Status of the Axion Dark-Matter eXperiment (ADMX)

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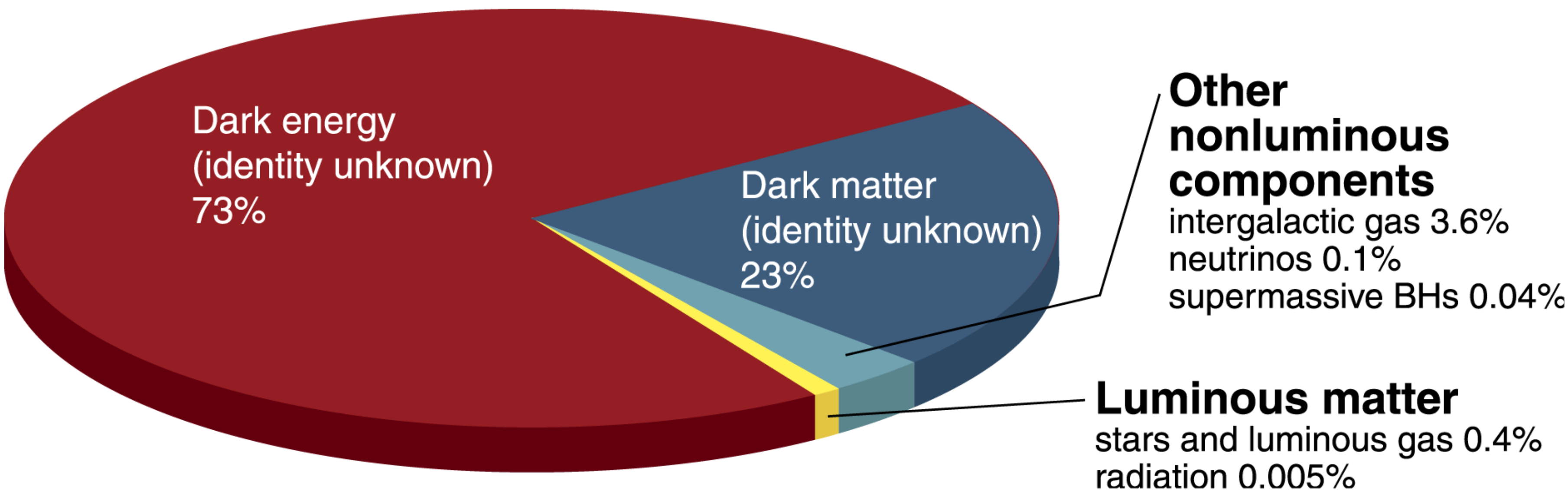
July 23, 2012

Dark-matter axions address the big question: We've inventoried the cosmos (the famous pie chart) …



Science (20 June 2003)

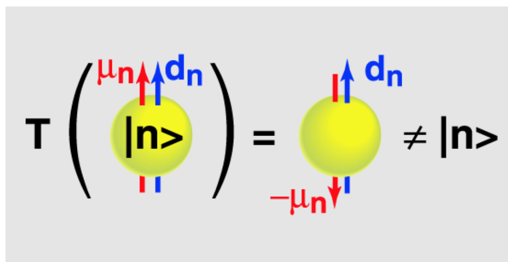
… but we know neither what the "dark energy" or the "dark matter" is. These are two of the very big questions.

What's an axion? (1)

Where did it come from? The "QCD Axion"

There's something disturbing about the Standard Model:
The Standard Model violates P and CP, we expect QCD to violate P and CP, yet QCD does not.

For instance, Why doesn't the neutron have an electric dipole moment?



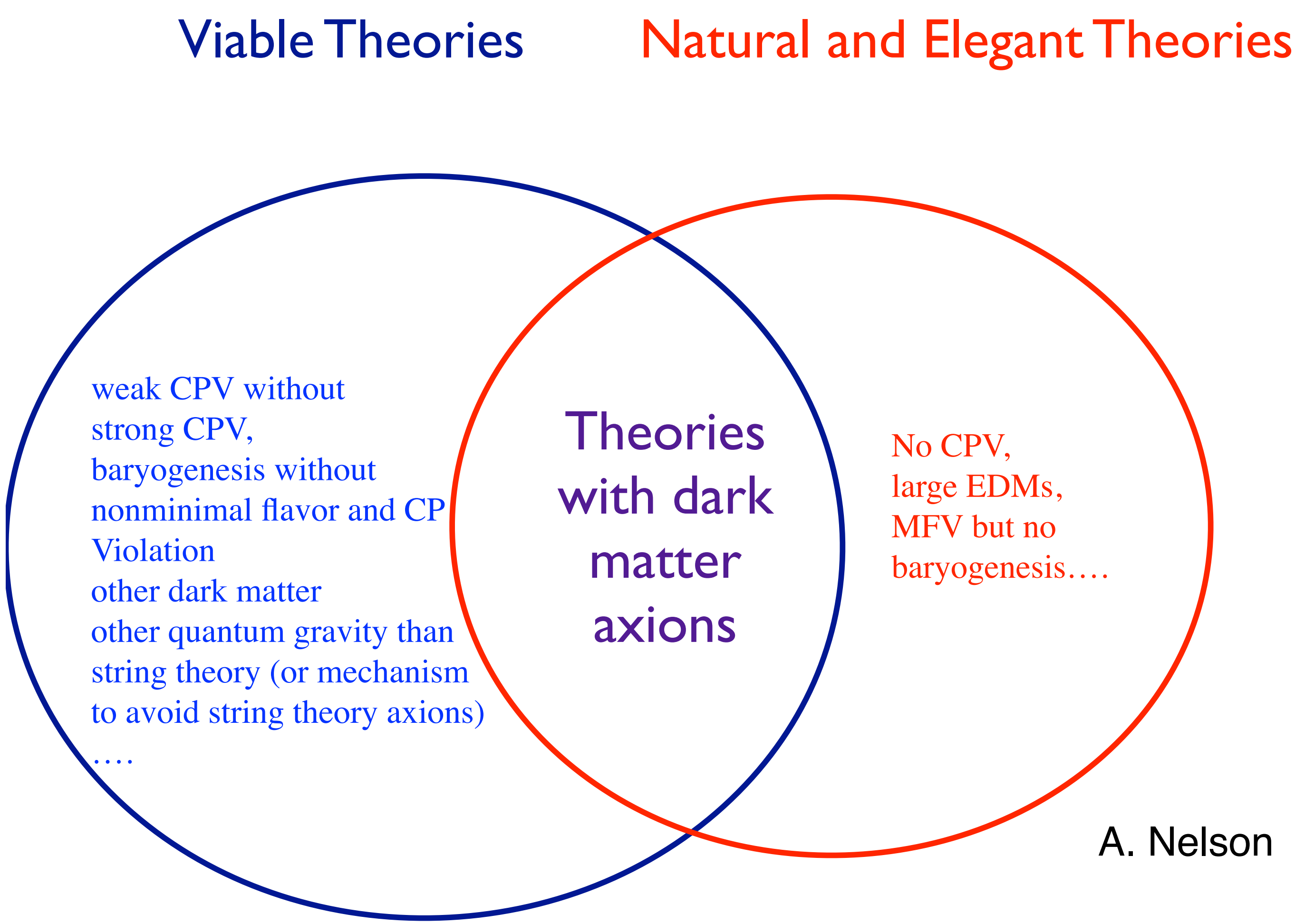
$\theta_{QCD} < 10^{-9}$

Leads to the "Strong CP Problem": Where did QCD CP violation go?

1977: Peccei and Quinn: Apply Higgs-like physics to the problem:
Posit a hidden broken U(1) symmetry $\Rightarrow$
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

Simple & Elegant

What’s an axion? (2): “Cut to the chase”



A. Nelson

What's an axion? Summary properties

- The Axion is a light pseudoscalar resulting from the Peccei-Quinn mechanism to enforce strong-CP conservation

- f_a, the SSB scale of PQ-symmetry, is the one important parameter in the theory

Mass and Couplings

$$m_a \sim 6\ \mu\text{eV} \cdot \left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

Generically, all couplings

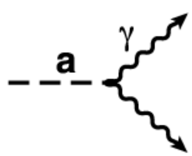
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

$$\Omega_a \sim \left(\frac{5\ \mu\text{eV}}{m_a}\right)^{7/6}$$

(Vacuum misalignment mechanism)

Coupling to Photons



$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = \begin{cases} 0.97\ \text{KSVZ} \\ -0.36\ \text{DFSZ} \end{cases}$$

Axion Mass 'Window'

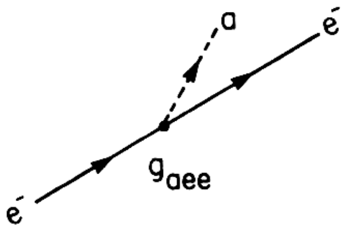
$$10^{-(5\text{ to }6)}\ \text{eV} < m_a < 10^{-(2\text{ to }3)}\ \text{eV}$$

(Overclosure) (SN1987a)

With lower end of window preferred if $\Omega_{CDM} \sim 1$

The a→γγ coupling is special

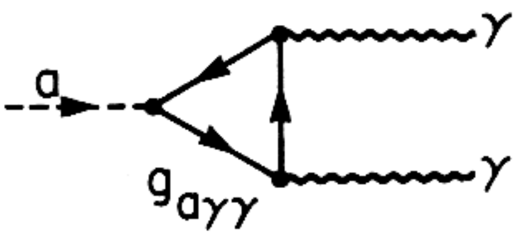
Compare, e.g., axion bremstrahlung off an electron to the axion decay into photons



bremstrahlung

???

$$g_{aee} = \left[\frac{X_e}{N} + \frac{3\alpha^2}{4\pi}\left(\frac{E_{PQ}}{N}\ln(f_{PQ}/m_e) - 1.95\ln(\Lambda_{QCD}/m_e)\right)\right] \times \frac{m_e}{f_{PQ}/N}$$



decay

$(3/8)^{-1}$ "GUT" axion

$$g_{a\gamma\gamma} = \frac{\alpha/2\pi}{f_{PQ}/N}(E_{PQ}/N - 1.95)$$

Few parameters, small residual model dependence

Axions in string theory

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It's true in string theory as well.

Abstract: In the context of string theory, axions appear to provide the most plausible solution of the strong CP problem. However, as has been known for a long time, in many

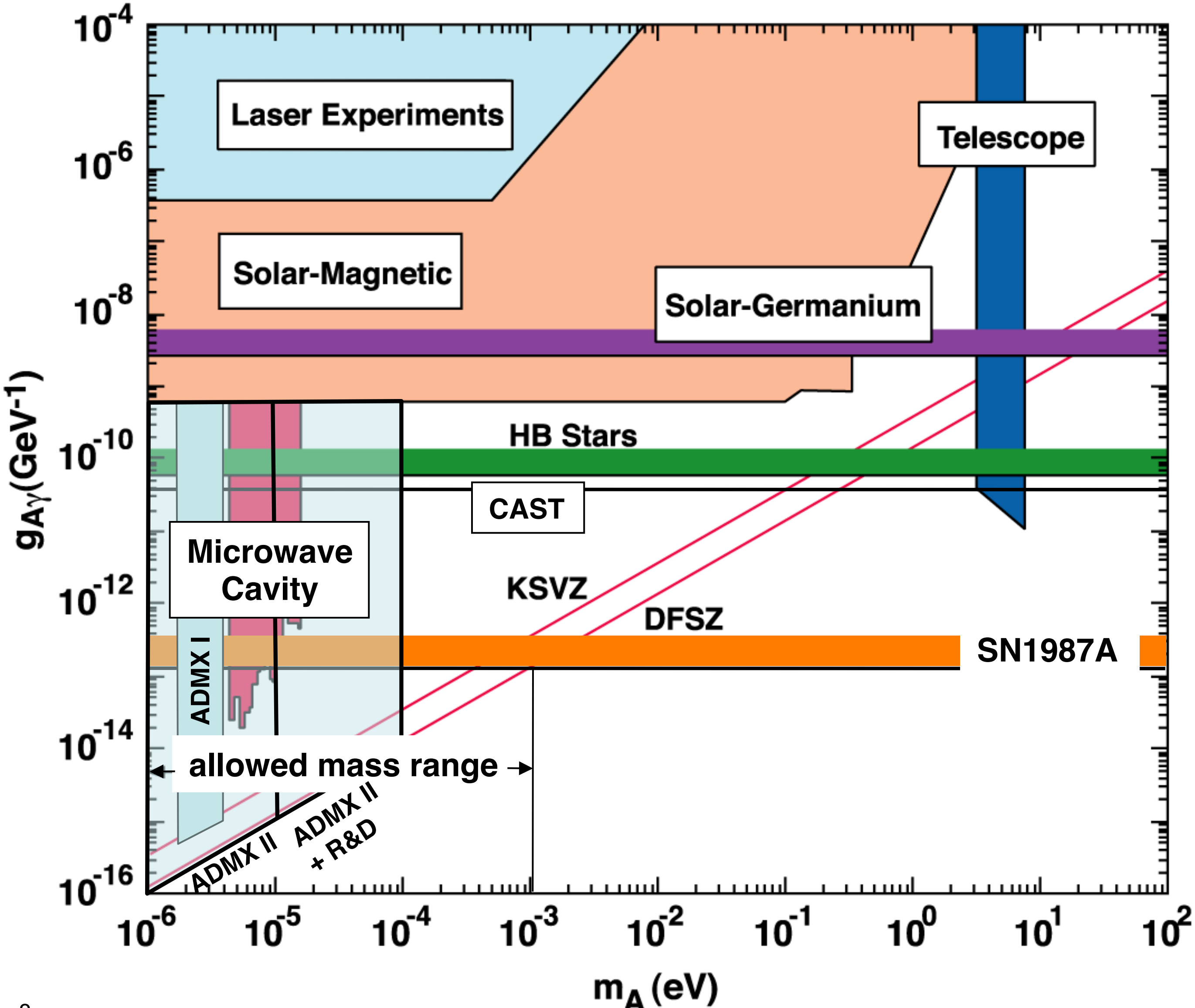
Recap: Axions and dark matter

Some properties of dark matter:
Almost no interactions with normal matter and radiation ("dark…");
Gravitational interactions ("…matter");
Cold (slow-moving in the early universe);

Low mass axions are an ideal dark matter candidate:
"Axions: the thinking persons DM candidate," Michael Turner.

Plus…
The axion mass is constrained to 1 or 2 orders-of-magnitude;
Some axion couplings are constrained to 1 order-of-magnitude;
The axion is doubly-well motivated…it solves 2 problems (Occam's razor).

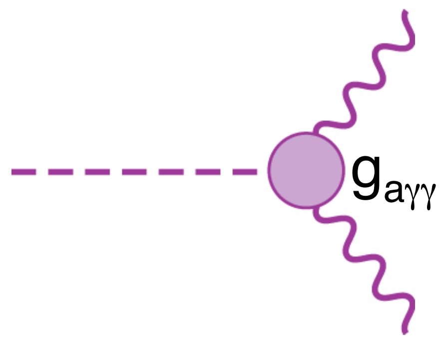
Selected limits: Showing RF-cavity sensitivity to “QCD dark-matter axions”



RF-cavity experiments.
RF-cavity experiments exploit the axion's 2-photon coupling

The axion couples (very weakly, indeed) to normal particles.
(μeV mass axions would live around 10^{50} seconds.)

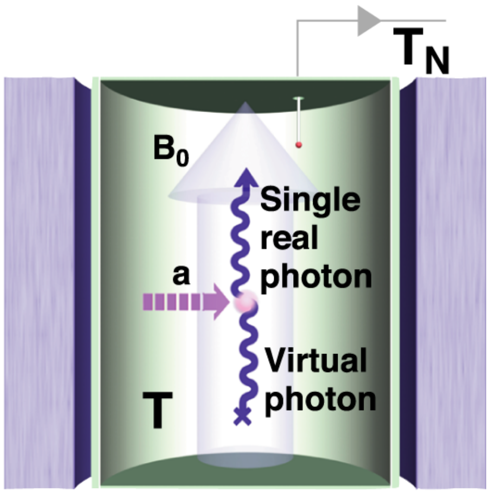
But it recall the axion 2γ coupling has relatively little axion-model dependence



Axions constituting our local galactic halo would have huge number density ~10^{14} cm^{-3}

RF-cavity axion search in practice

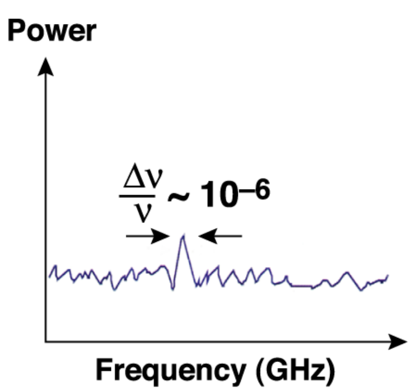
Primakoff Conversion



- 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

The search speed is quadratic in 1/Ts

Signal

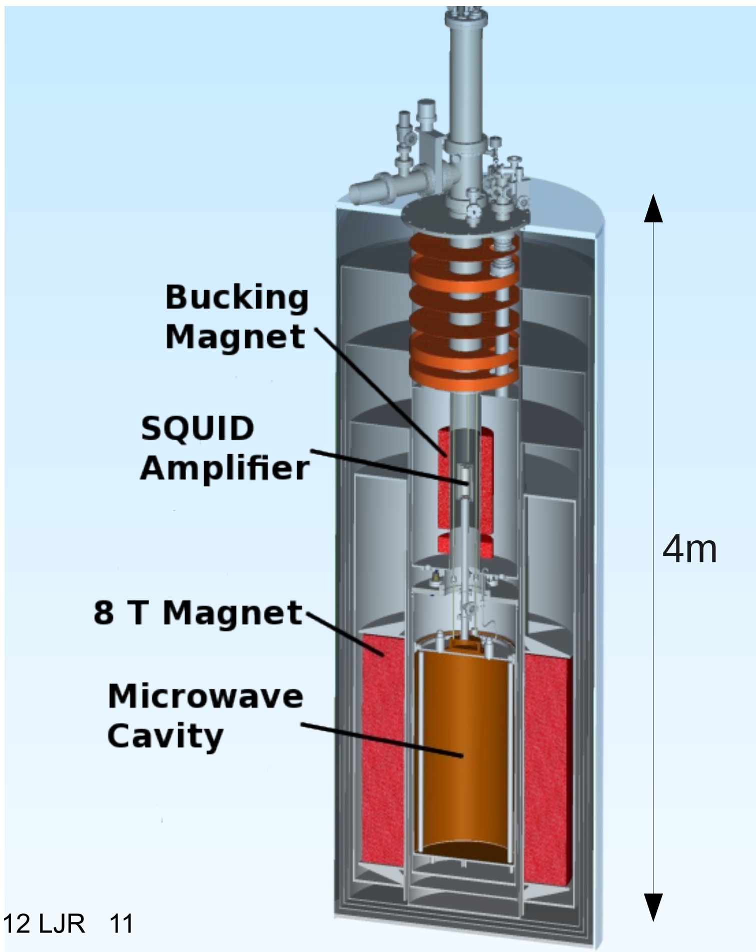


Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

ADMX: Axion Dark-Matter eXperiment
Currently the largest RF-cavity search

U. of Washington, LLNL, U. of Florida, U.C. Berkeley, National Radio Astronomy Observatory, U. of Virginia, Sheffield U., Yale U.

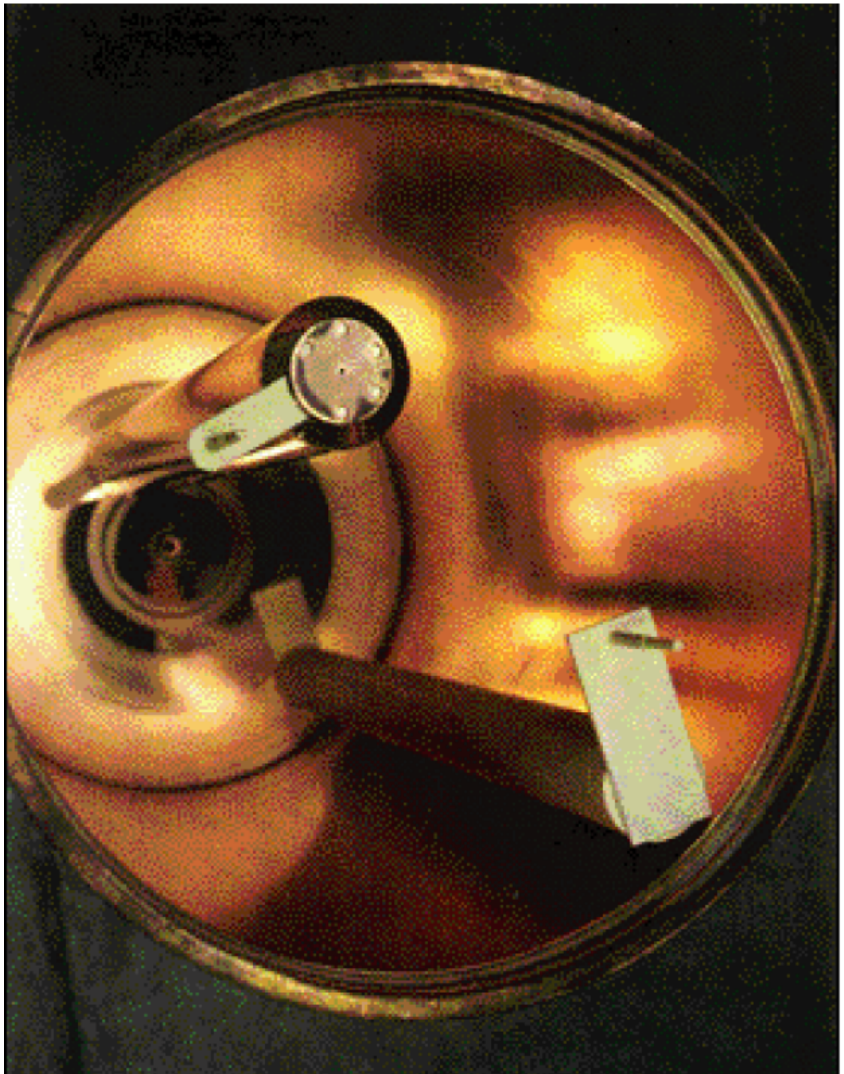
Magnet with insert



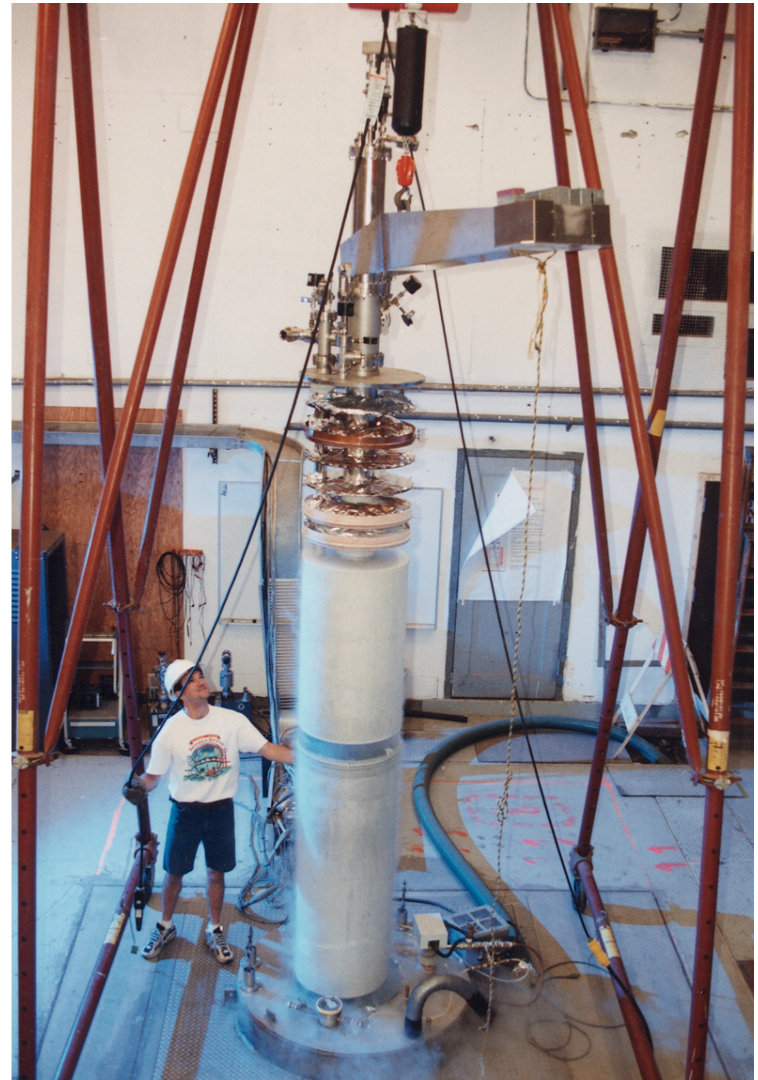
Magnet cryostat

ADMX hardware (1)

High-Q microwave cavity

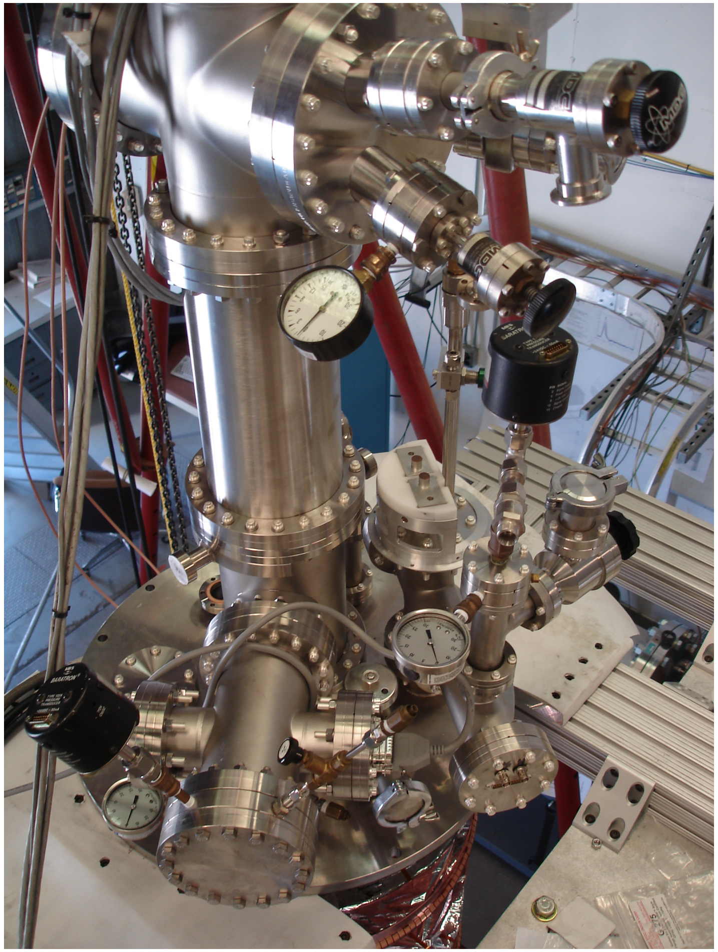


Experiment insert



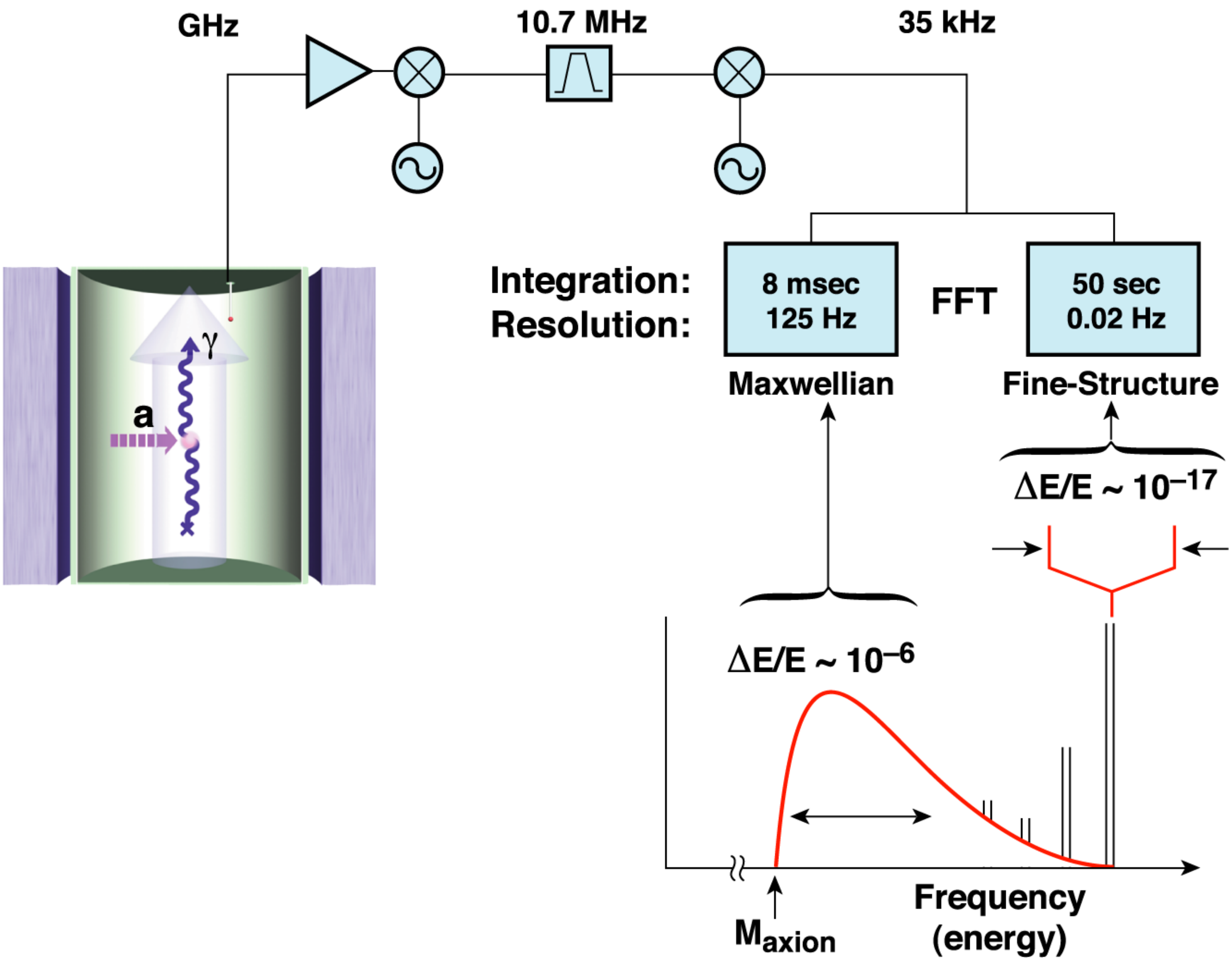
ADMX hardware (2)

Vacuum and cryo

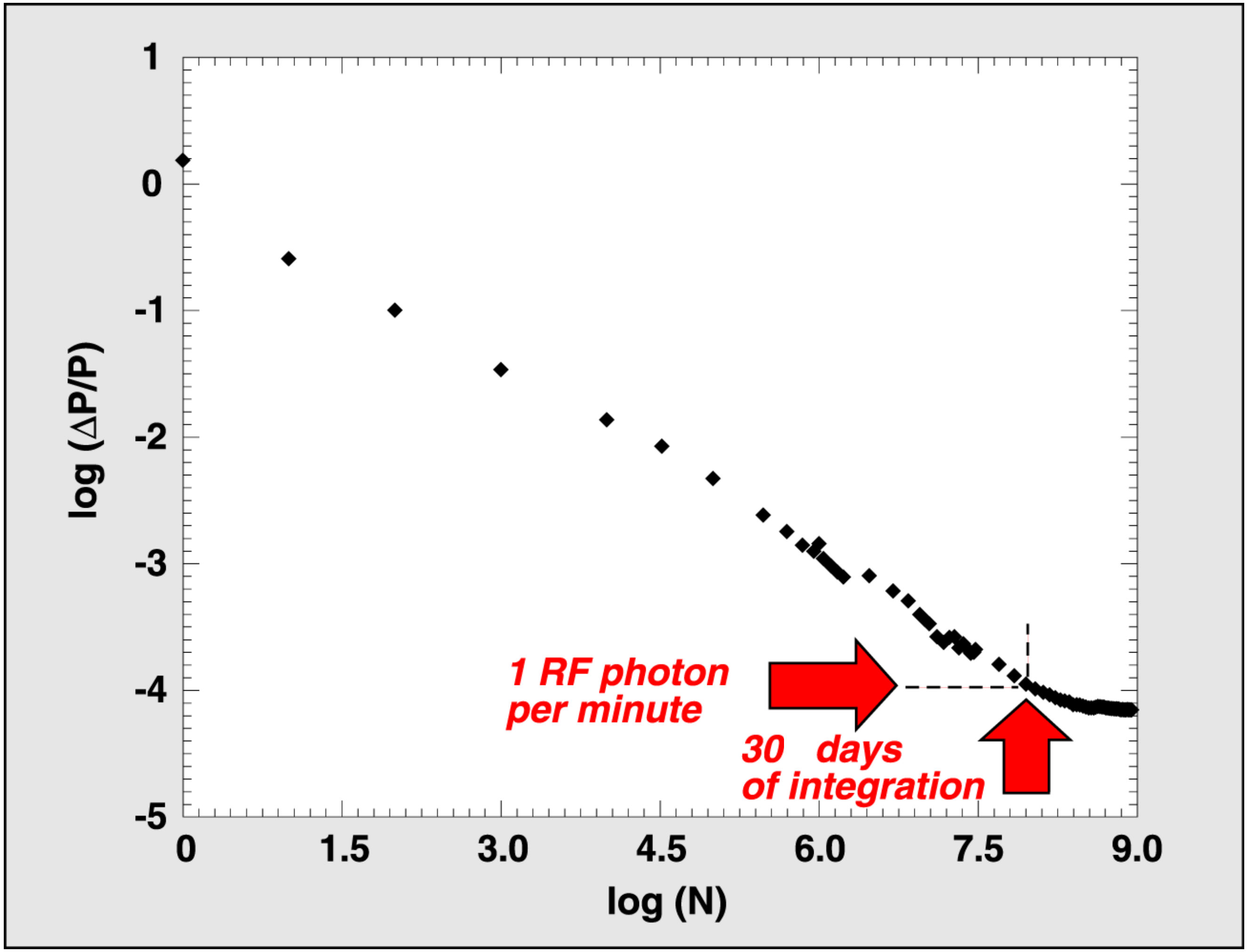


Cryostat lowering

ADMX receiver

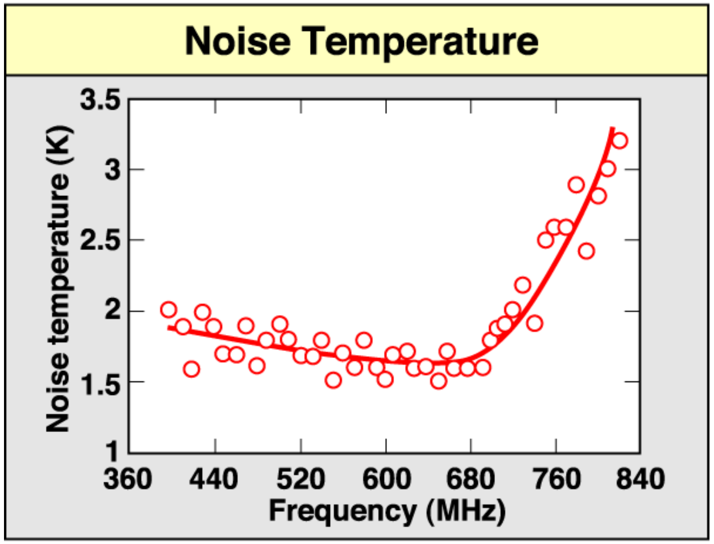


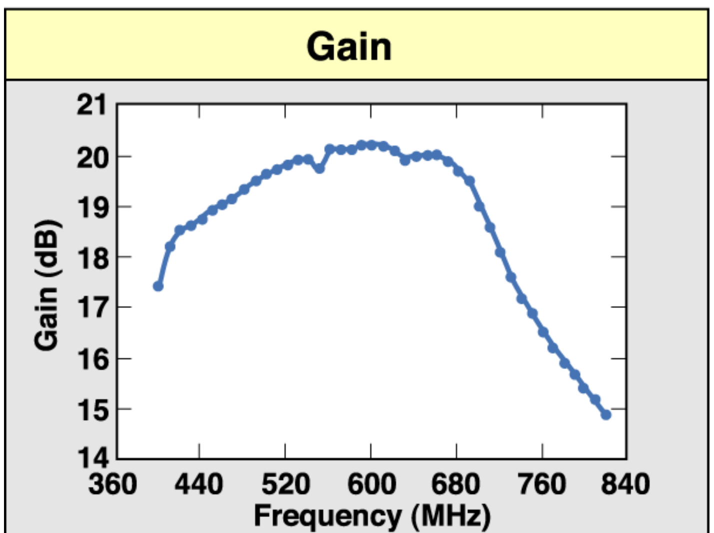
Converted microwave photons are detected by the world's quietest radio receiver



Now: Systematics-limited for signals of 10^{-26} W ~10^{-3} of "DFSZ" axion power (1/100 yoctoWatt).

A slight digression on microwave amplification





HFET amplifiers (Heterojunction Field-Effect Transistor)

- **A.k.a. HEMT™ (High Electron Mobility Transistor)**
- **Workhorse of radio astronomy, military communications, etc.**

- **Best to date $T_N \gtrsim 1$ K**

But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!

A quantum-limited amplifier would both give us definitive sensitivity, *and* dramatically speed up the search!

Upgrade path: Quantum-limited SQUID-based amplification.

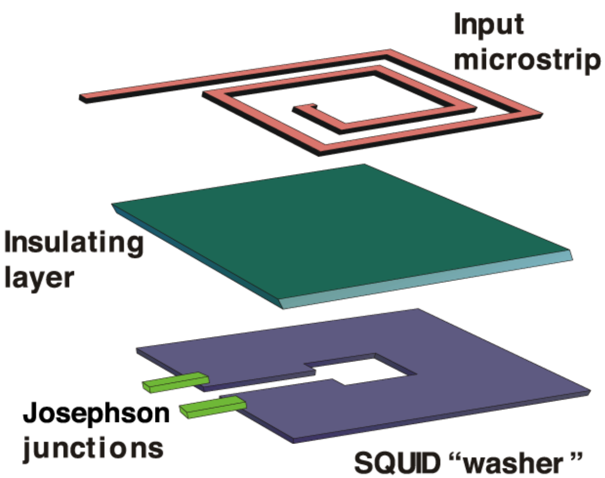
APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 7 12 FEBRUARY 2001

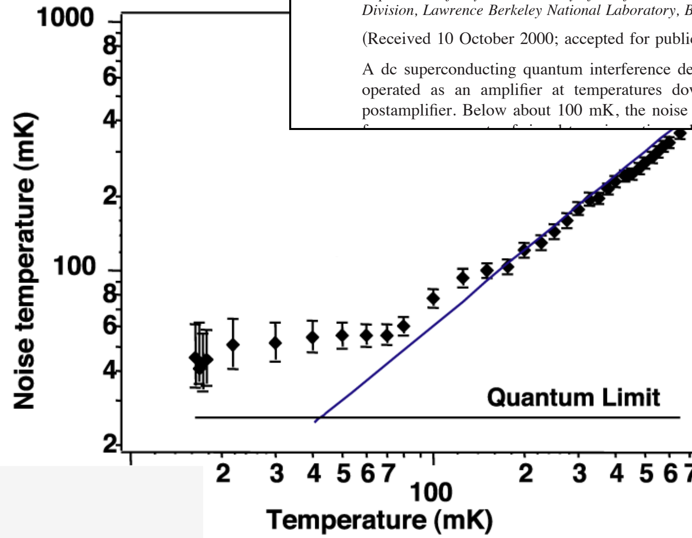
Superconducting quantum interference device as a near-quantum-limited amplifier at 0.5 GHz

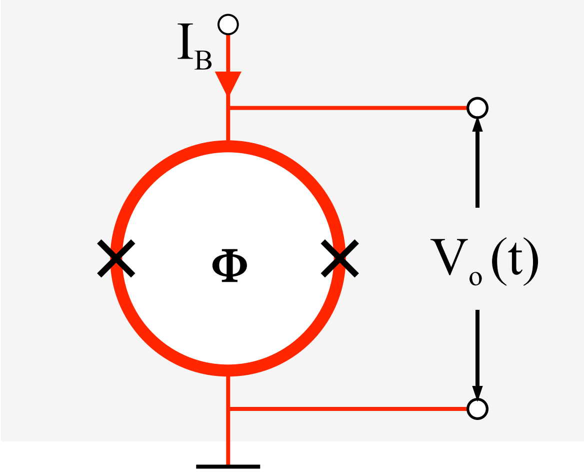
Michael Mück, J. B. Kycia, and John Clarke
Department of Physics, University of California, Berkeley, California 94720 and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

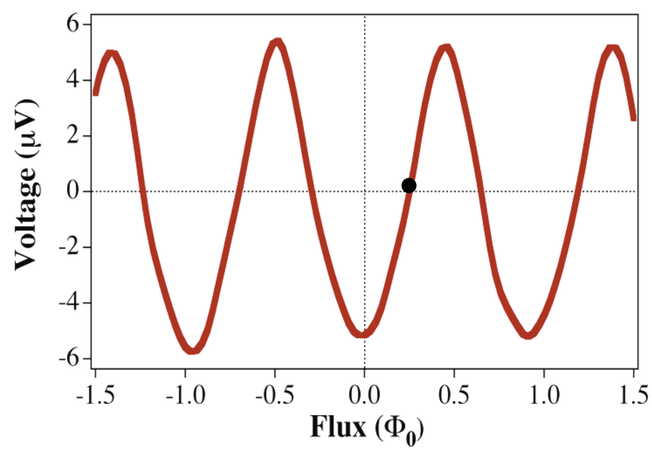
(Received 10 October 2000; accepted for publication 14 December 2000)

A dc superconducting quantum interference device (SQUID) with a resonant microstrip input is operated as an amplifier at temperatures down to 20 mK. A second SQUID is used as a postamplifier. Below about 100 mK, the noise temperature is 52±20 mK at 538 MHz, estimated



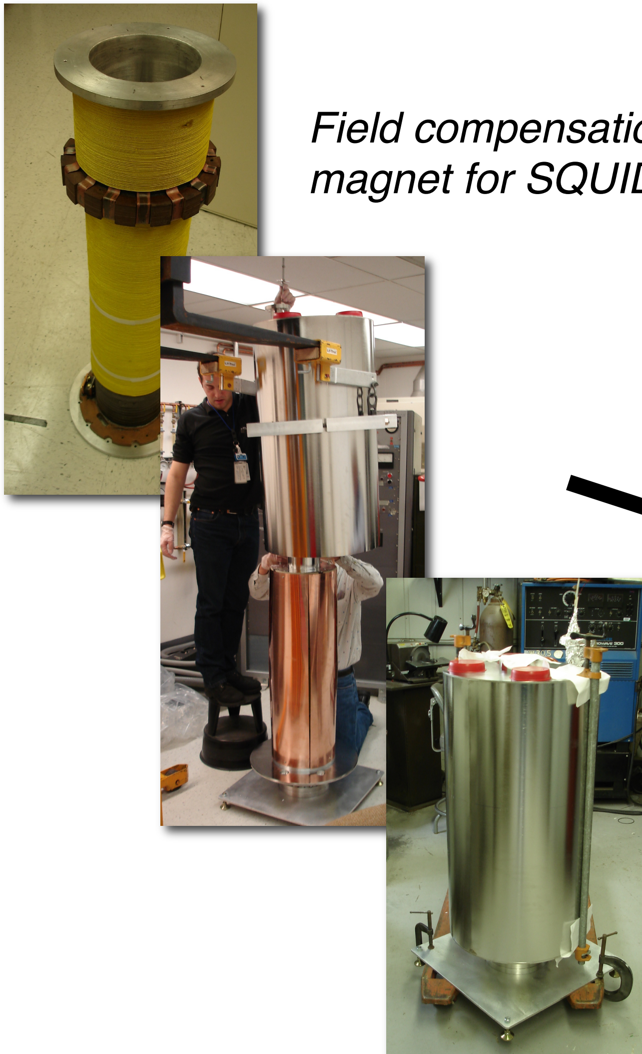




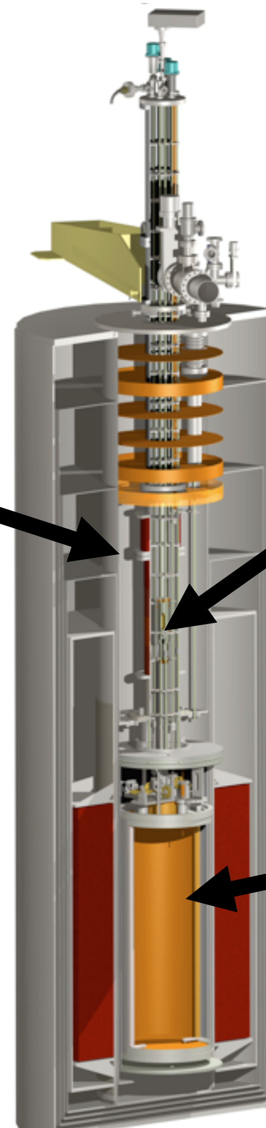


- **GHz SQUIDs have been measured with T_N ~50 mK**
- **Near quantum–limited noise**
- **This provides an enormous increase in ADMX sensitivity**

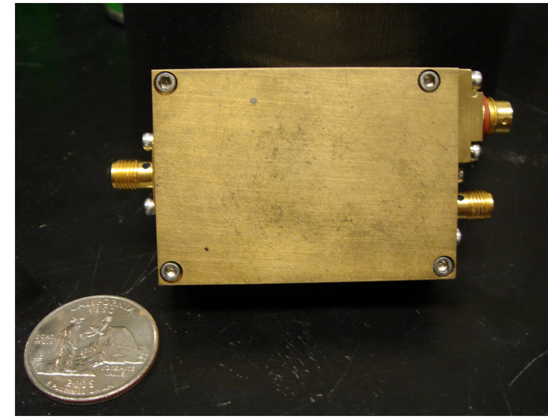
ADMX SQUID-based detector



Field compensation magnet for SQUIDs

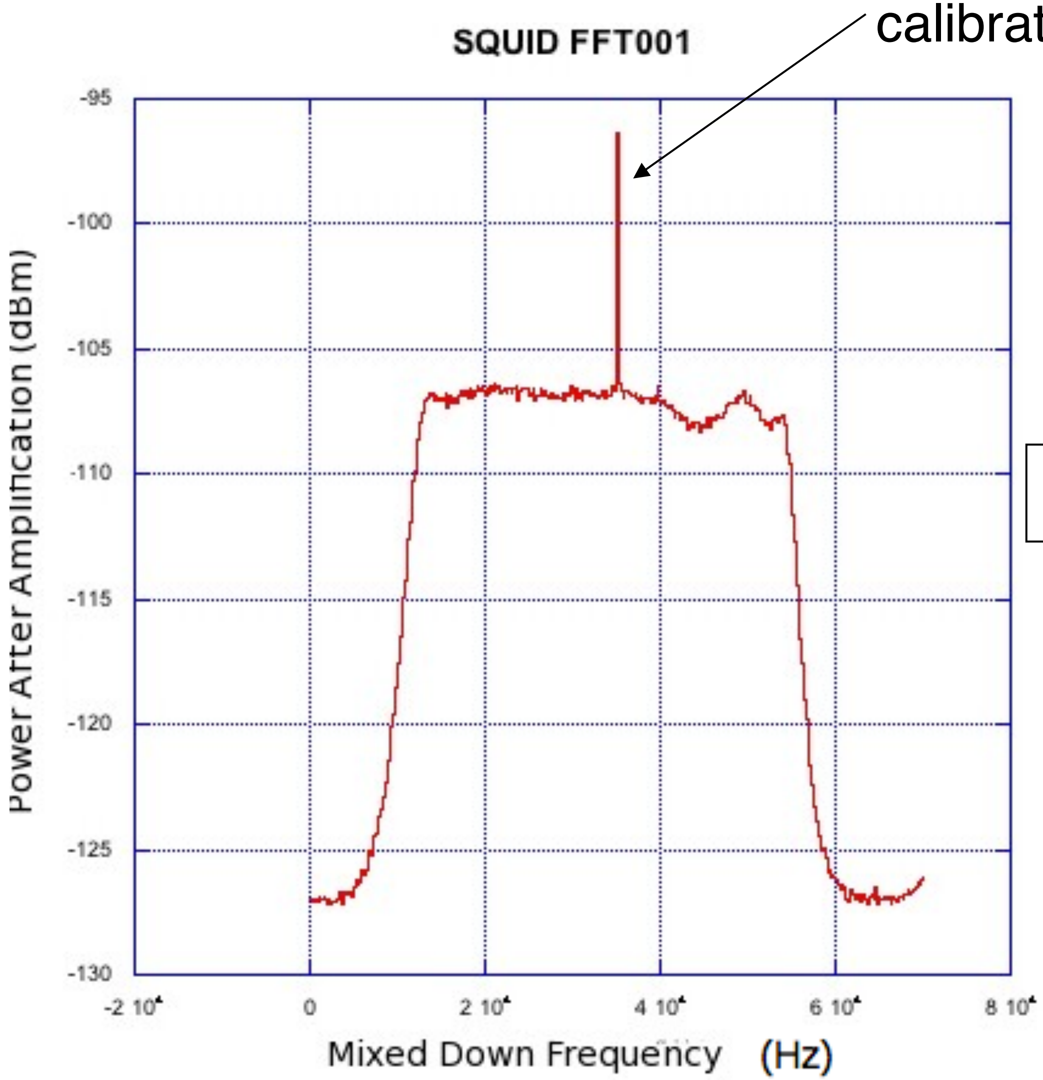


SQUID amplifier



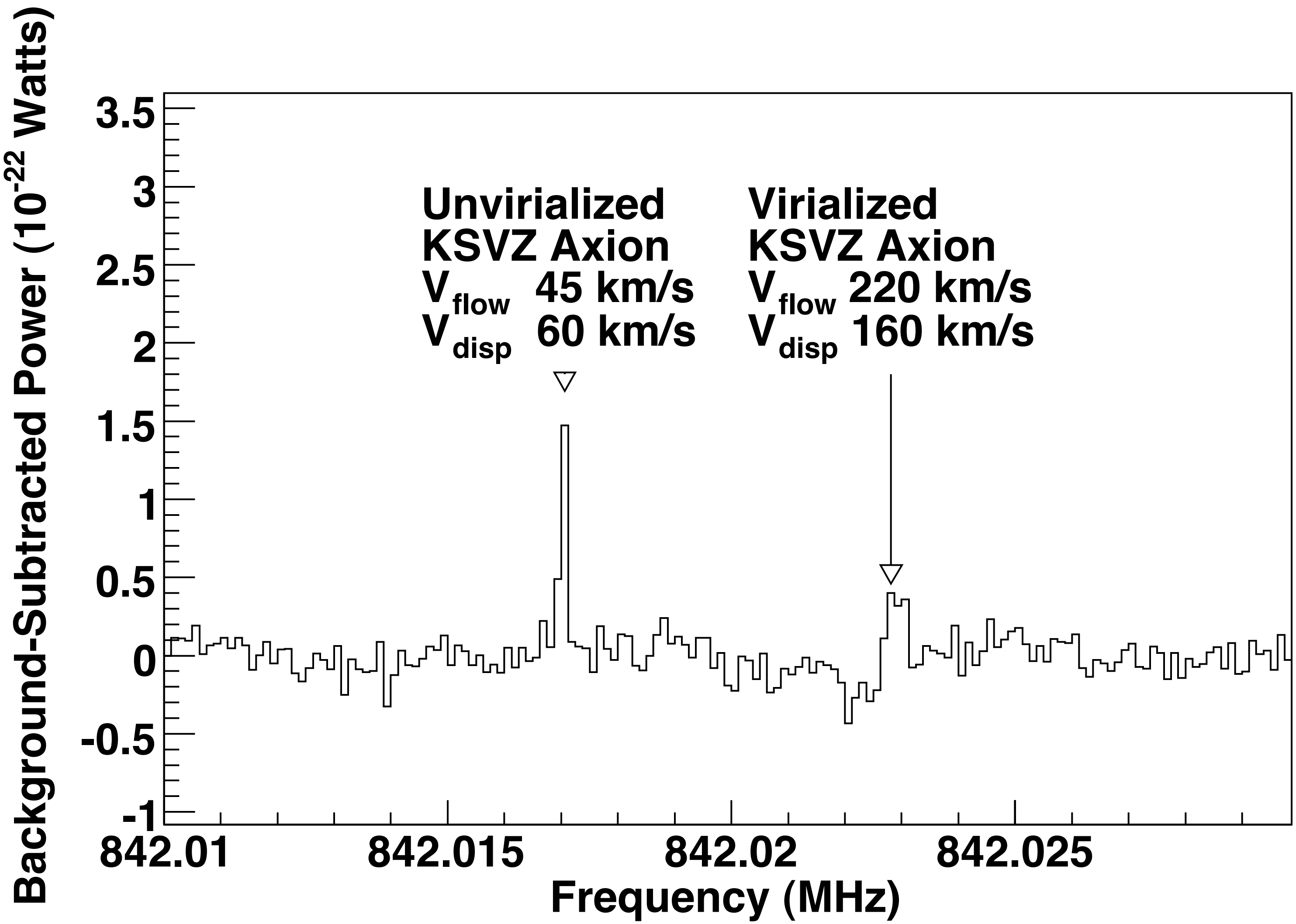
All new experiment package

ADMX: SQUID amplifier



SQUID microwave amplifier

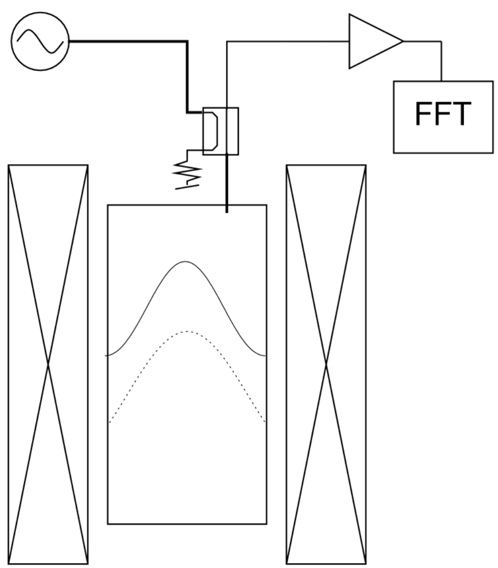
What would an axion look like in ADMX?



Operations include searches for exotics: "Chameleons" & hidden-sector photons

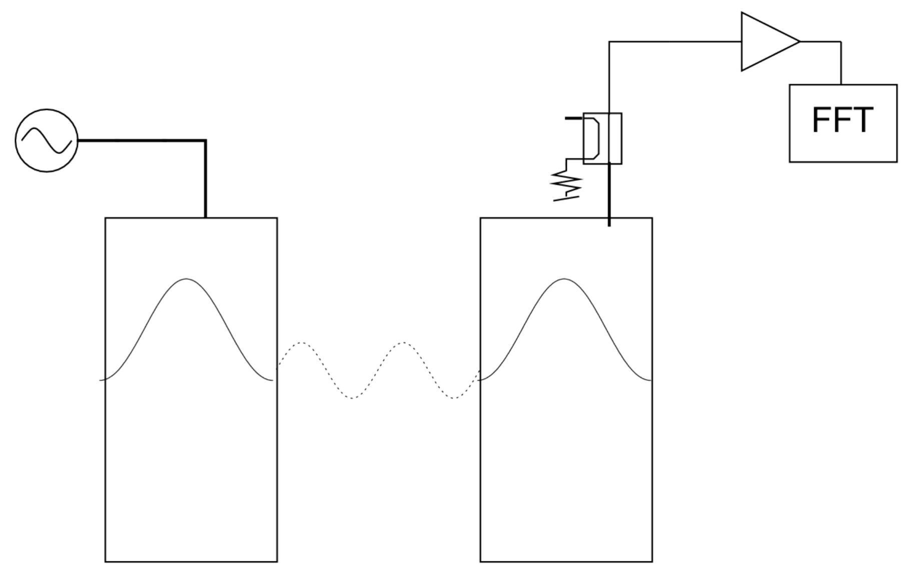
Chameleons

Scalars/pseudoscalars that mix with photons, and are trapped by cavity walls. Arise in some dark energy theories. Detectable by slow decay back into photons in cavity



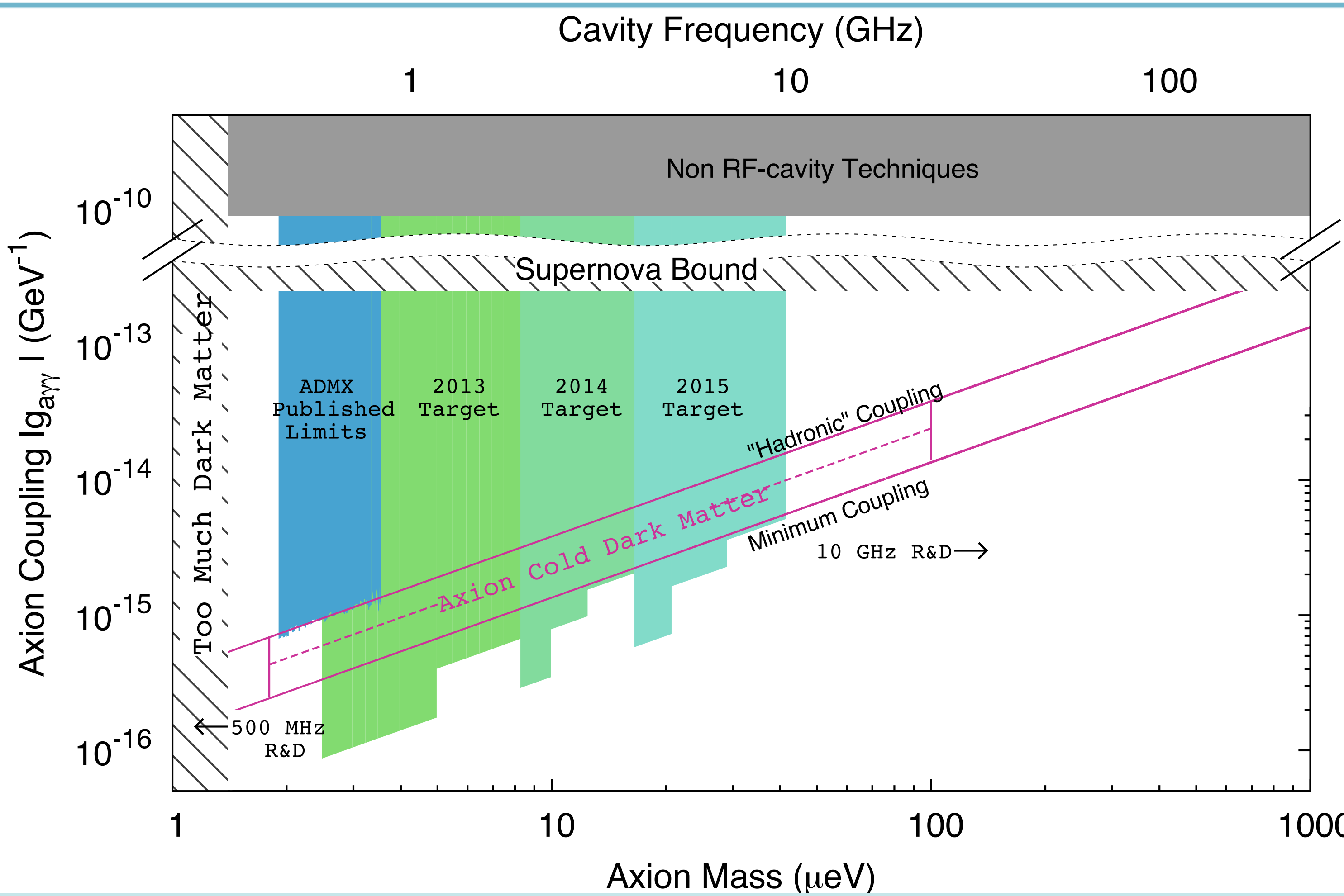
Hidden-sector photons

Vector bosons with photon quantum numbers and very weak interactions. Detectable by reconverting HSPs back into photons in ADMX cavity



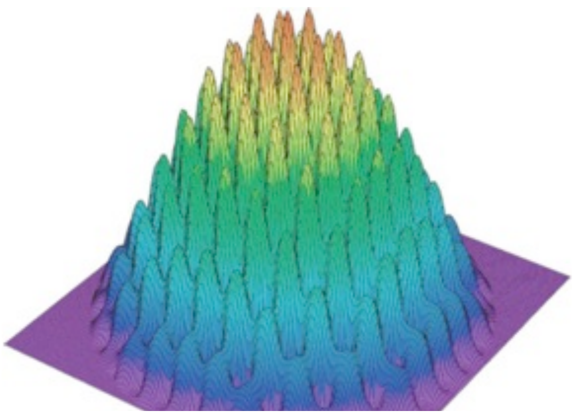
ADMX is sensitive to generic light exotic particles coupled to photons

ADMX near future:
Sensitivity with dilution-refrigerator cooling

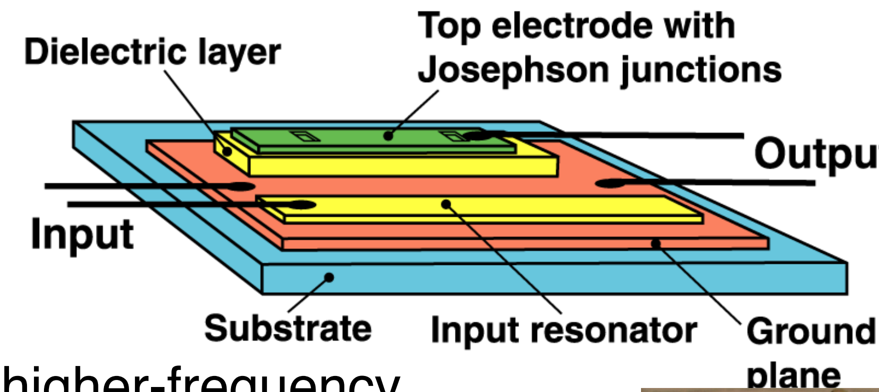


Dilution refrigerator cooled detectors allow scanning at or below "DFSZ" sensitivity at fractional dark-matter halo density.
This defines a "definitive" QCD dark-matter axion search

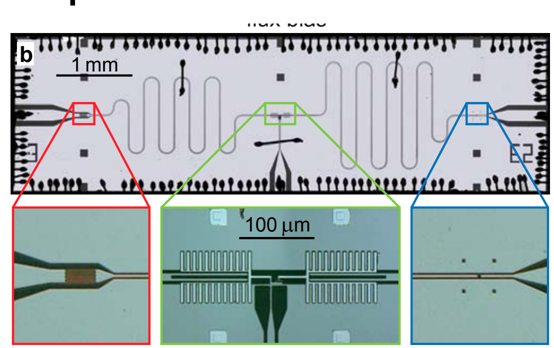
Can the RF-cavity experiments do better?
Higher frequencies, higher Q, squeezed states?
Active R&D paths.



higher-frequency, large volume resonant structures



higher-frequency quantum-limited SQUIDs



RF-Driven Josephson Bifurcation Amplifier for Quantum Measurement

I. Siddiqi, R. Vijay, F. Pierre, C. M. Wilson, M. Metcalfe, C. Rigetti, L. Frunzio, and M. H. Devoret
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(Received 11 February 2004; published 10 November 2004)

We have constructed a new type of amplifier whose primary purpose is the readout of superconducting quantum bits. It is based on the transition of a rf-driven Josephson junction between two distinct oscillation states near a dynamical bifurcation point. The main advantages of this new amplifier are speed, high sensitivity, low backaction, and the absence of on-chip dissipation. Pulsed microwave reflection measurements on nanofabricated Al junctions show that actual devices attain the performance predicted by theory.

new amplifier technologies

Quantum Non-demolition Detection of Single Microwave Photons in a Circuit

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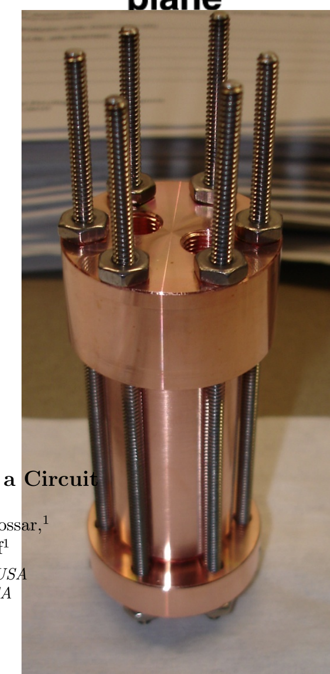
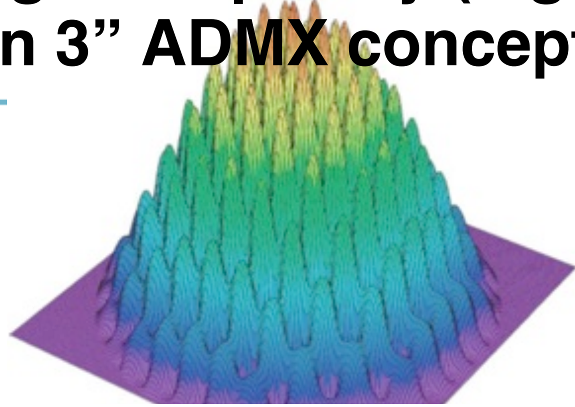
(Dated: March 12, 2010)

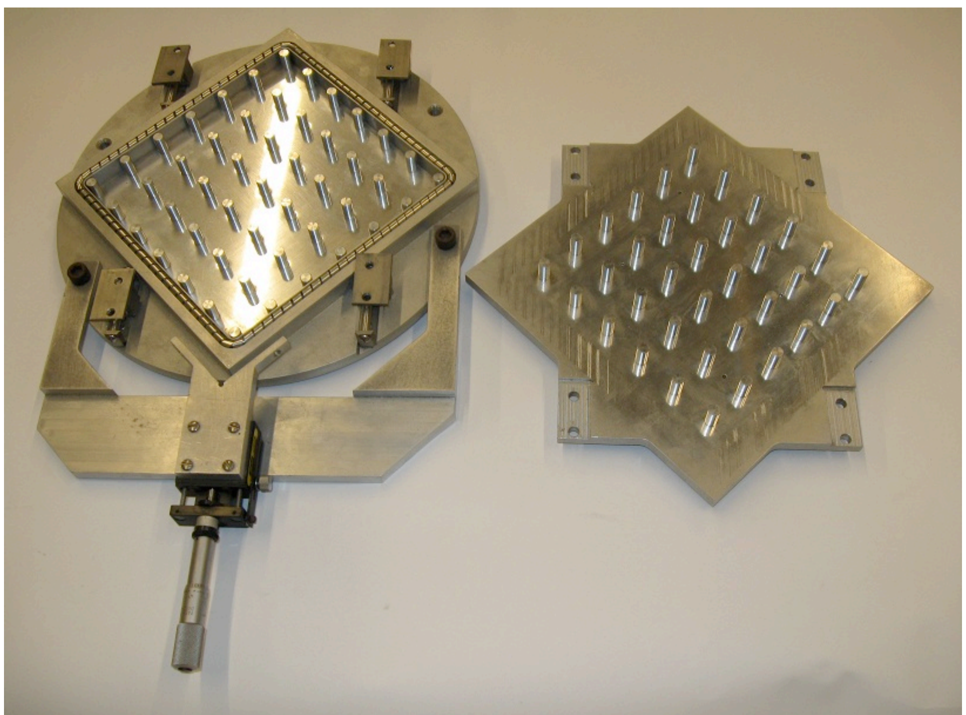


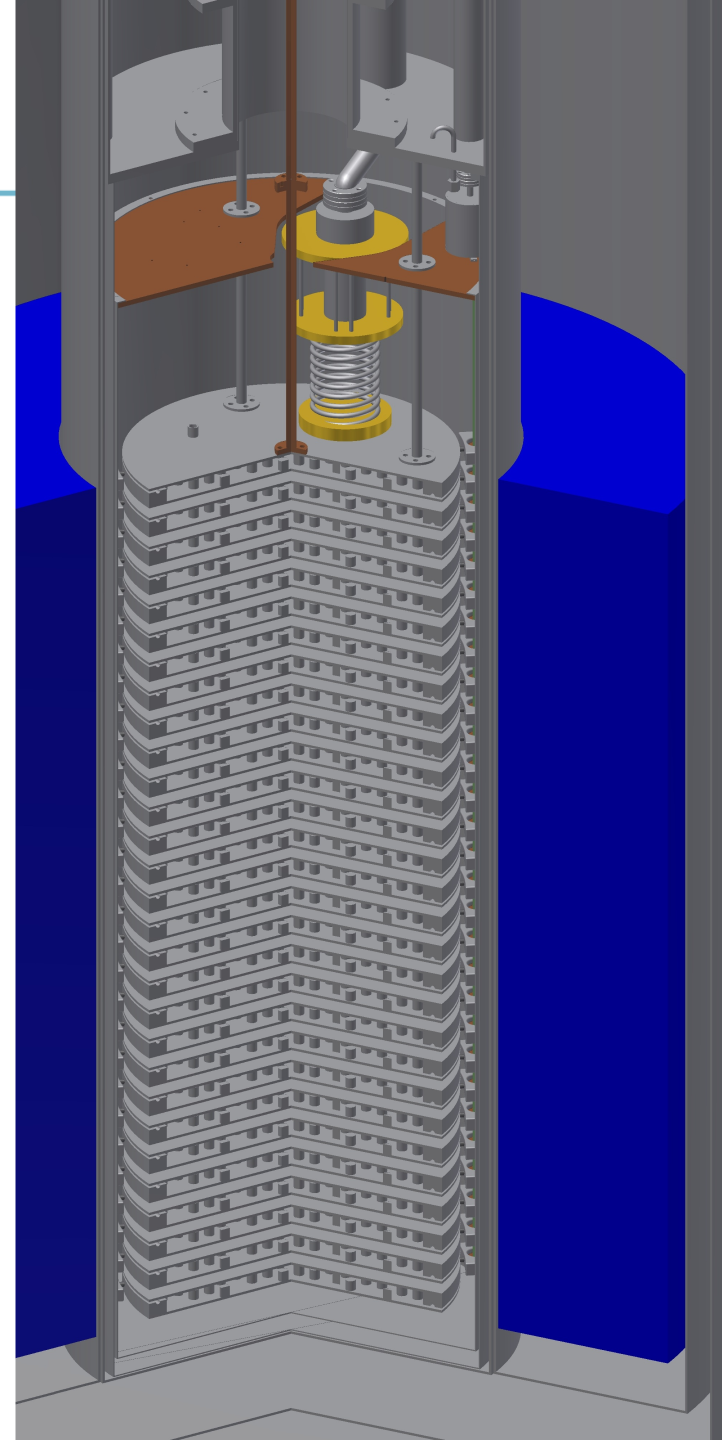
"hybrid" superconducting cavities (Yale group)

A High-Frequency (high-mass) "Gen 3" ADMX concept



higher-frequency, large volume resonant structures





ADMX RF-Cavity Futurism

ADMX "Phase IIa" is the current experiment:

Microwave amplification via SQUID amplifiers.
In process of installing pumped ^{3}He refrigerator.
Start "definitive" search in 1st mass decade.

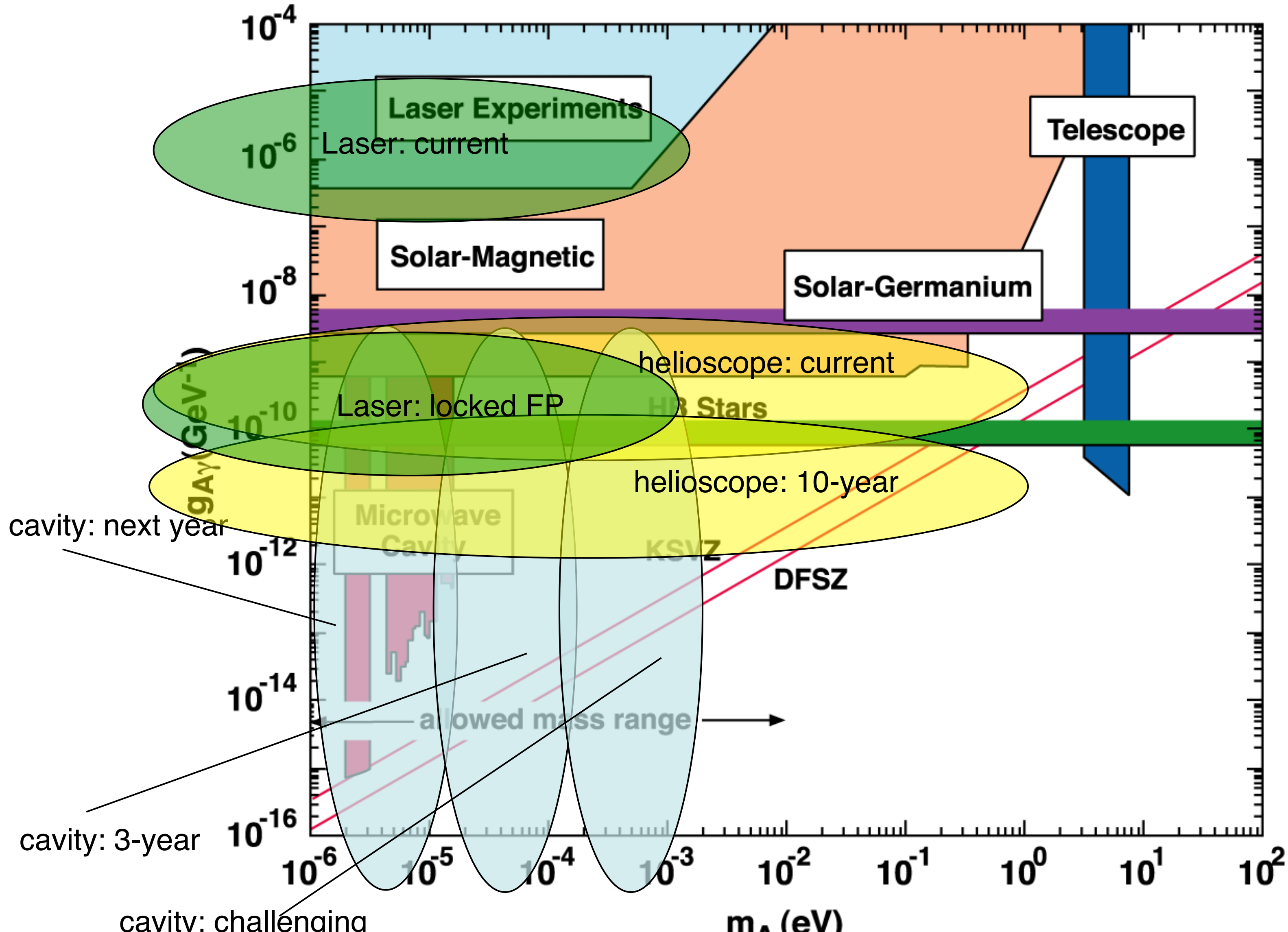
ADMX "Gen 2", anticipated start construction 2013:

Complete the installation of ^{3}He dilution refrigerator
Higher masses via modified cavity geometries.
"Definitive" search in 2nd mass decade.

Yale "HF", anticipated start 2013:

R&D on higher frequency structures, single-photon microcavities etc.
Regular data-taking above Phase Iia ADMX axion-masses
Extend ADMX to higher frequencies.

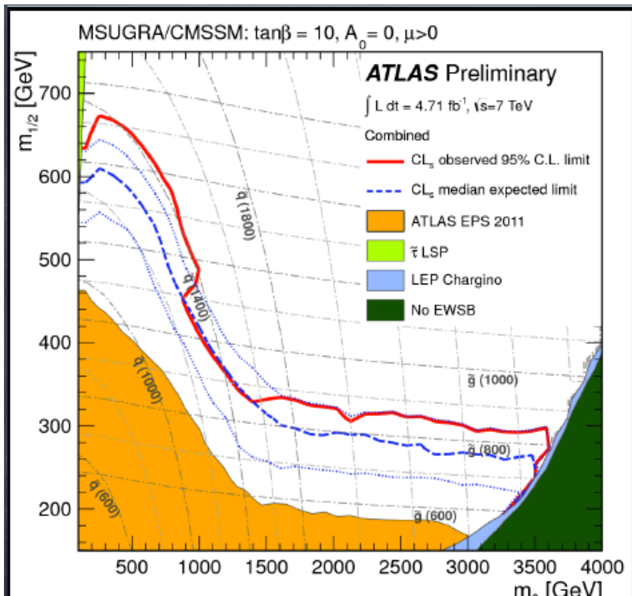
The Larger Axion-Search Landscape:
Focus on Three Key Technologies: RF-cavity, laser, solar

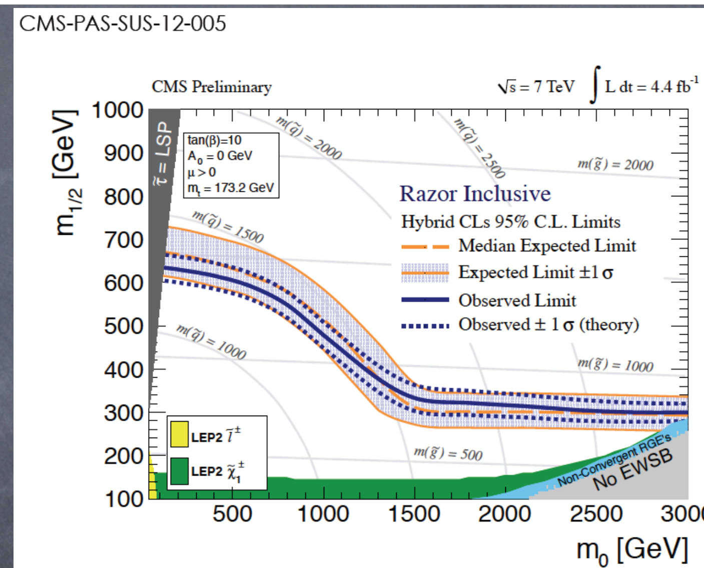


Conclusions (1)

We need to keep our eye on the LHC (and WIMP detectors).

The longer SUSY remains undetected, the more compelling axions become.





Atlas/CMS: no sign of mSUGRA at LHC7:

Conclusions (2)

On the other hand, LHC finding SUSY may strongly suggest axion dark matter   :)

Why thermally-produced neutralino-only DM is not the answer (in spite of the hype):

- Generates too much or too little DM; only rarely is $\Omega_\chi^{std} h^2 \sim 0.11$: fine-tuned!
- gravitino problem and BBN constraints
- neglects the strong CP problem and its solution

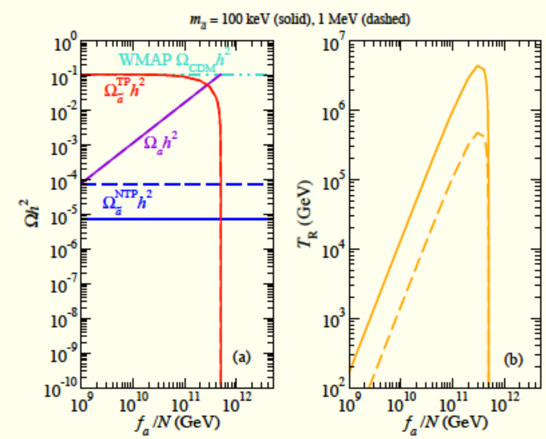
H. Baer

mSUGRA model with mixed axion/axino CDM: $m_{\tilde{a}}$ fixed

$(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (1000\text{ GeV}, 300\text{ GeV}, 0, 10, +1)$

$\Omega_a h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2 = 0.11$

model with *mainly* axion CDM favored for large T_R!



Overall Conclusions

Axions: A very compelling dark-matter candidate.
The QCD axion is well bounded in mass and couplings.
Dark-matter axion focus is 1-100 μeV axion masses.

There are many search techniques, but the RF-cavity one is most sensitive.
ADMX is largest and most mature.
The next several years will either see a discovery or reject the QCD dark-matter axion hypothesis.

Quite starkly: These experiments have the sensitivity and mass reach to either detect or rule out QCD dark-matter axions at high confidence.

Thank you DOE-HEP for your support