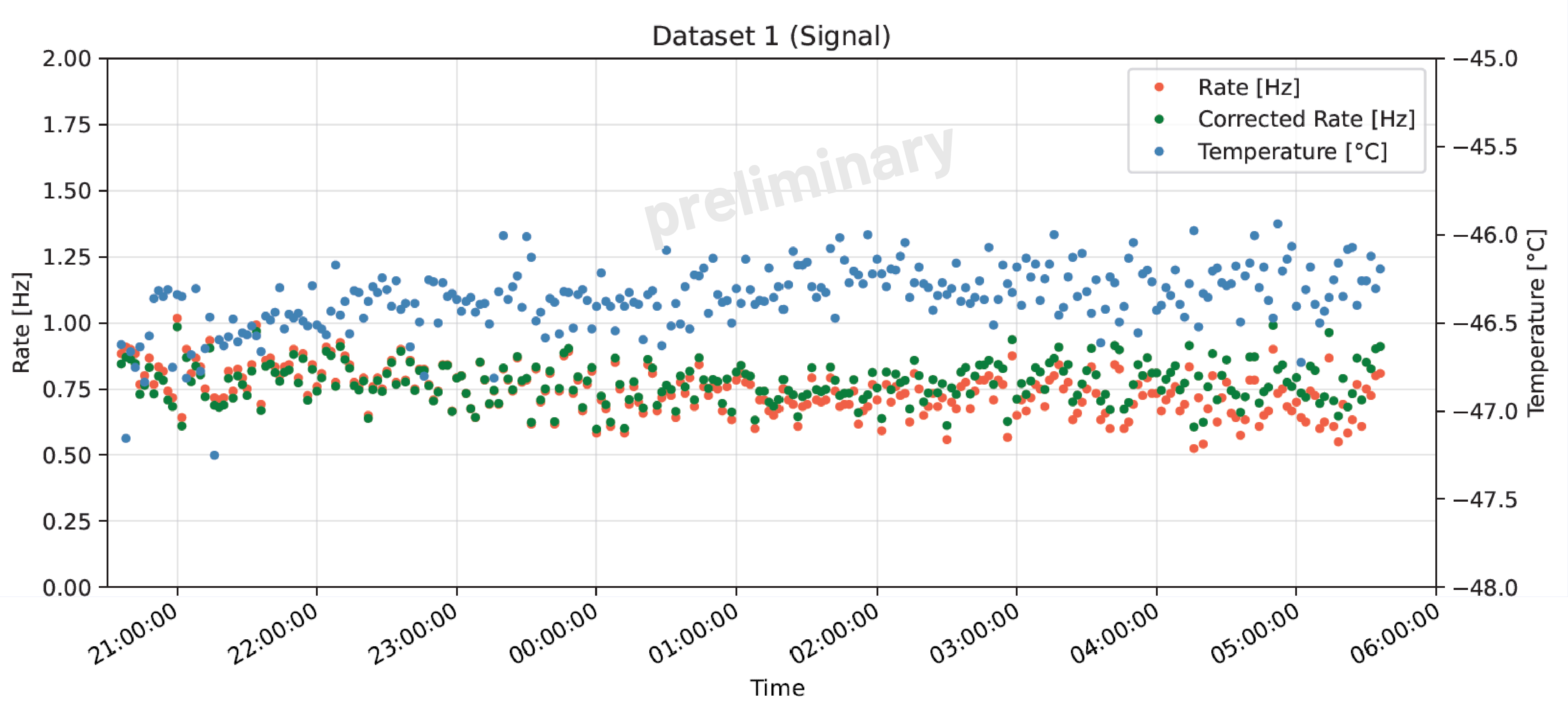



*@ Helmholtz Zentrum - Berlin*

# First Run


Rate during overnight window (20:00-06:00)
Counting rate (counts/s)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
20:00
21:00
22:00
23:00
00:00
01:00
02:00
03:00
04:00
05:00
06:00
Time of day
Civil twilight ends
Civil twilight starts
preliminary
Acquisition with stack
Acquisition without stack

# First Run




data analysis
in process

# Future Steps

**To improve in this haloscope**

- more precision in aligning the components (lens, mirror)
- optimization of the optical system
- more stability in the cooling system

→ potentially conducting a 2nd run by the end of the year

# Future Steps

**To improve for better detection**

- replacing SPAD with a photosensor with a significantly lower DCR
- increasing the effective area/conversion length of the haloscope
- stronger magnetic field

$$(S_h^{\text{noise}})^{1/2} \simeq 4 \times 10^{-21}\ \text{Hz}^{-1/2}\, \frac{1}{\beta}\left(\frac{1}{\eta}\right)^{1/2}\left(\frac{100\ \text{cm}^2}{A_{\text{eff}}}\right)^{1/2} \times \left(\frac{10\ \text{T}}{B}\right)\left(\frac{10\ \mu\text{m}}{\ell}\right)\left(\frac{3.7\times 10^{14}\ \text{Hz}}{f}\right) \times \left(\frac{\dot{N}_{\text{dc}}}{1\ \text{Hz}}\right)^{1/4}\left(\frac{\Delta f}{10^{13}\ \text{Hz}}\right)^{1/4}$$

# Summary

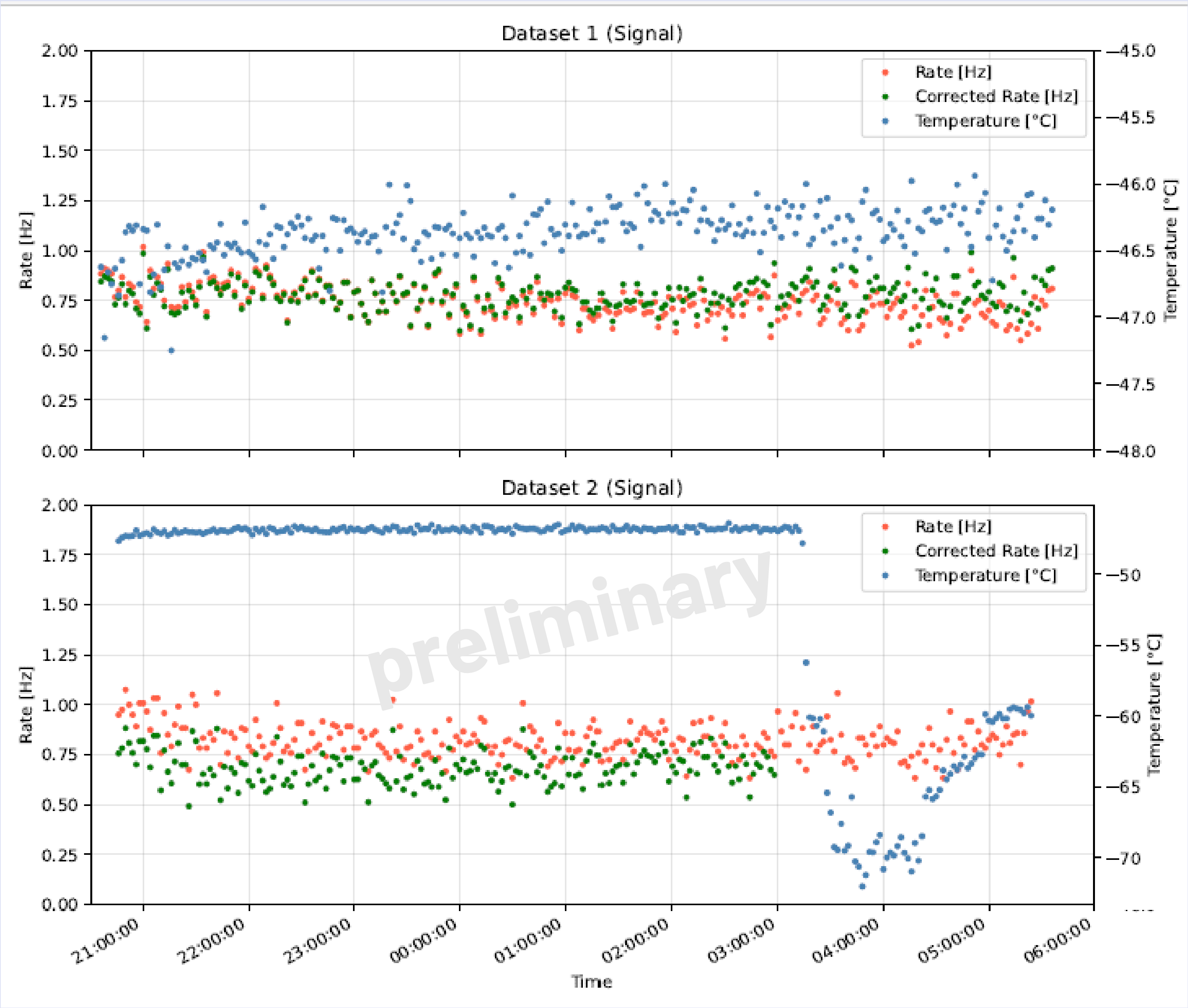
Dark-matter Axion Haloscope with Dielectric Layers [DALIL] experiment

- aimed at detecting axions [$m \sim 1\text{-}1.5\ eV/c^2$]
- repurposed for HFGWs search [$f \sim 300\text{-}450$ THz]
  estimated sensitivity $\sim 10^{-20}\ Hz^{-1/2}$
- ongoing data analysis of the first run
- path towards improved sensitivity

# Thank you!

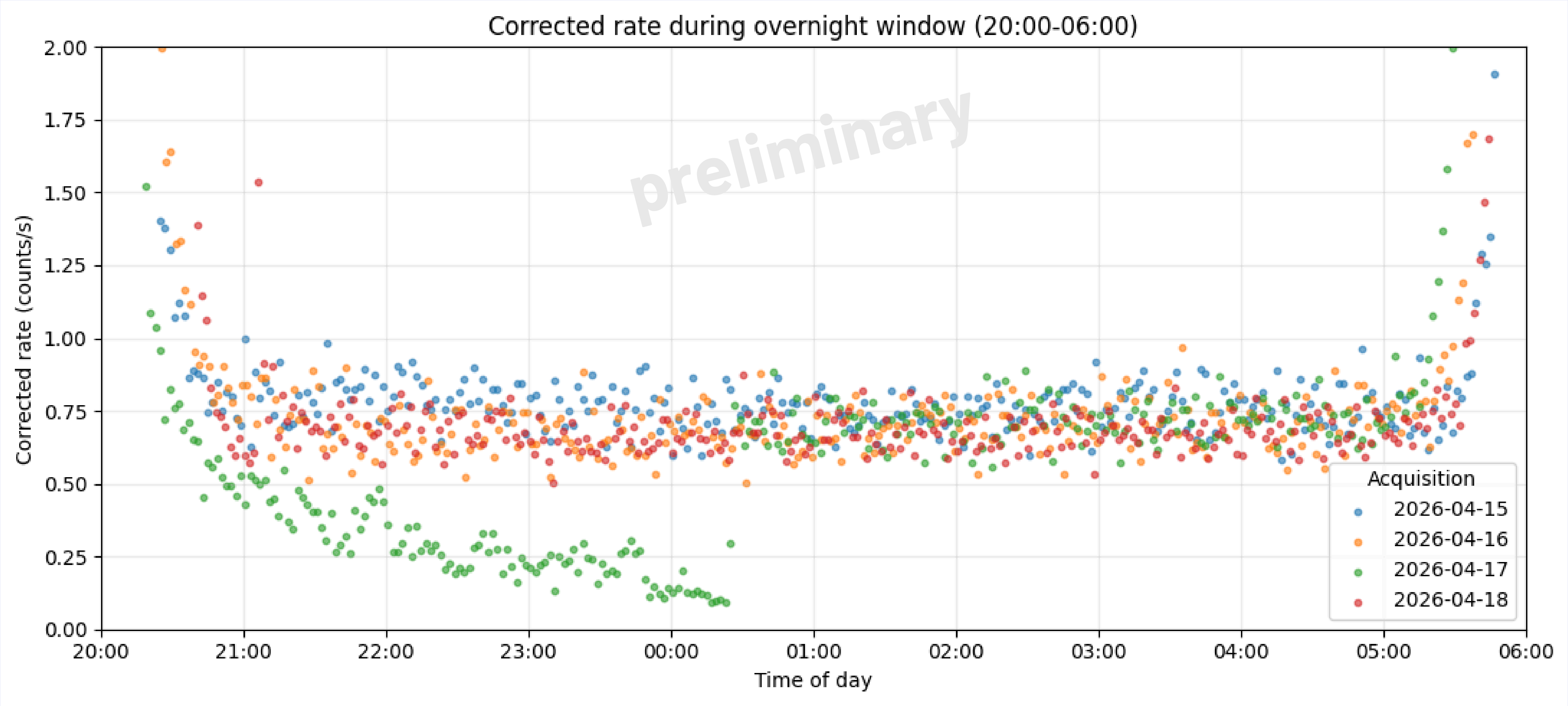
*Special thanks to the team:*
*Prof. Francesco Arneodo, Prof. Fernando Quevedo, Dr. Laura Manenti*
*Dr. Leandro Silveri, Safa Naseem, Dr. Sara Leardini, Dr. Antonio J. Iovino,*
*Dr. Nicolas Bernal, David Benavidez*

# First Run


Dataset 1 (Signal)
Rate [Hz]
Corrected Rate [Hz]
Temperature [°C]
Rate [Hz]
Temperature [°C]
Dataset 2 (Signal)
preliminary
Time
21:00:00
22:00:00
23:00:00
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
06:00:00


Dataset 3 (Signal)
Rate [Hz]
Corrected Rate [Hz]
Temperature [°C]
Rate [Hz]
Temperature [°C]
Dataset 4 (Background)
Time
21:00:00
22:00:00
23:00:00
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
06:00:00

# First Run


Corrected rate during overnight window (20:00-06:00)
preliminary
Corrected rate (counts/s)
2.00
1.75
1.50
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1.00
0.75
0.50
0.25
0.00
20:00
21:00
22:00
23:00
00:00
01:00
02:00
03:00
04:00
05:00
06:00
Time of day
Acquisition
2026-04-15
2026-04-16
2026-04-17
2026-04-18

# Future Steps

**Ideal case of our experiment** *(hypothetical)*

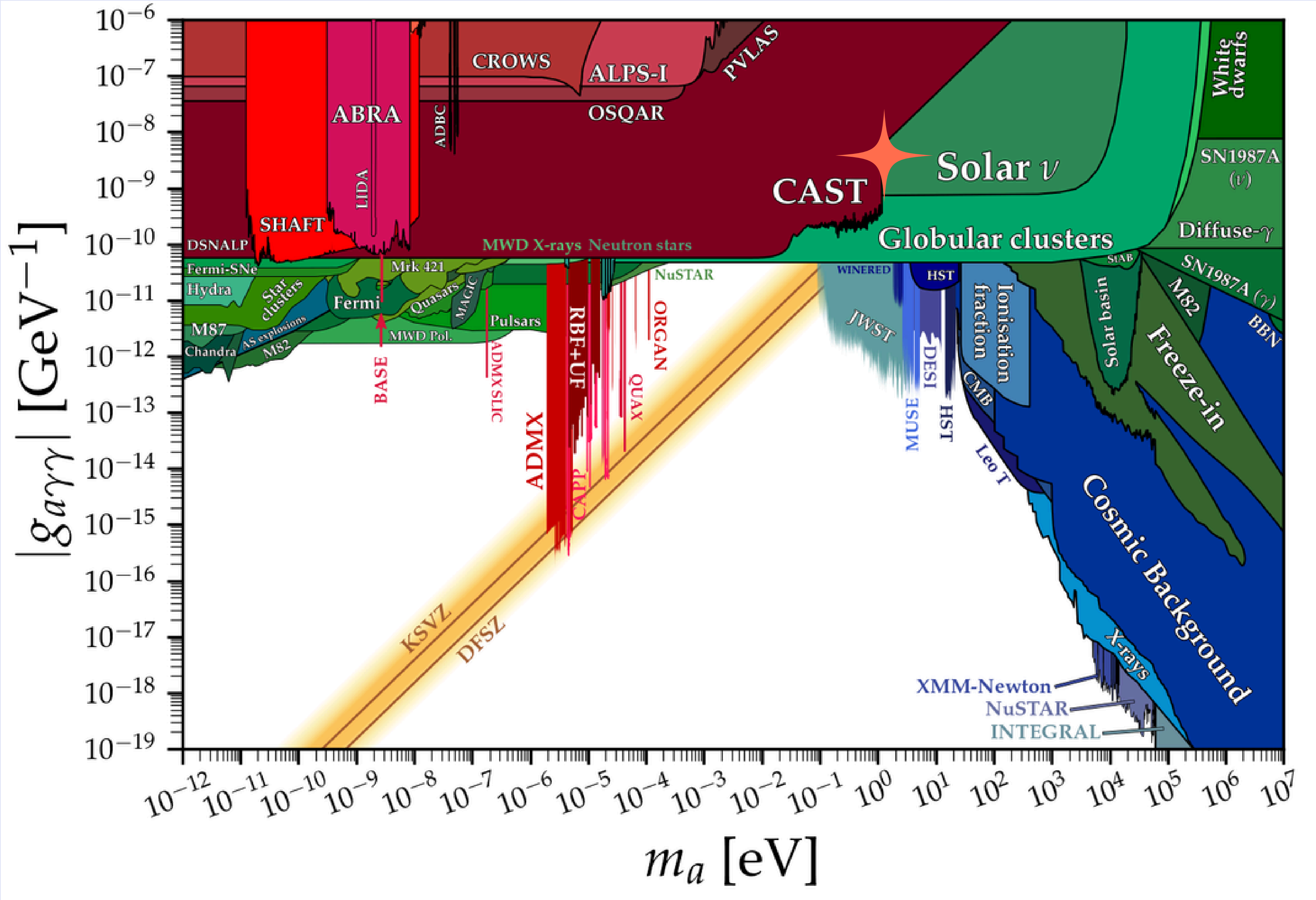
$$\eta = 0.5 \qquad \ell = 1.13mm \qquad \dot{N}_{\rm dc} = 10^{-4}\,\text{Hz}$$

→ **sensitivity ~ $10^{-26}$ Hz$^{-1/2}$**

$$(S_h^{\rm noise})^{1/2} \simeq 4 \times 10^{-21}\ \text{Hz}^{-1/2}\,\frac{1}{\beta}\left(\frac{1}{\eta}\right)^{1/2}\left(\frac{100\ \text{cm}^2}{A_{\rm eff}}\right)^{1/2} \times \left(\frac{10\ \text{T}}{B}\right)\left(\frac{10\ \mu\text{m}}{\ell}\right)\left(\frac{3.7\times 10^{14}\ \text{Hz}}{f}\right) \times \left(\frac{\dot{N}_{\rm dc}}{1\ \text{Hz}}\right)^{1/4}\left(\frac{\Delta f}{10^{13}\ \text{Hz}}\right)^{1/4}$$

# DALIL

**Axion-photon coupling limits vs. axion mass**




Adapted from O'Hare (2020–present)