PROBING DARK MATTER WITH AXION DARK MATTER EXPERIMENT (ADMX)

01/25/2018

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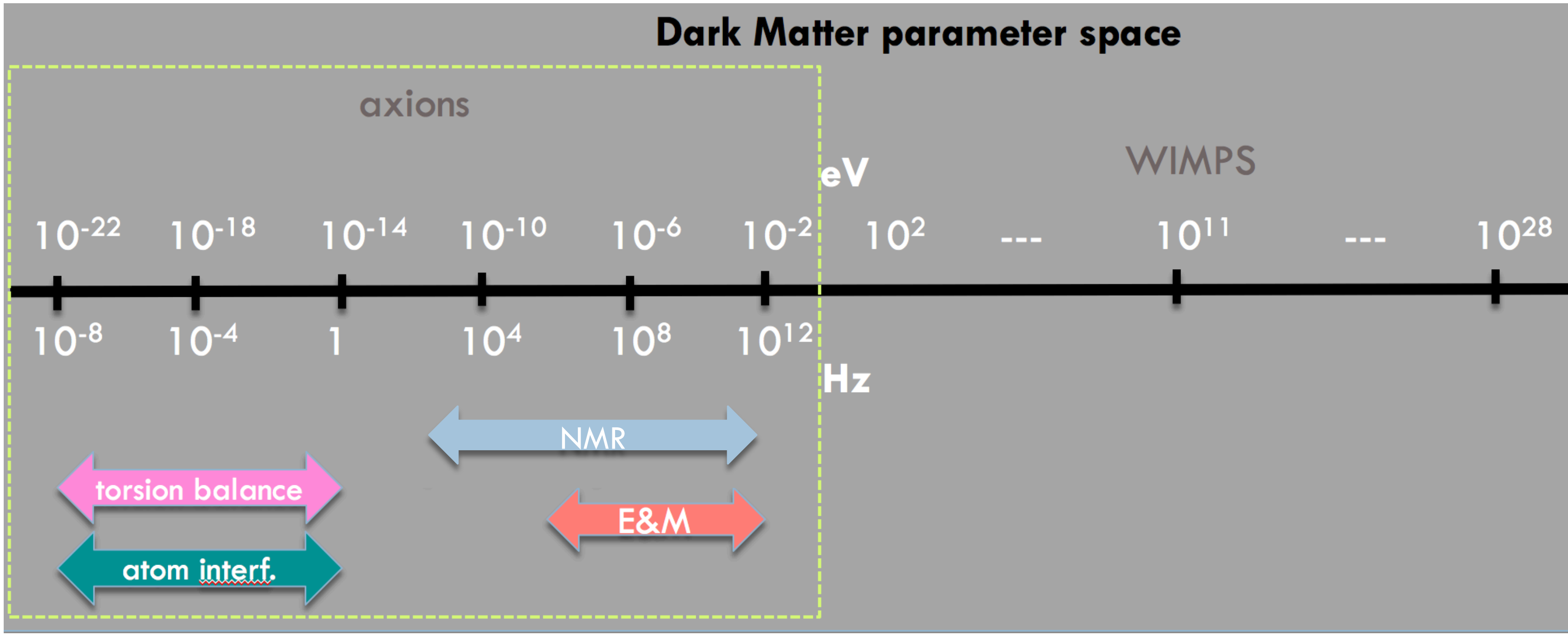
Outline

- ADMX (Axion Dark Matter eXperiment) overview
- Recent progress
- Results from run 1a -- 2017
- Run 1b in progress -- 2018
- Summary and future direction

ADMX
AXION DARK MATTER EXPERIMENT

Dark matter: overview



Axions Couple to:

*Electromagnetic field:

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

ADMX, ABRACADABRA, ORPHEUS, HAYSTAC, DM radio, LC circuit

*Fermions:

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Atom interferometry, ARIADNE, CASPER-wind SN1987A, Stellar cooling

*Gluon field:

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

CASPEr-Electric

Axion production and Strong CP problem

Big Bang → Axion before or after the inflation?

- → matter+anti-matter anhilation
- → matter anti-matter asymmetry
- → CP symmetry & baryon number violating mechanisms

- → Standard Model QCD Lagrangian -- CP violating parameter θ (0-2π)
- → $\theta \neq 0$ => CP violation in Strong Int. => neutron's electric dipole moment $d_n \neq 0$
- → Experimental upper limit on d_n very small

=> θ really really small ! => Strong CP problem

θ promoted to a field (Peccei-Quinn theory)

--adding new global symmetry to the SM--that gets spontaneously broken

→ Axion associated particle

QCD Axion

sub-eV mass, spin 0, charge 0

solution to the strong CP problem

ADMX is one of the three DOE Generation-2 dark matter experiments

weakly interacting with ordinary matter

cold dark matter candidate

ADMX Collaboration:

UNIVERSITY of WASHINGTON

Pacific Northwest NATIONAL LABORATORY

Fermilab

Berkeley

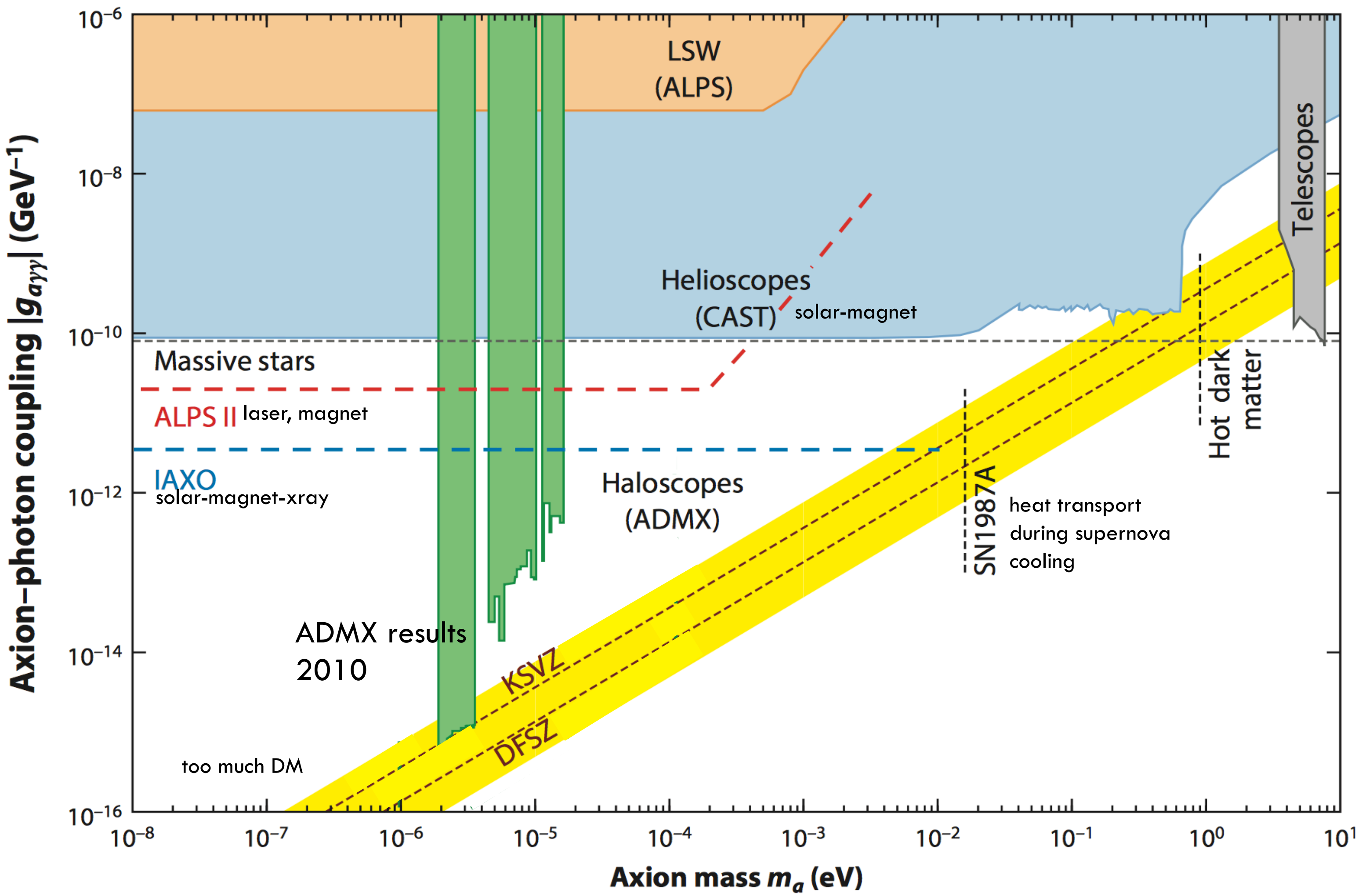
University of Florida

The University Of Sheffield.

NRAO

Lawrence Livermore National Laboratory

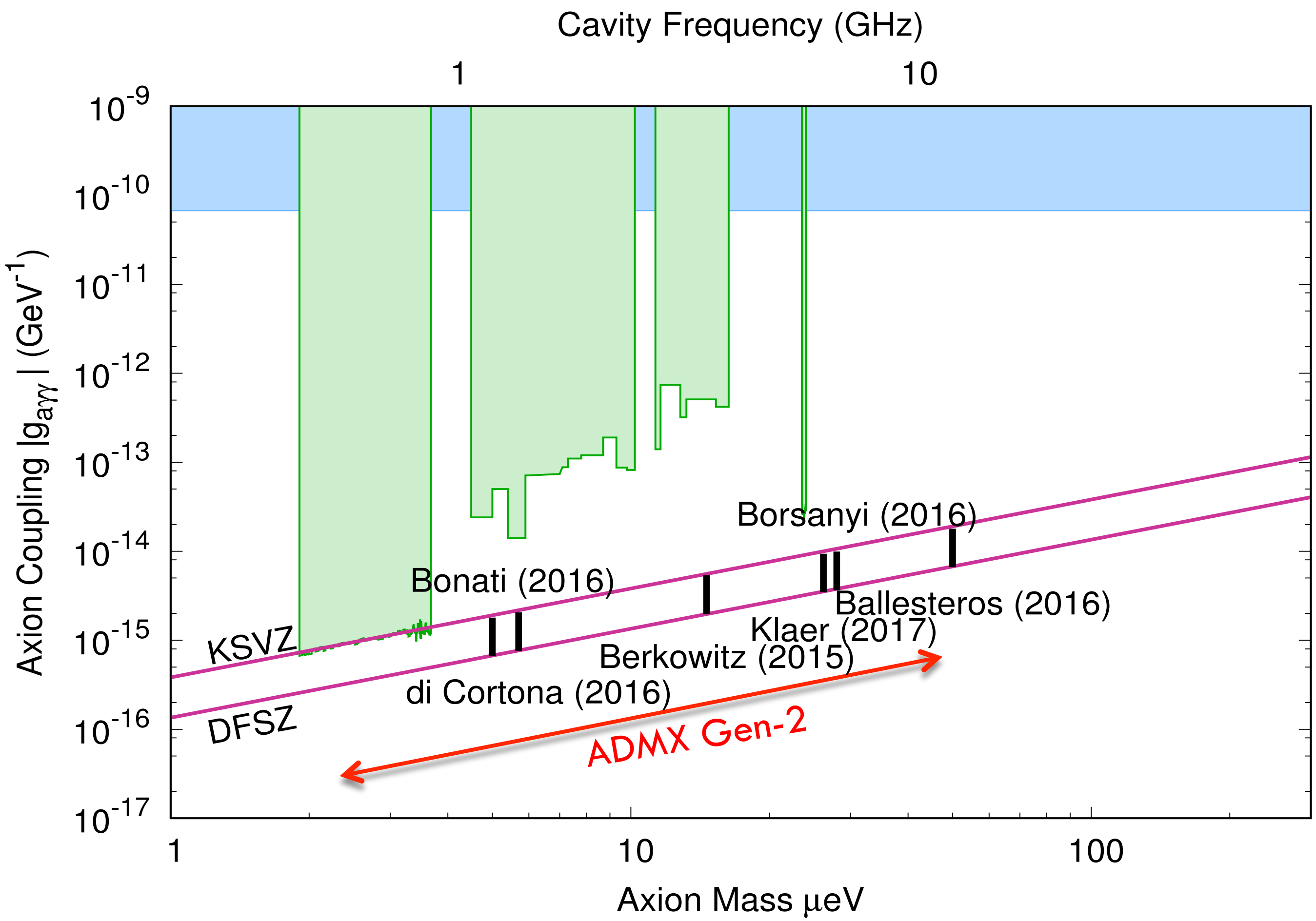
Axion searches overview



Graham, et. al (2016)

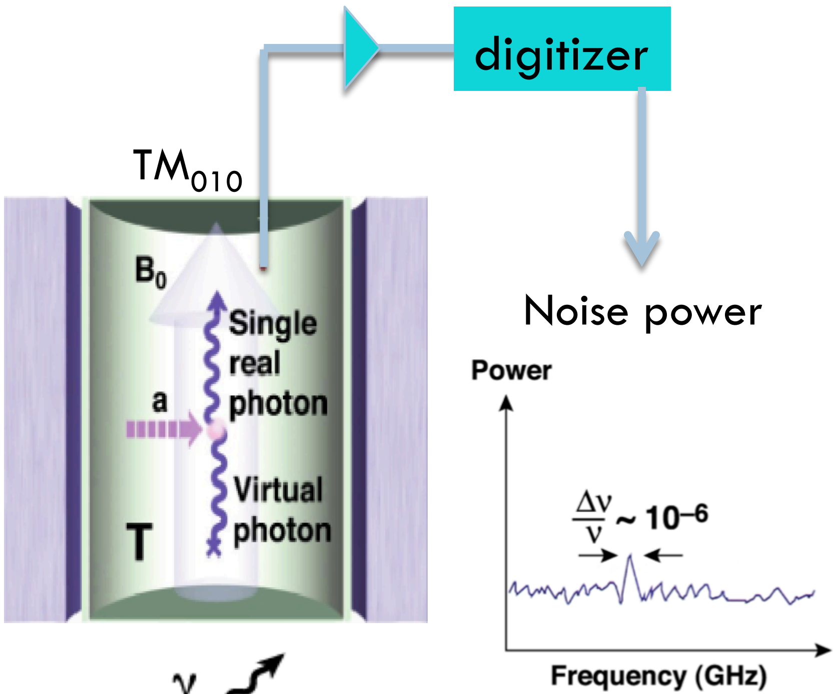
Axion searches overview contd.

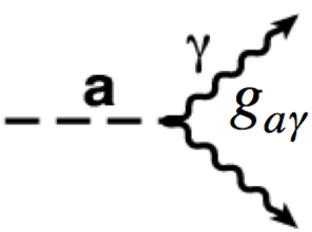
Analytic and lattice predictions of the axion mass, given it makes 100% Dark matter



Adapted from G.R, J. Phys. G, publication pending, courtesy of G. Rybka

ADMX: conceptual design





$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B},$$

$\beta_{\text{virial}} \sim 10^{-3}c$: $\lambda_{\text{De Broglie}} \sim 100$ m, $\lambda_\gamma = 12$ cm

 # density local galactic halo ≈ 10^{14} cm^{-3}
--- (ρ = 450 MeV/cm^3)

converts to photons in a strong magnetic field

conversion enhanced when microwave cavity's resonance frequency matches with the photon's frequency

mass: 1 μeV/c^2 – 40 μeV/c^2 ---- (0.5-10 GHz)

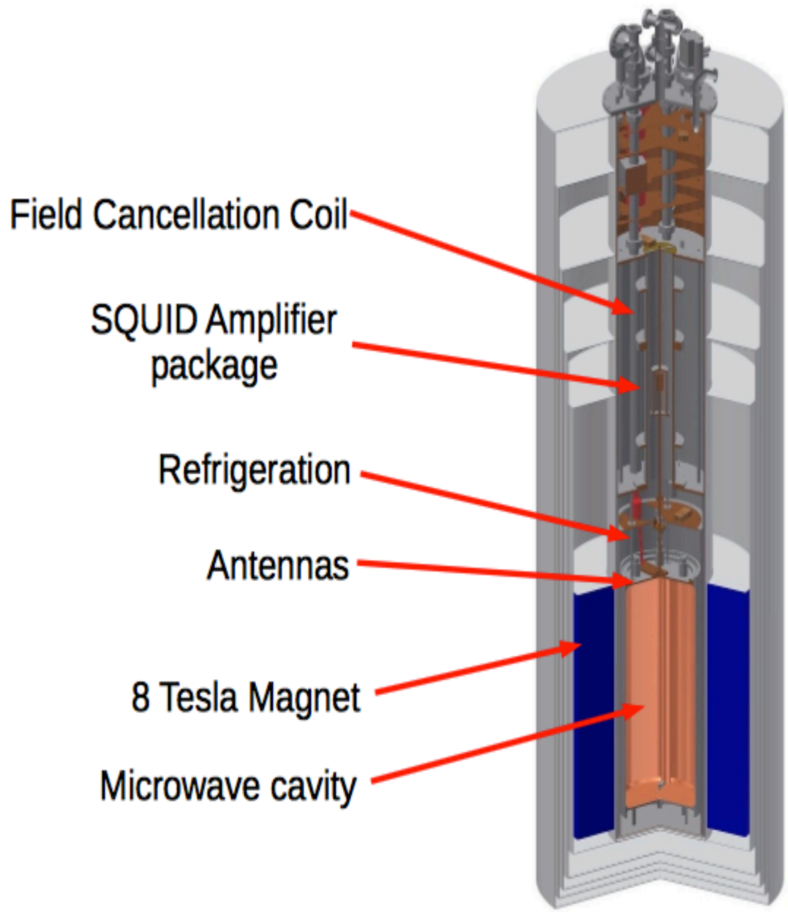
P = 10^{-23} Watts

$P \sim g^2 m_a \rho_a Q_{cav} C B^2 V$

Signal = excess power in the background thermal noise

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{BW}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{BW^{\frac{1}{2}} T_{system}}$$

ADMX insert



Insert + Magnet Schematic

Field cancellation coil: cancels the residual magnetic field around the SQUID electronics

Superconducting QUantum Interference Device (SQUID) amplifiers: amplifies the signal while being quantum noise limited

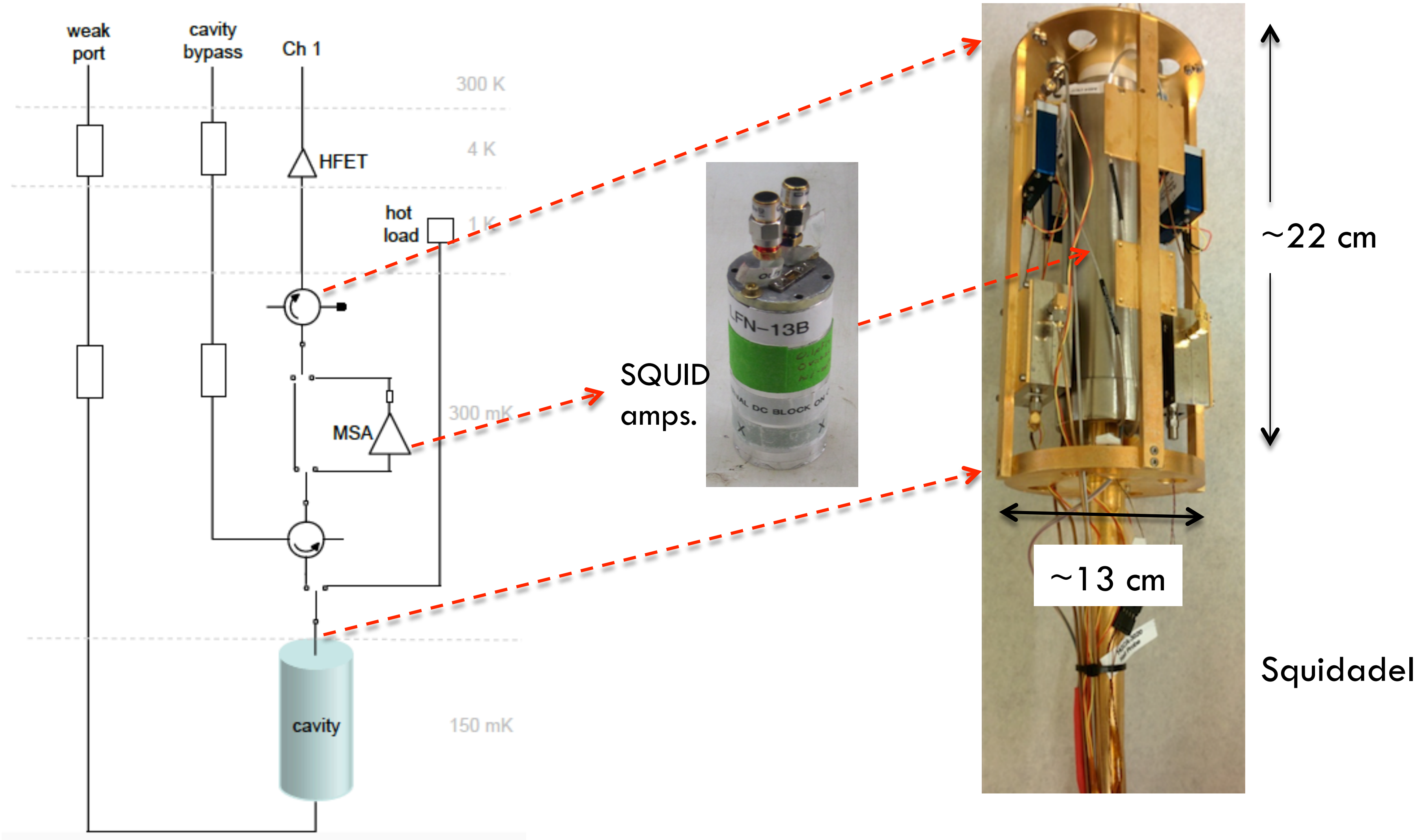
Dilution refrigerator: cools the insert to ~ 150 mK

Antennas: pick up signal

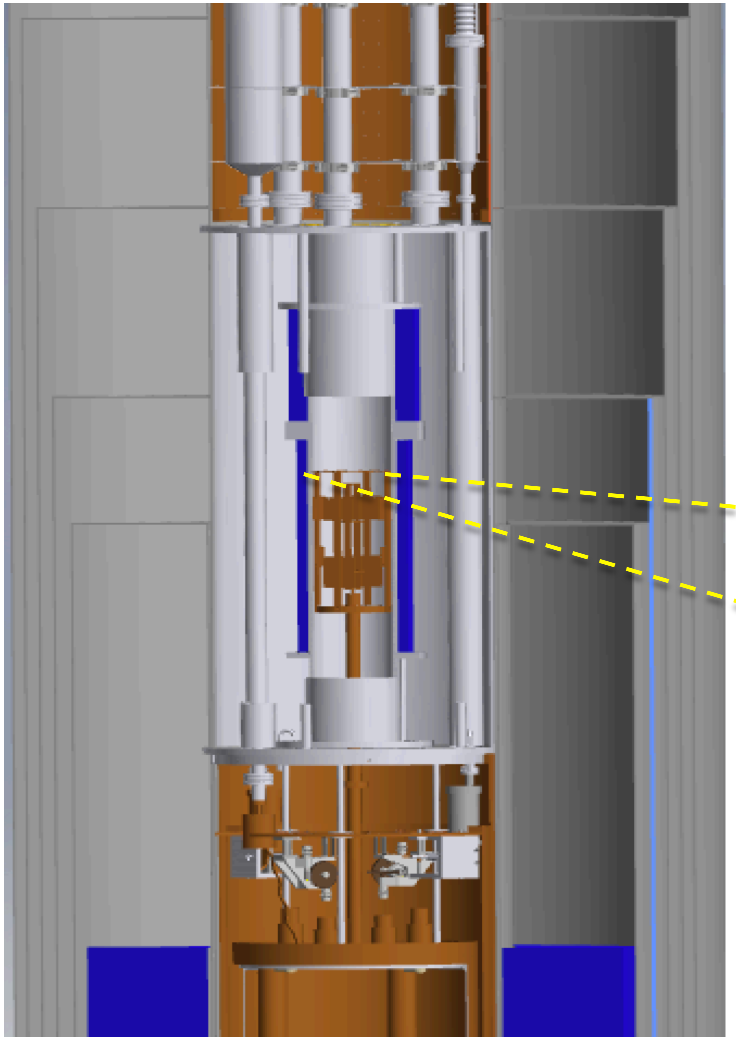
Magnet: facilitates the axion conversion to photons, 8T

Cavity: converts axions into photons, tunable

Insert: layout

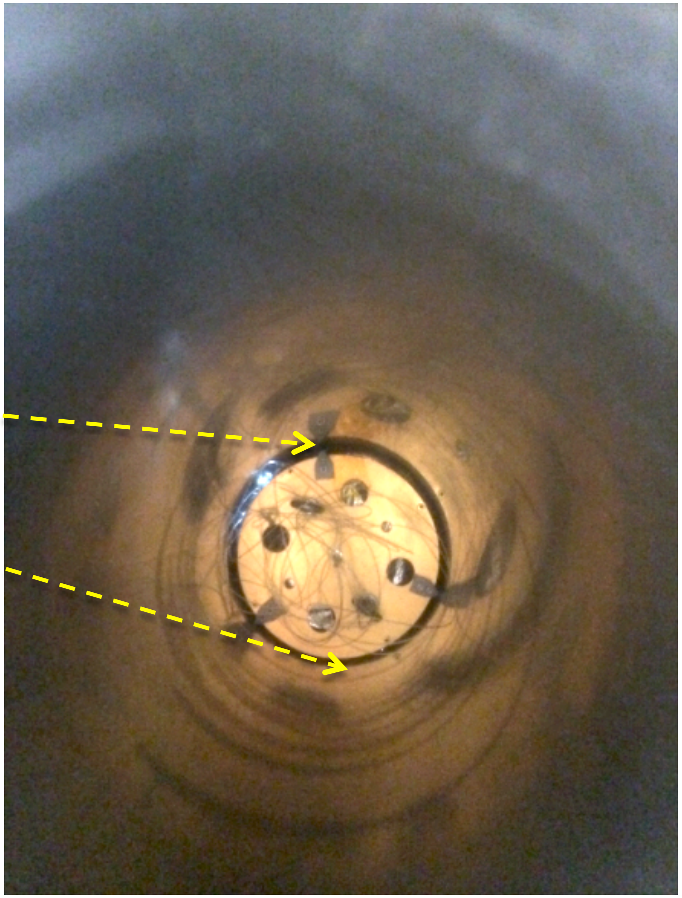


Insert: fitting

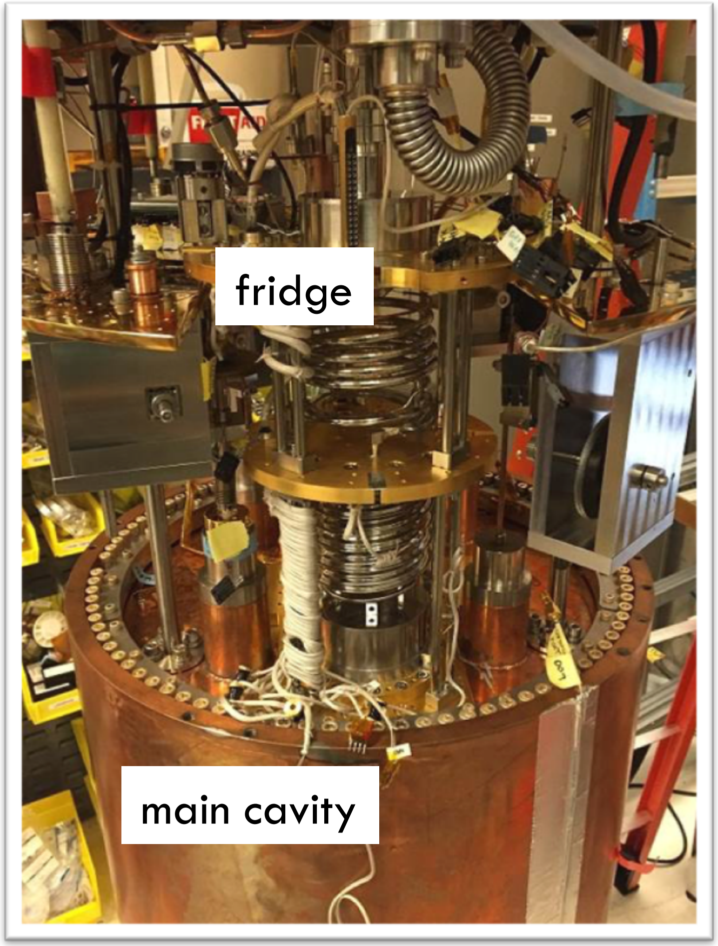


Squidadel top view

Inside the He reservoir



Insert: dilution refrigerator

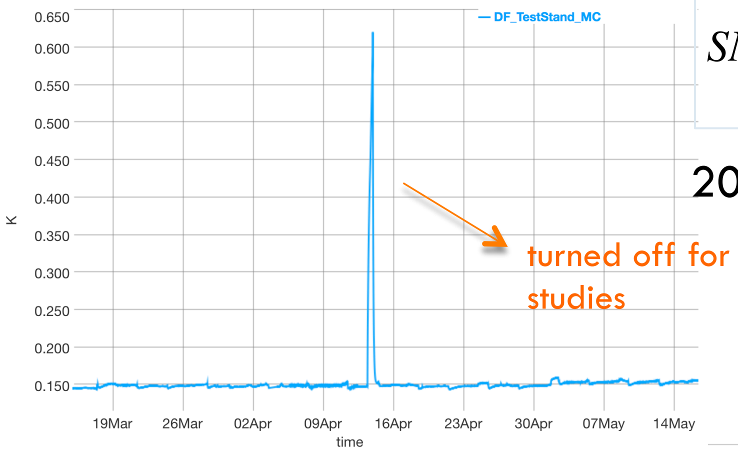


- *Cools cavity and electronics*
- *Successful operation since the end of 2016*
- *800 μW cooling power @ 100 mK*

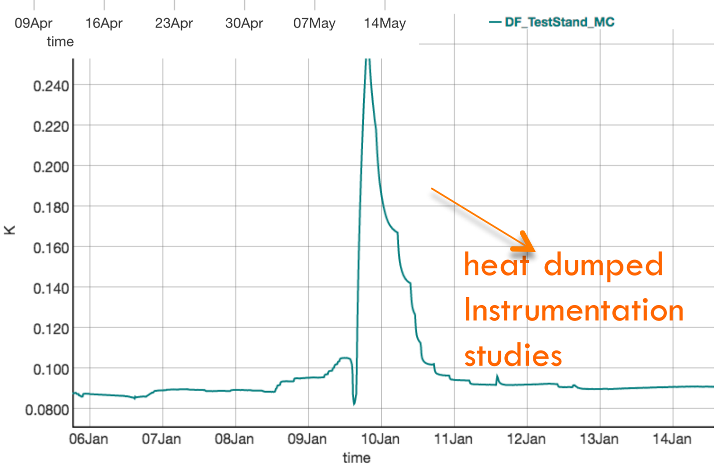
$$T_{sys} = T_{amps.} + T_{phy}$$

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{B}}$$

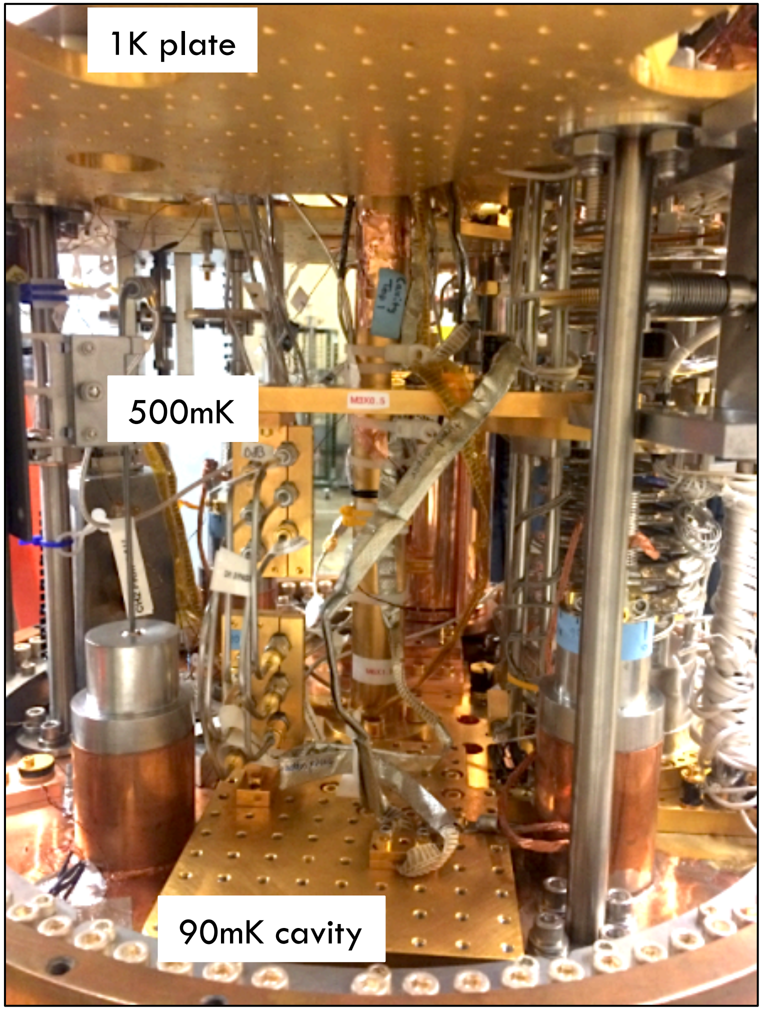
2017 @ 150mK

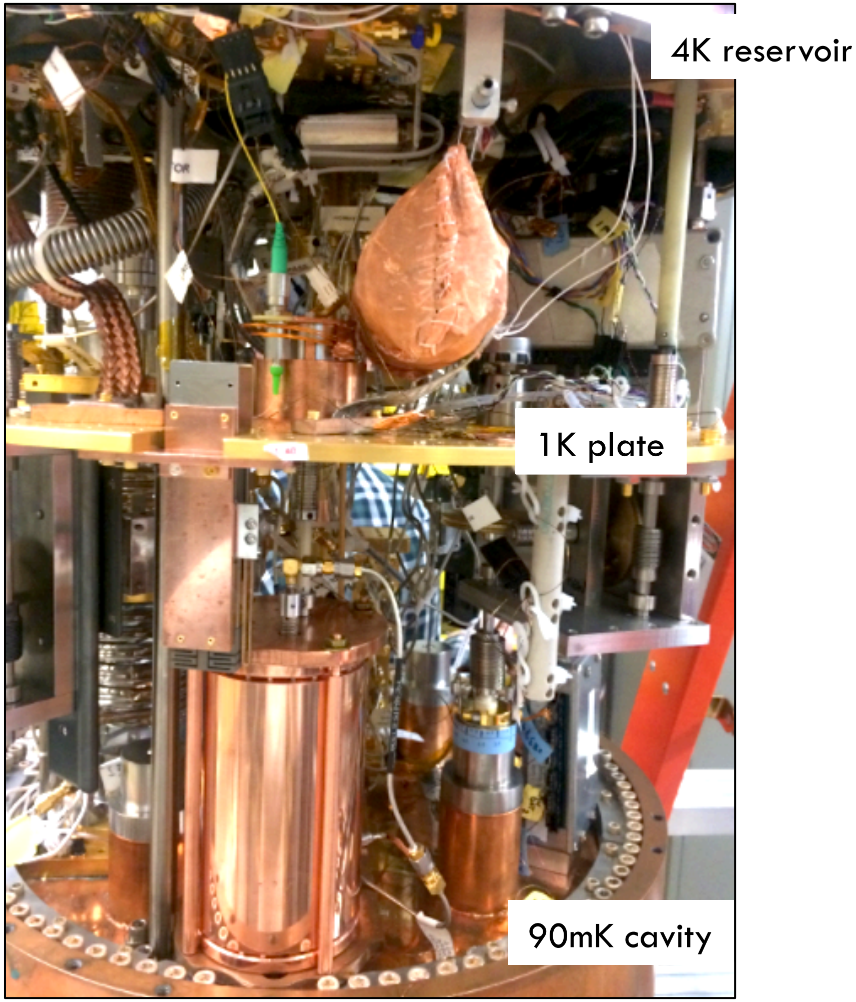


2018 @ 90mK

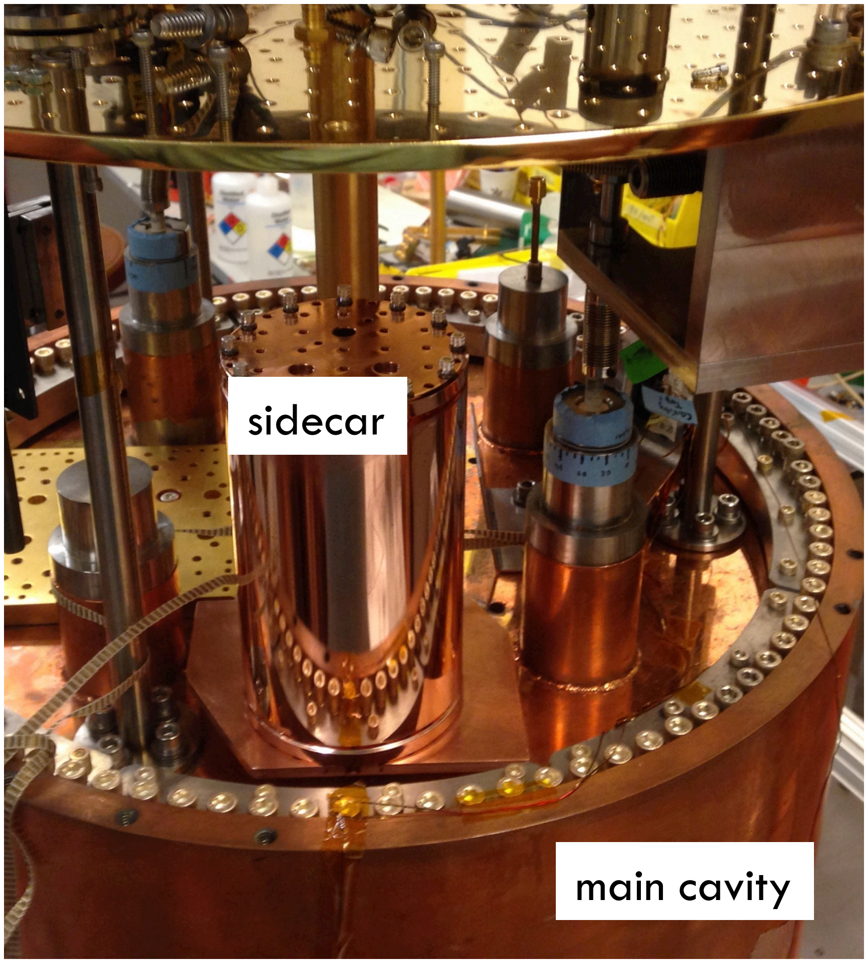


Insert: Thermal stages





Sidecar: a higher frequency prototype



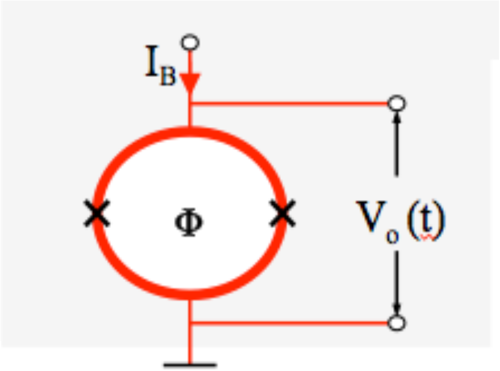
- Mounted on top of the main cavity
- Successful higher frequency prototype (4-7 GHz)
- Operates in parallel with the main experiment
- Piezo motor/mechanical components test
- Newer operations/limites at 5.1-5.8 GHz with B~2T & 7.1-7.2 GHz with B~7T
- Potential to reach KSVZ sensitivity with addition of SQUID amplifiers

Insert: SQUID amps.

MSA

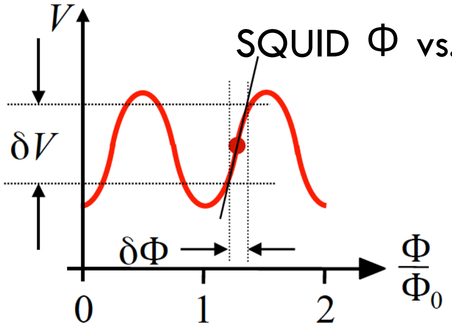
JPA

Based on dc SQUID



Microstrip SQUID Amplifier

- Resonator inductively coupled to SQUID
- Tunable: varactor tuning effectively changes the length of the resonator
- Tunability ~100 MHz/device



Josephson Parametric Amplifier

- Flux tunable inductance of SQUID shunted by a parallel plate C with

$$\omega_0 = \frac{1}{2\pi\sqrt{C(L_{stray} + L_{SQUID})}}$$

- amplifies weak signal by pumping
- Tunability ~ several 100 MHz/ device

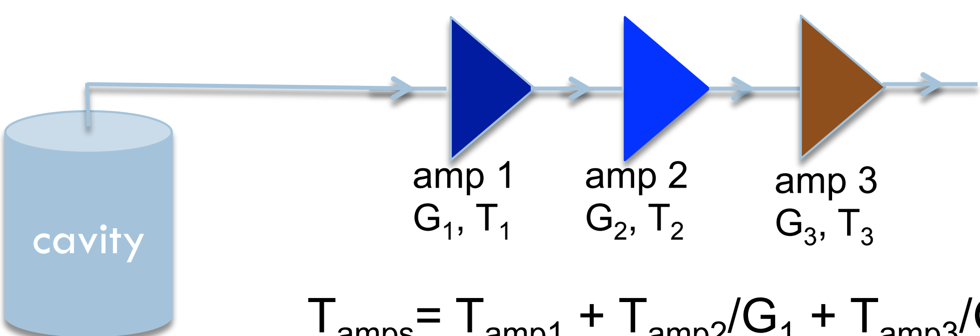
Insert: SQUID amps. noise

Near quantum noise limited

48 mK (hf/k_B @1GHz)

$$\mathbf{T_{system} = T_{amps.} + T_{physical}}$$

$$\downarrow$$



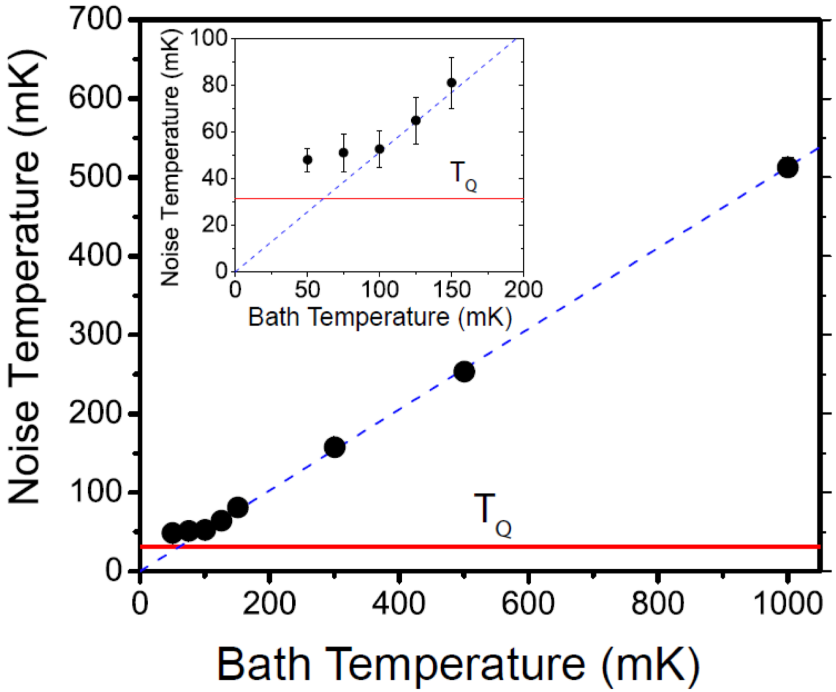
$$T_{amps} = T_{amp1} + T_{amp2}/G_1 + T_{amp3}/G_1G_2 + ..$$

<u>For ADMX</u>
amp_1: MSA/JPA
amp_2: cryo-transistor
amp_3: post amps.

SQUID amps: noise temperature

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{B}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{B^{\frac{1}{2}} T_{system}}$$

- SQUID amplifiers T_N generally 1/2 of $T_{physical}$
- Scan rate = df/dt ∝ $(1/T_{system}^2)$
  ➔ **COLDER IS BETTER**
- Huge improvement in the scan rate with dilution fridge and SQUID amps.
- Without SQUID amplifiers, time ≥ 100 years to scan through Axion window (1μeV – 40μeV)

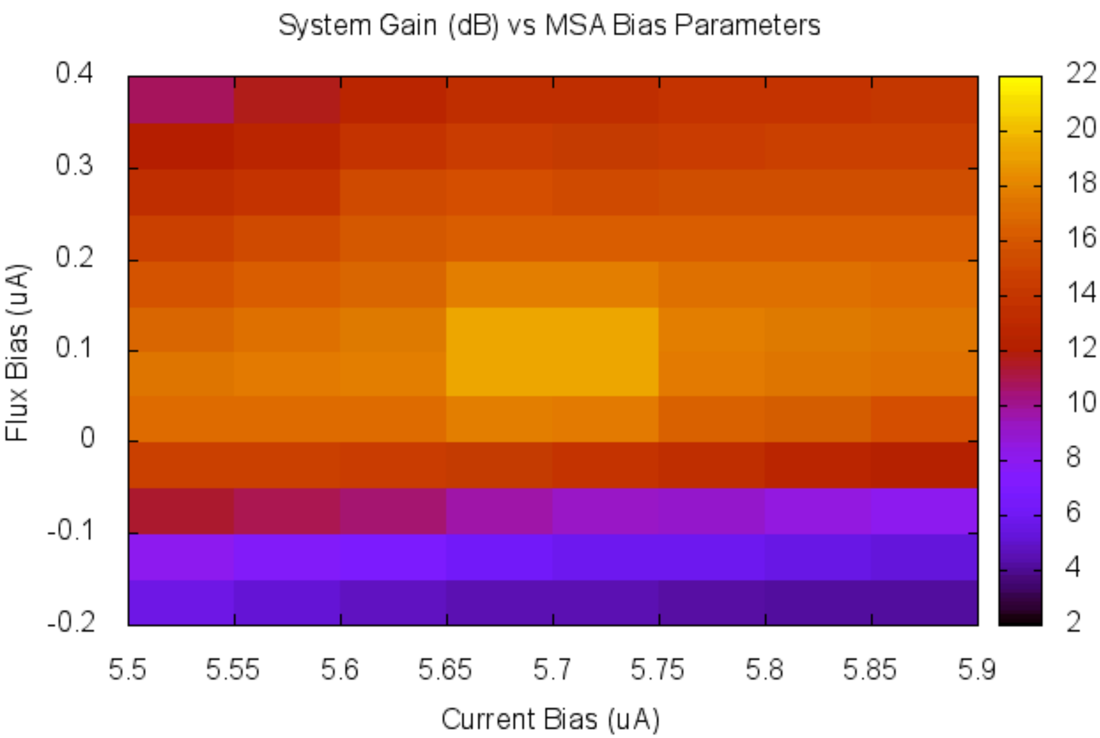


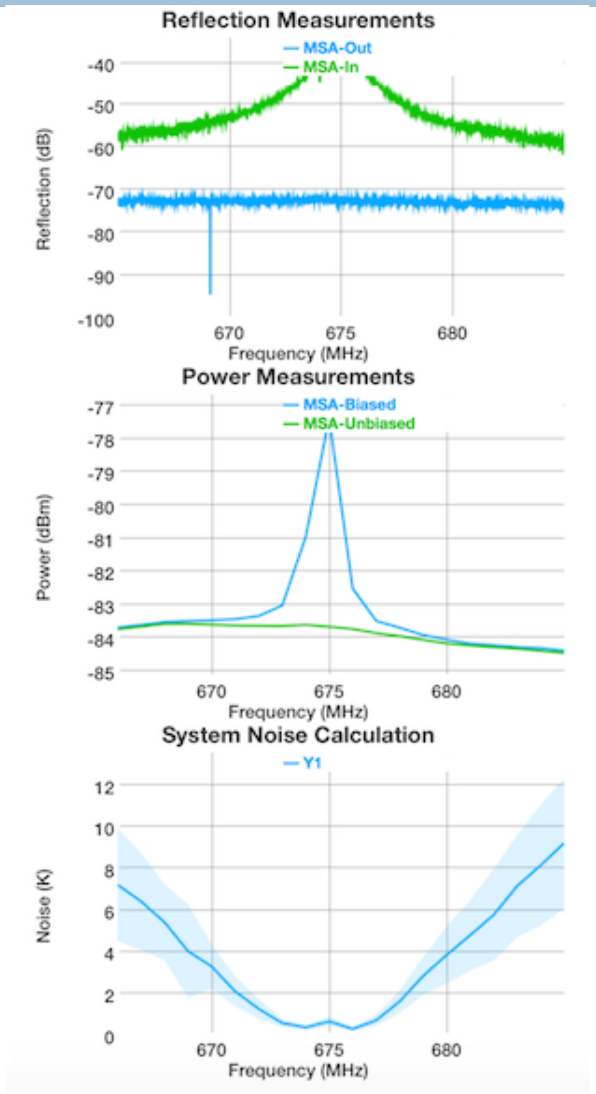
Amplifier	T	T_N
Si Amp.	300 K	60 K
HEMT	4.2 K	2 K
SQUID amps.	<300 mK	$T_N \approx \max(T/2, T_Q)$
Quantum Limit	--	hf/k_B (48mK @ 1GHz)

SQUID amps: operation

- Bias amps: manual and automated
- Estimate noise temp. of the MSA
  1. Hot-load method
  2. SNR method

  => Noise temp. of the system





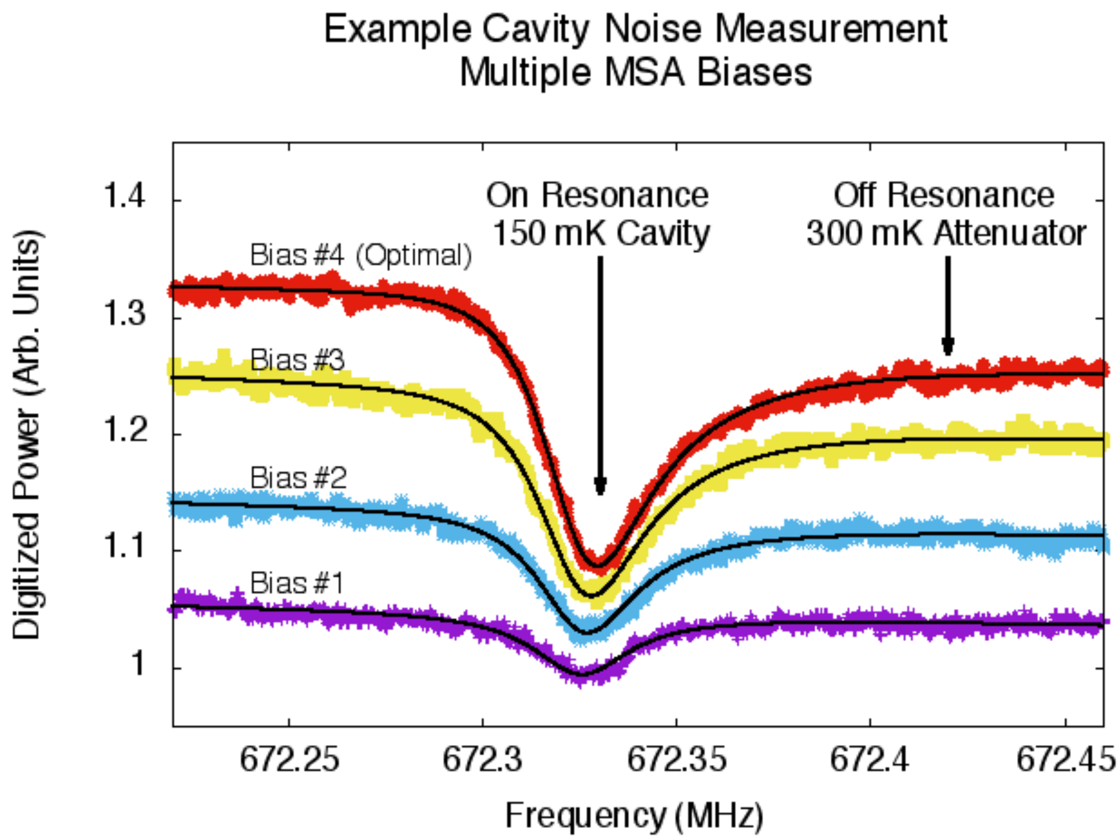
System noise temperature

T_{system} ~ 500-700 mK achieved--2017

<u>Data taking mechanism:</u>

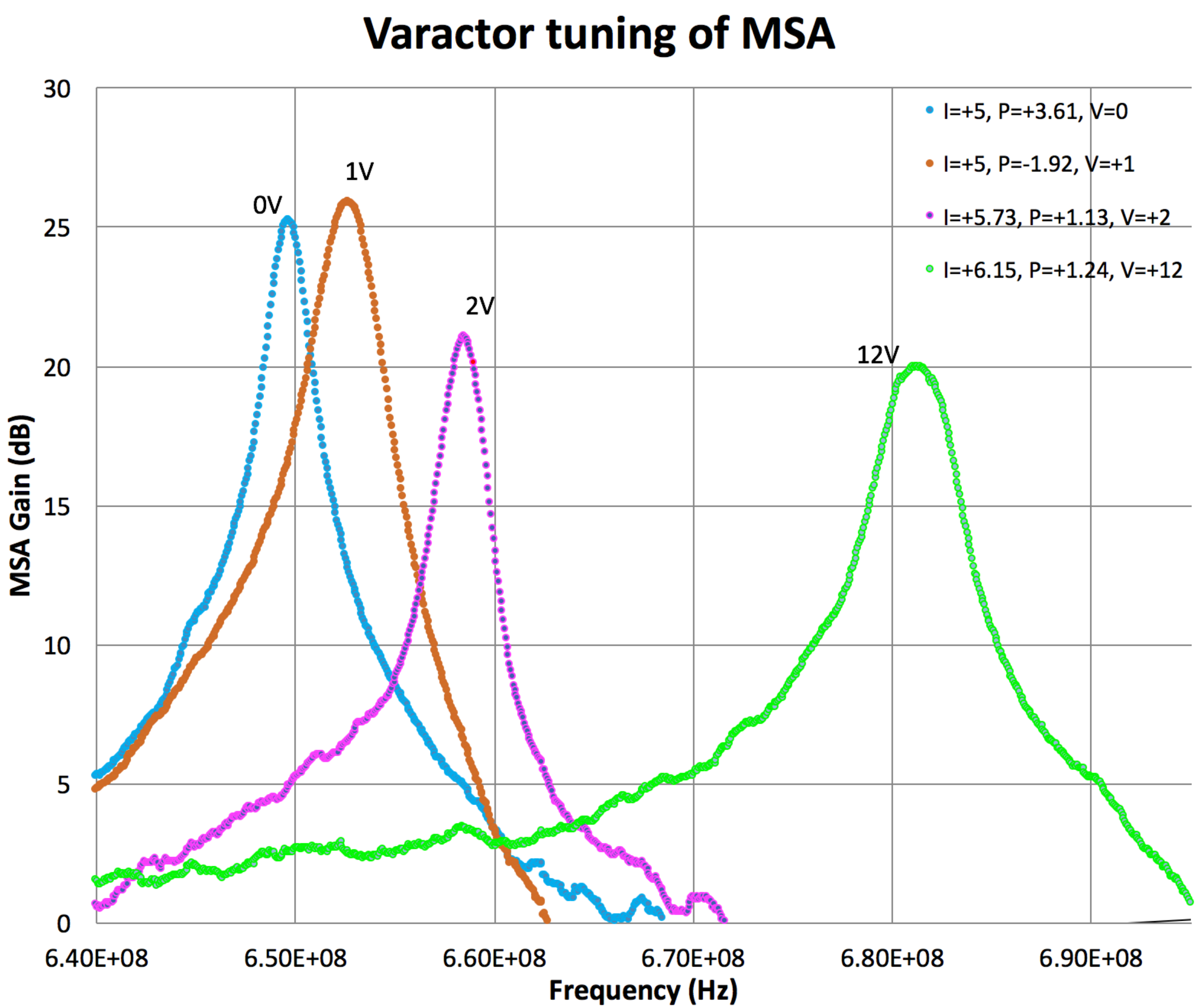
1. Tune the cavity and SQUID amps. to the desired frequency -- m_a
2. Achieve lowest noise temp
3. Record noise power
4. digitize

   Repeat until desired SNR
5. Analyze data
6. Excess power signals rescanned
7. Individually probed
8. Put limits

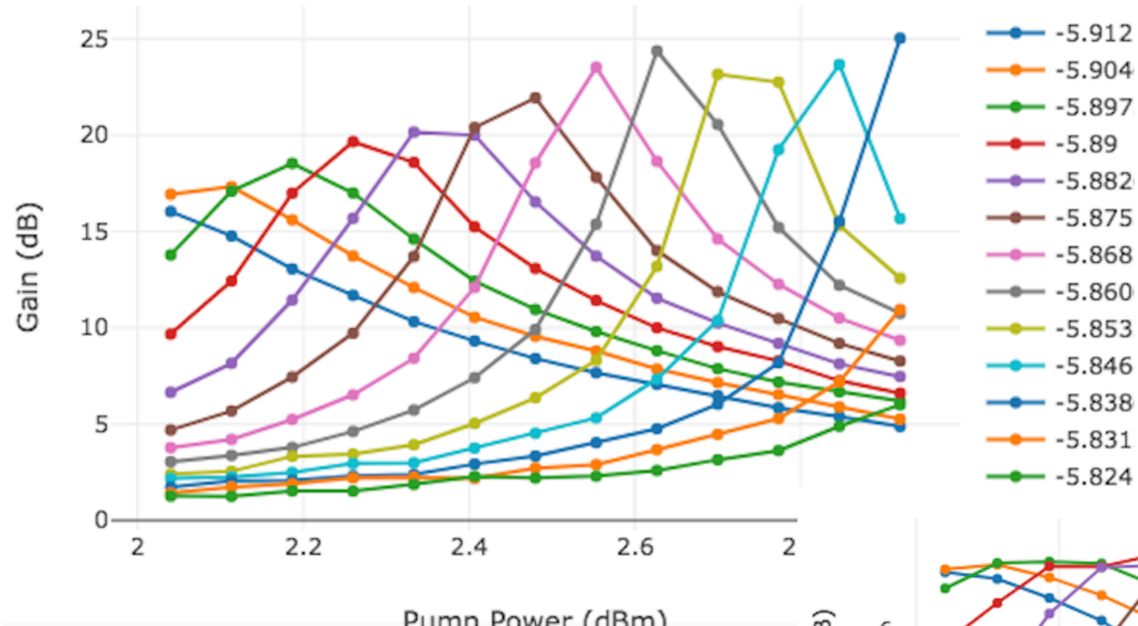


MSA results -- 2017

- **MSA:** 645-680 MHz
  range ~35 MHz
- MSA run @300 mK
- Range limited by MSA tuning/microwave technology
- Fabricated by UC Berkeley

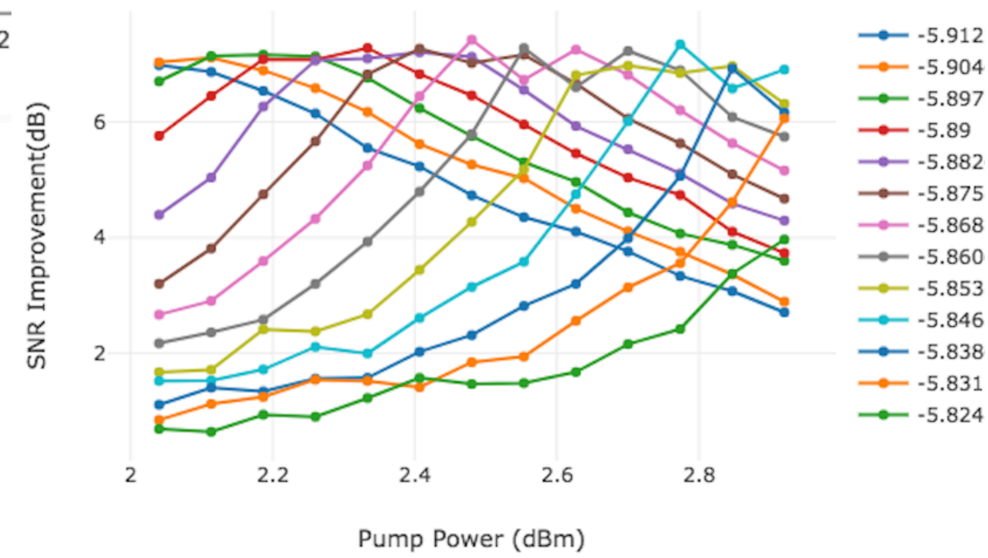


JPA preliminary operation -- 2018

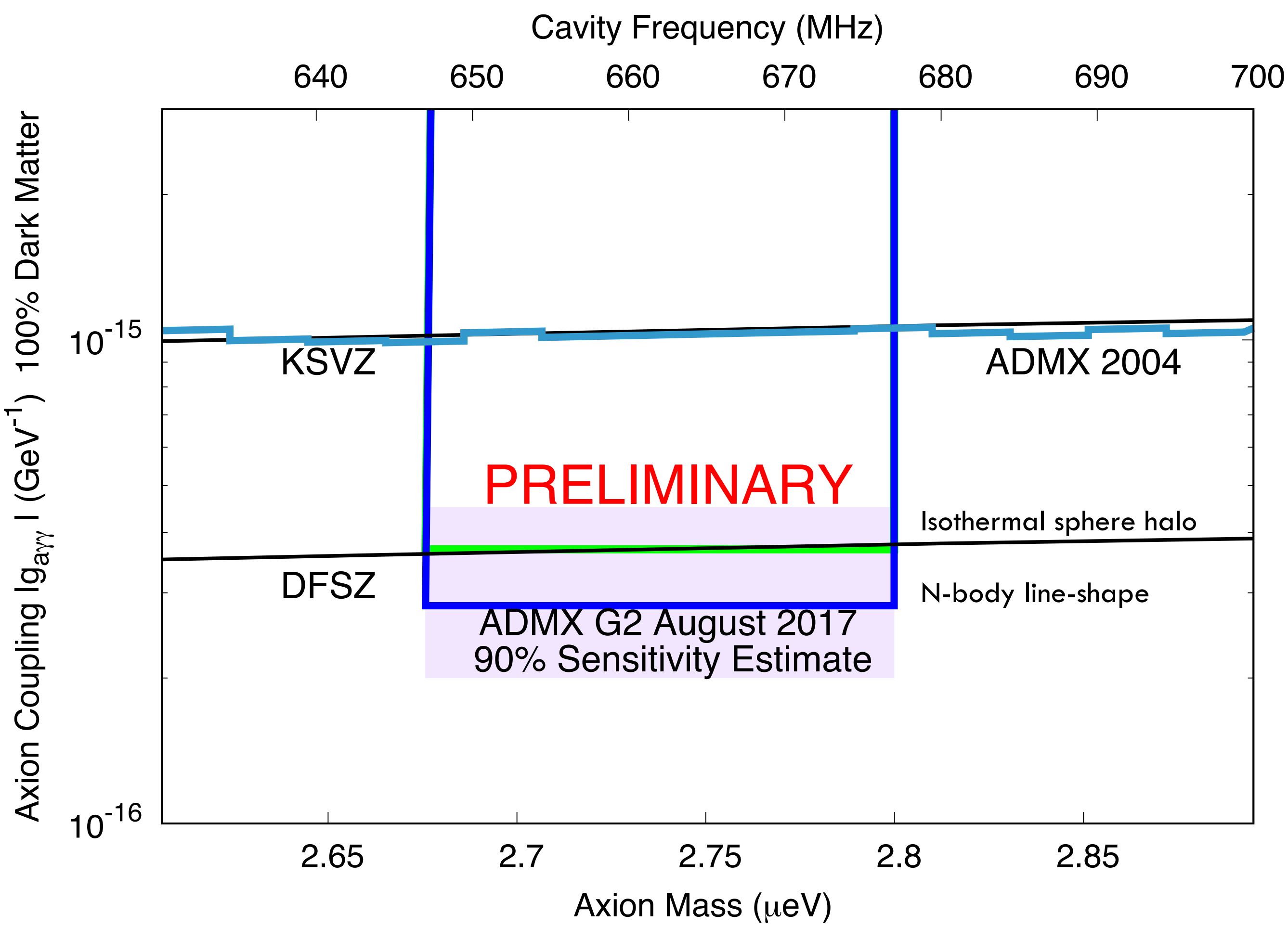


Current run started January 2018

-- 680-800 MHz (JPA)
-- 850-890 MHz (MSA)



ADMX results-2017



Science data taking Jan-June 2017 (645-680 MHz)

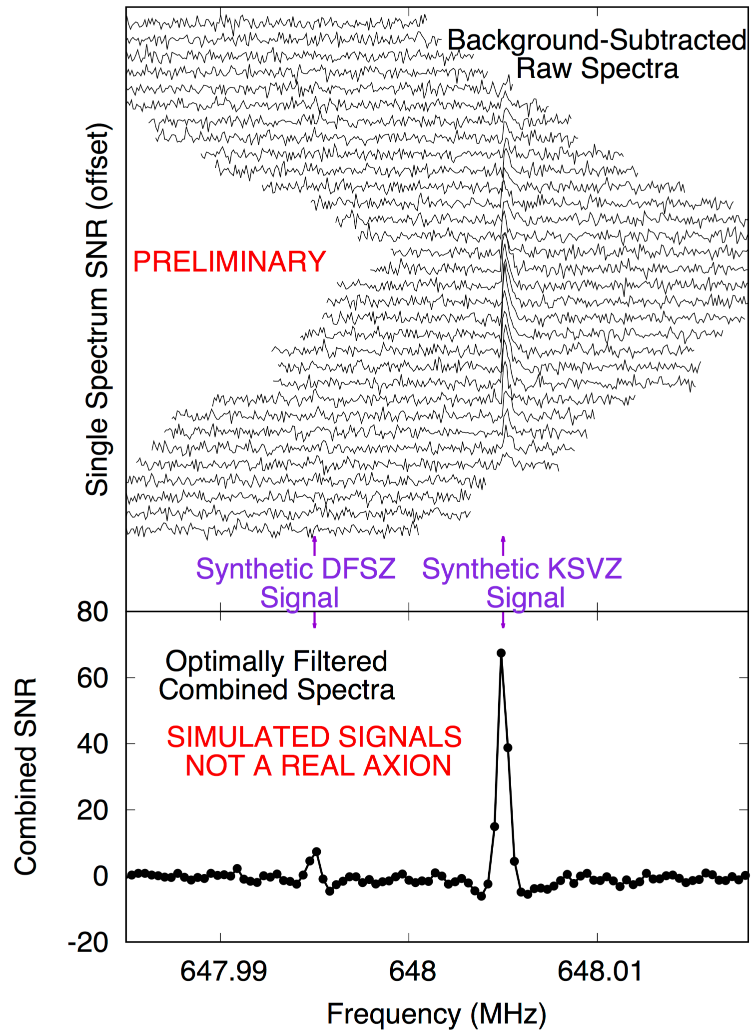
x7 better than previous results

First expt. to reach DFSZ sensitivity!

--submitted to PRL

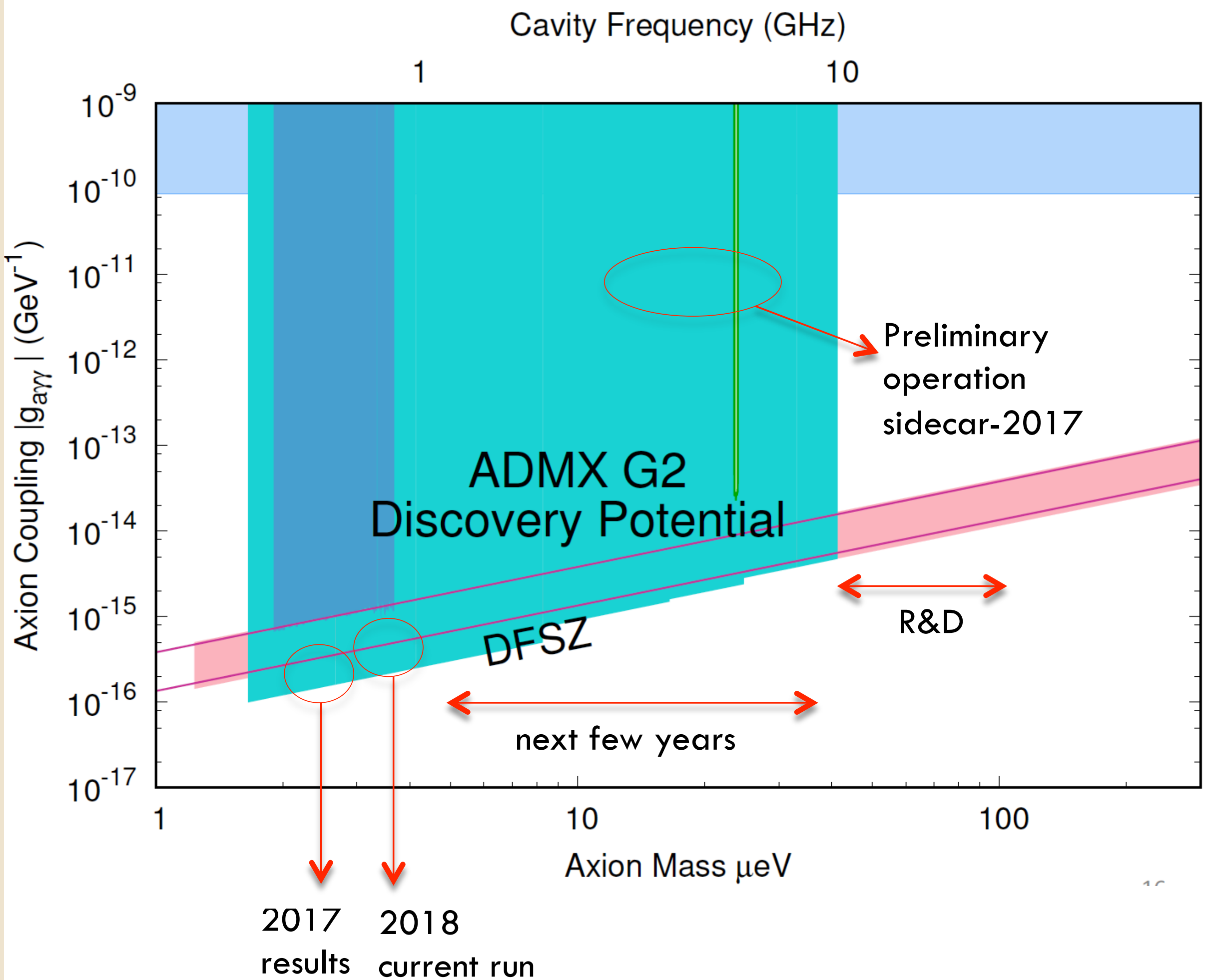
What would an Axion signal look like?

- Synthetic Axion Generator (SAG)--software simulated axion signal added to real data
- Many random injections
- Individual spectra Analysis
  -background: remove receiver transfer function (low order poly fit – flat)
  -weighted signal by Lorentzian line shape
- Combined added spectra:
  -Apply optimal filters (fit expected axion line-shape--make it narrow)
  background: 1√n



Summary

- 680-715, began starting 2018
- Sidecar new limits 5.1-5.8 GHz with B~2T & 7.1-7.2 MHz with B~7T
- >1GHz cavities in production and development phase
- Separate sets of SQUID amplifiers and components necessary
- Yearly cavity and components R & D along with data taking



Popular coverage

SEARCHING FOR THE DARK

ASTROPHYSICS

The Axion Dark Matter Experiment just entered the most sensitive phase yet in its search for invisible particles to explain the universe's hidden mass

By Leslie Rosenberg

IN THE BACKGROUND, the insert containing the heart of the ADMX experiment sits in a clean room. It will soon be lowered into a hole (covered in this image) in the foreground to begin a new run.

Photographs by Jan Allen

January 2018, ScientificAmerican.com 51

Leslie Rosenberg is a professor of physics at the University of Washington. He has been hunting for axion dark matter for more than two decades.

Future direction

- **Higher frequency search:**

$$f = \frac{c}{2.61 * R} \, or \, \frac{R}{1cm} = \frac{11.5GHz}{f}$$

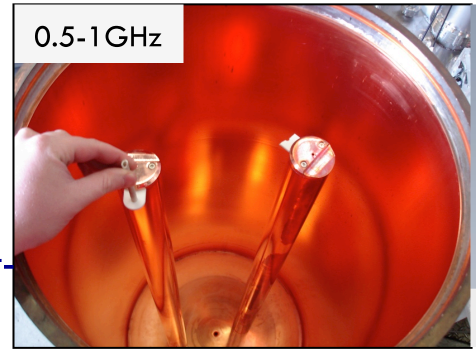
$$f = 550MHz \Rightarrow R = 21cm, L = 100cm$$

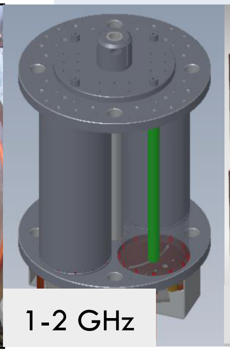
$$f = 4.5GHz \Rightarrow R = 2.6cm, L = 5.6cm$$

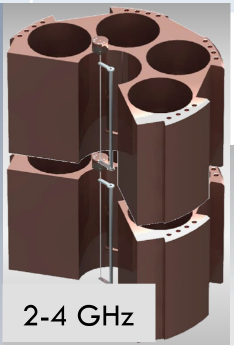
- Cavities get smaller -- use many cavities
- Need to be in phase/identical resonance
  -- frequency lock system
- Power combiner and divider R &D
- >1 GHz in production/development

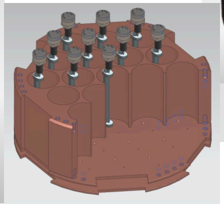
Cavities #	Res freq. MHz	Tuning range MHz	Tuning range μ eV
1	575	402-575	1.7-2.4
1	575	575-908	2.4-3.8
2	897	897-1417	3.7-5.9
4	1207	1207-1907	5-7.9
8	1899	1899-3001	7.8-12
16	2959	2959-4675	12-19
32	3983	3983-6293	16-26

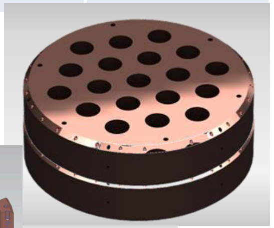
Cavities etc.:
multi-array,
photonic band-gap,
open resonators,
photon counting (qubit-cavity)


0.5-1GHz


1-2 GHz


2-4 GHz




4-6 GHz

1.5-2 GHz design

UW -- cryogenic electronic package

UF -- cavity tuning mechanism

-- power combination

PNLL -- ”

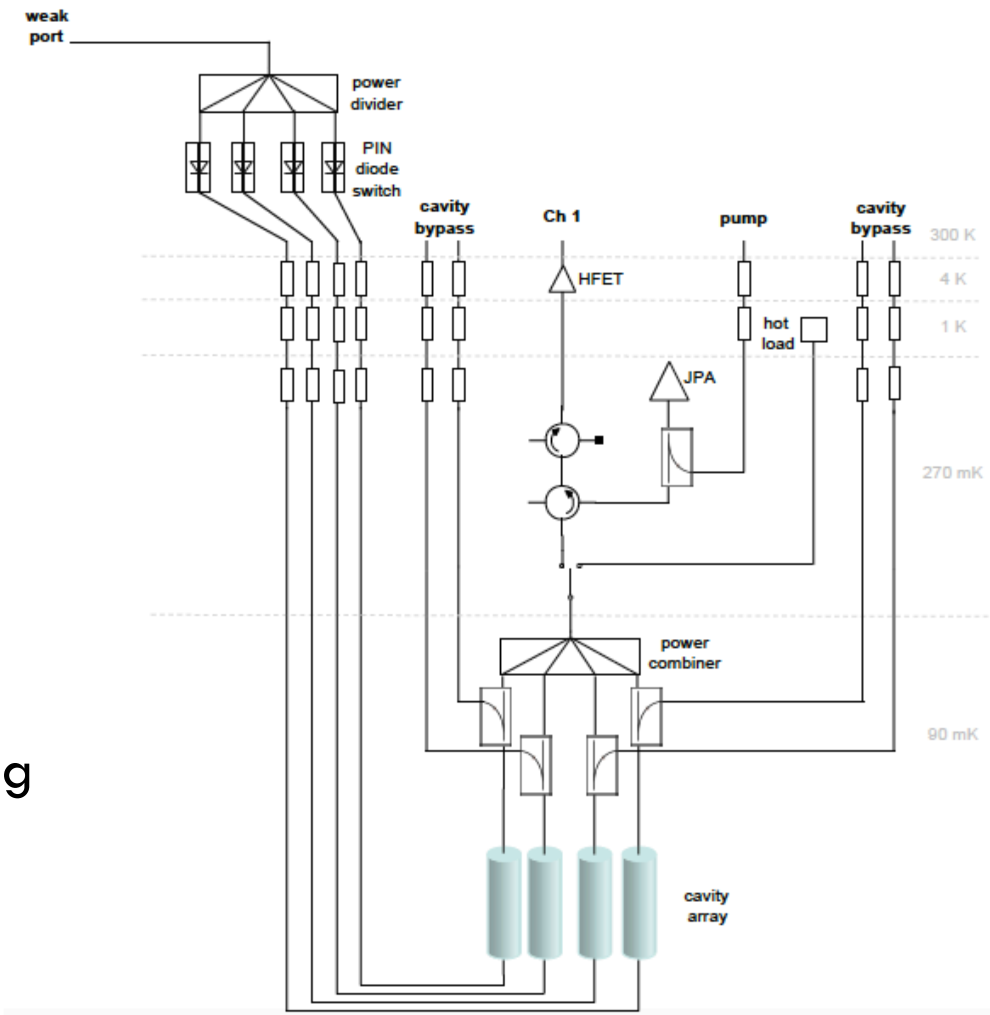
LANL -- cavity motion control

-- components testing

Wash. U -- power combiner and dividers

-- components testing

Operation: End of 2019



Axion search future

- A lot of interest in the last few years -- direct/indirect search
- ADMX is growing
- More sensitive than ever – forefront of Axion Dark Matter search
- Future improvements:

  -- cavity design

  -- higher field magnet

  -- structured/advanced SQUID amps. control

  -- fine refinement in hardware and cryo. techniques
- Busy next few years

  -- Axion will be discovered or eliminated!

Collaboration

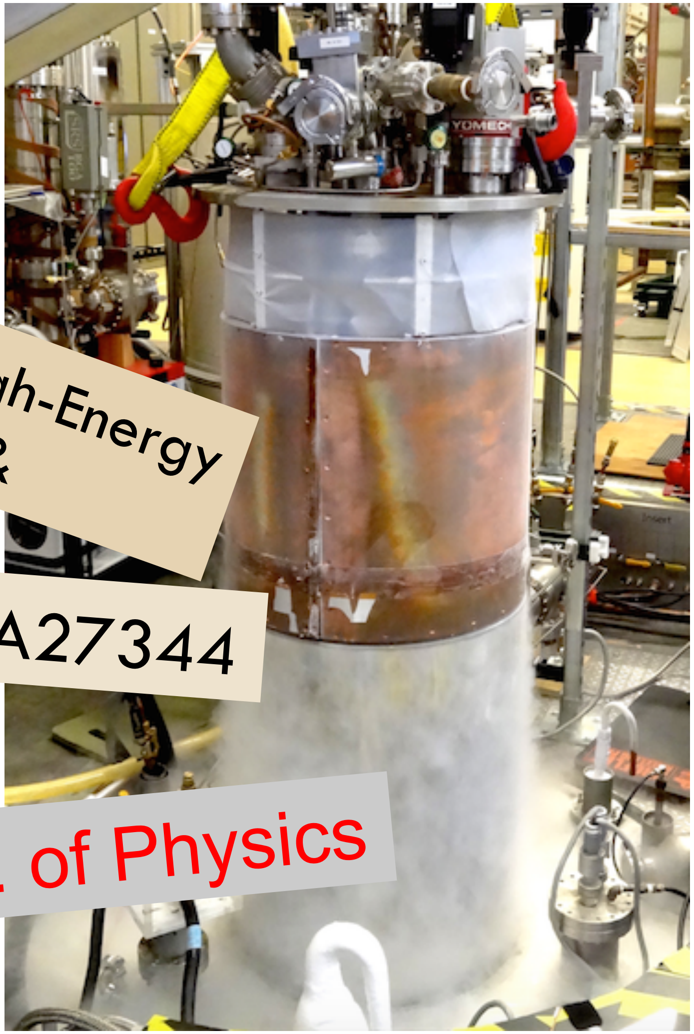
Acknowledgement

U.S. Department of Energy, Office of High-Energy Physics contract DE SC0011665 &

DE-SC0010280 & DE-AC52-07NA27344

Heising-Simons Foundation

University of Washington, Dept. of Physics



Additional slides

Axion Power

$$P_{\mathrm{axion}} = 1.9 \times 10^{-22}\mathrm{W} \left(\frac{V}{136\ l}\right) \left(\frac{B}{6.8\ \mathrm{T}}\right)^2 \left(\frac{C}{0.4}\right) \left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{\rho_{\mathrm{a}}}{0.45\ \mathrm{GeV\,cm^{-3}}}\right) \left(\frac{f}{650\ \mathrm{MHz}}\right) \left(\frac{Q}{50,000}\right).$$

Data Taking/Analysis steps

- Tune the cavity resonance TM_{010} to the desired mass of Axion (photon frequency), tune the SQUID amps. to match this.
- NA checks at this frequency: antenna coupling, Q_{cav}
- SA (Digitize): Record noise power spectra data for 100s in a BW of 25kHz centered at TM_{010}
- For one bin with this BW (25kHz), use at least 20 overlapping noise power spectra
- Receiver transfer function shapes were removed to 95% of least-deviant power bins using Savitsky Golay filter shapes (length 121, polynomial order 4) – removes signal much broader than axions.
- Power scaled to known T_{sys} and weighted by Q_L to produce excess power in each bin for Axion signal
- This excess power is then filtered using two astrophysical signal shapes— Maxwellean predicted by Standard Halo Model and N-body shape.
- When the data were statistically consistent with no Axion signal, the Power equation is used to put the limits on the coupling.
- Frequencies with $>3\sigma$ above the mean power were flagged candidates for rescan/analysis
- If persists, individually checked for RF interference

ADMX site: University of Washington

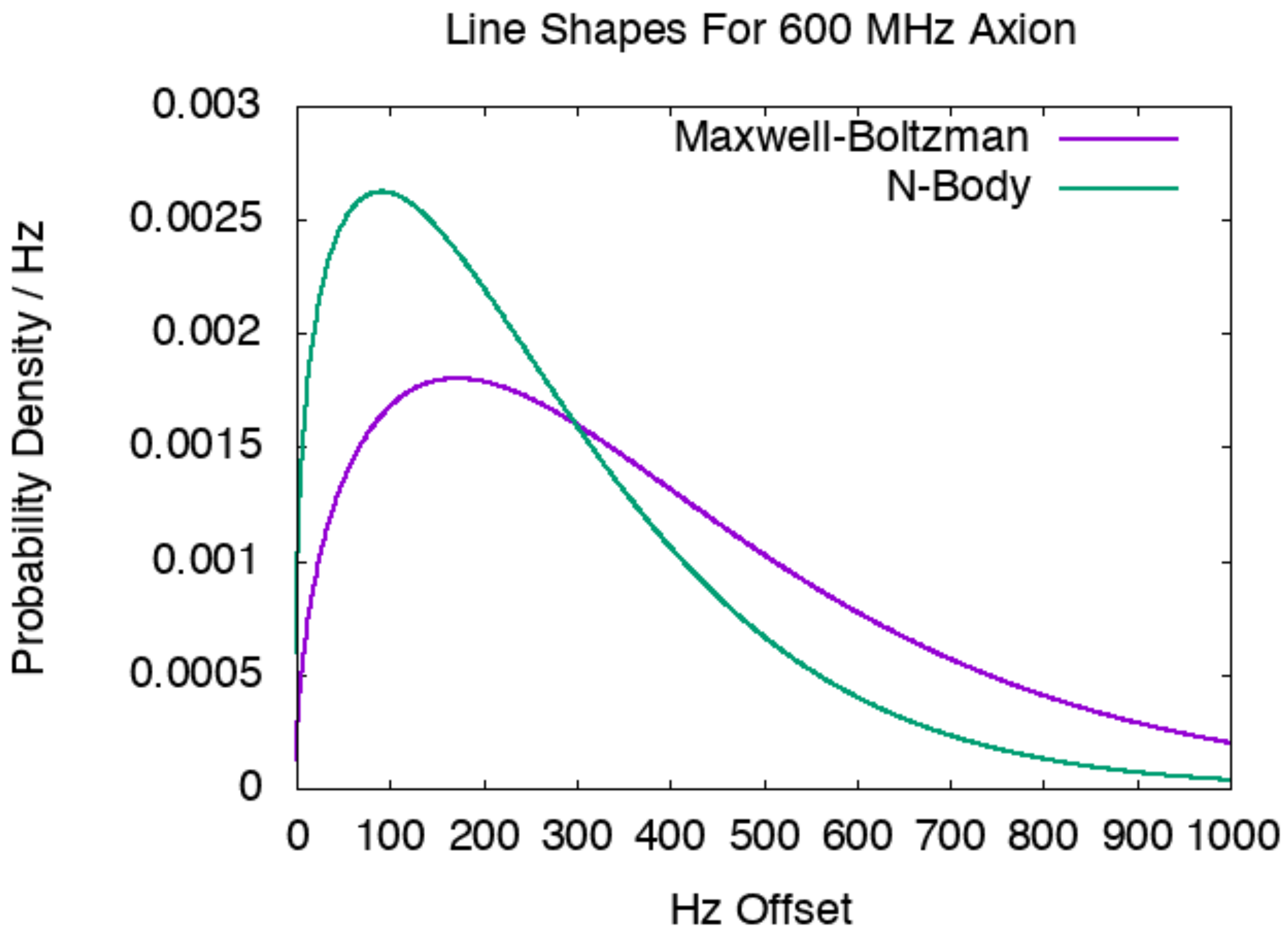
Center for Experimental Nuclear Physics and Astrophysics

Cleanroom (with insert)

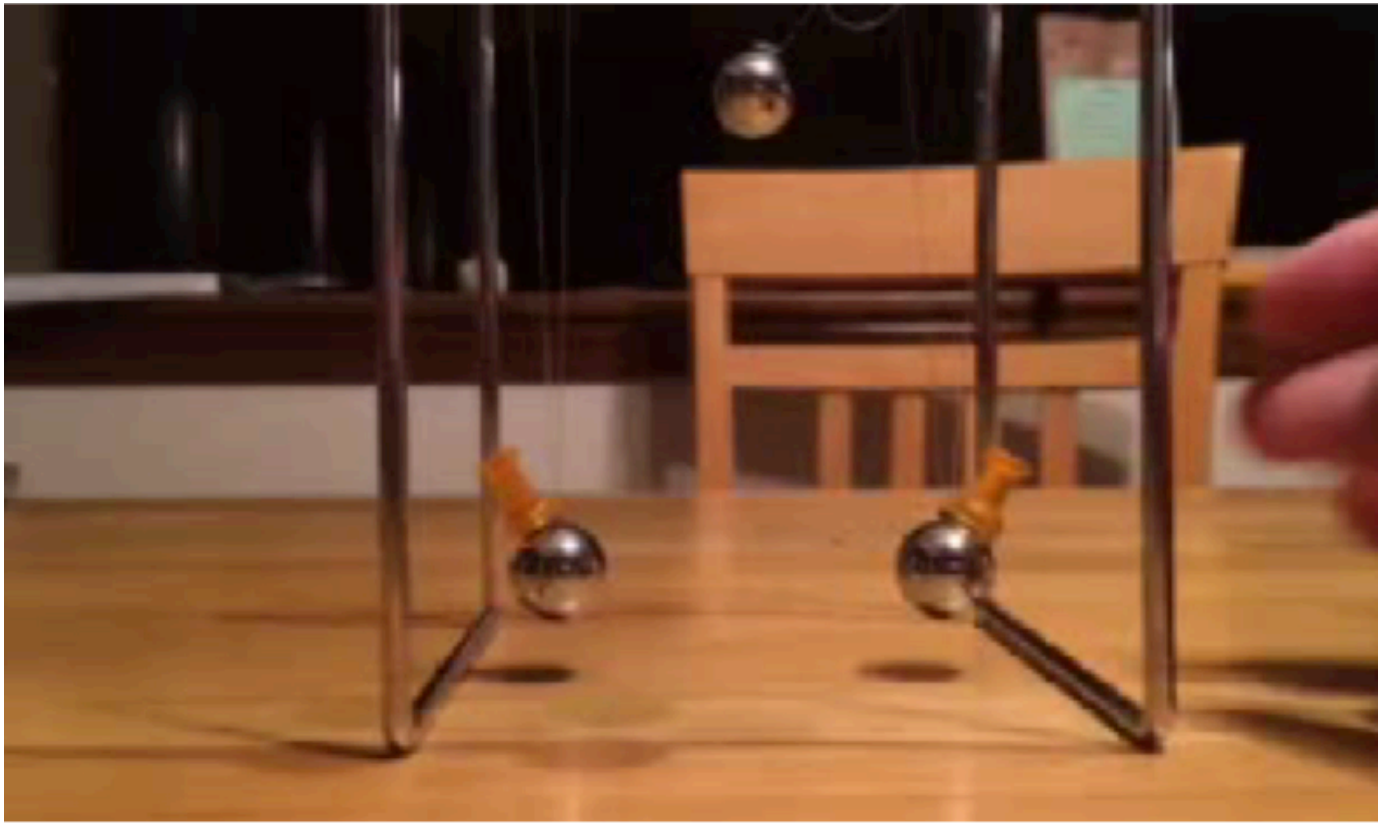
ADMX underground magnet

Helium liquefier

N-body line-shape



Power transfer increased by coherence between cavity E-field and axion field

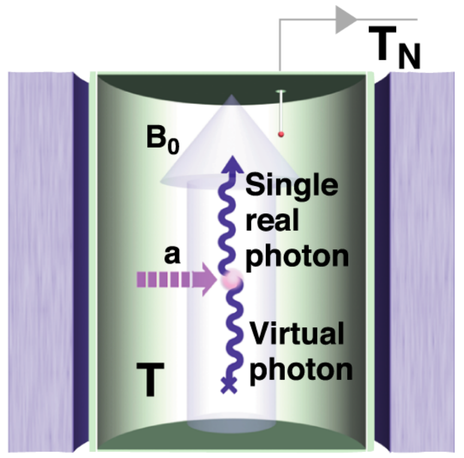


Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

Slide from Aaron Chou (FNAL)

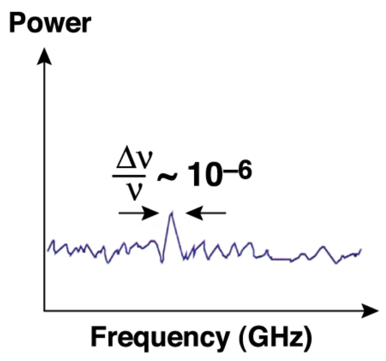
Scaling laws

Primakoff Conversion



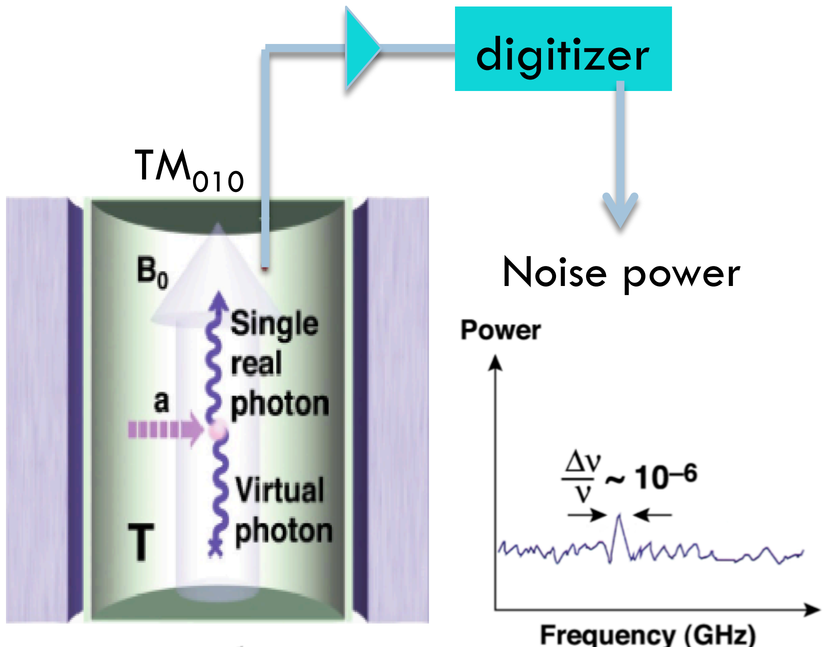
- The conversion is resonant, i.e. the frequency must equal the mass + K. E.
- The total system noise temperature $T_S = T + T_N$ is the critical factor

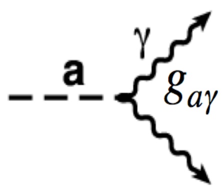
Signal



Scaling Laws	
$\frac{d\nu}{dt} \propto B^4V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

Axion current



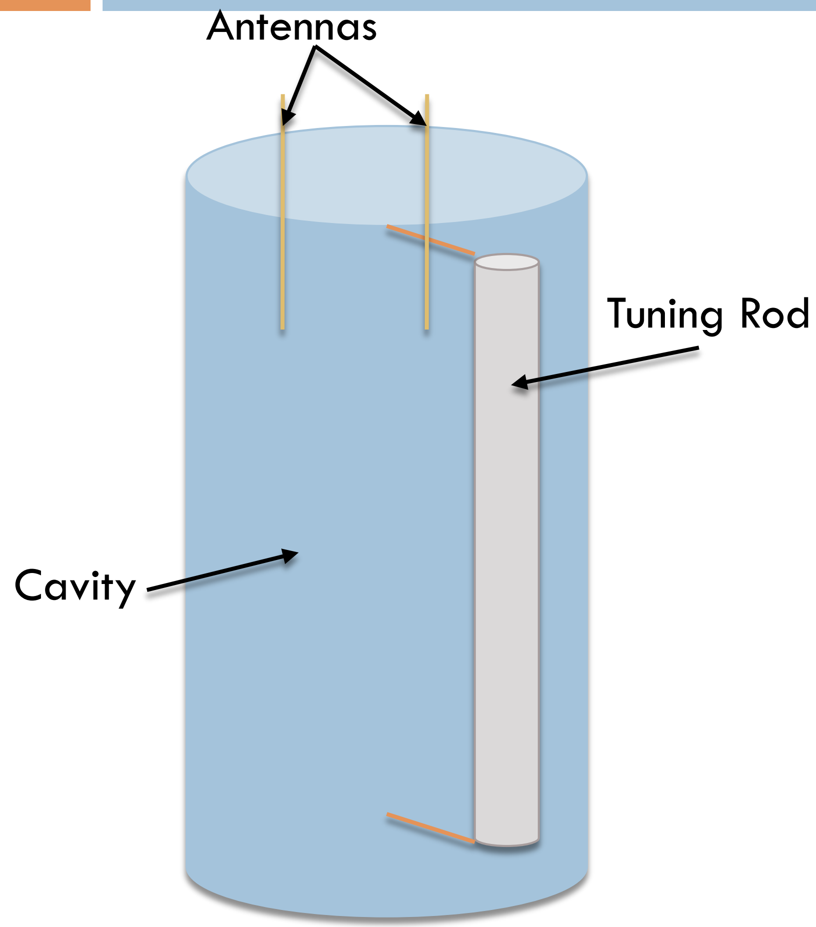


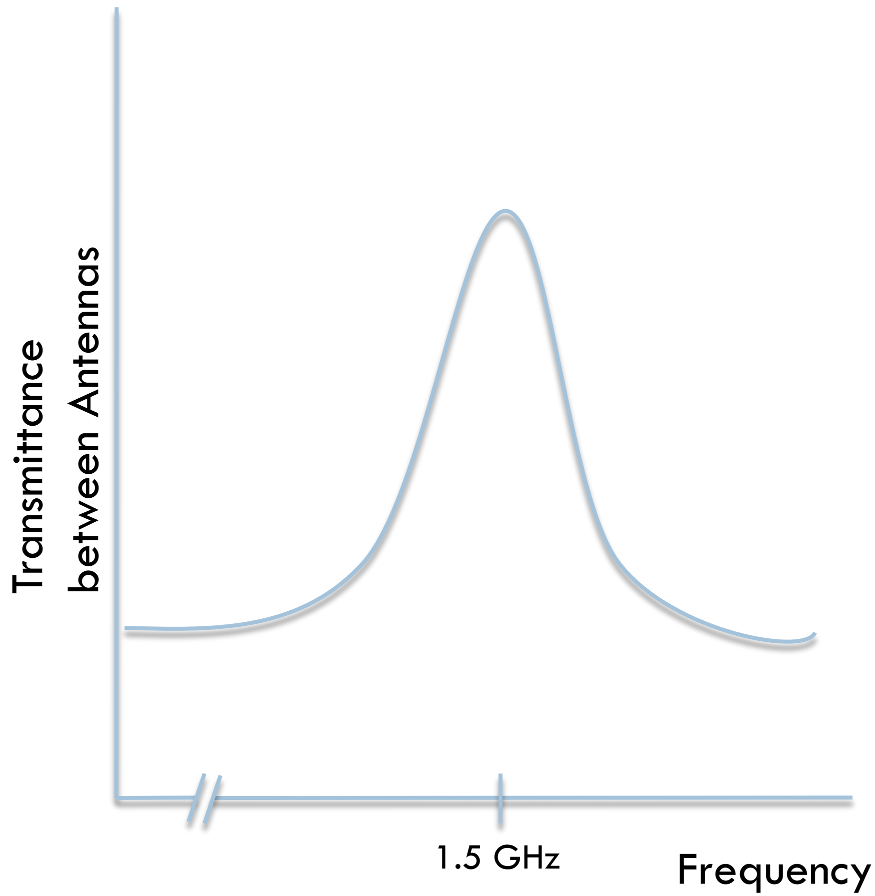
$$\mathcal{L}_{\text{int}} = g_\gamma \theta \vec{B}_0 \cdot \vec{E}$$
$$= g_\gamma \partial_t \theta \vec{B}_0 \cdot \vec{A} + \ldots$$

$$\vec{J}_a(t)$$

$$\vec{\nabla} \times \vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

Microwave Cavity tunable resonance

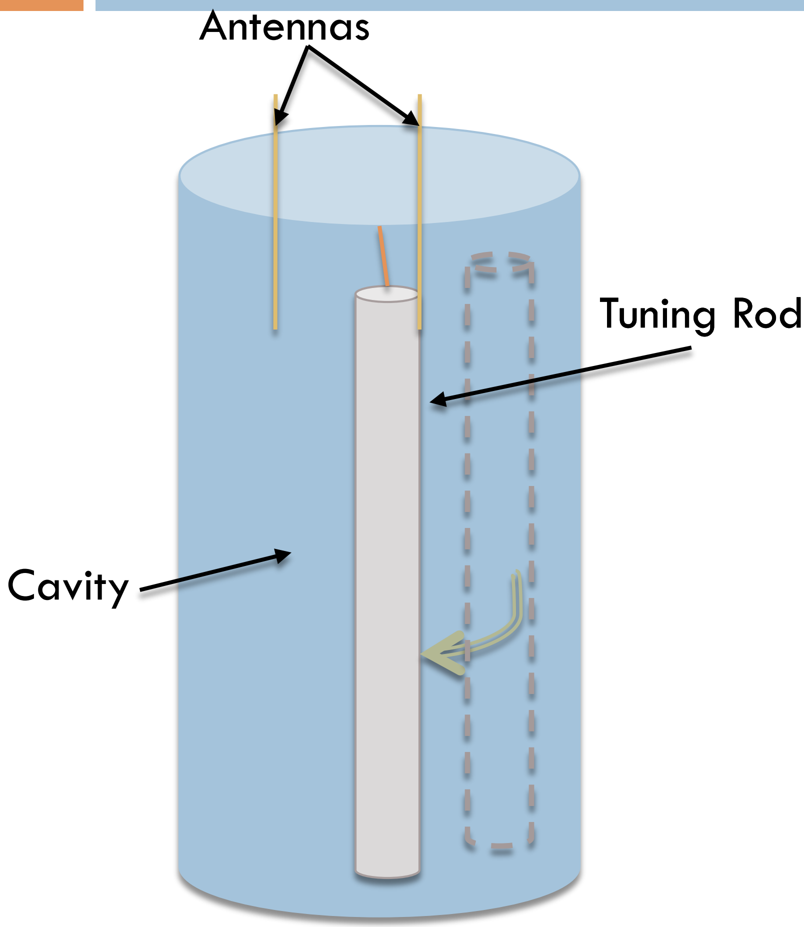


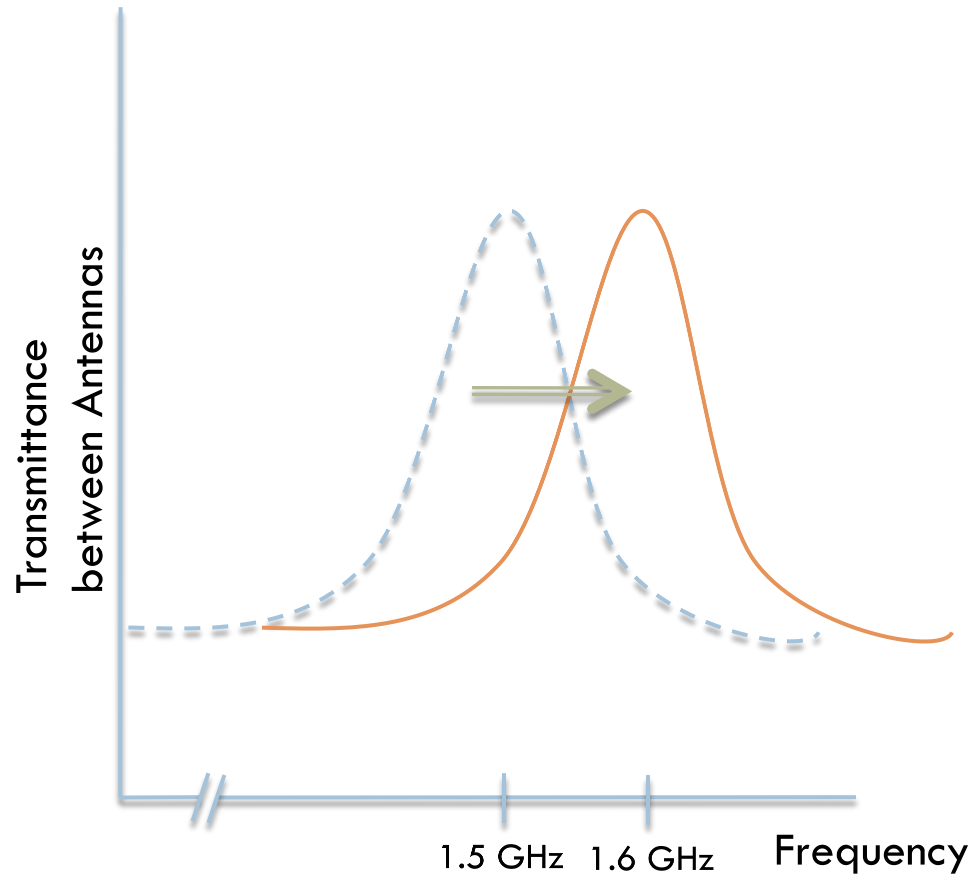


* LLNL sponsored HMC Clinic Final Presentation – 2010

ADMX AXION DARK MATTER EXPERIMENT

Microwave Cavity tunable resonance





* LLNL sponsored HMC Clinic Final Presentation – 2010

Typical ADMX Run Cadence

- Start by injecting a broad, swept RF signal to record cavity response. Record state data (temperatures, hall sensors, pressures, etc)

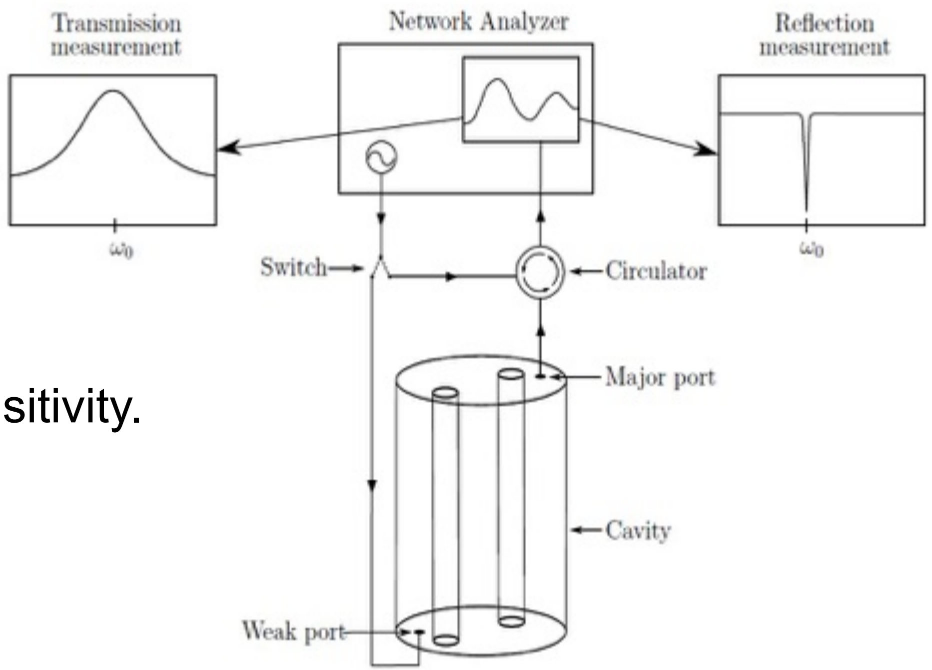
- Integrate for ~ 100 sec to 10s of minutes (final integration time dependent experimental parameters).

- Every few days adjust the critical coupling of the antennas

- Scan rate is trade off in sensitivity vs frequency (mass) coverage

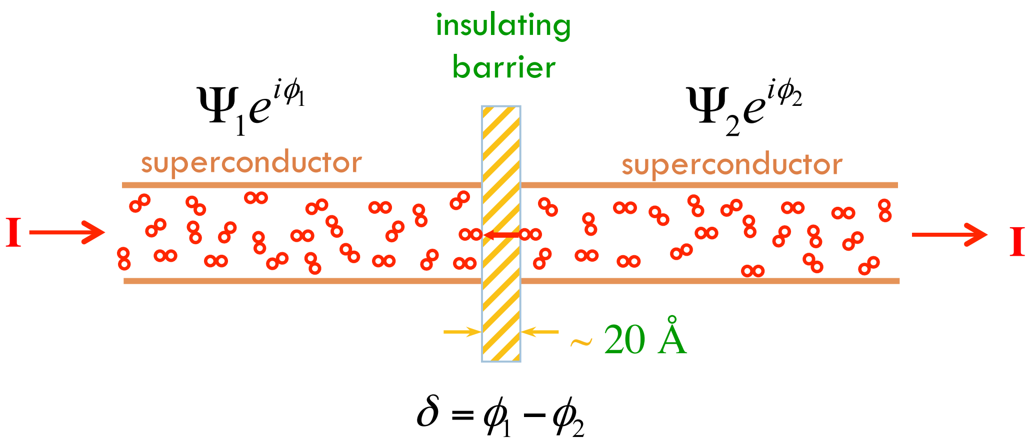
- The scan rate uses a threshold sensitivity.

- Any candidate above threshold is flagged for further study.



Josephson Junction

Josephson Tunneling

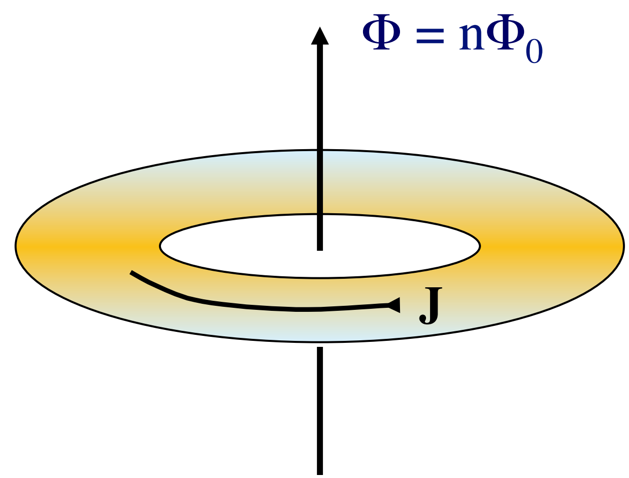


Superconducting state has macroscopic wavefunction.

I and V across the junction are given by the Josephson relations:

$I = I_0 \sin \delta$ $V = \delta\, \Phi_0 / 2\pi$

Flux Quantization



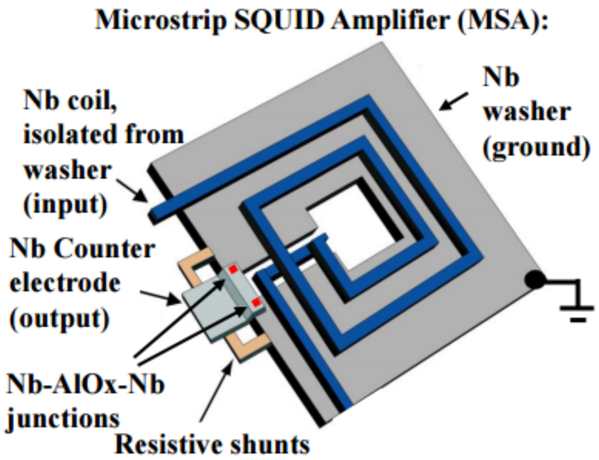
$$\Phi = n\Phi_0 \ (n = 0, \pm 1, \pm 2, \ldots)$$
$$\Phi_0 = h/2e$$

In presence of Josephson element the quantization condition becomes:

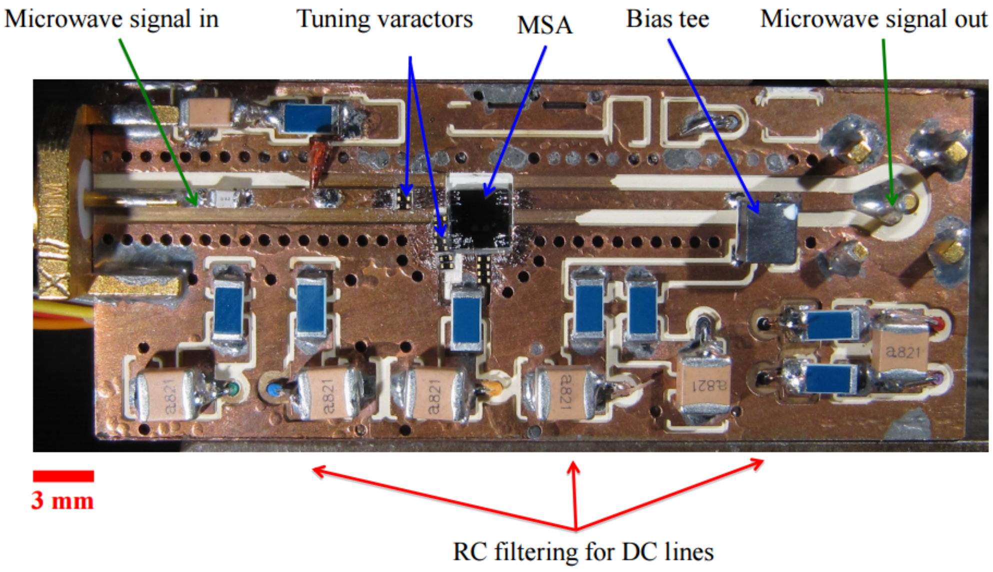
$$\Phi - (\delta/2\pi)\ \Phi_0 = n\Phi_0$$

Courtesy: Sean O'Kelley, UC Berkeley

MSA



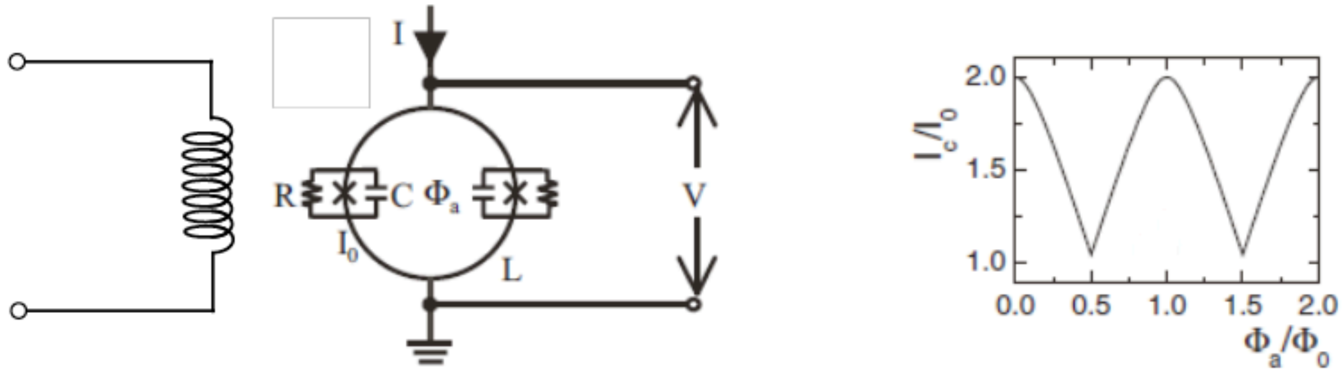
Microstrip SQUID Amplifier (MSA):
Nb coil, isolated from washer (input)
Nb washer (ground)
Nb Counter electrode (output)
Nb-AlOx-Nb junctions
Resistive shunts



Microwave signal in
Tuning varactors
MSA
Bias tee
Microwave signal out
3 mm
RC filtering for DC lines

MSA contd.

Two Josephson junctions on a superconducting ring



Critical Current I_c is modulated by magnetic flux

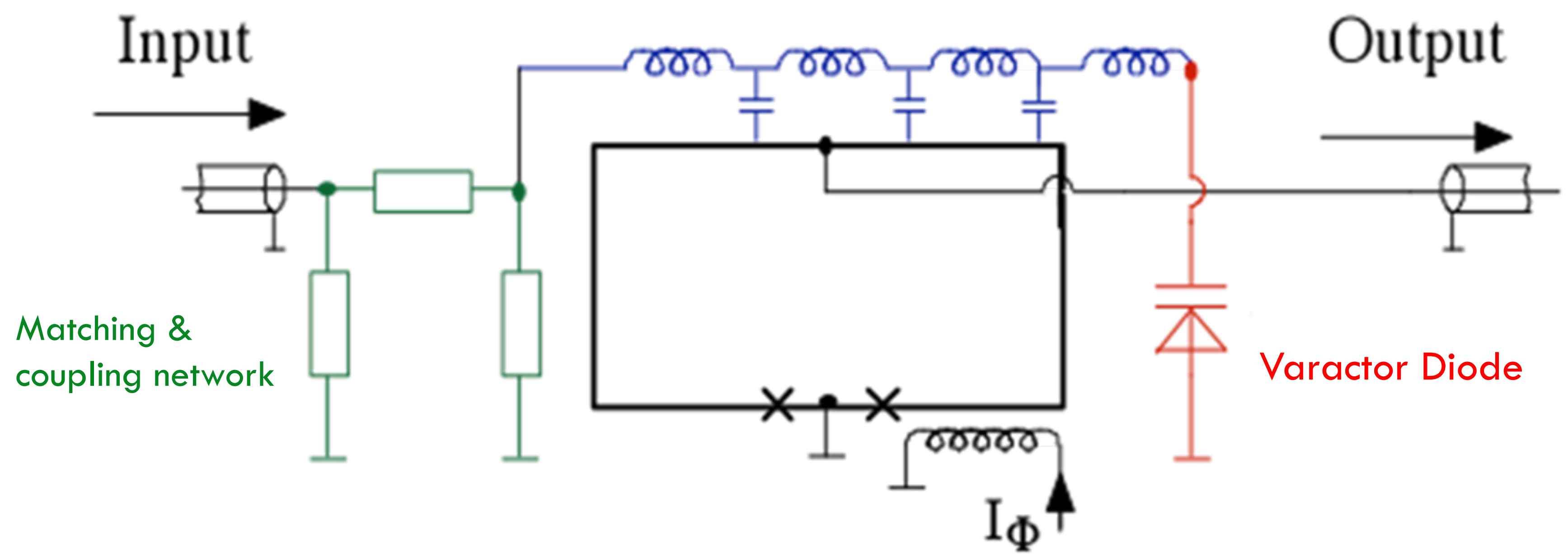
A flux through the SQUID loop (Φ_a) induces a circulating current to satisfy the flux quanitzation condition, adding to the current through one junction, subtracting from the other, and inducing a difference in the phases across the junctions.

Interference of the superconducting wave functions in the two SQUID arms sets the maximum current Ic that can flow at V = 0

With some simplifying assumptions (like symmetric junctions) the DC SQUID can be treated as a single, flux-modulated Josephson junction

Courtesy of Sean O'Kelley

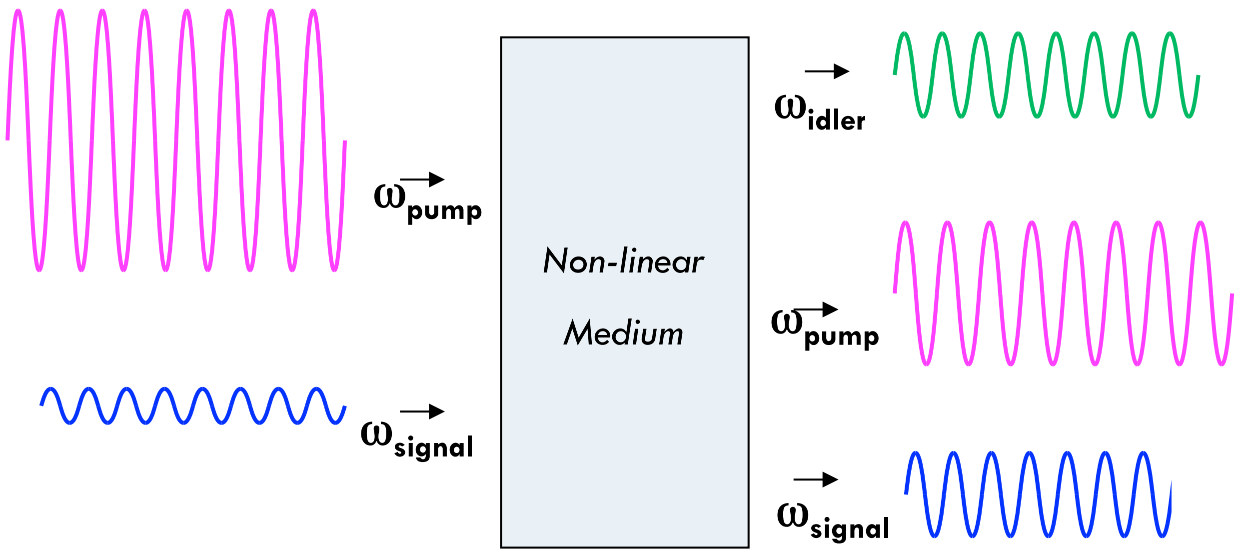
MSA Schematic



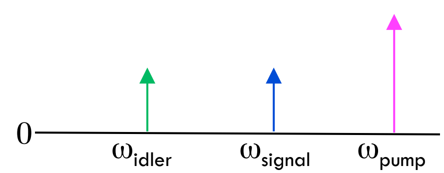
- Varying the capacitance modifies the phase change on reflection, effectively changing the length of the microstrip
- As the phase changes from a node to anti-node, the standing wave changes from $\lambda/2$ to $\lambda/4$, and the resonant frequency varies by a factor of 2
- Varactors must be GaAs (Si freezes out), high Q, very low inductance

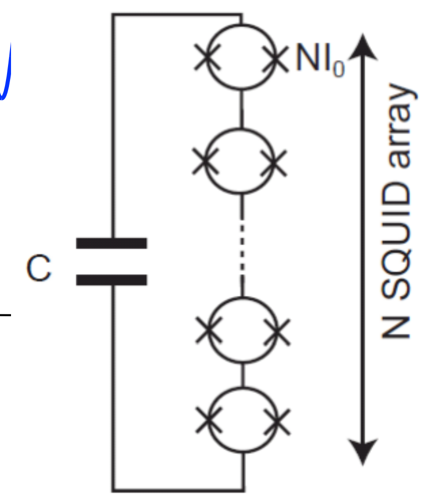
Courtesy: Sean O'Kelley, UC Berkeley

JPA



- $\omega_{pump} = \omega_{signal} + \omega_{idler}$





Squeezed states/ultra noiseless amps.

- JPA-nonlinear-phase insensitive (measures both amplitude and phase of the signal)– by definition, quantum noise limited since simultaneous measurement on amplitude and phase.
- Ultra noiseless amps (degenerate/squeezed state para amp.) —phase sensitive (measures one or the other)– no limit from quantum noise since not measuring two quantities simultaneously

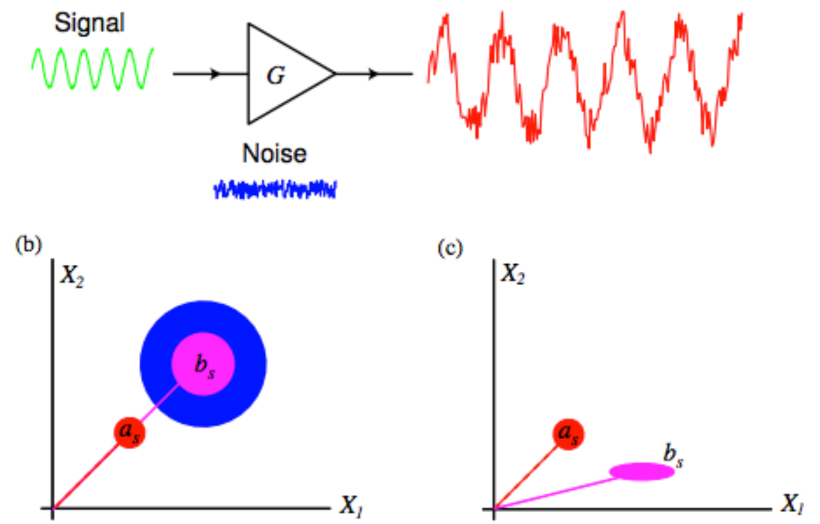


Figure 1.1: (a) In general, the amplification process will degrade the signal to noise ratio by adding certain amount of noise to the signal before amplifying it. (b) Quantum mechanics places a restriction on the minimum amount of this added noise when the amplifier amplifies both quadratures of the signal. When an amplifier achieves this limit, it is said to be quantum limited. (c) On other hand, if the amplifier is a phase-sensitive amplifier, and only amplifies one of the quadratures, then it can do that ideally without adding any noise.

Castellano-thesis

Cavities etc.

- Photonic bandgap: Isolate a single mode using a defect in an open periodic lattice of metal and/or dielectric rods. Well defined TM010 mode, much higher volume at a given frequency than conventional cylindrical cavity. Challenge is to make them tunable. Work at UC Berkeley.

Open resonators retain high Qs at high frequencies. Cold prototype under construction at 20 GHz.

Photon counting method is not limited by Quantum noise limit --10 GHz
Qubit – axion cavity – currently under development at U Chicago/Fermilab

ADMX operations

Live Analysis – Automatic scanning

1. Cavity frequency scanned until a desired signal-to-noise level is reached.
2. Regions with power above trigger threshold are flagged as potential statistical anomalies, external RF leakage, synthetic injected axions
3. Rescan persistent candidates to see if they persist.
4. If they persist have a couple of checks.
   a. Switch to resonant mode that doesn’t couple to axions (TEM mode).
   b. Turn B-Field down (axion power should scale as B^2).

Further Offline Analysis

- Ability to vary the bin size from time-series data.
- High Resolution analysis to look for ultra-sharp lines.

Dilution Refrigerator
(800 µW at 100 mK)