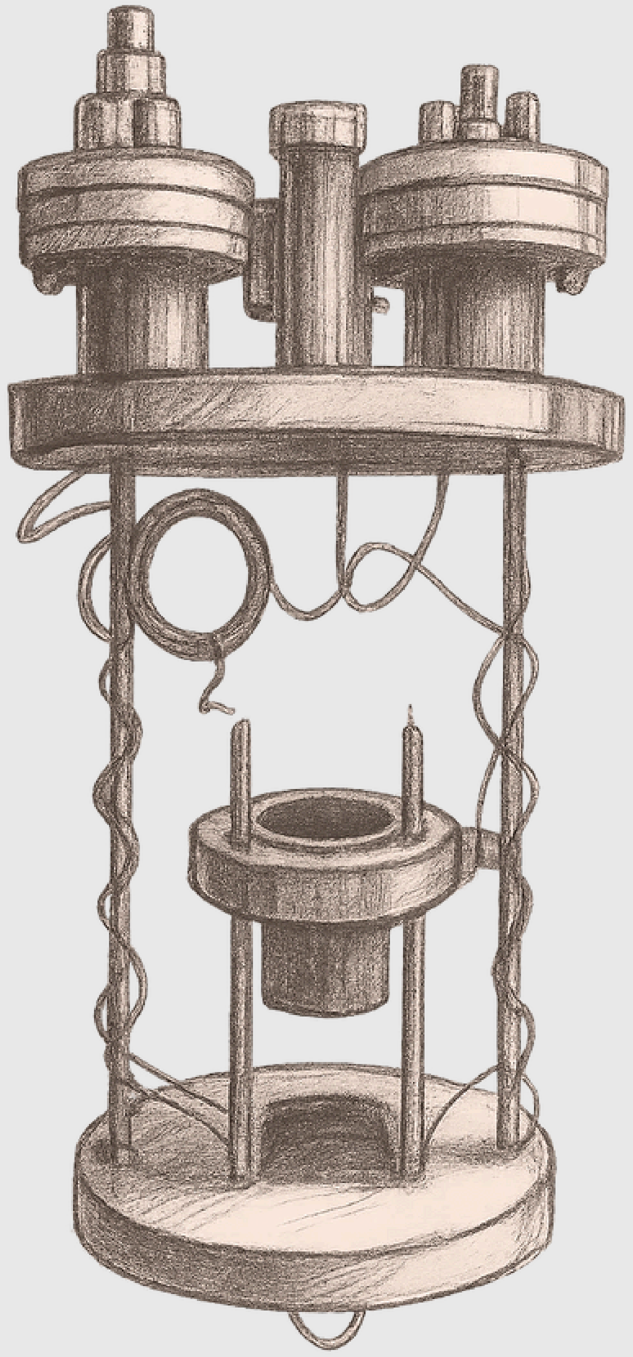
ASTROPARTICLE
PHYSICS LAB

جامعة نيويورك أبوظبي
NYU ABU DHABI

Dielectric Haloscope



Astroparticle Physics Lab

PI: Prof. Francesco Arneodo

Alia Zino

Overview

About the Lab

Dark Matter Search

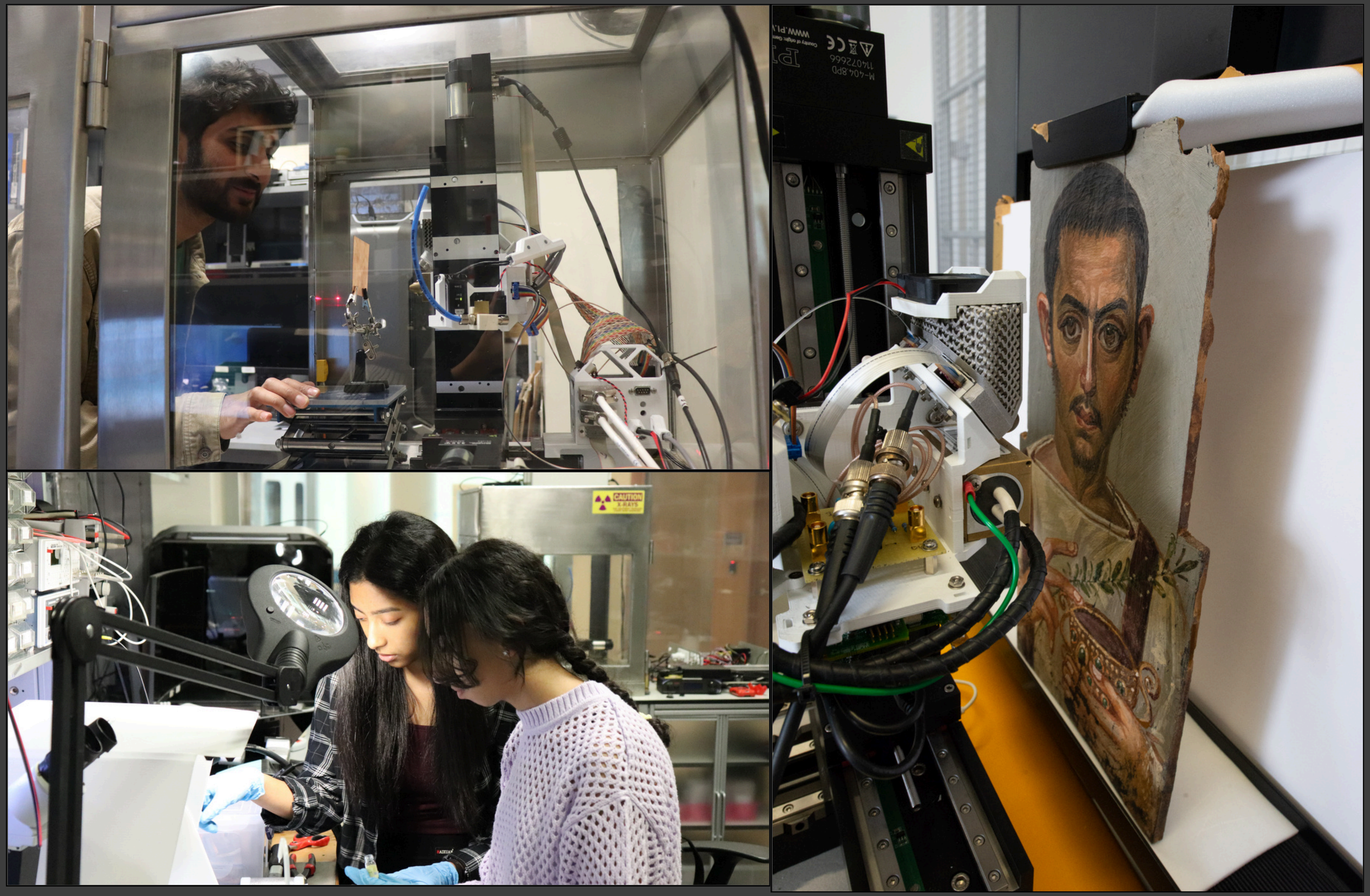
- Dark Photon
- Axion

Gravitational Wave Search

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 - project under development

MuDHI Experiment

Target

“dark photon”
a theorized particle belonging to the "dark sector" - neutral under Standard Model (SM) interactions

Principle

kinetic mixing (vector portal) between a dark boson & ordinary boson

Detector

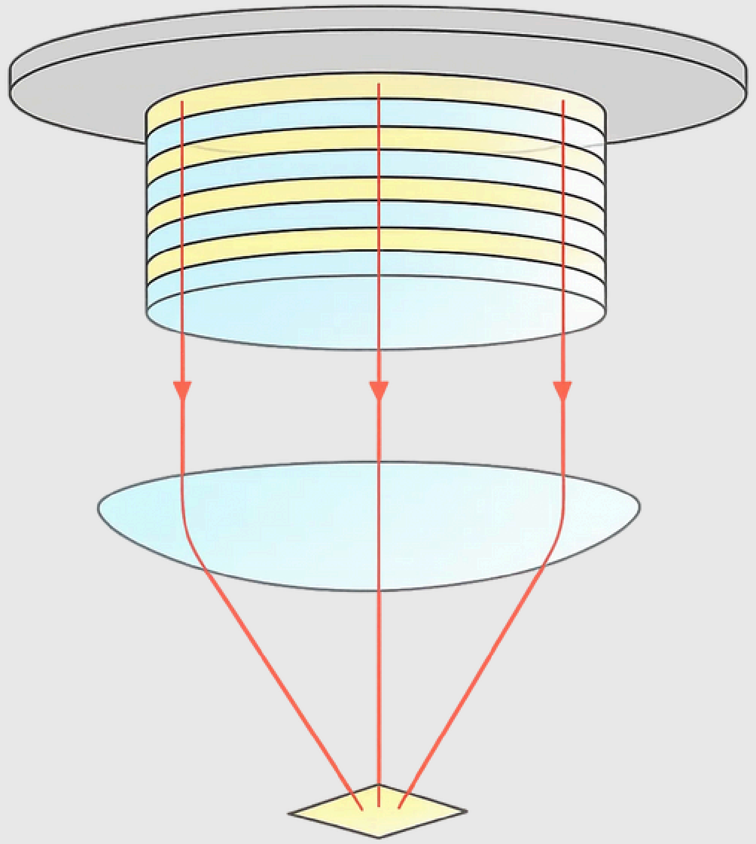
dielectric haloscope

- dielectric layers for conversion
- photosensor for detecting converted photons

MuDHI Experiment

Haloscope components:

- Stack
- Single-Photon sensor
- Lens
- Mirror

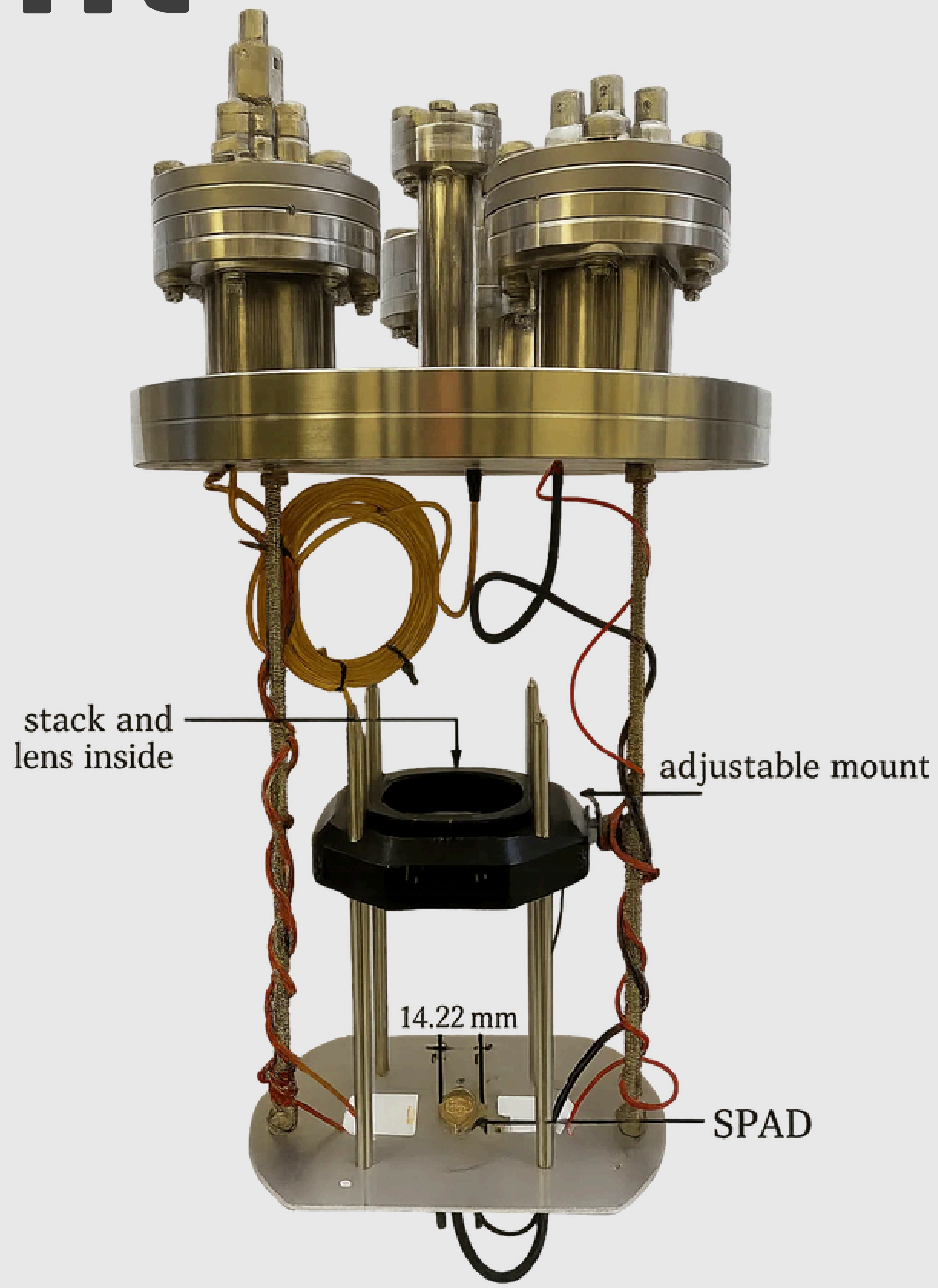


Adapted from Baryakhtar et al. (2018)

MuDHI Experiment

Haloscope components:

- 23 dielectric layers of Si_3N_4 & SiO_2
- SPAD operated in Geiger mode, peak quantum efficiency at 810 nm → $m_{DP} \sim 1.5\ eV/c^2$
- aspherical converging lens
- mirror



MuDHI Experiment

Operation Phases

- **Off Measurement**
  - recording counts without the dielectric stack
  - assumes no DP signal present - measurement of background noise
  - lasted 30 minutes
- **On Measurement**
  - recording counts with stack in place
  - search for potential DP signal
  - lasted 2 hours

MuDHI Experiment

Results

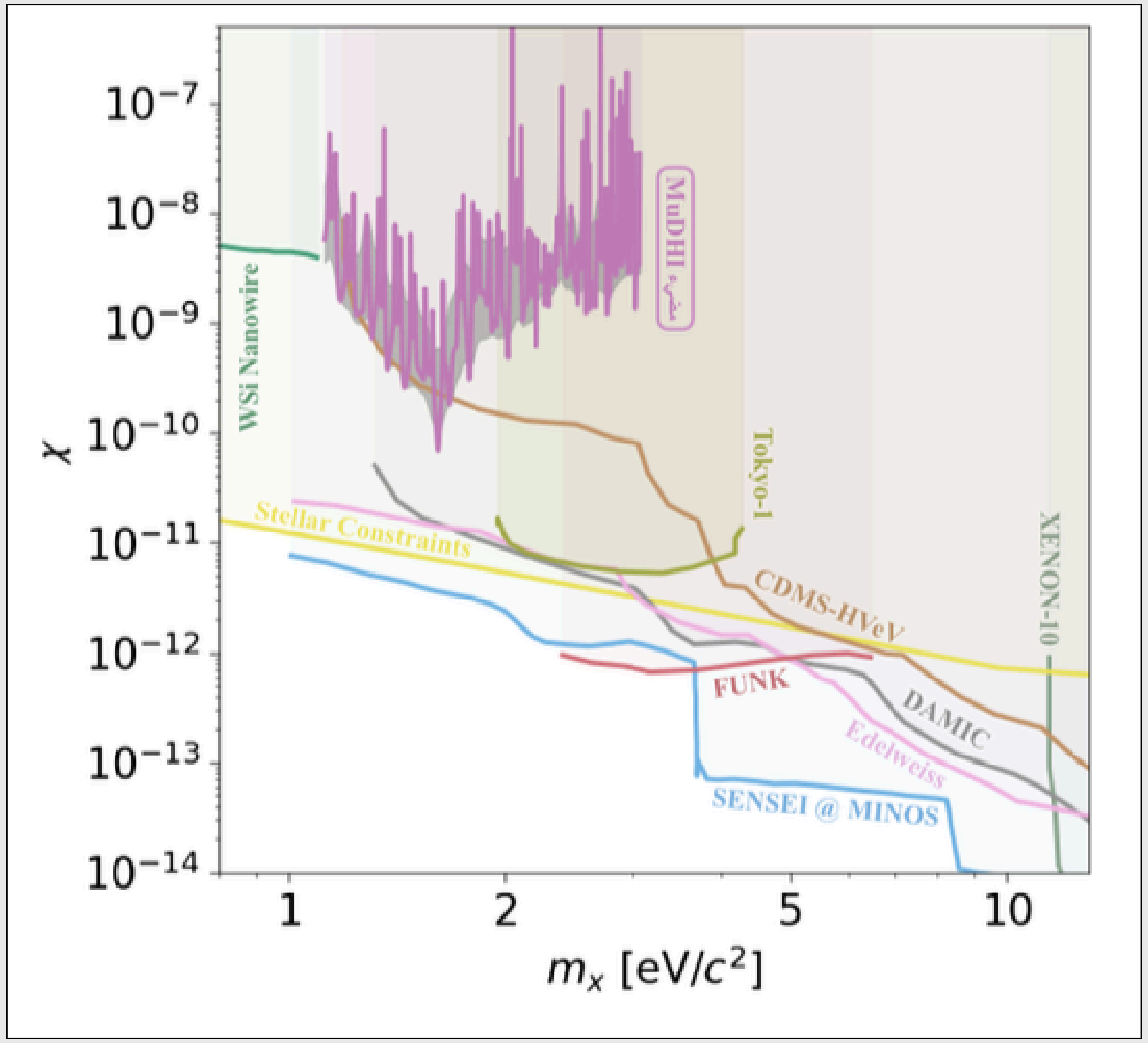
- **final observed count rates**
  - On measurement (with stack): n_{on} = 98.6 Hz ± 2.6 Hz
  - Off measurement (without stack): n_{off} = 96.5 Hz ± 2.3 Hz

The observed count rates (n_{on} and n_{off}) are consistent with **no signal observed**

MuDHI Experiment

Results

- **exclusion limits**
  - max. log likelihood: set **exclusion limits at 90% confidence level (CL)** on the kinetic mixing coupling constant between dark photons and ordinary photons
  - min. kinetic mixing parameter of **6.86×10^{-11}** @ **m_{DP}** of **$1.61\ eV/c^2$**



Adapted from Manenti et al. (2021)

MuDHI Experiment

Results

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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(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.

Axion Haloscope

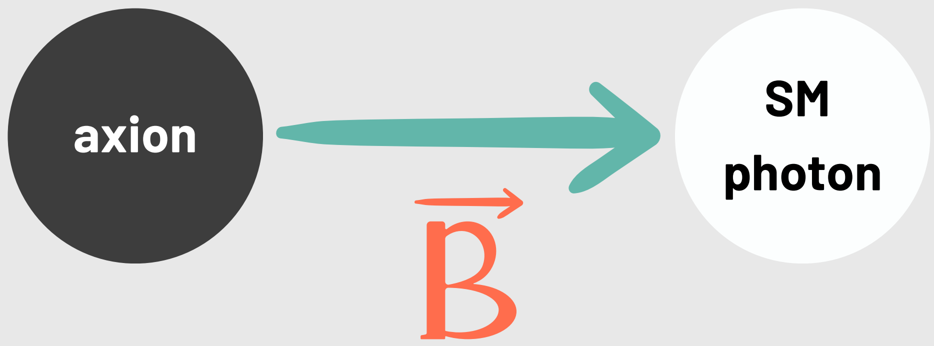
Target

“axion”

a non-relativistic dark matter particle candidate

Principle

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



Detector

dielectric haloscope

- dielectric layers + <u>static magnetic field</u> for conversion
- photosensor for detecting converted photons

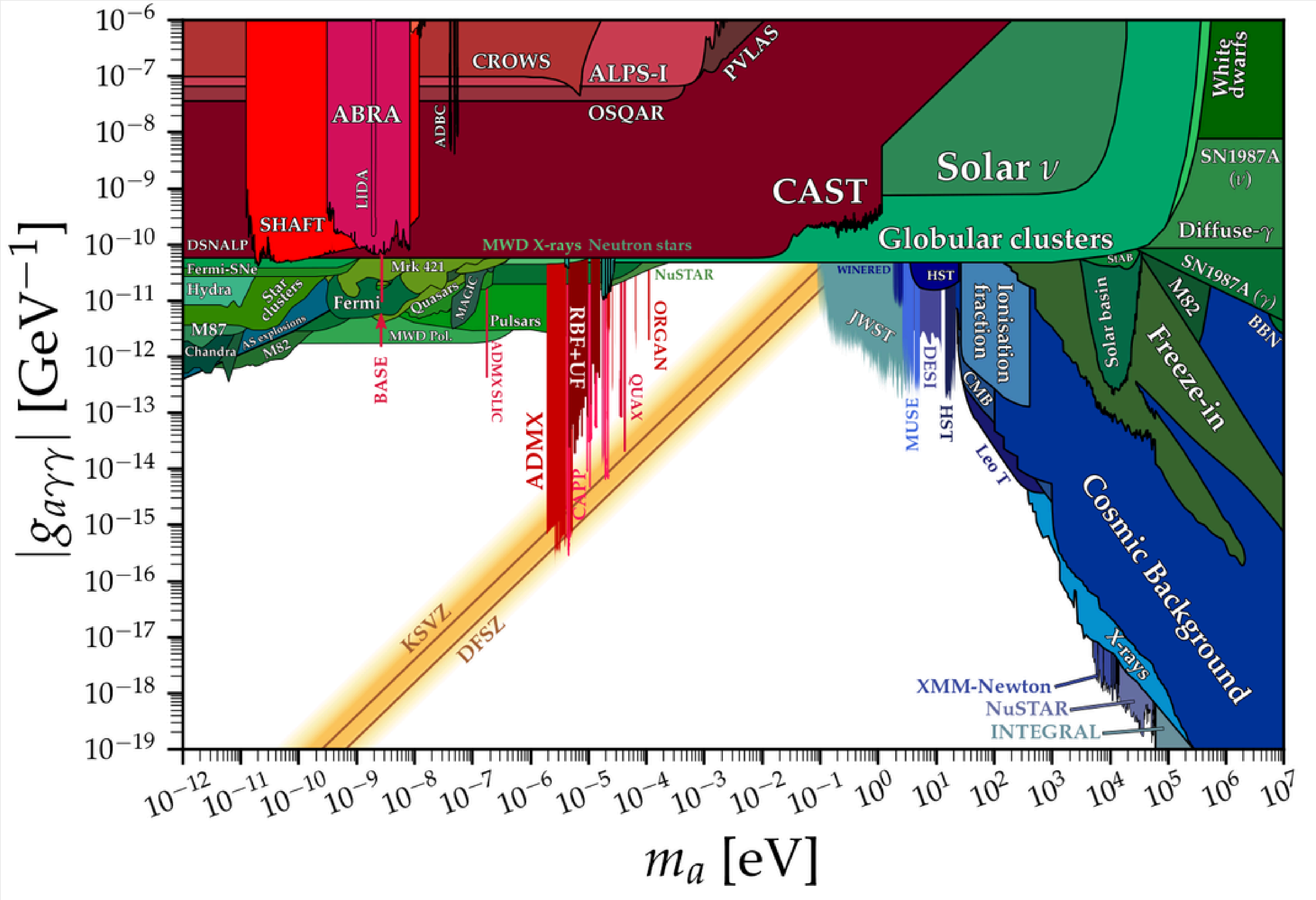
Axion Haloscope

Haloscope components:

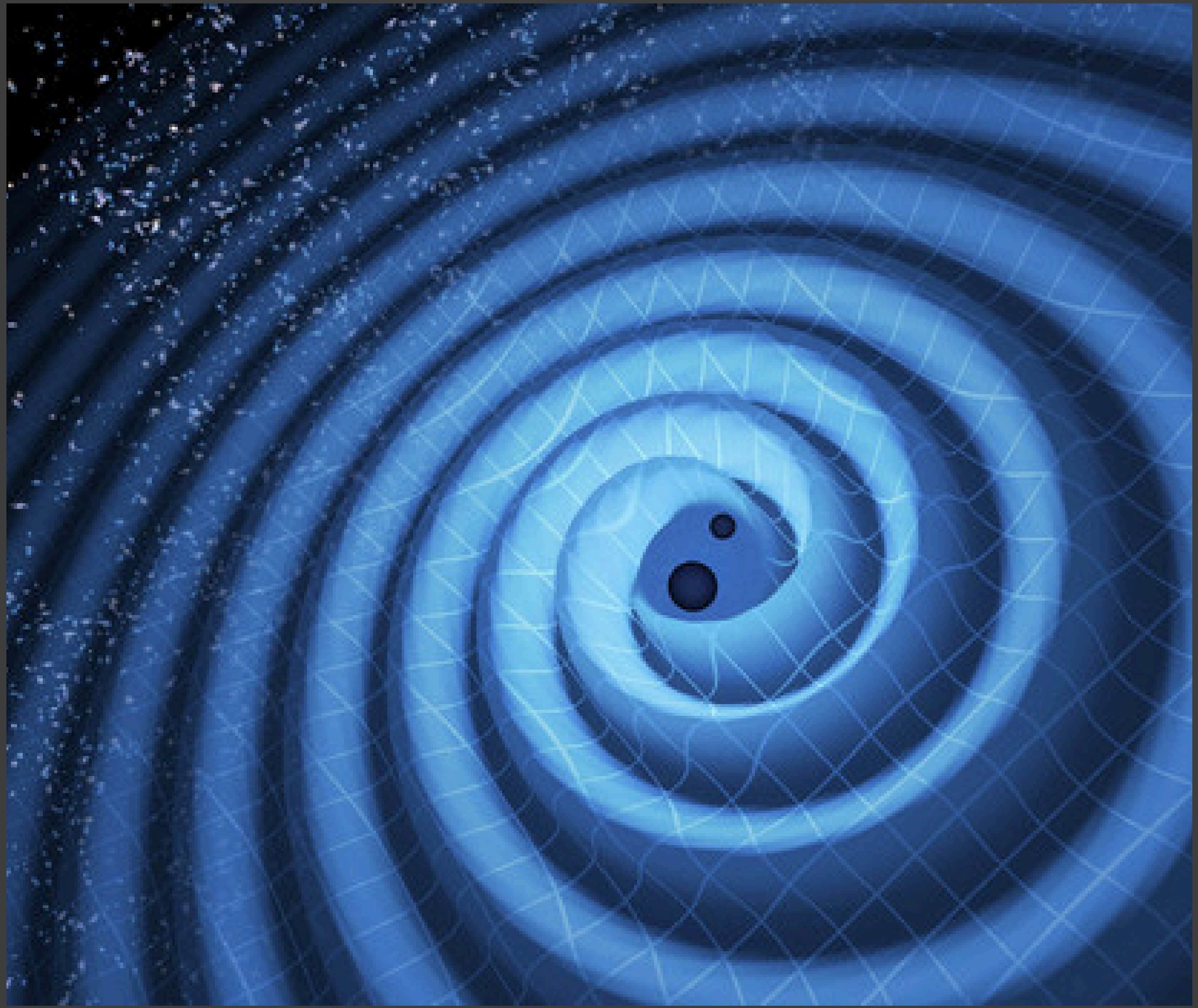
- 25 dielectric layers of Si_3N_4 & SiO_2
- SPAD
- converging lens
- Mirror
- set-up prepared for Nuclear Magnetic Resonance (NMR) machine in NYUAD ~ 14 T

Axion Haloscope

Axion-photon coupling limits vs. axion mass



Adapted from O'Hare (2020–present)



Adapted from LIGO Scientific Collaboration (2025)

Gravitational Waves

a new target for haloscopes

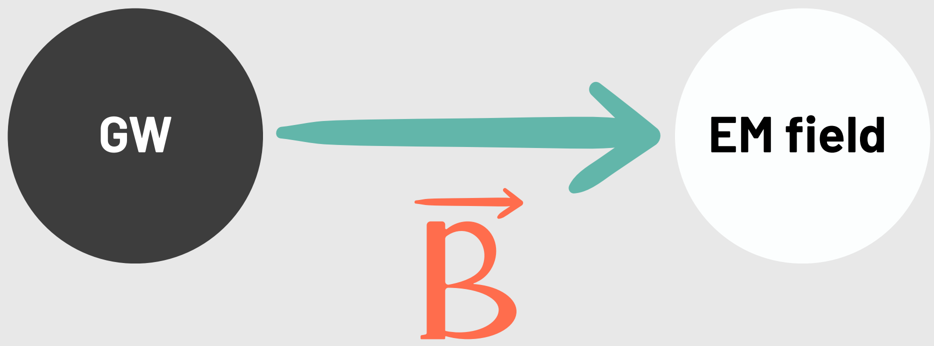
GW Detection

Target

“gravitational wave”
ripples in spacetime
relativistic nature

Principle

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

GW Detection

Main Differences

- GW $\to$ photon conversion also occurs in vacuum
- sourced EM waves inherit:
  - GW phase (position dependent)
  - GW propagation direction

GW Detection

Main Alterations

- operation in multiple modes (vacuum or dielectric stack)
- requirements
  - resonant operation: new requirement on effective disk thickness + limited number of disks
  - relaxed requirement on disk surface smoothness

GW Detection

Options with Axion Haloscope

- operation in GW **resonant mode** (with stack) → target specific frequency
- operation in GW **broadband mode** (without stack) → target frequency range
- next step: **hybrid mode**

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 f range
  - GW spectrum of the sun
  - primordial black holes
    - mergers
    - evaporating

GW Detection

Options with Axion Haloscope

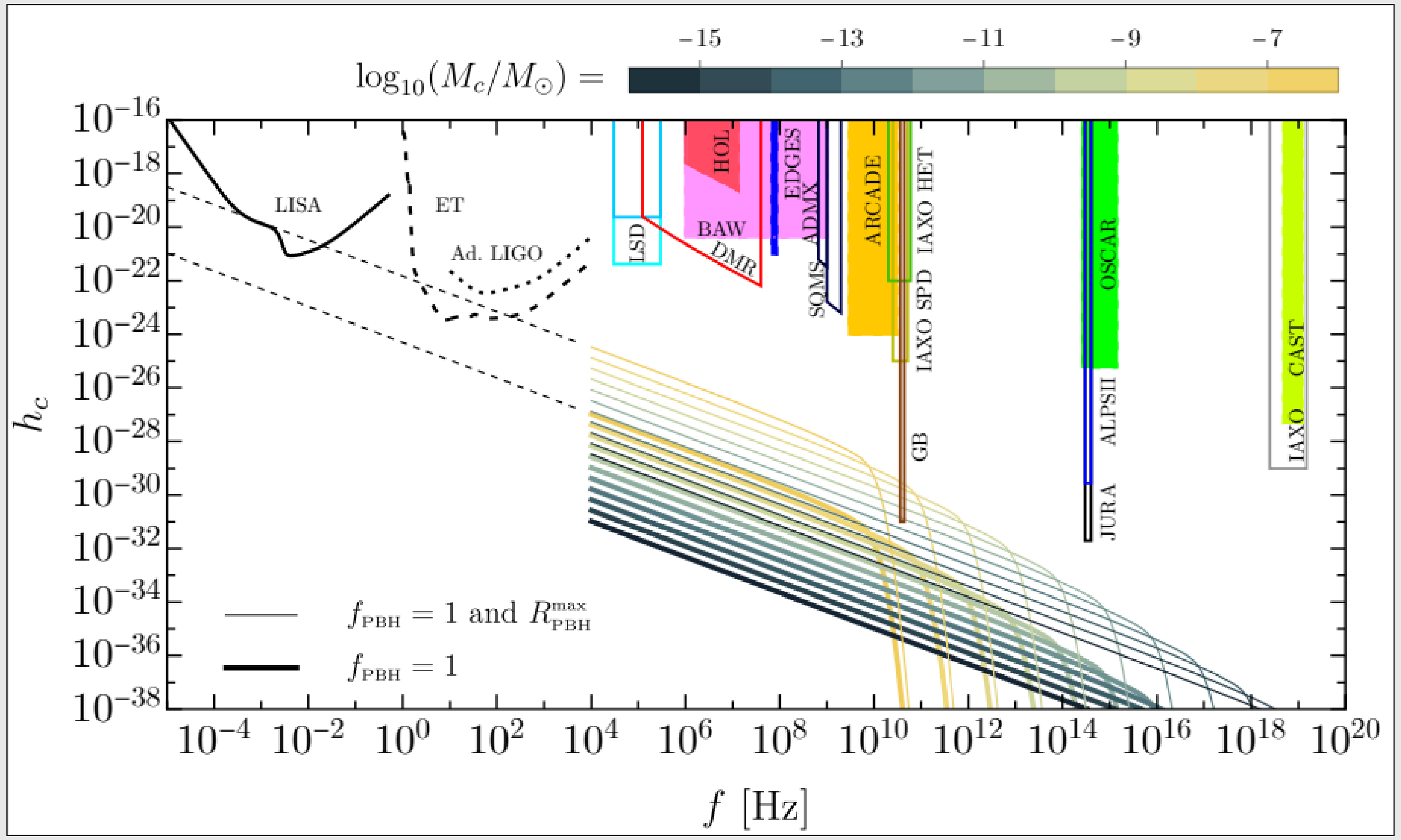
- still in research phase
- estimation of sensitivity - looked into
  - microwave cavity model (ADMX like)

GW Detection

Options with Axion Haloscope

- still in research phase
- estimation of sensitivity - looked into
    - microwave cavity model (ADMX like)

- $h_0 \sim 10^{-21}$: far from observation

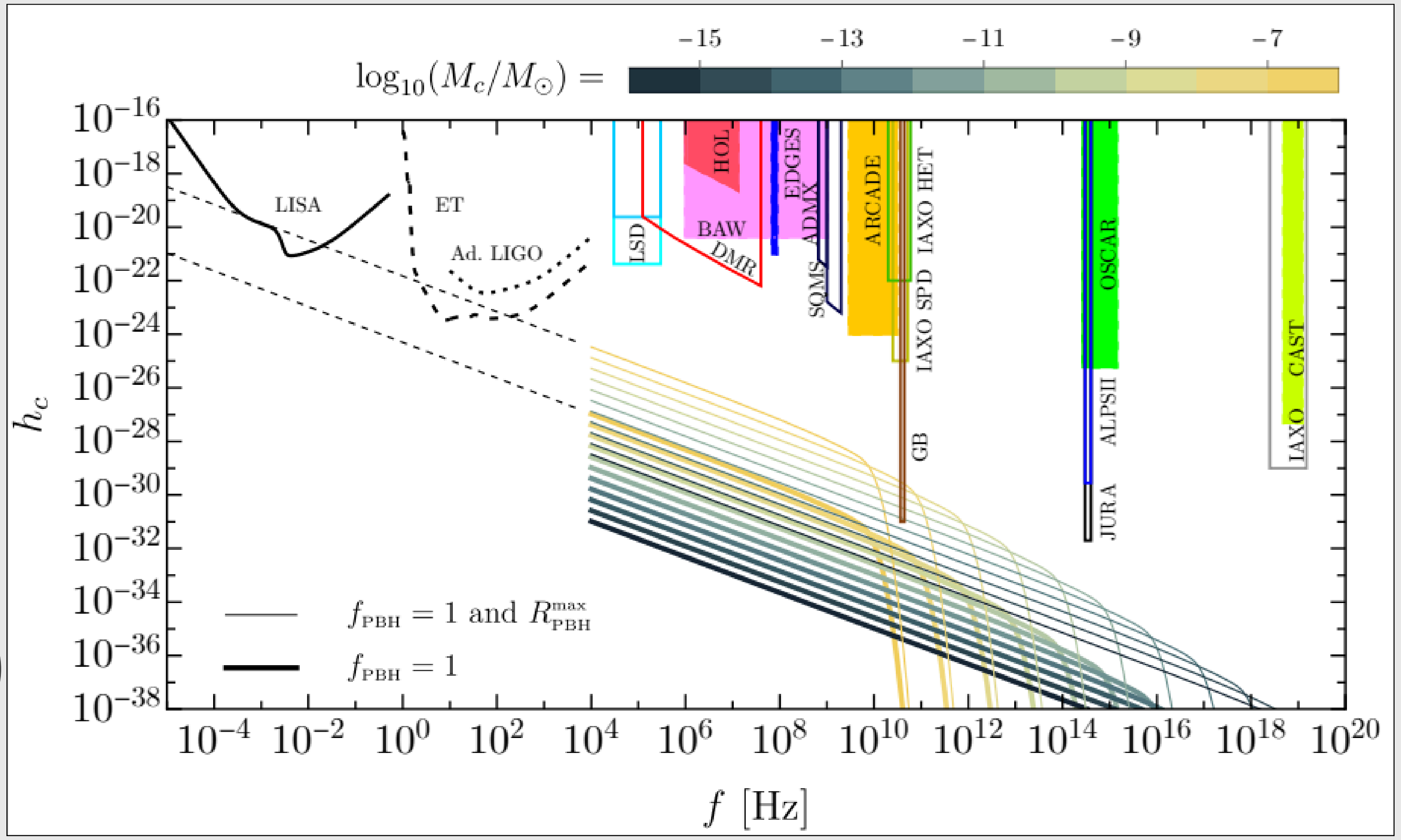


Adapted from Franciolini et al. (2022)

GW Detection

Options with Axion Haloscope

- still in research phase
- estimation of sensitivity - looked into
  - microwave cavity model (ADMX like)
  - dielectric haloscopes (MADMAX like)



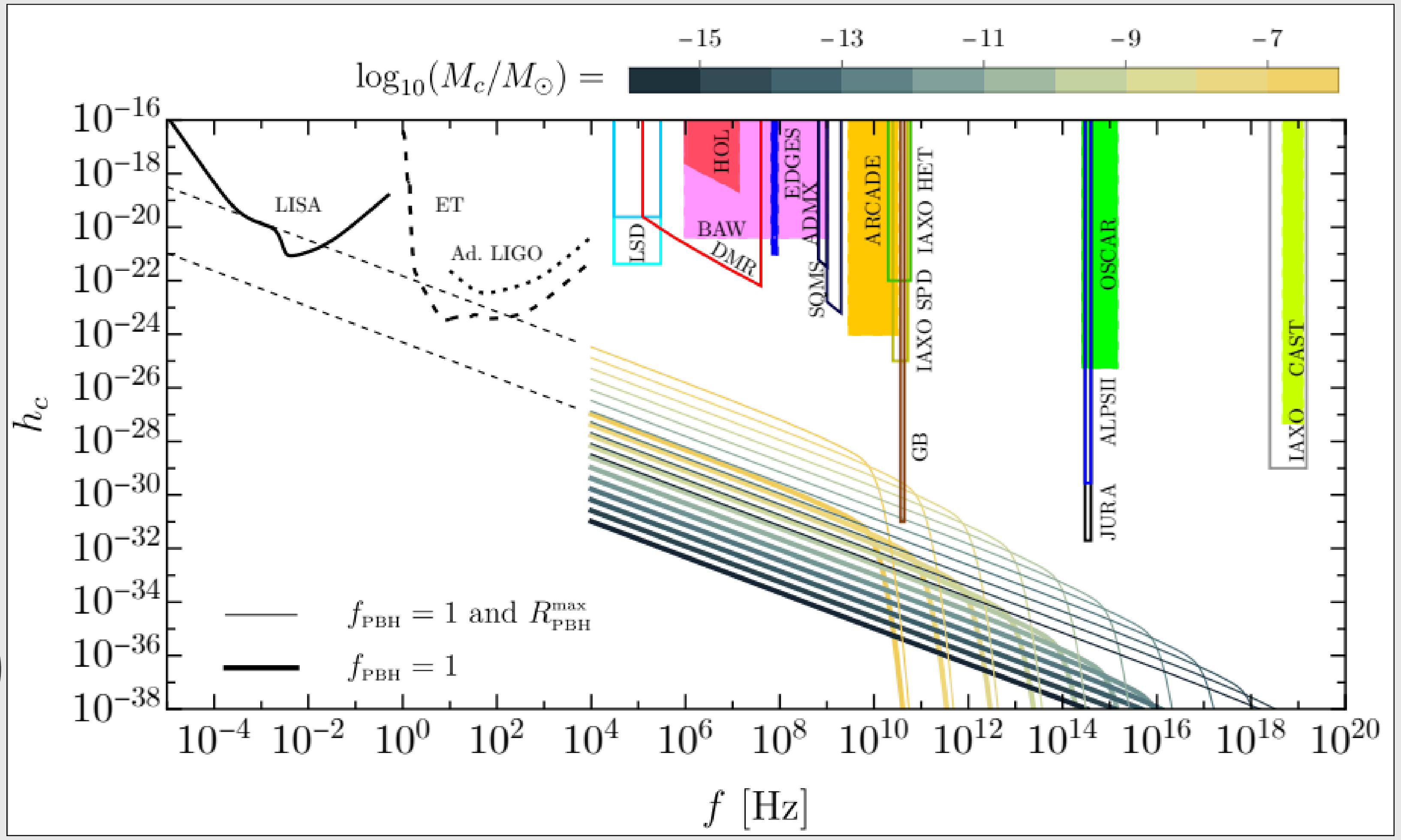
Adapted from Franciolini et al. (2022)

GW Detection

Options with Axion Haloscope

- still in research phase
- estimation of sensitivity - looked into
  - microwave cavity model (ADMX like)
  - dielectric haloscopes (MADMAX like)

- $h_0 \sim 10^{-26}$: unrealistically good!



Adapted from Franciolini et al. (2022)

GW Detection

Options with Axion Haloscope

- higher frequency = weaker signal
- main challenge is reaching high sensitivities

$$h_{c,\mathrm{sto}} \equiv \sqrt{f\, S_h(f)}\,,$$

$$h_{e,\mathrm{sto}} = \frac{H_0}{2\pi f}\left(3\Omega_{\mathrm{GW}/f/}\right)^{1/2}$$

Adapted from Aggarwal et al. (2025)

Thank you!