Axion Dark Matter eXperiment

A challenging attempt to reveal light, exotic particles

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Low Energy Seminar

Experimental Physics PhD (*Cycle XXXVI*)

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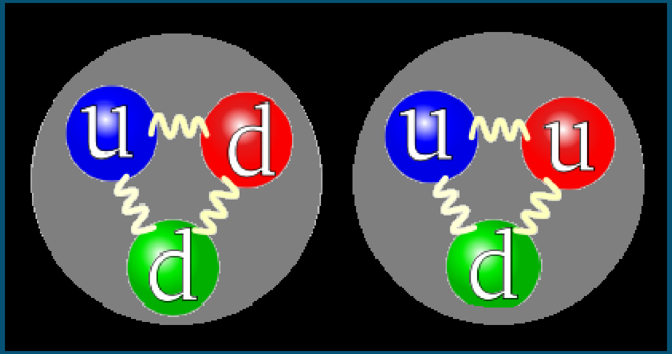
DI SIENA
1240

CONTENTS

THE STRONG CP PROBLEM

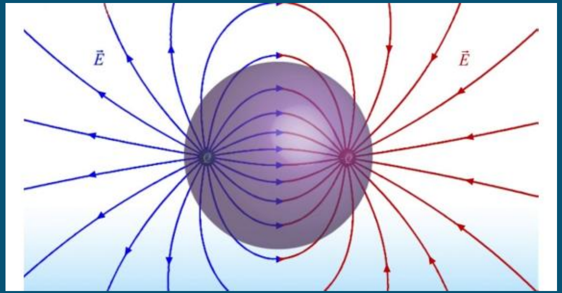


https://outrasverdadesinconvenientes.blogspot.com

QCD := Quantum Chromo Dynamics

Interactions between quarks making up hadrons (mediated by "gluons")

The fundamental *Strong Interaction* should show a violation of Charge/Parity simmetry, e.g. causing the neutron to still exhibit a dipole-like electric field…but no such detection!



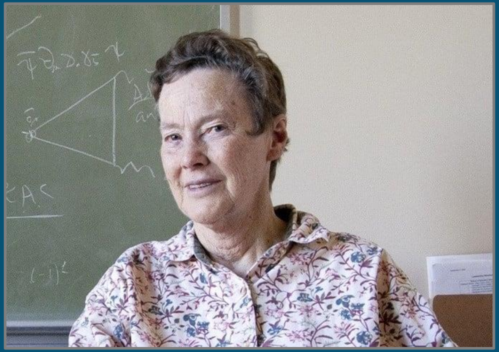
https://limetool.blogspot.com

POSSIBLE HINTS...?

R. Peccei & H. Quinn (1977)

https://newsroom.ucla.edu

https://www.donnesulweb.it



$$\mathcal{L}_{\mathrm{QCD}} = \overline{\psi}_{\mathrm{i}} \left(i \left(\gamma^{\mu} D_{\mu} \right)_{\mathrm{ij}} - m\, \delta_{\mathrm{ij}} \right) \psi_{\mathrm{j}} - \frac{1}{4} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha} - \theta \frac{g^2}{32\pi^2} G^{\alpha}_{\mu\nu} G^{\alpha\mu\nu}$$

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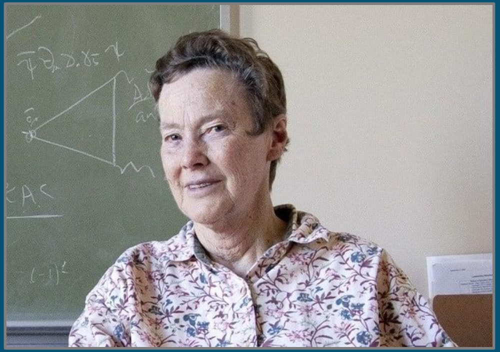
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This constant is practically 0...

What about a space-time variable, tending to a null value in order to reach the lowest E configuration?

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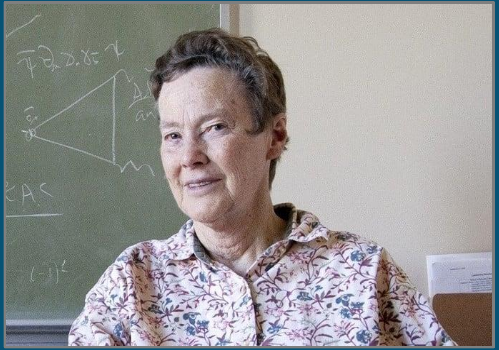

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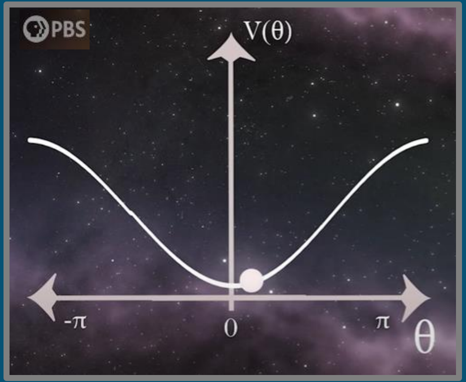
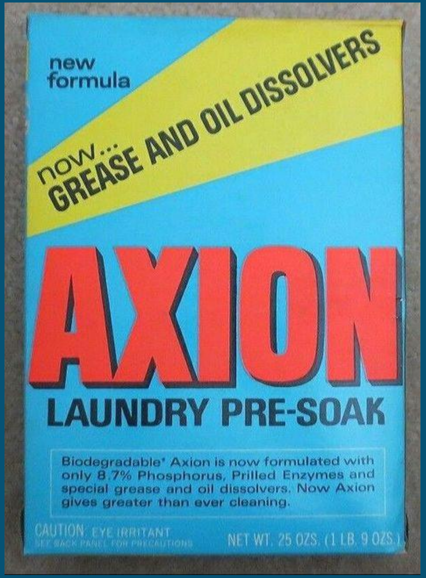


https://youtube.com/watch?v=e7yXqF32Yvw

Oscillations around that position give rise to a new field!

AN EFFECTIVE SOLUTION...AXION!

BUY NOW!



BUY NOW

F. Wilczek and S. Weinberg independently proposed a quantized nature for the hypothetical field; properties of the correspondent **Axion** (A^0) particle:

- No electric charge
- No quantum spin
- Non-relativistic
- Extremely light ($1 \div 100\ \mu\text{eV} \longleftrightarrow \simeq 10^{-10}\, m_e$)
- Very faint interaction via strong/weak/gravity force
- Highly stable

PERFECT EXOTIC CANDIDATE

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Axions are promising particles…likely produced in prodigious quantity in the early Universe, they could explain all the *Dark Matter* amount!

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Stellar remnants?

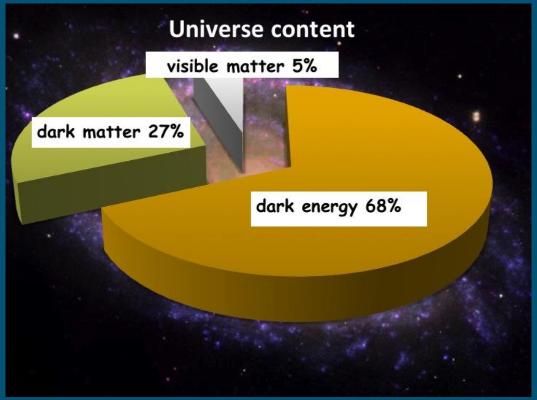
WIMPs (SUSY)? Axions?

"Sterile" neutrinos?

Kaluza-Klein States?

Planets?

Superheavy particles?



http://www.astronomycafe.net

Visible "standard" matter is only a small fraction of the total (from galaxy rotation curves, CMB, cluster dynamics, gravitational lensing…)

?

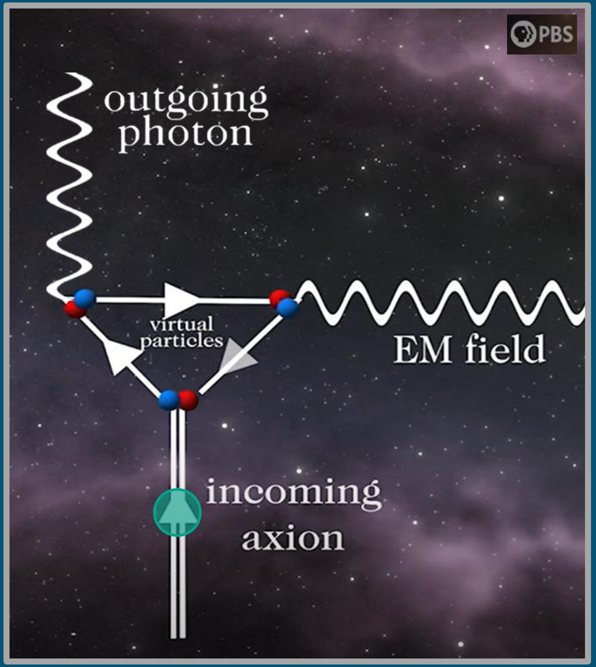
BUT…HOW TO DETECT?

Axions would be extremely elusive, and practically impossible to be seen…
However, a way does exist!

Primakoff Effect

Axions can interact with e.m. field (virtual photons) via the strong force, producing a pair of virtual quarks which decay into photons

The process is reversible!

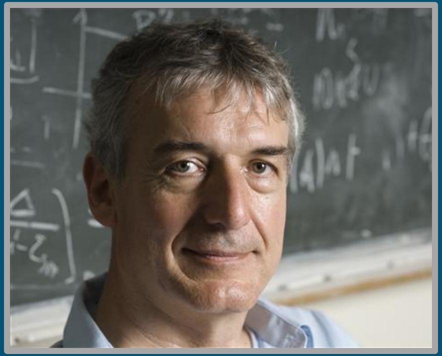


KSVZ Model
Kim-Shifman-Vainshtein-Zakharov
(hadrons, $g_{a\gamma\gamma} \approx 0.97$)

DFSZ Model
Dine-Fischler-Srednicki-Zhitnitsky
(hadrons+leptons, $g_{a\gamma\gamma} \approx 0.36$)

HALOSCOPE TECHNIQUE

https://cds.cern.ch

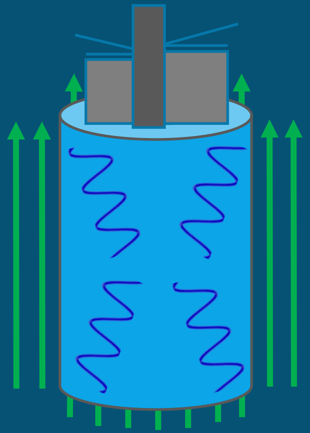


In 1983, theoretical physicist Pierre Sikivie paved the way to a concrete detection method, i.e., the ***axion haloscope***

(*P. Sikivie, Phys. Rev. Lett., 1983*)

Typically:

A *resonant cavity* immersed in a *strong magnetic field*



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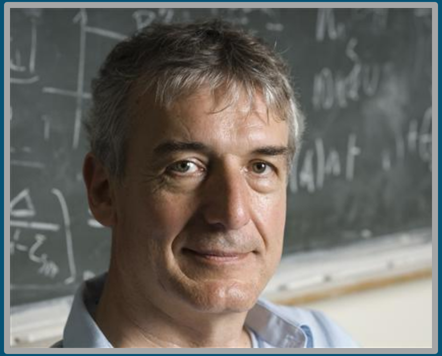

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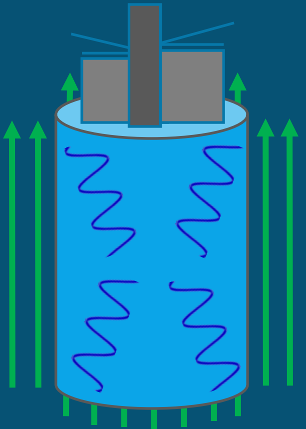

A resonant cavity immersed in a strong magnetic field

E.m. waves at certain frequencies are confined inside the enclosure (~ with no amplitude losses), "filter effect"

High enough density of virtual photons provided to trigger the axion-photon conversion

If $\nu_{res} = \nu_{pht}$ → enhanced process, and photons produced visible as power excess

ADMX

Axion Dark Matter eXperiment

- Center for Experimental Nuclear Physics and Astrophysics (CENPA), University of Washington, Seattle (47° N, 122° W), U.S.A.
- Haloscope searching for axions in the 2.66 ÷ 3.31 μeV range
- Microwave resonance (≈ 600 ÷ 900 MHz)
- State-of-the-art Quantum amplifiers + Dilution refrigerator ensuring ultra low noise

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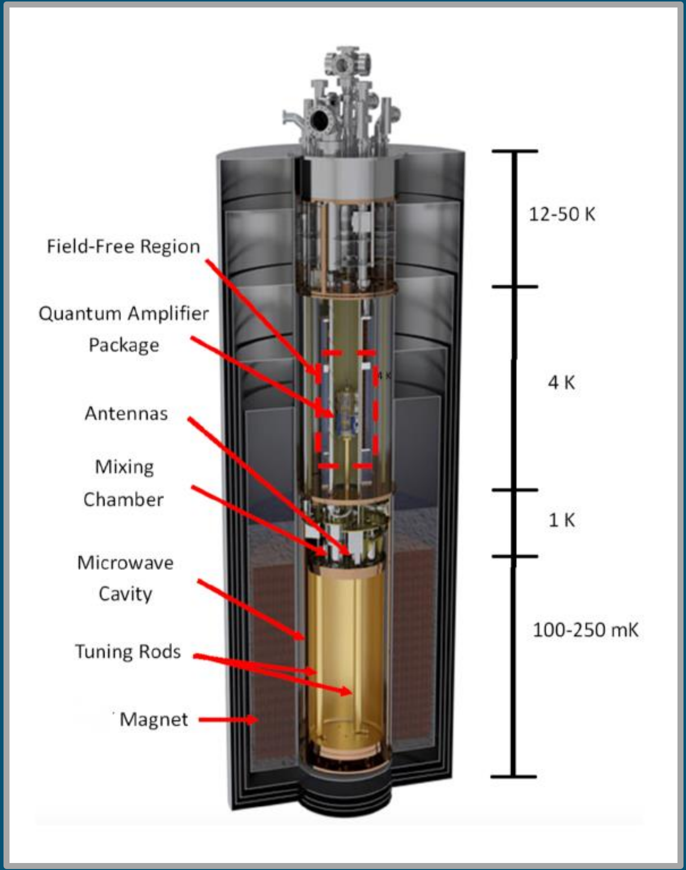
➡ ...no underground location, and unprecedented sensitivity!

DETECTOR SKETCH

The "insert"

(D = 0.59 m, h = 3 m)



ADMX Collab., arXiv:2010.00169v1 [astro-ph.IM], 2020

DETECTOR SKETCH

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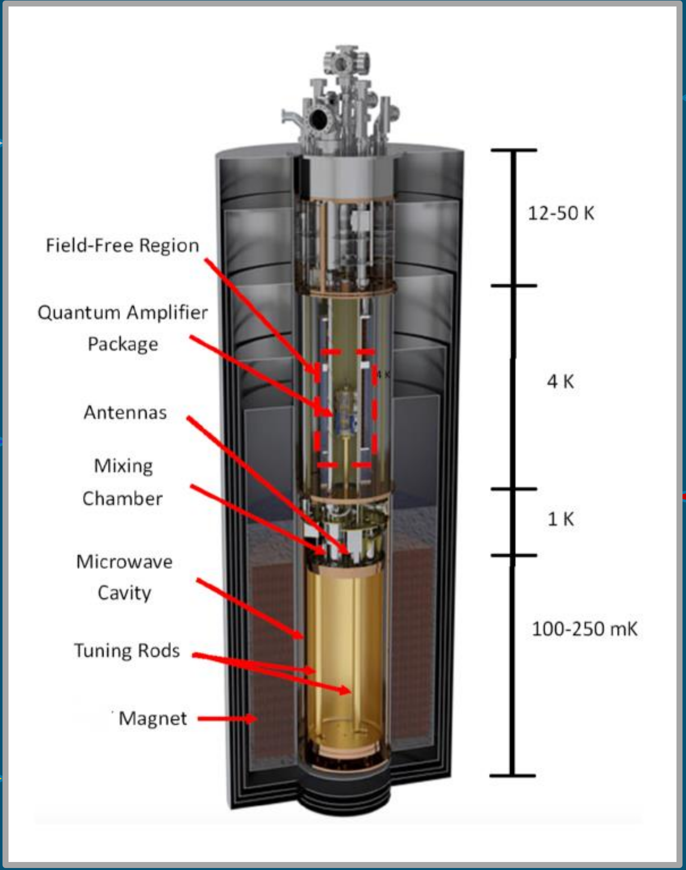
(D = 0.59 m, h = 3 m)

Variable depth antenna (semirigid, coaxial) transmitting axion signal to amplifiers

Dilution refrigerator as final cooling stage (^{3}He and ^{4}He circulation from dilute to gas phase, + mixture purification)

Copper-plated stainless steel OFHC cold microwave cavity (D = 0.4 m, h = 1 m) with two "tuning" rods (D = 0.05 m) through it for ν adjustment



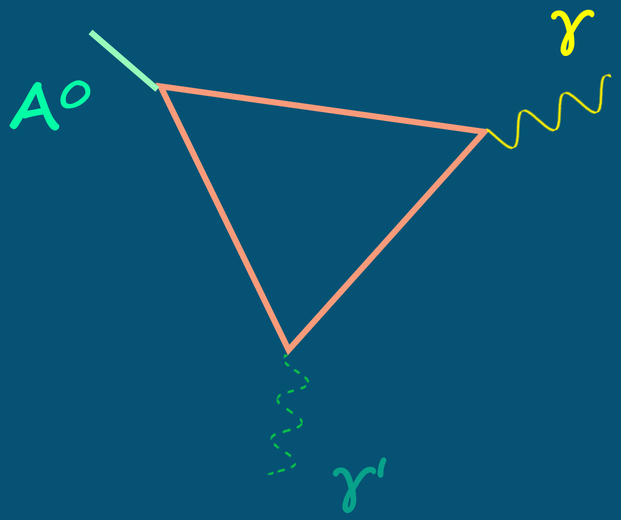
ADMX Collab., arXiv:2010.00169v1 [astro-ph.IM], 2020

Field-free region hosting the most delicate components, i.e., cryogenic RF electronics + quantum amplifier package (noise limited MSA/JPA amplifiers, circulators, couplers, switches, etc.)

Superconducting solenoid magnet ($\lesssim$ 8 T, for data-taking)

N.B.:
look at the T scale!

WORK FREQUENCIES



The strong magnetic field (γ') must be inhomogeneus to properly trigger the conversion process of an axion (A^0) into a microwave photon (γ) inside the cavity

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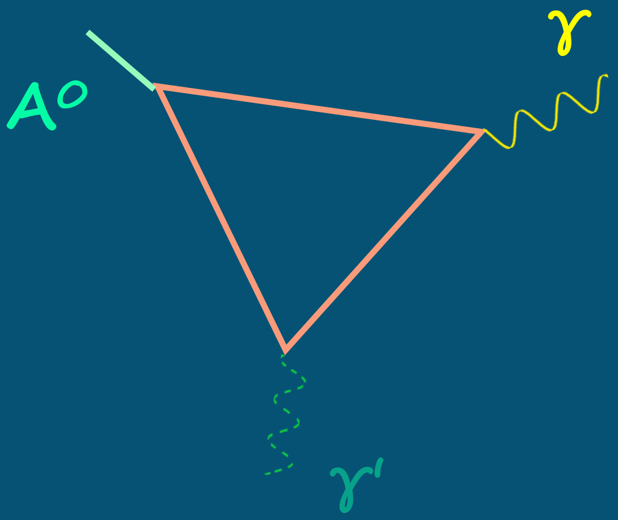

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Resultant photon frequency:

$$\boxed{\nu = \frac{E}{h}}$$

→ Axion $E_{tot} \approx$ rest mass (+ small E_{kin})

→ Planck constant ≈ $6.626 \cdot 10^{-34}$ J s

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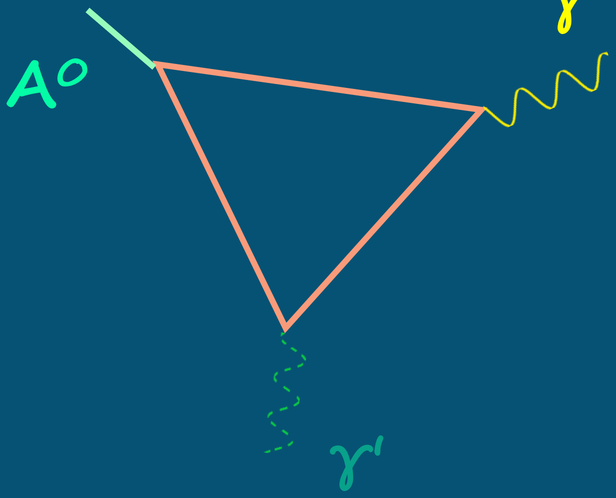

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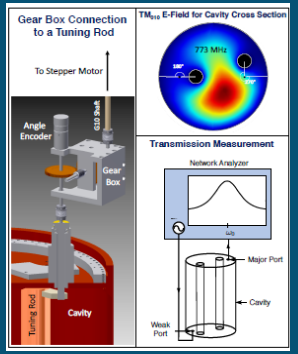
Micro-rad tuning of the rods (according to circles towards the cavity axis) allows geometry change, in order to match the resonance frequency to the axion one ➔ TM_{010} mode (optimal for ADMX "form factor")

↳ *Conversion rate significantly enhanced, up to detectable levels!*



ADMX Collab., arXiv, 2020

POWER FROM CONVERSION

What is the energy per unit time inside the cavity from the axion conversion?

$$\mathcal{P}_{\mathrm{A}\to\gamma} \approx 1.9\cdot 10^{-22}\,\mathrm{W}\left(\frac{V}{[136\,\mathrm{L}]}\right)\left(\frac{B}{[6.8\,\mathrm{T}]}\right)^{2}\left(\frac{C_{nlm}}{0.4}\right)\left(\frac{g_{\gamma}}{0.97}\right)^{2}\left(\frac{\rho_{\mathrm{A}}}{[0.45\,\mathrm{GeV/cm^{3}}]}\right)\left(\frac{\nu_{\mathrm{p}}}{[650\,\mathrm{MHz}]}\right)\left(\frac{Q}{50\,000}\right)$$

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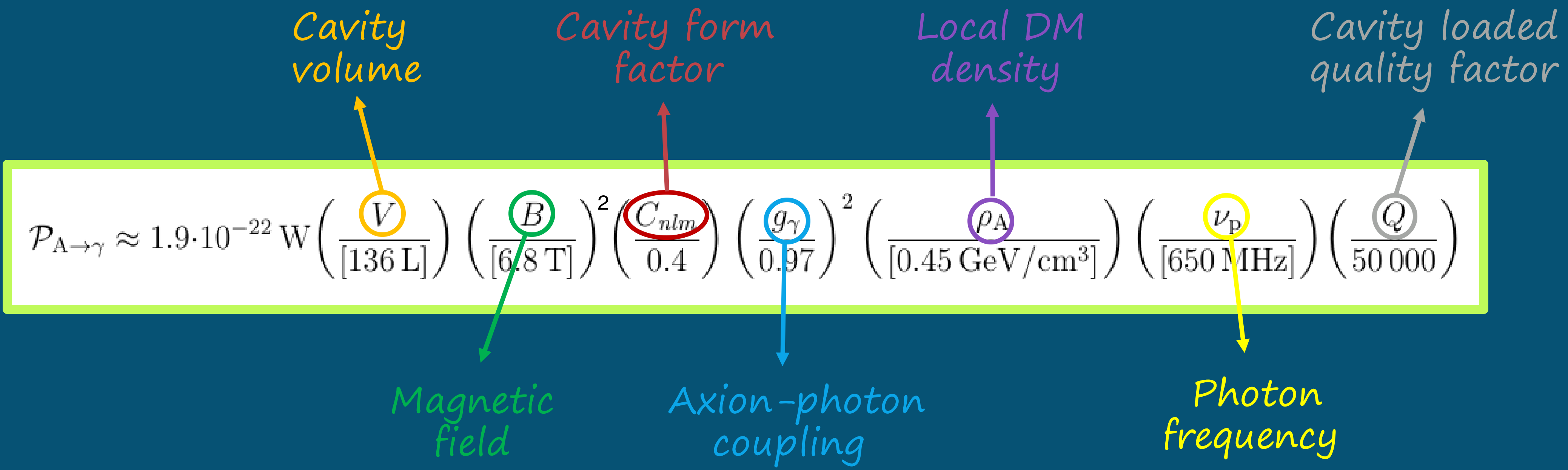

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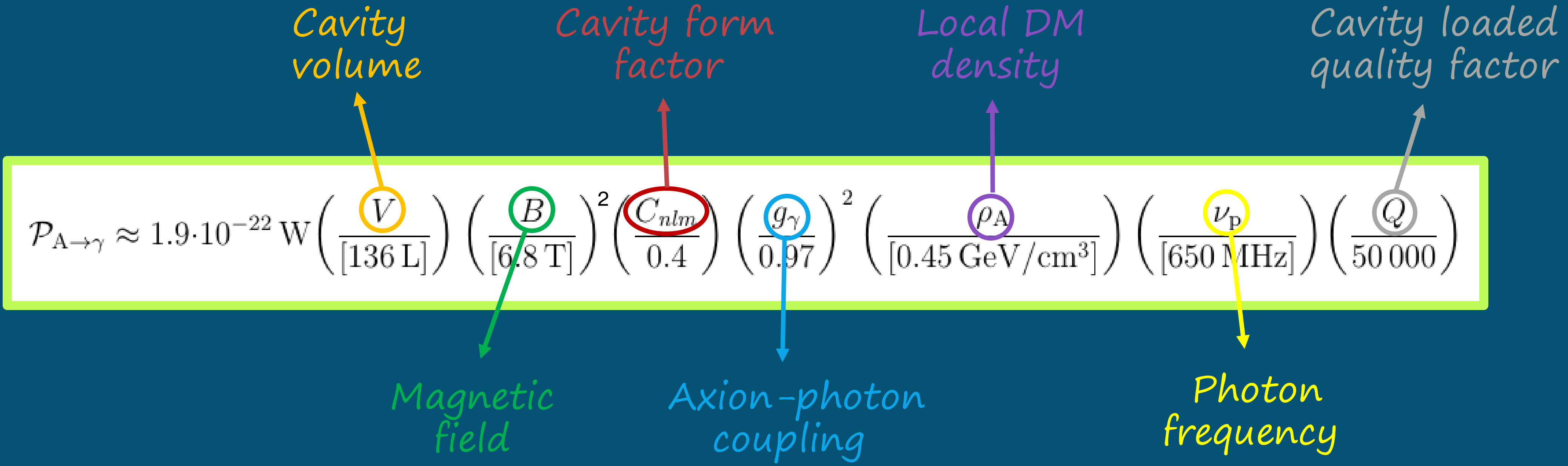

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To be maximized:

V, B, Q could be improved, but g_γ and ρ_A are fixed by nature...

SIGNAL PATH

Any axion-generated photon signal is extracted from the cavity by means of a "critically coupled" antenna, goes through output chain electronics (specific switches and circulators) to the 1st stage quantum amplifiers, then passes to the High Electron Mobility Transistor (further amplifiers, Minicircuits), and at the end is digitized (Signatech)

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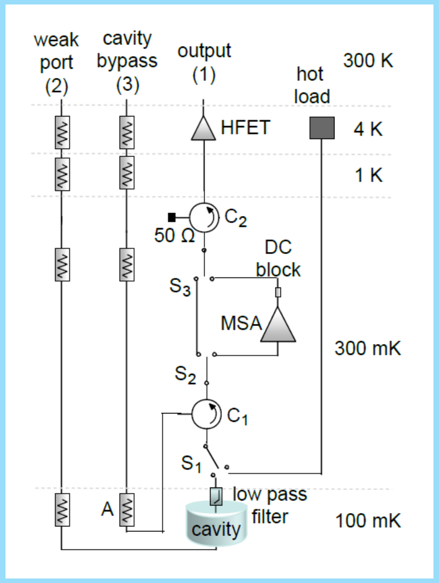
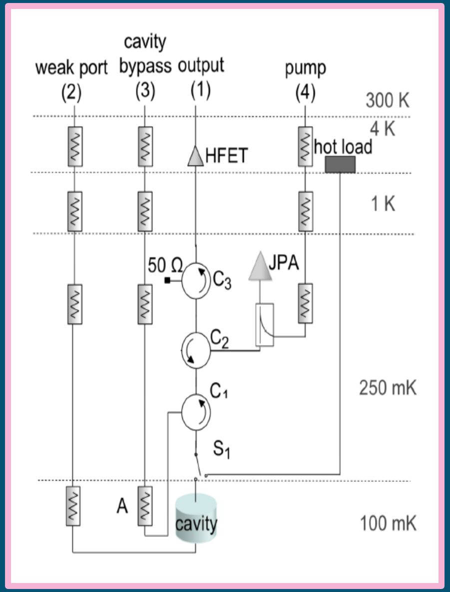
Run 1A

(January-June 2017, $m_A \approx 2.66 \div 2.81$ μeV, MSA used)





Run 1B

(January-October 2018, $m_A \approx 2.81 \div 3.31$ μeV, JPA used)

ADMX Collab., arXiv:2010.00169v1 [astro-ph.IM], 2020

MSA vs JPA

DC SQUID (Superconducting QUantum Interference Device)
is the building block of modern quantum amplifiers

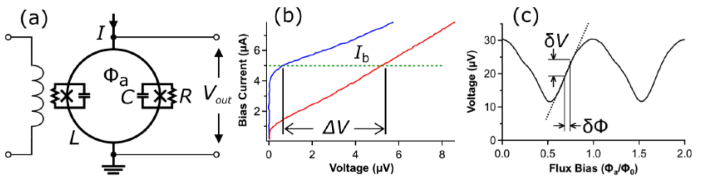


FIG. 10. DC SQUID. (a) Schematic, with Josephson junctions indicated with "X". (b) Voltage V vs. current I for applied magnetic flux $\Phi_a = n\Phi_0$ and $(n + 1/2)\Phi_0$. Voltage change ΔV at a constant bias current I_b. (c) Voltage V vs. normalized magnetic flux Φ_a/Φ_0 at constant I_b.

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Integrated, tuned
RF input coil

Microstrip SQUID Amplifier

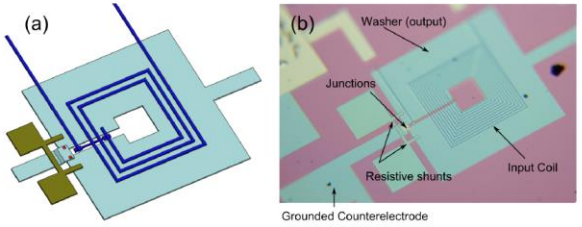
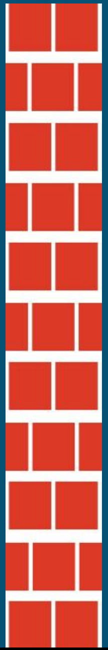


FIG. 11. Microstrip SQUID Amplifier (MSA). (a) Simplified schematic diagram (not to scale). Small red squares are Josephson junctions. (b) Optical photograph of 11-turn MSA. Microstrip leads enter from the top. Junctions and resistors at lower left edge.



2 Josephson junctions and
shunting capacitance (SQUID loop)

Josephson Parametric Amplifier

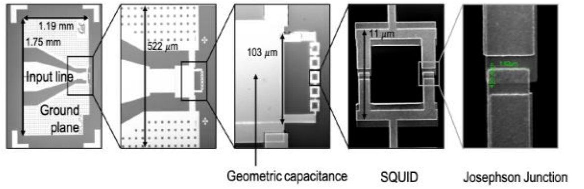


FIG. 18. JPA chip. The input line and ground plane form a coplanar waveguide leading to an array of five SQUIDs, which is shunted by a large parallel plate capacitor. The dimensions of a typical Josephson junction can be precisely fabricated on the order of tens to hundreds of nanometers. From left to right, the images are increasingly enlarged to show the array of SQUIDS and Josephson junction.

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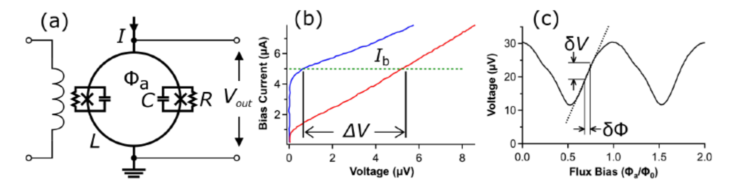

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ADMX Collab., arXiv:2010.00169v1 [astro-ph.IM], 2020

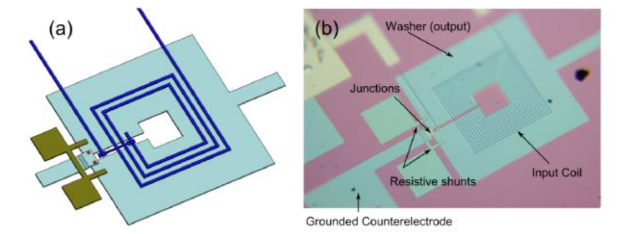
Invented for ADMX, it overcomes the common operating frequency limitation ($\lesssim$ 100 MHz)

+

Integrated, tuned RF input coil

=

Microstrip SQUID Amplifier



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Low-noise non-linear oscillator developed to achieve quantum limited amplification

+

2 Josephson junctions and shunting capacitance (SQUID loop)

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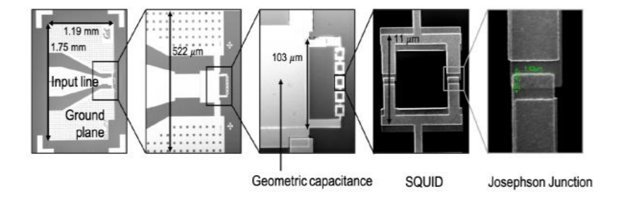
Josephson Parametric Amplifier



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NOISE BITTER ENEMY

Noise level is crucial for ADMX: as the expected $P_{A\text{->}\gamma}$ is so small ($\lesssim 10^{-23}$ W), it is of paramount importance to be able to drastically reduce spurious signals!

Main Signal-to-Noise Ratio:

$$\boxed{\frac{S}{N} = \frac{P_{\mathrm{a}\to\gamma}}{k_{\mathrm{B}}\,T_{\mathrm{sys}}}\sqrt{\frac{t}{b}}}$$

Dicke Radiometer Equation

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Dicke Radiometer Equation

Boltzmann constant

System noise temperature

Measurement ν bandwidth

Integration time

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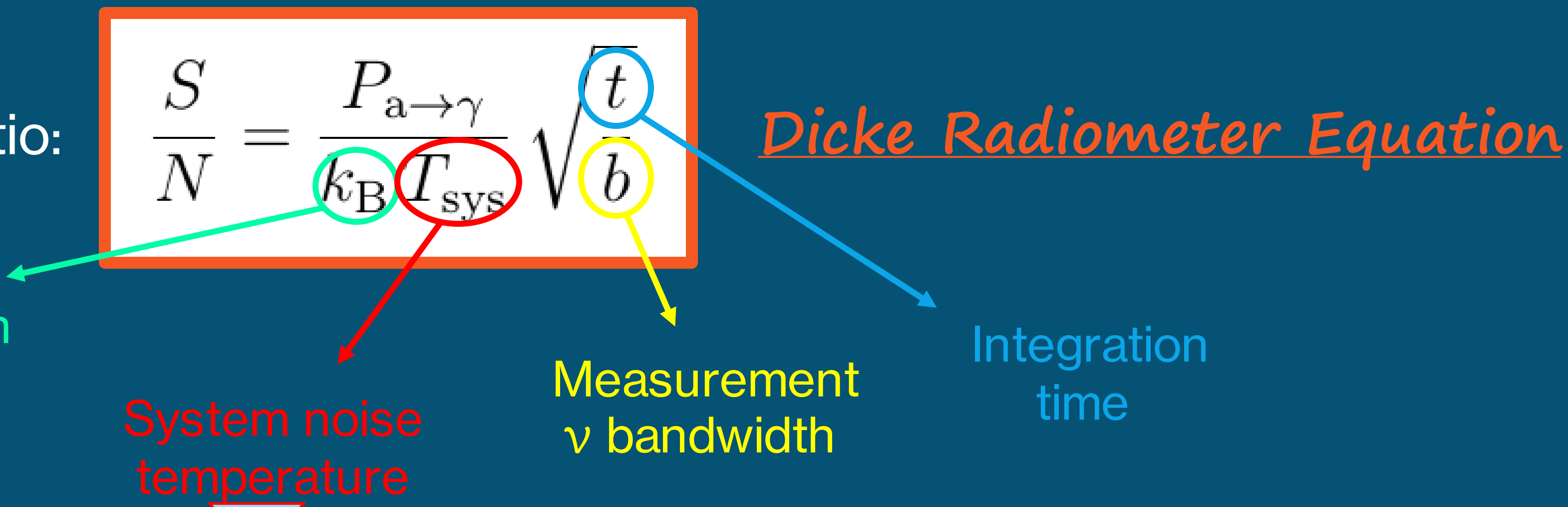

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T_{sys} = cavity physical T + receiver noise T (amplification chain) ⟶ ~ blackbody

Considering a thermal source followed by amplifiers or attenuators (related $T_{equivalent}$) may help...

IN SITU NOISE

ADMX **total noise** estimation was performed with great effort; basically a two-step process:

Heated Load Measurements

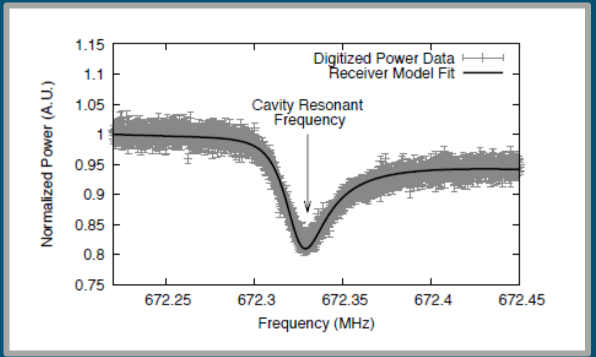
T change of one component while
P monitoring over a bandwidth

+

Signal-to-Noise Ratio Improvements (SNRI)

Total system gain and power output in a bandwith
with the amplifier included/excluded from RF chain

Also some variants do exist, or different methods
e.g. relative thermal power on/off resonance...



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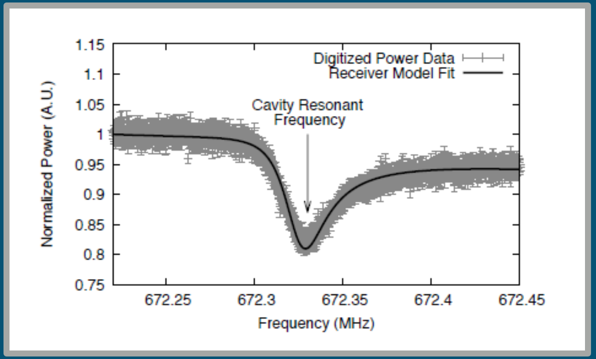
Total system gain and power output in a bandwith
with the amplifier included/excluded from RF chain

Also some variants do exist, or different methods
e.g. relative thermal power on/off resonance…

A combination of them yields a more reliable result!

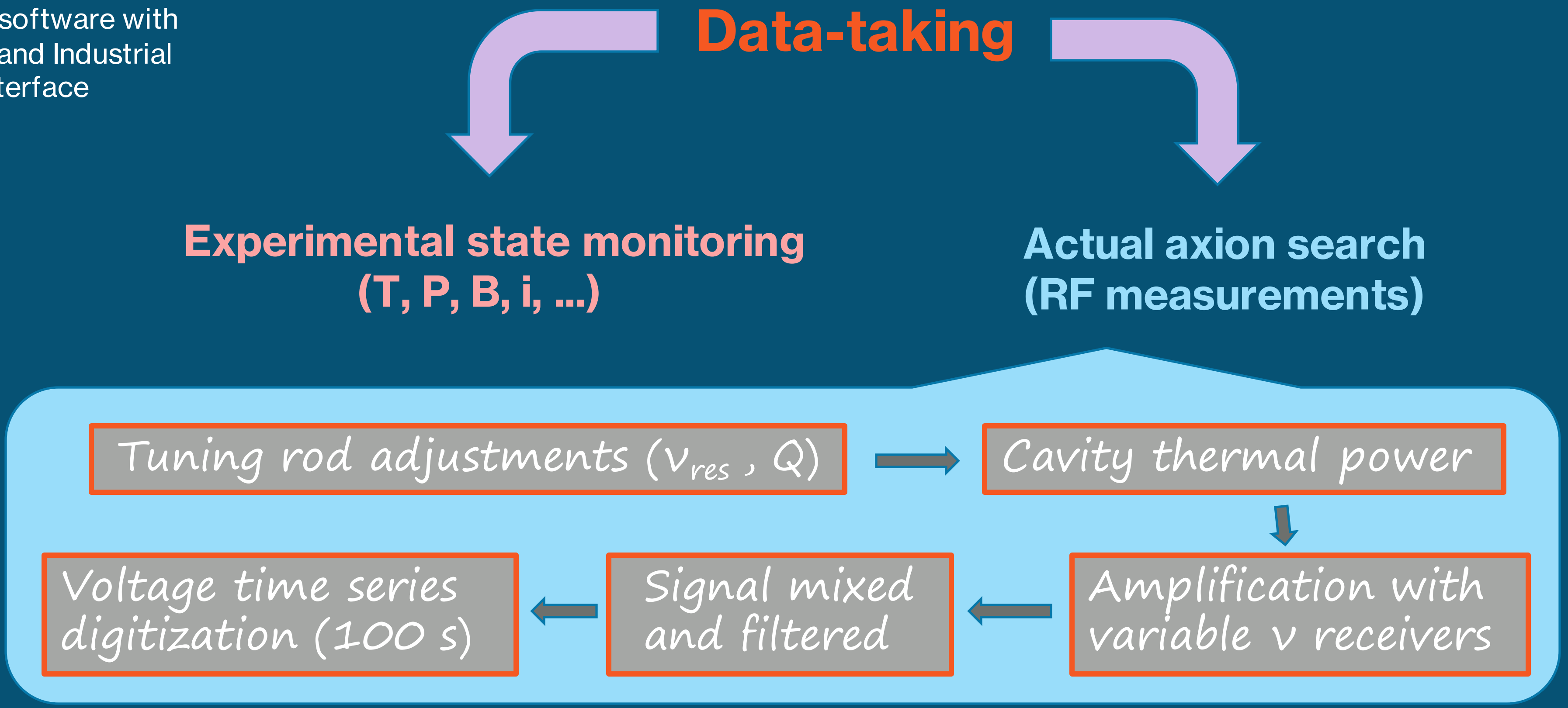


ADMX Collab., arXiv:2010.00169v1 [astro-ph.IM], 2020

Thanks to advanced quantum amplifiers and dilution refrigerator, ADMX cut off noise reaching an outstanding sensitivity…to explore DFSZ coupling too!

DATA ACQUISITION

DAQ fully automated, custom software with EPICS (Experimental Physics and Industrial Control System) as general interface



Data-taking

Experimental state monitoring (T, P, B, i, ...)

Actual axion search (RF measurements)

Tuning rod adjustments (ν_{res} , Q) → Cavity thermal power → Amplification with variable ν receivers → Signal mixed and filtered → Voltage time series digitization (100 s)

Data usually taken as 10 MHz wide "nibbles", and periodically logged in a SQL database (both onsite and remote for backup and analysis, Lua scripts)

DATA ANALYSIS

After DAQ (state information and system noise accounted for):

i Background receiver shape filtered out from individual scans
(Savitsky-Golay polynomial in Run 1A, Padé polynomial in Run 1B)

ii Single scans scaled to (T_{sys} , Q), individual bins weighted according to ν_{res}
(Lorentzian line shape; result is excess power eventually due to axions)

iii Combination of filtered and weighted scans to a single ***Grand Spectrum***
(to check for signals across the entire frequency range, SNR increased)

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Medium resolution channel -> virial A^0

High resolution channel -> non-virial A^0

Boosted Maxwell-Boltzmann shape (standard DM halo)

Final Convolution

Numerical shape (N-body simulations)

Suspected signals ($P = 3\sigma$ above $\overline{P}$) flagged as A^0 candidates, with re-scanning at longer t

ARTIFICIAL AXIONS

…is ADMX really robust in detecting axions?

To test it, isothermally-modeled "*synthetic axions*" (power as RF signals with Maxwell-Boltzmann-like line shape) were injected into the system, then mixed up to the observed ν_s

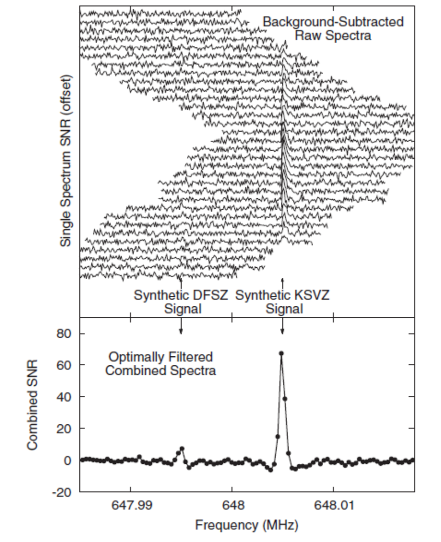

FIG. 3. Upper figure: Series of background-subtracted single scans with synthetic axion signals with the N-body inspired signal shape [37], one at KSVZ coupling and one at DFSZ coupling. The KSVZ signal is easily visible in these individual spectra; the DFSZ signal being a factor of 7 smaller is not. Lower figure: Same data after the individual scans have been optimally filtered and combined. Both KSVZ and DFSZ signals are visible with high SNR.

ADMX Collaboration and G. C. Hilton, Phys. Rev. Lett., 2018

RESULTS...AXION CAUGHT?

In the 645-680 and 680-790 MHz ranges, there were two and three persisting candidates respectively

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iStock

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dreamstime

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dreamstime

So, no statistically significant A^0 signals found, and related parameter space still unexplored…

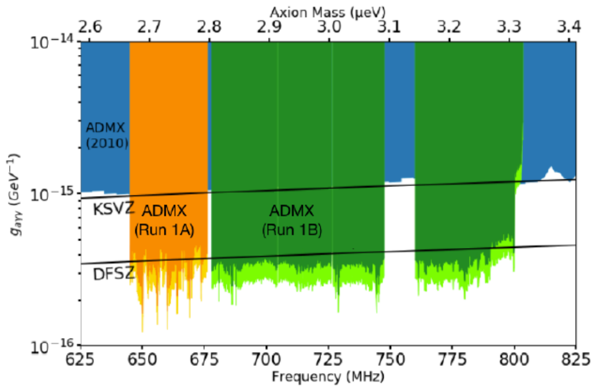

FIG. 28. Recent limits set by Runs 1A and Run 1B. 90% confidence exclusion on axion-photon coupling as a function of axion mass for the Maxwell-Boltzmann (MB) dark-matter model (dark green) and N-body model (light green) from Ref[2]. Blue and Orange denote limits reported in [64] and [1] respectively.

ADMX Collab., arXiv:2010.00169v1 [astro-ph.IM], 2020

However, more stringent upper limits (90% confidence, apart from uncertainties) on the axion-photon coupling in the mass range examined!

CONCLUSIONS

- Axions are light and "invisible" hypothetical particles introduced to solve the "strong CP problem", very likely able to also explain all the Dark Matter in the Universe
- The most promising detection technique is the axion haloscope, i.e., a resonant cavity aiming at observing their conversion into low-energy photons by means of a strong magnetic field (Primakoff effect)
- ADMX represents a revolution: not underground, but ultra low noise thanks to new quantum amplifiers (MSA/JPA technology) and dilution refrigerator (cooling down to ~ 0.1 K), so the only sensitive in the explored M range (2÷4 μeV) also for DFSZ coupling
- So far, no axion signal evidence => upper limits on coupling, but extended search to higher masses (~ GHz) and improvements foreseen, e.g. magnetic field increase and squeezing techniques to further lower both T and noise

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Is the hunt worth to be continued? Just see 1st point...!

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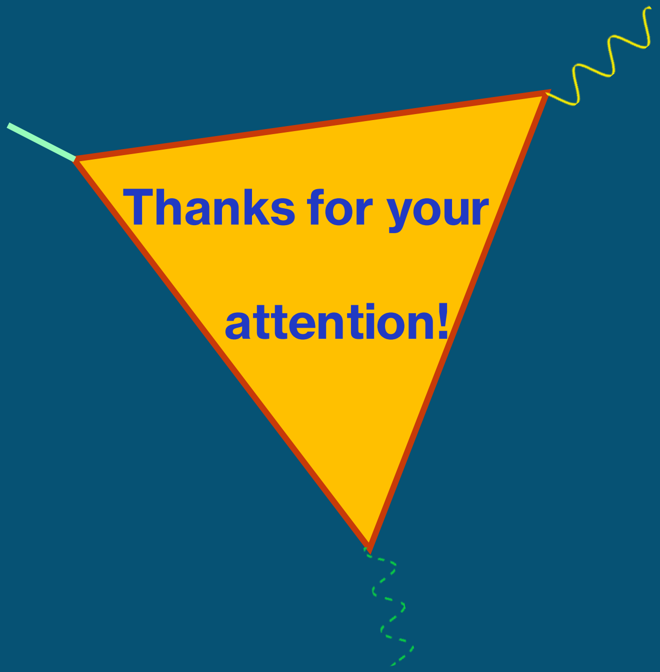

Thanks for your attention!