Hunting Axions with Metamaterials
the ALPHA haloscope

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Fysikdagarna, June 16, 2023

THE AXION

Strong CP problem

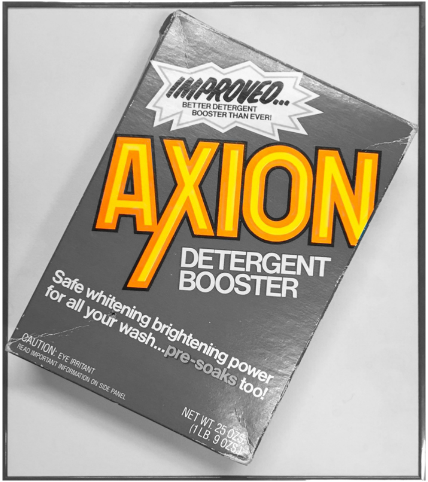
$$\left.\begin{aligned} d_\mathrm{n} &\approx 2.4 \cdot 10^{-3}\,\mathrm{e\,fm} \times \bar{\theta} \\ d_\mathrm{n} &< 1.8 \cdot 10^{-13}\,\mathrm{e\,fm} \end{aligned}\right\} \Rightarrow |\bar{\theta}| < 8{\cdot}10^{-11}$$

Peccei-Quinn-Weinberg-Wilczek

1. $\theta \to \theta(\vec{x}, t) \leftrightharpoons U(1)_{PQ}$ symmetry
2. Spontaneous symmetry breaking
3. Evolution to CP-conserving value

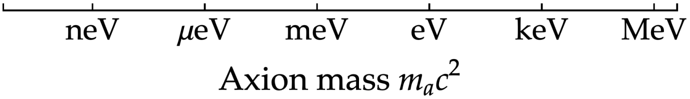
Dark matter

Non-thermal production of NR bosons



[1] See e.g. arXiv: 1801.08127, 2003.01100, 2012.05029, 2104.07634, 2105.01406, 2109.07376.

PREDICTIONS AND CONSTRAINTS



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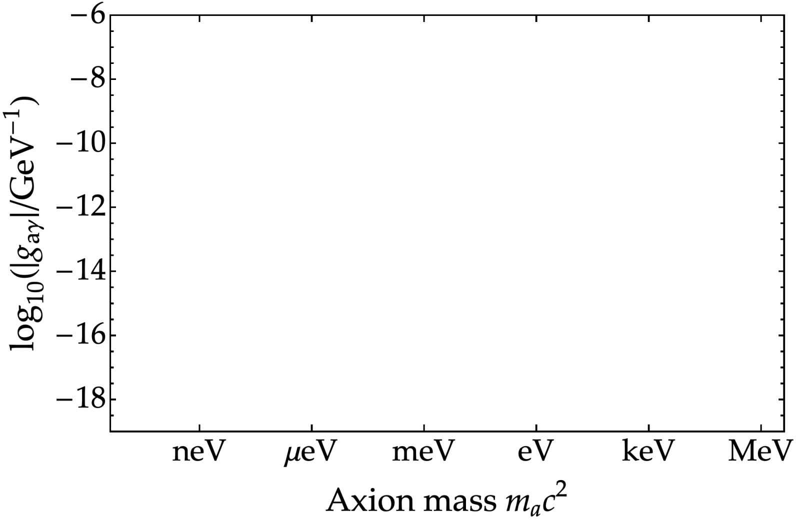

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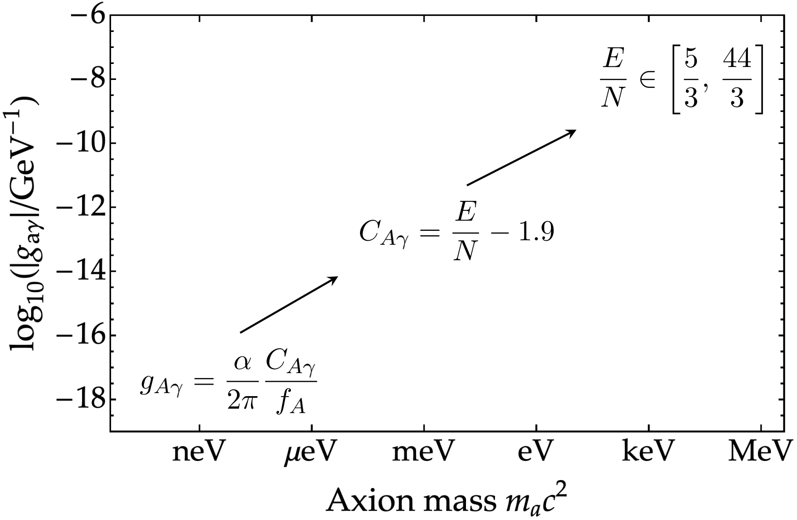

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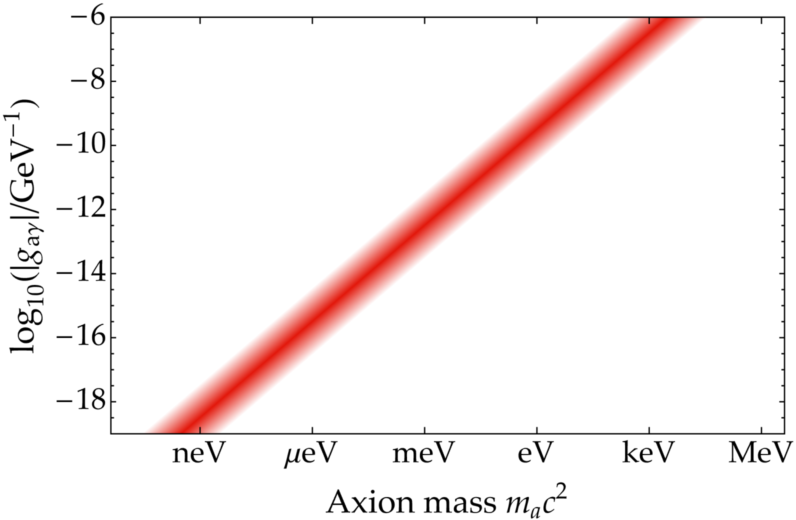

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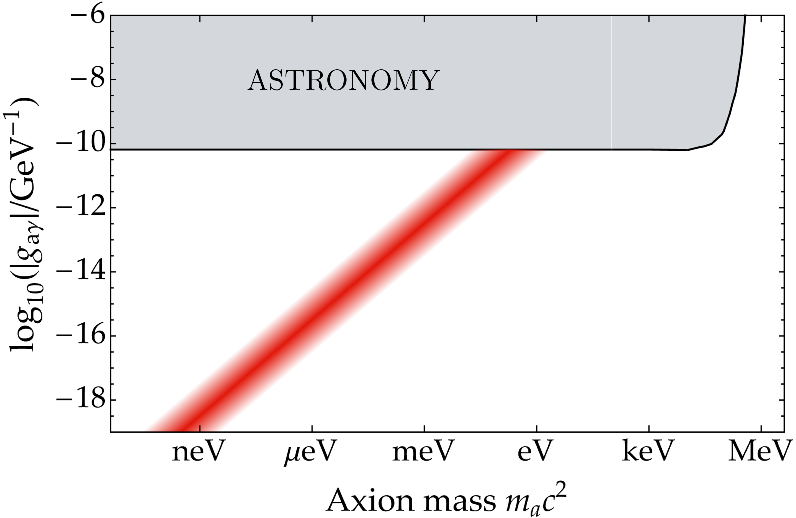

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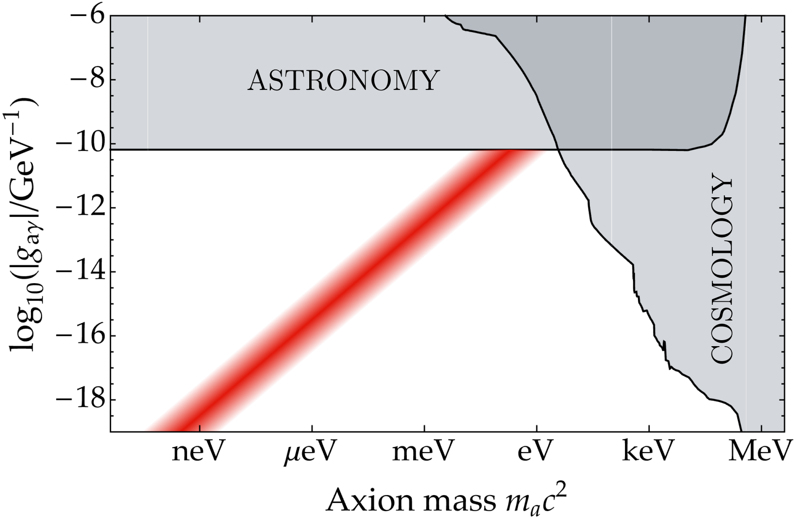

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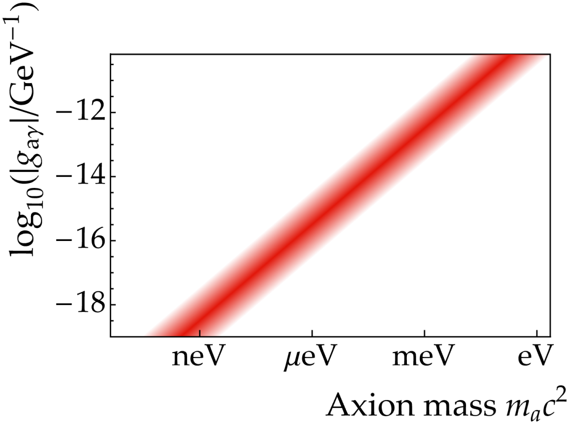
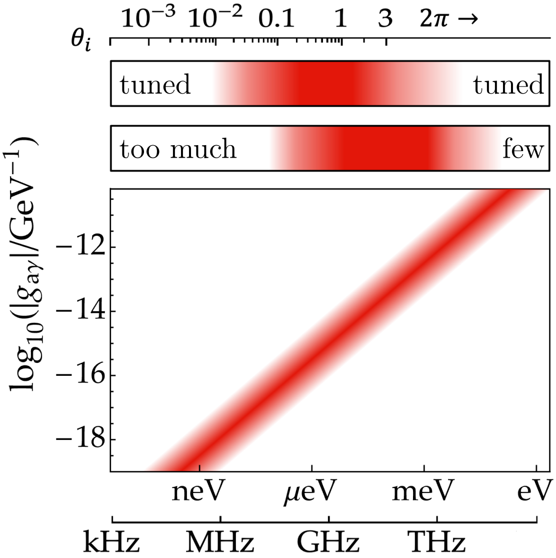


PREDICTIONS AND CONSTRAINTS



Pre-inflation scenario

Post-inflation scenario

NARROW SIGNAL $Q \sim 10^6$
ORDERS OF MAGNITUDE

A CLASSIC APPROACH

SIKIVIE'S HALOSCOPE

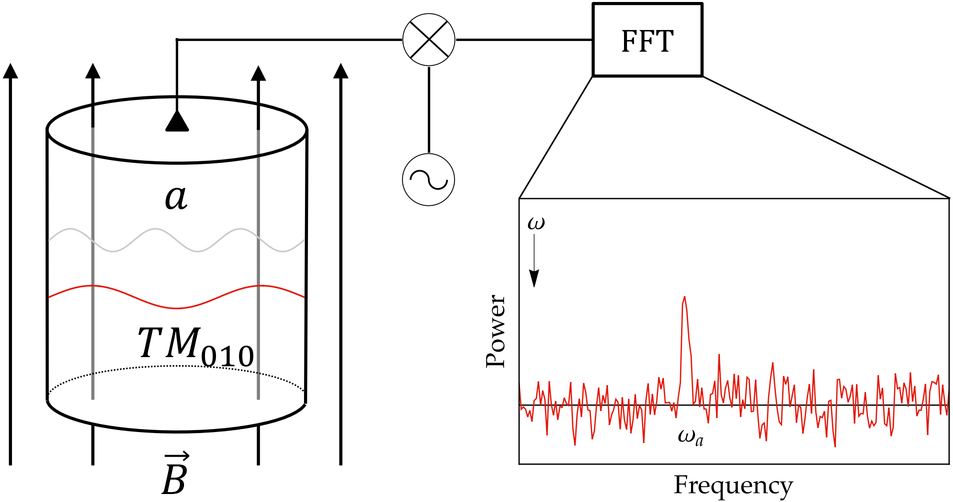
$$|\boldsymbol{E}| = g_{a\gamma} B_{\mathrm{e}} a_0 \left(1 - \frac{\omega_p}{\omega_a^2 - i\omega_a^2 \Gamma_p}\right)^{-1}$$

SIGNATURE

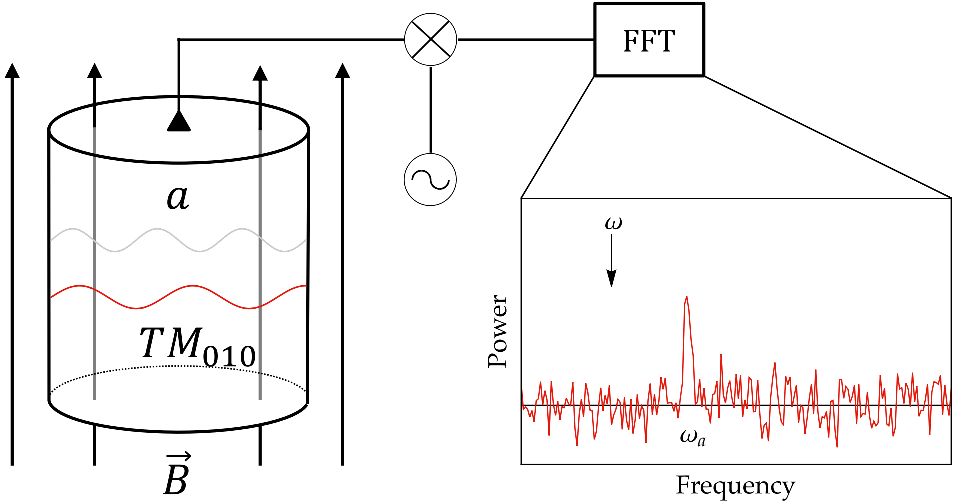
EM radiation in vacuum in the presence of a magnetic field

[2] P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983).

SIKIVIE'S HALOSCOPE



SIKIVIE'S HALOSCOPE



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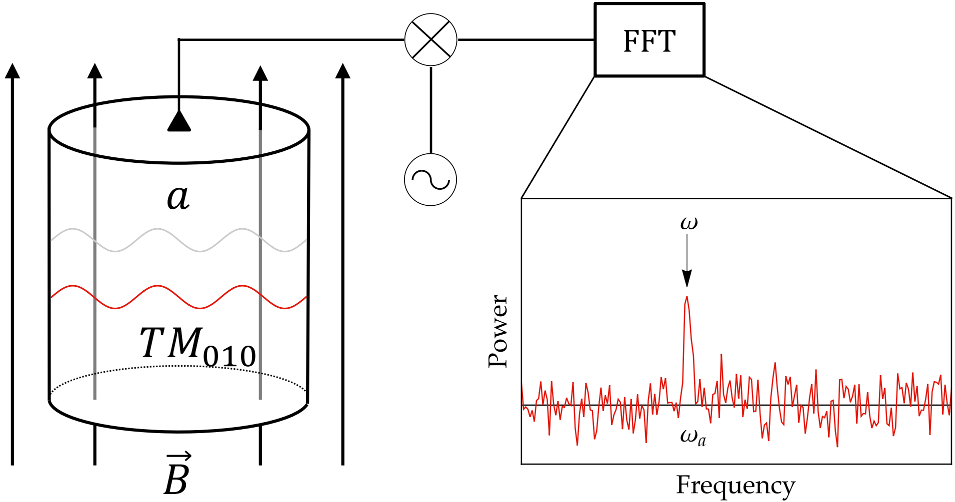
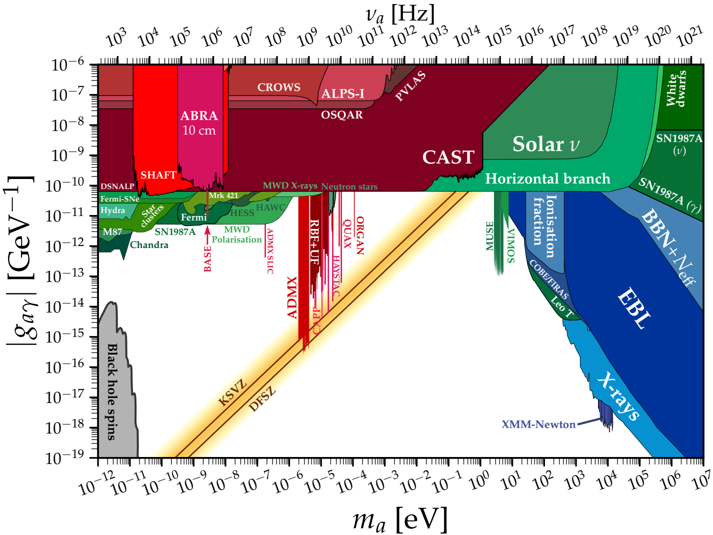


CURRENT LIMITS

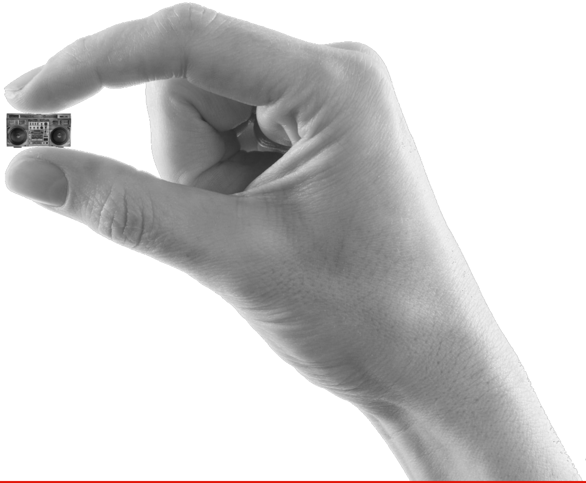


[3] O' Hare, `cajohare/AxionLimits:AxionLimits`.

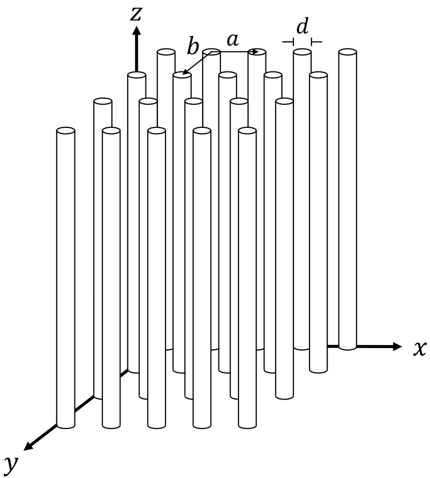
MATCHING WAVELENGTHS

Desiderata

- Cryogenic temperature
- Tunability
- Large volume
- “Low” plasma frequency



WIRE METAMATERIALS



Metamaterials

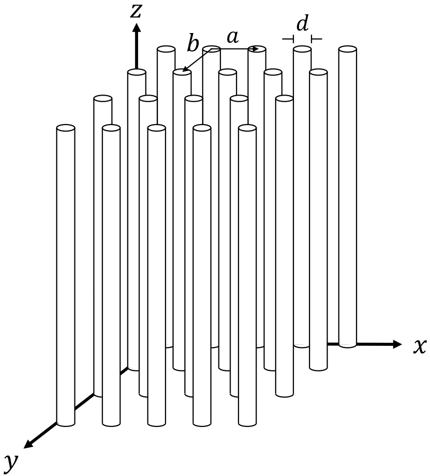
Composite materials with different properties than their single parts

[4] P.A. Belov *et al.*, J. Electromagn. Waves. Appl. 16, 8 (2002).

WIRE METAMATERIALS

$$\frac{\omega_p^2}{c^2} = \frac{2\pi}{ab}\left[\log\left(\frac{\sqrt{a\,b}}{\pi\,d}\right) + F\left(\frac{a}{b}\right)\right]^{-1}$$

$$F(u) = -\frac{\log u}{2} + \sum_{n=1}^{\infty}\left(\frac{\coth(\pi n u) - 1}{n}\right) + \frac{\pi u}{6}$$



[4] P.A. Belov *et al.*, J. Electromagn. Waves. Appl. 16, 8 (2002).

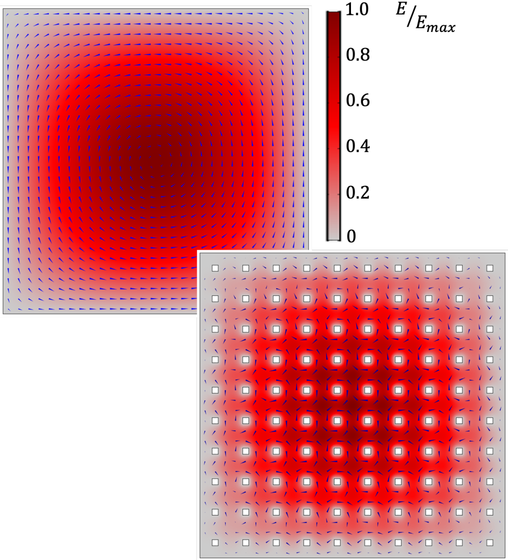
WIRE METAMATERIALS

TM_{110} mode structure

Behavior as an effective medium

Properties

- Cryogenic
- Solenoidal magnet
- Much larger volume than cavities



[5] A. Millar *et al.*, Phys. Rev. D 107 (2023) 5, 055013.

ALPHA CONSORTIUM

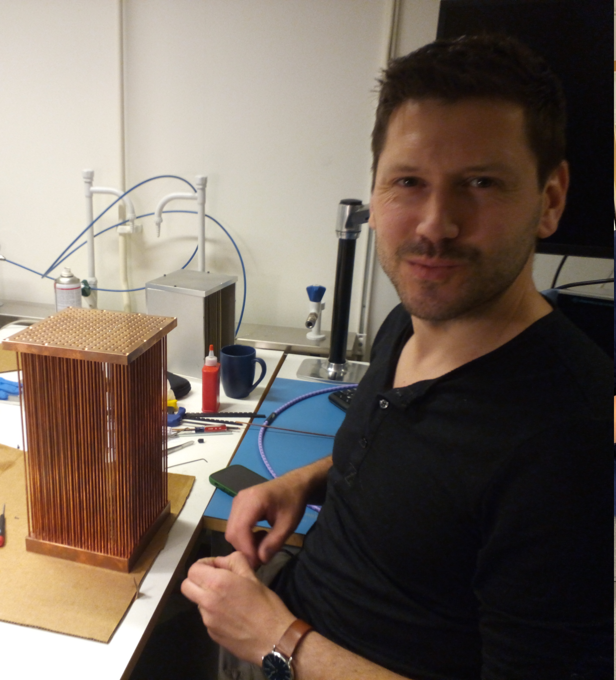
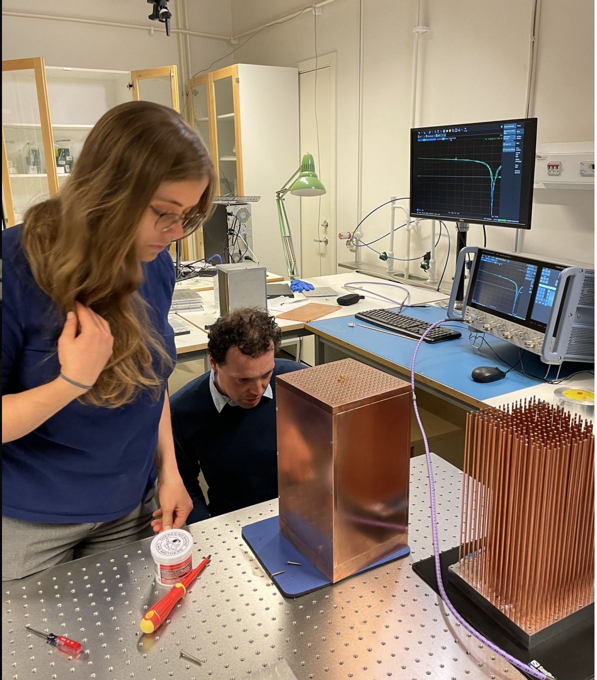
Fermilab
IIT Chicago
IIT Kanpur
ITMO University
MIT Cambridge
Niels Bohr Institute
Oak Ridge National Labs
Stockholm University & OKC
UC Berkeley
UC Davis
UCL London
University of Maryland
University of Oxford
Uppsala University

STOCKHOLM UNIVERSITY

Jan Conrad
AGR

Hiranya Peiris

Jón Guðmundsson
Gaganpreet Singh
Gagandeep Kaur
Frank Wilczek

DISCOVERY REACH

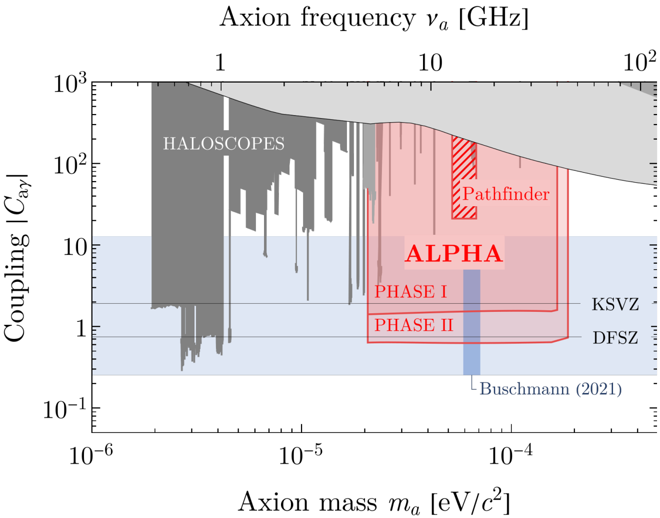
- $Q \sim (1 \div 3) \cdot 10^4$
- $B = 13\,\mathrm{T}$
- $V = \pi \times 35^2 \times 75\,\mathrm{cm}^3$

ALPHA PHASE I

- $(5 \div 40)$ GHz
- HEMT amplifiers

ALPHA PHASE II

- $(5 \div 45)$ GHz
- Quantum noise



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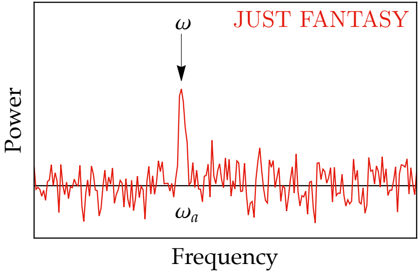
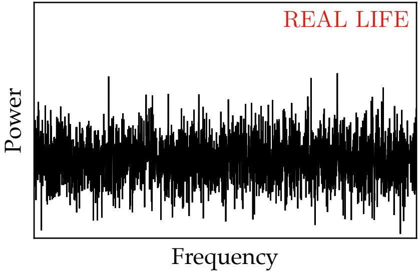
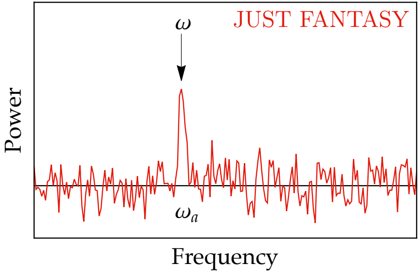
[5] A. Millar *et al.*, Phys. Rev. D 107 (2023) 5, 055013.

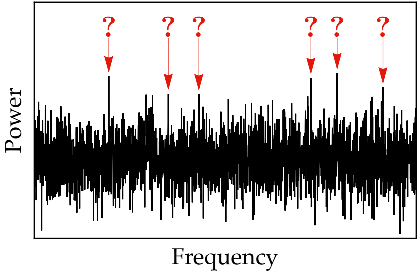
TUNING IN

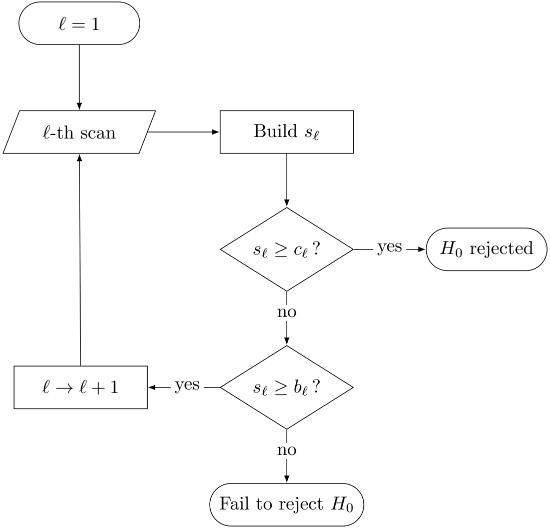

JUST FANTASY
ω
ω_a
Power
Frequency


REAL LIFE
Power
Frequency

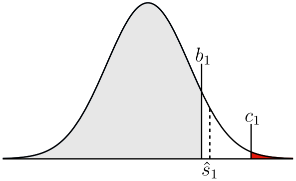
TUNING IN


JUST FANTASY
ω
ω_a
Power
Frequency

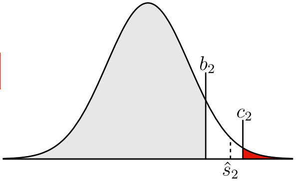

? ? ? ? ? ?
Power
Frequency



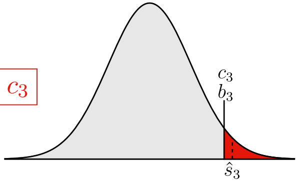
$$\hat{s}_1 = \frac{\hat{x}_1}{\sqrt{u_1}} \begin{cases} \boxed{\geq c_1} \\ \geq b_1 \end{cases}$$



$$\hat{s}_2 = \frac{\hat{x}_1 + \hat{x}_2}{\sqrt{u_1 + u_2}} \begin{cases} \boxed{\geq c_2} \\ \geq b_2 \end{cases}$$

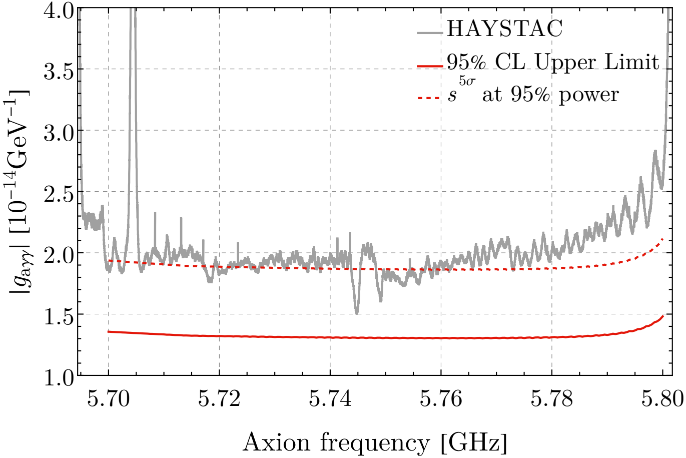


$$\hat{s}_3 = \frac{\hat{x}_1 + \hat{x}_2 + \hat{x}_3}{\sqrt{u_1 + u_2 + u_3}} \boxed{\geq c_3}$$



[6] A. Gallo Rosso *et al.* arXiv:2210.16095.

APPLICATION TO HAYSTAC



[7] B.M. Brubaker *et al.* Phys. Rev. Lett. 118.6 (2017).

SUMMARY

ALPHA

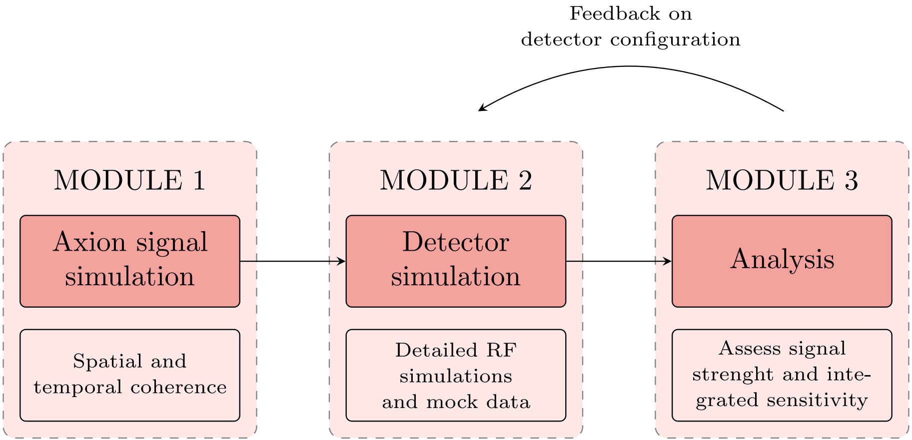
- First data run expected in 2026
  $\hookrightarrow$ VR and KAW grants
- KSVZ and DFSZ at reach

DAQ & ANALYSIS

- Framework for inference on sequential tests
- Protocol and computational optimizations

IMPROVE SYNERGY FOR SIMULATION & ANALYSIS

SUMMARY



IMPROVE SYNERGY FOR SIMULATION & ANALYSIS