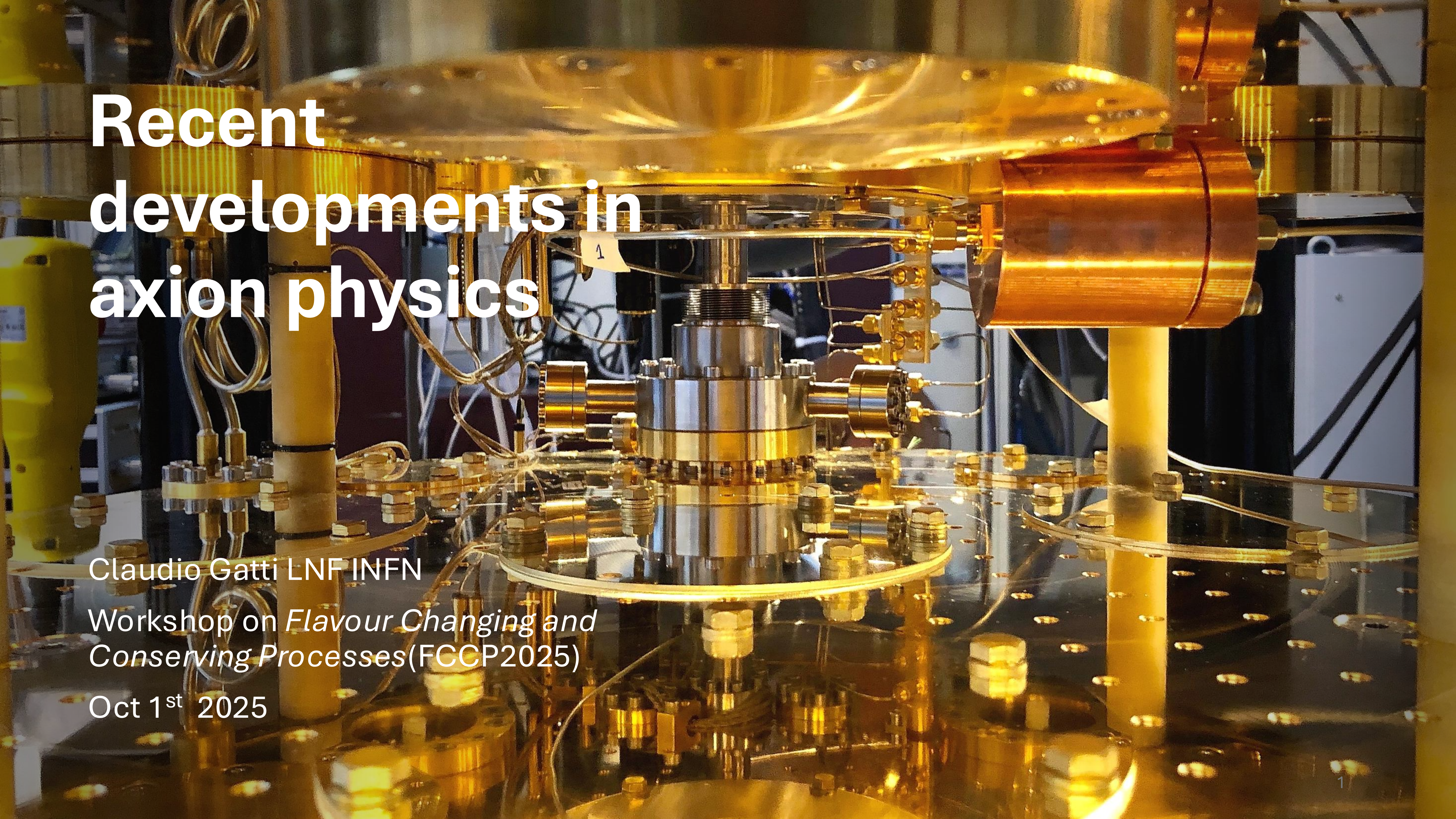


Recent developments in axion physics

Claudio Gatti LNF INFN

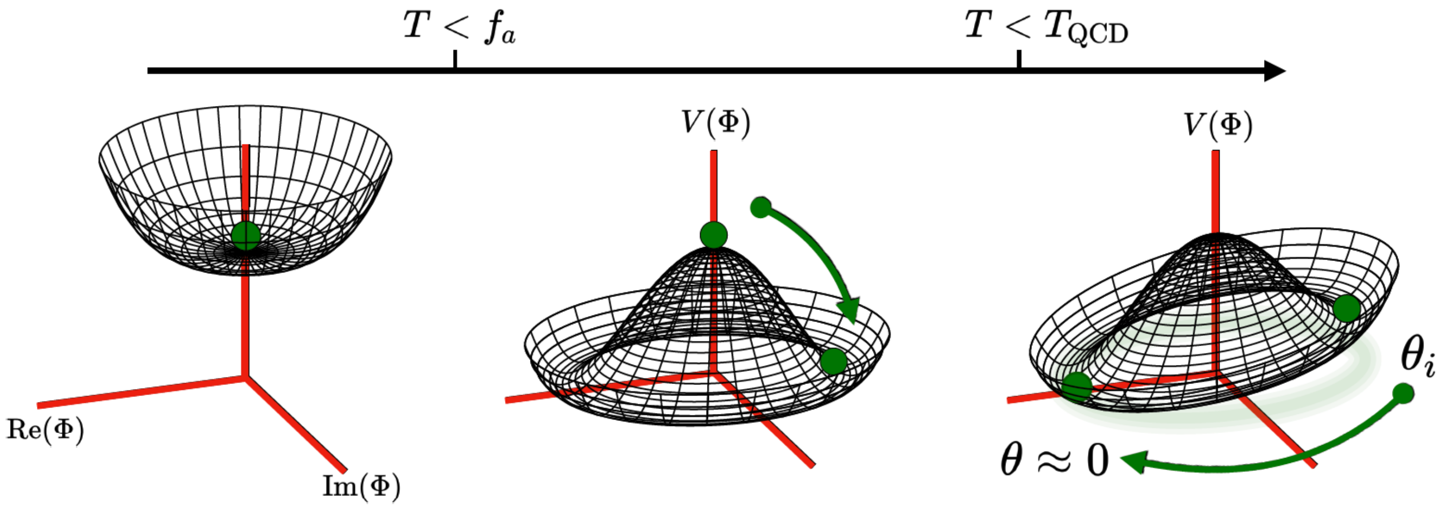
Workshop on *Flavour Changing and Conserving Processes*(FCCP2025)

Oct 1st 2025

The QCD Axion

Introduced to cancel the CP violating theta term in QCD lagrangian:

$$\delta\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$



_CP_ Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 31 March 1977)

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{(m_u + m_d)} \simeq 5.7 \left(\frac{10^{12}\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

Neutron Electric Dipole Moment

The θ term induces an electric dipole moment of the neutron

Natural size of EDM

$$d_n \simeq \bar{\theta} \frac{e}{m_N} \frac{m_q}{m_N}$$

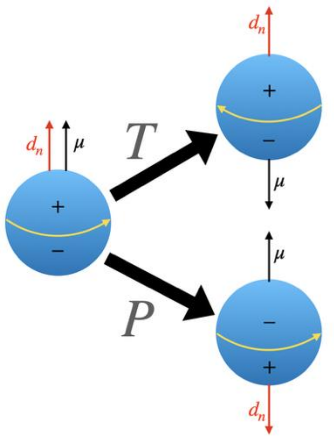
Disappears when $m_q=0$

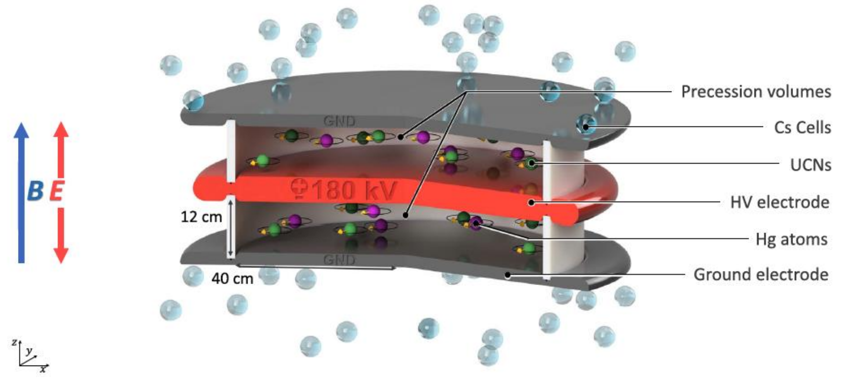
CP violating term

$$\theta < 10^{-10}$$

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} \ e.\text{cm}.$$

nEDM experiment at PSI, Phys. Rev. Lett. 124, 081803 (2020)





n2EDM at PSI, Eur. Phys. J. C (2021) 81:512
Expected:

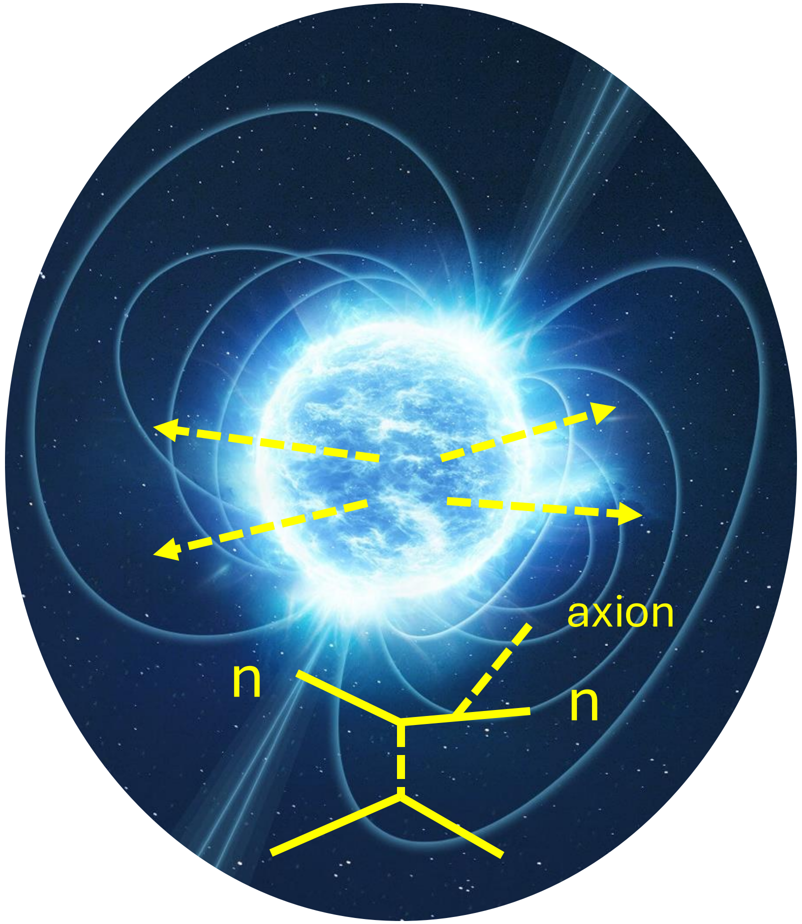
$$\sigma_{d_n} = 10^{-27} \ e \ cm$$

m_a from Neutron Star Cooling

Axions may modify NS cooling:

$$\mathcal{L} \supset (C_N/2f_a)\bar{\psi}_N\gamma^\mu\gamma_5\psi_N\partial_\mu a$$

$g_N \propto m_a$



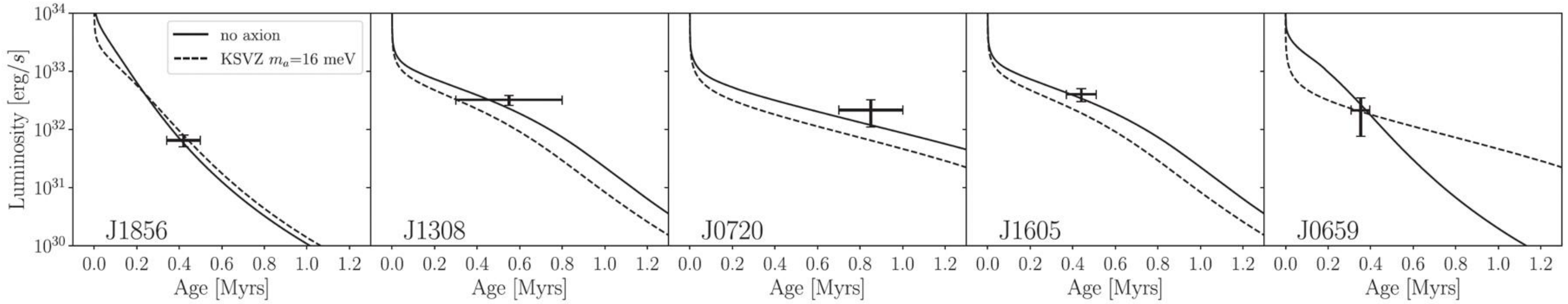
PRL 128 091102 (2022)

m_a from Neutron Star Cooling

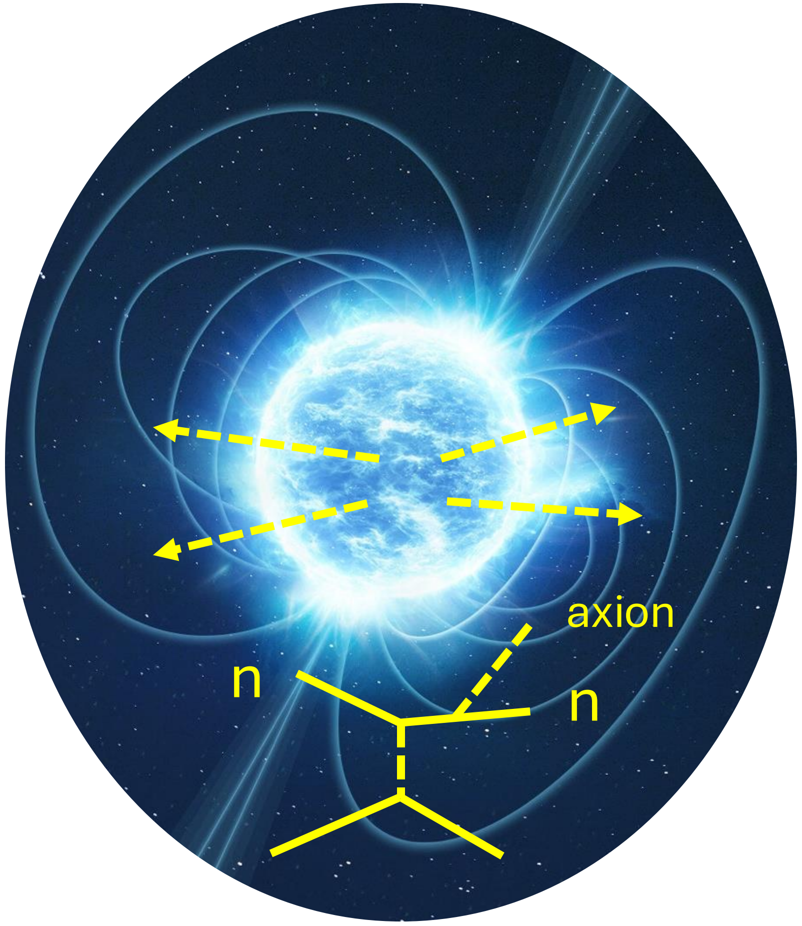
Axions may modify NS cooling:

$$\mathcal{L} \supset (C_N/2f_a)\bar{\psi}_N\gamma^\mu\gamma_5\psi_N\partial_\mu a$$

$g_N \propto m_a$



Luminosity vs NS age, for 5 different NS.
Prediction with and without axion compared to measurements.



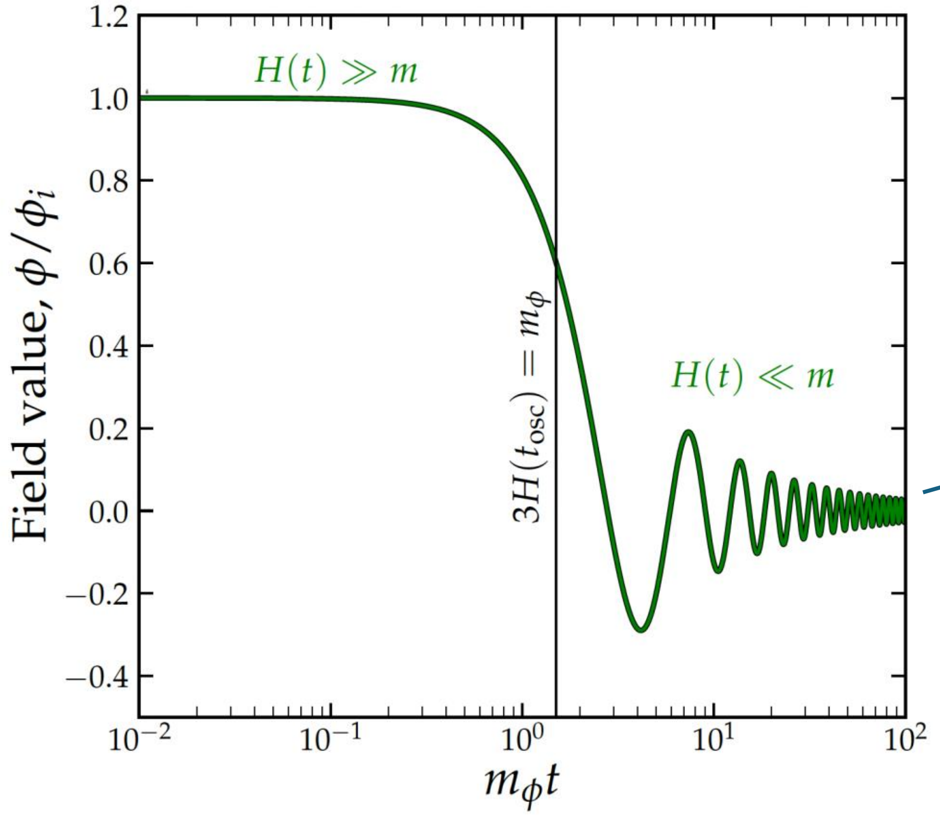
$$f_a > 10^9 \text{ GeV}$$

PRL 128 091102 (2022)

$m_a < 16$ meV for KSVZ axions

Cosmological Evolution of Axion Field

Axion field evolution in an expanding universe $\longrightarrow$ $\ddot{a} + 3H(t)\dot{a} + m_a(T)^2 a = 0$



Axion Dark Matter

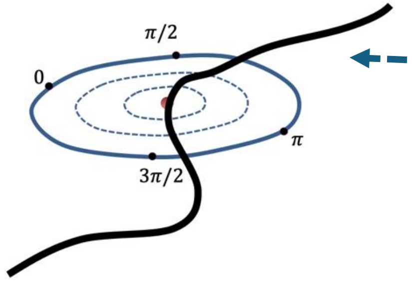
$$a(t) = a_0 \cos(m_a t)$$

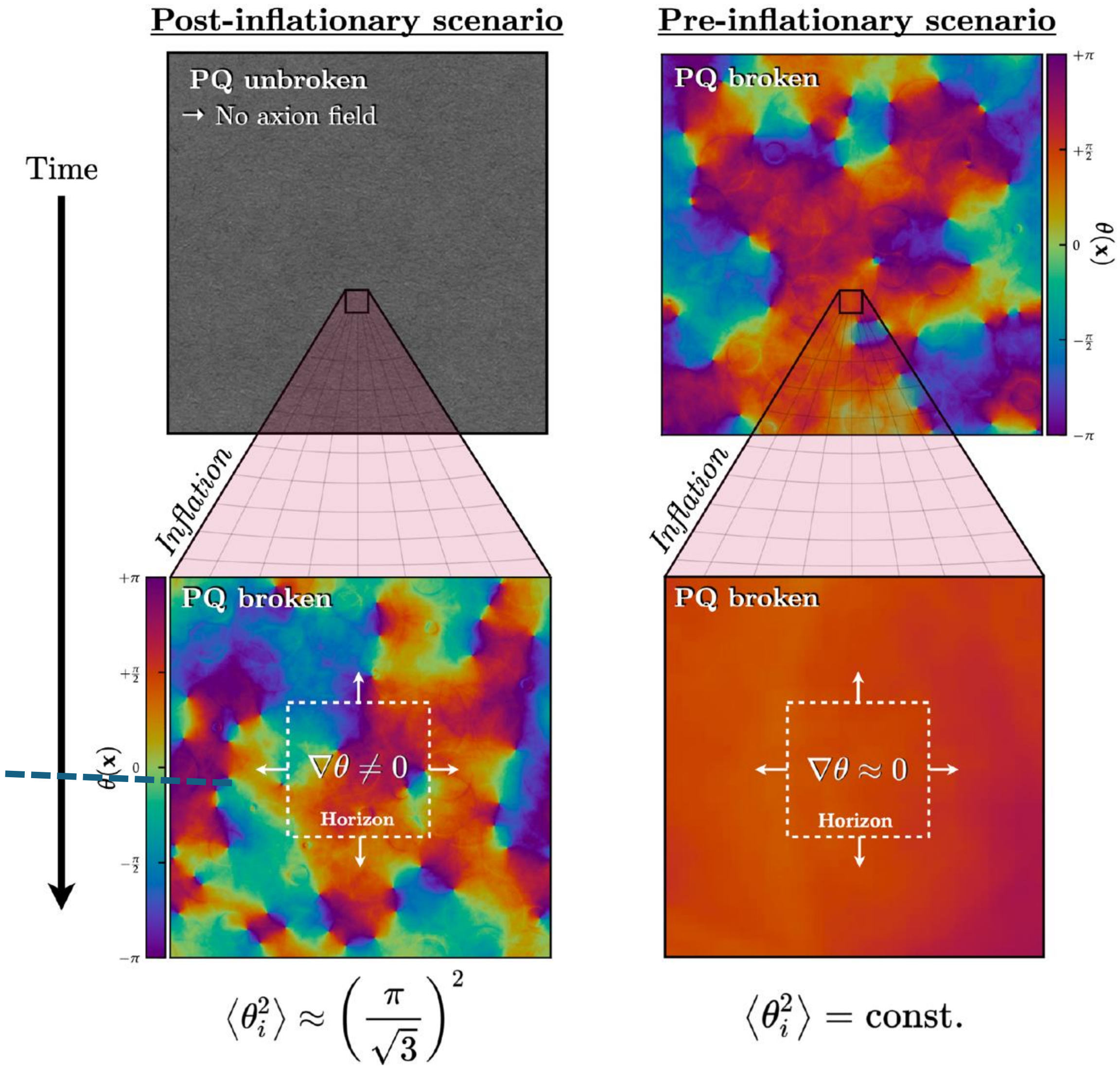
$$\rho_a = \frac{1}{2} m_a^2 a_0^2$$

Pre- and Post-Inflationary Scenarios

$$\Omega_a = \Omega_{DM} \left(\frac{\theta_i}{2.155}\right)^2 \left(\frac{28\mu\text{eV}}{m_a}\right)^{1.16}$$

Axion String

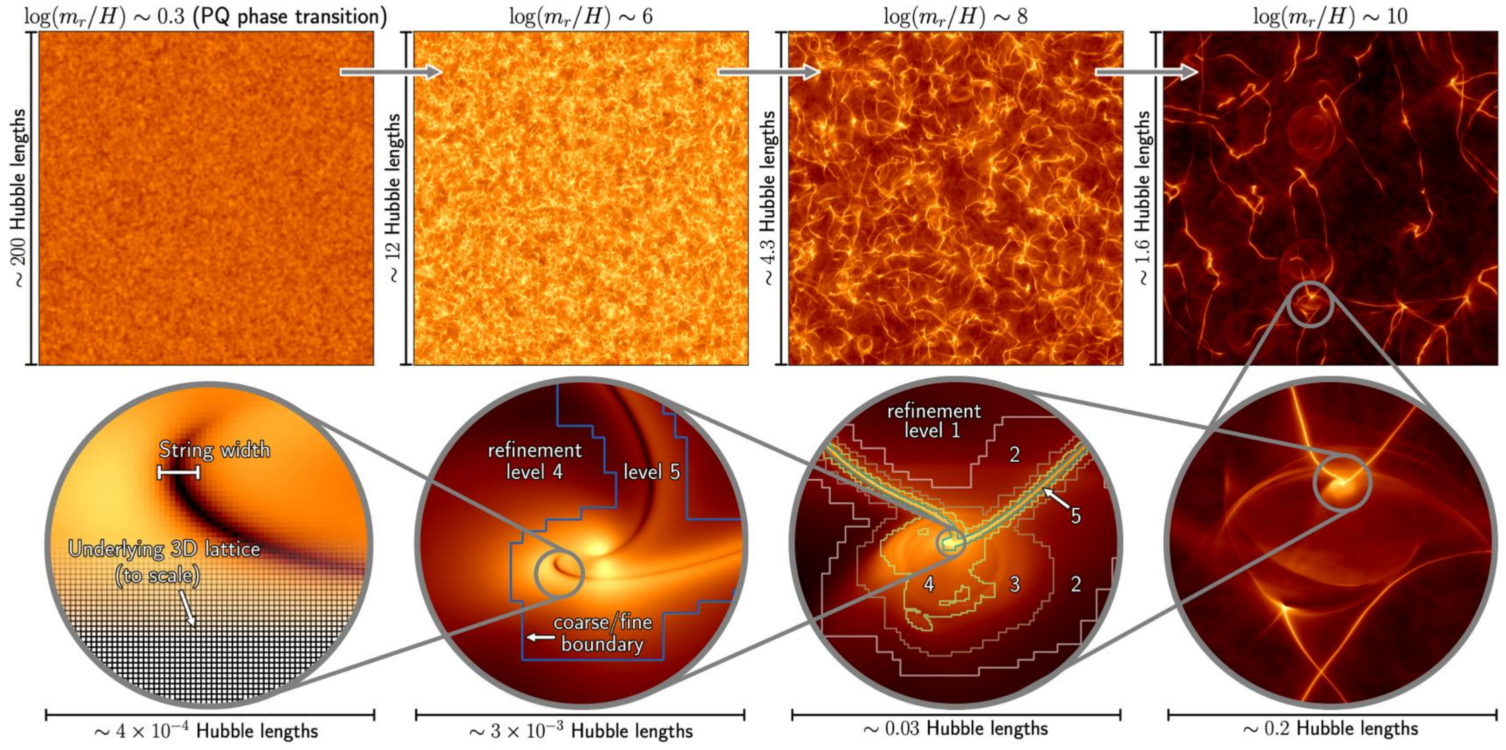


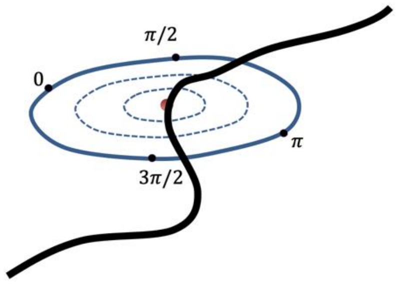


Axions DM From Axion Strings

Simulation of axion-string formation and decays in post inflationary scenarios

$$m_a \in (40, 300)\mu eV$$



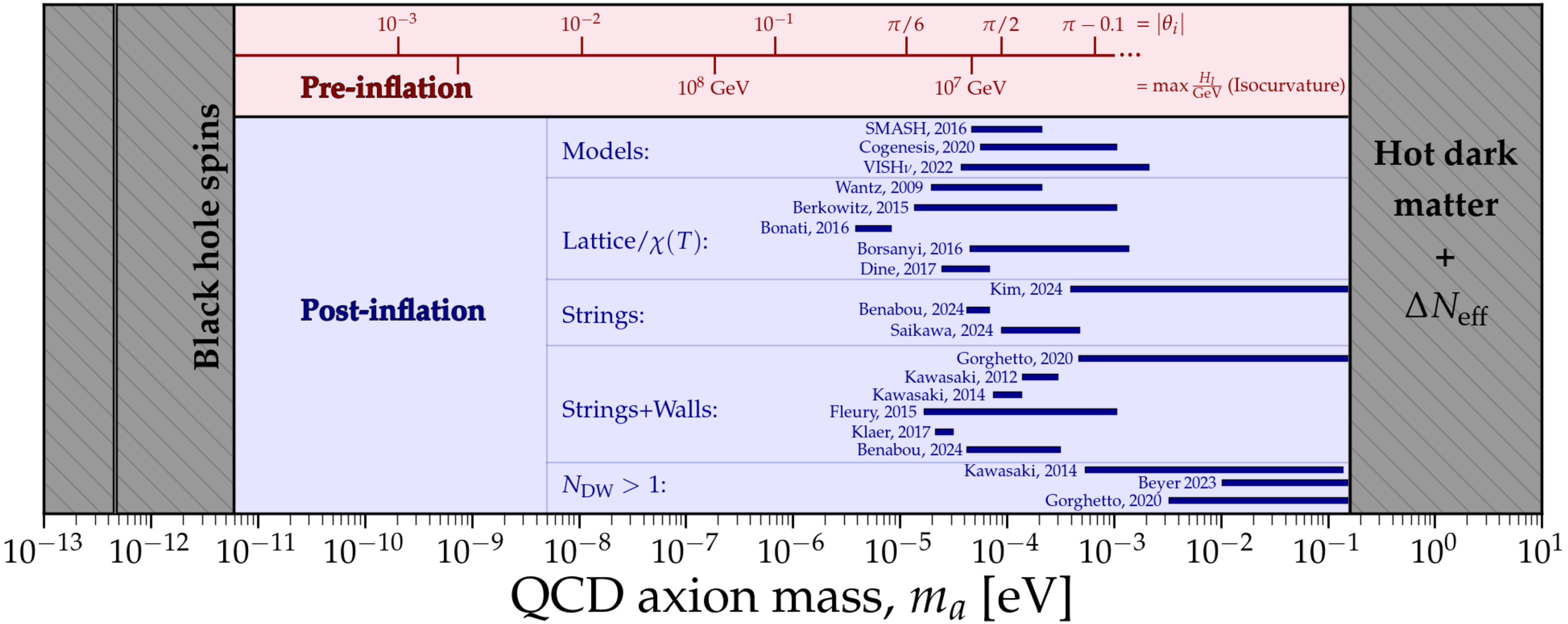


Benabou et al. arXiv:2412.08699v1

Buschmann, M., Foster, J.W., Hook, A. *et al.* Dark matter from axion strings with adaptive mesh refinement. *Nat Commun* **13**, 1049 (2022).

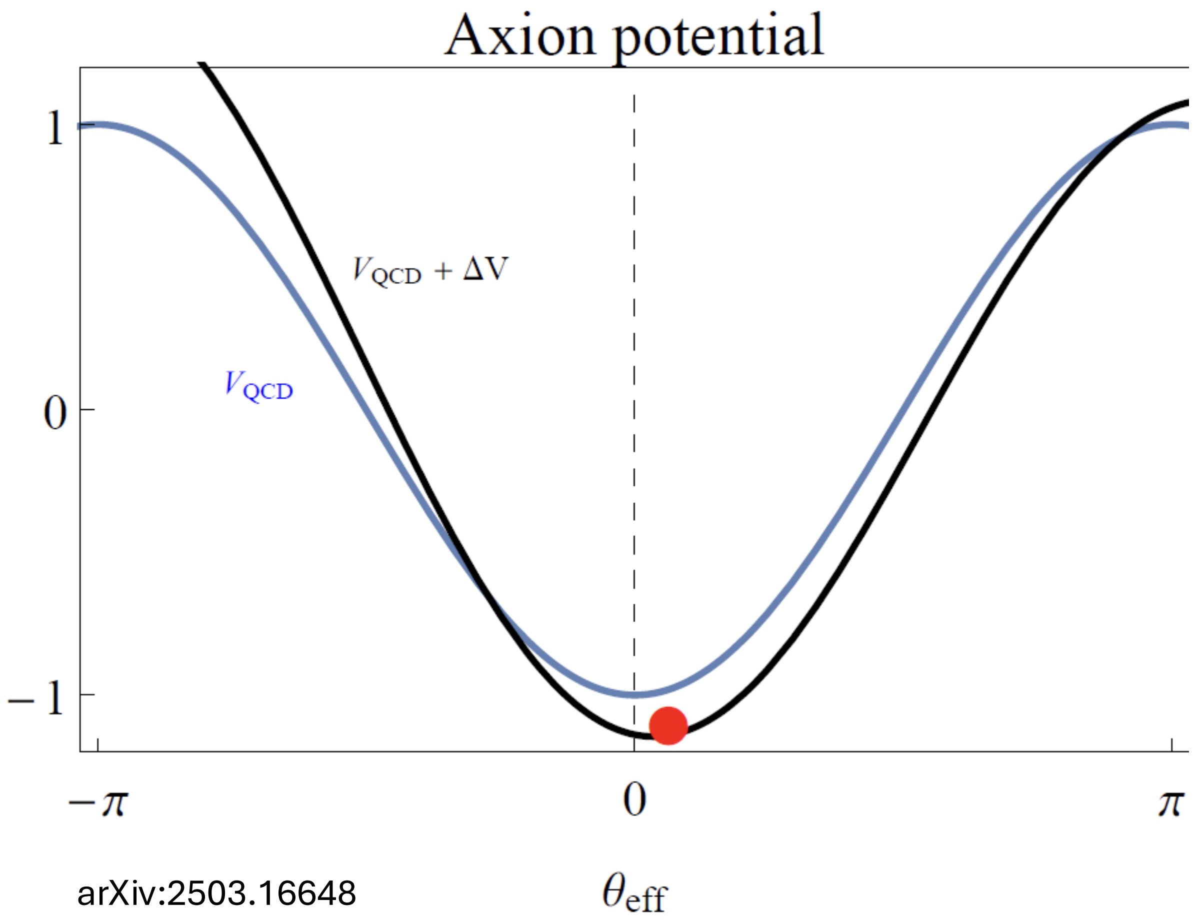
Axion Mass Predictions

$$m_a = \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{(m_u+m_d)} \simeq 5.7\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)\mu\mathrm{eV}$$



https://cajohare.github.io/AxionLimits/

Axion Quality Problem



arXiv:2503.16648

arXiv:2505.07122

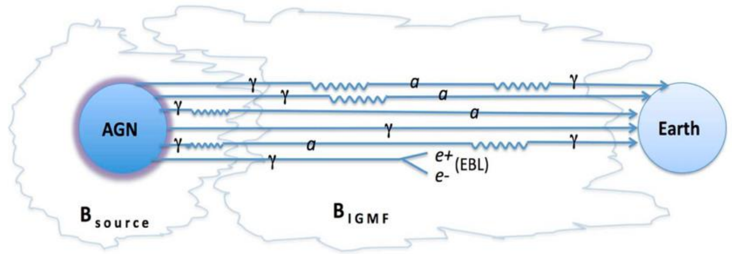
PQ global symmetry broken by UV physics (QG)

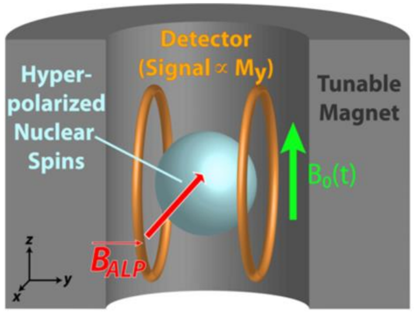
$$\Delta\mathcal{L}_{\rm UV}^{\cancel{\rm PQ}} \sim \frac{1}{\Lambda_{\rm UV}^{d-4}}\mathcal{O}^{[d]}$$

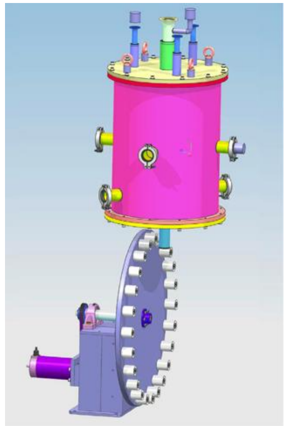
In arXiv:2503.16648 the authors study a class of axion models where an accidental U(1) Peccei-Quinn (PQ) symmetry automatically emerges.

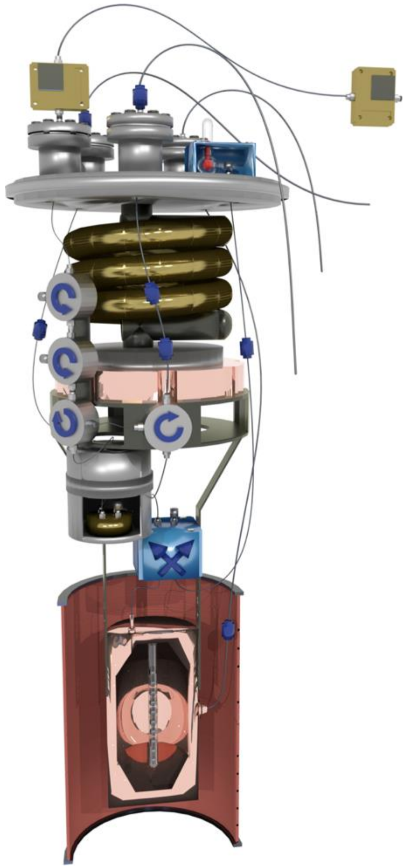
A **high-quality axion**, immune to the PQ quality problem, is obtained for

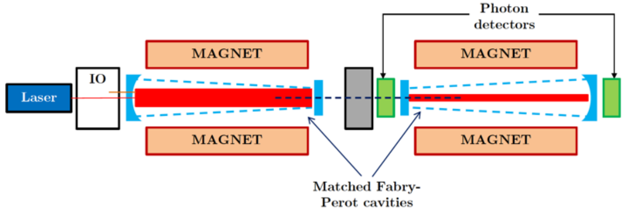
$$m_a \gtrsim 0.01\ \text{eV}$$

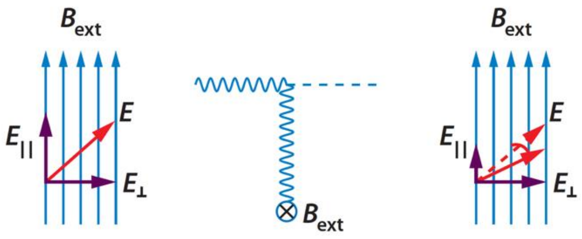


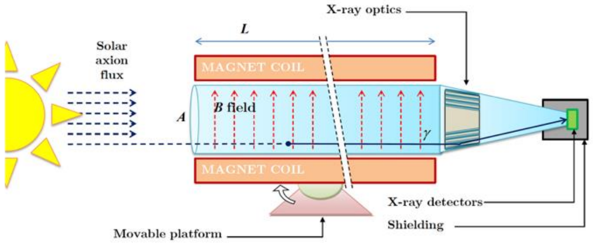


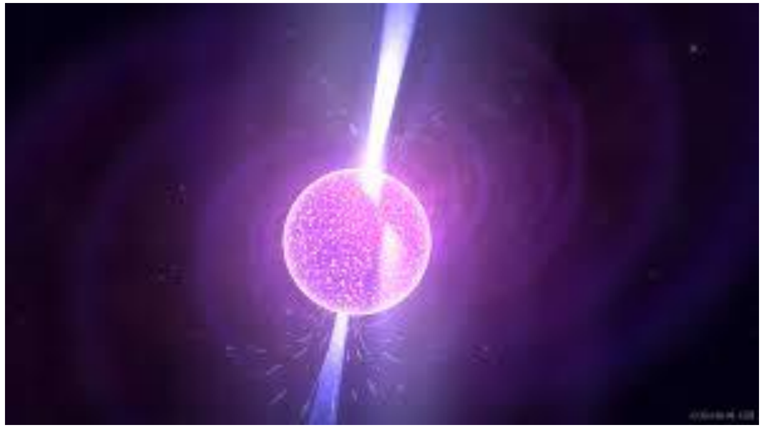




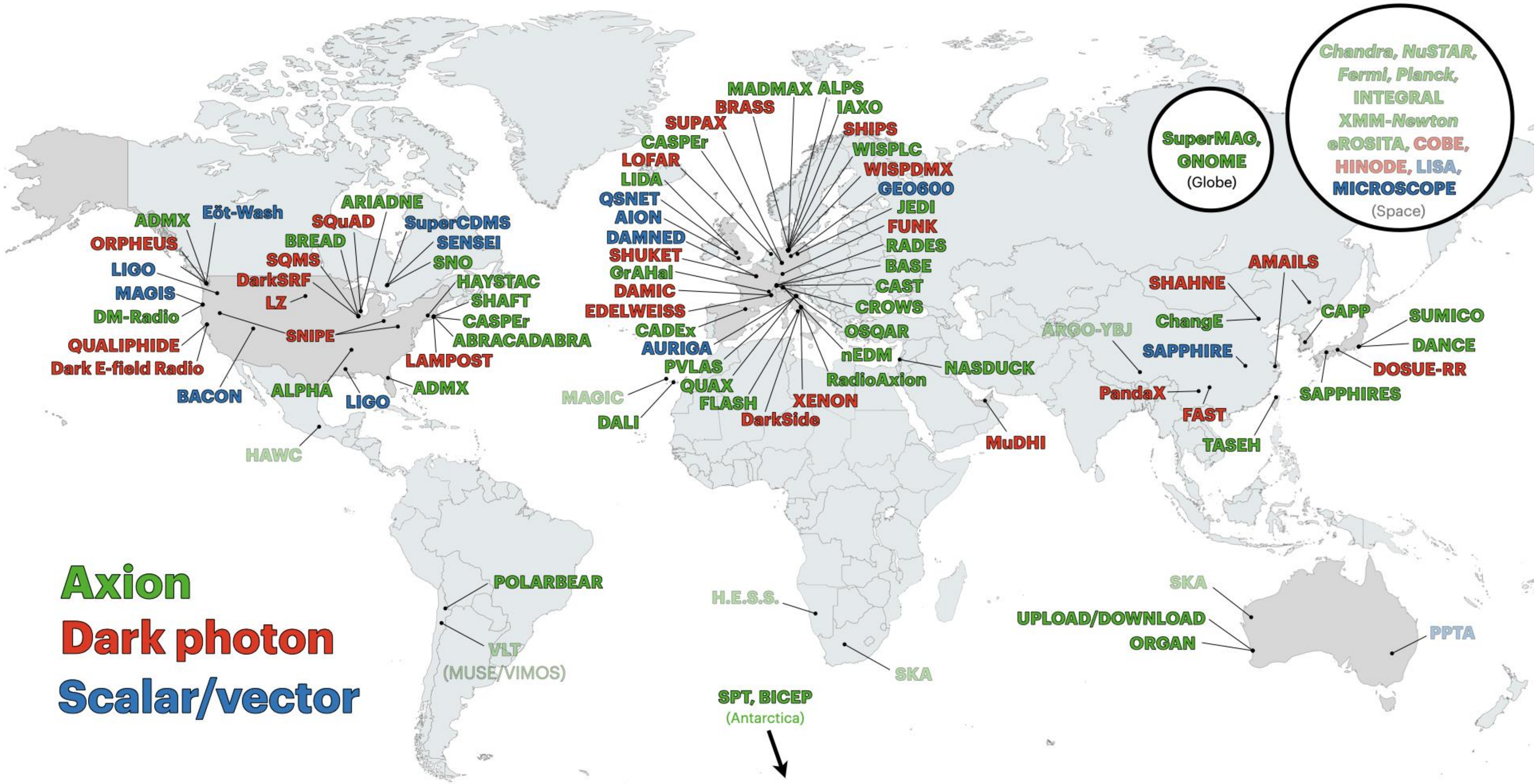








Axion Experiments



https://cajohare.github.io/AxionLimits/

Axion Interactions with Matter

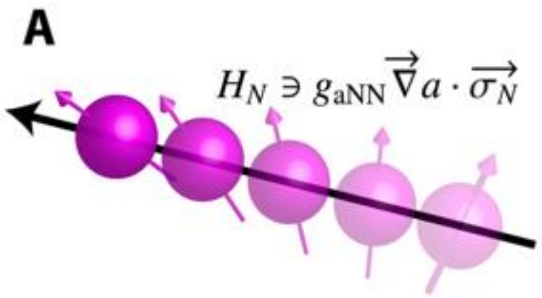
EDM

Nuclear Spin

Electron Spin

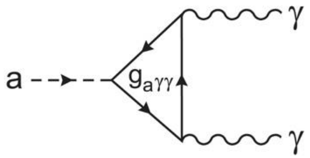
Photon

$$\mathcal{L} = i\frac{g_d}{2}a\left(\bar{N}\sigma_{\mu\nu}\gamma^5 N\right)F^{\mu\nu} + i\frac{g_{aNN}}{2m_N}\partial_\mu a\left(\bar{N}\gamma^\mu\gamma^5 N\right) + i\frac{g_{aee}}{2m_e}\partial_\mu a\left(\bar{e}\gamma^\mu\gamma^5 e\right) + g_{a\gamma\gamma}aE\cdot B$$



Exotic Spin Interactions

$$\begin{aligned}
\vec{\nabla}\cdot\left(\varepsilon\vec{E} - ga\vec{B}\right) &= \rho_{el} \\
\vec{\nabla}\times\left(\frac{1}{\mu}\vec{B} + ga\vec{E}\right) - \partial_t\left(\varepsilon\vec{E} - ga\vec{B}\right) &= \vec{j}_{el} \\
\vec{\nabla}\times\vec{E} + \partial_t\vec{B} &= 0 \\
\vec{\nabla}\cdot\vec{B} &= 0 \\
\partial_t^2 a - \nabla^2 a + m_a^2 a &= -g\vec{E}\cdot\vec{B}
\end{aligned}$$



$$g \equiv g_{a\gamma\gamma} = g_\gamma(\alpha/\pi)(1/f_a)$$

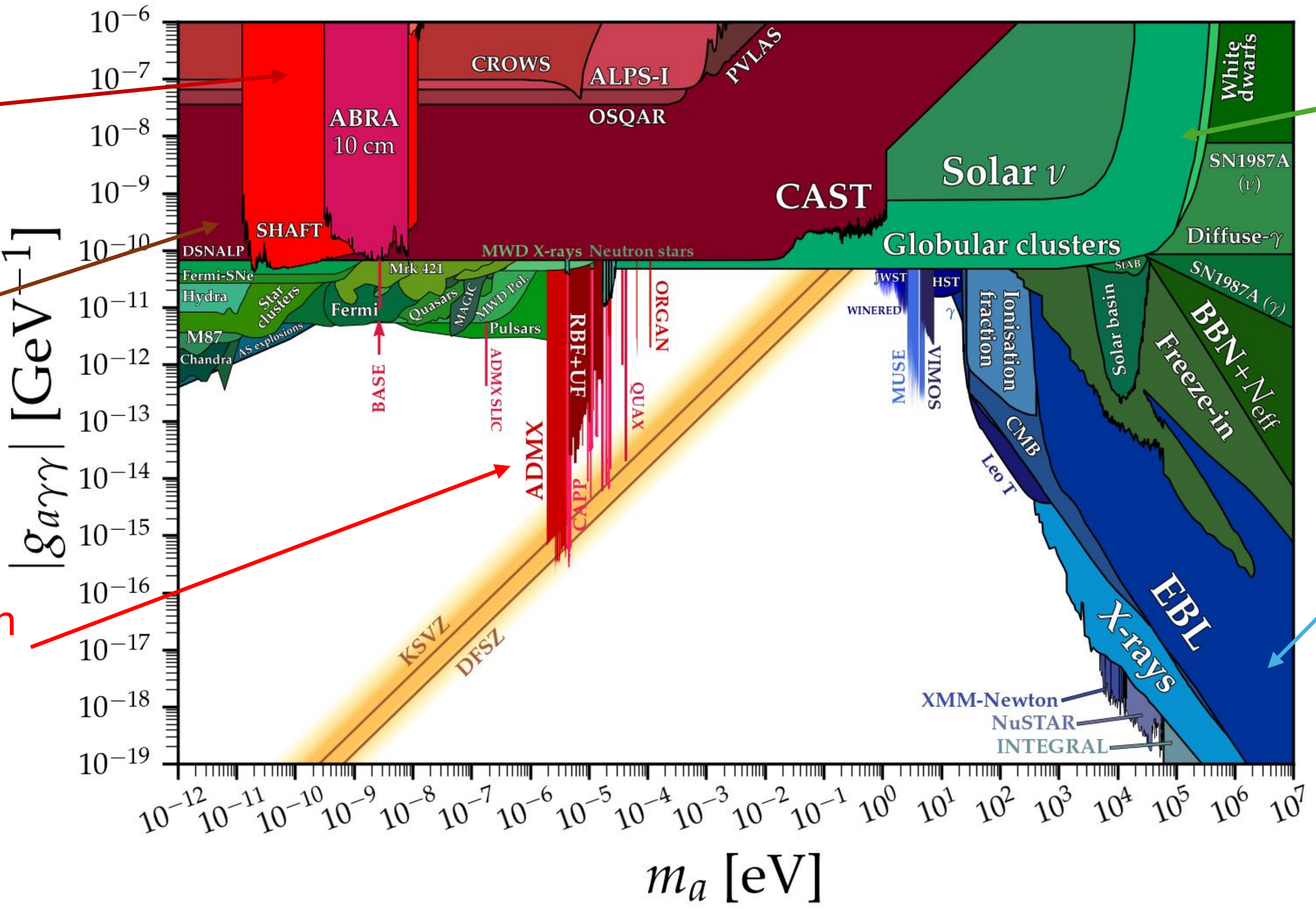
Modified Maxwell Equations

Axion Experiments

Laboratory experiments

Detection of axions from the Sun (Helioscopes)

DM axion detection (Haloscopes)



Stellar physics: Constraints on stellar lifetime or energy-loss rates.

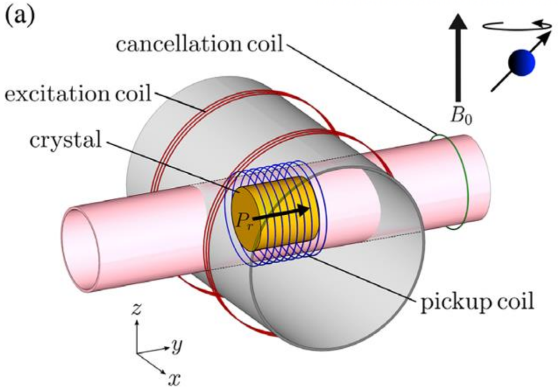
Astronomy: No DM $a \rightarrow \gamma\gamma$ decays seen in the visible region from galaxies with telecopes. Similar searches with X-rays and extragalactic background light (EBL) or H ionization.

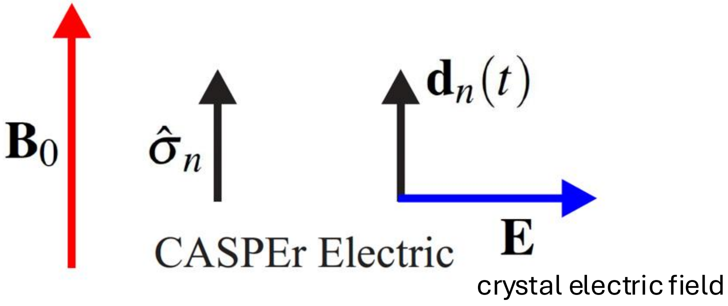
https://cajohare.github.io/AxionLimits/

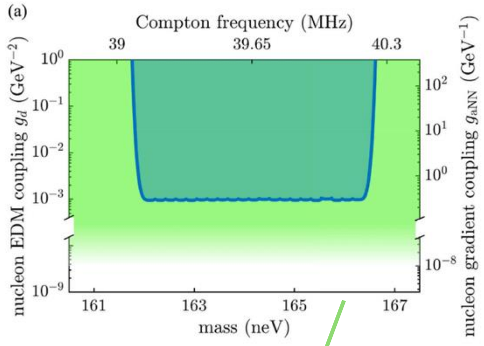
Casper-e Search for axion dark matter using solid-state NMR

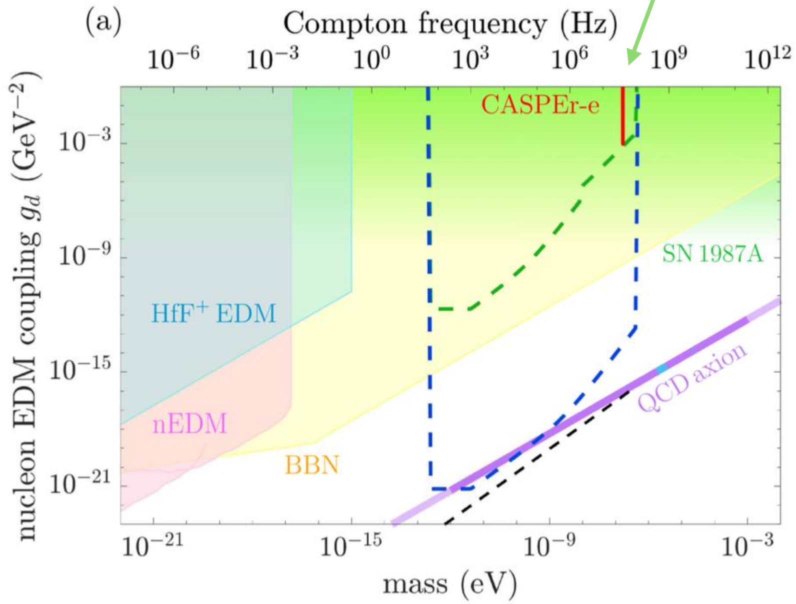
resonance condition

$$\Omega_L = \gamma_n B_0 \qquad \Omega_L \approx \omega_a$$









Sample: poled cylindrical ferroelectric PMN-PT crystal

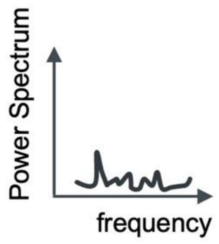
$$\vec{d}_n(t) = g_d a_0 \cos(\omega_a t)\hat{\vec{\sigma}}_n$$ DM induced EDM

$$H_{\mathrm{EDM}} = -\vec{d}_n(t) \cdot \vec{E}$$

Phys. Rev. Lett. 126, 141802 (2021)

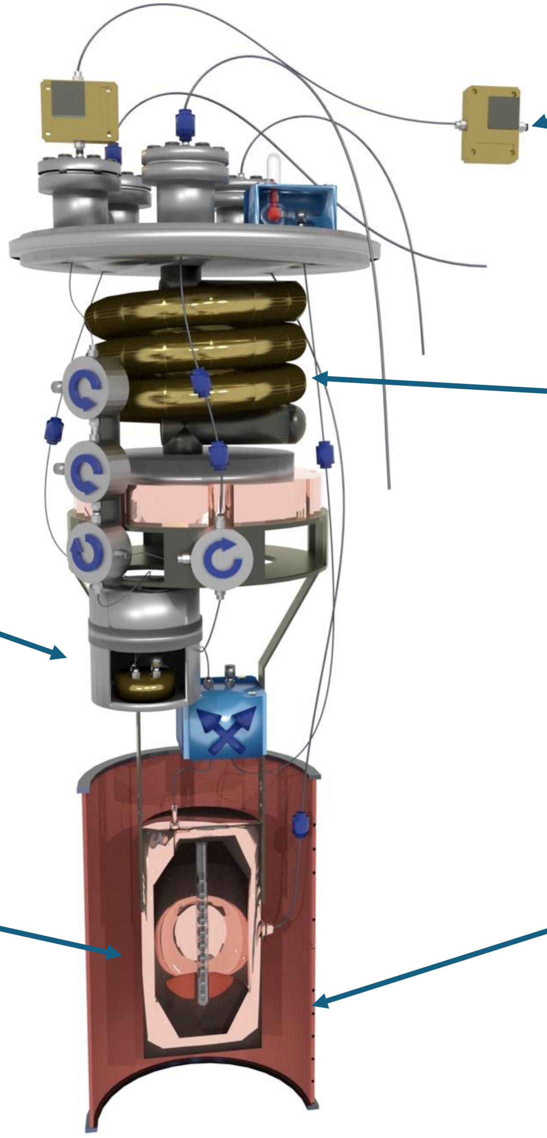
State of Art Sikivie's Haloscope

Room Temperature Amplifiers



Dilution Refrigeretor T<100 mK

Cryogenic Amplifier (noise at SQL)



Scan rate

$$\frac{df}{dt} \propto \frac{B^4 V^2 Q_L}{T_{sys}^2}$$

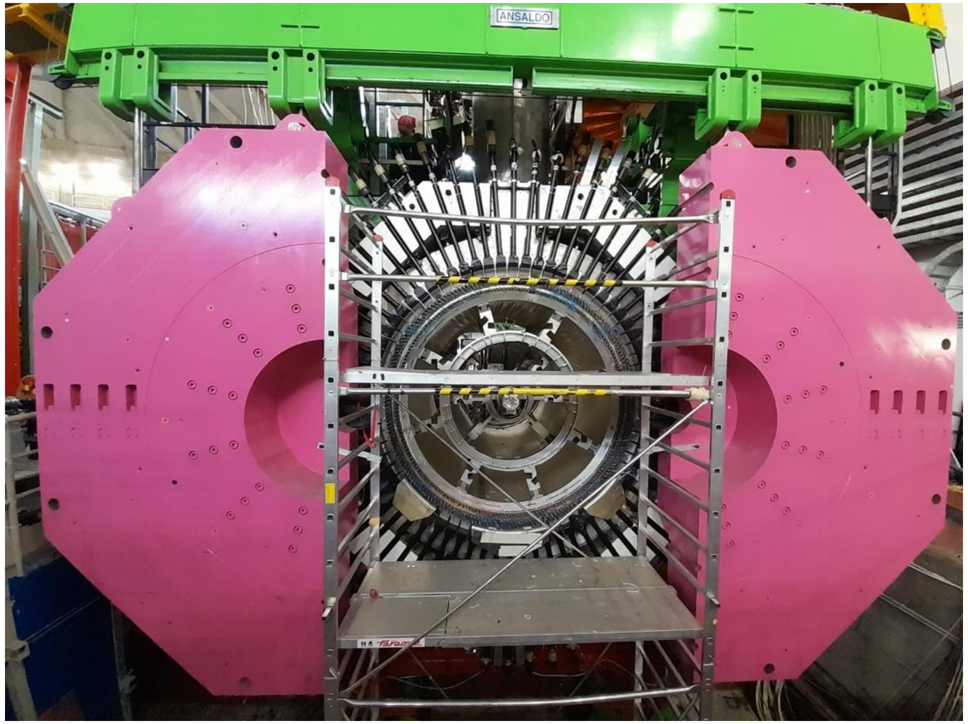
Resonant cavity

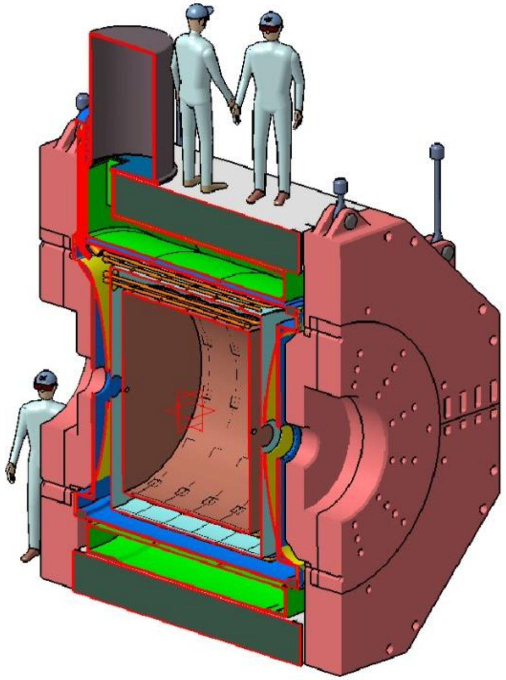
SC magnet (~10 T)

Sikivie Phys. Rev. D 32,11 (1985)

FLASH FINUDA magnet for Light Axion Search Haloscope

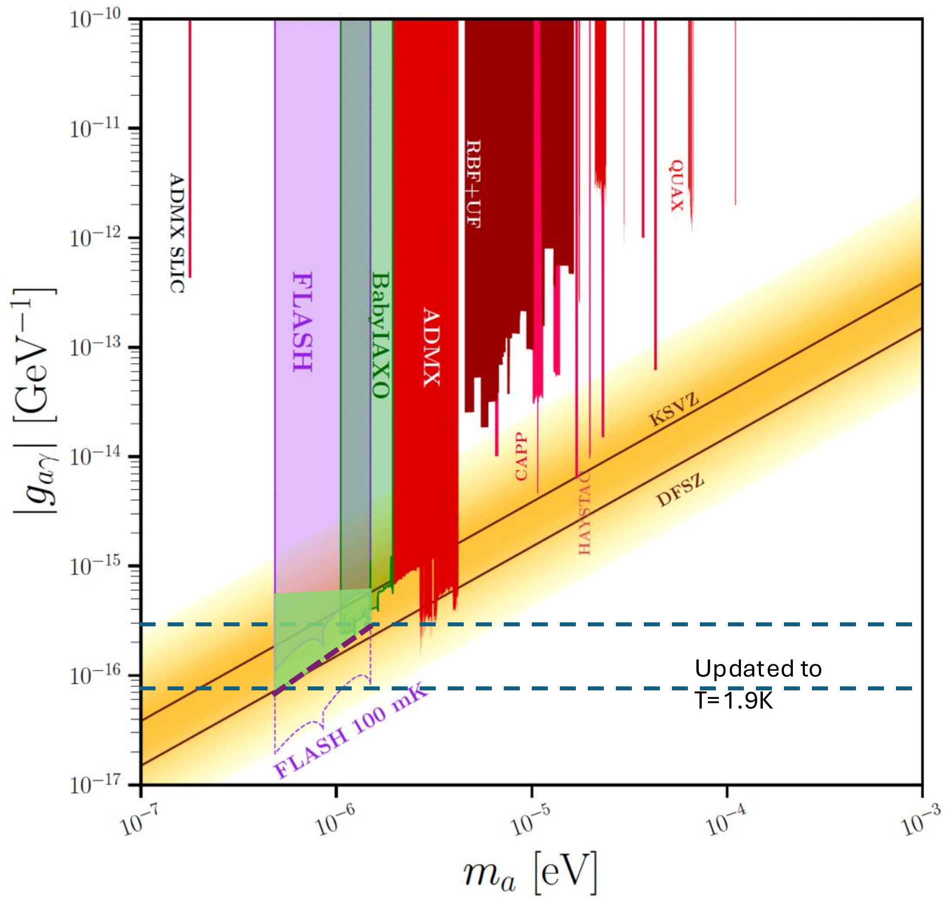
- The FLASH haloscope will operate between 100 and 300 MHz at a temperature of 1.9 K.
- It will be built inside the 3-m diameter superconducting magnet of the FINUDA experiment at LNF.

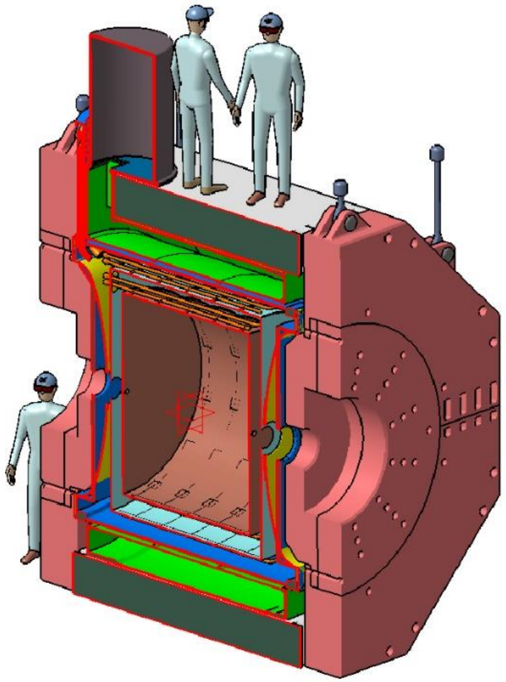




“The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories”
Physics of the Dark Universe 42 (2023) 101370

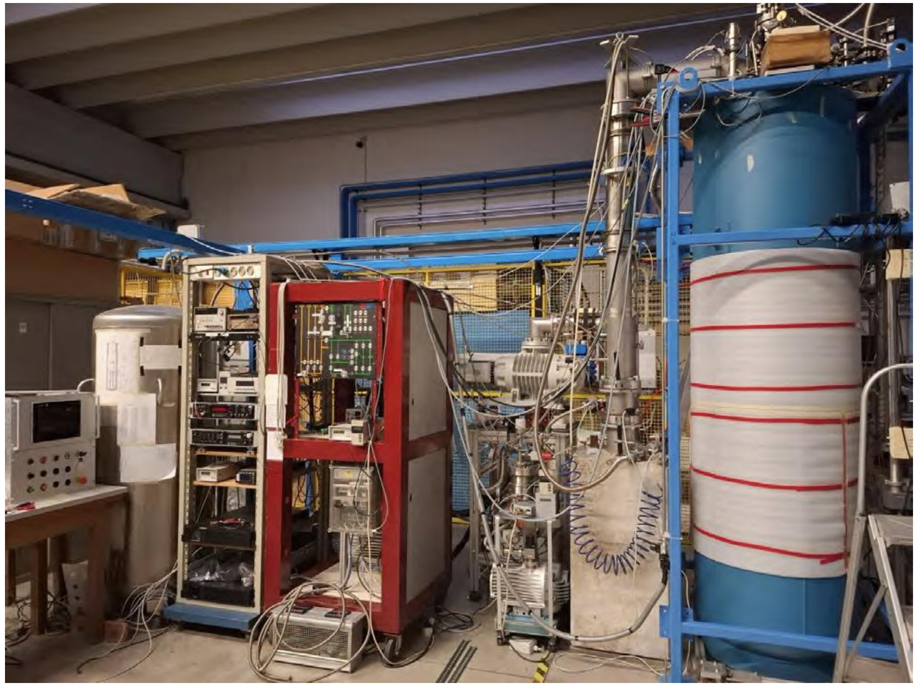
FLASH FINUDA Light Axion Search Haloscope





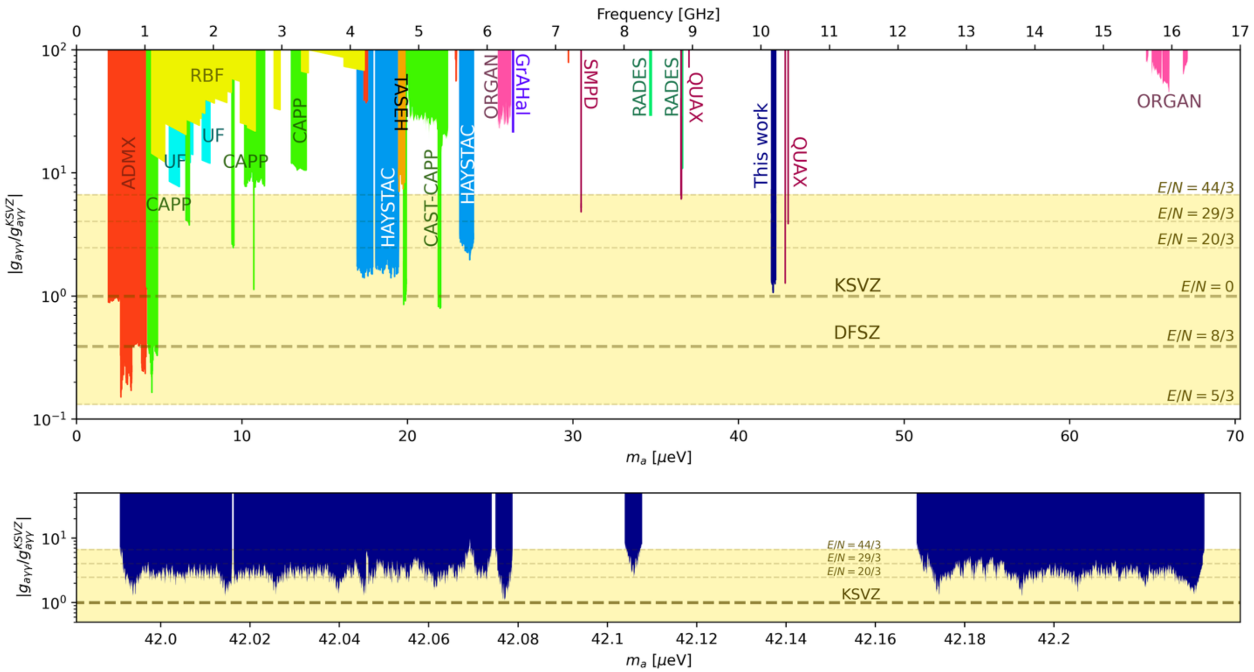
"The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories"
Physics of the Dark Universe 42 (2023) 101370

INFN QUAX



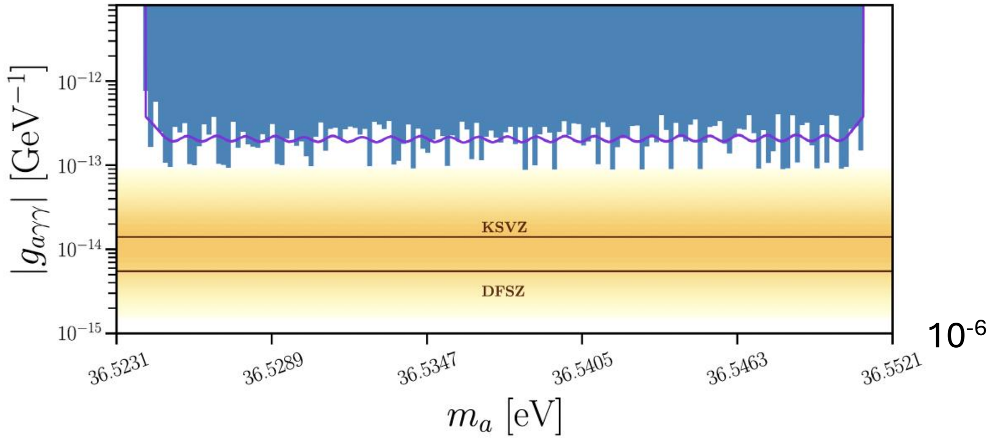
The QUAX experiment has two haloscopes in the National Laboratories of INFN in Legnaro and Frascati

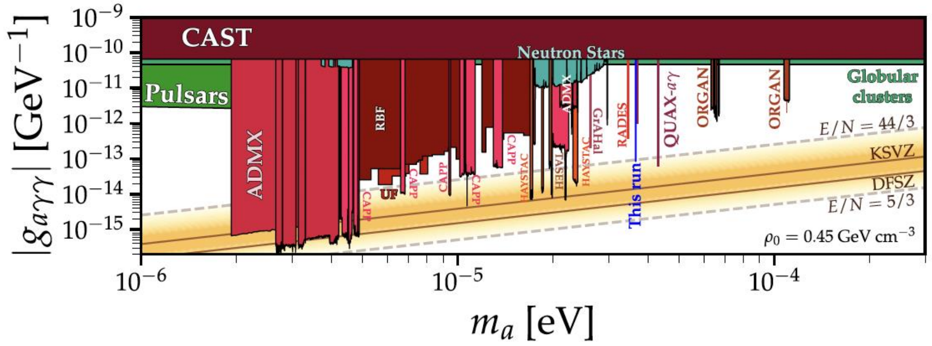
QUAX LNL HALOSCOPE

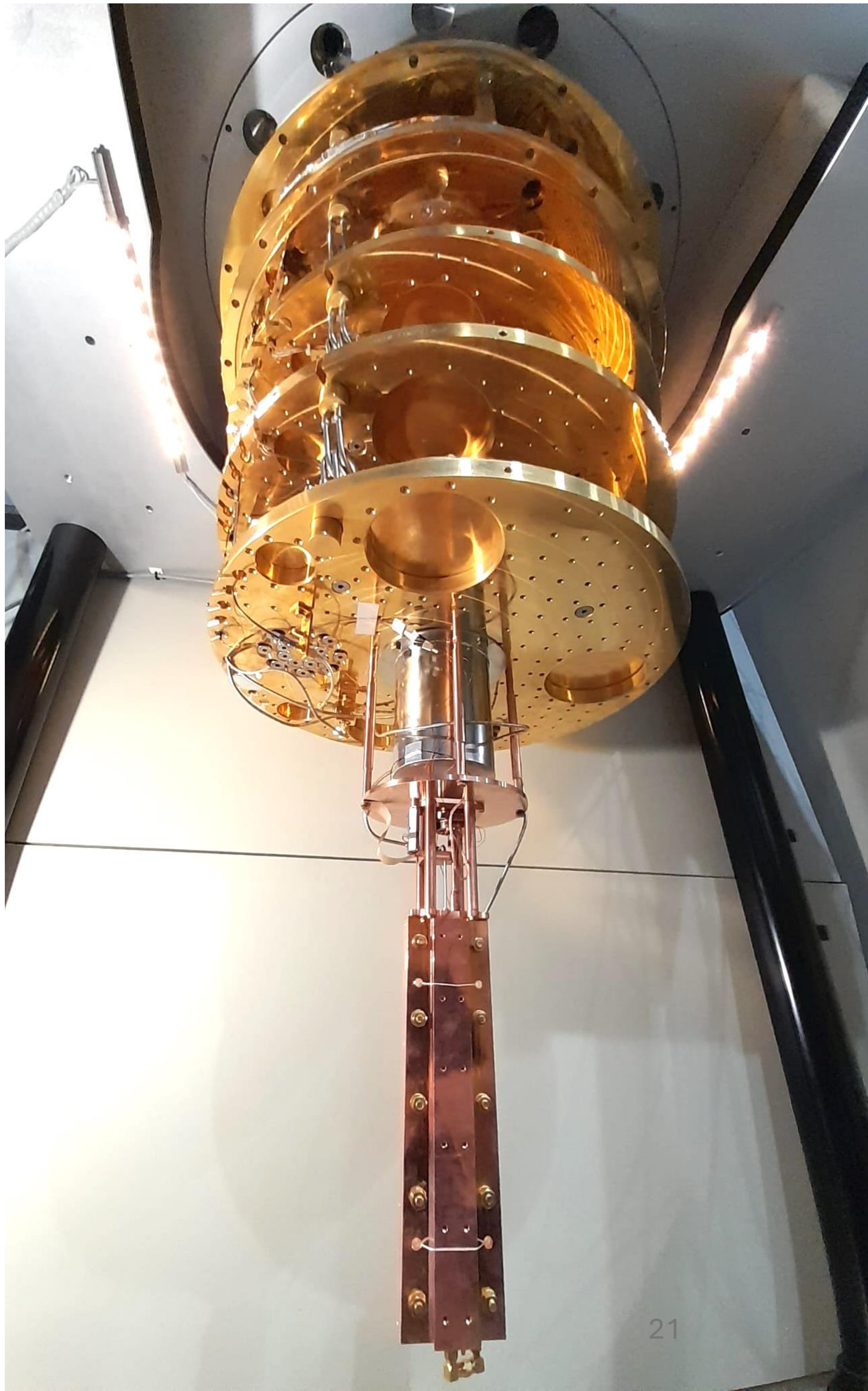


arXiv:2506.11589

QUAX LNF HALOSCOPE

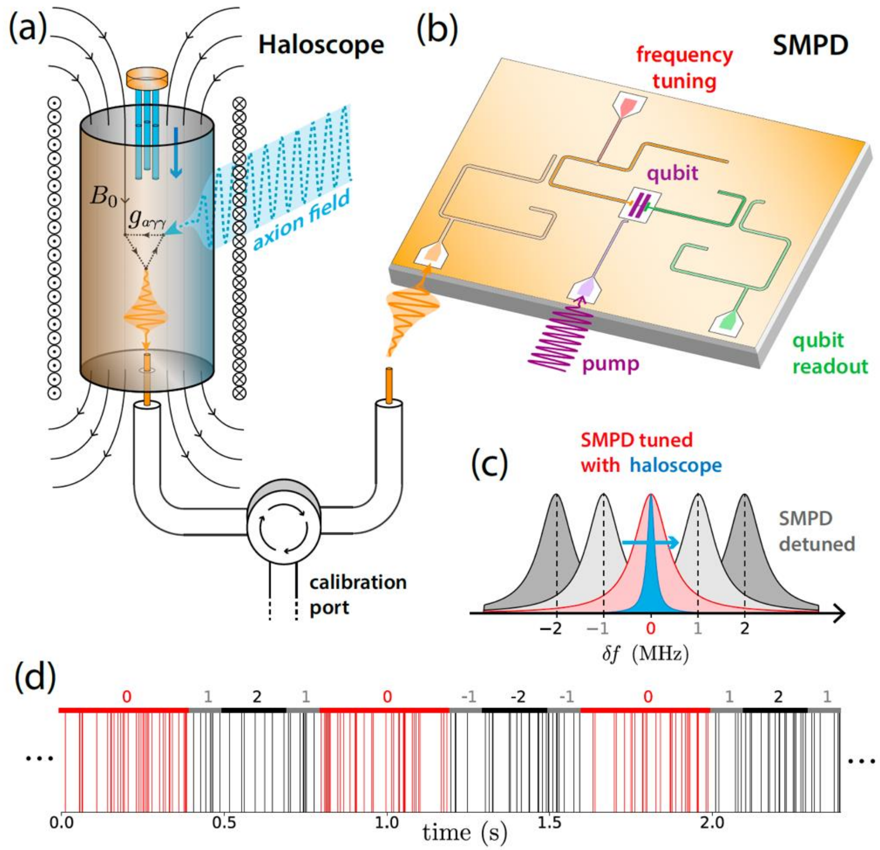


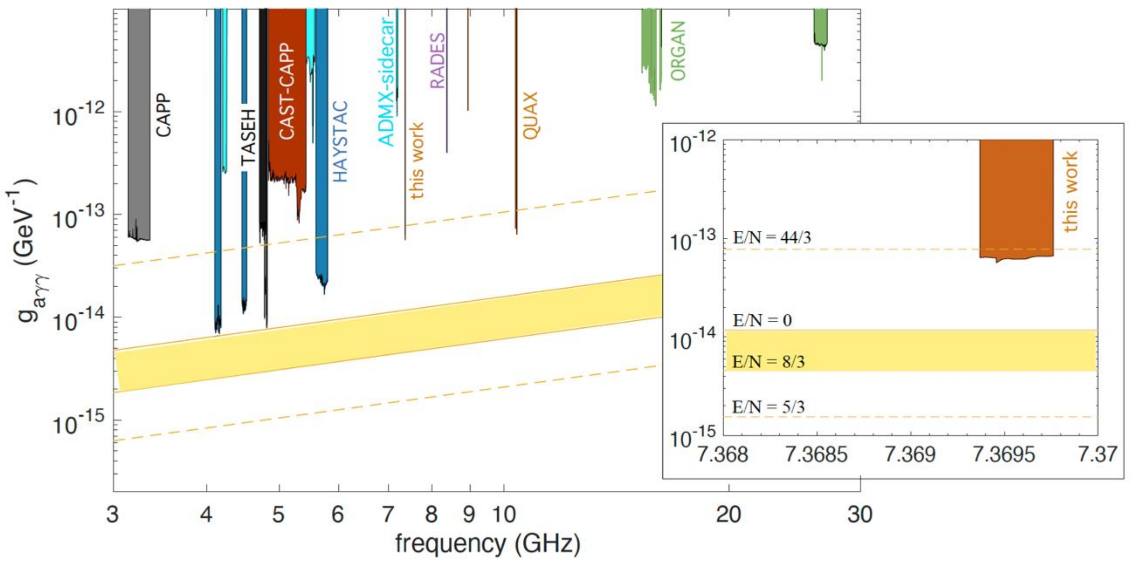




Phys. Rev. D 110, 022008 (2024)

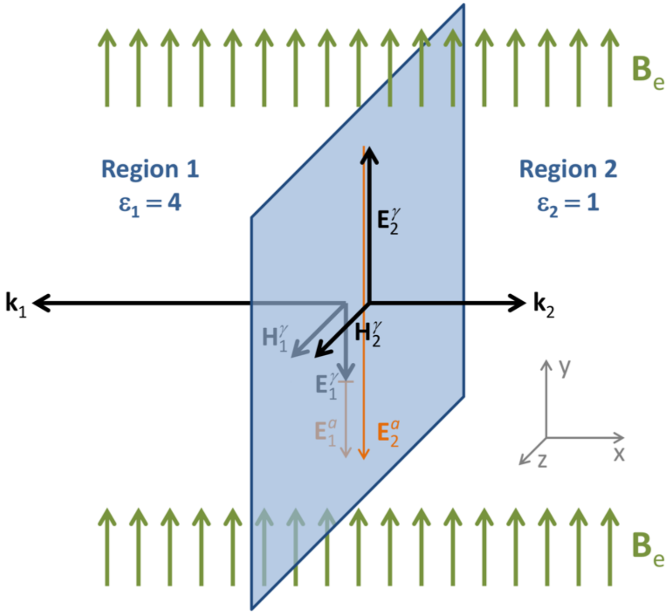
Quantum-Enhanced Sensing of Axion Dark Matter with a Transmon-Based Single Microwave Photon Counter



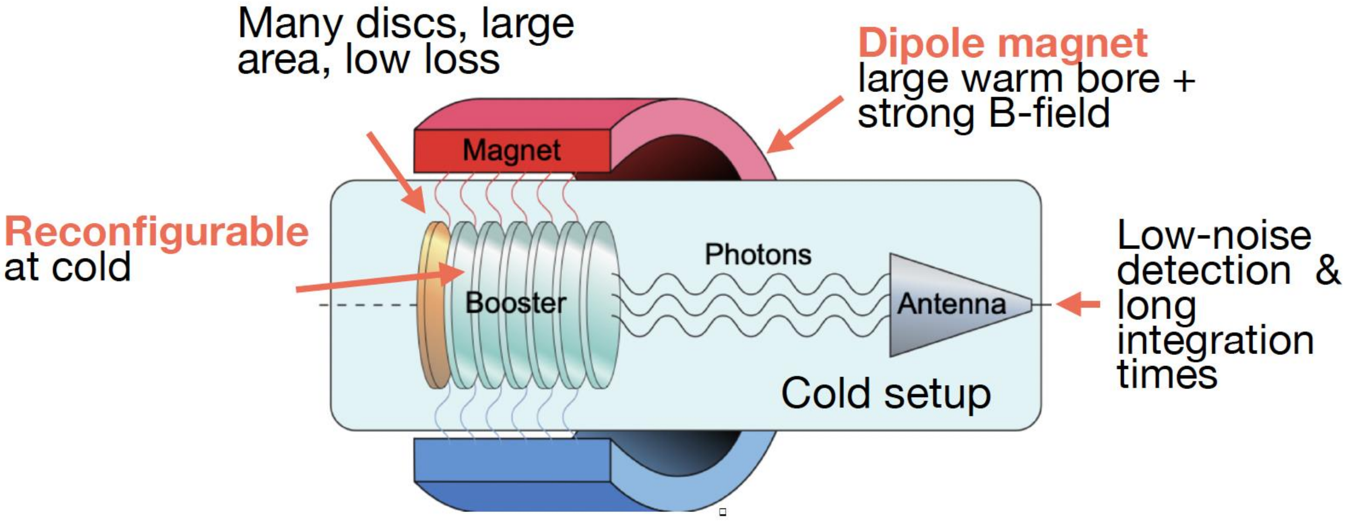


Phys. Rev. X 15, 021031

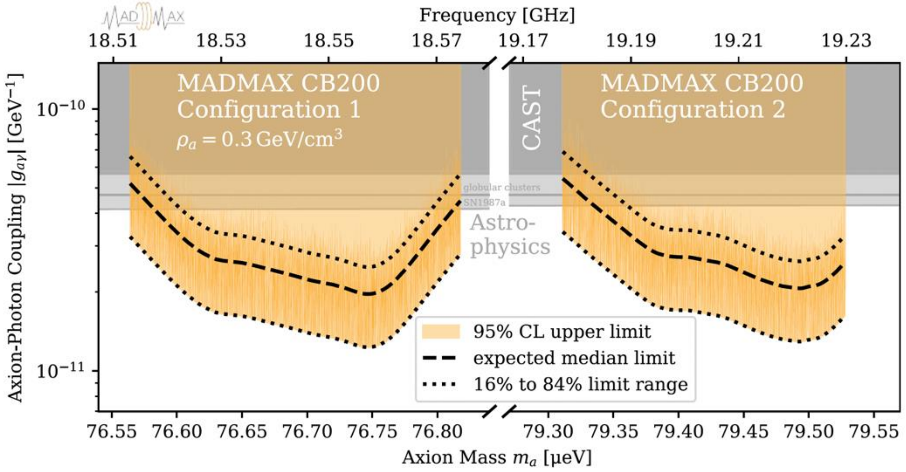
MADMAX Magnetized Disk and Mirror Axion eXperiment at 10-50 GHz

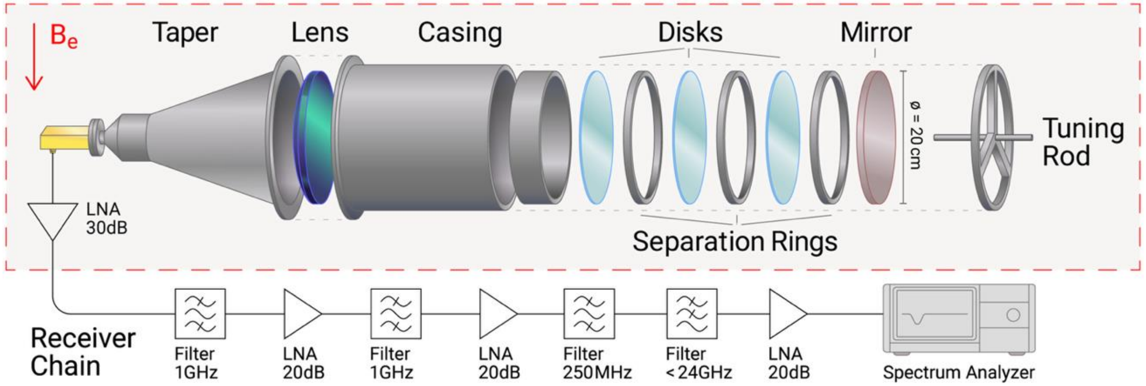


JCAP 1701:061,2017



MADMAX Magnetized Disk and Mirror Axion eXperiment at 10-50 GHz

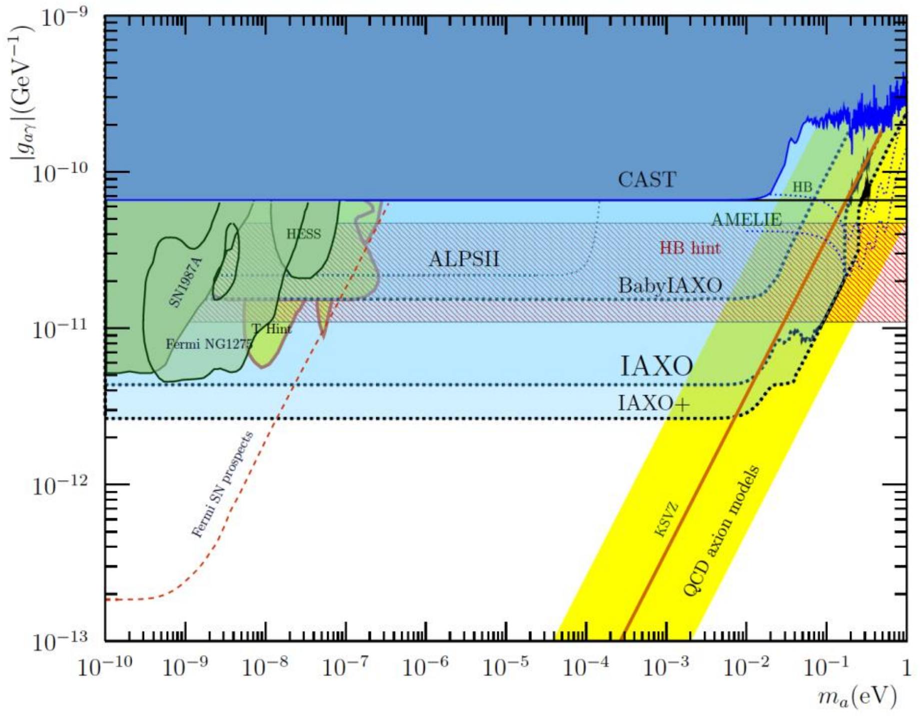


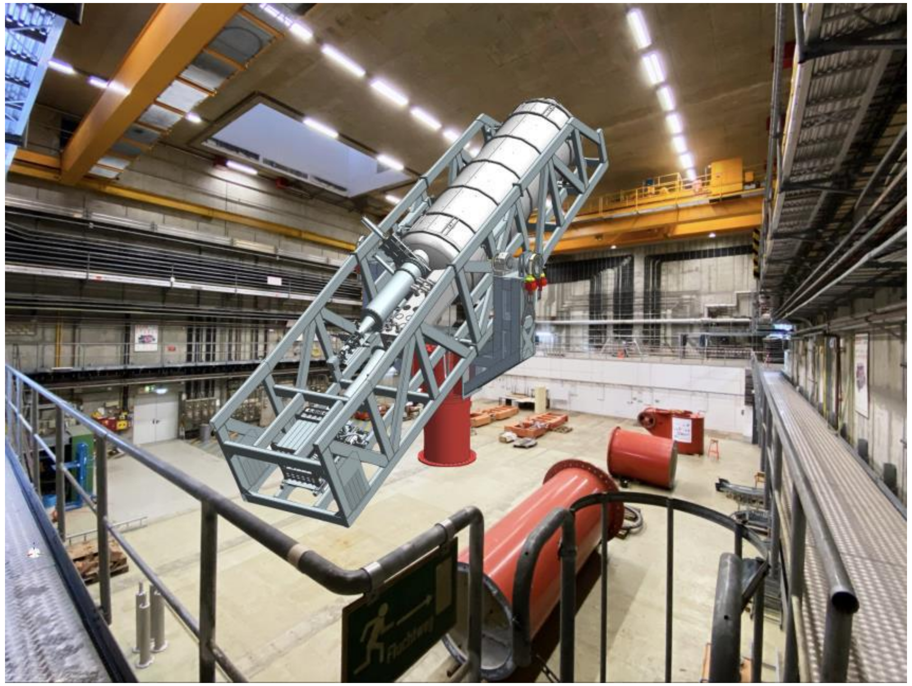


Results obtained with the MADMAX prototype using the Morpurgo magnet (B=1.6 T) at CERN (T=300 K)

PHYSICAL REVIEW LETTERS 135, 041001 (2025)

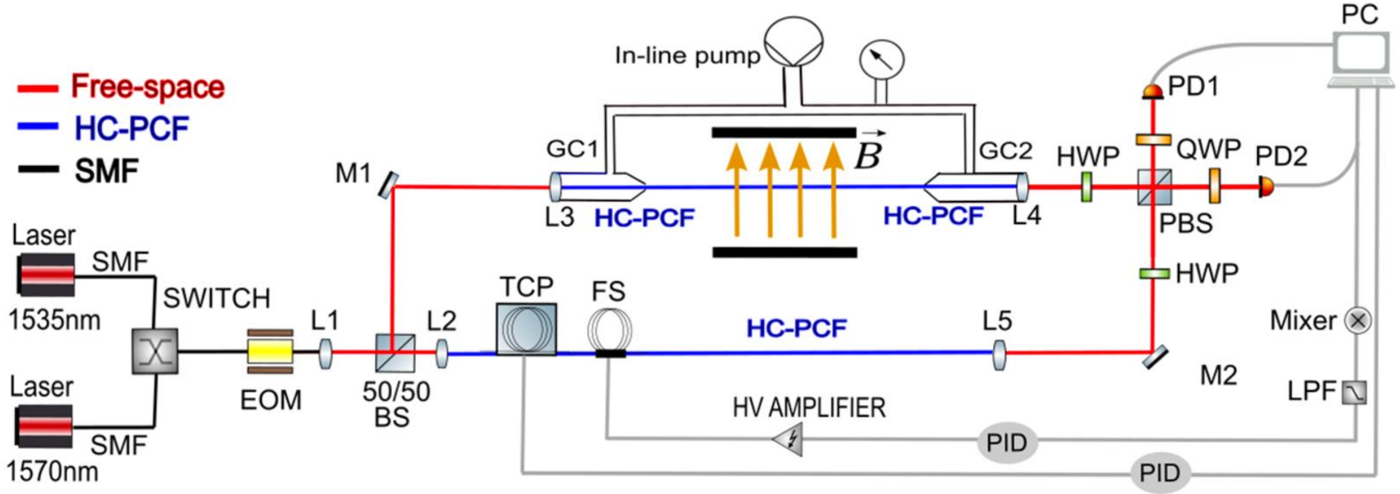
BabyIAXO under construction

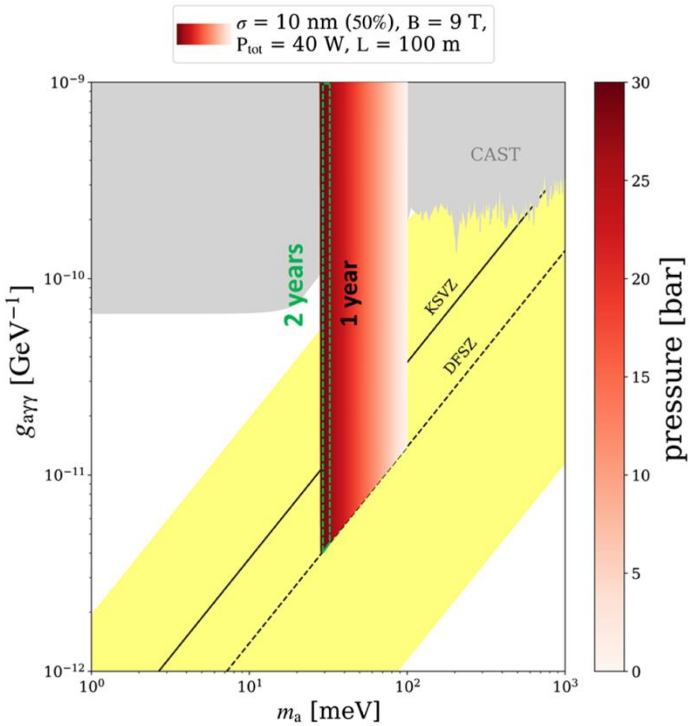




WISPFI WISP Searches with Fiber Interferometer

Mach-Zehnder Interferometer $\mathcal{P}(\gamma \to a)$





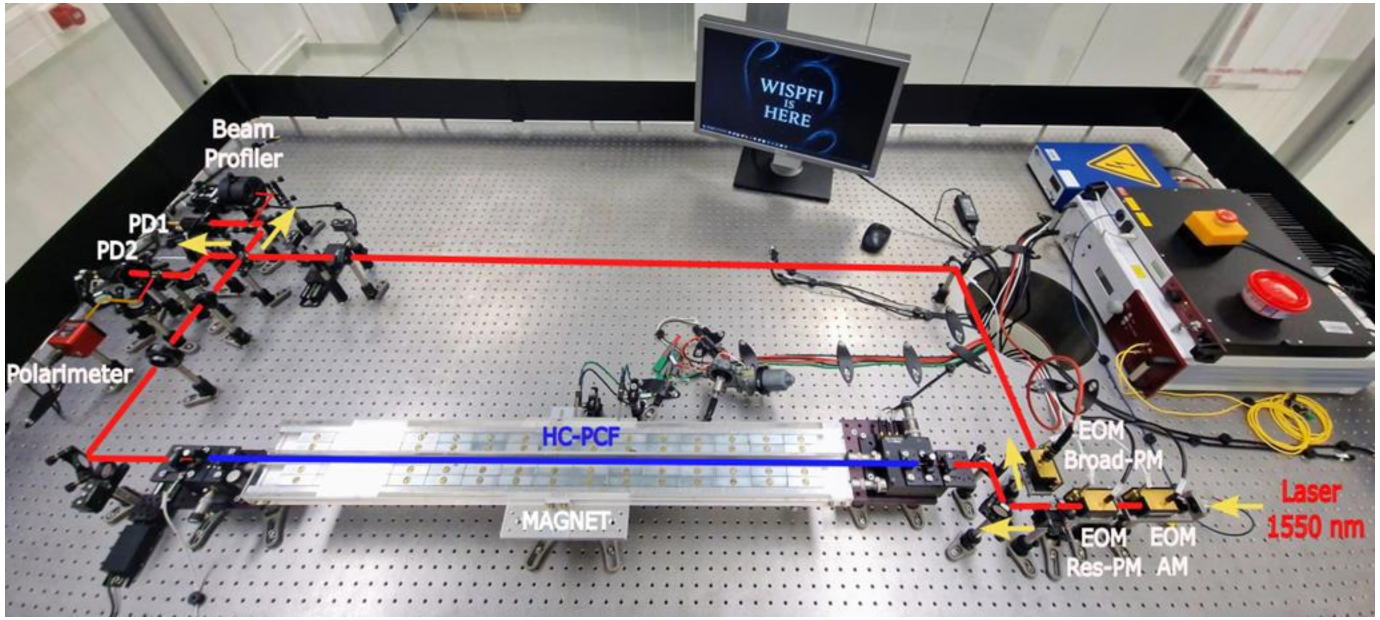
$$m_a = \omega\sqrt{1 - n_{\mathrm{eff}}^2}$$

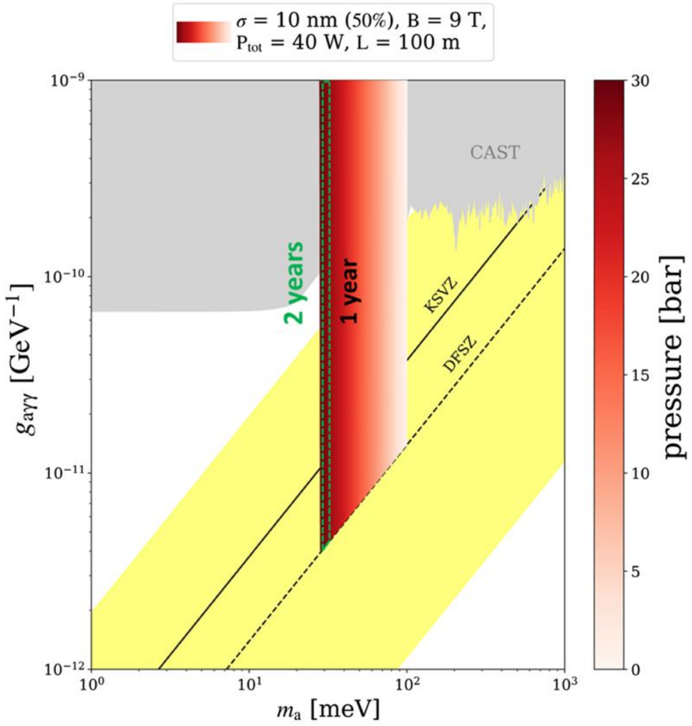
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Phys. Rev. D **109**, 123001 (2024)

WISPFI WISP Searches with Fiber Interferometer

Mach-Zehnder Interferometer $\mathcal{P}(\gamma \to a)$





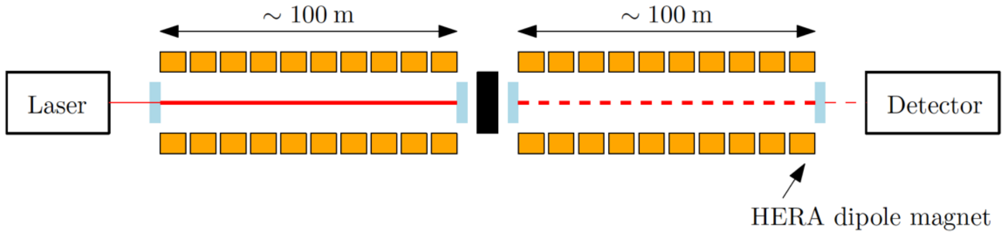
$$m_a = \omega\sqrt{1 - n_{\mathrm{eff}}^2}$$

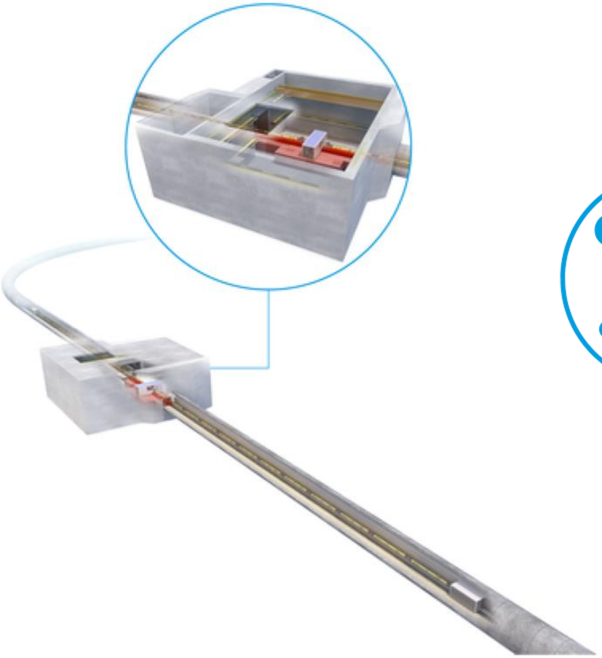
Phys. Rev. D **109**, 123001 (2024)

ALPS II

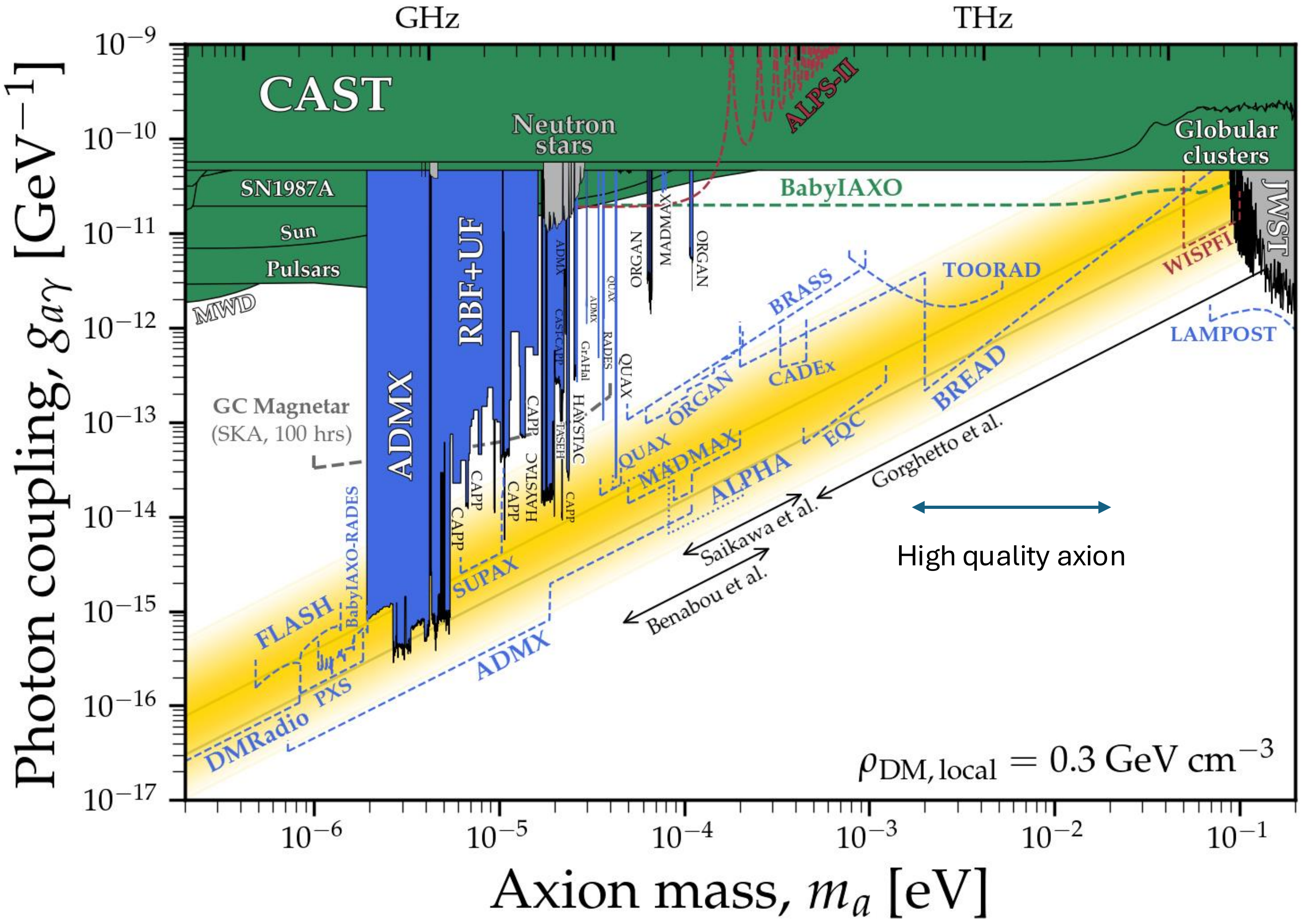
Data taking started in 2023

$$\mathcal{P}(\gamma \to a) \quad \mathcal{P}(a \to \gamma)$$





DESY.


GHz
THz
CAST
Neutron stars
ALPS-II
Globular clusters
SN1987A
Sun
Pulsars
MWD
BabyIAXO
JWST
ADMX
RBF+UF
ORGAN
MADMAX
QUAX
RADES
CAPP
HAYSTAC
TASEH
GrAHal
TOORAD
BRASS
WISPFI
LAMPOST
CADEx
BREAD
EQC
ALPHA
SUPAX
FLASH
BabyIAXO-RADES
PXS
DMRadio
GC Magnetar
(SKA, 100 hrs)
Gorghetto et al.
Saikawa et al.
Benabou et al.
High quality axion
$\rho_{\rm DM,local} = 0.3$ GeV cm^{-3}
Photon coupling, $g_{a\gamma}$ [GeV^{-1}]
Axion mass, m_a [eV]

Fine