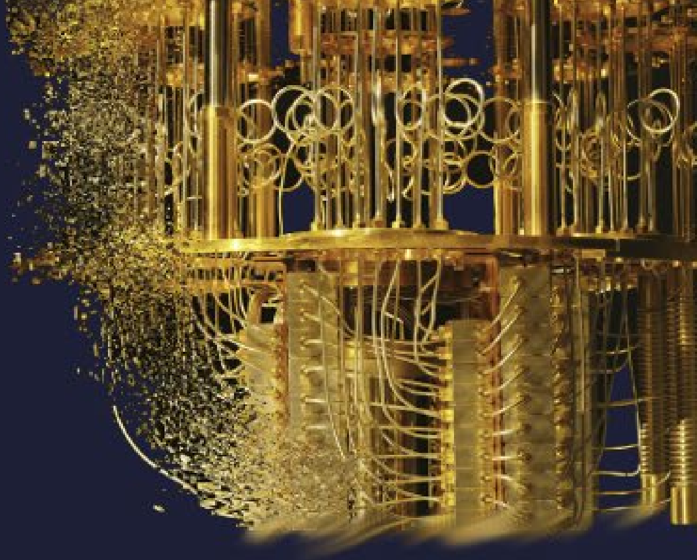


"Experimental approaches in the search for low mass axion-like particles"

Pisa, 17/2/2023

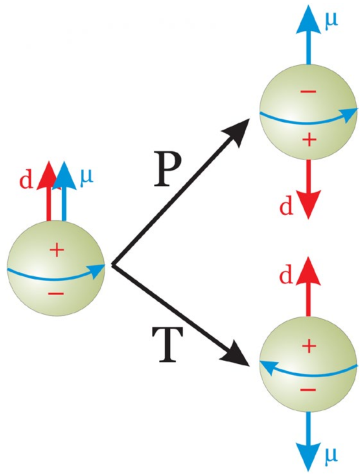
Gianluca Lamanna (Univ.Pisa & INFN)

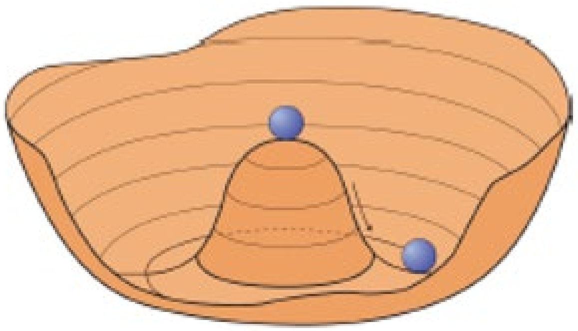
- The axion is the most convincing solution of the strong CP problem
- WISPs (weakly interacting slim particles) are a possible solution of DM problem
- The ALPS can solve some astrophysical problem
  - Trasparency of the universe at Ultra High Energy photons
  - Anomalous stellar cooling
- Different experimental techniques targeting at different mass ranges

Axions theory

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

- Strong CP problem:
  - Unavoidable (in case of 6 massives quarks) θ term
  - Prediction → $d_N = (5.2 \cdot 10^{-16}\, e \cdot cm)\bar{\theta}$
  - Measurement → $d_N < 10^{-26} e \cdot cm$



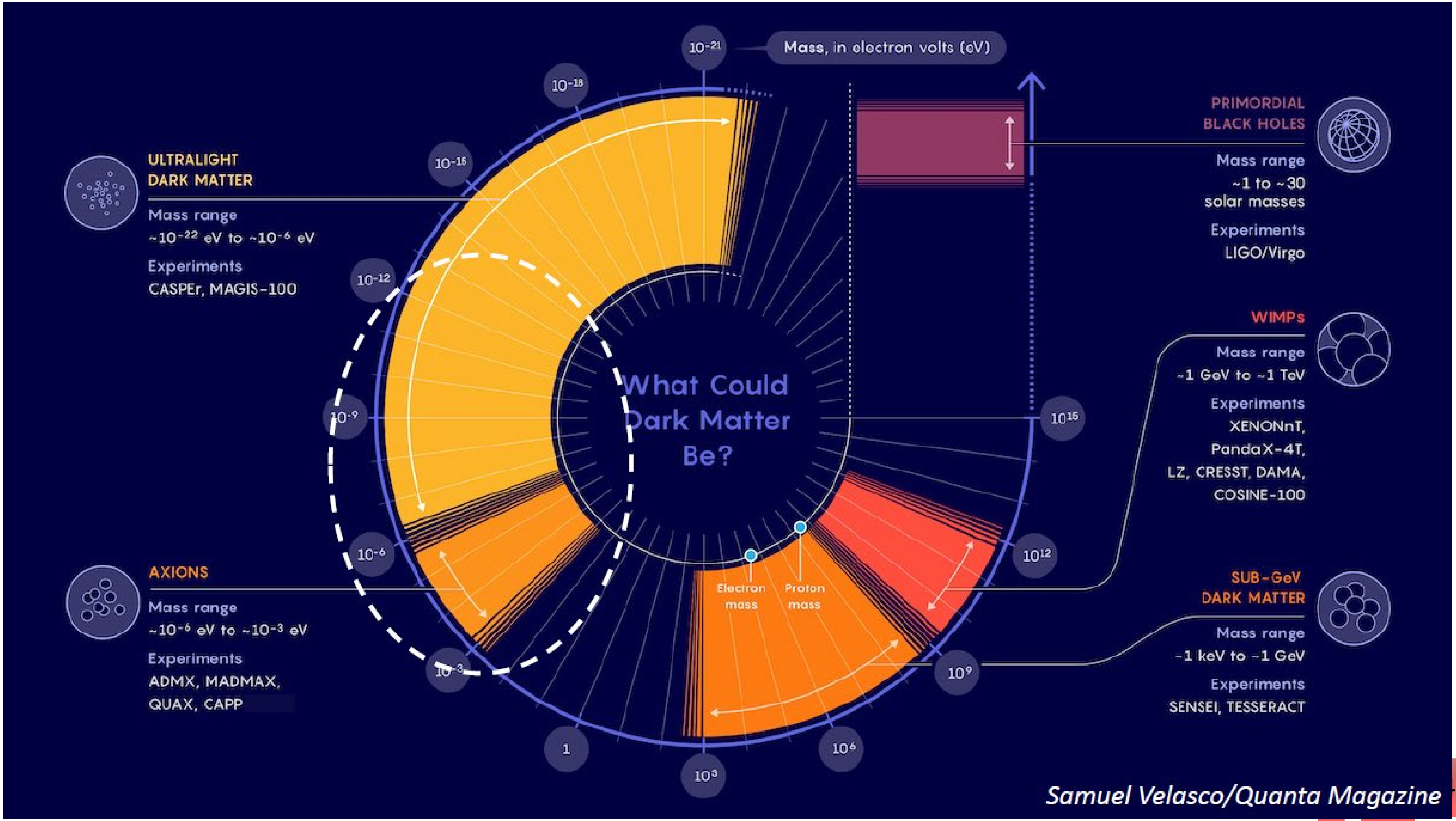


- Peccei-Quinn mechanism (1977):
  - New scalar field to cancel out the θ term:

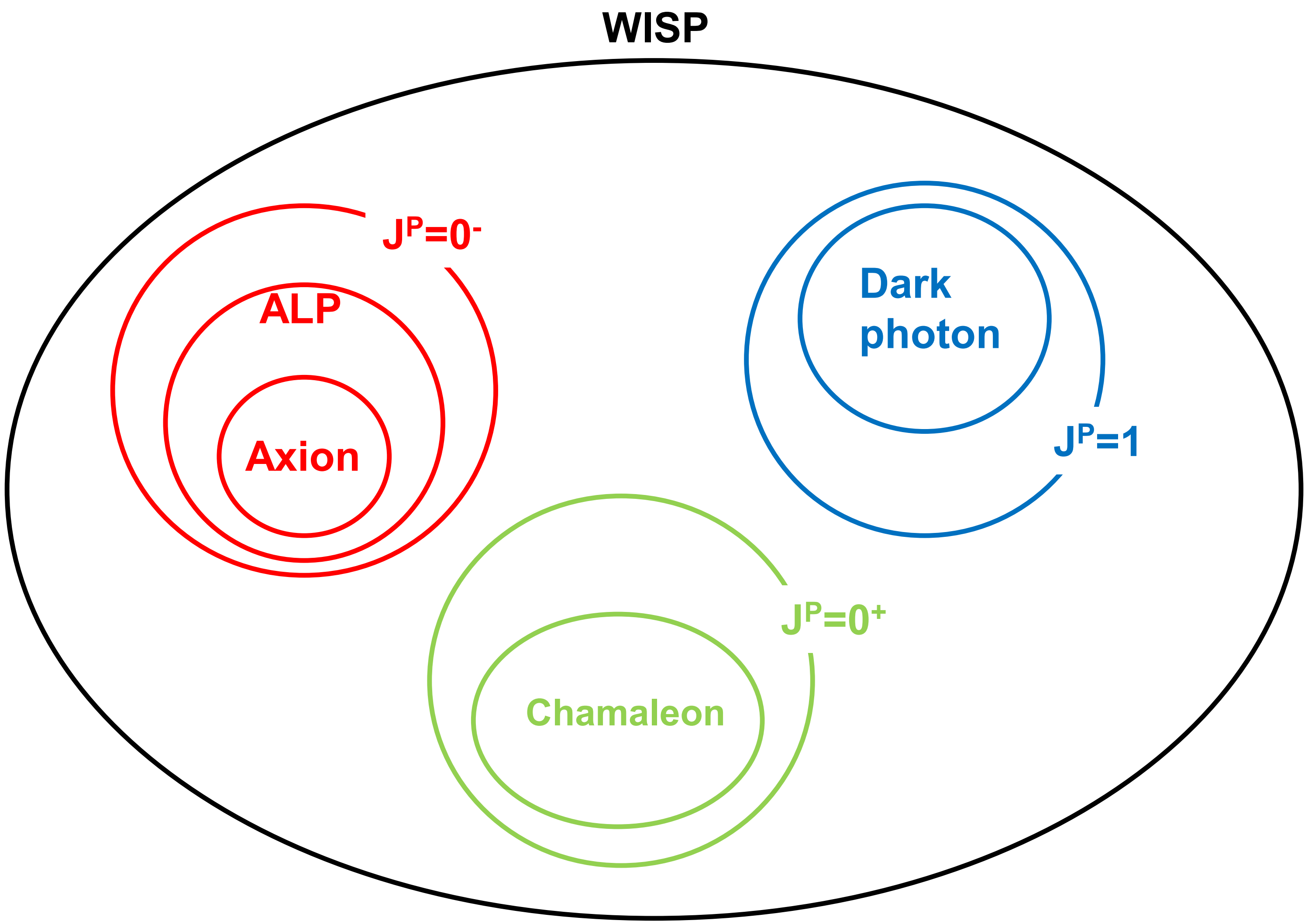
$$\mathcal{L} \supset \left(\theta - \frac{a}{f_a}\right)\frac{\alpha_S}{32\pi^2}\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

  - Spontaneous breaking of the U(1)→ $a = \theta \cdot f_a$
  - The axion is the pseudoscalar Nambu_Goldstone boson → relation between mass and coupling

Dark matter candidates



- WISP: Weakly Interacting Slim Particle



- Pseudo-scalar
  - Axion: solution of strong CP problem
  - Axion-like particle (ALP): generic axion no relation between mass and coupling
- Scalar
  - Chamaleon: dark energy
- Vector
  - Dark photon: new interaction

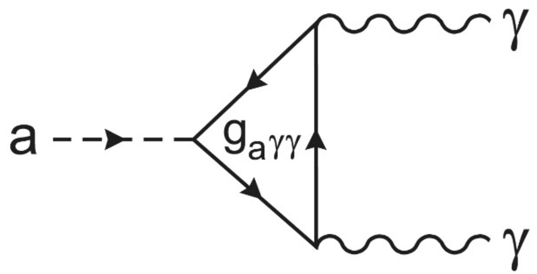
How to detect axions ?

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

	Photons	Fermions	nEDMs
Lagrangian	$g_{a\gamma\gamma}a\vec{E}\cdot\vec{B}$	$g_{aff}\vec{\nabla}a\cdot\hat{S}$	$g_{EDM}a\hat{S}\cdot\vec{E}$
Observable	Photon	Spin preces.	Oscillating EDM
Detection	Power Spectrum, photon counter, resonator in magnetic field	Magnetometer, NMR…	NMR, polarimeter…
Examples	ADMX, CAPP, MADMAX, …	GNOME QUAX, ARIADNE, …	CASPEr, srEDM, ..

How to detect axions?

- Most common search with EM interaction



$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$$

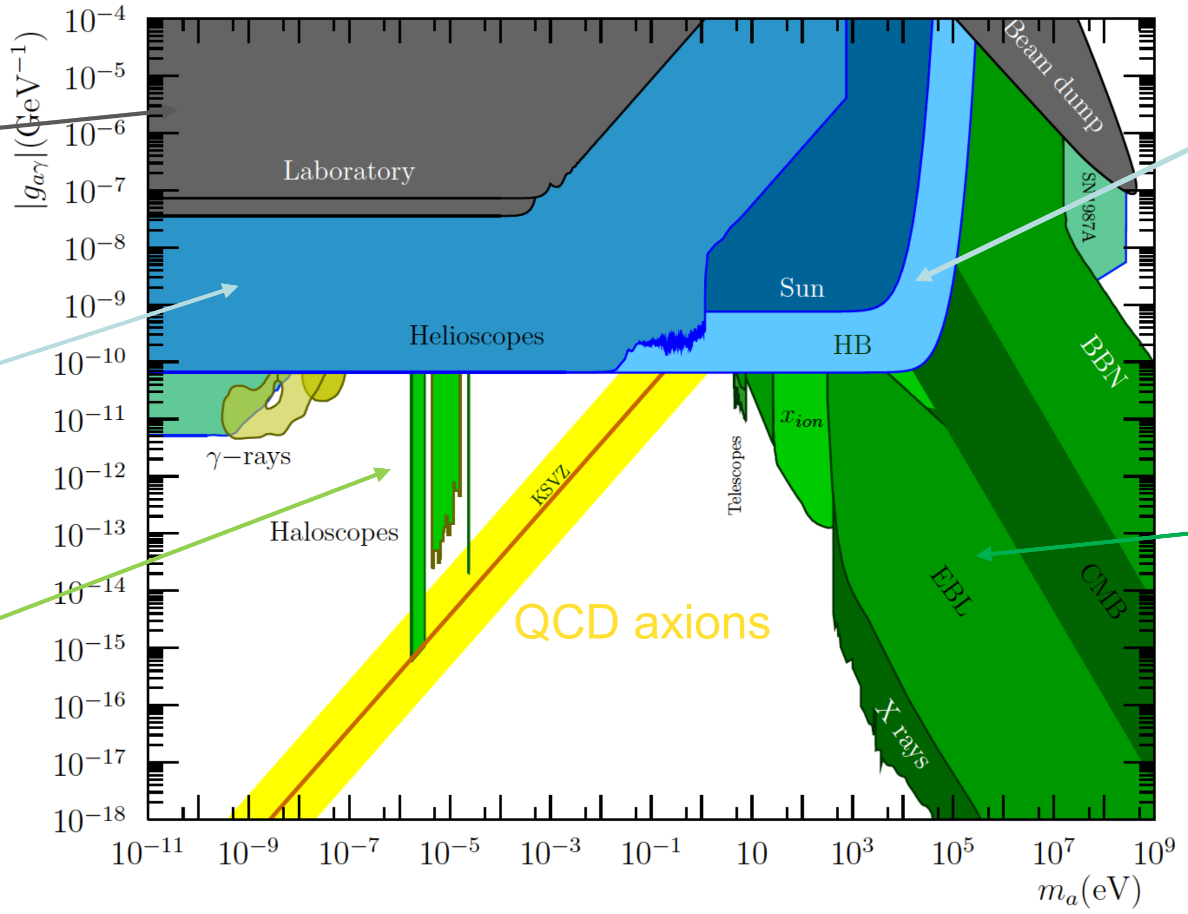
- Coupling inversely proportional to U(1) breaking scale
- The effective coupling is model dependent:
  - E/N=0 in KSVZ, E/N=8/3 DFSZ model

Limits

Laboratory experiments

Detection of axions from the Sun (Elioscopes)

DM axion detection (Haloscopes)



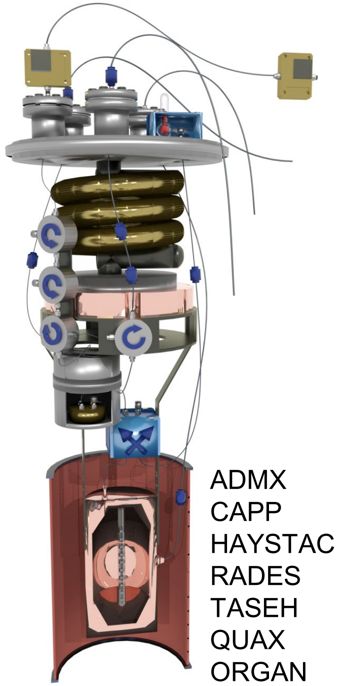
Stellar physics:
Primakoff process in stars $\gamma Ze \rightarrow a\ Ze$.
Constraints on stellar lifetime or energy-loss rates: Sun, HB.

Cosmology:
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.

Ringwald et al. PDG 2017
Irastorza Redondo arxiv:1801.08127

Experimental searches

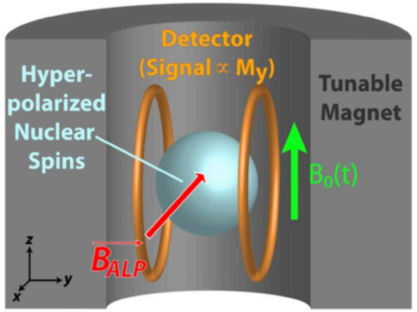
Haloscopes



ADMX
CAPP
HAYSTAC
RADES
TASEH
QUAX
ORGAN

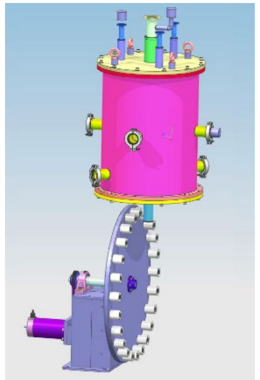
Spin resonance

Casper
Quax-ae



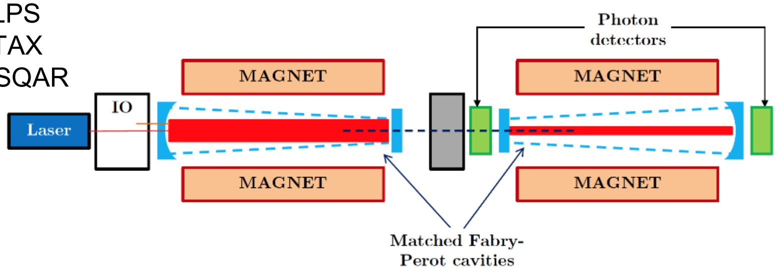
Fifth force experiments

Quax gpgs
Ariadne



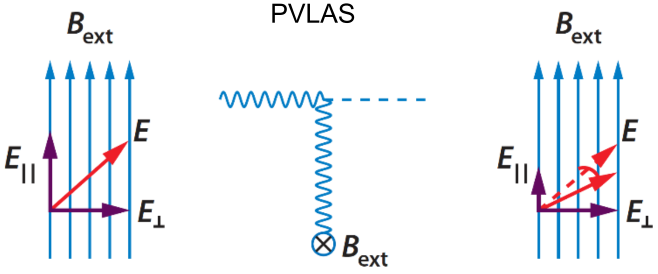
Light shining through wall experiments

ALPS
STAX
OSQAR

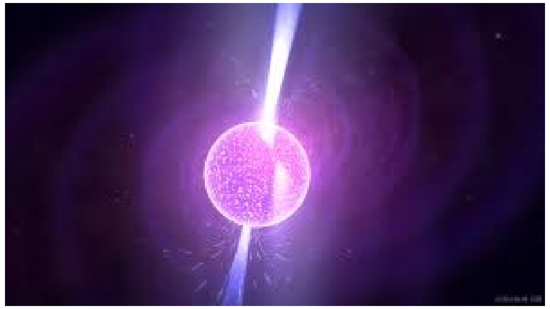


Polarization experiments

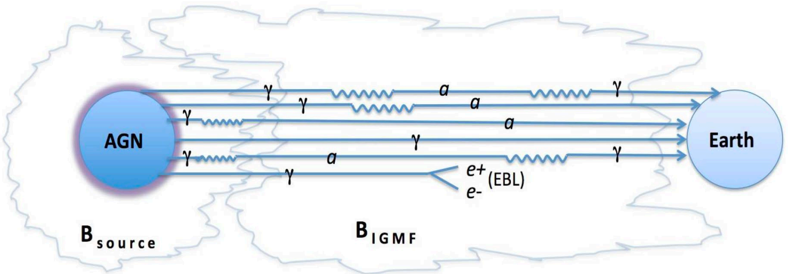
PVLAS



Stars

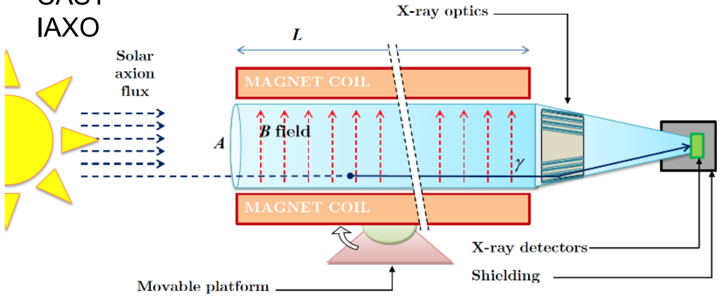


Gamma ray transparency



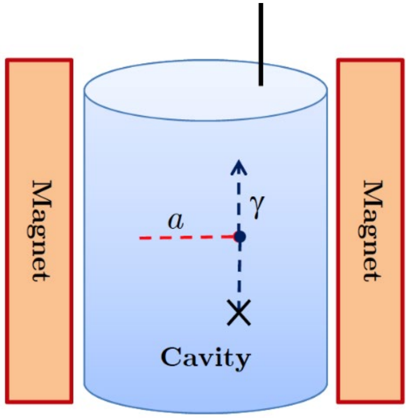
Helioscopes

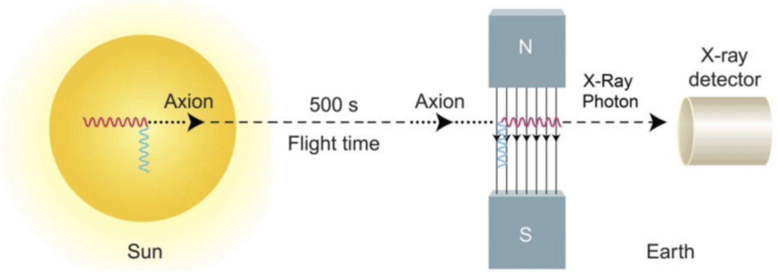
CAST
IAXO



Search Strategies

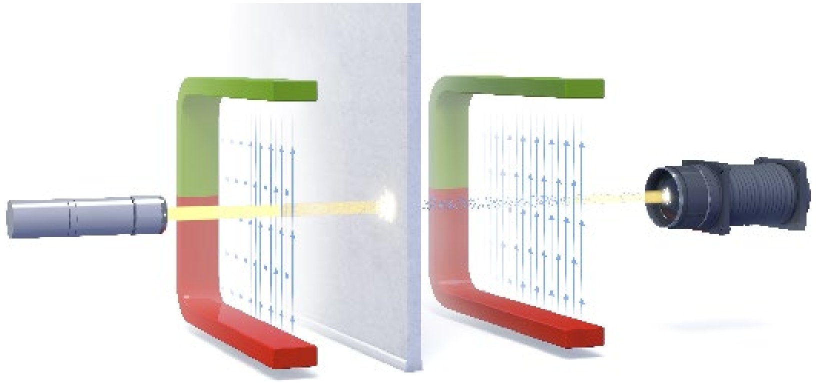
- Haloscope
  - Axions in galactic halo
  - Based in microwave resonators (RF cavities)
  - ADMX, HAYSTAC, CAPP, …





- Helioscope
  - Axions produced in the solar core
  - CAST, IAXO,…

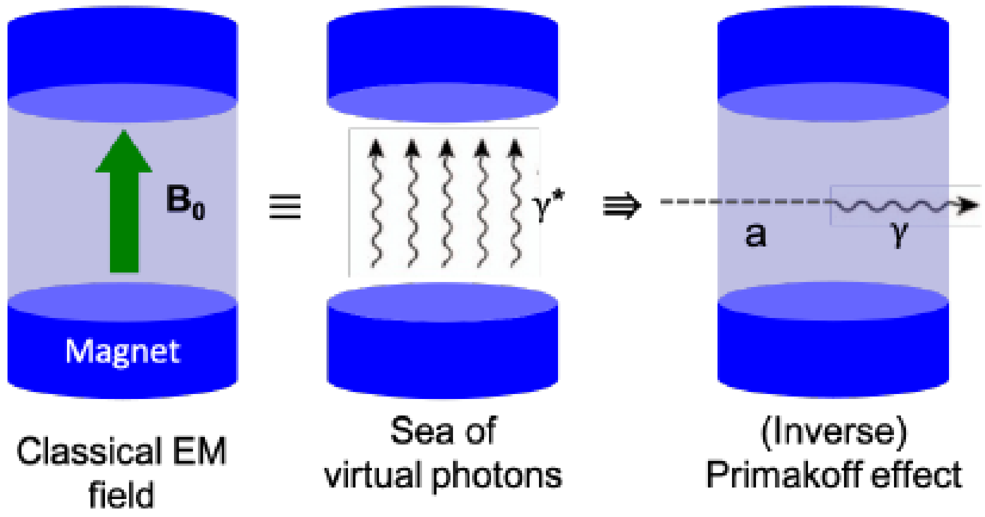
- Photon regeneration
  - Light Shining Through Wall
  - Axions produced at the lab
  - ALPS, OSQAR,…

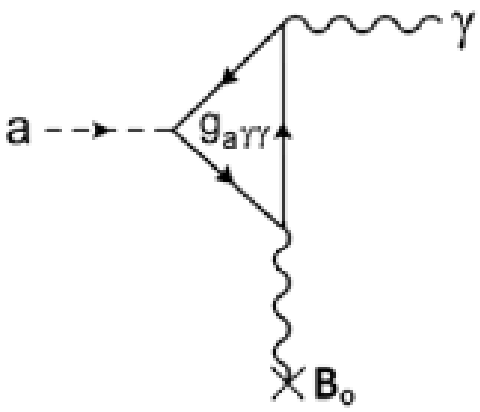


- The axion field modifies the Maxwell's equations
  - The axions allow to turn virtual photons from a magnetic field in real photons
  - Resonant cavity modes are excited by axion field

$$P_{\rm sig} = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4}\right) \times \left(\frac{\beta}{1+\beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mnl} Q_L\right)$$

- β antenna coupling to cavity
- V cavity volume
- C_{mnl} mode factor (0.6 for TM_{010})
- QL cavity «loaded» quality factor

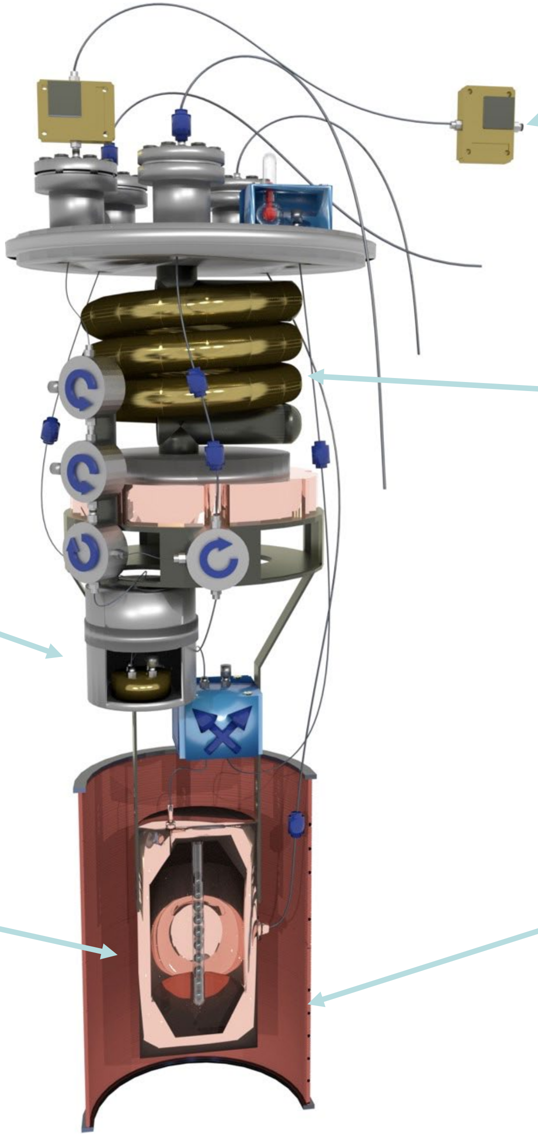




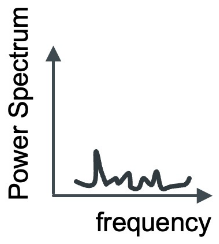
Sikivie Phys. Rev. D 32,11 (1985)

Modern haloscope

- Cryogenic
  - Lowering termal noise
- High magnetic field
  - Increase rate production
- Quantum noise limited amplifiers
  - Minimal noise added
- High Q resonator (tunable)
  - Increase photons in cavity



Room Temperature Amplifiers



Dilution Refrigeretor T<100 mK

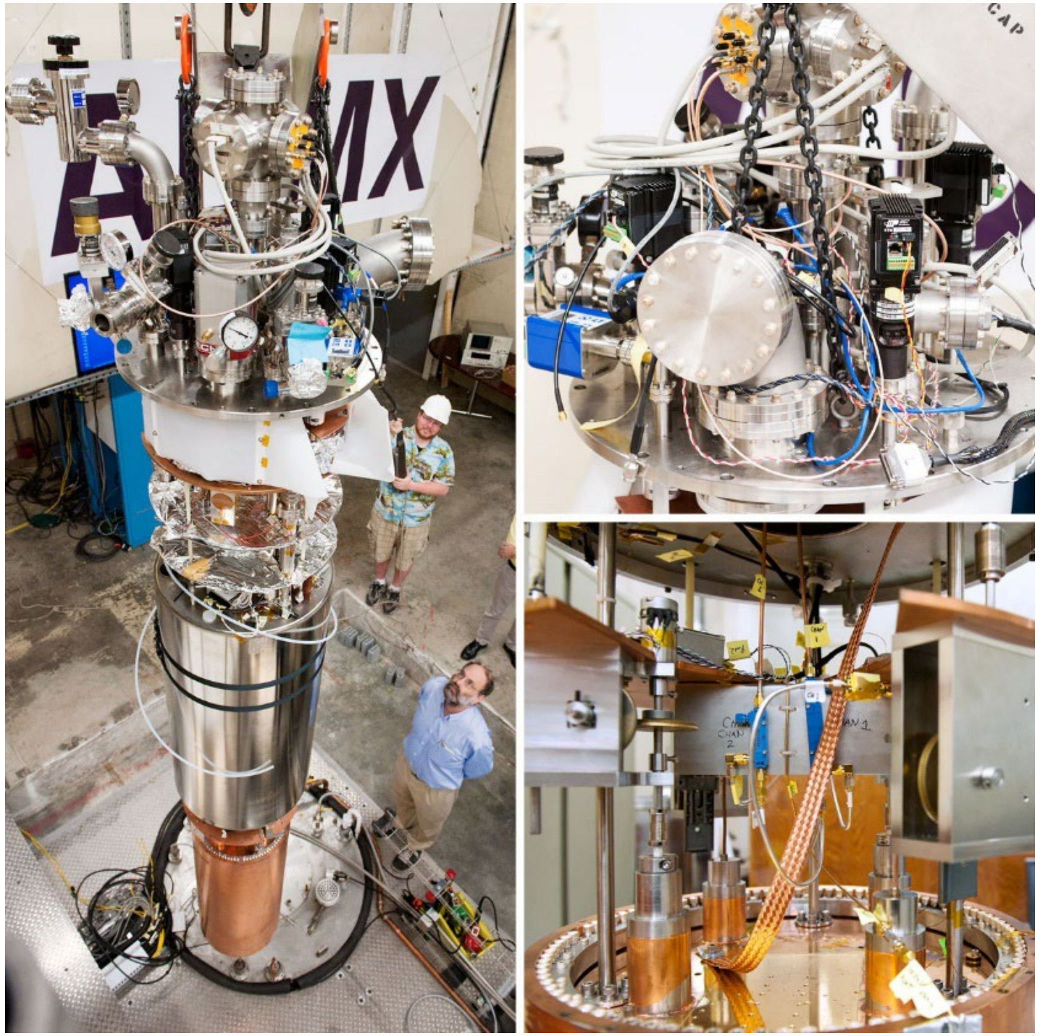
Cryogenic Amplifier (noise at SQL)

Resonant cavity

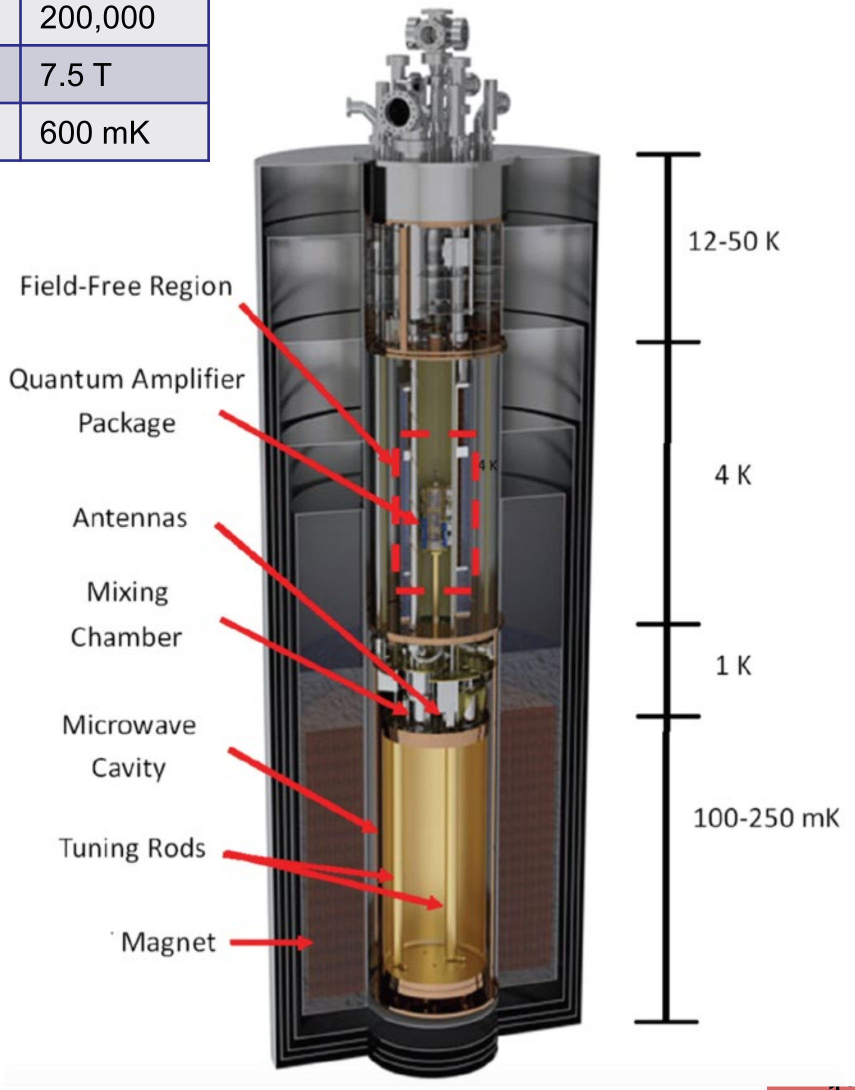
SC magnet (~10 T)

ADMX – Axion Dark Matter Experiment

ADMX	800 MHz
Volume	136 L
Q_0	200,000
B	7.5 T
T_{noise}	600 mK

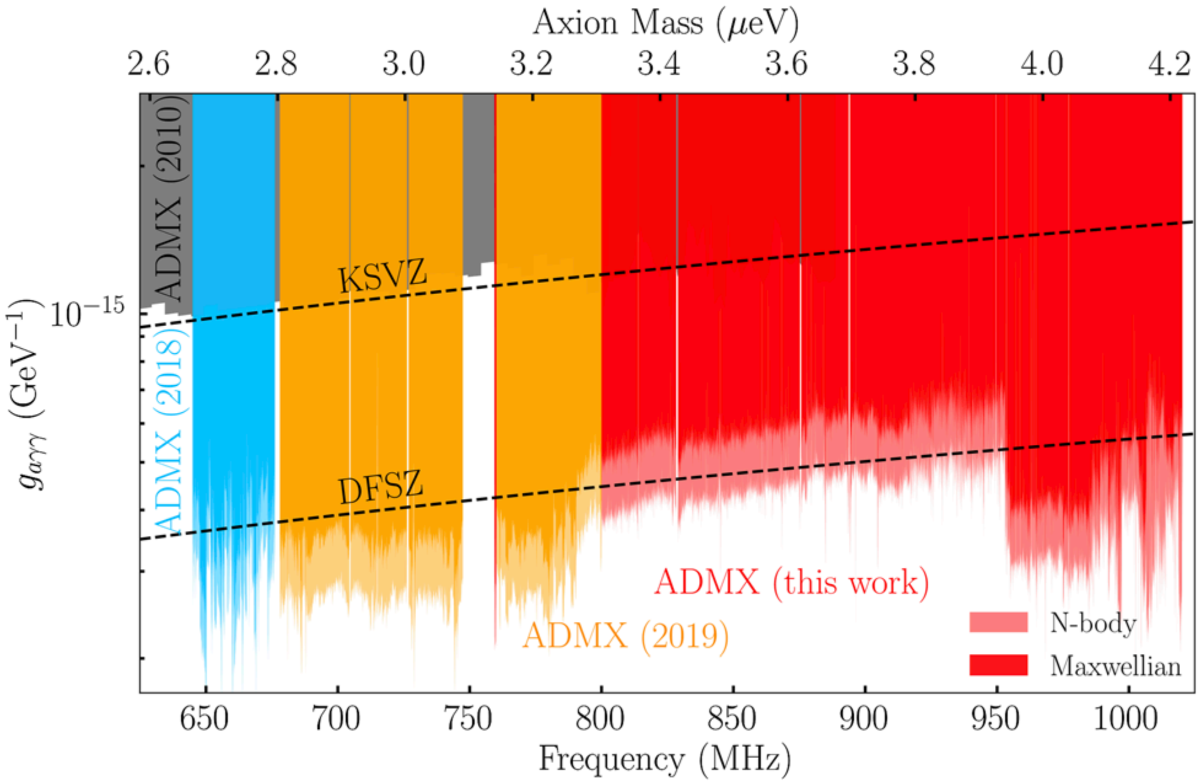


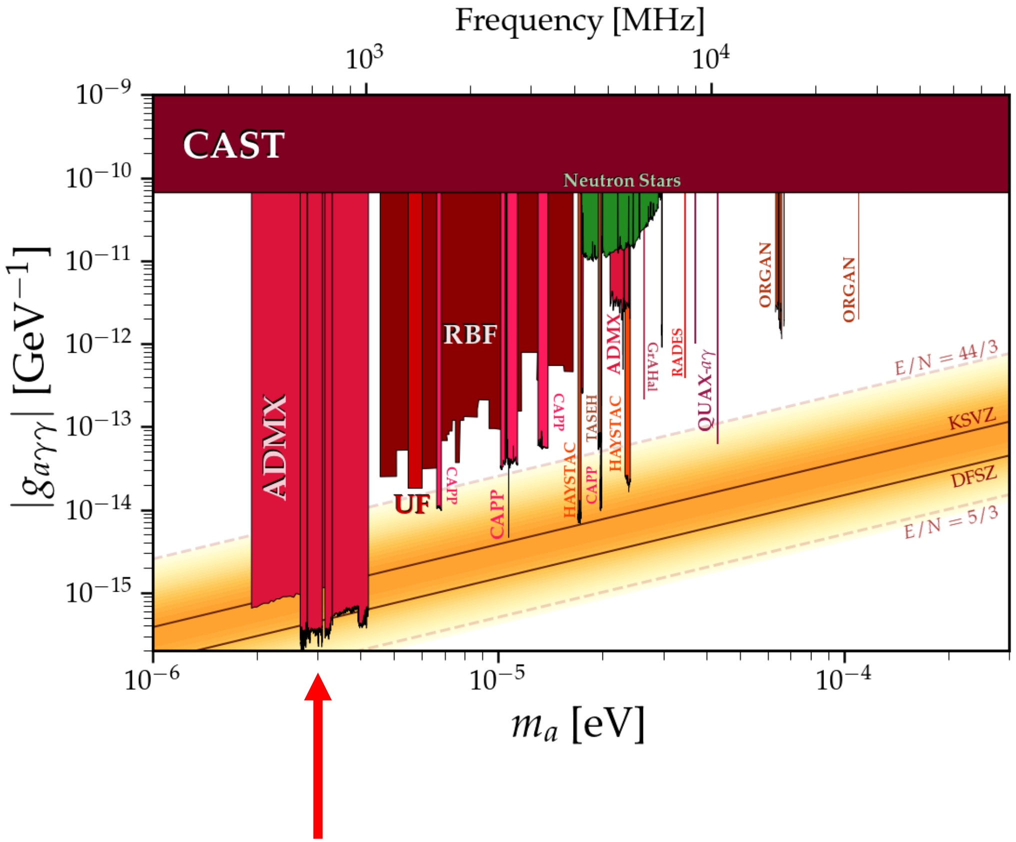
Washington University



PHYSICAL REVIEW LETTERS 120, 151301 (2018)

ADMX recent results

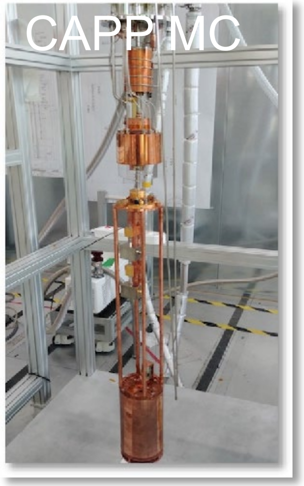


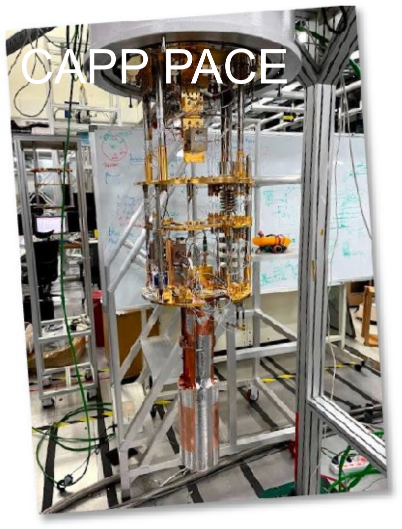


PHYSICAL REVIEW LETTERS 127, 261803 (2021)

CAPP – Center of Axion and precesion Physics

South Korea





CAPP 12T	1.1 GHz
Volume	37 L
Q_0	90,000
B	12 T
T_{noise}	120 mK

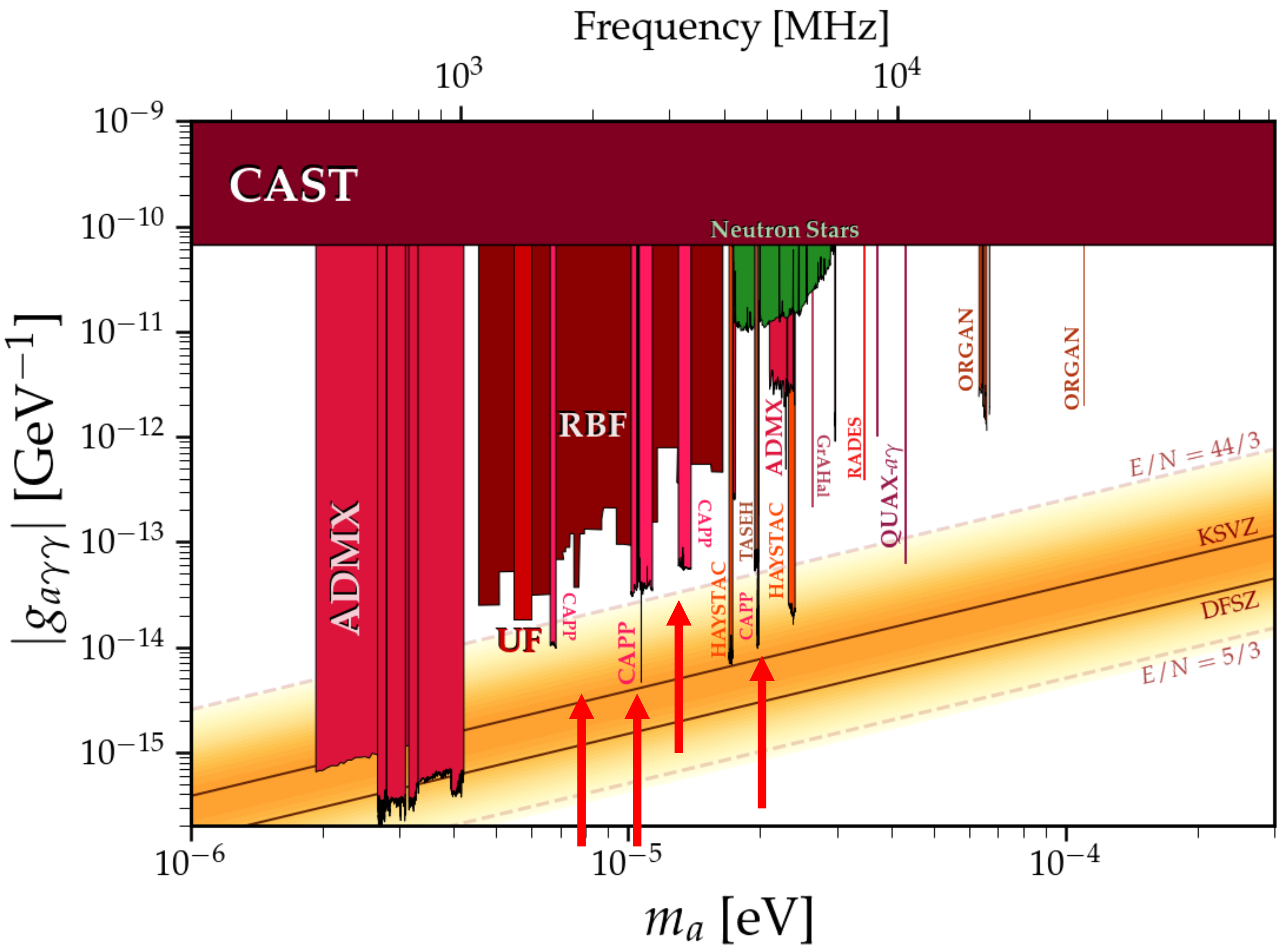
CAPP 8T	1.6 GHz
Volume	3.47 L
Q_0	90,000
B	8 T
T_{noise}	900 mK

PACE	2.2 GHz
Volume	1.12 L
Q_0	90,000
B	7.2 T
T_{noise}	200 mK

CAPP MC	3.2 GHz
Volume	0.65 L
Q_0	60,000
B	8 T
T_{noise}	3.8 K

CAPP 18T	4.79 GHz
Volume	1 L
Q_0	70,000
B	18 T
T_{noise}	500 mK

CAPP recent results



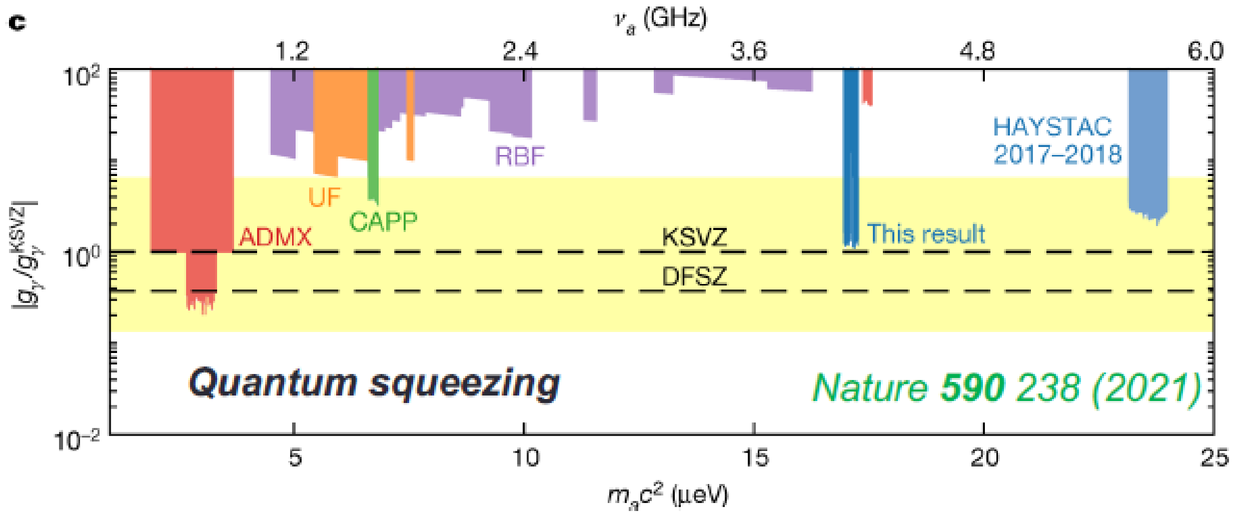
- SC cavity
- Pizza cavity
- 18 T magnet
- JPA
- …

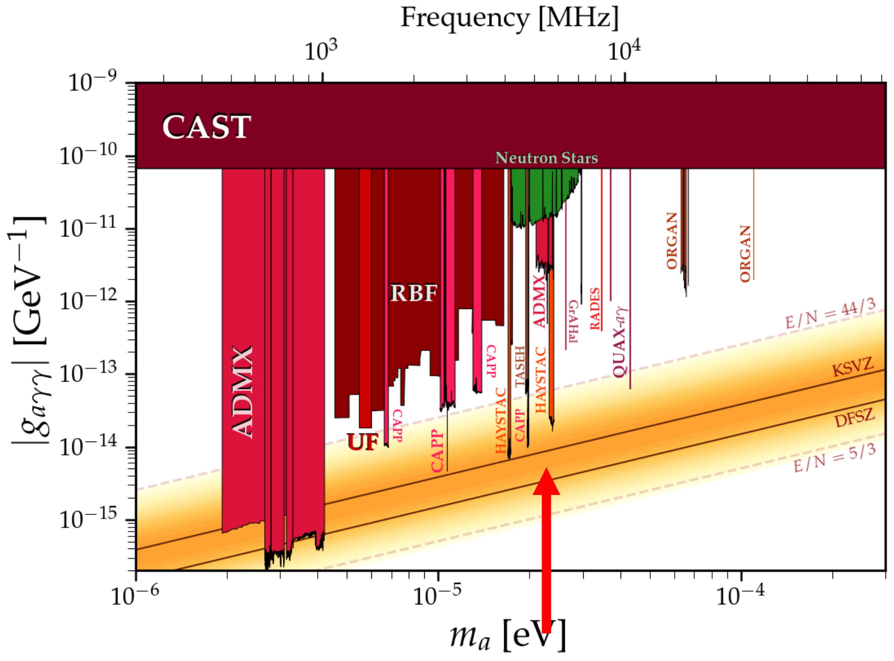
PHYSICAL REVIEW LETTERS 124, 101802 (2020)
PHYSICAL REVIEW LETTERS 125, 221302 (2020)
PHYSICAL REVIEW LETTERS 126, 191802 (2021)
PHYSICAL REVIEW LETTERS 128, 241805 (2022)
arXiv:2207.13597

22

Haystac

Yale's Wright Lab





HAYSTAC	5 GHz
Volume	1.5 L
Q_L	30,000
B	8 T
T_{noise}	120 mK

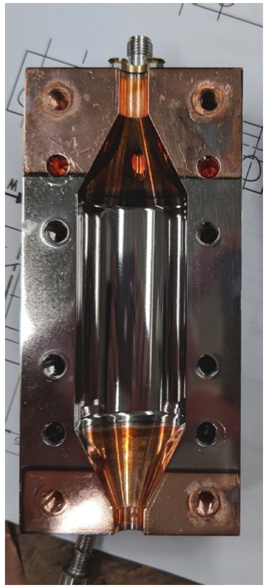
QUAX

Upgrade (2023 -> 2025)

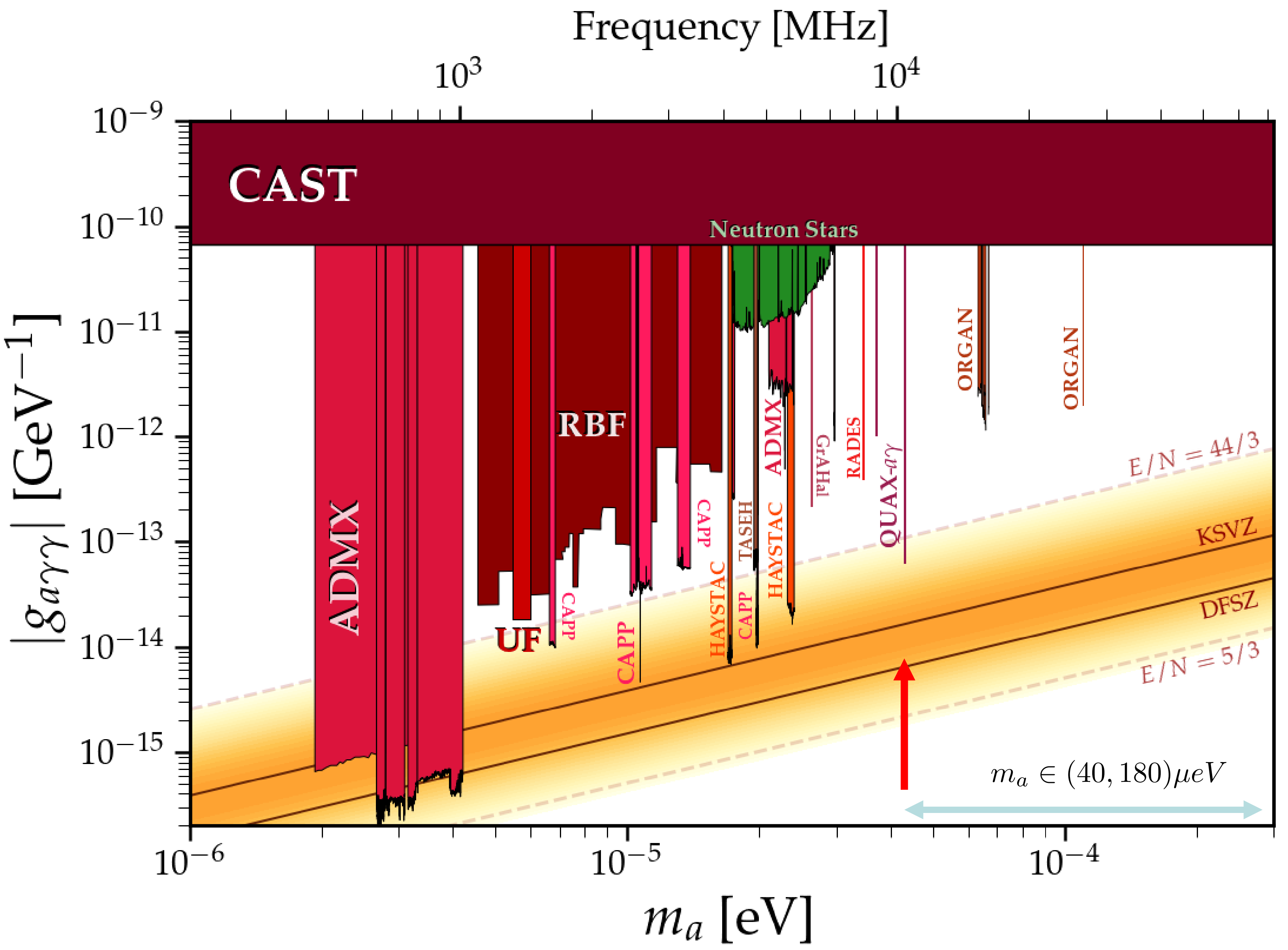
- LNF
  - Superconducting cavity $Q_0>2x10^5$
  - B=9T
  - Multicavity
- LNL
  - Dielectric cavity $Q_0>10^6$
  - B=14 T
  - Single cavity

QUAX - LNL	10 GHz
Volume	0.08 L
Q_0	80,000
B	8 T
T_{noise}	1 K

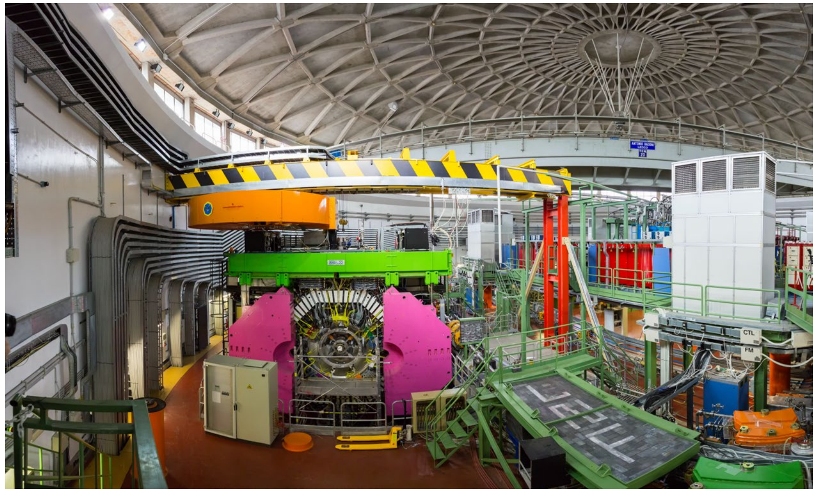
QUAX - LNF	8.5 GHz
Volume	0.14 L
Q_0	100,000
B	9 T
T_{noise}	5 K

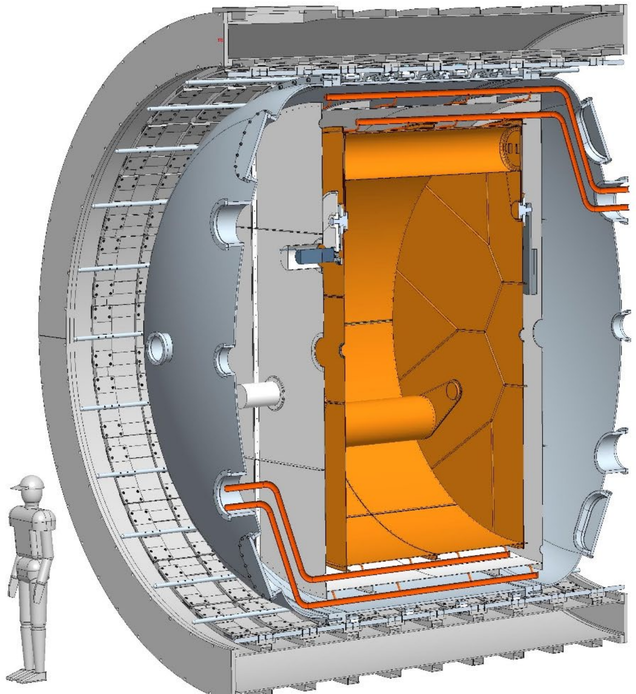


Quax results and future



KLASH & FLASH



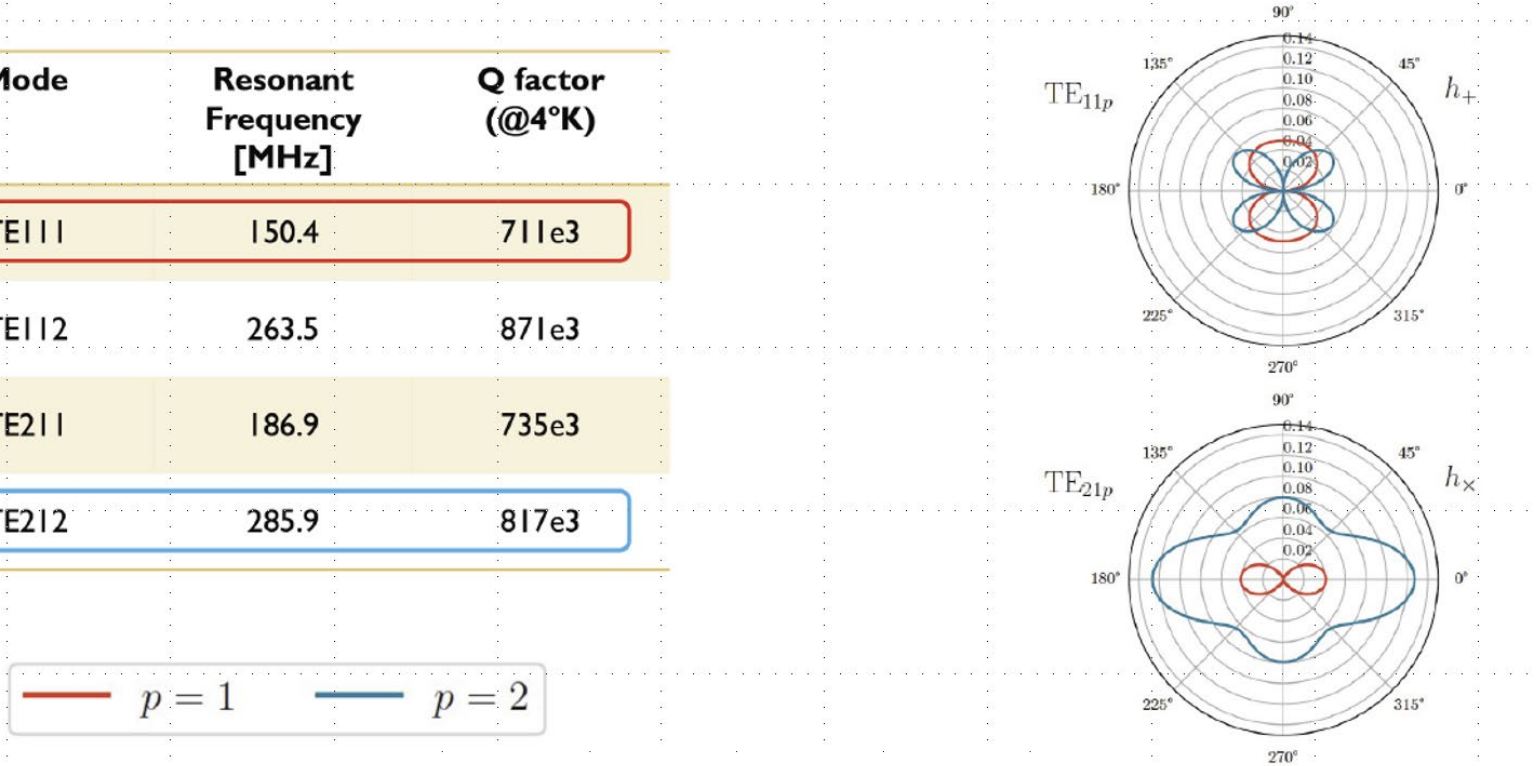


- Search of galactic axions in the mass range 0.5-1.5 μeV
- Large volume RF cavity (4 m^3)
- Moderate magnetic field (1.1 T)
- Copper cavity Q=500000
- T=4.5 K

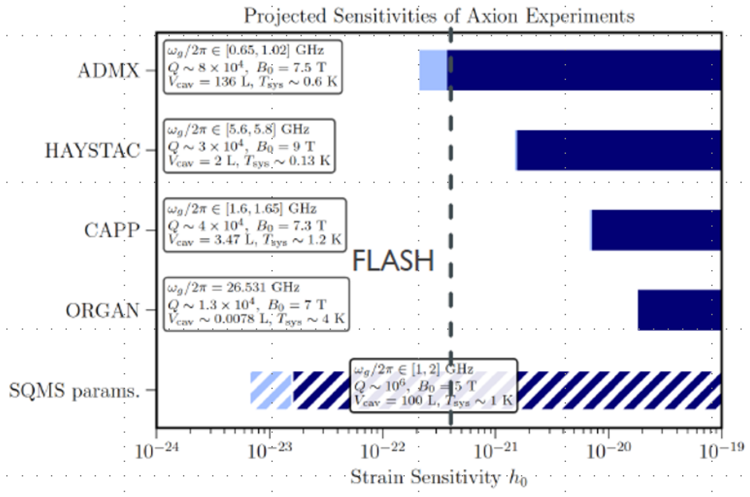
KLASH CDR arxiv:1911.02427
Flash CDR in preparation

FLASH: sensitivity to High Frequency Gravitational Waves

Mode	Resonant Frequency [MHz]	Q factor (@4°K)
TE111	150.4	711e3
TE112	263.5	871e3
TE211	186.9	735e3
TE212	285.9	817e3



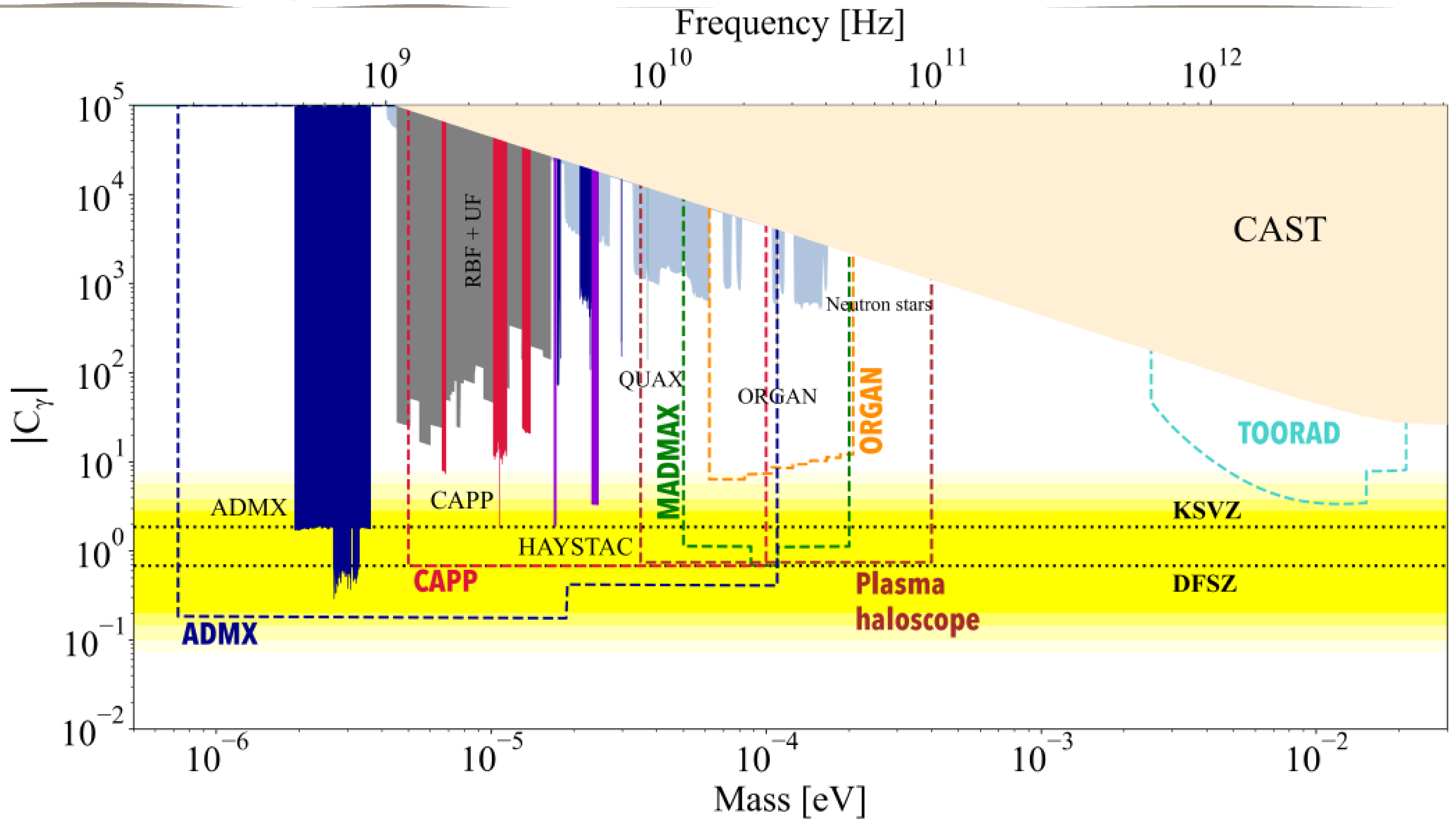
arXiv:2112.11465 and D. Blas's Talk



A. Berlin et al. Phys. Rev. D 105, 116011

G.Lamanna – NePSi23 – 17/2/2023 Pisa

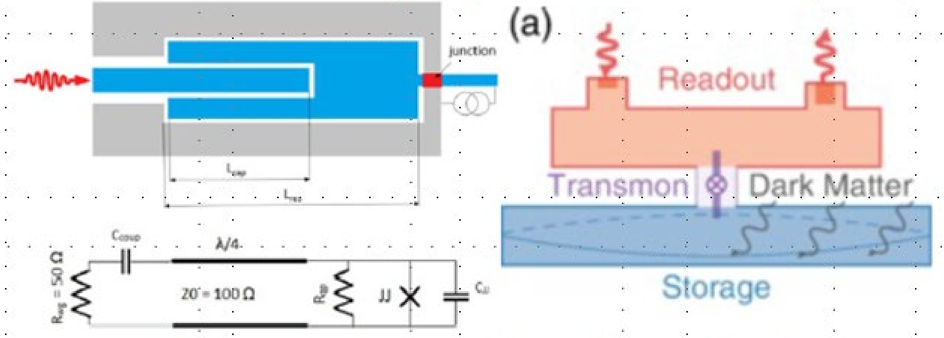
Haloscopes: present and future



Microwave photon detector

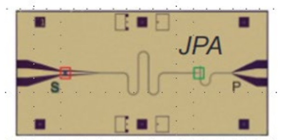
- Several techniques under investigation
  - HEMT
  - JPA
  - TWPA
  - Transmons
  - Nano-TES
- Power detection with amplifiers vs single photon detector

IEEE TASC 2850019 (2018) PRL **126** 141302 (2021)

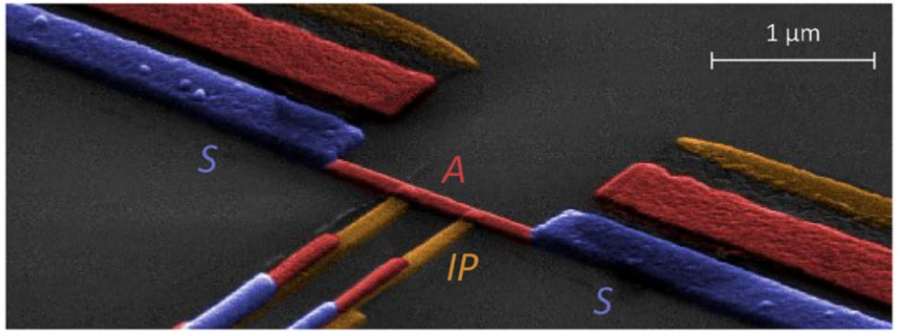


Single photon counting ($T_N << T_{SQL}$)

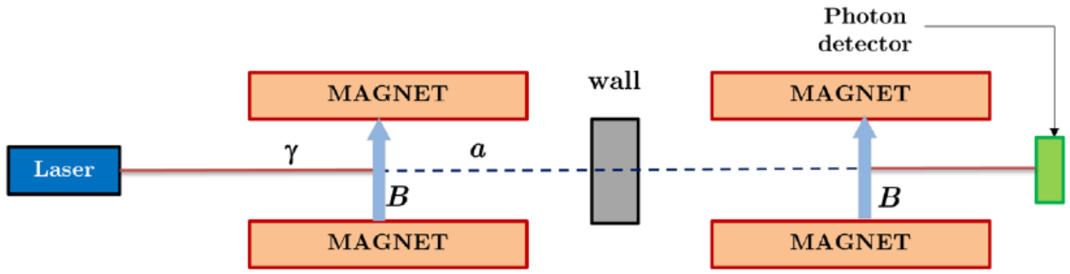
Transistor-based ($T_N \sim K$)



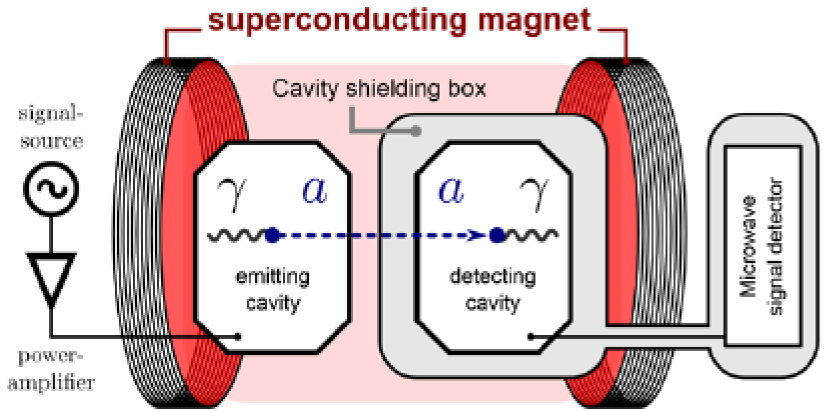
Quantum limited ($T_{SQL} \sim 50$ mK x f [GHz])



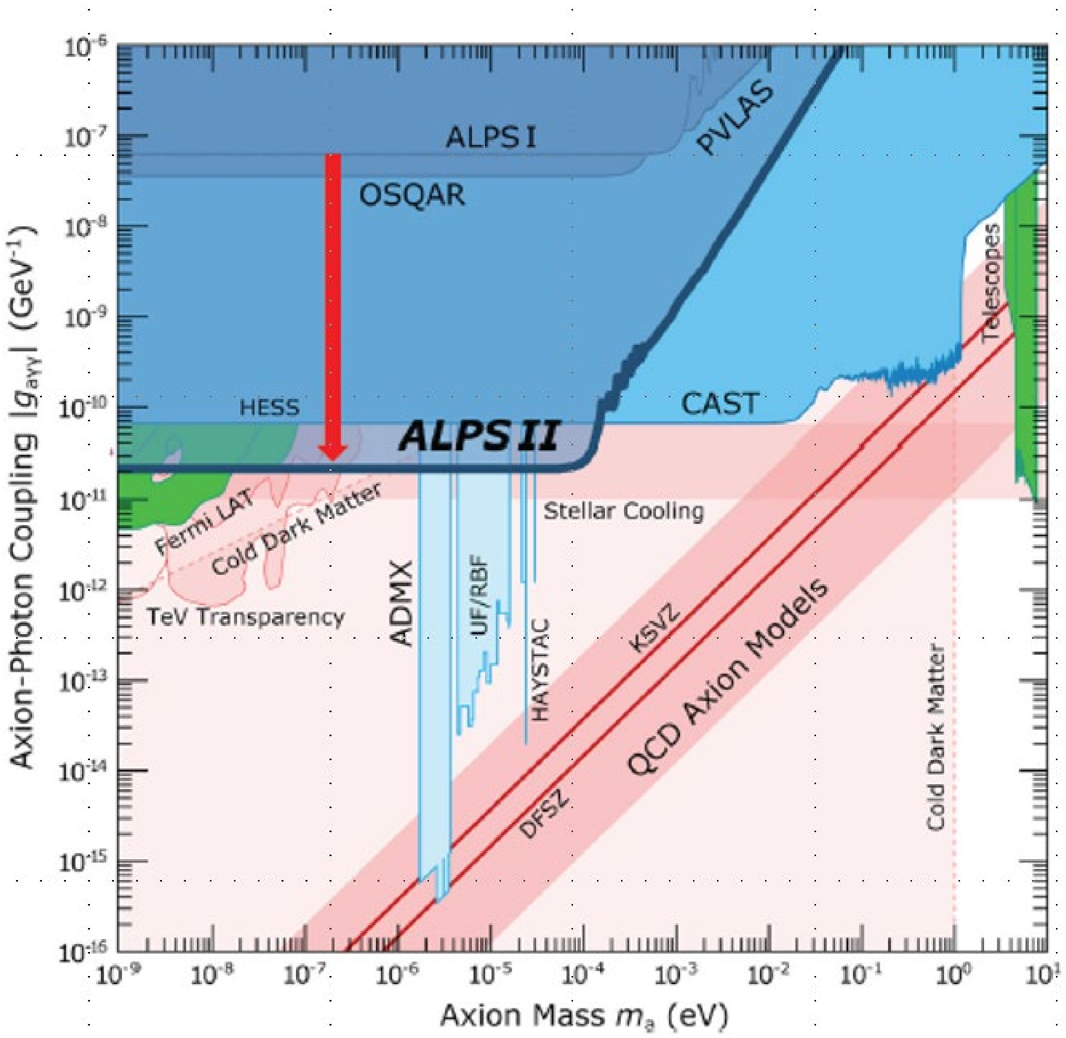
- Light Shining Through Wall
  - ALPs are produced in the production cavity and seen in the regeneration cavity
  - No cosmological assumption
  - Reduction of uncertainty (better noise control)
  - Can be done at various light frequencies
  - Two process → fourth power of coupling
  - OSQAR, CROWS, ALPS, ALPSII,…

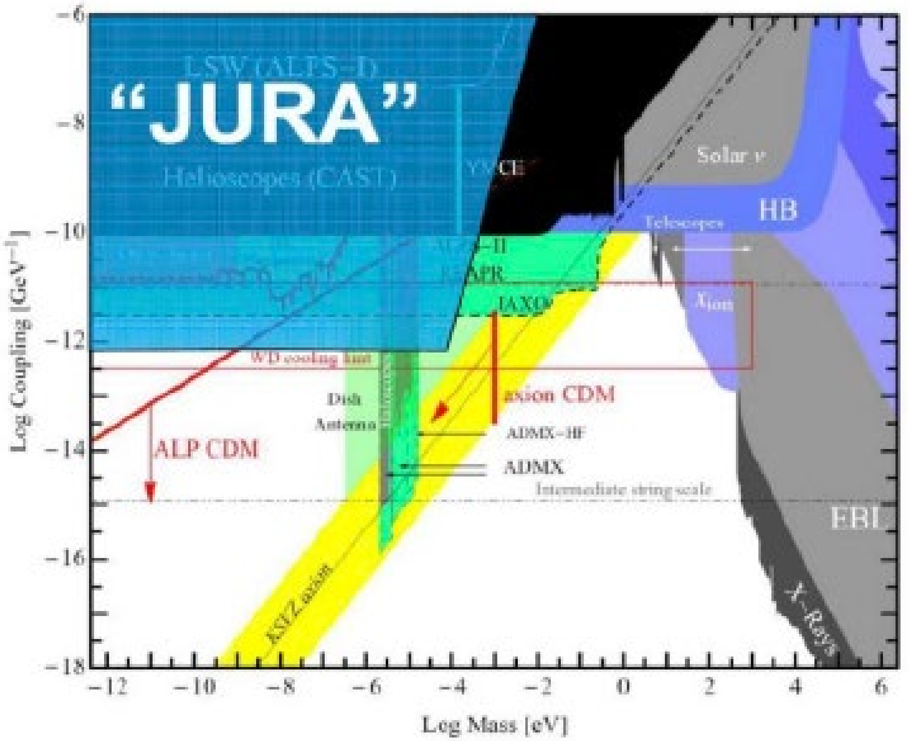


$$P(\gamma \to a \to \gamma) \sim \left(\frac{g_{a\gamma}BL}{2}\right)^4 \beta_P \beta_R$$



ALPSII & JURA



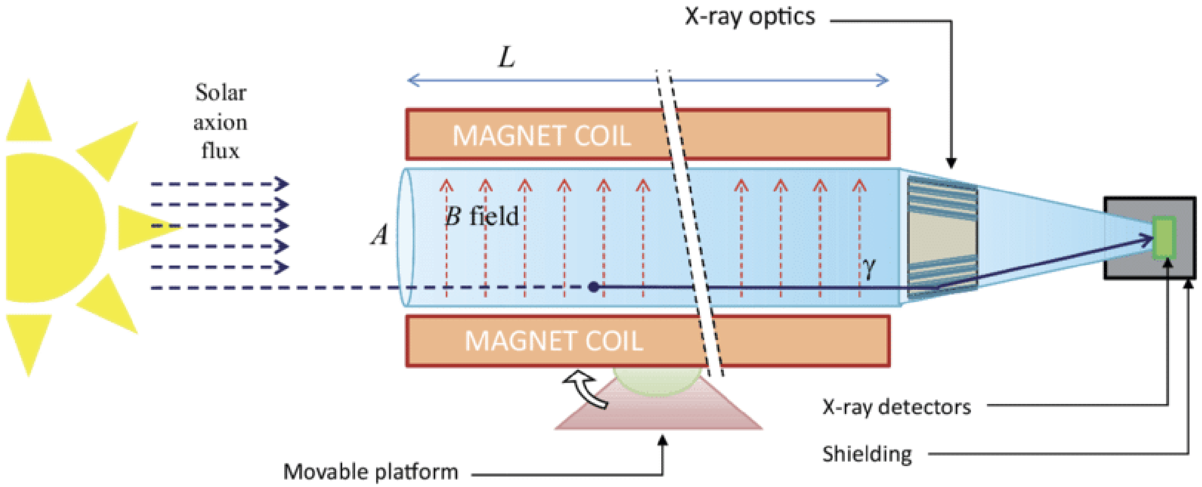


Parameter	Sensitivity	ALPS II	JURA	Rel. sensitivity JURA / ALPS II
Magnet aperture		50 mm	100 mm	
Magnetic field B	$g_{a\gamma} \sim B^{-1}$	5.3 T	13 T	2.5
Magnetic length L	$g_{a\gamma} \sim L^{-1}$	189 m	960 m	5.1
Effective laser power P	$g_{a\gamma} \sim P^{-1/4}$	0.15 MW	2.5 MW	2.0
Power-built up Q (behind the wall)	$g_{a\gamma} \sim Q^{-1/4}$	40,000	100,000	1.3
Detector noise DC	$g_{a\gamma} \sim DC^{1/8}$	10^{-4} 1/s	10^{-6} 1/s	1.8
Total sens. increase				56

Table 1: comparison of experimental parameters of ALPS II at DESY and the JURA proposal.

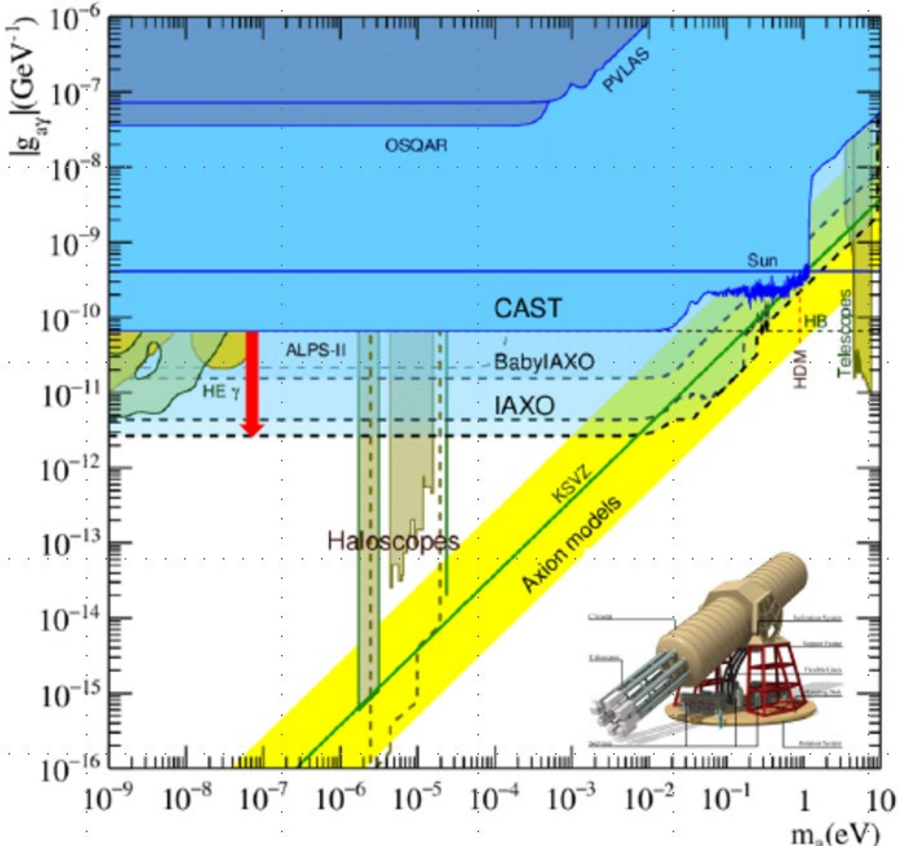
- The stars are the main axions producer
  - Inverse Primakoff scattering
  - Solar axions convert in a strong magnetic field into X-rays
  - CAST completed in 2015

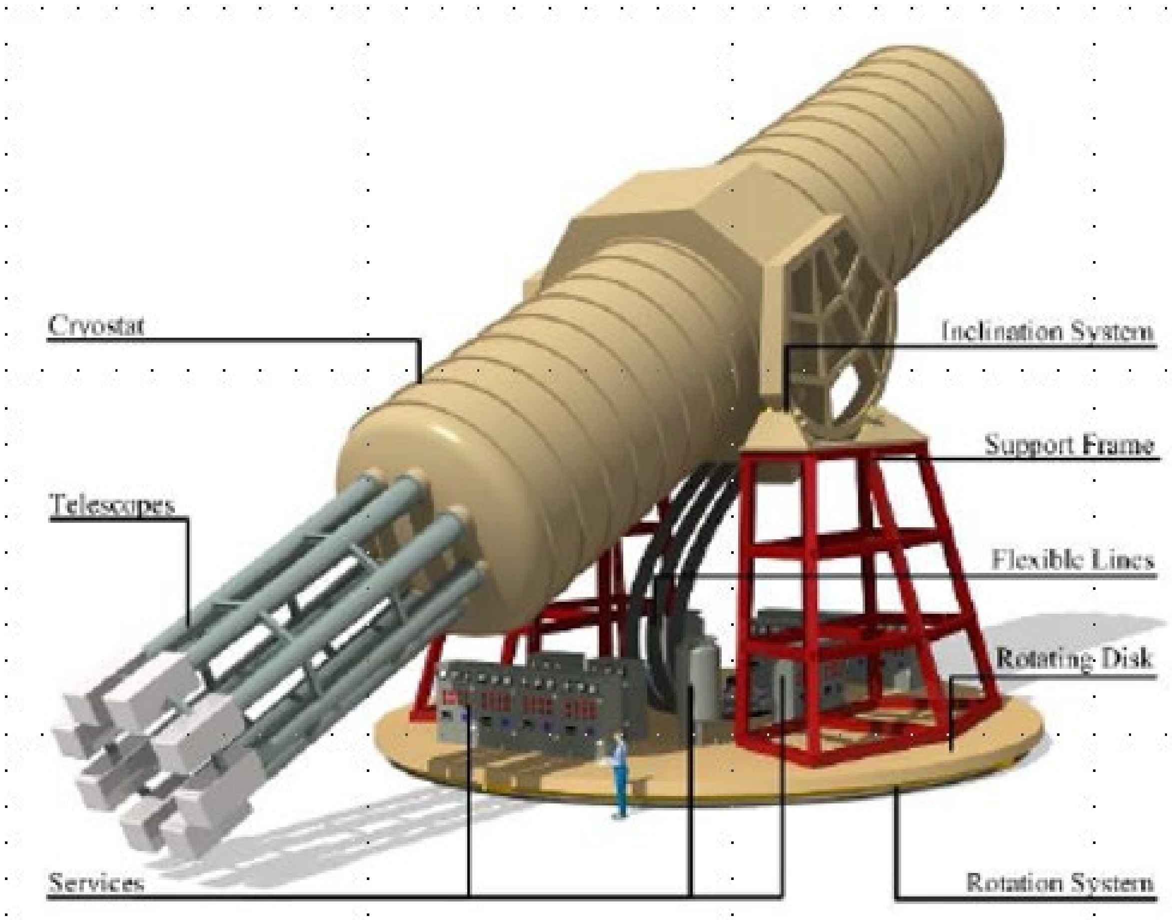
$$P_{a\gamma\gamma} \sim \left(\frac{g_{a\gamma\gamma} B_0}{q}\right) \sin\left(\frac{qL}{2}\right), q = \frac{m_a^2}{2E_a}$$



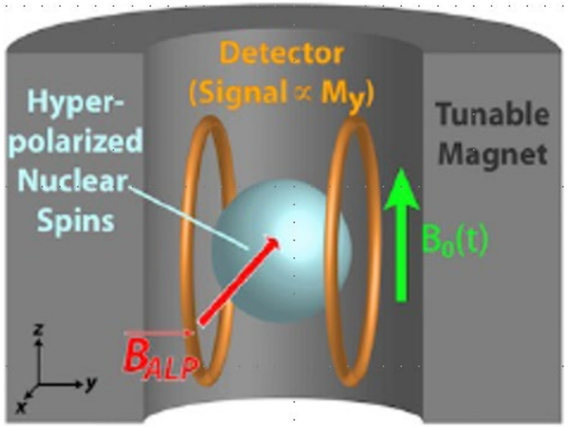
Baby-IAXO and IAXO

- International Axions Observatory
- Large toroidal 8-coil magnet (5.4 T), L=20 m
- 8 bores: 600 mm each
- 8 x-rays telescopes
- Goal: coupling below 10^{-12}
- Baby-IAXO: 4T/10 m



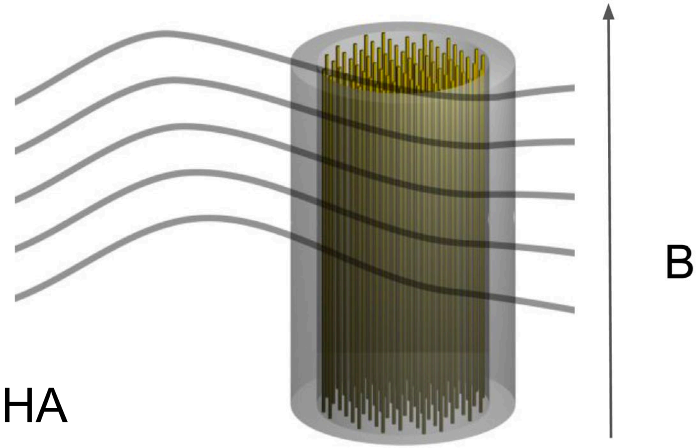


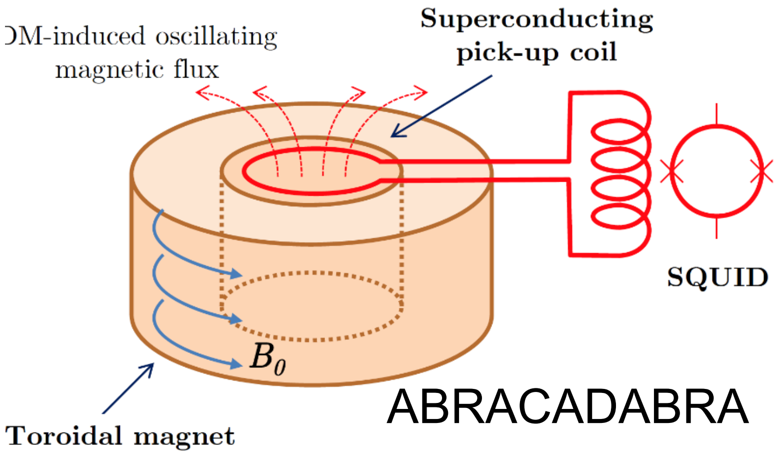
Other ideas



CASPEr

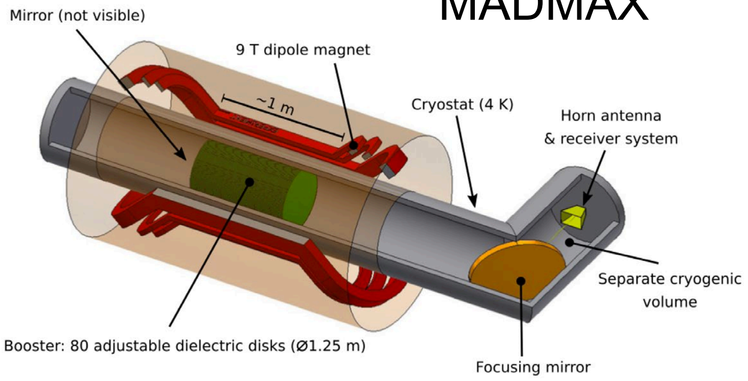
ALPHA



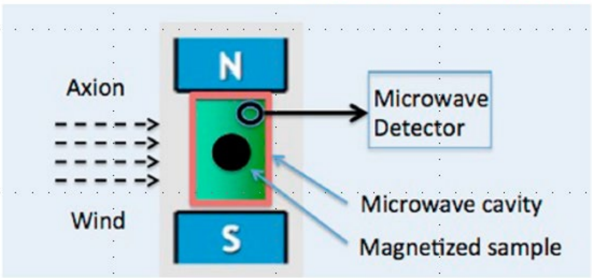


ABRACADABRA

MADMAX

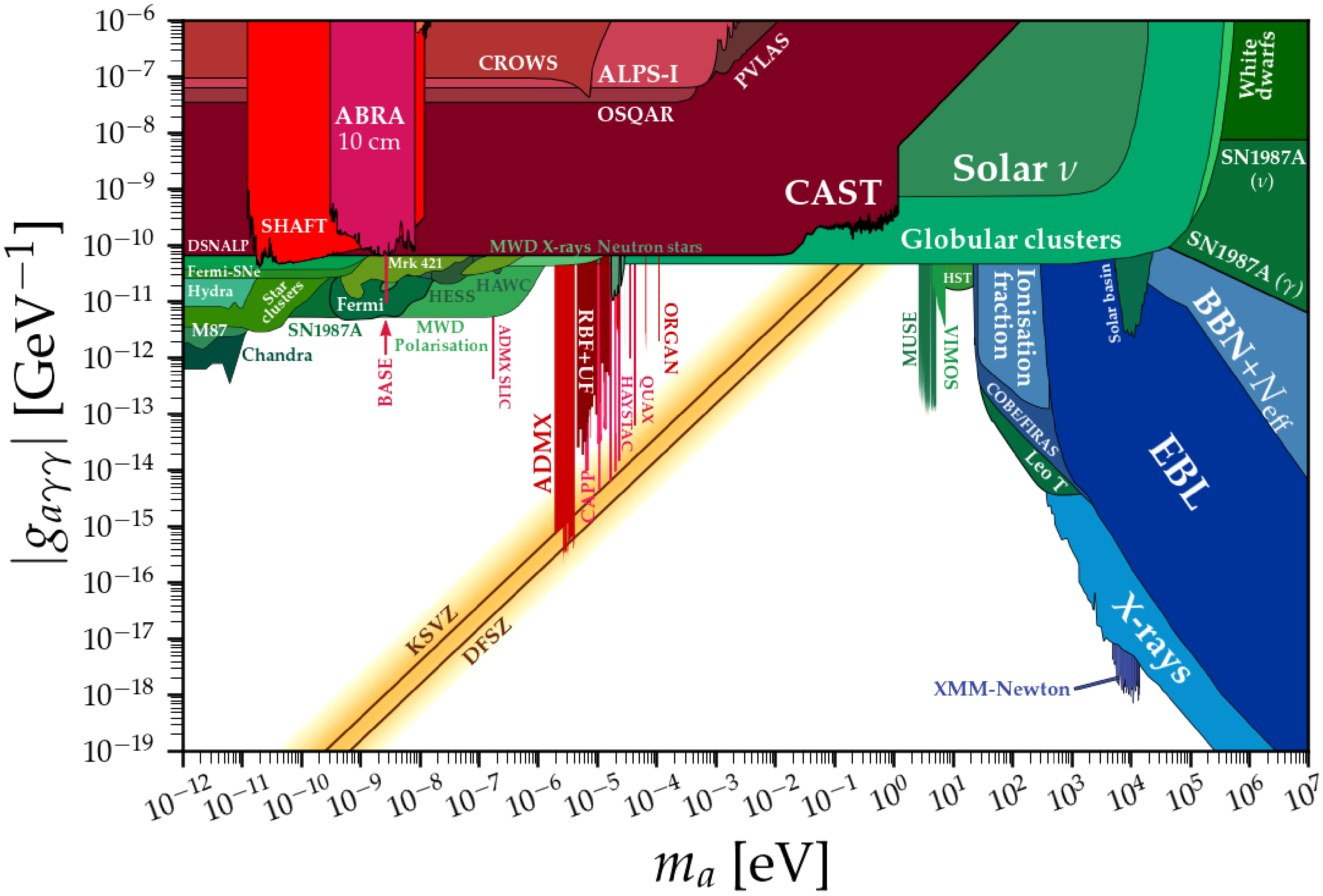


*PRL **124** 171801 (2020)*



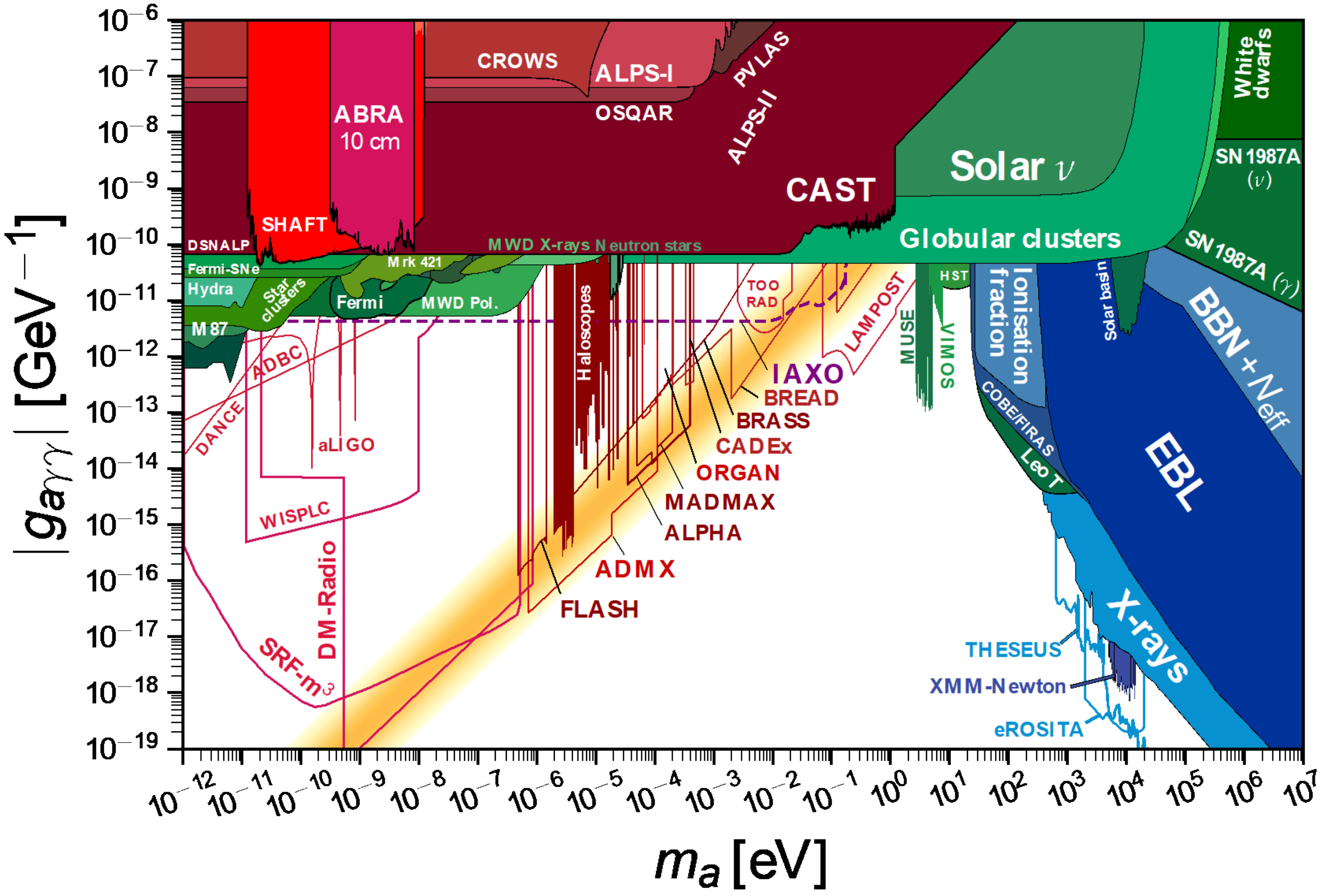
QUAX-ae

Axion DM searches today



G.Lamanna – NePSi23 – 17/2/2023 Pisa

Axion DM searches in the future



Conclusions

- QCD axions are introduced to solve the strong CP problem
  - Axions and ALPS are believable candidates for dark matter
- Experimentally challenging
  - Very weak coupling
  - Unconstrained mass (ALPS)
- Different experimental techniques
  - only few covered in this talk
  - Several innovatives technologies involved
- Exciting future
  - In the next years a substantial portion of the parameter space will be covered