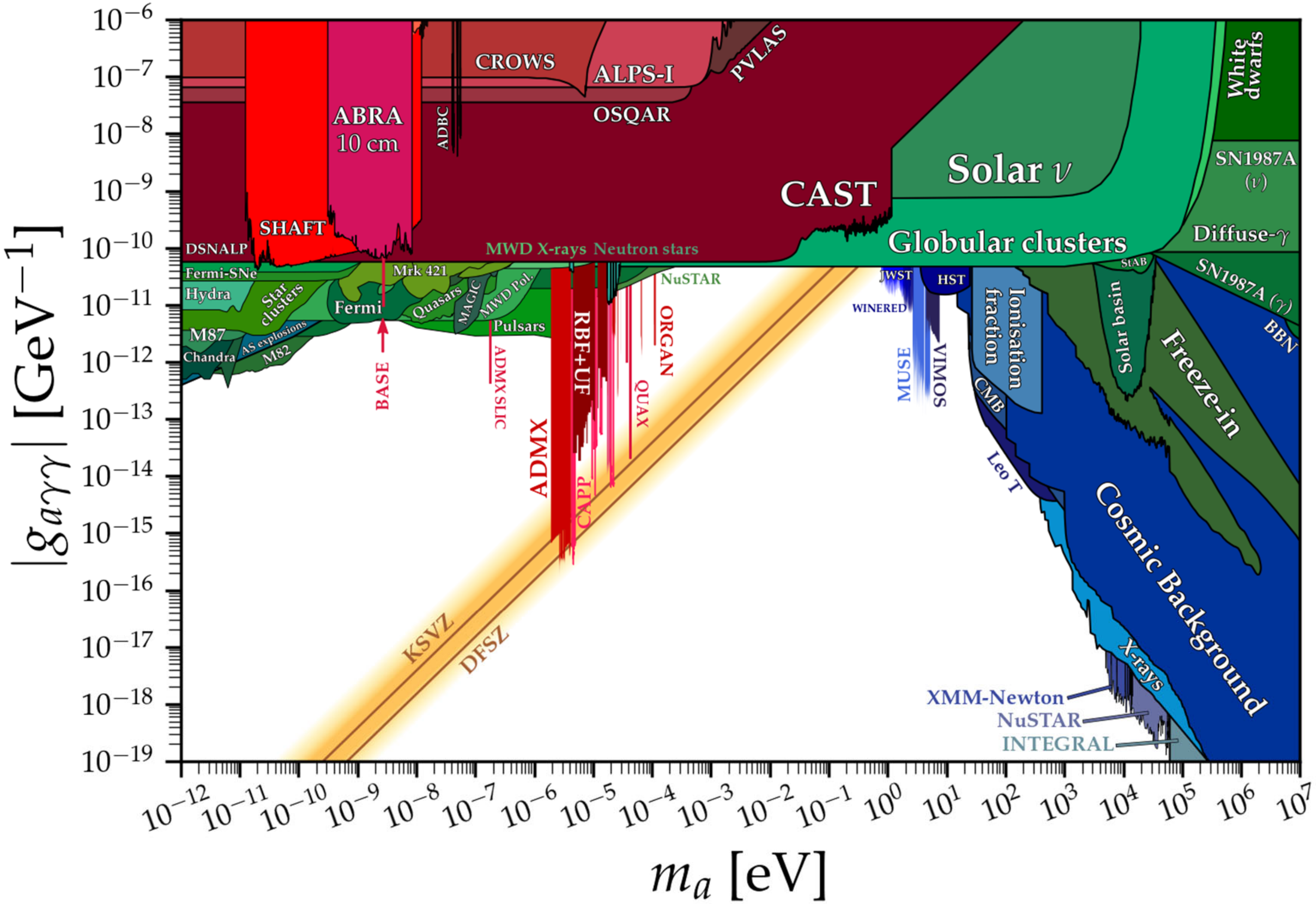
Microwave Cavity Axion Dark Matter Search

IHEP-KU workshop@KU, 2024 Oct. 14

Byeong Rok Ko

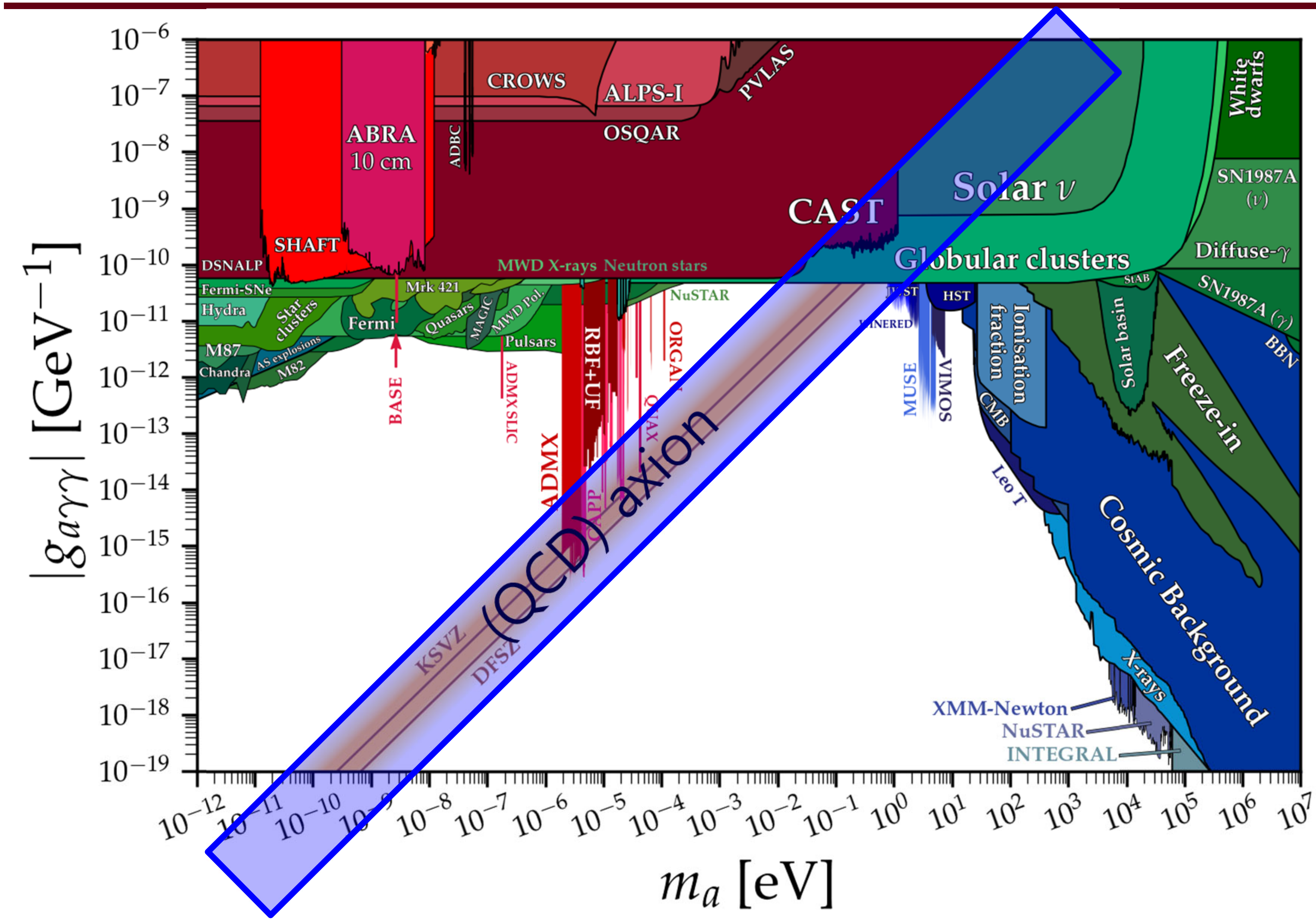
(Dept. of Accelerator Science, Korea Univ. Sejong Campus)

Axion dark matter search = Microwave cavity search



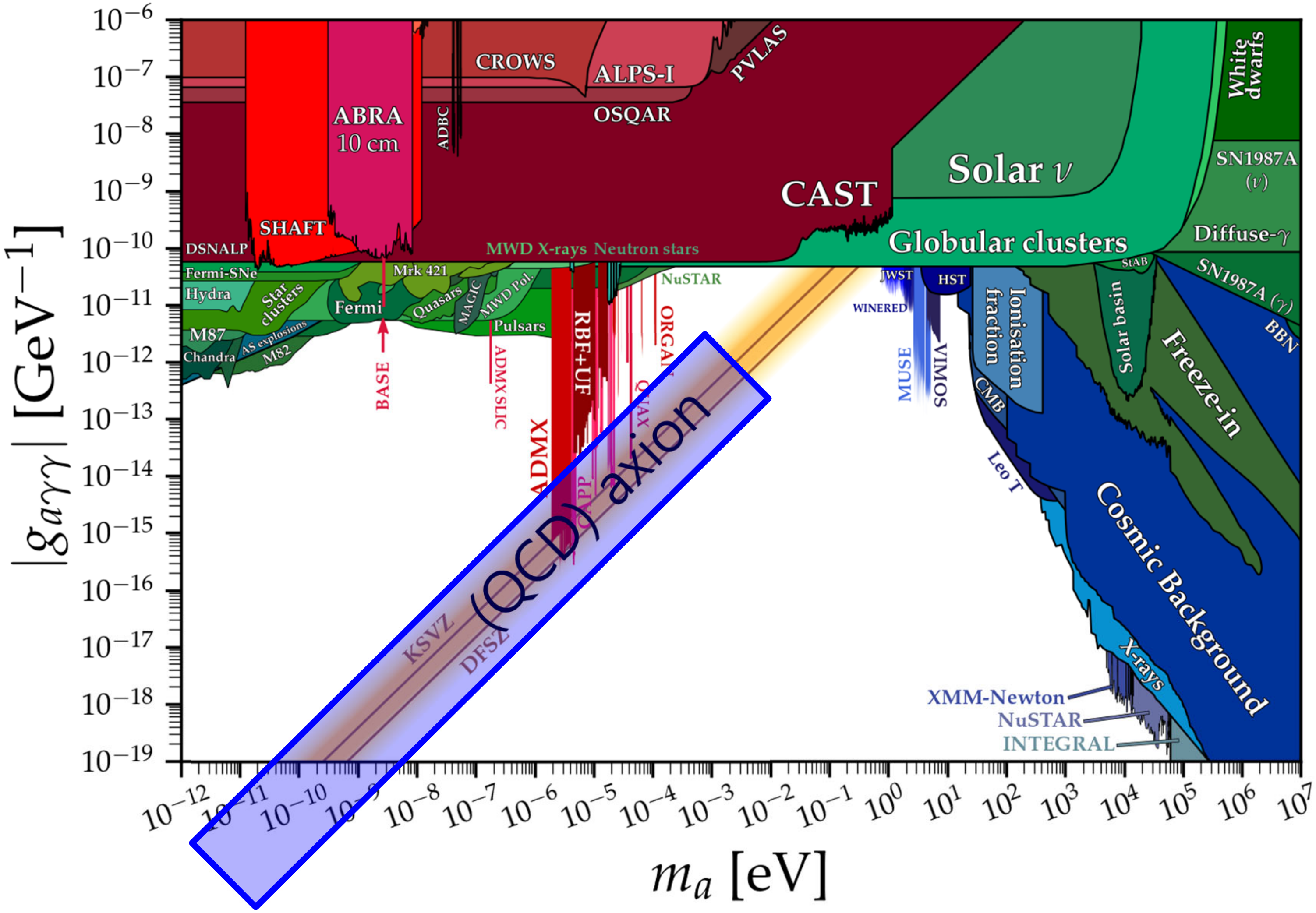
white : unexplored
colored : excluded
to date

Axion dark matter search = Microwave cavity search



yellow band : (QCD) axion, a natural solution of the strong CP problem in the Standard Model (SM)

Axion dark matter search = Microwave cavity search



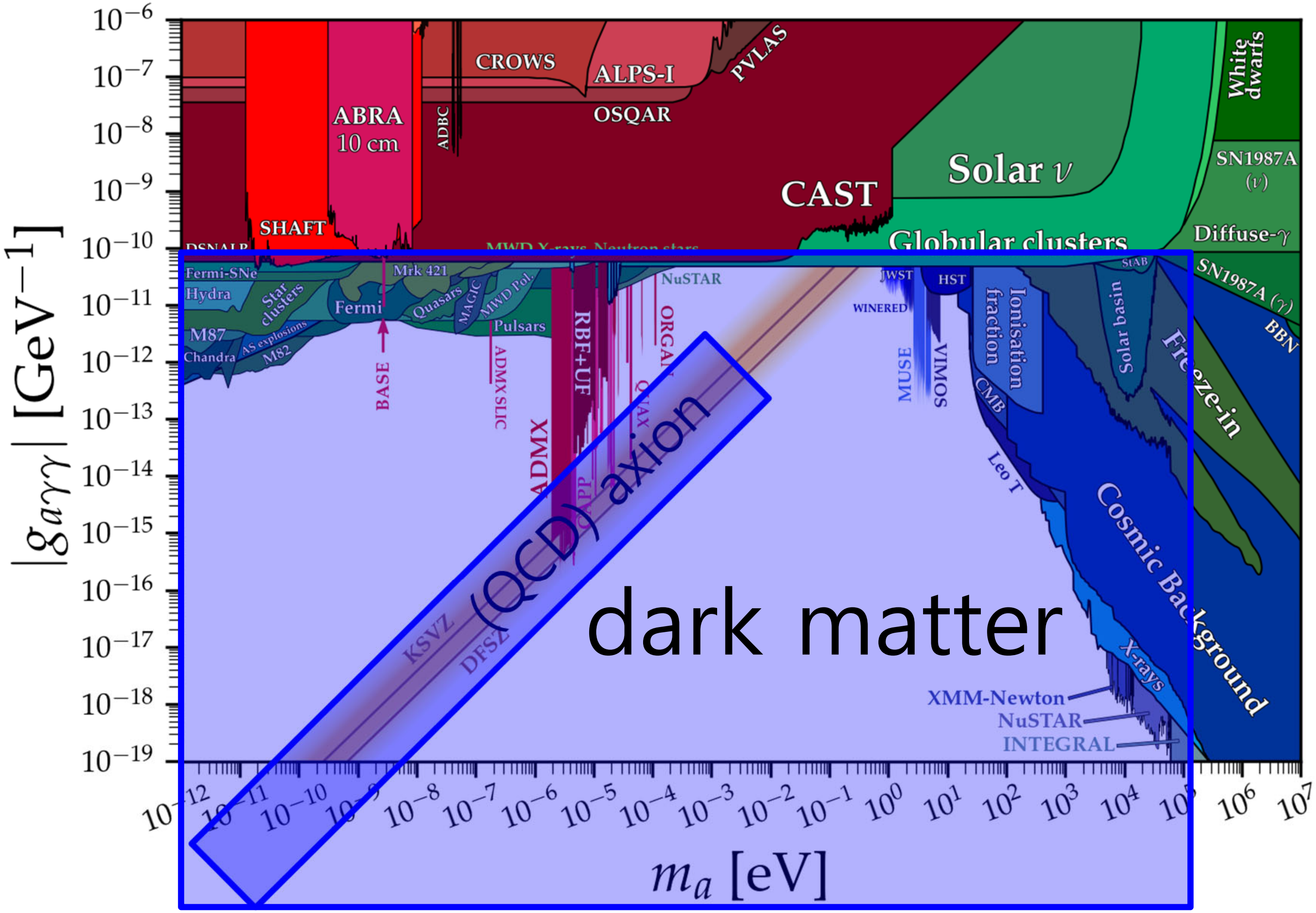
Upper limit by SN 1987A

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 the axion emission, the neutrino burst is excessively reduced.

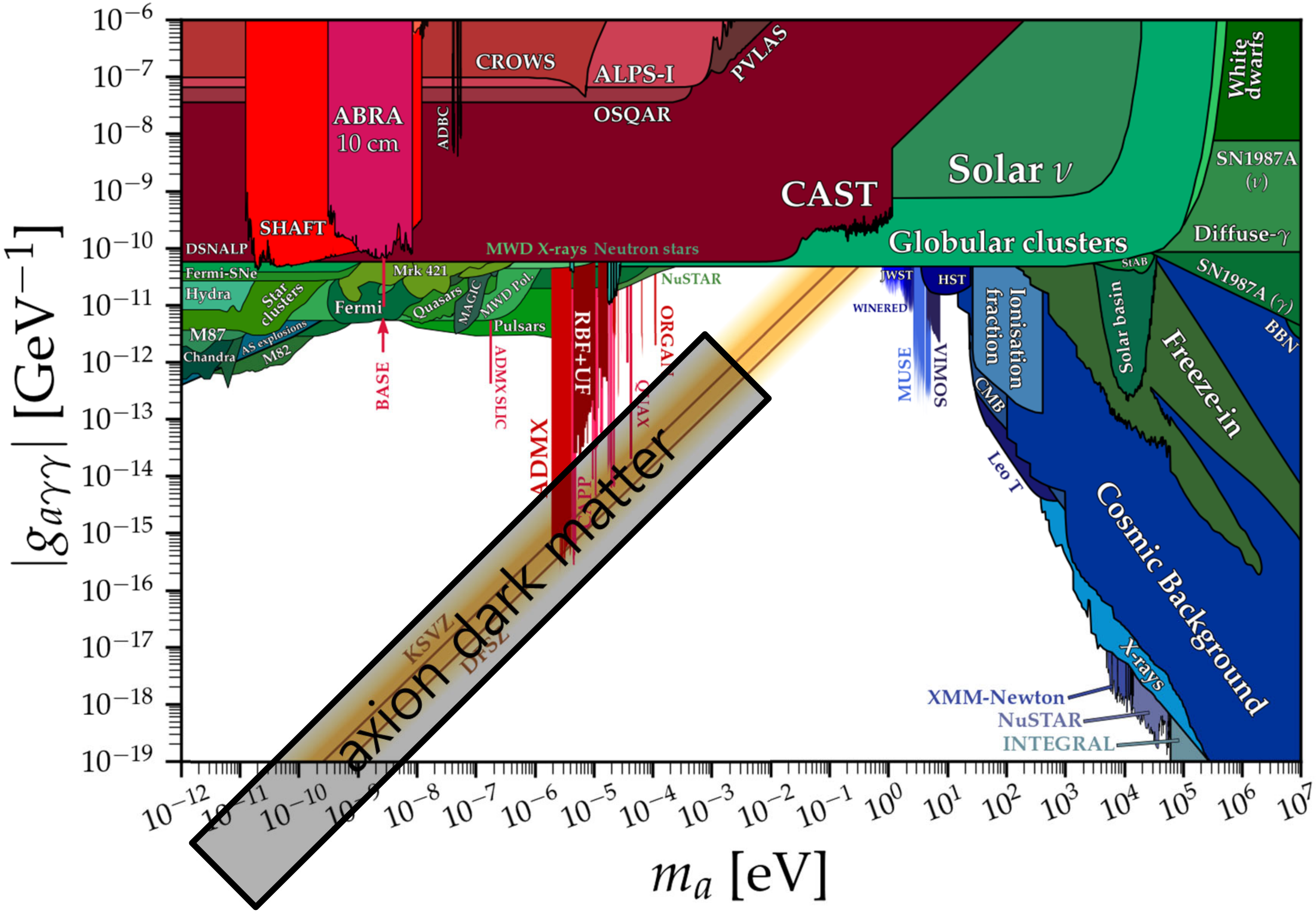
$$m_a < O(\text{meV})$$

Axion dark matter search = Microwave cavity search



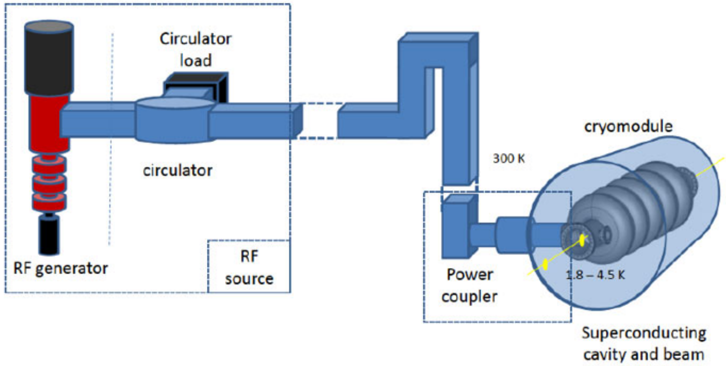
white : unexplored as dark matter for the coupling

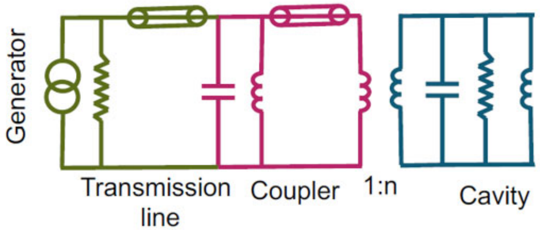
Axion dark matter search = Microwave cavity search



They (narrow spikes) are all employing a microwave cavity

Microwave cavity is a crucial ingredient in accelerators and axion dark matter searches

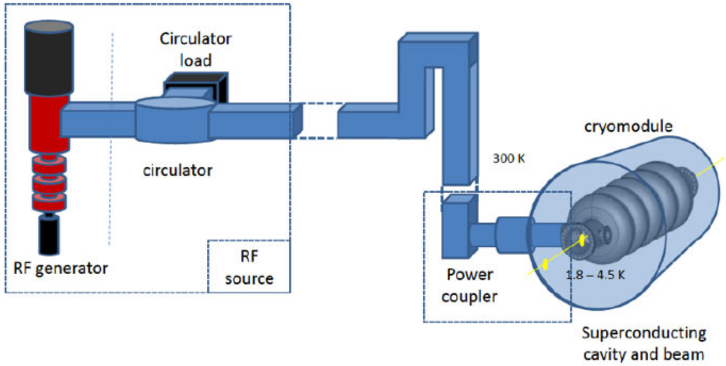


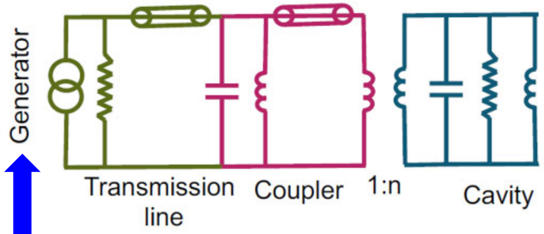


accelerating gradient

$$E_{acc} \propto \sqrt{Q_{cavity}}$$

Microwave cavity is a crucial ingredient in accelerators and axion dark matter searches





accelerating gradient

$E_{acc} \propto \sqrt{Q_{cavity}}$

axion dark matter halo

$g_{a\gamma\gamma}$

cavity mode $E_a^{a\gamma\gamma}$

axion signal power

$P_a^{a\gamma\gamma} \propto Q_{cavity}$

$\rightarrow E_a^{a\gamma\gamma} \propto \sqrt{Q_{cavity}}$

if $m_a = \nu_{cavity}$

Axion as a solution of the Strong CP problem in the Standard Model

$U(1)_A$ problem

- S. Weinberg, $m_{\eta'} < \sqrt{3} m_\pi \sim 240$ MeV from the perturbed QCD, nominal $m_{\eta'} = 958$ MeV > $m_p = 938$ MeV

Axion as a solution of the Strong CP problem in the Standard Model

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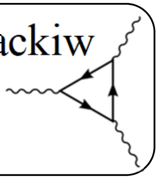
Adler-Bell-Jackiw anomaly



•G. 't Hooft, $U(1)_A$ is not a symmetry $\theta_{QCD} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{\mu\nu a}$, succeeded to derive the nominal η' mass

$\theta_{QCD} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{\mu\nu a}$ is CP odd $\because G_a^{\mu\nu} \tilde{G}_{\mu\nu a} \sim \vec{E}^a \cdot \vec{B}^a$ and θ_{QCD} is a parameter,

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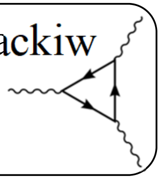

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No neutron electric dipole moment (EDM)

•$d_n \sim \theta_{SM} \frac{m_u m_d}{m_u + m_d}$, $\theta_{SM} = \theta_{QCD} + \theta_{EW}$ with non-zero quark masses

however, measured $\theta_{SM} \leq 10^{-10} \rightarrow$ very small, just putting θ_{SM} to 0 is not unnatural. The matter is zero θ_{SM} means CP is a good symmetry in the SM, but now know CPV in the kaon and B systems, and that in the kaon system at the time $\rightarrow$ unnatural cancellation in θ_{QCD} & θ_{EW} $\rightarrow$ Strong CP problem in the SM

Axion as a solution of the Strong CP problem in the Standard Model

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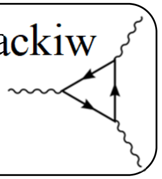

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θ_{SM} promoted to a dynamic variable

$\theta_{SM} \rightarrow \theta_{SM} + \frac{a}{f_a}$

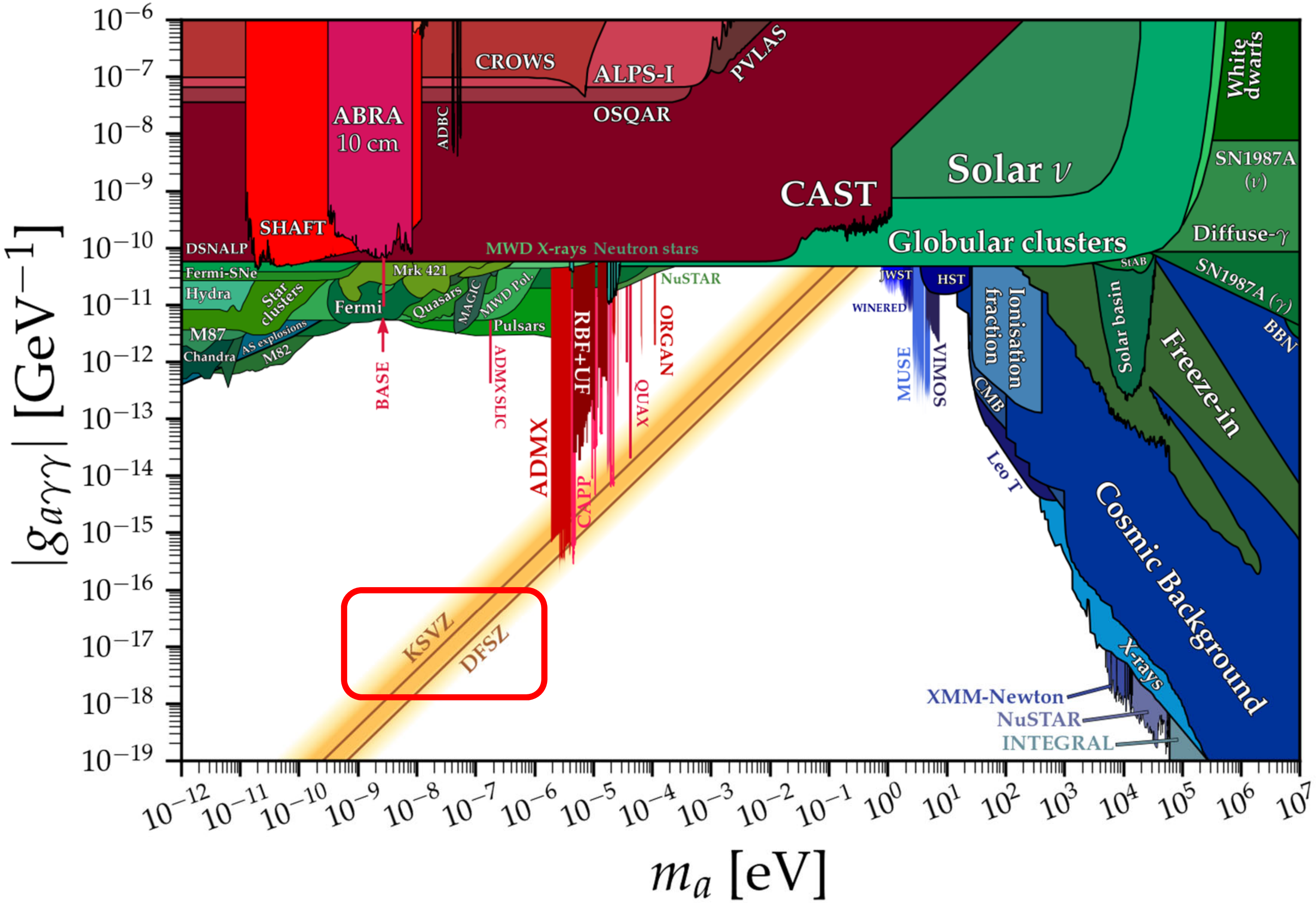
•by Peccei and Quinn (PQ), $\frac{g^2}{32\pi^2} \theta_{SM} G_a^{\mu\nu} \tilde{G}_{\mu\nu a} \rightarrow \frac{g^2}{32\pi^2} \left(\theta_{SM} + \frac{a}{f_a} \right) G_a^{\mu\nu} \tilde{G}_{\mu\nu a}$

f_a is the axion decay constant $\propto 1/m_a$ $\rightarrow$ the only ***unknown***

$a = \langle a \rangle + a_{phy} \rightarrow \frac{g^2}{32\pi^2} \frac{a_{phy}}{f_a} G_a^{\mu\nu} \tilde{G}_{\mu\nu a}$ which is CP even with ***pseudoscalar*** axion field

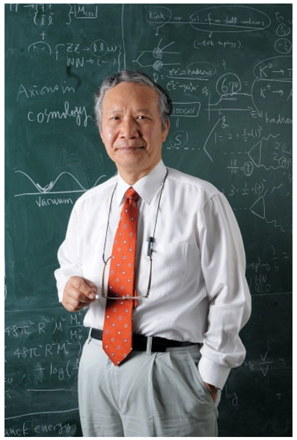
Axion advent as a natural solution of the Strong CP problem in the SM

Axion models : KSVZ vs. DFSZ, invisible axion models

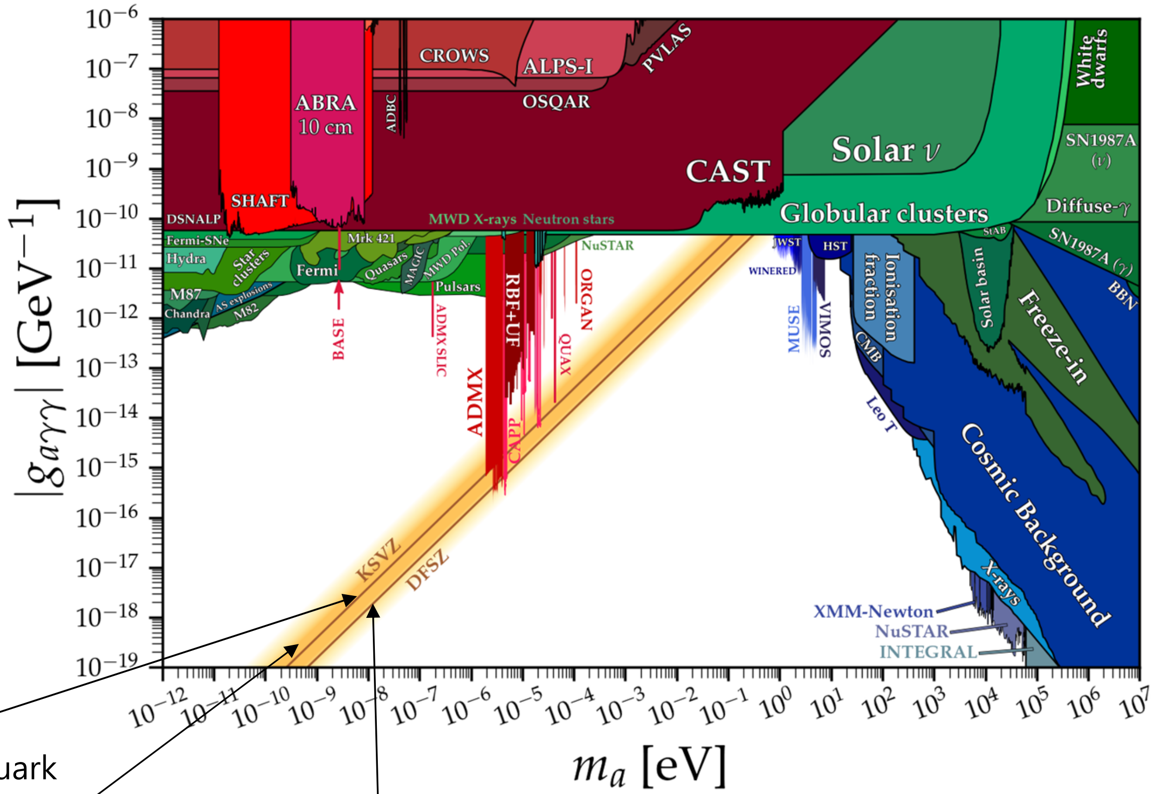


Axion models : KSVZ vs. DFSZ, invisible axion models

	beyond the SM	direct couplings
DFSZ; Dine–Fischler–Srednicki–Zhitnitsky	two Higgs Doublet	SM particles
KSVZ; Kim–Shifman–Vainshtein–Zakharov	new heavy quark	new heavy quark



Prof. Jhin E. Kim, inventor of invisible axion



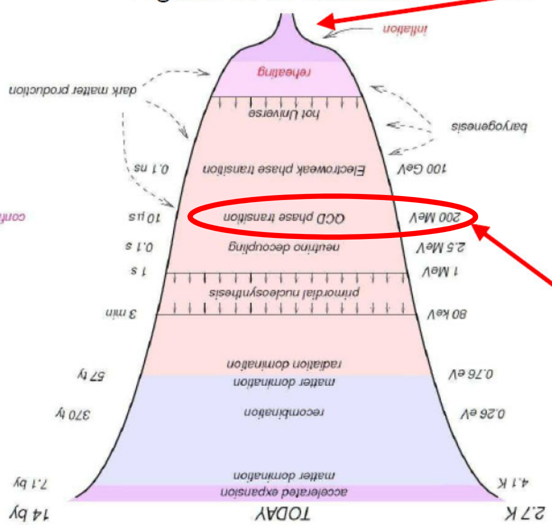
upper line:
standard KSVZ axion
with a neutral heavy quark

yellow band:
KSVZ axion depending on
the heavy quark charge

lower line:
DFSZ axion with type-I 2HDM
(SM particles couple to Φ_2 (or H_u))

Axion production : Misalignment mechanism

Figure: D. S. Gorbunov



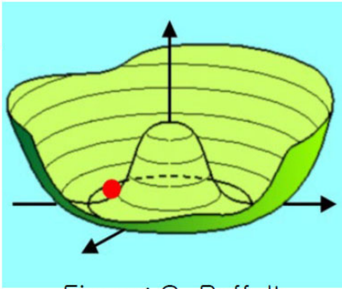
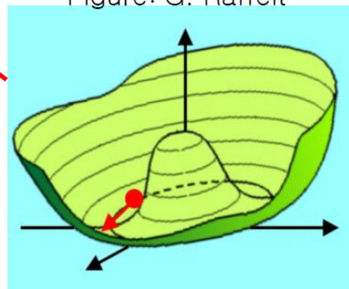


Figure: G. Raffelt

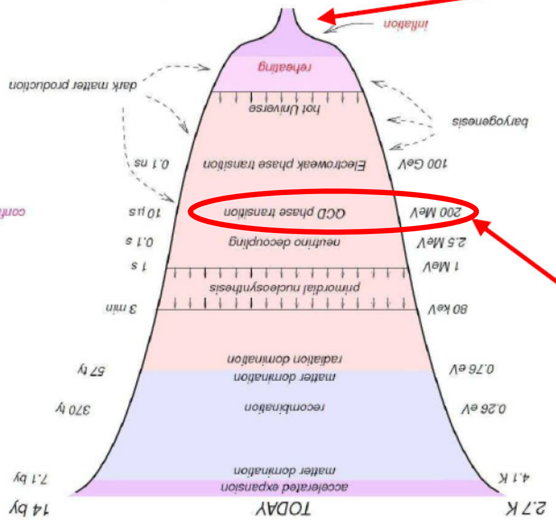


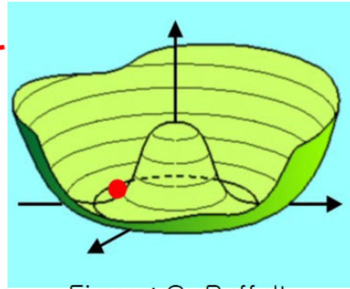
- axion produced with PQ symmetry breaking before the inflation
- axion at θ_{SM} w.r.t. the minimum $\rightarrow$ called misalignment production

- potential tilted by QCD $\rightarrow$ axion rolls down and starts small coherent oscillation around the minimum $\rightarrow$ the oscillation energy makes up a sizeable fraction of the energy density of our Universe

Axion born as cold

Figure: D. S. Gorbunov





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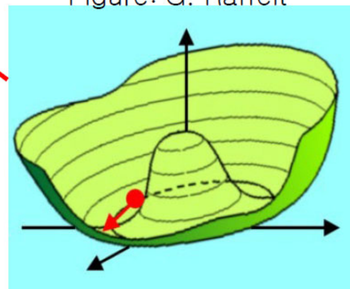

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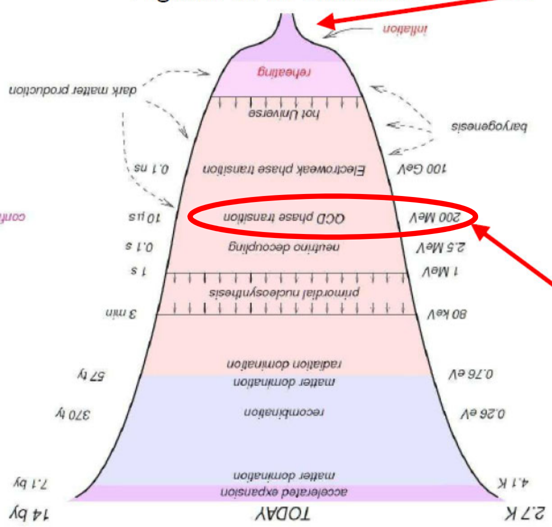
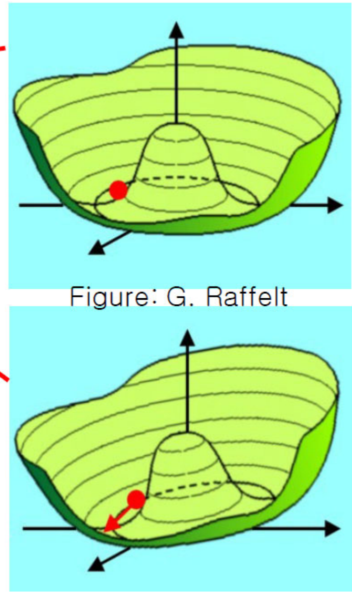
- small oscillation $\rightarrow \vec{\nabla} a \simeq 0 \rightarrow \vec{p} a \simeq 0 \rightarrow$ non-relativistic $\rightarrow$ cold
- axion energy, $E_a = m_a c^2 + \frac{1}{2} m_a v^2 = m_a c^2 \left(1 + \frac{1}{2} \left(\frac{v}{c} \right)^2 \right)$

Axion as cold dark matter

Figure: D. S. Gorbunov





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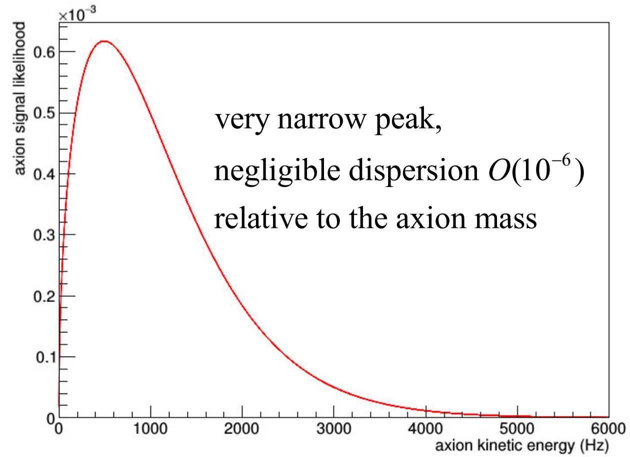

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- using the standard halo model, $v^2/c^2 \sim O(10^{-6})$ and the v distribution follows the Maxwell-Boltzmann

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Axion as cold dark matter

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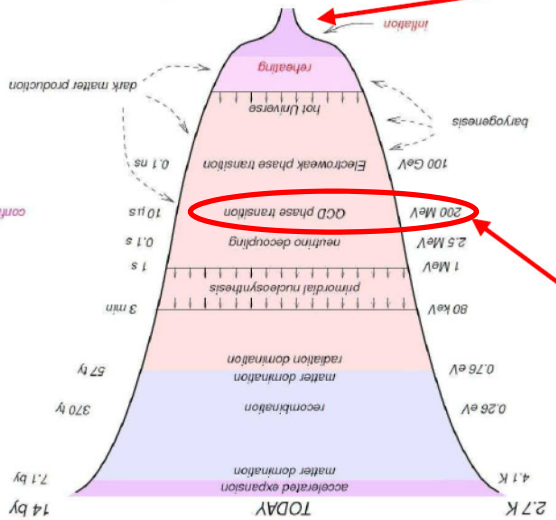

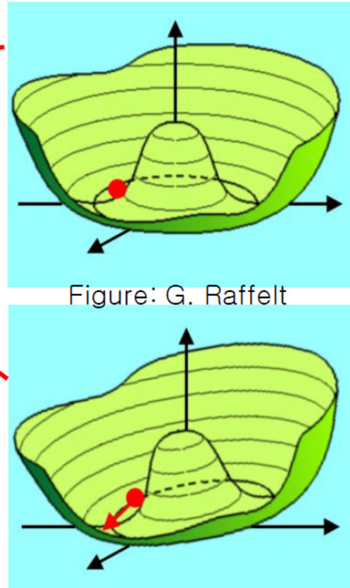

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oscillation around th
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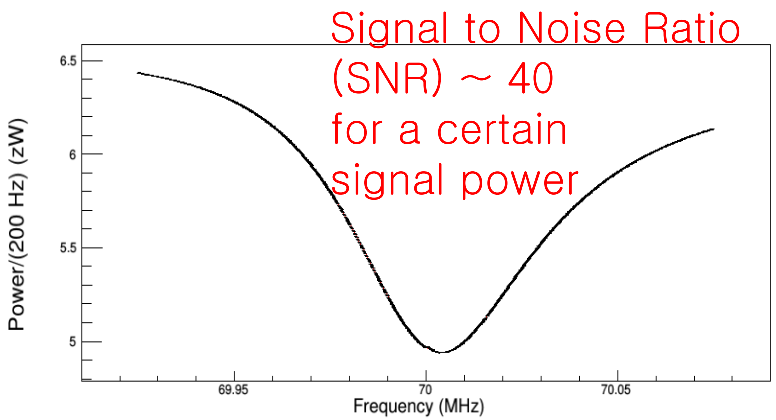

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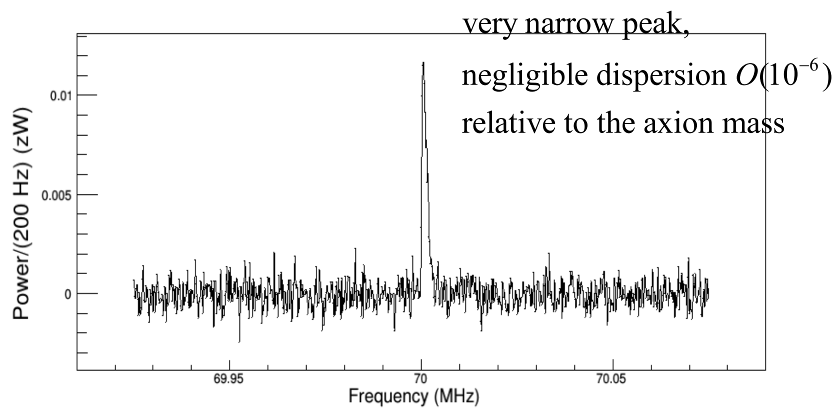
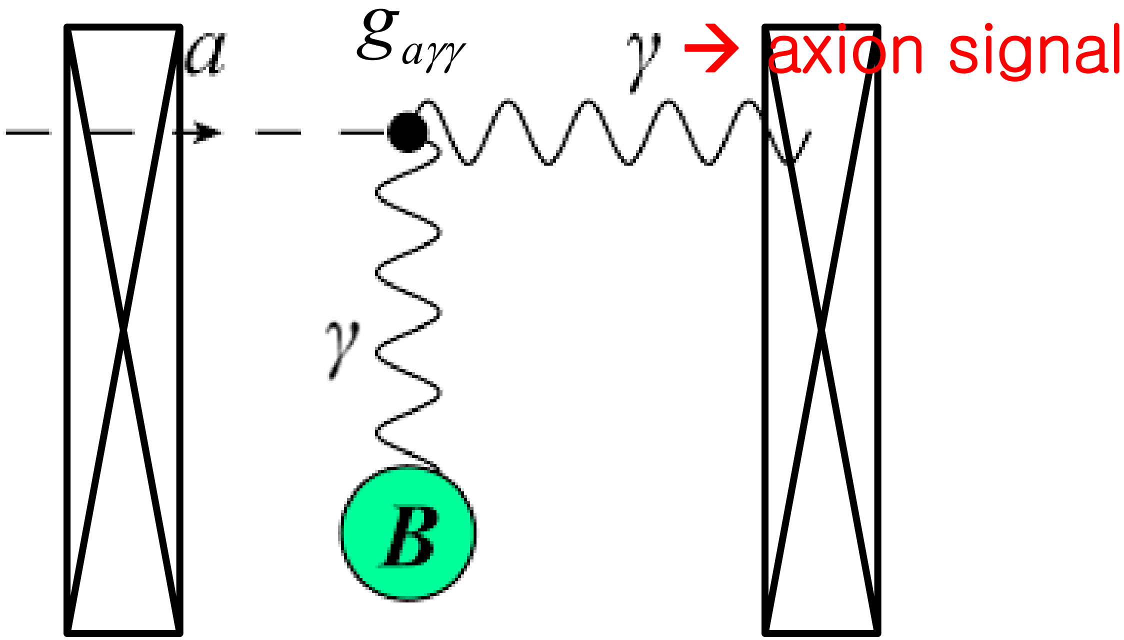


Axion detection

- use axion-photon conversion @ B-field



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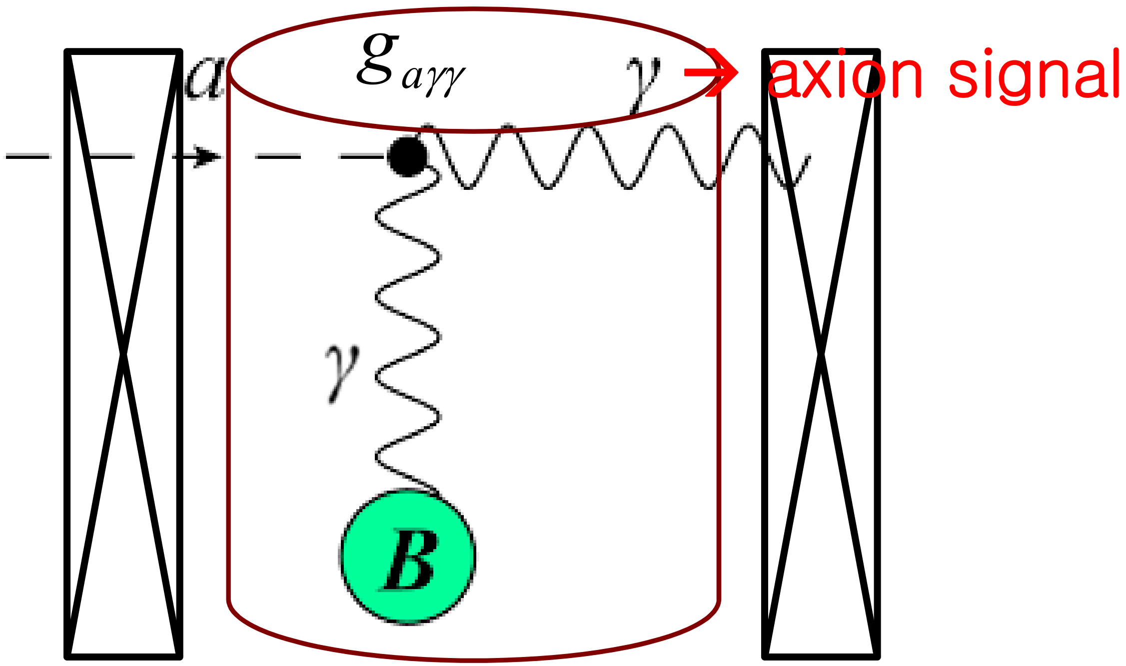
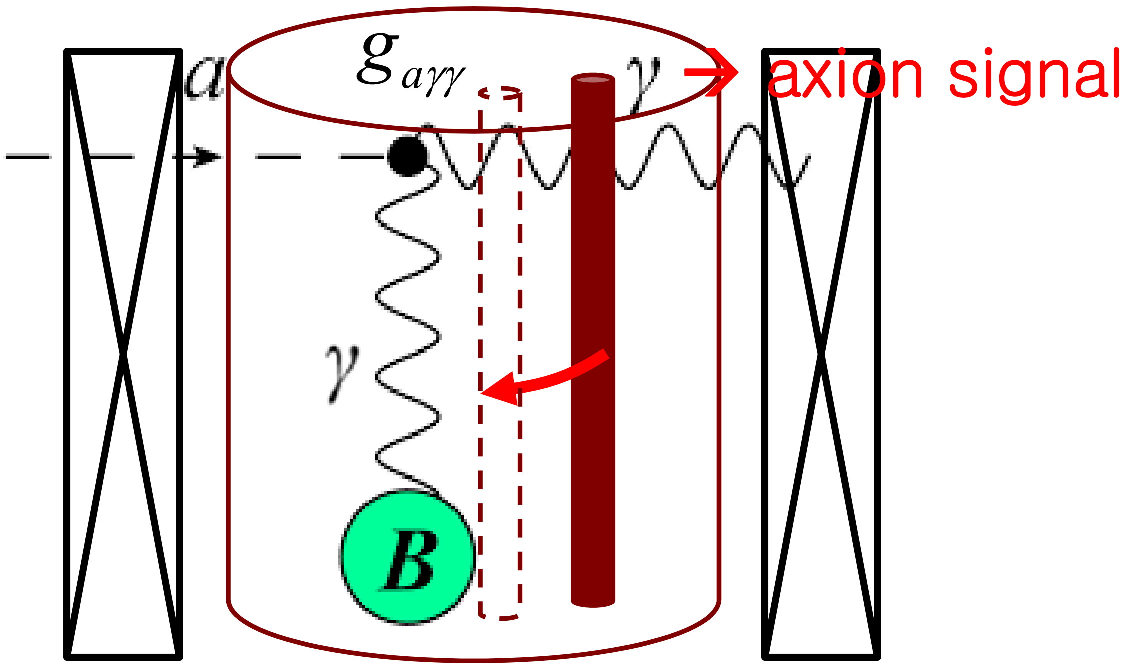


- use axion–photon conversion @ B–field
- resonant conversion with a cavity

Axion detection

- $P_a^{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B^2 V \omega_{TM_{010}} Q_{cavity} a^2 / \mu_0$



- use axion–photon conversion @ B-field
- resonant conversion with a cavity
- frequency tuning with a tuning rod due to unknown axion mass and the resonant conversion

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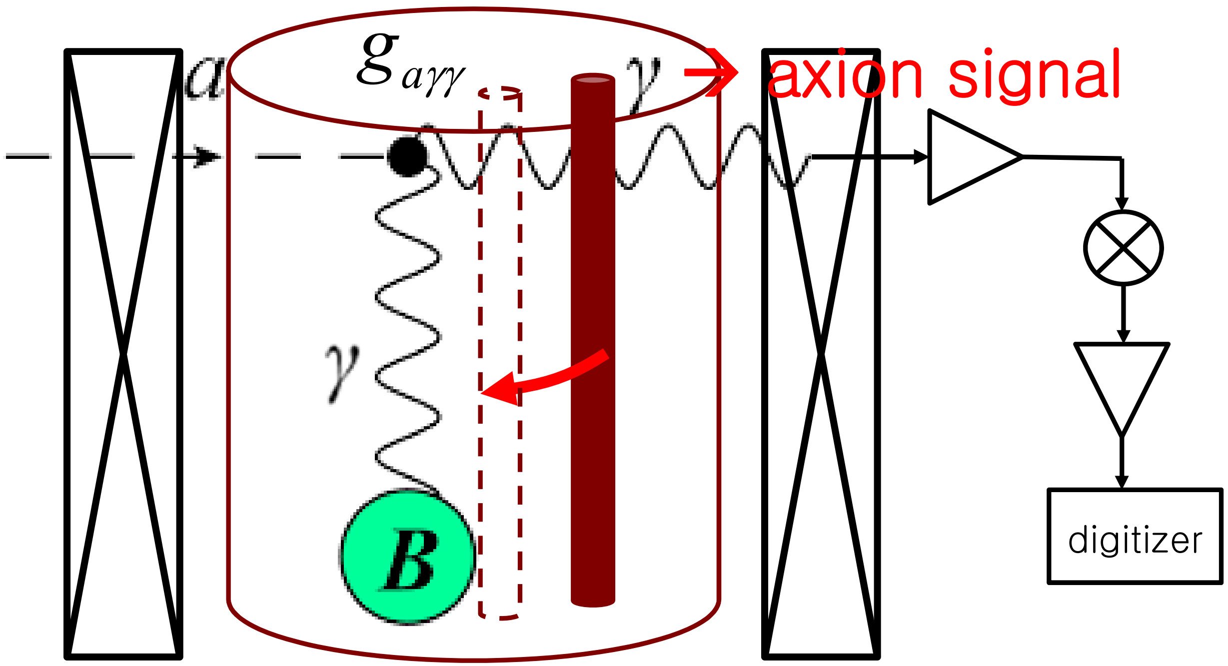
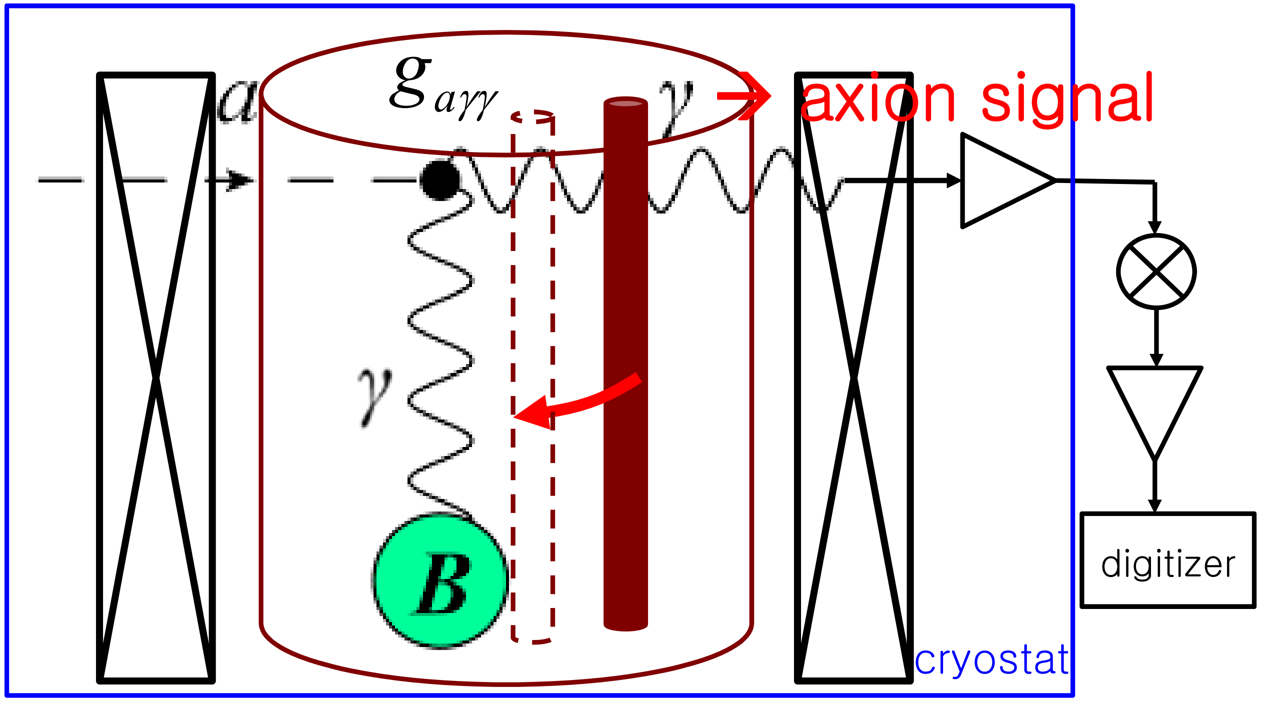


- use axion−photon conversion @ B−field
- resonant conversion with a cavity
- frequency tuning with a tuning rod due to unknown axion mass and the resonant conversion
- typical heterodyne receiver
- signal processing with a fast digitizer

Axion detection

- $P_a^{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B^2 V \omega_{TM_{010}} Q_{cavity} a^2 / \mu_0$ $\Rightarrow SNR = \dfrac{P_a^{a\gamma\gamma}}{\sigma_{P_{noise}}}$

$P_{noise} = k_B \Delta f T_{sys}$, $T_{sys} = T_{cavity} + T_{chain}$



- use axion-photon conversion @ B-field
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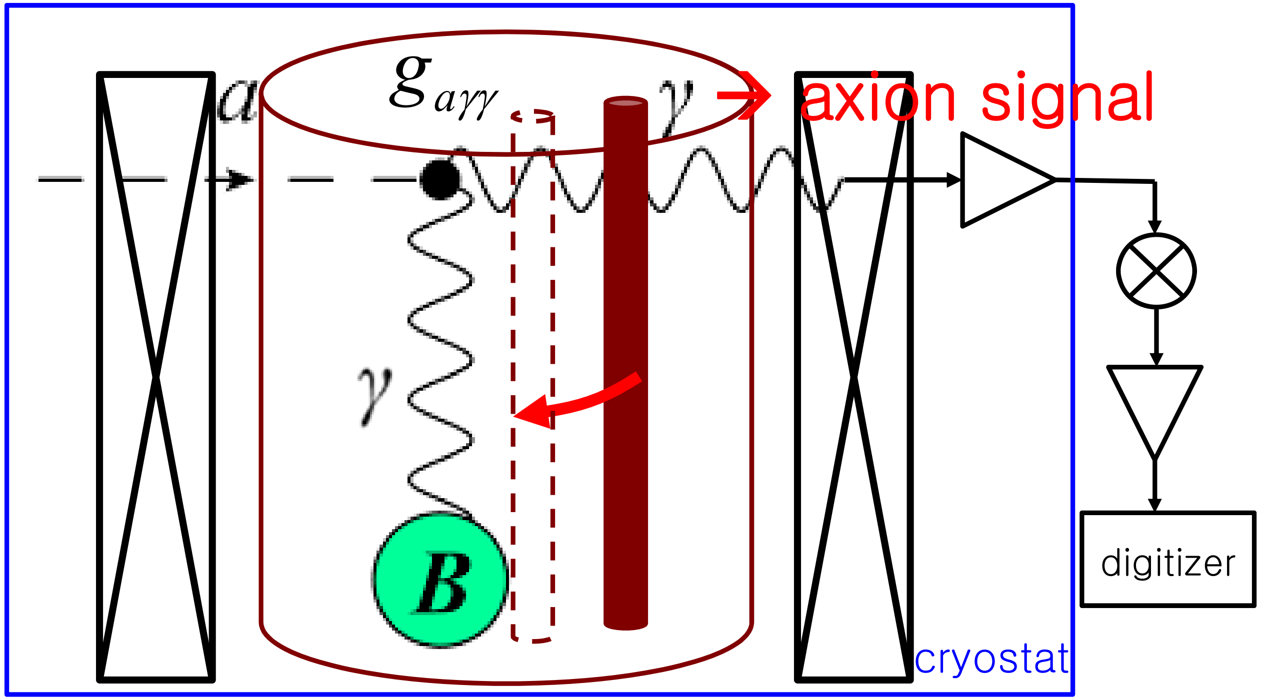
- cryogenic to suppress the noise temperature from the cavity and receiver chain

Axion detection

- $P_a^{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B^2 V \omega_{TM_{010}} Q_{cavity} a^2 / \mu_0$ $\Rightarrow$ scanning rate $\frac{d\nu_{TM_{010}}}{dt} \propto \frac{g_{a\gamma\gamma}^4 B^4 V^2 Q_{cavity} a^4}{T_{noise}^2}$ $\rightarrow$ Figure of merit

$$P_{noise} = k_B \Delta f T_{sys}, \; T_{sys} = T_{cavity} + T_{chain}$$



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Axion dark matter detection

- $P_a^{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B^2 V \omega_{TM_{010}} Q_{cavity} a^2 / \mu_0$

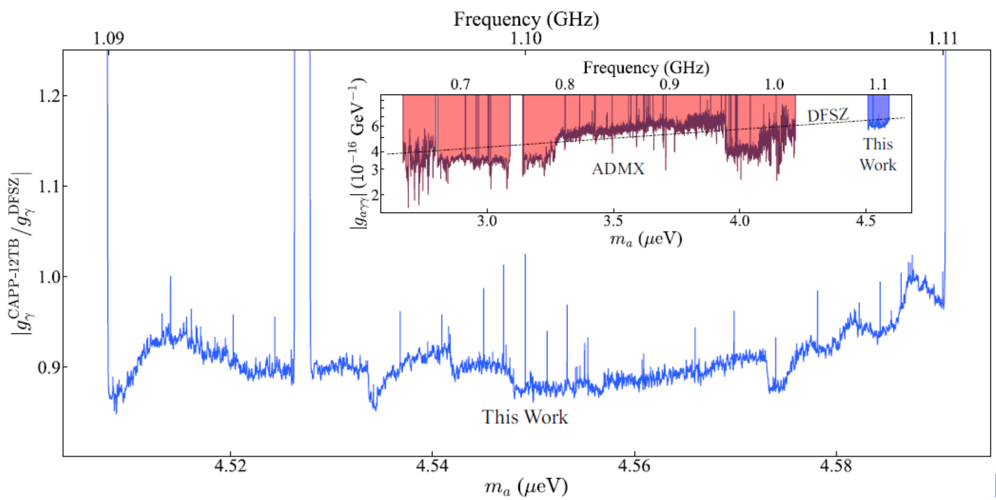
$[a^2] = \frac{\text{kg}}{\text{s}} \rightarrow a^2 = \frac{\rho_a \hbar^2}{m_a^2 c}$ in SI units,

ρ_a (local dark matter density) = 0.3 ~ 0.45 GeV/cc in natural units

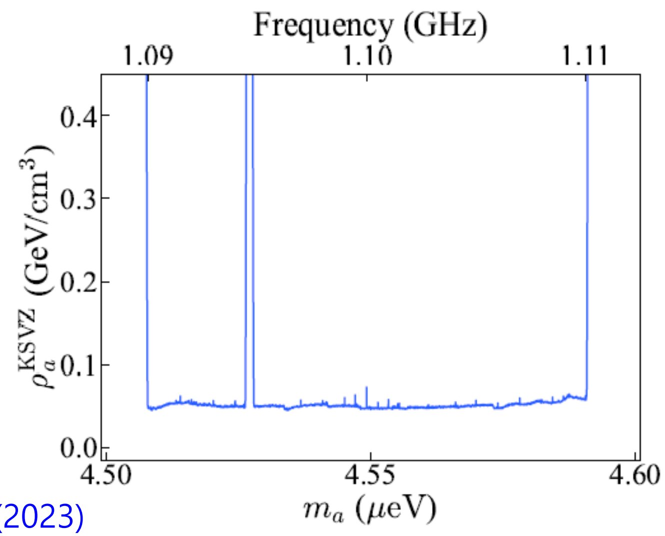
$P_a^{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B^2 V \omega_{TM_{010}} Q_{cavity} \frac{\rho_a}{m_a^2} \rightarrow$ axion signal depends on the local dark matter density ρ_a as well as $g_{a\gamma\gamma}$

for a given ρ_a,

$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$



for a given $g_{a\gamma\gamma}^{KSVZ}$



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Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme

Magnet

•scanning rate $\frac{d\nu_{TM_{010}}}{dt} \propto \frac{B^4 V^2 Q_{cavity}}{T_{noise}^2} \rightarrow$ Figure of merit

Superconductor magnet from Oxford Instruments (OI)

Magnet parameters	Values
Central field	12 T@4.2 K
Magnet bore	320 mm
Operating current	266 A
Inductance	161 H
Stored energy	5.7 MJ

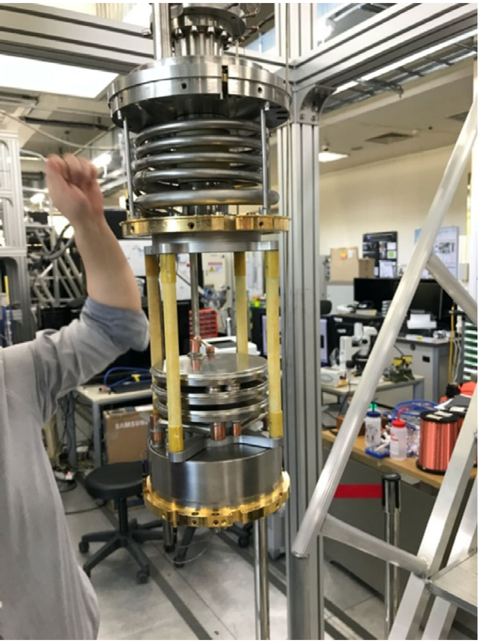
300,000 times stronger than the geomagnetic field there
→ ~8x10^{21} for the scanning rate

Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme

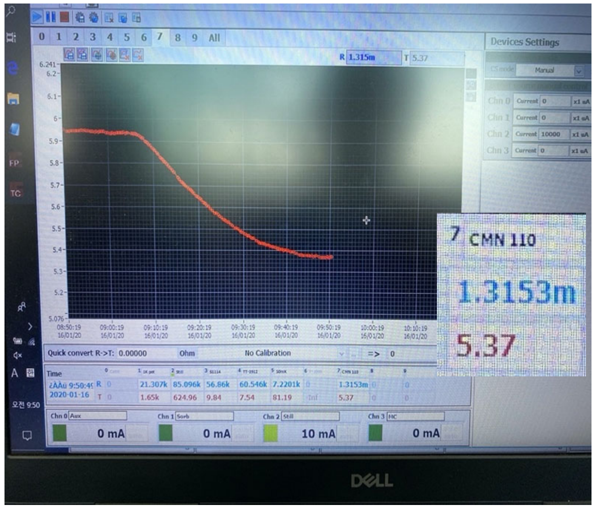
Fridge

•scanning rate $\frac{d\nu_{TM_{010}}}{dt} \propto \frac{B^4 V^2 Q_{cavity}}{T_{noise}^2} \rightarrow$ Figure of merit $\quad T_{noise} = T_{cavity} + T_{chain}$

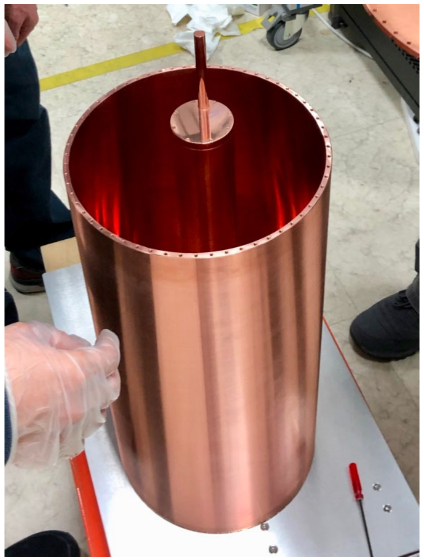
Dilution fridge from Leiden Cryogenic B.V.



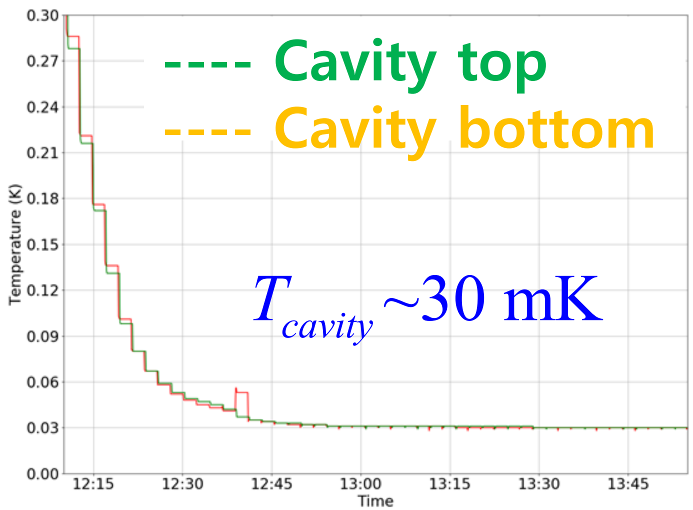
dilution insert unit



- base temperature 5.4 mK without load
- cooling power measured to be 1 mW at 90 mK



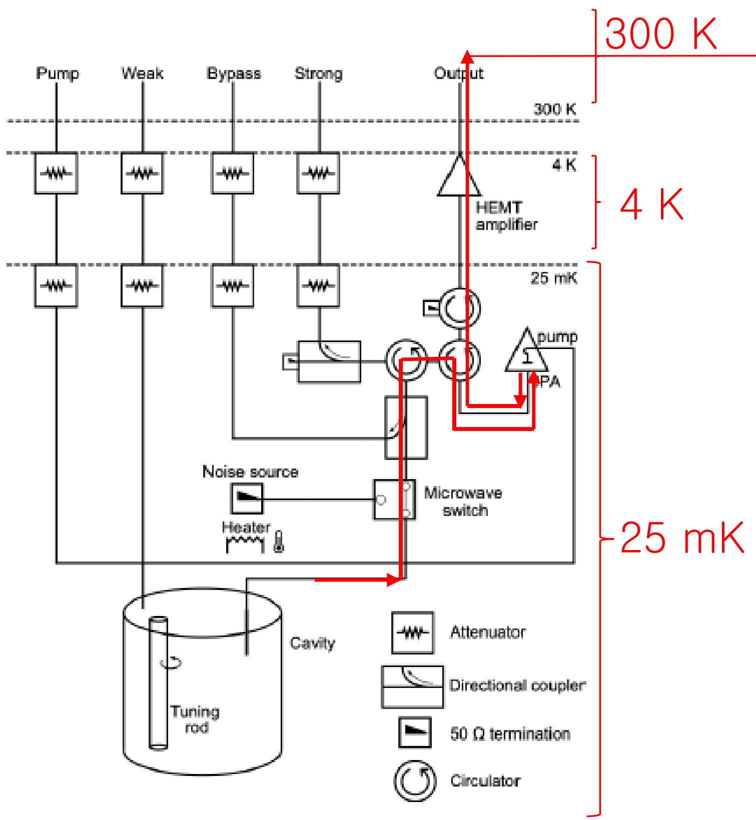
~55 kg

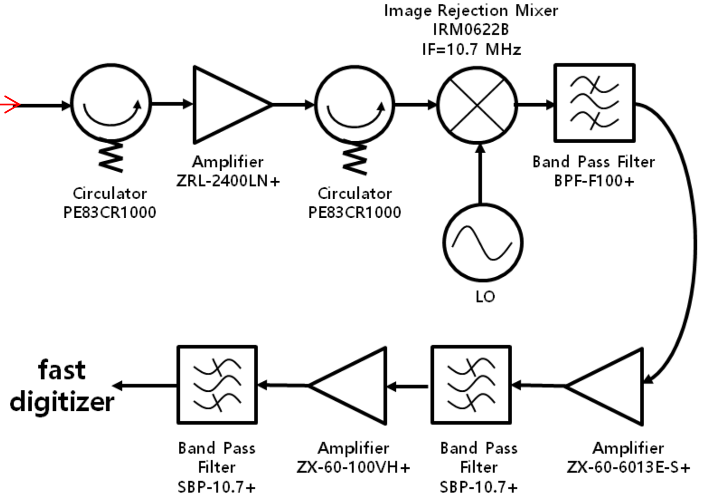


Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme

Readout electronics

- scanning rate $\frac{d\nu_{TM_{010}}}{dt} \propto \frac{B^4 V^2 Q_{cavity}}{T_{noise}^2} \rightarrow$ Figure of merit $\quad T_{noise} = T_{cavity} + T_{chain}$





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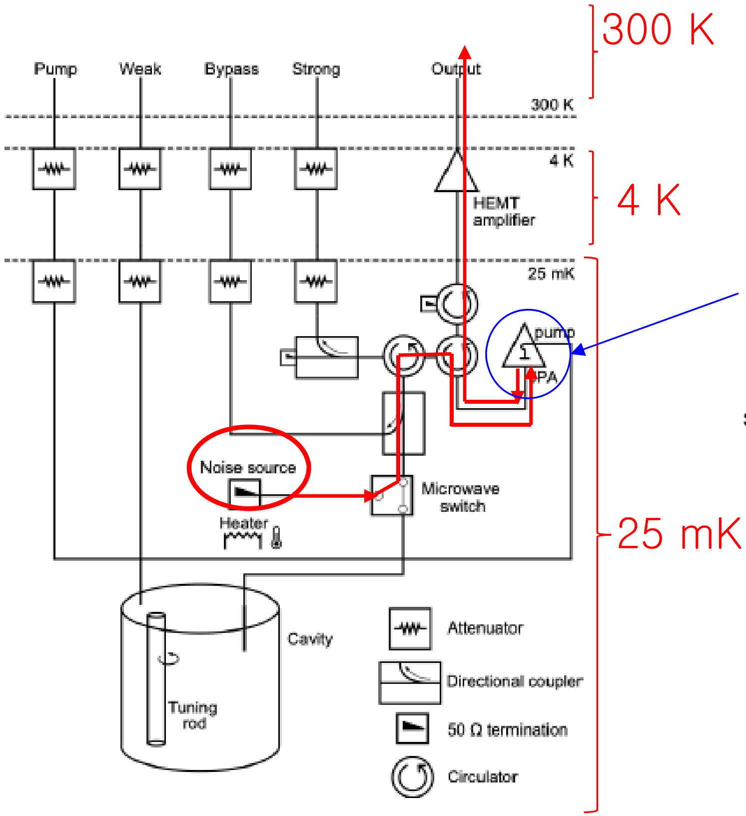
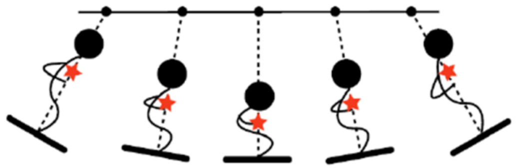
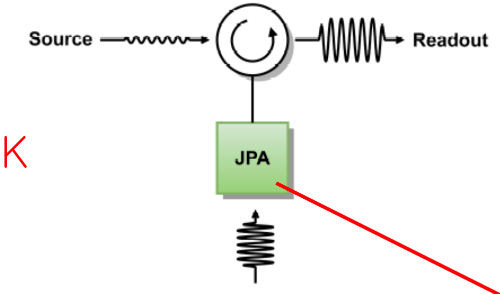
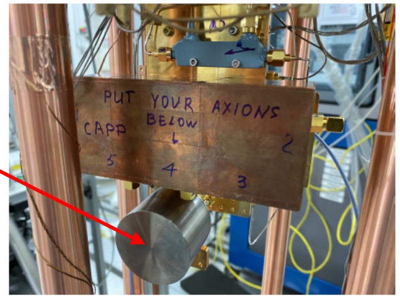


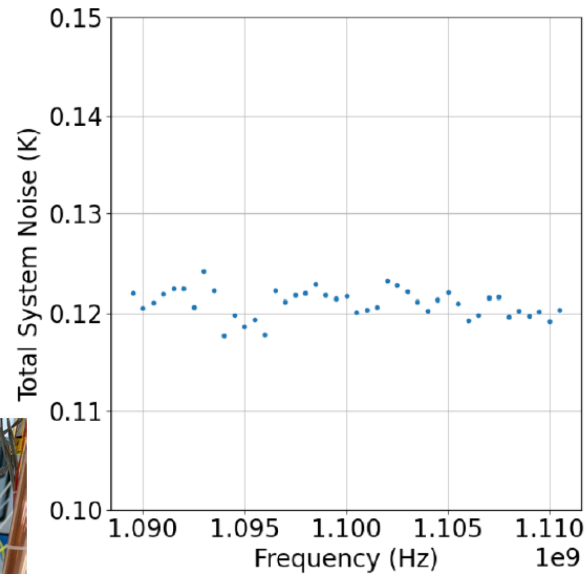


Josephson Parametric Amplifier (JPA)



periodic standing and squatting

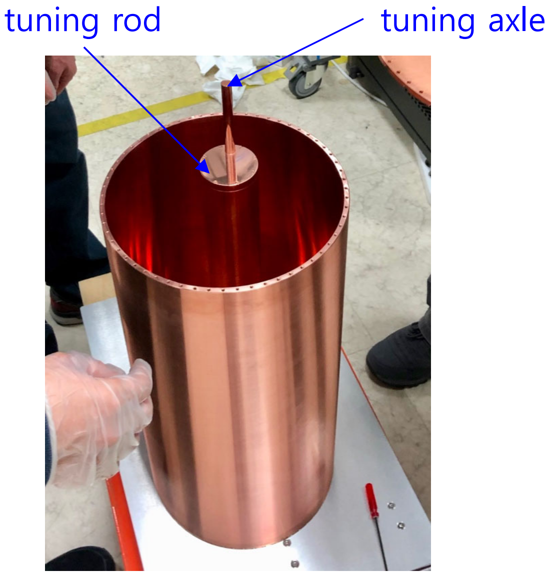




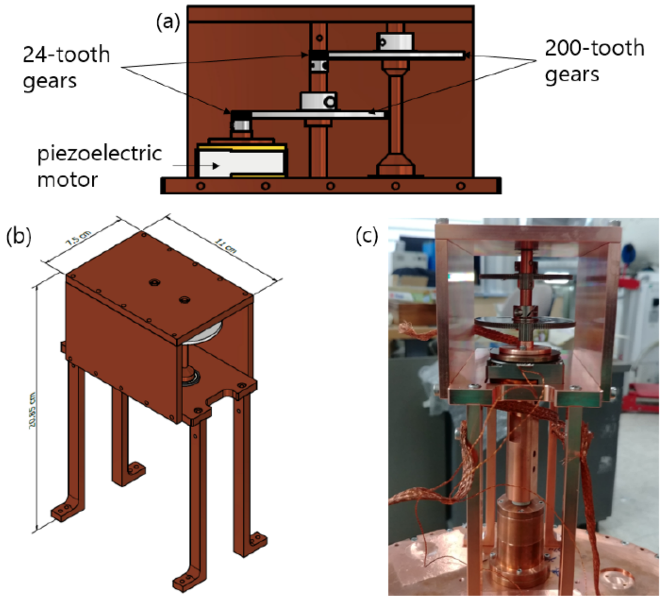
Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme

Tunable microwave cavity

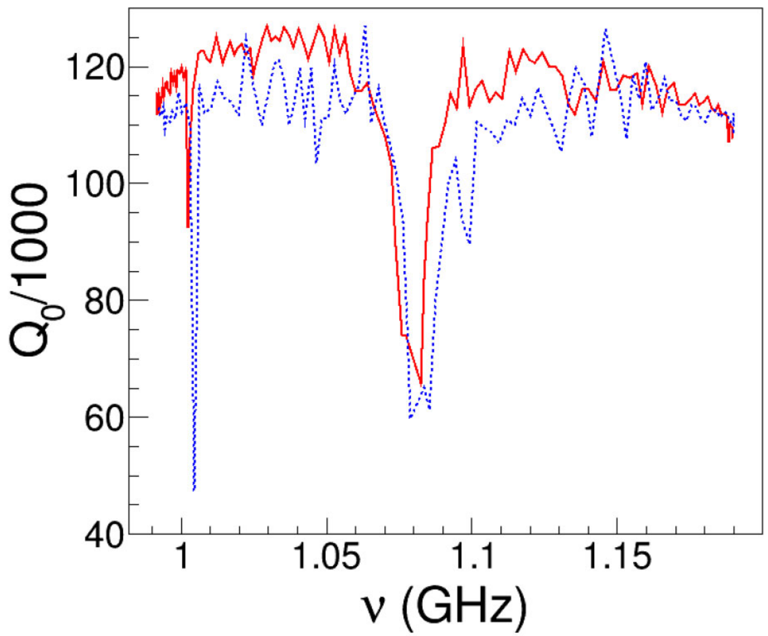
•scanning rate $\frac{d\nu_{TM_{010}}}{dt} \propto \frac{B^4 V^2 Q_{cavity}}{T^2_{noise}} \rightarrow$ Figure of merit



OFHC copper
ID=262 mm, h=560 mm
tunable TM_{010} using
the tuning rod (OD=64 mm)
1.0~1.2 GHz



tuning mechanism by
piezo and gear combination
reduction ratio 69.4:1

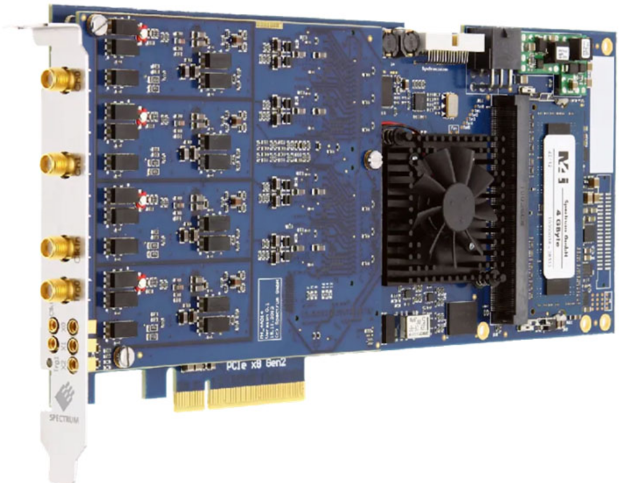


Q measurement at ~4 K

Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme
fast DAQ

- scanning rate $\frac{d\nu_{TM_{010}}}{dt} \propto \varepsilon_{DAQ} \frac{B^4 V^2 Q_{cavity}}{T^2_{noise}} \rightarrow$ Figure of merit

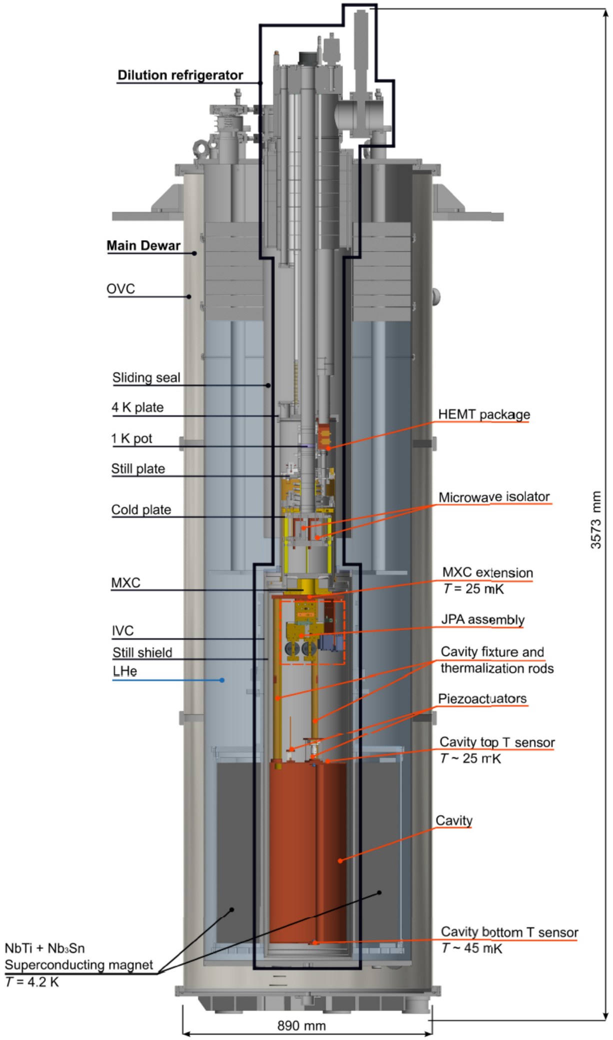
commercial spectrum analyzer
provides online FFT → easy to use
DAQ efficiency at best ~47%

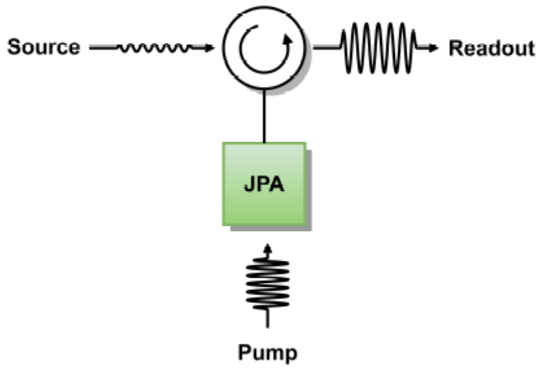


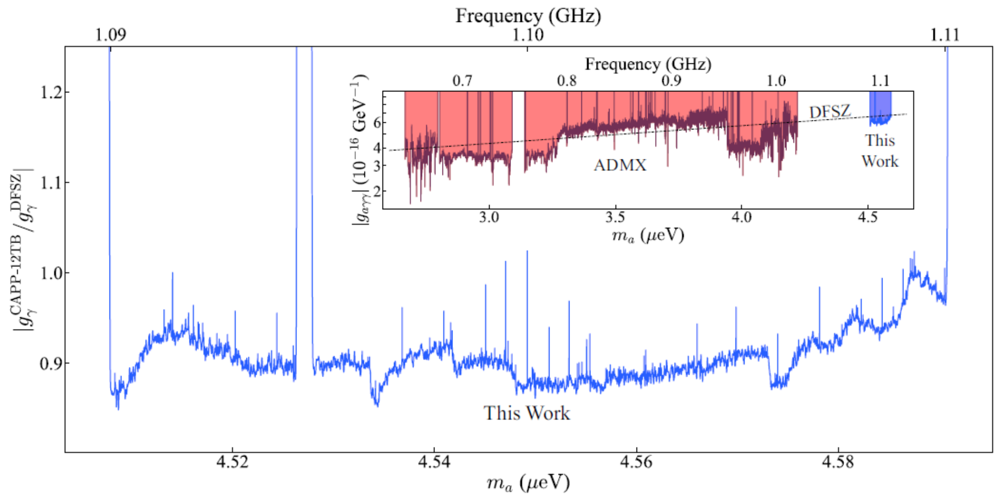
using a fast digitizer,
developed a novel algorithm for online FFT
→ realized a DAQ efficiency of ~100%
(2022 JINST 17 P05025)

This is huge because you can finish your experiment twice faster.

Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme
put it together







Scan 20 MHz in 18 days
Rate > 1 MHz/day maintaining DFSZ sensitivity
→ best scanning rate ever

2nd experiment sensitive to DFSZ axions followed by ADMX (Axion Dark Matter eXperiment) at U. of Washington

PRL **130**, 071002 (2023),
assuming axions make up 100% of the local dark matter density

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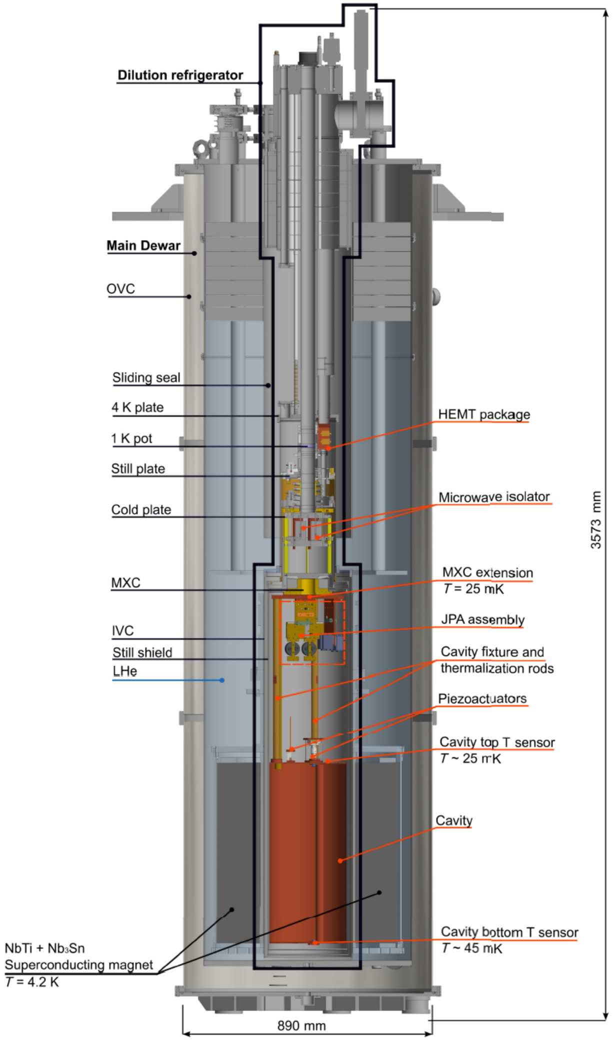
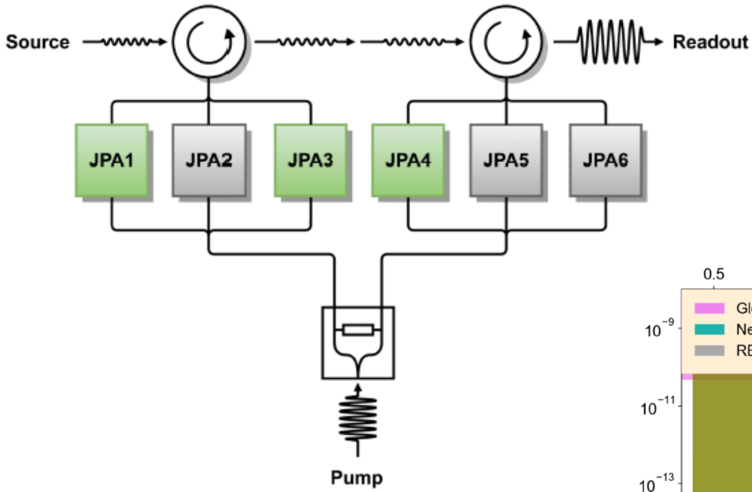
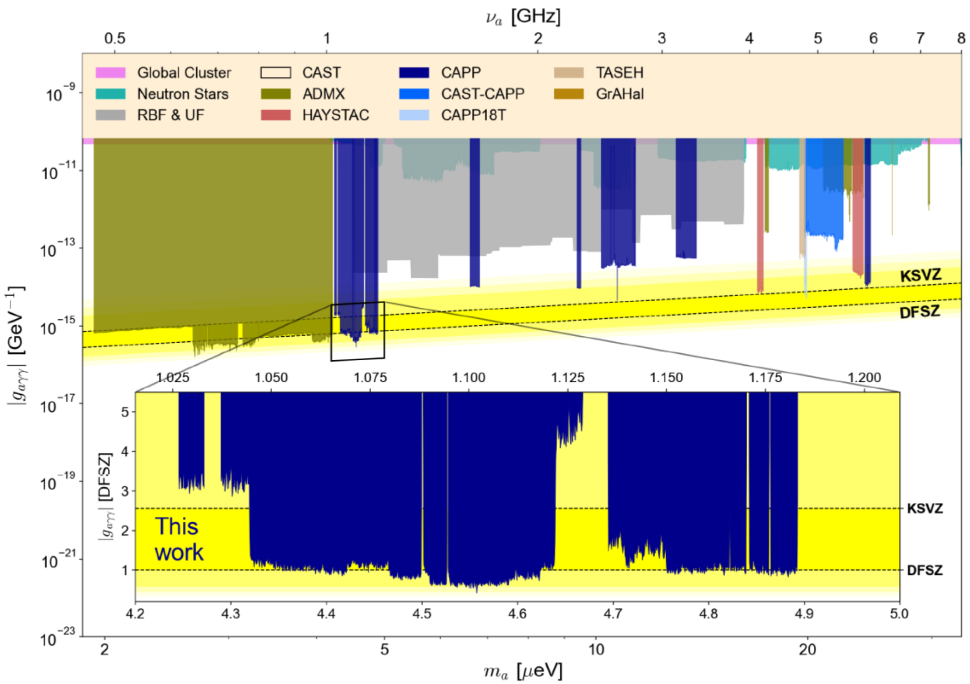
Axion experiment at IBS-CAPP—pushing the experimental parameters to extreme
put it together



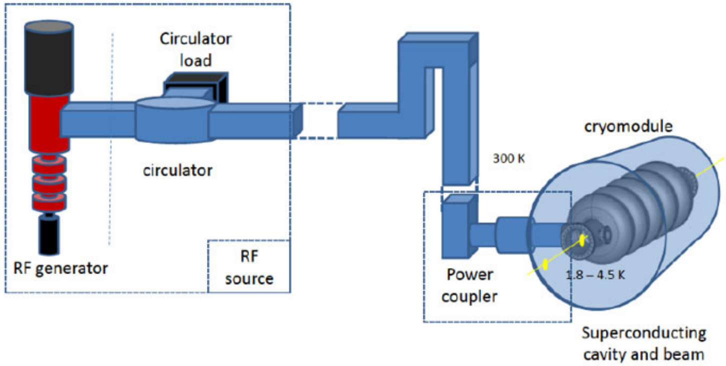


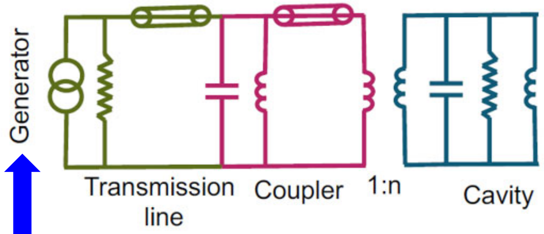
Scan > 100 MHz
Very non-trivial



PRX **14**, 031023 (2024),
assuming axions make up 100% of the local dark matter density

Summary





axion dark matter halo

$g_{a\gamma\gamma}$

cavity mode

$E_a^{a\gamma\gamma}$

accelerating gradient

$E_{acc} \propto \sqrt{Q_{cavity}}$

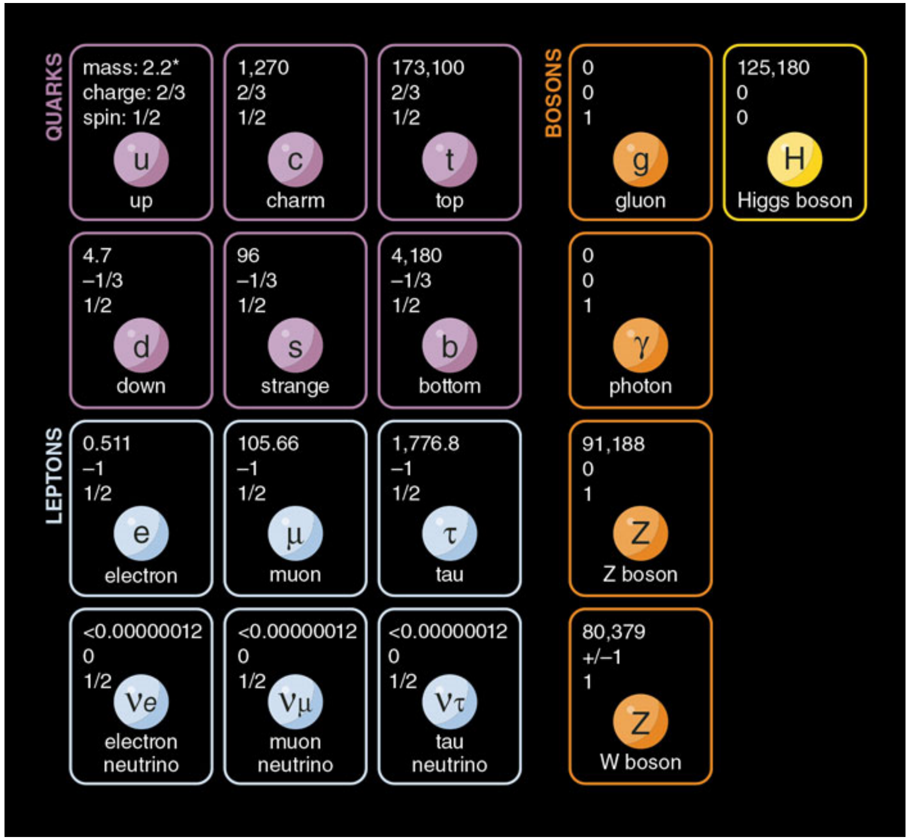
axion signal power

$P_a^{a\gamma\gamma} \propto Q_{cavity}$

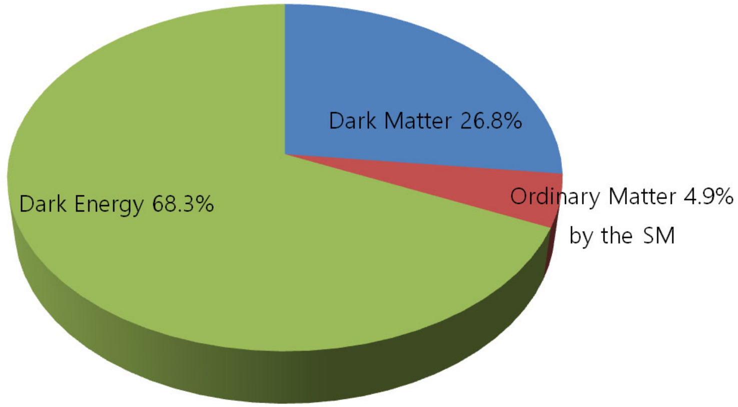
$\rightarrow E_a^{a\gamma\gamma} \propto \sqrt{Q_{cavity}}$

if $m_a = \nu_{cavity}$

Summary

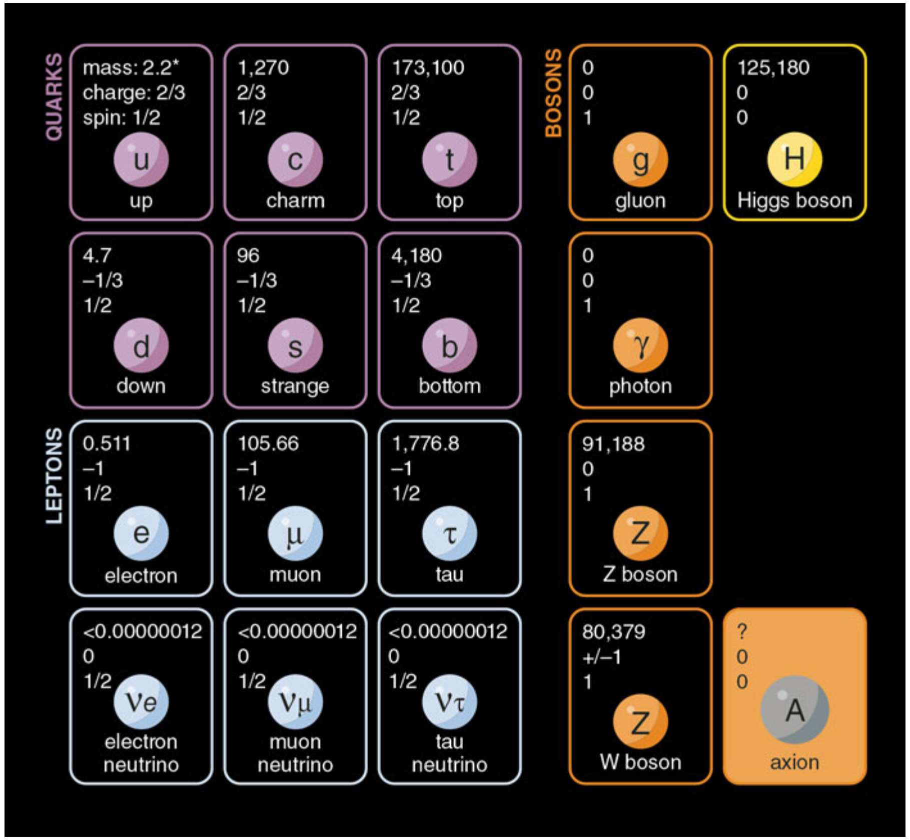


Energy budget of the Universe

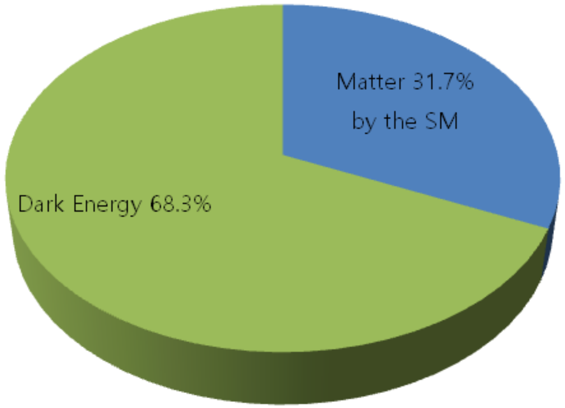


- SM governs ~5% of the Universe

Summary



Energy budget of the Universe



- We govern all matter (~32% of the Universe) together with axion dark matter

→ promotion of the SM ?

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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Magnet details

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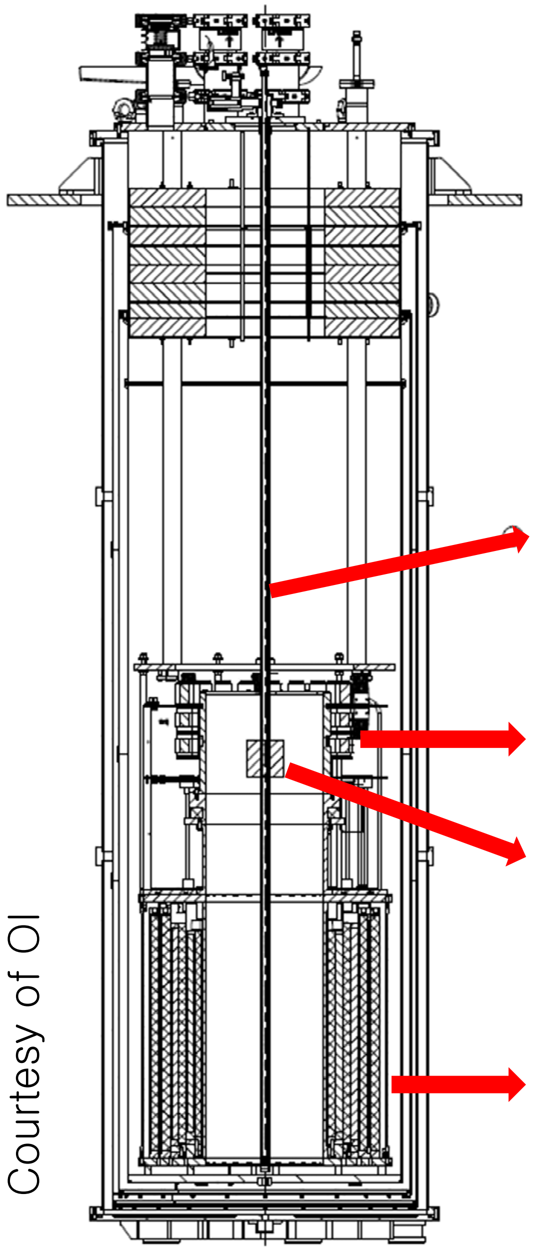
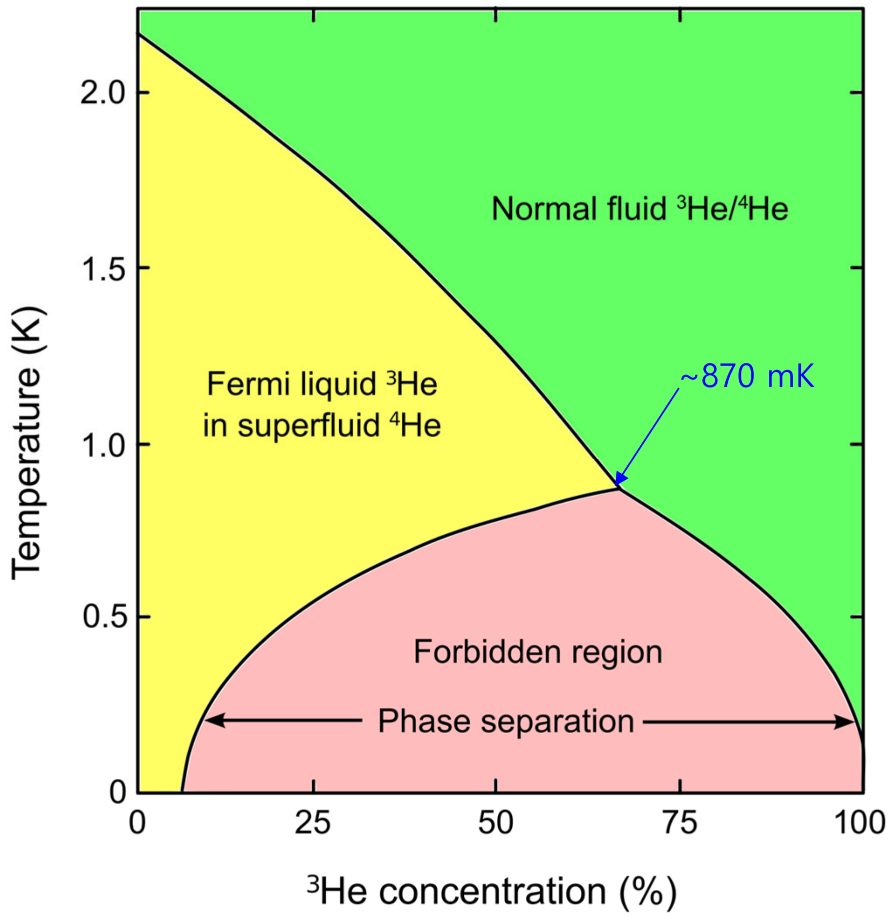


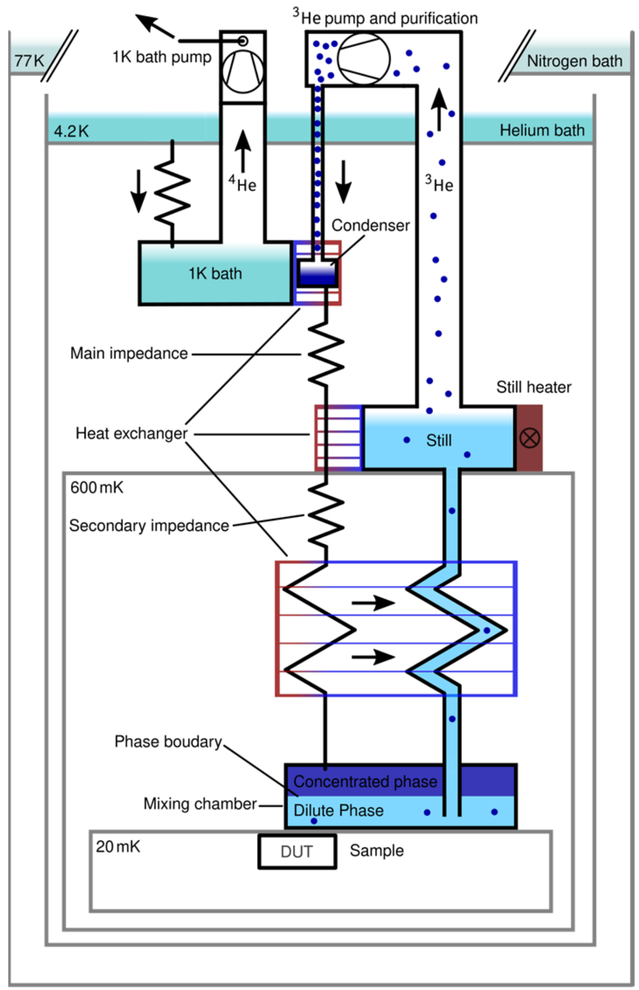
Hall probes for the factory test

cancellation coil : NbTi only

cancellation region : <100 G
over 100 mm (D) x100 mm (h)

main coil : nested coils
with Nb_3Sn (600mm, inner) and
NbTi (800mm, outer)





^{3}He is diluted from the concentrated phase to the diluted phase through the phase boundary

Haus-Caves theorem

$$V(t) = V_0\left(\hat{X}_1(t)\cos\omega_0 t + \hat{X}_2(t)\sin\omega_0 t\right)$$

quadratures $\hat{X}_1 = \frac{1}{2}\left(\hat{a} + \hat{a}^\dagger\right)$ and $\hat{X}_2 = \frac{1}{2}\left(\hat{a} - \hat{a}^\dagger\right)$

$\left[\hat{X}_1, \hat{X}_2\right] = \frac{i}{2}$ and $\left[\hat{a}, \hat{a}^\dagger\right] = 1$

$$\hat{Y}_1 = \sqrt{G_1}\hat{X}_1 + \hat{F}_1$$

$$\hat{Y}_2 = \sqrt{G_1}\hat{X}_2 + \hat{F}_2$$

$$\left[\hat{F}_1, \hat{F}_2\right][] = \frac{i}{2}\left(1 - \sqrt{G_1 G_2}\right) = \frac{i}{2}(1 - G)$$

$$A_N = \frac{1}{2}\left|1 \mp \frac{1}{G}\right|$$

Axion quality problem

Quantum-gravity effects at the Planck scale spoil the PQ solution to the strong CP problem