Axion Dark Matter Searches

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Institute for Basic Science
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기초과학연구원

CAPP

Center for
Axion and Precision
Physics Research

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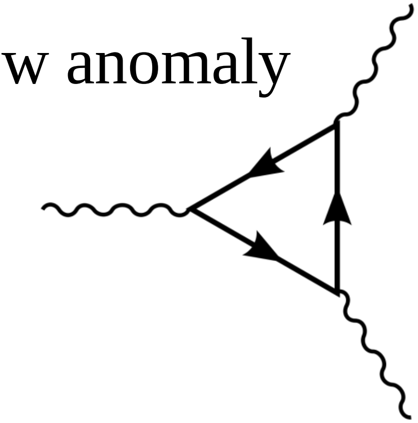
Contents

Axion

How did axion come to show up?

- $U(1)_A$ problem in 3-flavor (u, d, s) QCD
  - ∘ $\mathcal{L}_{QCD} = \mathcal{L}_{quarks} + \mathcal{L}_{gluon}$ predicts all the relevant particles in the limit, $m_u \sim m_d \sim m_s \sim 0$, except for η' whose mass 958 MeV is too heavy
  - ∘ According to S. Weinberg, $m_{\eta'} < \sqrt{3} m_\pi \sim 240$ MeV in the massless limit → dubbed $U(1)_A$ problem

- Solution of the $U(1)_A$ problem
  - ∘ $U(1)_A$ is not a symmetry with the Adler-Bell-Jackiw anomaly



$$\mathcal{L}_{QCD} = \mathcal{L}_{quarks} + \mathcal{L}_{gluon} + \theta_{QCD} \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{\mu\nu a}$$

$, \theta_{QCD}$ is a parameter of QCD

  - ∘ 't Hooft derived the nominal η' mass

Axion

How did axion come to show up?

- Solution of the $U(1)_A$ problem results in the strong CP problem in the standard model (SM)

∘ $\mathcal{L}_{QCD}$ with $\theta_{QCD}\dfrac{g^2}{32\pi^2}F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$ is CP odd ($\because F_a^{\mu\nu}\tilde{F}_{\mu\nu a}\sim\vec{E}^a\cdot\vec{B}^a$)

∘ CPV could be tested by the neutron electric dipole moment (EDM)

$d_n\sim\theta_{SM}\dfrac{m_u m_d}{m_u+m_d}$, where $\theta_{SM}=\theta_{QCD}+\theta_{EW}$ with non-zero m_u and m_d

(turn on $EW\rightarrow SM$) and expected to be $\sim 10^{-16}\theta_{SM}\ e\cdot\text{cm}$

∘ experiments result in $\theta_{SM}\leq 10^{-10}$ → very unnatural

According to "naturalness" in theoretical physics; it would take a value of order 1.

$\theta_{SM}\sim 0$ if CP is a symmetry in the SM. However, we know the SM violates CP

→ Strong CP problem in the SM

Axion

How did axion come to show up?

- Axion as a solution of the strong *CP* problem in the SM
  - promotes the θ_{SM} from a parameter to a dynamic variable by Peccei and Quinn (PQ), introducing $U(1)_{PQ}$ with the anomaly

    $$\frac{g^2}{32\pi^2}\theta_{SM} F_a^{\mu\nu}\tilde{F}_{\mu\nu a} \to \frac{g^2}{32\pi^2}\left(\theta_{SM}+\frac{a}{f_a}\right)F_a^{\mu\nu}\tilde{F}_{\mu\nu a} \text{ and}$$

    the axion field a relaxes to the minumim $\langle a\rangle = -\theta_{SM} f_a$,

    f_a is the axion decay constant,

    PQ symmetry breaking scale, but ***unknown***
  - $a = \langle a\rangle + a_{phy} \to \frac{g^2}{32\pi^2}\frac{a_{phy}}{f_a} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$ which is *CP* even

    with pseudoscalar axion field

Axion

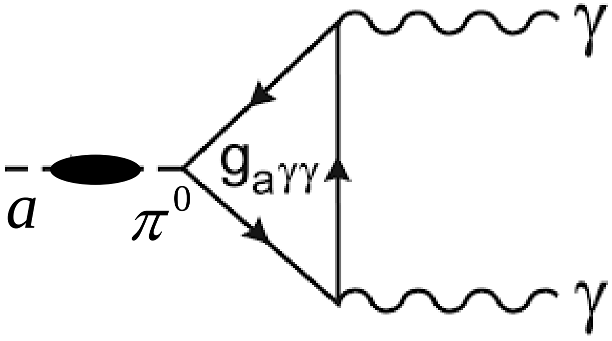
Axion models

	f_a ($U(1)_{PQ}$ breaking scale)	tree level couplings	
PQWW; **Peccei-Quinn-Weinberg-Wilczek**	$f_a \sim v_{EW}$ $\tau_a \sim 10^{-2}\, s$ for $m_a \sim 100$ keV	SM particles	Ruled out by accelerator experiments
DFSZ; **Dine-Fischler-Srednicki-Zhitnitsky**	$f_a >> v_{EW}$ τ_a is longer than the age of our Universe, $m_a \sim O(\mu eV)$ for $f_a \sim 10^{12}$ GeV		Have served as useful benchmarks for experiments
KSVZ; **Kim-Shifman-Vainshtein-Zakharov**		New very heavy quarks beyond the SM	

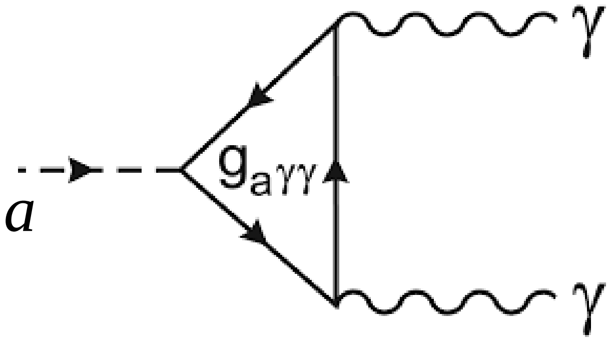
Axion

Axion photon coupling ($g_{a\gamma\gamma}$)

- important coupling for axion detection
- $\mathcal{L}_{a\gamma\gamma} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$

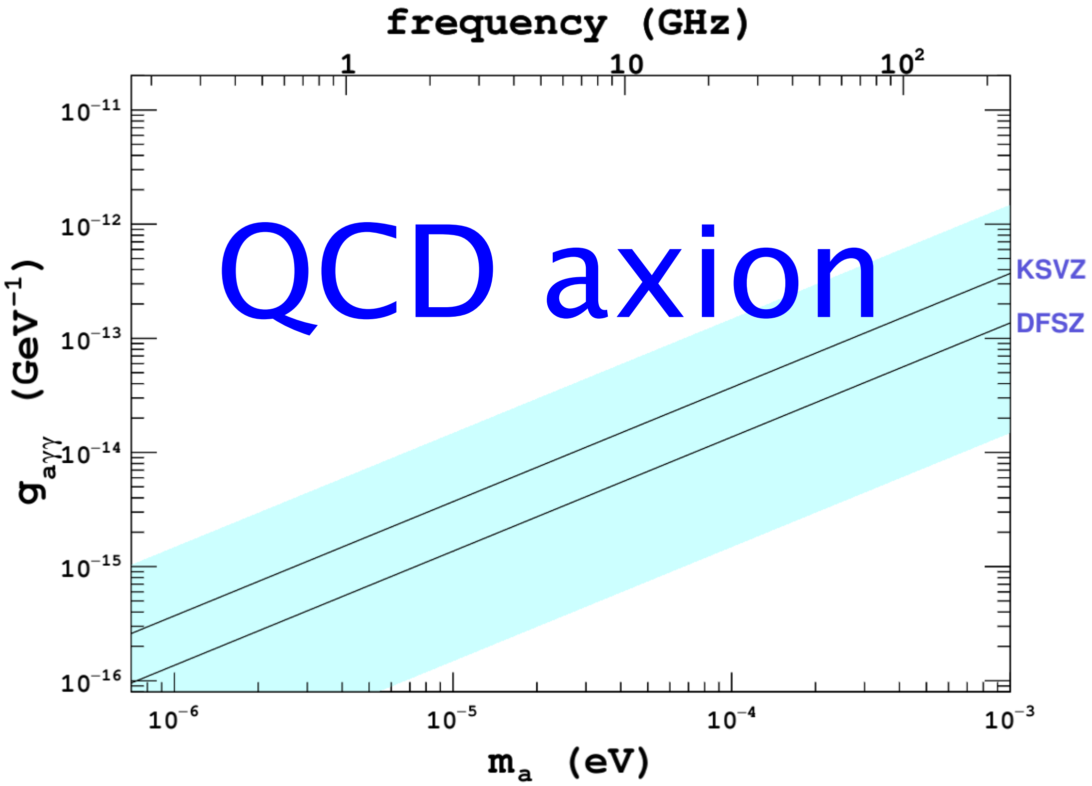


both KSVZ and DFSZ axions



not for the standard KSVZ axion

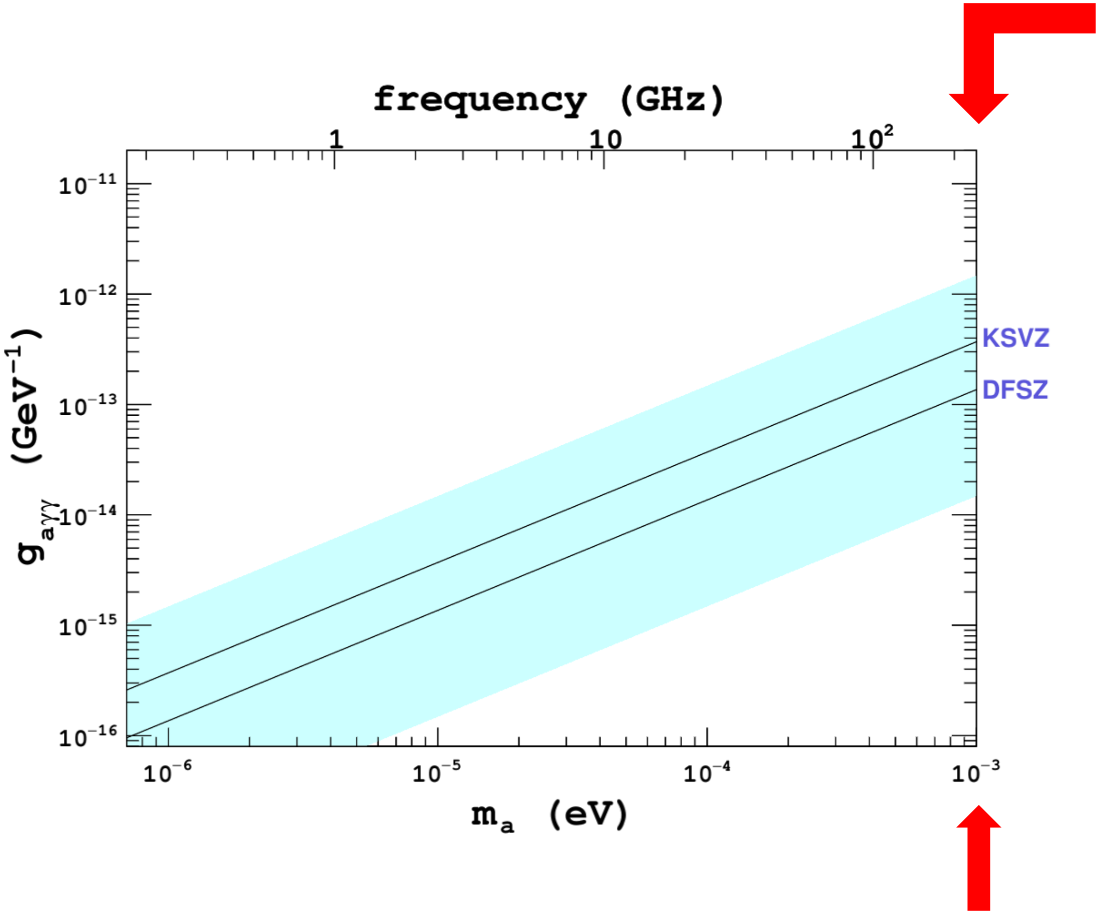
(neutral heavy quark)



Axion

Astrophysical boundary

SN 1987A



Observation associated with neutrino events is consistent with the expectations assuming that the collapsed supernova core cools solely by neutrino emission

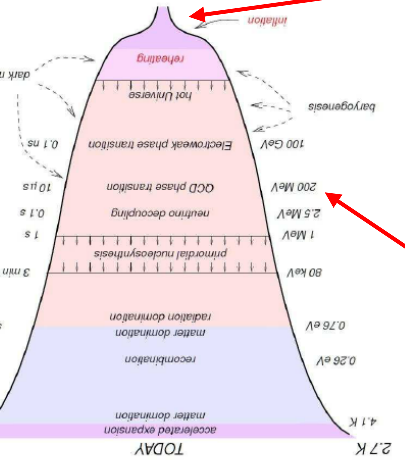
If the core also cools by axion emission, the neutrino burst is excessively foreshortened

$$m_a < O(\mathrm{meV})$$

Axion

Cosmological production & boundary

Figure: D. S. Gorbunov



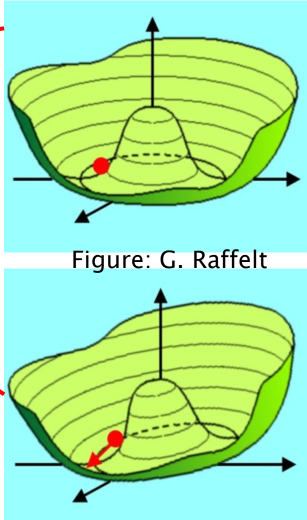


Figure: G. Raffelt

- produced with PQ symmetry breaking
- axion misaligned w.r.t. the minimum, θ_{SM} → called misalignment production

- potential tilted by QCD
- axion rolls down and starts coherent oscillation around $\theta_{SM} = 0$ → the oscillation energy constitutes a sizeable fraction of the energy density of our Universe

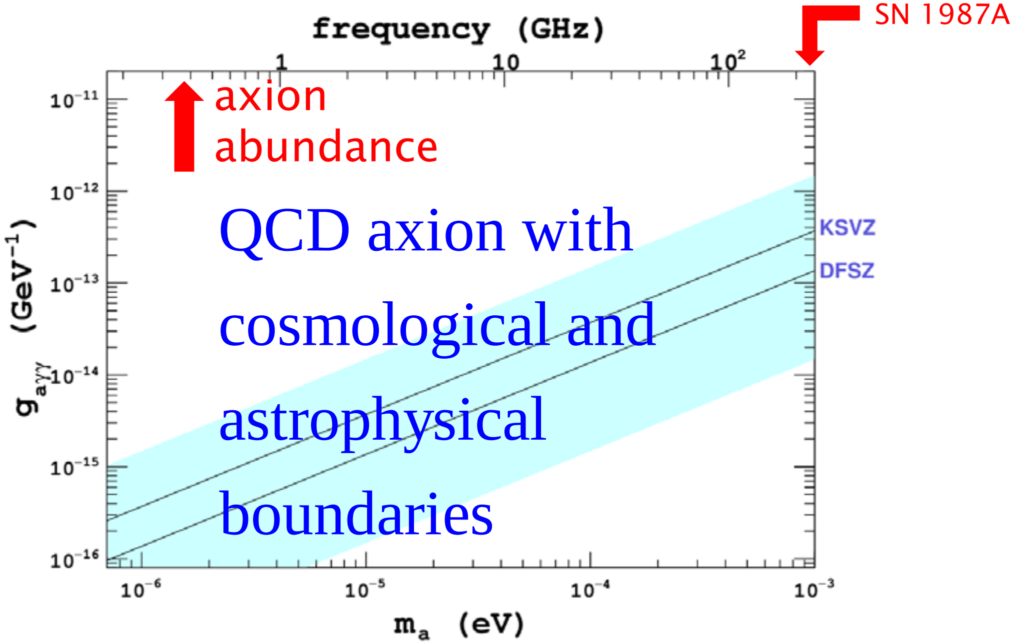
- the axion energy denisity Ω_a from the misalignment

$$\Omega_a h^2 \approx 0.12 \left(\frac{6\ \mu\text{eV}}{m_a} \right)^{1.165} \theta_{SM}^2 \quad \text{(PDG 2018)}$$

and the observed CDM density

$$\Omega_{\text{CDM}} h^2 = 0.12 \text{ (PDG 2018)}$$

→ give us m_a should be above 6 μeV in order that Ω_a doesn't exceed the observed Ω_{CDM} with the natural $\theta_{SM} \sim 1$



SN 1987A

axion abundance

QCD axion with cosmological and astrophysical boundaries

Axion Dark Matter

Axion Cold Dark Matter

- dark matter candidates

1) must have nonzero mass (energy budget : ~27% of the Universe)
2) stable on cosmological timescales
3) cold according to the standard model of Big Bang cosmology

- axion

1) μeV (cosmological) $< m_a <$ meV (astrophysical)
2) τ_a is longer than the age of our Universe for even with $m_a \sim O(\text{meV})$
3) coherent oscillation → non-thermal → born as cold

Axion is a good candidate
for cold dark matter in our Universe

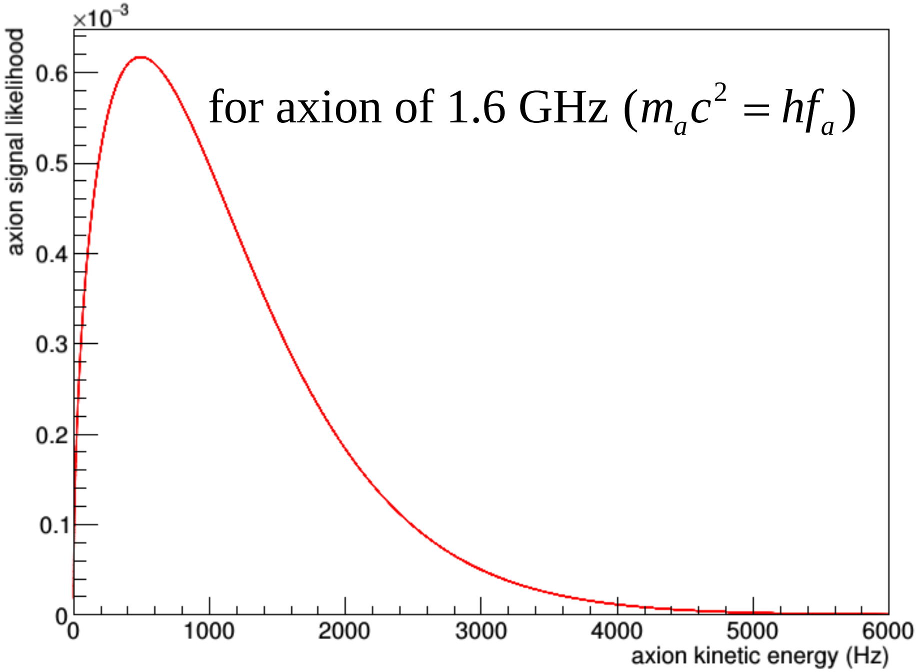
Axion Dark Matter

Energy and lineshape

- cold $\Leftrightarrow$ non-relativistic

$$\text{axion energy } E_a = m_a c^2 + \frac{1}{2} m_a v^2 = m_a c^2 \left(1 + \frac{1}{2}\left(\frac{v}{c}\right)^2\right), \text{ where } \left(\frac{v}{c}\right)^2 \sim O(10^{-6})$$

- with simple halo model, v distribution follows the Maxwell-Boltzmann



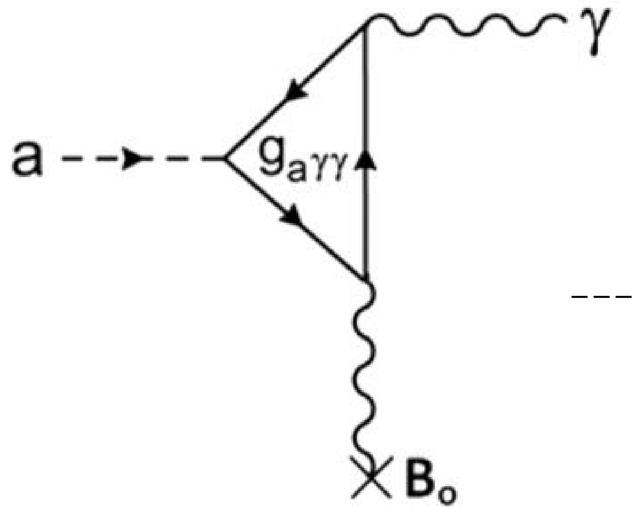
for axion of 1.6 GHz ($m_a c^2 = h f_a$)

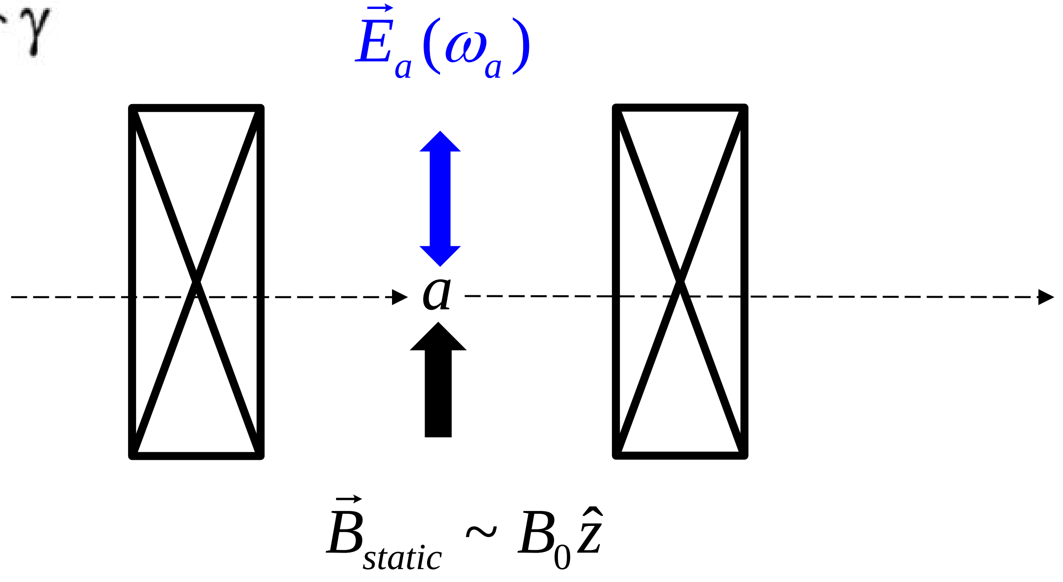
- very narrow peak, negligible dispersion $O(10^{-6})$ relative to the axion mass
- axion energy shows up as a very narrow peak, easy to isolate the signal from backgrounds → very similar to search for new particle signals by looking at invariant mass spectrum

Axion Dark Matter Searches

Axion haloscope searches

- invented by P. Sikivie, $\mathcal{L}_{a\gamma\gamma} \sim g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$



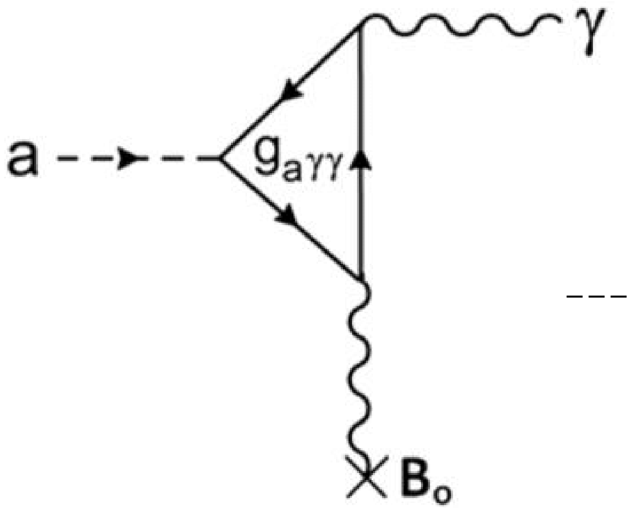


- interaction energy $U_{a\gamma\gamma}$ (or axion energy inherited to the photon), then detected as axion signal power $P_a = \omega_a U_{a\gamma\gamma}$

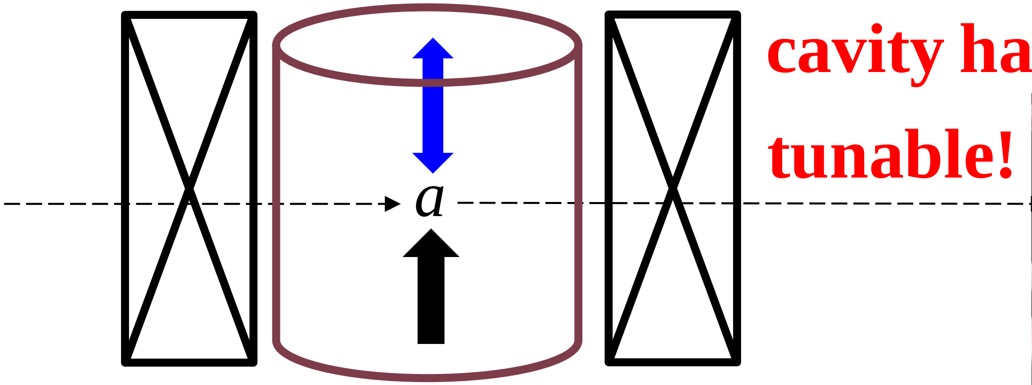
Axion Dark Matter Searches

Axion haloscope searches

- invented by P. Sikivie, $\mathcal{L}_{a\gamma\gamma} \sim g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$

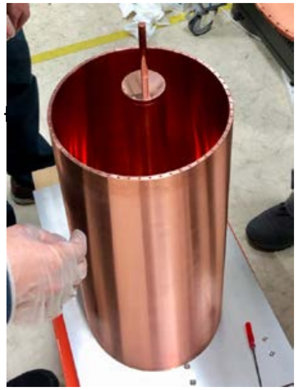


$\vec{E}_{a,\text{ cavity mode}}(\omega_a)$, where $\omega_a = \omega_{\text{cavity mode}}$



$\vec{B}_{static} \sim B_0\hat{z}$

cavity has to be tunable!



- resonated axion signal power $P_a = Q\omega_a U_{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B_0^2 VQ \frac{\left(\int_V \vec{E}_{a,\text{ cavity mode}}\cdot\vec{B}_{static}\,dV\right)^2}{B_0^2 V\int_V \vec{E}^2_{a,\text{ cavity mode}}\,dV}$,

(easy to realize a cavity whose $Q > 10,000$)

Q : Q of the cavity mode, V : cavity volume, $C \equiv \frac{\left(\int_V \vec{E}_{a,\text{ cavity mode}}\cdot\vec{B}_{static}\,dV\right)^2}{B_0^2 V\int_V \vec{E}^2_{a,\text{ cavity mode}}\,dV}$: form factor of the cavity mode

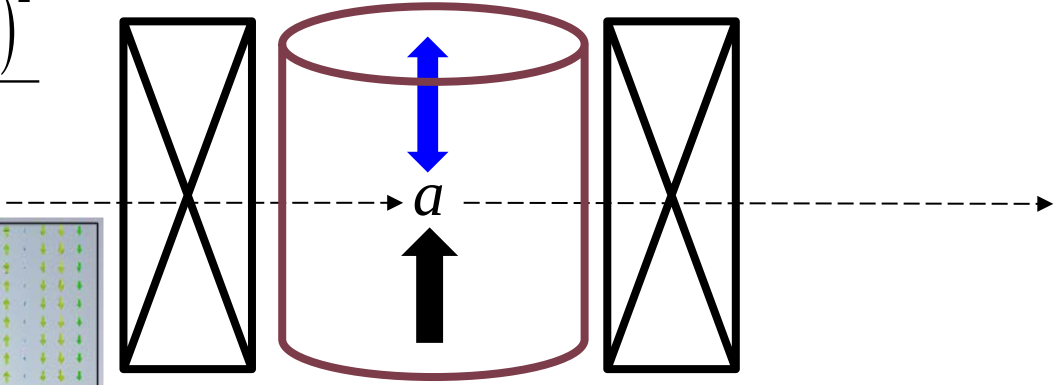
Axion Dark Matter Searches

Axion haloscope searches

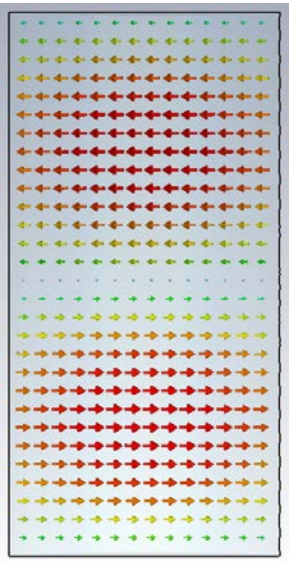
- axion signal power at haloscope searches

$$P_a \propto g_{a\gamma\gamma}^2 B_0^2 VQ \frac{\left(\int_V \vec{E}_{a,\text{cavity mode}} \cdot \vec{B}_{static} dV\right)^2}{B_0^2 V \int_V \vec{E}^2_{a,\text{ cavity mode}} dV}$$

$\vec{E}_{a,\text{ cavity mode}}(\omega_a)$, where $\omega_a = \omega_{\text{cavity mode}}$



$\vec{B}_{static} \sim B_0 \hat{z}$

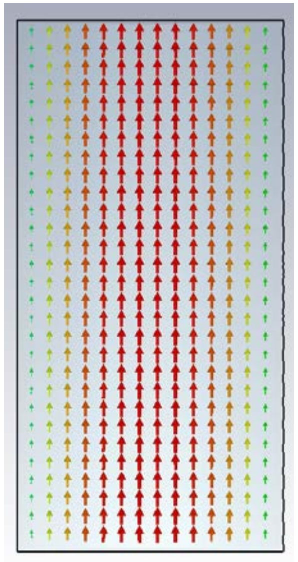


$\vec{E}_{TE} \perp \vec{B}_{static}$

$\rightarrow C \sim 0$

$\rightarrow P_a \sim 0$

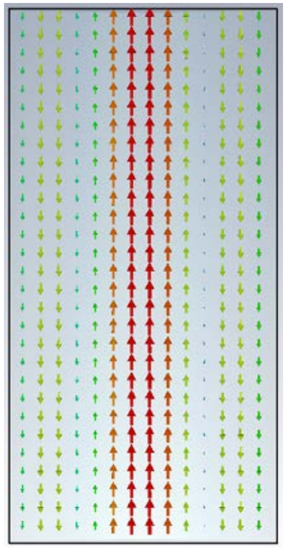
undesirable



$\vec{E}_{TM_{010}} \parallel \vec{B}_{static}$

$C \sim 0.69$

best mode



$\vec{E}_{TM_{020}}$ some cancelation, but feasible with $C \sim 0.13$

- resonant frequencies

$$\omega_{TM_{010}} = \frac{1}{\sqrt{\mu\varepsilon}} \frac{2.405}{r_{cavity}} \text{ and } \omega_{TM_{020}} = \frac{1}{\sqrt{\mu\varepsilon}} \frac{5.520}{r_{cavity}}$$

- r_{cavity} is constrained by the magnet bore

Magnets practically define axion haloscope searches!

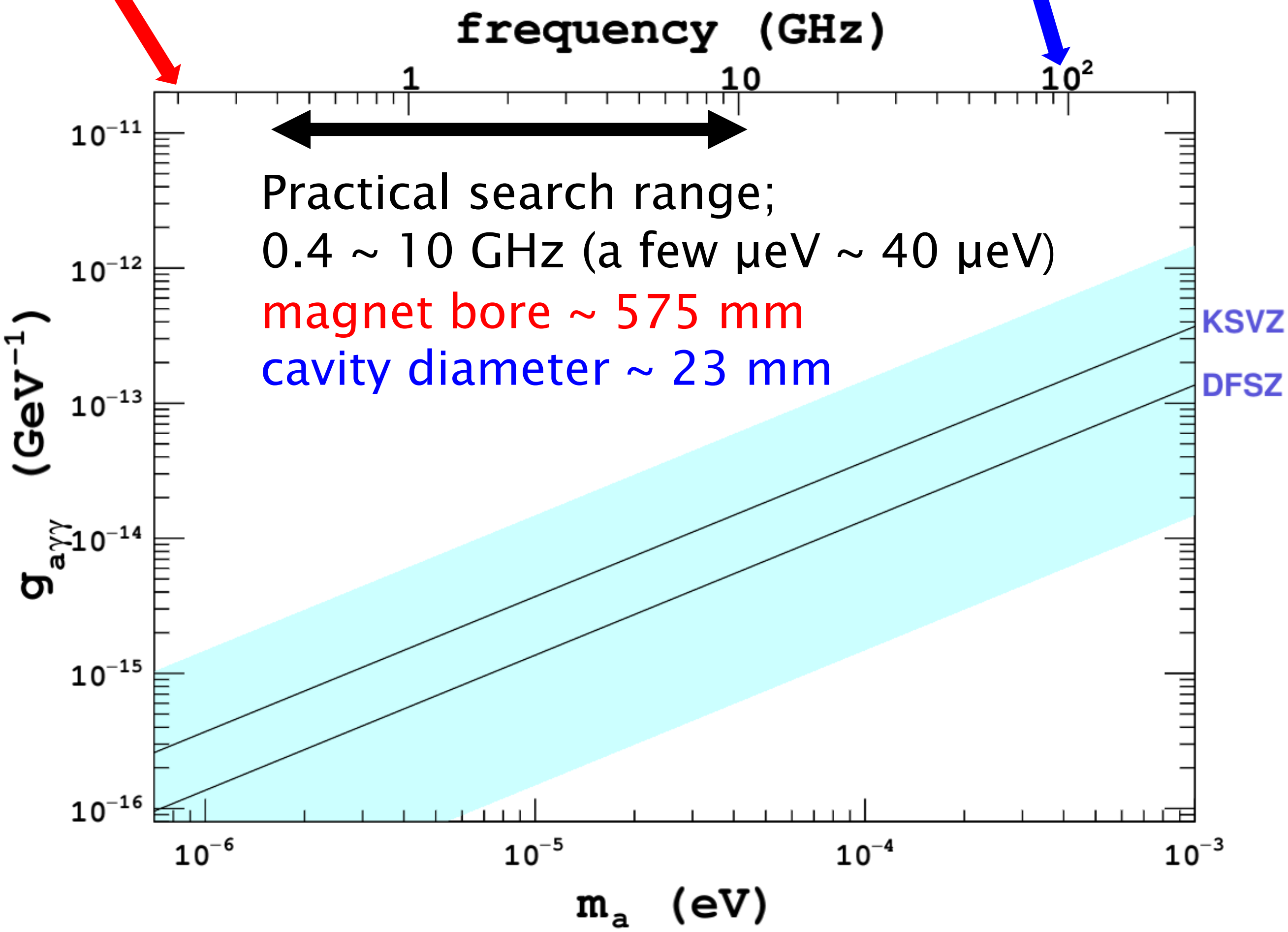
Axion Dark Matter Searches

Axion haloscope searches

axion frequency of 0.2 GHz;
magnet bore ~ 1,150 mm

axion frequency of 100 GHz;
tunable cavity diameter ~ 0.23 mm

solenoid
at collider
detector
can do it,
but…



Practical search range;
0.4 ~ 10 GHz (a few μeV ~ 40 μeV)
magnet bore ~ 575 mm
cavity diameter ~ 23 mm

Axion Dark Matter Searches

Axion haloscope searches

Figure of merit

- Practical search range; 0.4 ~ 10 GHz (a few μeV ~ 40 μeV)

→ only thermal noise background contribution (cavity + amplifier)

- Signal to Noise Ratio (SNR) $= \dfrac{P_a}{k_B T_N}\sqrt{\dfrac{t_{\text{integration}}}{\Delta f_a}}$, Dicke radiometer eq.,

$T_N = T_{cavity} + T_{amplifier\_noise}$: system noise temperature, Δf_a : axion signal bandwidth

- Resonant mode search, have to scan the resonant frequencies,

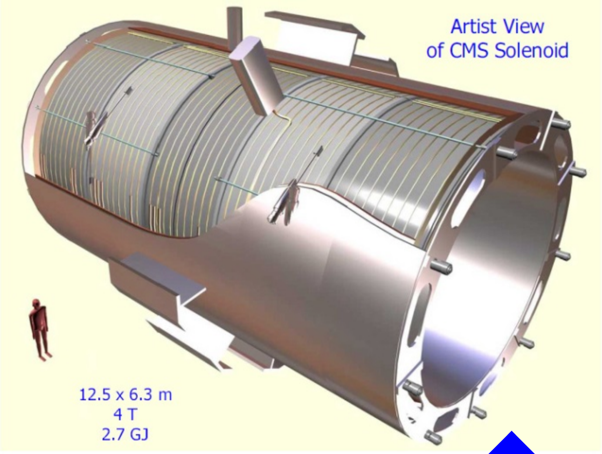
Practical figure of merit in axion haloscope searches,

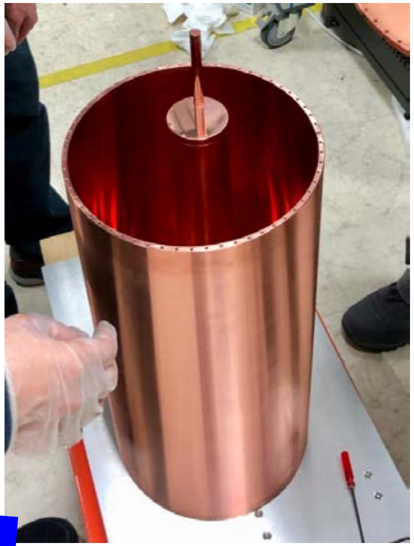
Scanning rate $\dfrac{df}{dt} \propto \dfrac{B_0^4 V^2 C^2 Q}{T_N^2}$

Axion Dark Matter Searches

Axion haloscope searches

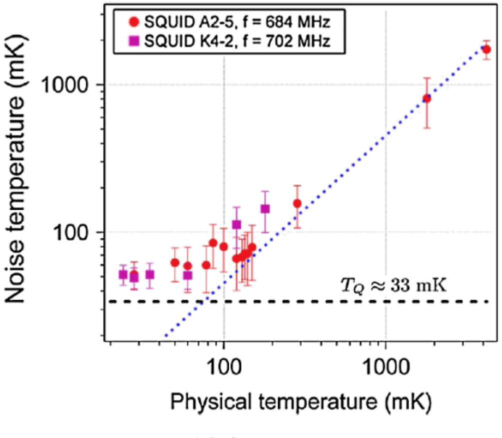
Key experimental devices





- $$\frac{df}{dt} \propto \frac{B_0^4 V^2 C^2 Q}{T_N^2}$$

$$T_N = T_{cavity} + T_{amplifier\_noise}$$



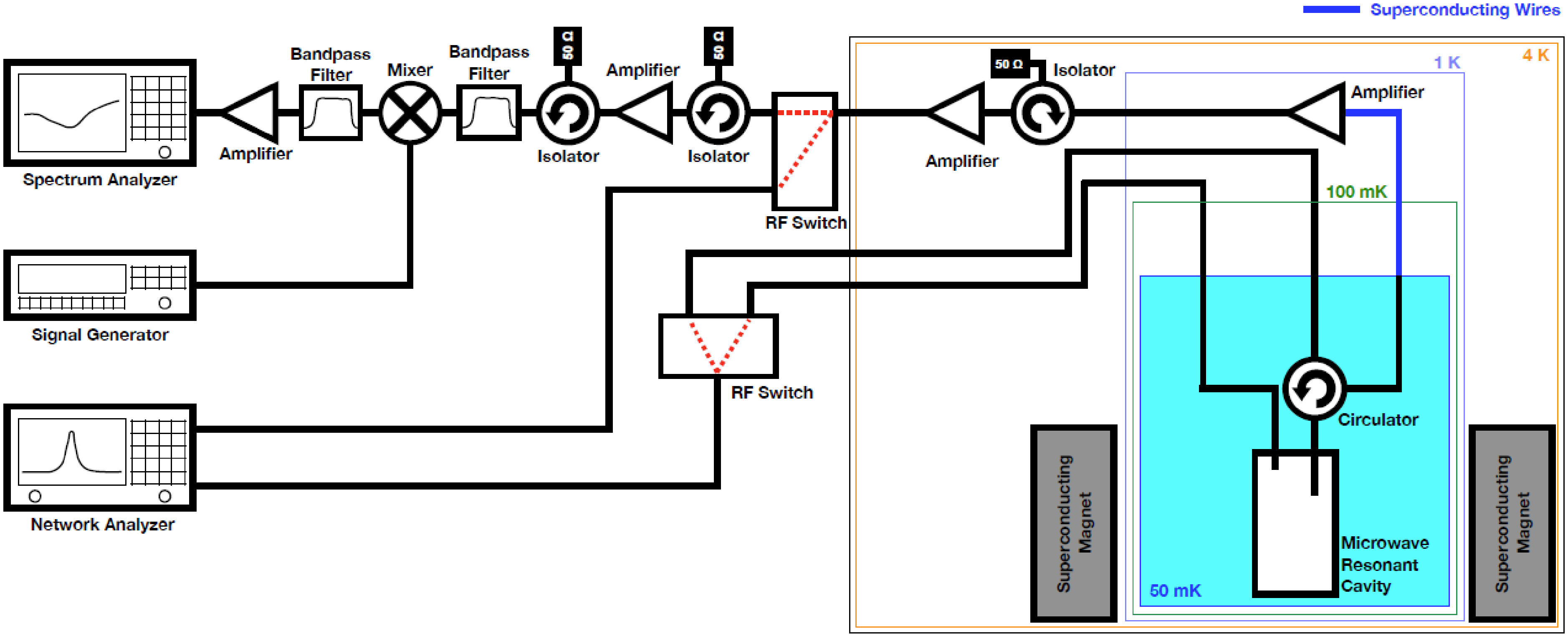
PRL **104**, 041301 (2010)

Dilution fridge insert, Leiden DRS-1000

Axion Dark Matter Searches

Axion haloscope searches

Overview of an axion haloscope



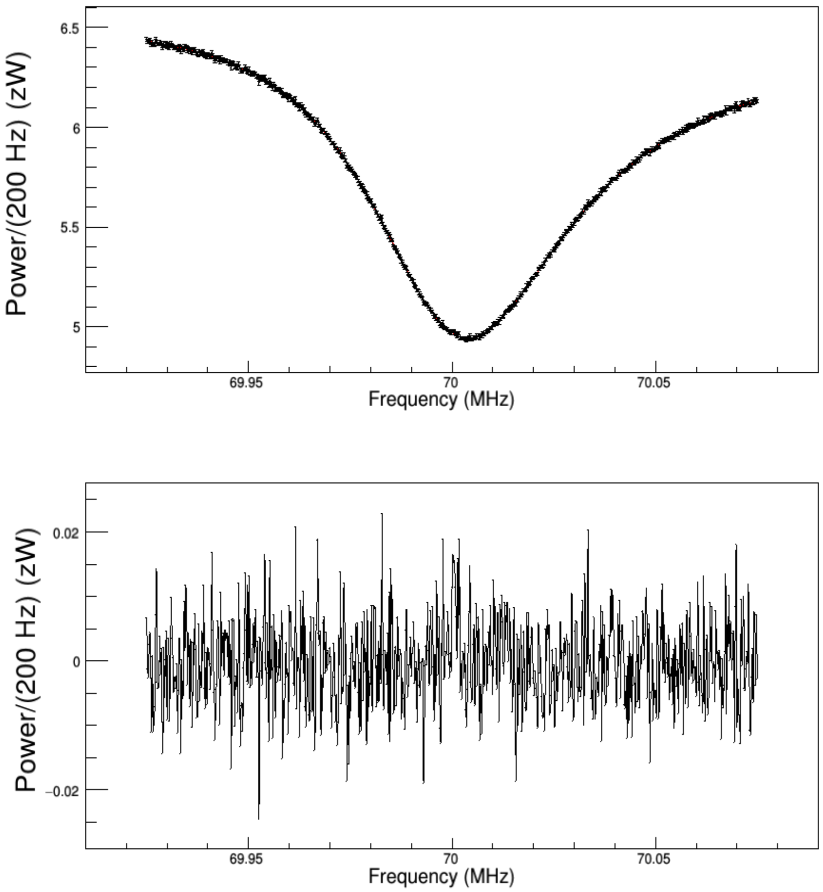
receiver @300 K

fridge

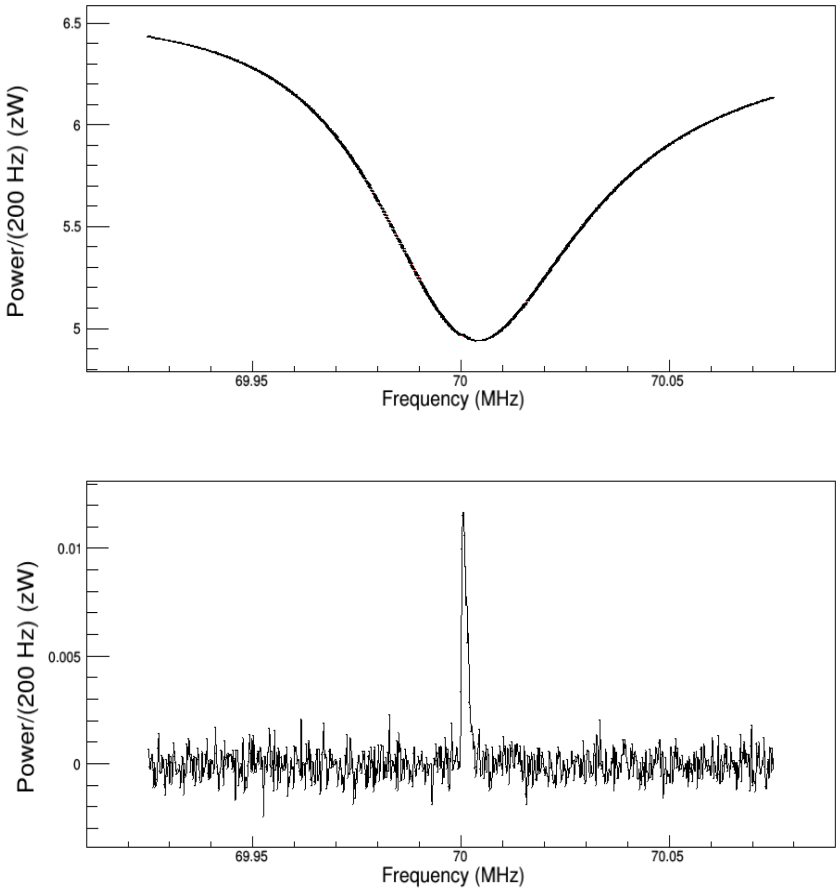
Axion Dark Matter Searches

Axion haloscope searches

Signal (simulation) and background spectrum (real)



SNR ~ 4 for a certain signal power



SNR ~ 40 for a certain signal power, but with much longer $t_{\text{integration}}$

Axion Dark Matter Searches

Ongoing axion haloscope searches

ADMX (**A**xion **D**ark **M**atter e**X**periment)

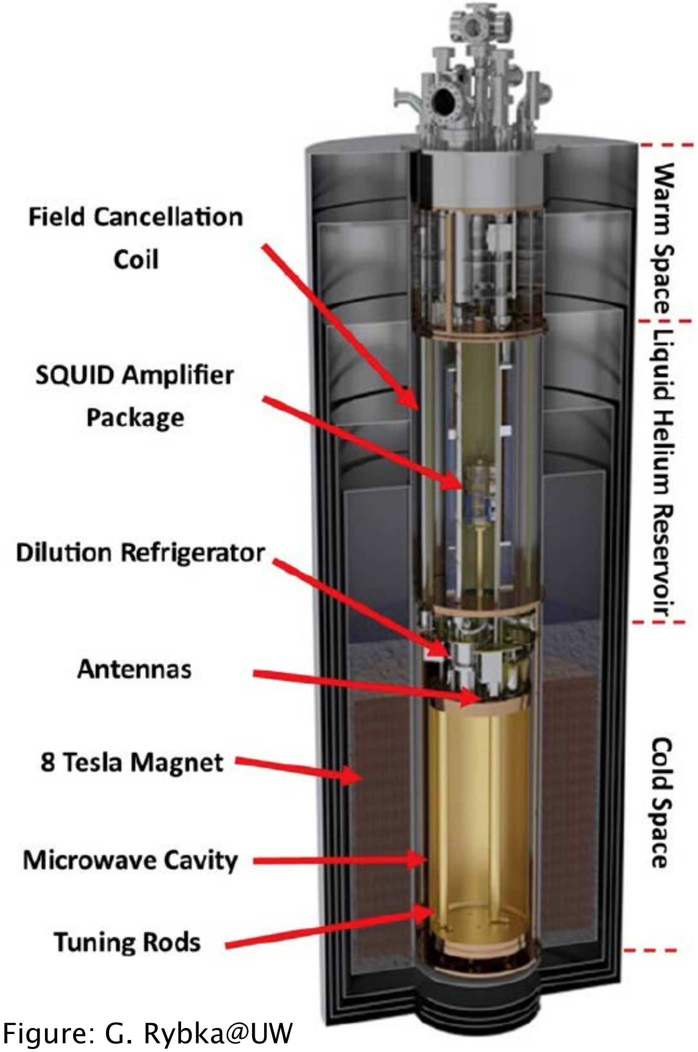


Figure: G. Rybka@UW

- ~ 3.5 m tall
- $B_0 = 8$ T and

  the magnet bore ~ 600 mm, $V = 136$ L
- $C \sim 0.4$ and $Q \sim 50{,}000$
- $T_N \sim 500$ mK

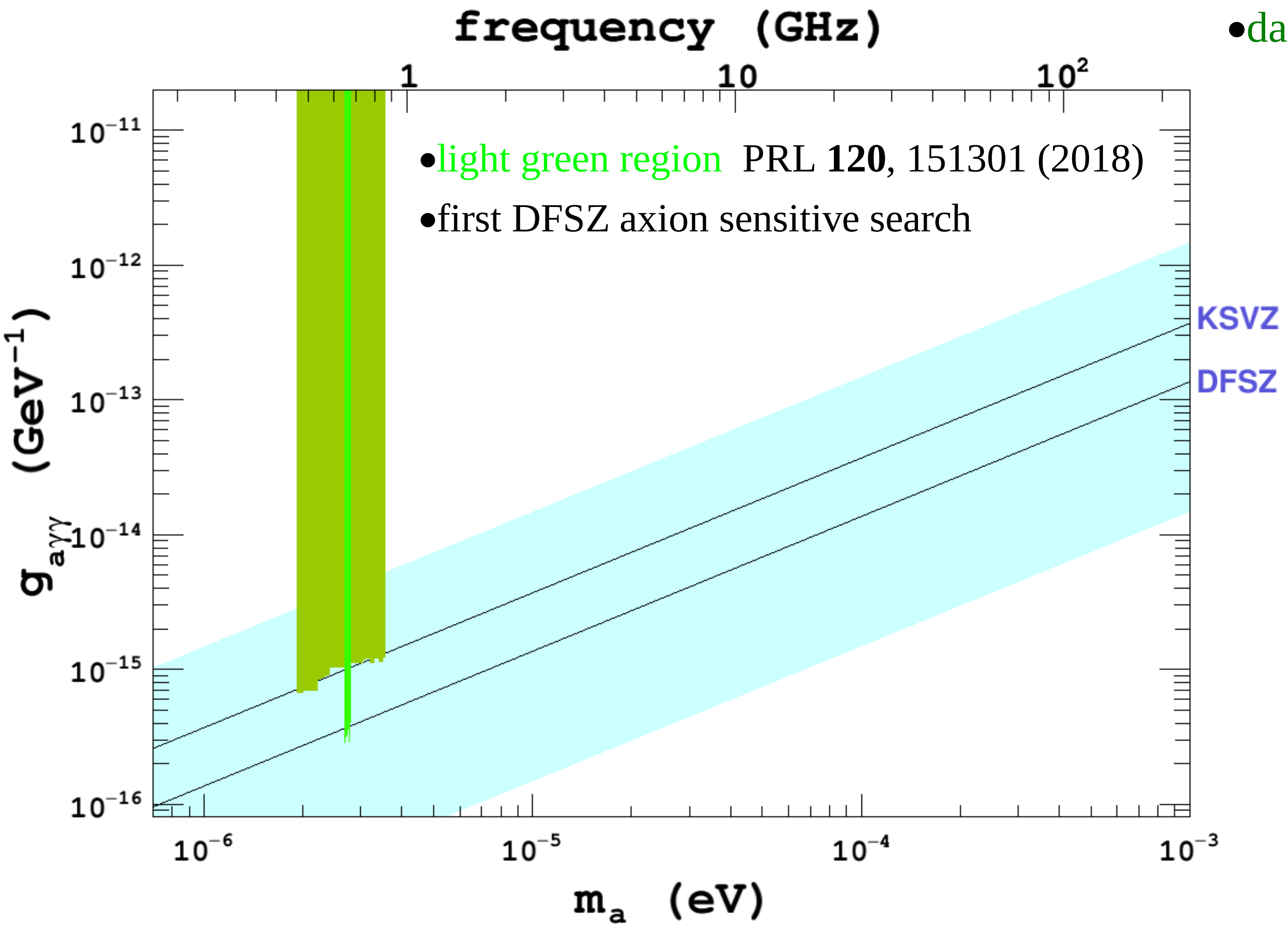
  $= 190$ mK (T_{cavity})

  $+ 310$ mK $(T_{amplifier\_noise})$

Axion Dark Matter Searches

Ongoing axion haloscope searches

ADMX (**A**xion **D**ark **M**atter e**X**periment)



- light green region PRL **120**, 151301 (2018)
- first DFSZ axion sensitive search

- dark green region

  PRL **80**, 2043 (1998),
  APJ Lett 572, 27 (2002),
  PRD 69, 011101 (2004),
  PRL **104**, 041301 (2010)

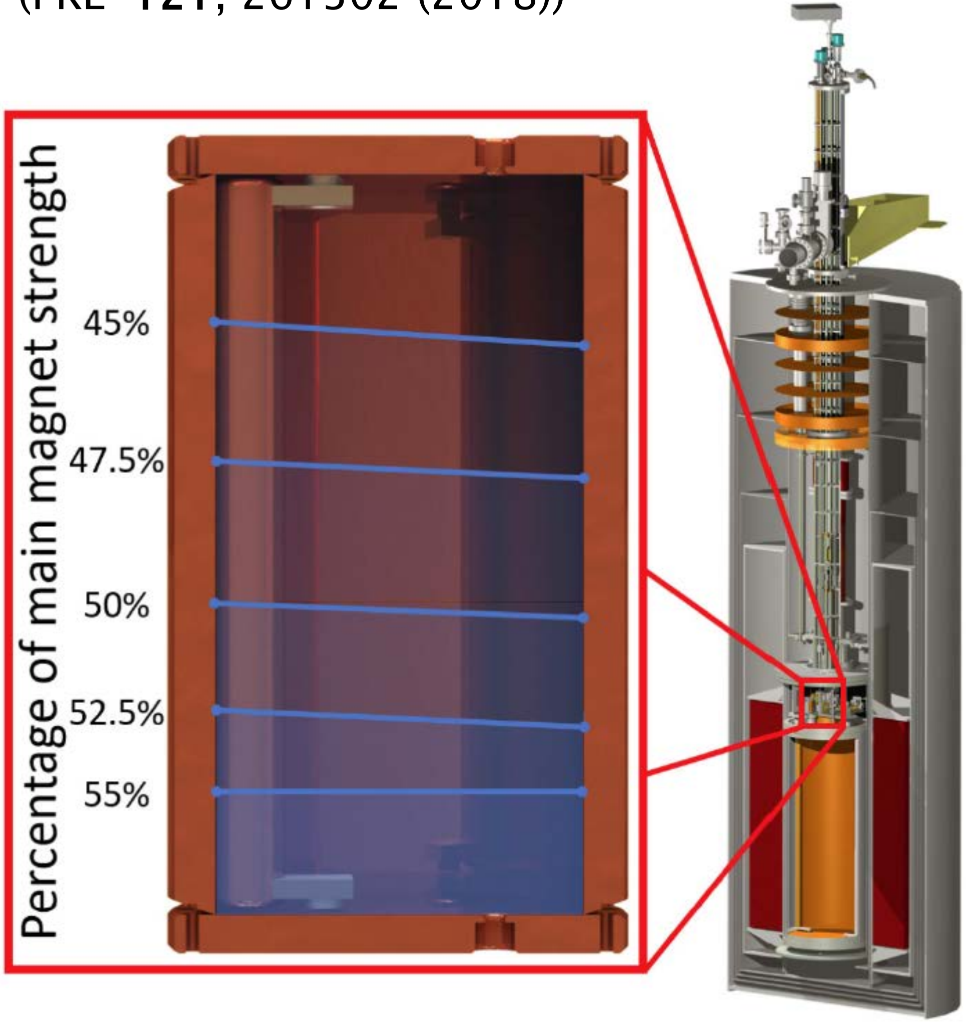
  - No dilution fridge, instead pumped LHe temperature, 2 K $\rightarrow T_N \sim 3$ K (PRL 2010) or 4 K (others)
  - sensitive to the standard KSVZ axion

Axion Dark Matter Searches

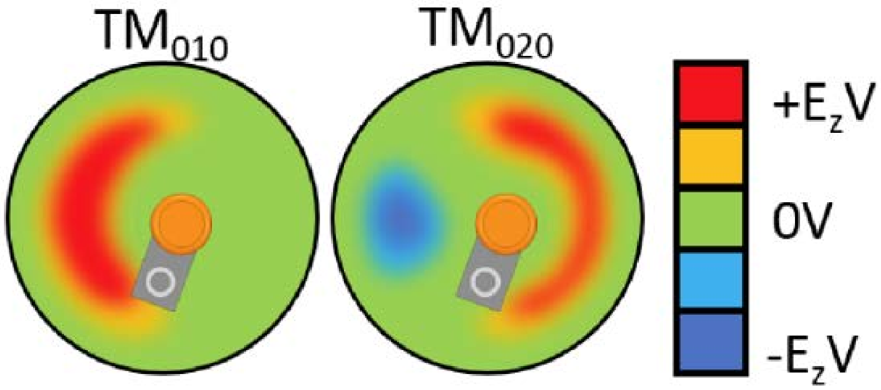
Ongoing axion haloscope searches

ADMX Sidecar

(PRL **121**, 261302 (2018))



- $B_0 = 3.11$ T at most, $V \sim 0.38$ L
- $T_N \sim 7$ K with transitor based amplifier
- But, TM_{010} and TM_{020} at the same time for the first time



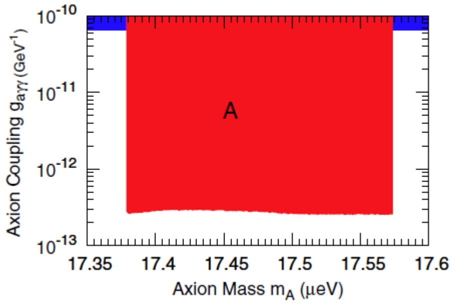
- C (0.4 ~ 0.04) and Q (6,000 ~ 2,000) depend on the cavity modes

Axion Dark Matter Searches

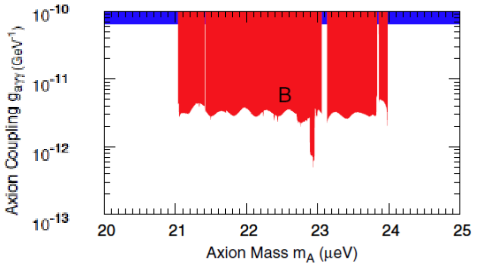
Ongoing axion haloscope searches

ADMX Sidecar

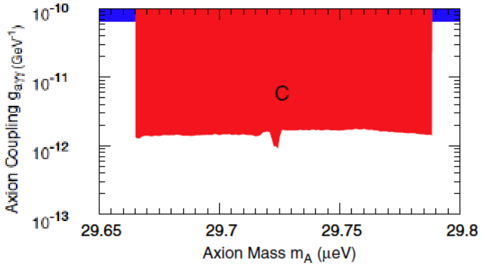
(PRL **121**, 261302 (2018))



•TM_{010} mode with $B_0 = 3.11$ T

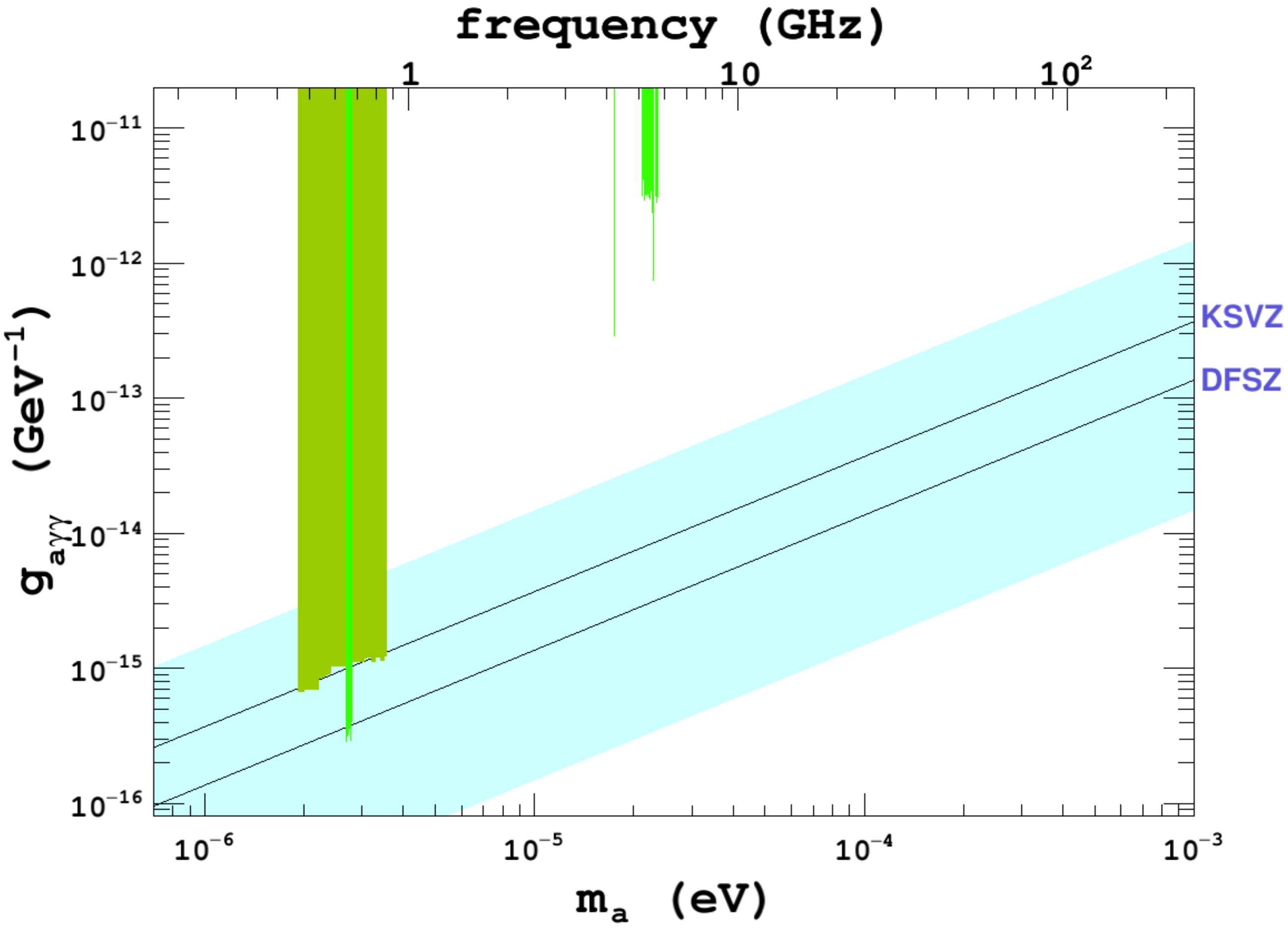


•TM_{010} mode, but $B_0 = 0.78$ T



•TM_{020} mode with $B_0 = 3.11$ T

Be careful, this is a log-log plot!



Not sensitive to the QCD axion, but ongoing cavity experiment

Axion Dark Matter Searches

Ongoing axion haloscope searches

HAYSTAC
(Haloscope At Yale Sensitive To Axion CDM)

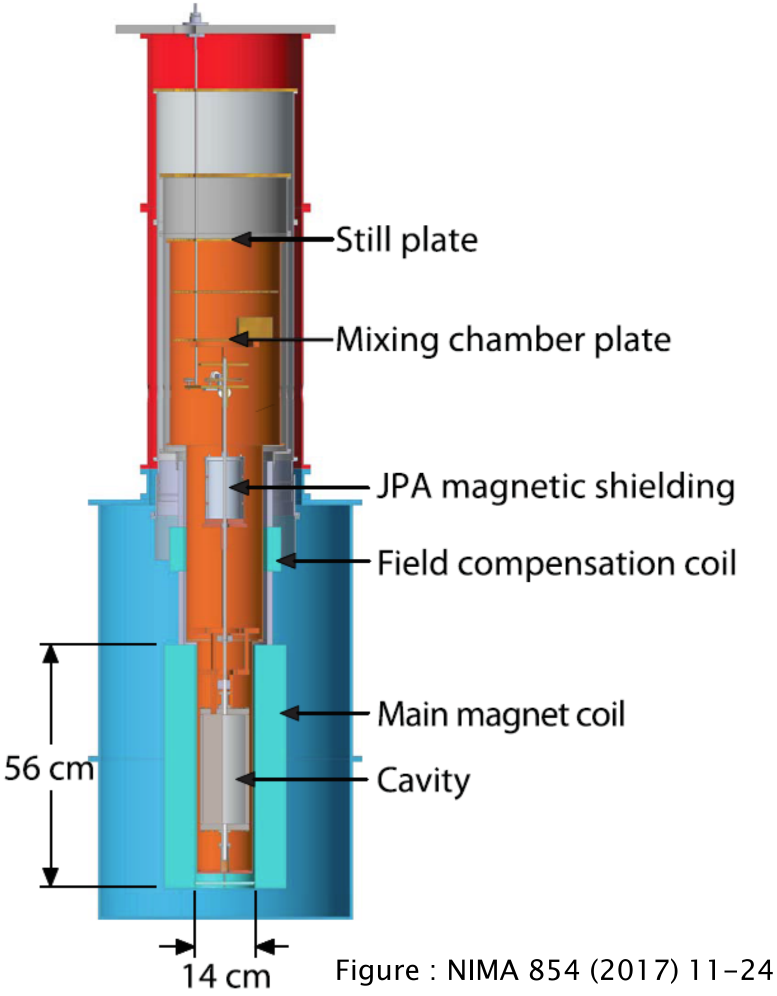


Figure : NIMA 854 (2017) 11-24

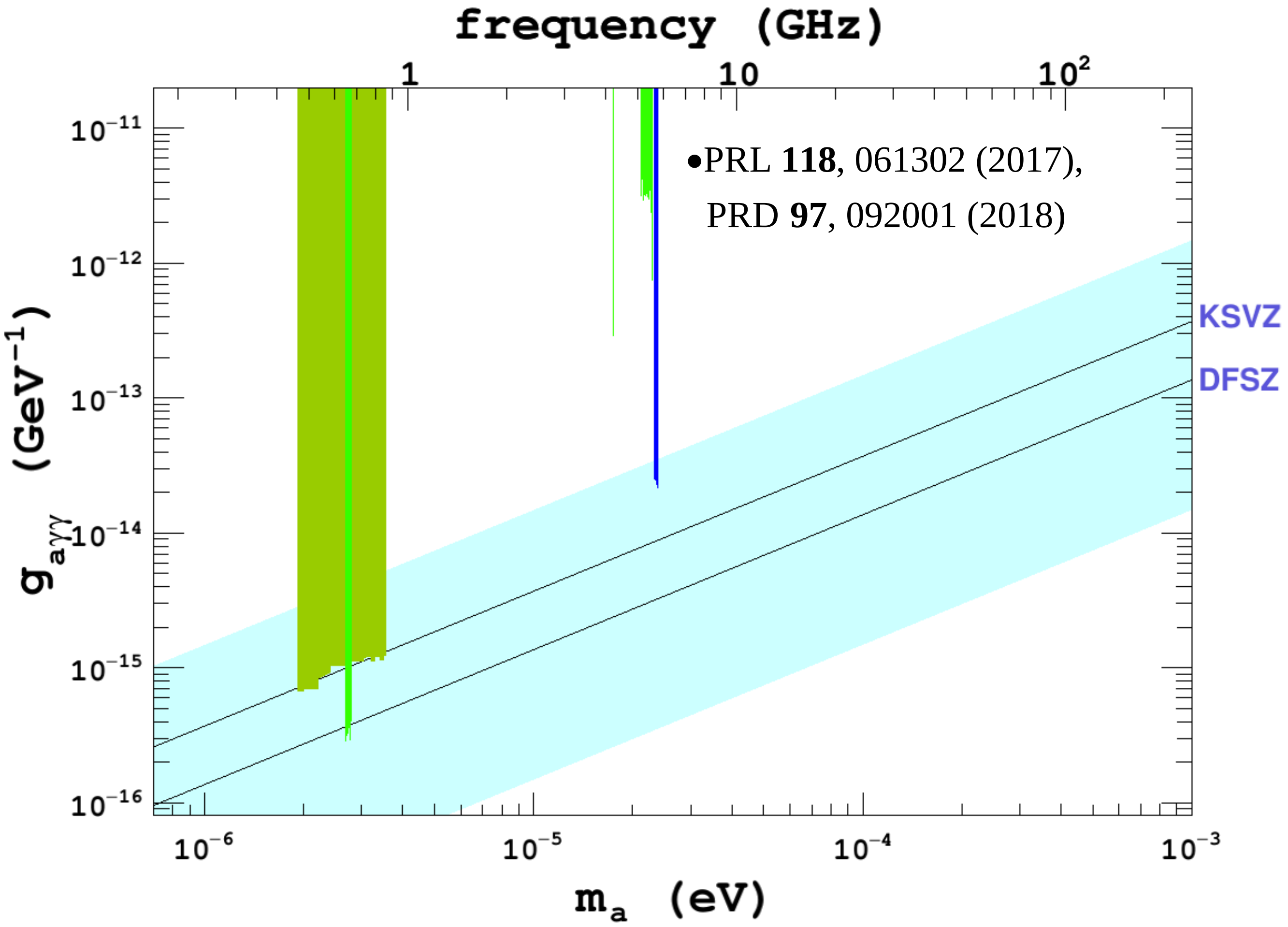
- $B_0 = 9$ T and
  the magnet bore ~ 140 mm,
  higher frequency dedicated, $V = 2$ L
- $C \sim 0.5$ and $Q \sim 10,000$
- $T_N \sim 3$ quanta ~2.2 quanta
  (828 mK ~ 607 mK for 5.75 GHz)
- first successful operation of
  an axion detector incorporating
  a dilution fridge and
  quantum-noise-limited amplifier

Axion Dark Matter Searches

Ongoing axion haloscope searches

HAYSTAC

(**H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **CDM**)



- PRL **118**, 061302 (2017), PRD **97**, 092001 (2018)

- log-log plot!
- HAYSTAC scanned over 200 MHz, sensitive to the QCD axion

Ongoing axion haloscope searches

CULTASK
(CAPP Ultra Low Temperature Axion Search in Korea)

- CAPP is established in October 2013
- mainly building infrastructure so far and time to do physics
- parallel searches with different magnets (= in different frequency ranges)

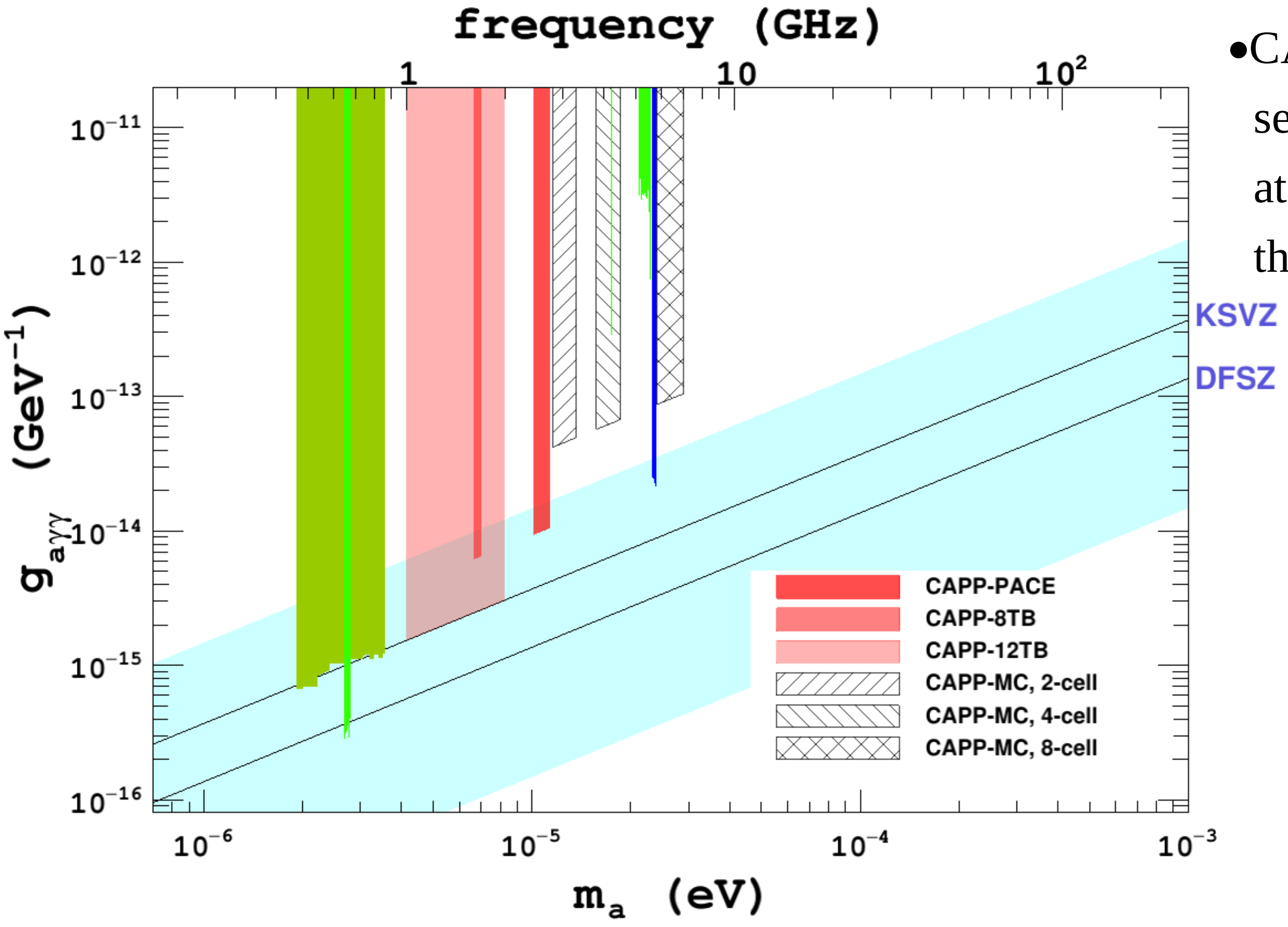
→ the best way to increase the scanning rate which is the practical FoM

B_0	bore	system cooling	target	a.k.a.
8 T	125 mm	dilution	sensitive to QCD axion	CAPP-PACE
8 T	165 mm			CAPP-8TB
12 T	320 mm		sensitive to DFSZ axion	CAPP-12TB
9 T	125 mm	pumped LHe	testbed	CAPP-MC

Axion Dark Matter Searches

Ongoing axion haloscope searches

CULTASK
(CAPP Ultra Low Temperature Axion Search in Korea)



- CAPP-12TB : DFSZ axion sensitive, but axion could be at that level, decided to go with the standard KSVZ axion scan

top view of
the 4-cell cavity

Summary

- Axion

solves the strong CP problem in the SM

- Axion Dark Matter

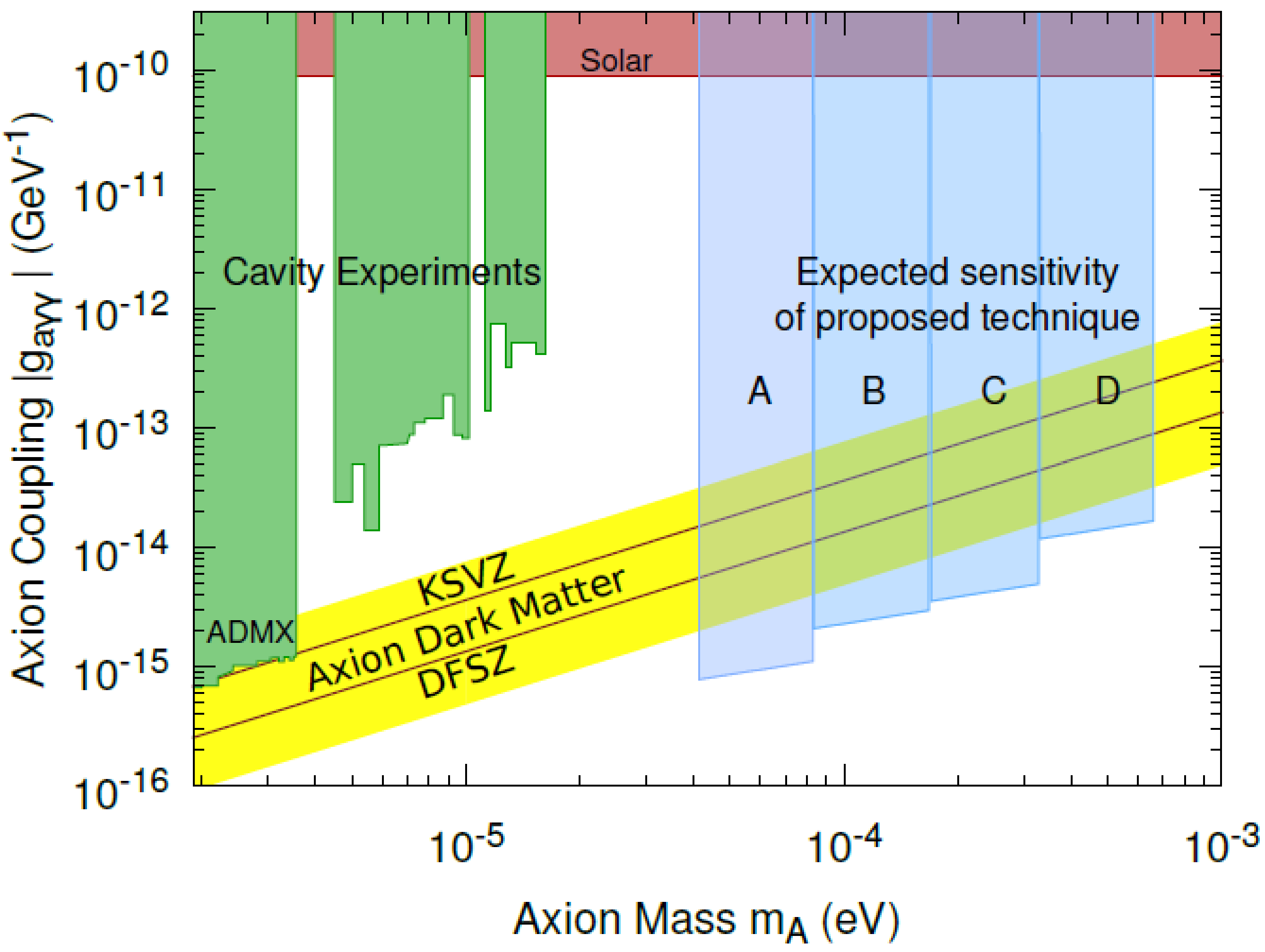
strong CDM candidate

- Axion Dark Matter Searches

two rabbits at the same time

Thank you very much

Open resonator

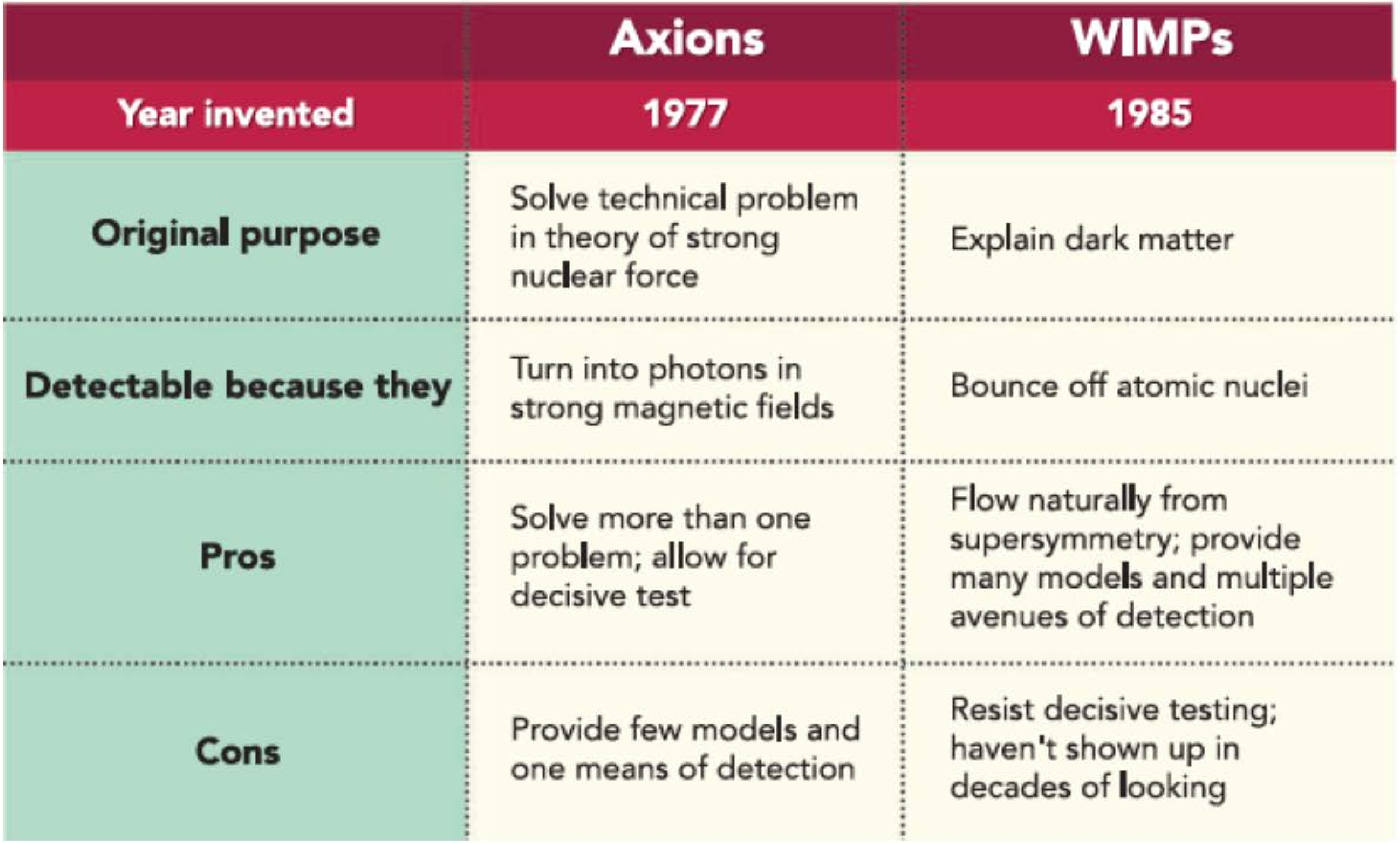


Fabry-Pérot resonator Phys. Rev. D 91, 011701(R) (2015)

Friis's formula

$$T_{\text{sys}} = T_{\text{phys}} + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots,$$

Dark Matter Candidates



	Axions	**WIMPs**
Year invented	**1977**	**1985**
Original purpose	Solve technical problem in theory of strong nuclear force	Explain dark matter
Detectable because they	Turn into photons in strong magnetic fields	Bounce off atomic nuclei
Pros	Solve more than one problem; allow for decisive test	Flow naturally from supersymmetry; provide many models and multiple avenues of detection
Cons	Provide few models and one means of detection	Resist decisive testing; haven't shown up in decades of looking

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