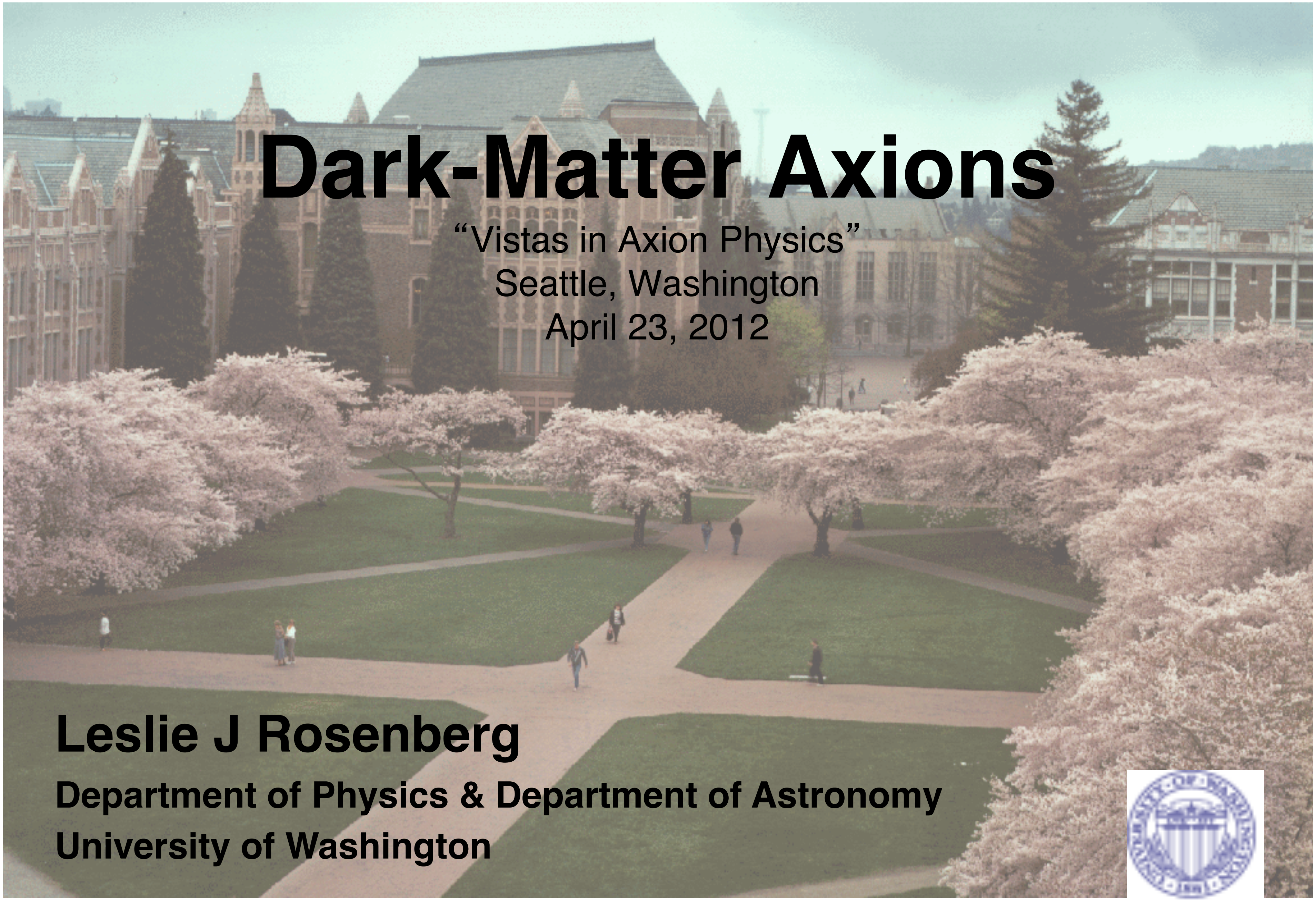


Dark-Matter Axions

"Vistas in Axion Physics"
Seattle, Washington
April 23, 2012

Leslie J Rosenberg

Department of Physics & Department of Astronomy

University of Washington

Dark Matter Axions: Simplified Overview and talk outline

1930s – Stellar motions & stellar mass-functions: Our galaxy has a dark-matter problem.

1970's – Spiral-galaxy rotation curves: mass-to-light ratio strongly weighted towards mass.
- Primordial nucleosynthesis: Dark-matter is exotic.
- QCD (theory of strong interactions) & instantons: All sensible, but QCD CP-violation not seen.
- Modern ideas of spontaneously broken symmetries: CP conserved, leads to the axion.

1980's – Negative searches for axions. If the axion exists, it's light, but not too light & very hard to detect.
- The light axion is an ideal dark-matter candidate.

1990's – Axion searches reach sensitivity to dark-matter axions.

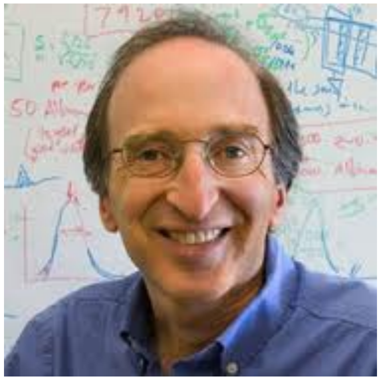
2000's – Axions embedded in richer landscape (SUSY, string theory).
- Cosmology & particle physics: Explosion of experimental and theory activity

Several crucial concepts of the late 20th Century … (see, e.g., "Quarks to Cosmos" NRC study)

Inflation
Particle Dark Matter
Dark Energy

Alan Guth

Lord Rees
of Ludlow



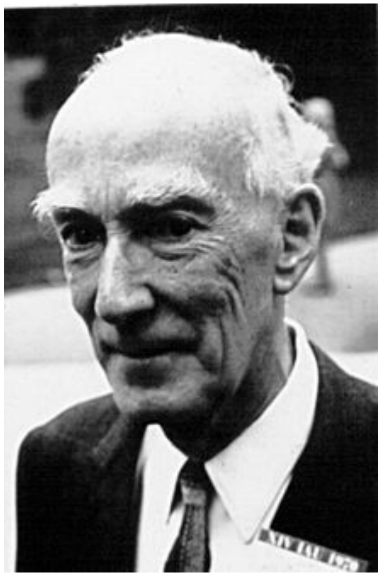
Saul Perlmutter

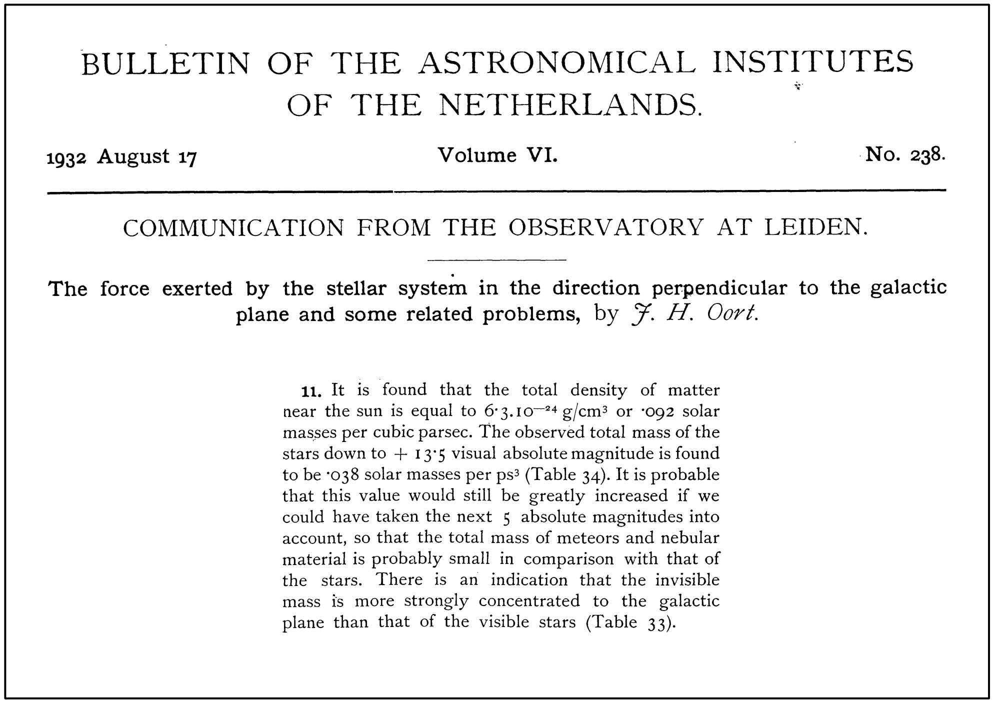
… lead to questions:
What drove the Big Bang?
What is the dark-matter particle?
What is the dark energy?

Origins of dark-matter: Starting with Oort

From stellar motions in our solar neighborhood:

"… a serious discrepancy between observed material and dynamically-estimated mass." He suggested the term "dark matter".





BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS.

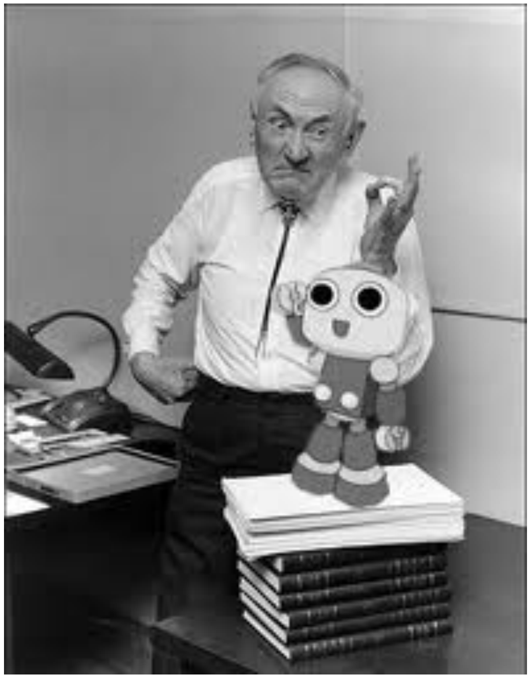
1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

11. It is found that the total density of matter near the sun is equal to $6{\cdot}3.10^{-24}$ g/cm^3 or ·092 solar masses per cubic parsec. The observed total mass of the stars down to + 13·5 visual absolute magnitude is found to be ·038 solar masses per ps^3 (Table 34). It is probable that this value would still be greatly increased if we could have taken the next 5 absolute magnitudes into account, so that the total mass of meteors and nebular material is probably small in comparison with that of the stars. There is an indication that the invisible mass is more strongly concentrated to the galactic plane than that of the visible stars (Table 33).

Origins of dark-matter: Zwicky (Coma cluster) & Smith (Virgo cluster)



Coma Cluster

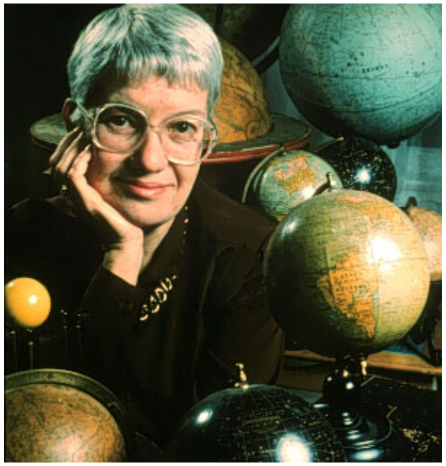
Virial motions within galaxy clusters:

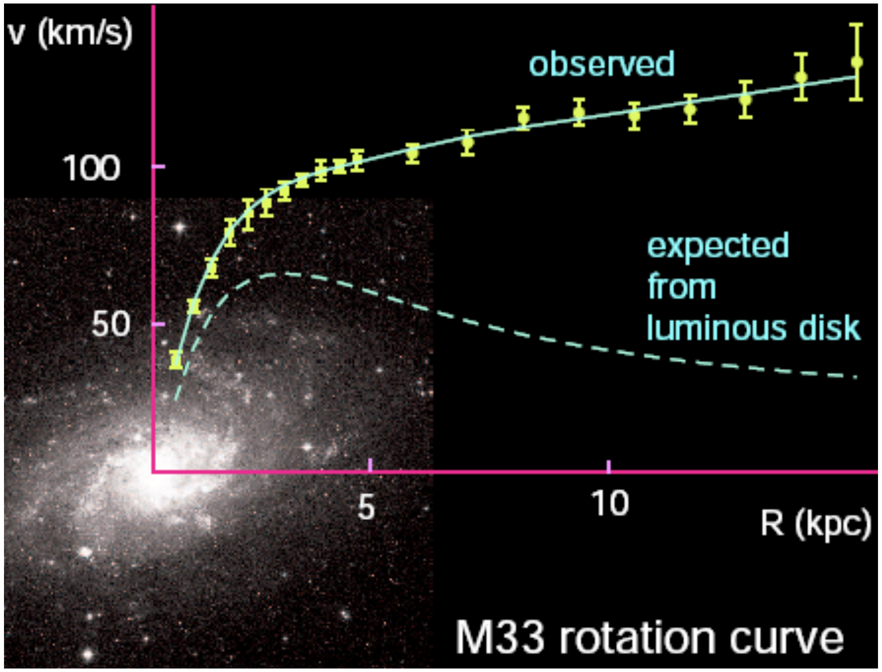
“The difference between this result and Hubble’s value for the average mass of a nebula must remain unexplained until further information becomes available.”

The “dunkelmaterie” of Zwicky 1936

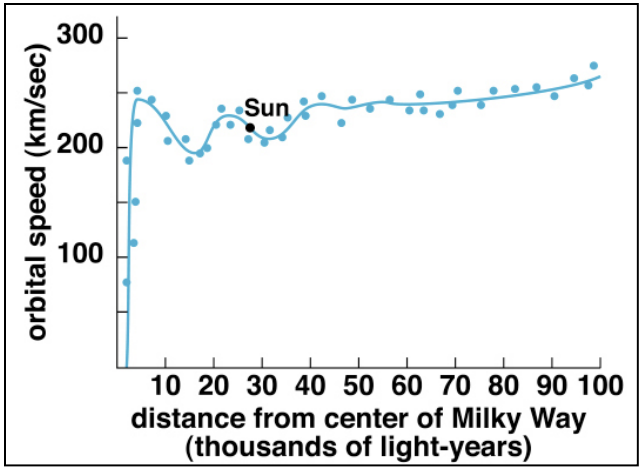
Origins of dark matter: Rubin, Gallagher, Faber et al.

Flat galactic rotation curves
Rubin, “1970’s: The decade of seeing is believing.”



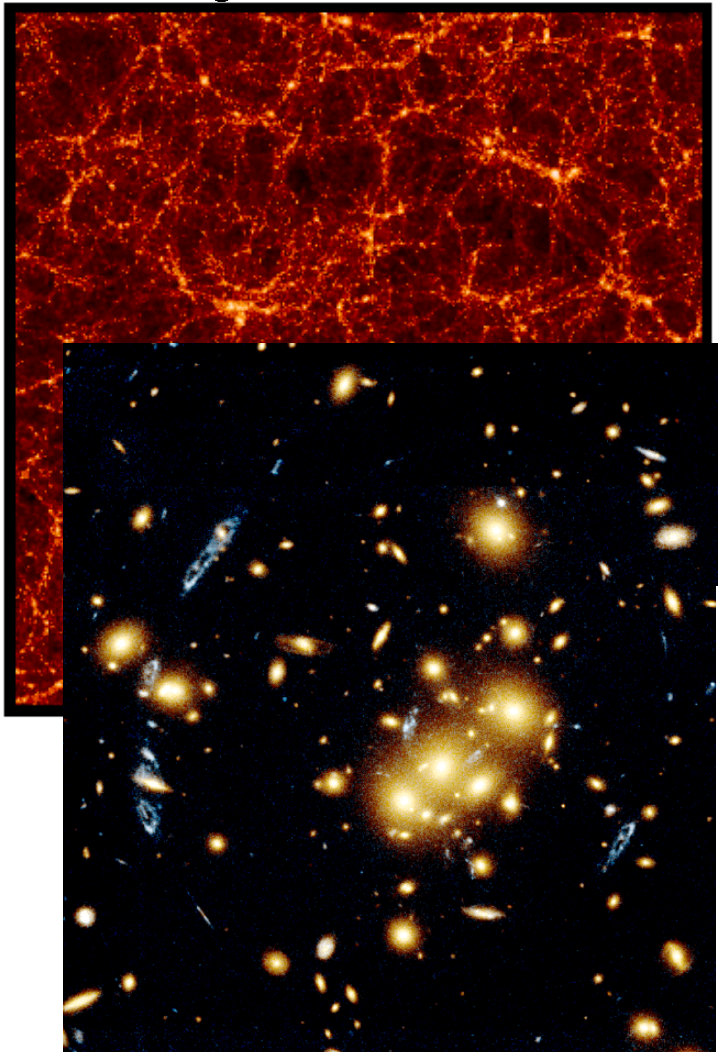


Paolo Saluchi

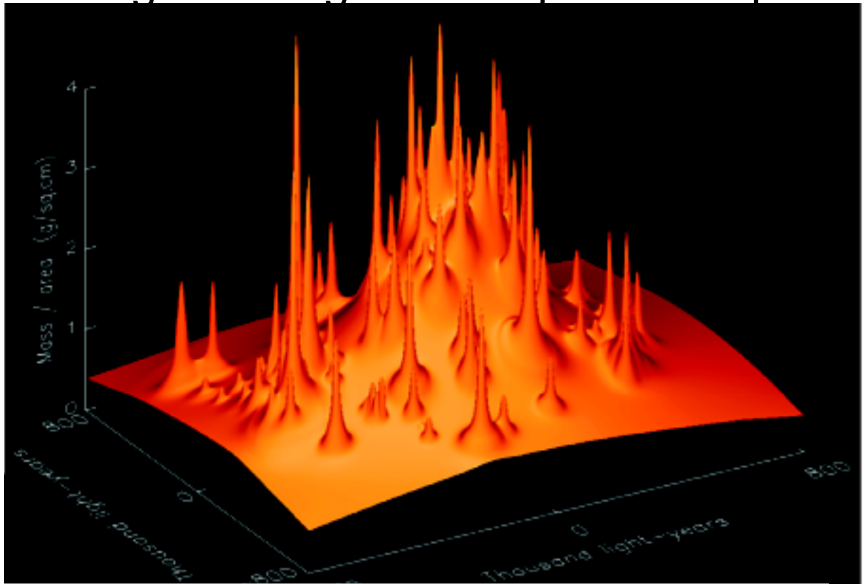


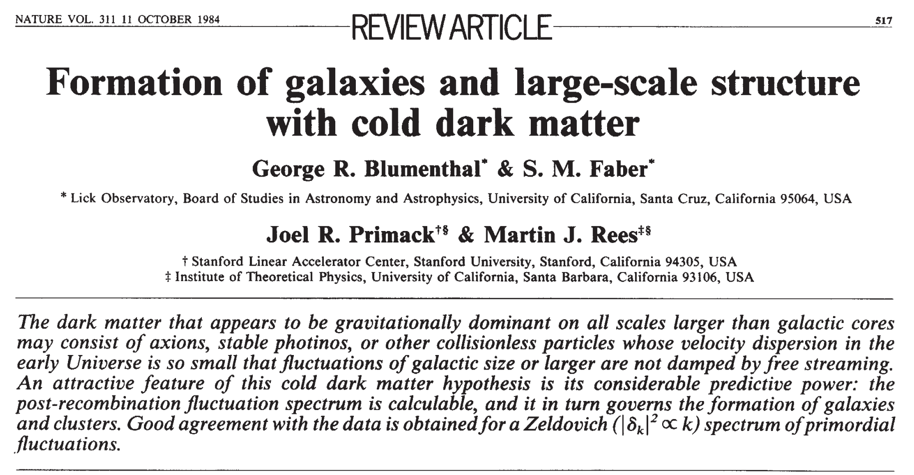
Origins of cold dark matter: The cosmology “explosion”

Model growth of structures



Lensing of background objects as a probe





NATURE VOL. 311 11 OCTOBER 1984 REVIEW ARTICLE 517

Formation of galaxies and large-scale structure with cold dark matter

George R. Blumenthal* & S. M. Faber*

* Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA

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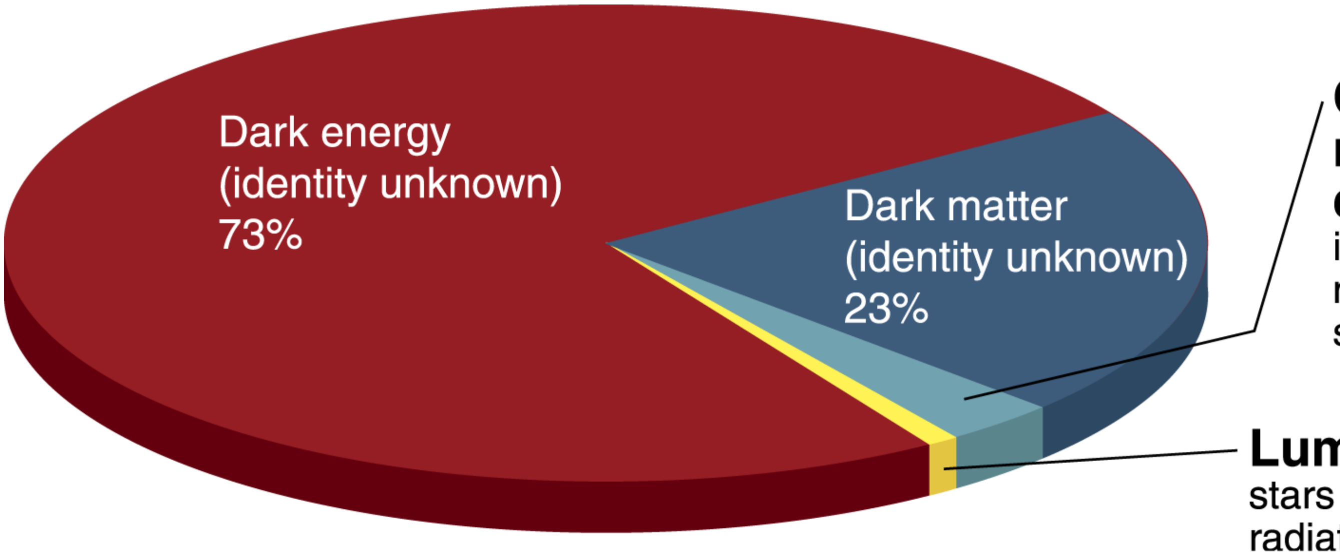
The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) *spectrum of primordial fluctuations.*

As a result: We are measuring the mass/energy “pie” with better and better precision and greater confidence



Other nonluminous components
intergalactic gas 3.6%
neutrinos 0.1%
supermassive BHs 0.04%

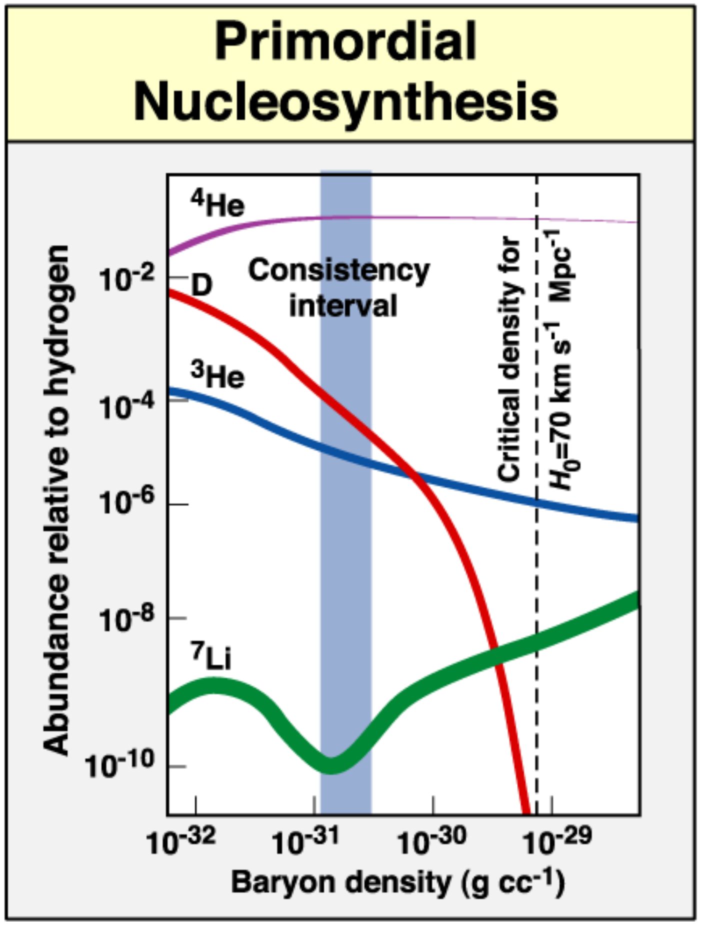
Luminous matter
stars and luminous gas 0.4%
radiation 0.005%

Science (20 June 2003)

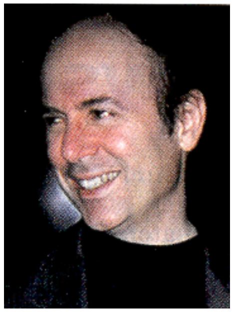
But, we don’t know what the “dark energy” and the “dark matter” are. These are two of the very big questions.

What do we know about the nature of dark matter? Its not normal matter or radiation and it's "cold"

(1) From light element abundance:
Dark matter probably isn't bowling balls or anything else made of baryons.



(2) Is dark matter made of, e.g., light neutrinos?
Probably not: fast moving neutrinos would have washed-out structure.
Dark matter is substantially "cold".



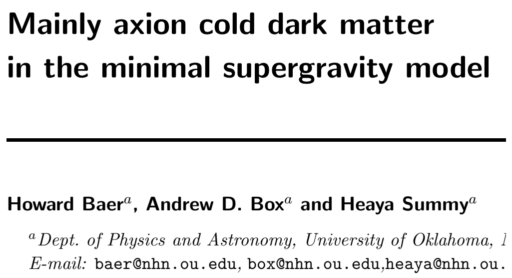
(3) "Dark matter: I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist…"

Frank Wilczek in Physics Today

Frank's referring to WIMPS and Axions

Is there a way to tell if dark-matter is axionic? Maybe.

WIMPs haven't been found; some people are surprised by this.
WIMPs Not found in CDMS & XENON 100;
LHC hasn't found SUSY, let alone the LSP.



Mainly axion cold dark matter
in the minimal supergravity model

Howard Baer[a], Andrew D. Box[a] and Heaya Summy[a]

[a] *Dept. of Physics and Astronomy, University of Oklahoma,*
E-mail: `baer@nhn.ou.edu`, `box@nhn.ou.edu`,`heaya@nhn.ou.`

Even in a SUSY universe, are axions a sensible
dark matter?
(c.f., H. Baer's discussion on what we've learned from the LHC)

Is conventional wisdom wrong? Can you observe a difference between axionic and WIMP dark matter? Certainly? Maybe? No?

Certainly: Axion and WIMP have different freeze-out time. You could conceive an experiment to measure thickness of "phase space sheet" (velocity dispersion). A WIMP velocity dispersion is barely resolvable, but the axion not.

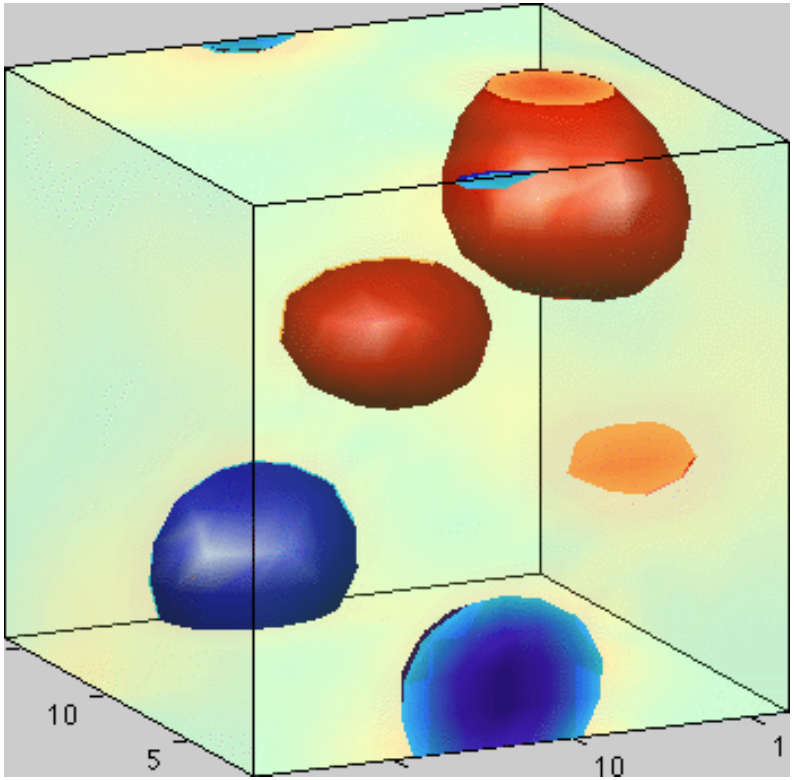
Perhaps: There's too little ^{7}Li. Maybe there's a new process between the end of BBN and decoupling that cools photons.

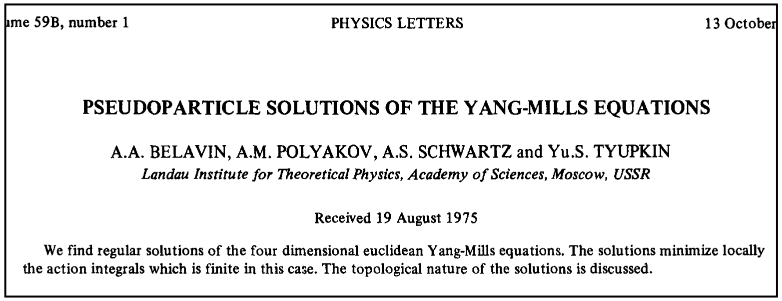
Maybe: Specifics of galactic caustic structures may be axion-specific.
(c.f., P.Sikivie's discussion on BEC dark matter)

New thread: Why does QCD conserve the symmetry CP?

1973: QCD…a gauge theory of color.
QCD theory respected the observed conservation of C, P and CP.

1975: QCD + “instantons” ⇒ QCD is expected to be hugely CP-violating.




ıme 59B, number 1 PHYSICS LETTERS 13 October

PSEUDOPARTICLE SOLUTIONS OF THE YANG-MILLS EQUATIONS

A.A. BELAVIN, A.M. POLYAKOV, A.S. SCHWARTZ and Yu.S. TYUPKIN
Landau Institute for Theoretical Physics, Academy of Sciences, Moscow, USSR

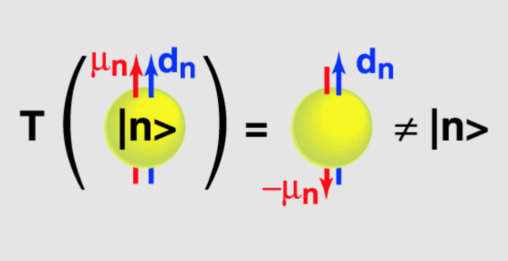
Received 19 August 1975

We find regular solutions of the four dimensional euclidean Yang-Mills equations. The solutions minimize locally the action integrals which is finite in this case. The topological nature of the solutions is discussed.

QCD on the lattice:
CP-violating instantons in E4D

Peccei and Quinn: CP conserved through a hidden symmetry

QCD CP violation should, e.g., give a large neutron electric dipole moment $(\cancel{T} + CPT = \cancel{CP})$; none is unobserved.
(9 orders-of-magnitude discrepancy)



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

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

1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry ⇒
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.
(Ask Pierre Sikivie how this is analogous to energy stored in a pendulum.)

Properties of the axion

- 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

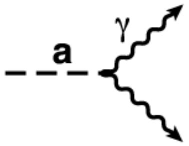
$$g_{aii} \propto \frac{1}{f_a}$$

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’

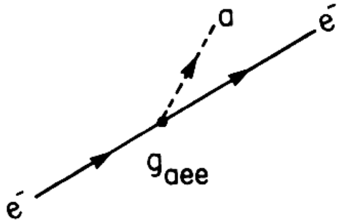
$$10^{-(5\text{ to }6)}\ \text{eV} < m_a < 10^{-(2\text{ to }3)}\ \text{eV}$$

(Overclosure) (SN1987a)

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

The special role of the a➔γγ coupling

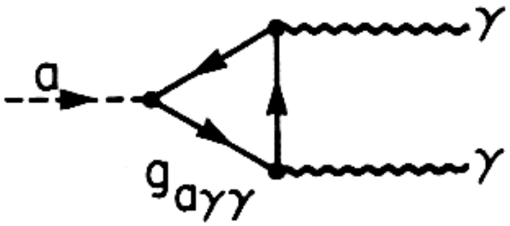
Compare, e.g., axion bremstrahlung off an electron
to the axion decay into photons



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

$(3/8)^{-1}$

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

Small specific-model dependence:
Experimenters and funding agencies like that.

Axions in string theory

Peter Svrček
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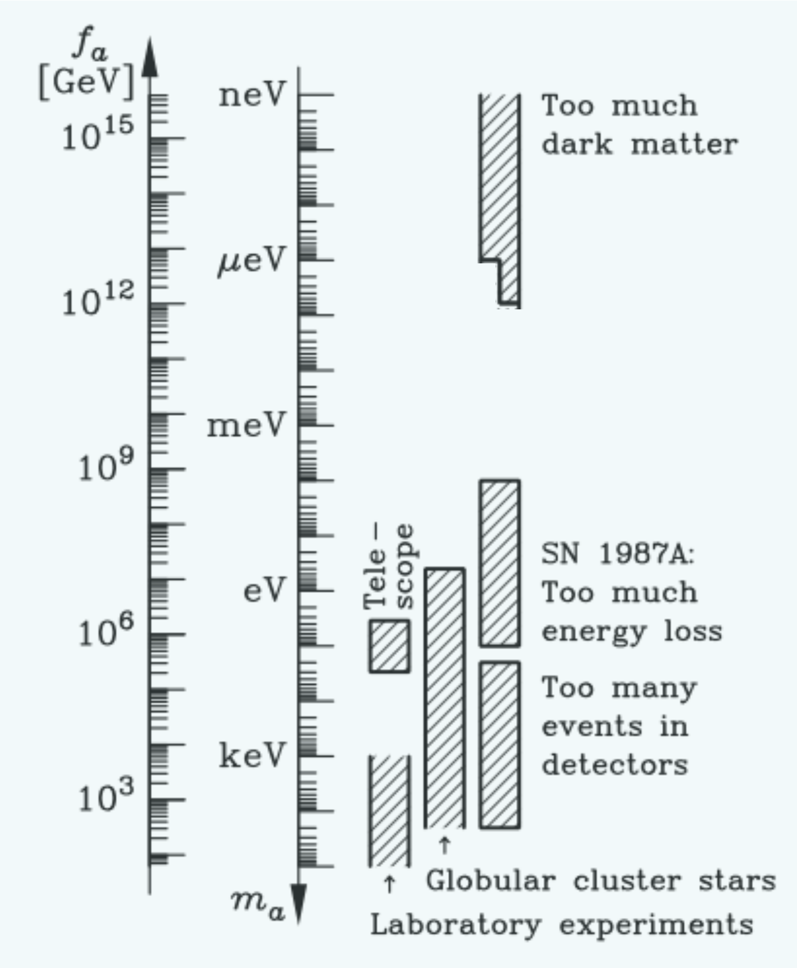
Edward Witten
Institute For Advanced Study
Princeton NJ 08540 U.S.A.
E-mail: `witten@ias.edu`

Amazingly: It’s fundamentally 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

Present bounded window of allowed axion masses



Very light axions forbidden: else too much dark matter

⇐Dark matter range:"axion window"

very hard to detect "invisible axions"

Heavy axions forbidden: else new pion-like particle

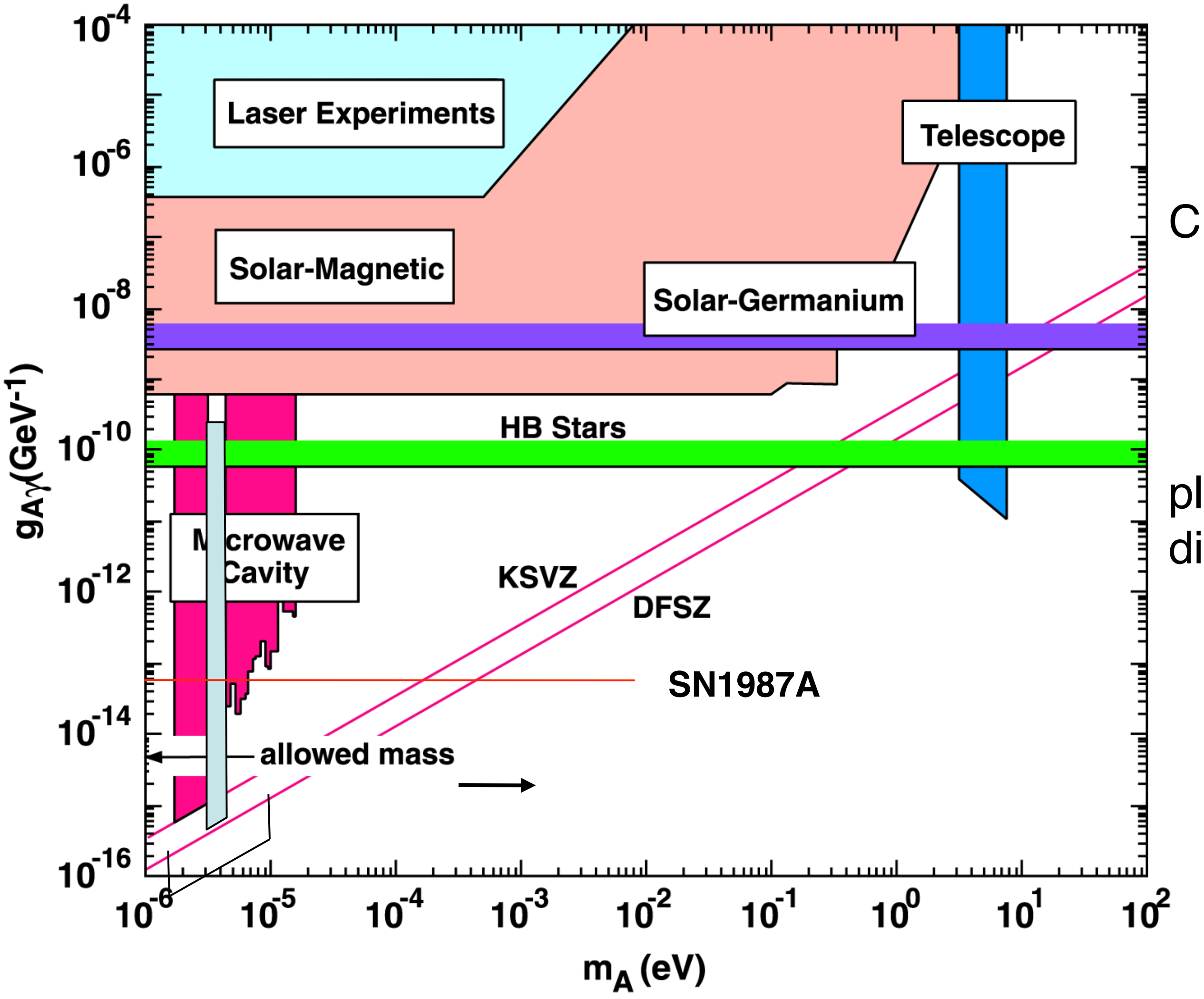
Recap: Axions and dark matter

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

Dark matter properties are those of a low-mass axion:
Low mass axions are an ideal dark matter candidate:
“Axions: the thinking persons dark-matter 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 on dark-matter QCD-axion masses and couplings



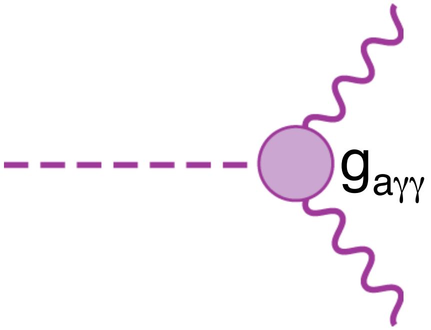
Current large experiments:
RF-cavity
Solar
Laser

plus others. Topics of intense discussion at the workshop

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.)

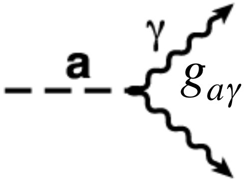
But it recall the axion 2γ coupling has relatively little axion-model dependence



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

Pierre Sikivies RF-cavity idea (1983): Axion and electromagnetic fields exchange energy

The axion-photon coupling…



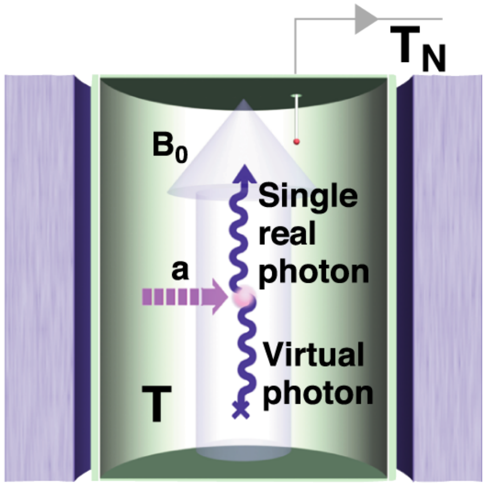
…is a source term in Maxwell’s Equations

$$\frac{\partial\left(\mathbf{E}^2/2\right)}{\partial t} - \mathbf{E}\cdot\left(\nabla\times\mathbf{B}\right) = g_{a\gamma}\dot{a}\left(\mathbf{E}\cdot\mathbf{B}\right)$$

So imposing a strong external magnetic field B transfers axion field energy into cavity electromagnetic energy.

Some experimental details of the RF-cavity technique

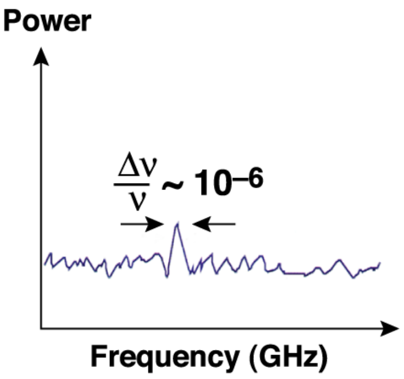
Primakoff Conversion



- **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

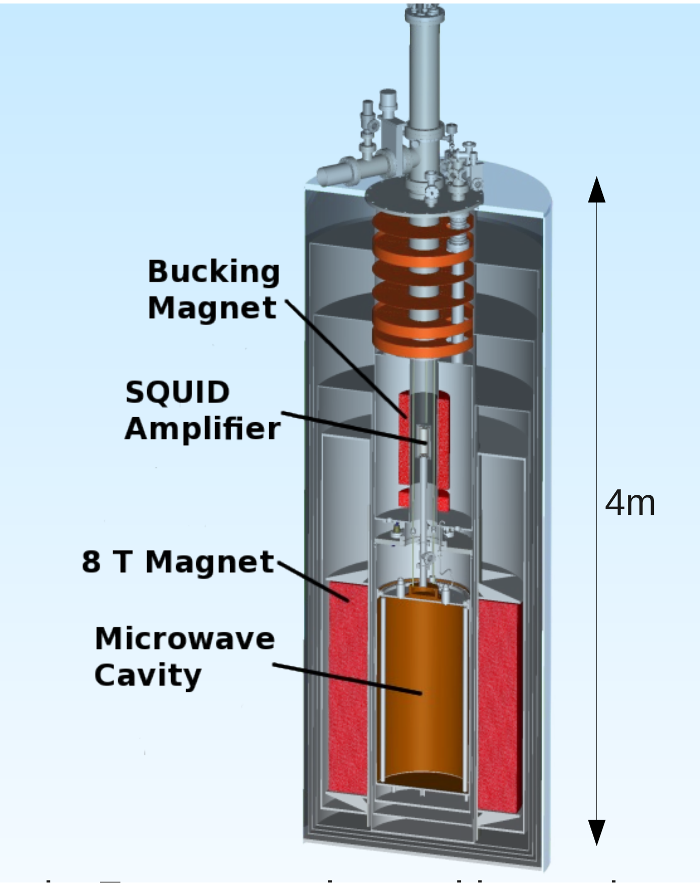


Scaling Laws	
$\frac{d\nu}{dt} \propto B^4V^2 \cdot \boxed{\frac{1}{T_S^2}}$	$g_\gamma^2 \propto \left(B^2V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	For fixed scan rate $\frac{d\nu}{dt}$

ADMX: Axion Dark-Matter eXperiment
The largest RF-cavity QCD dark-matter axion search

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

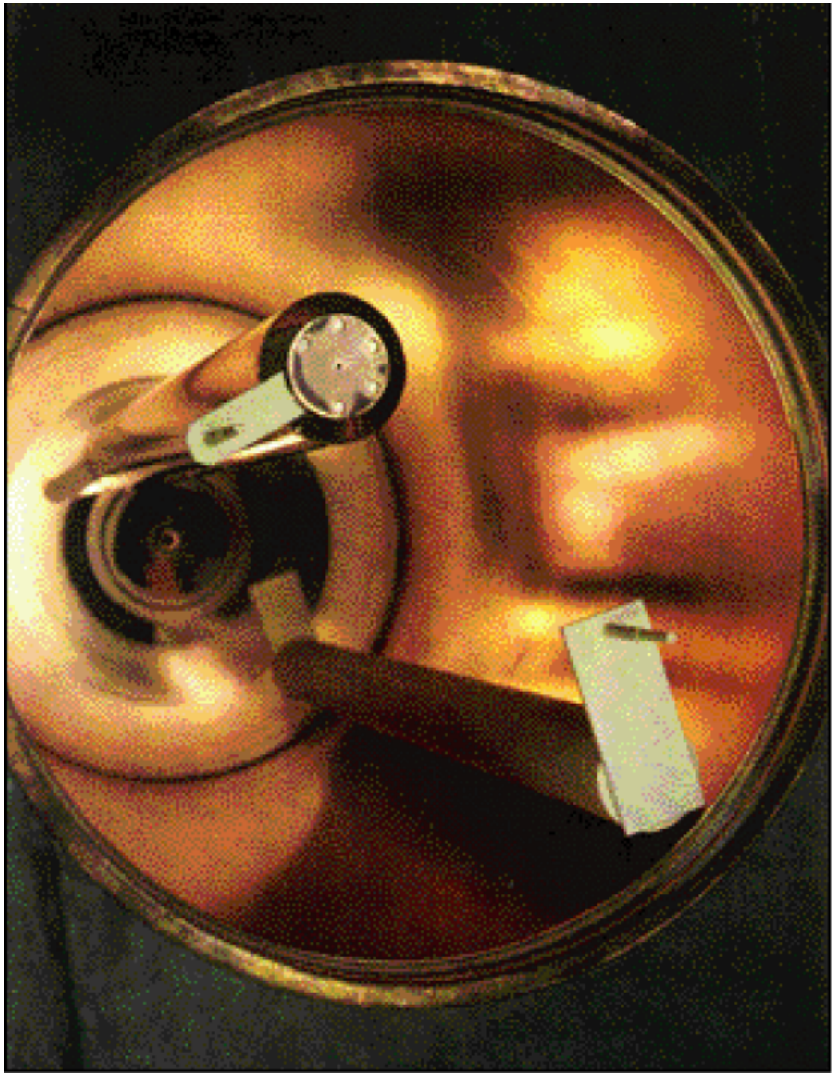
Magnet with insert



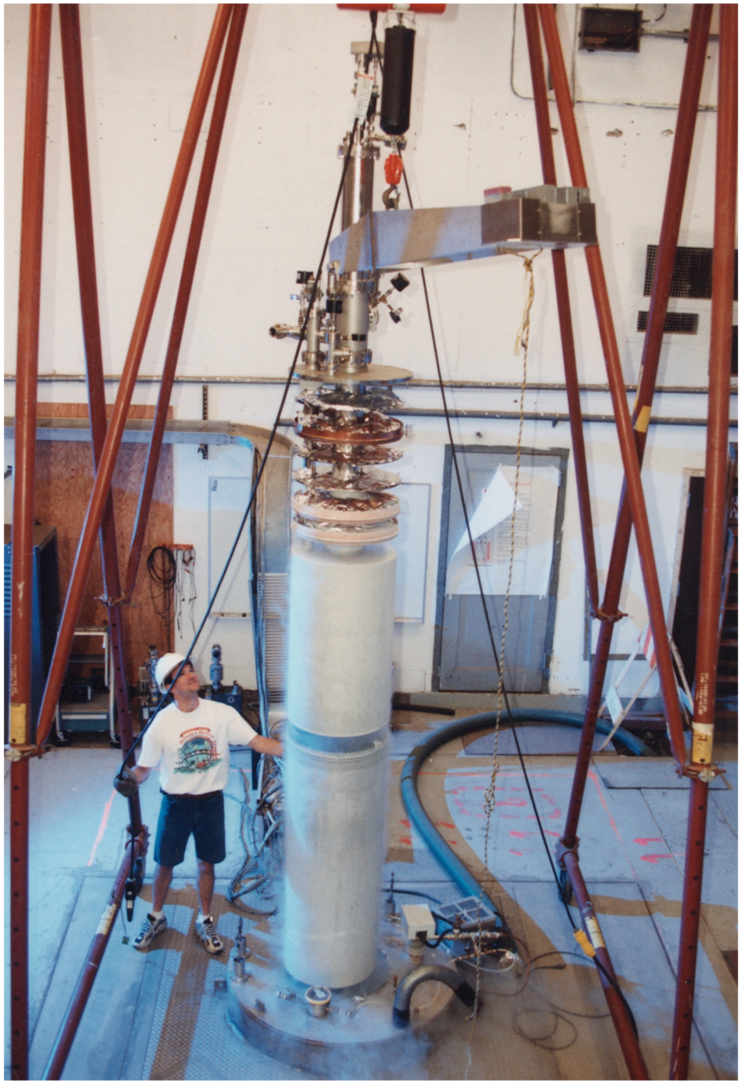
Magnet cryostat

ADMX hardware 1

High-Q microwave cavity

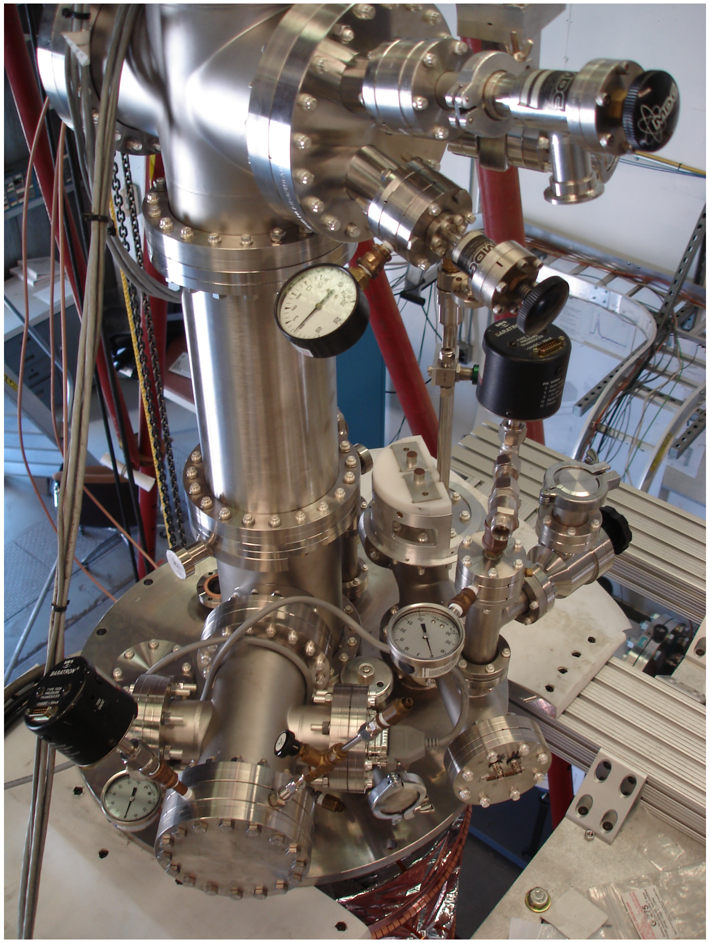


Experiment insert



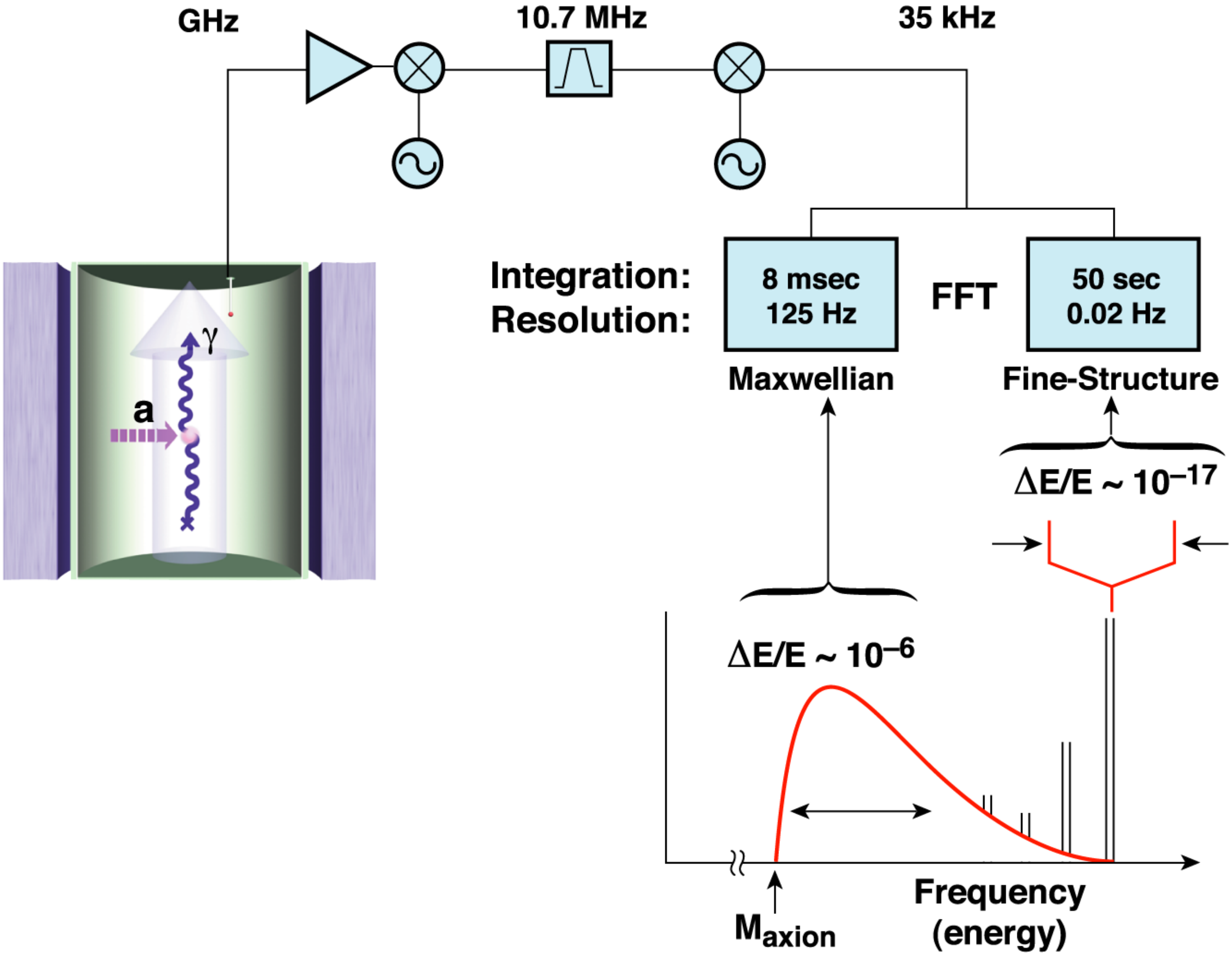
ADMX hardware 2

Vacuum and cryo



Quantum electronics

ADMX axion receiver



GHz

10.7 MHz

35 kHz

a

γ

Integration: 8 msec | 50 sec

Resolution: 125 Hz | 0.02 Hz

FFT

Maxwellian

Fine-Structure

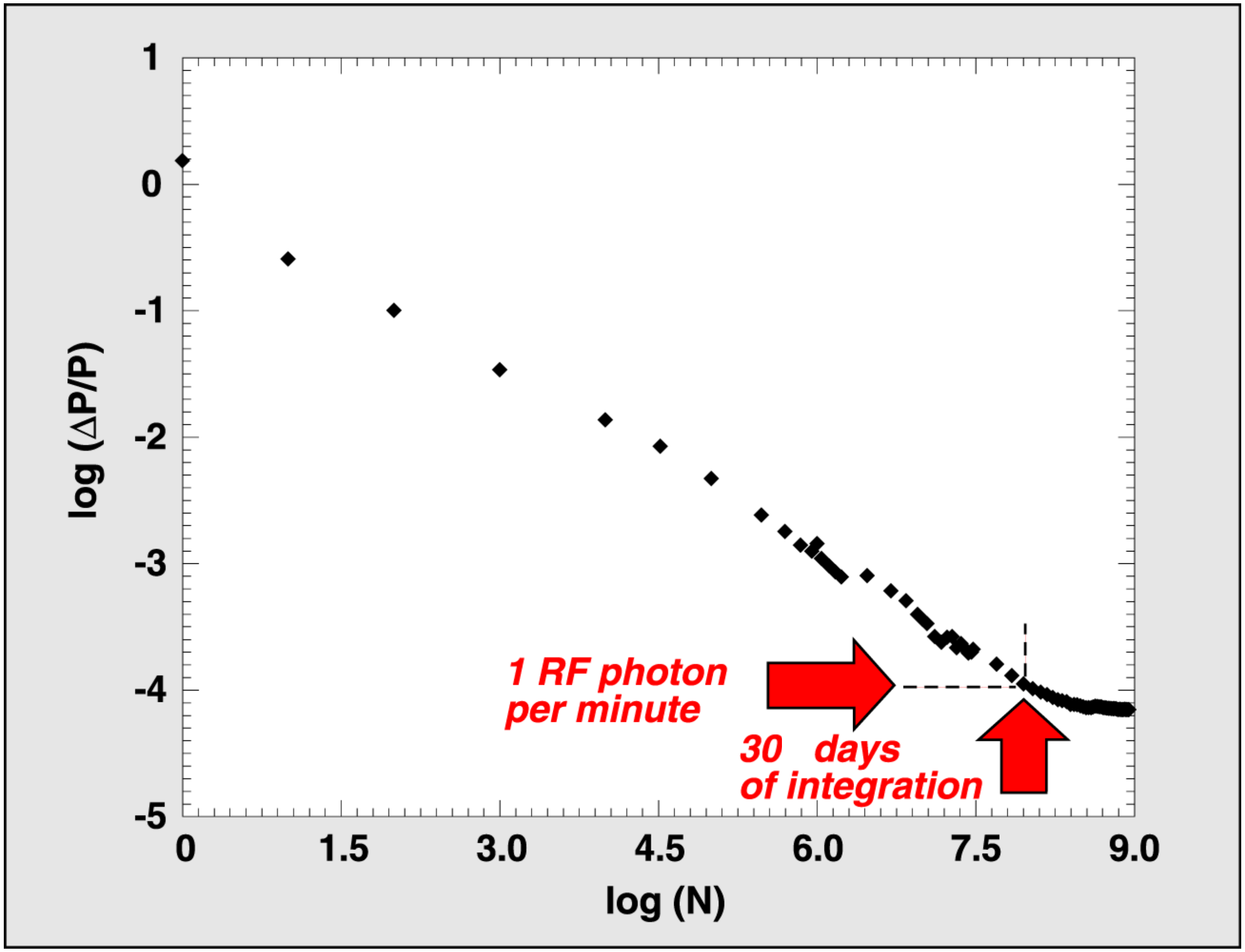
$\Delta E/E \sim 10^{-17}$

$\Delta E/E \sim 10^{-6}$

M_{axion}

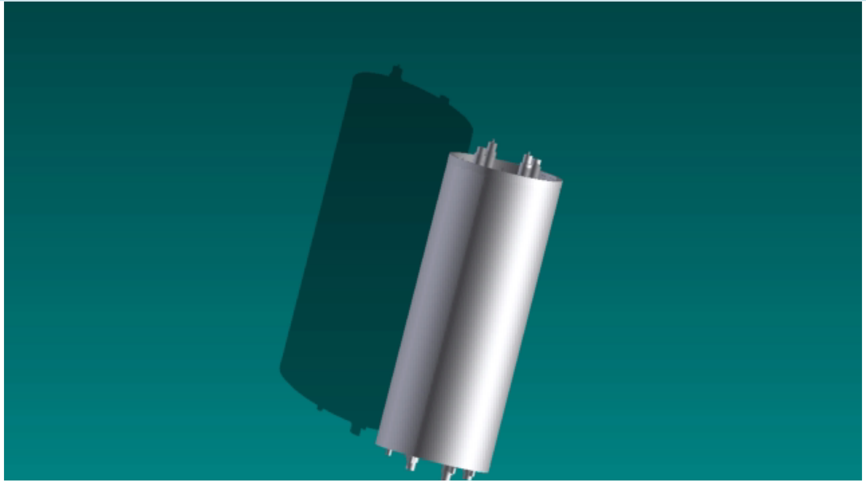
Frequency (energy)

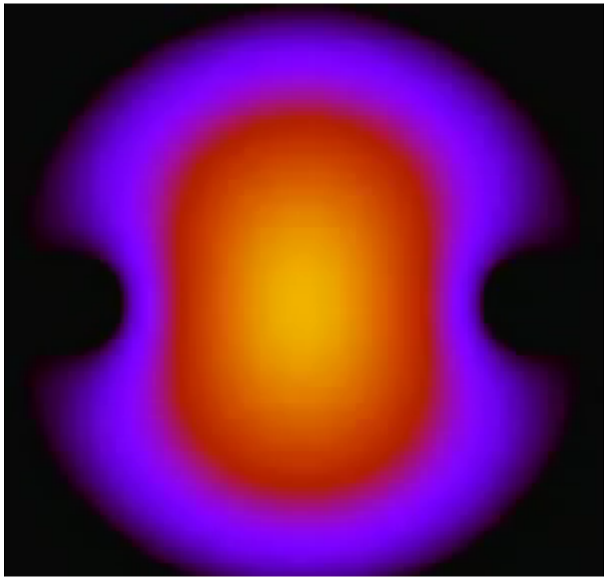
Converted microwave photons are detected by the world’s lowest-noise radio receiver

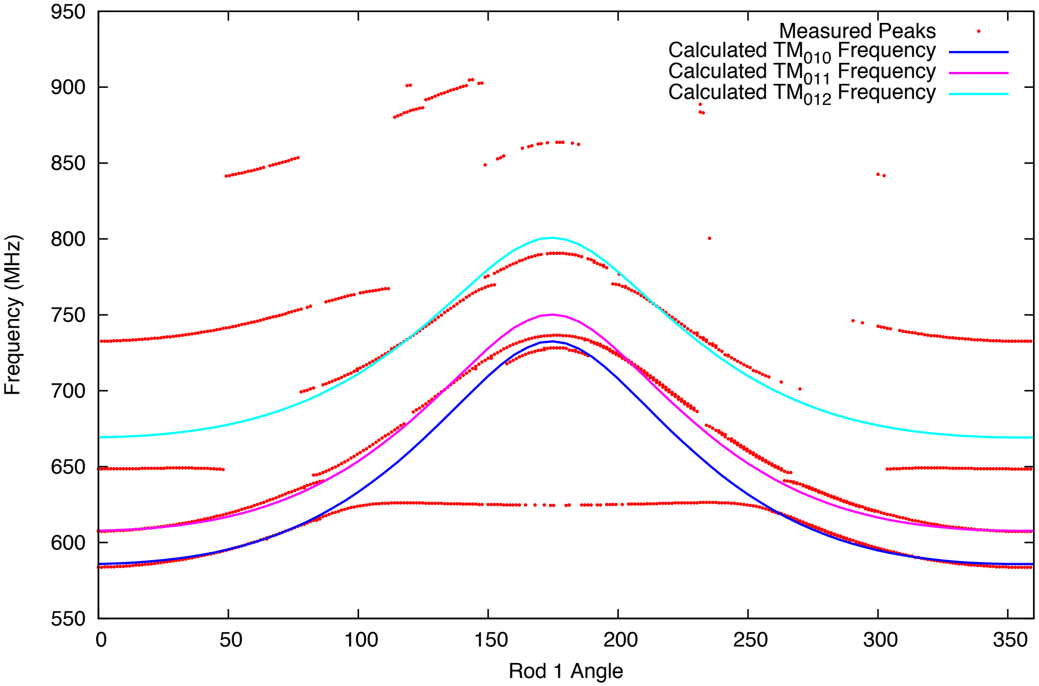


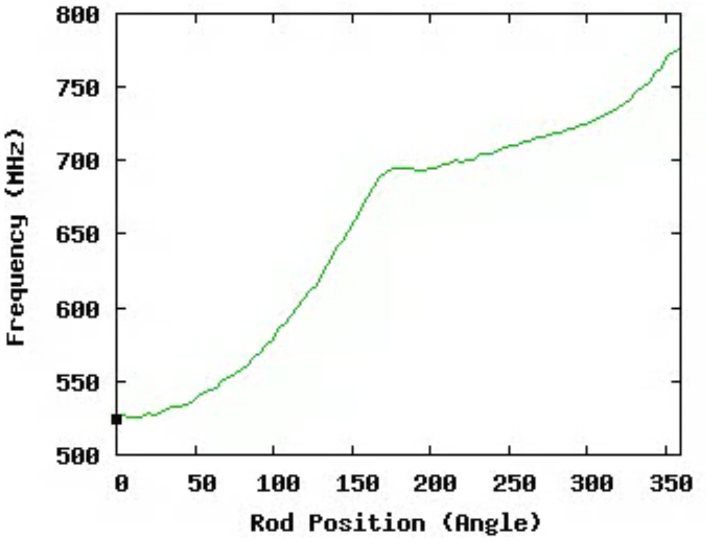
Systematics-limited for signals of 10^{-26} W
~10^{-3} of “DFSZ” axion power (1/100 yoctoWatt).

Cavity Tuning: Change shape via tuning Rods



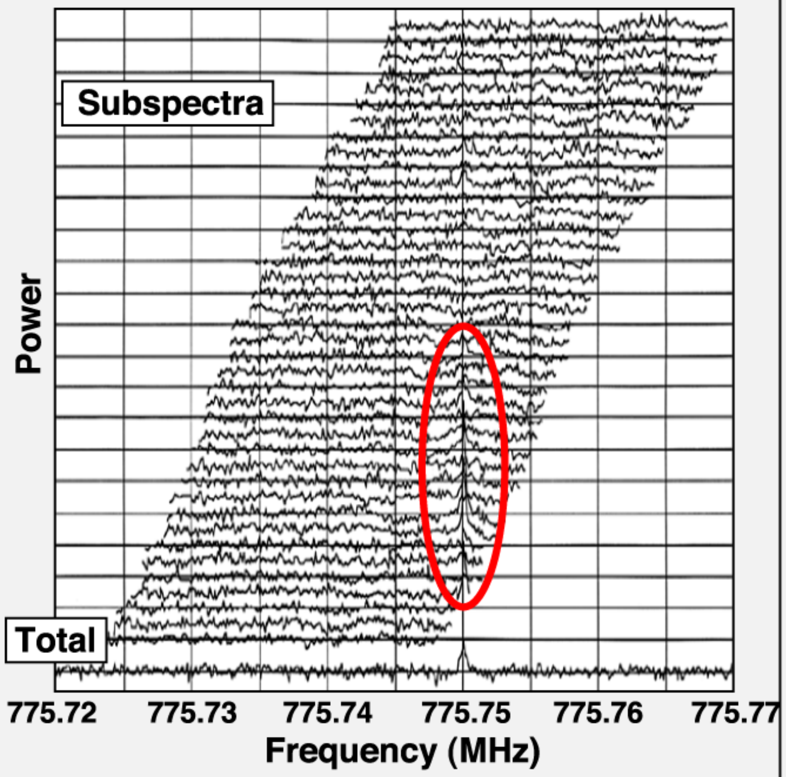






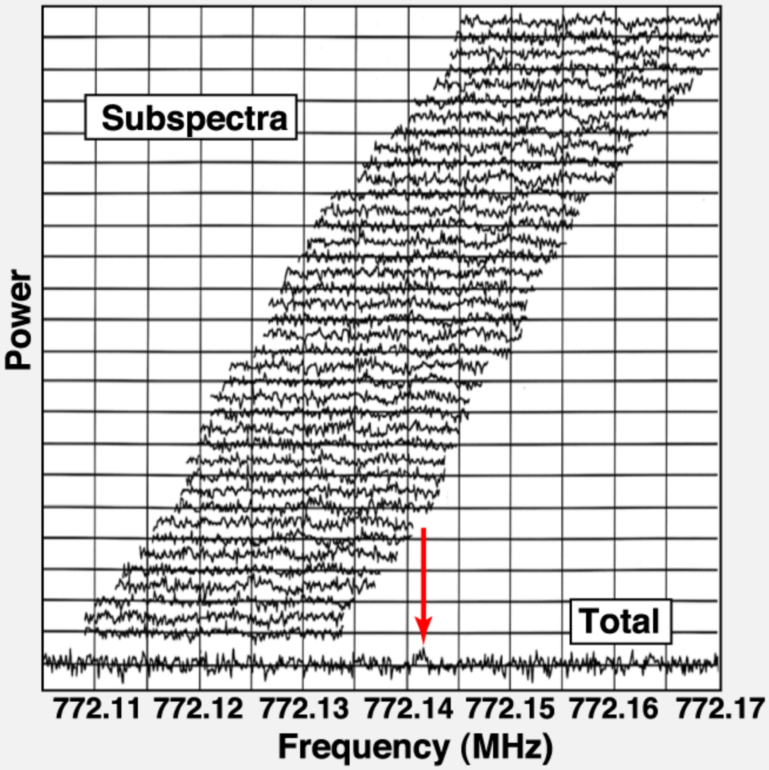
Sample data and candidates

Environmental



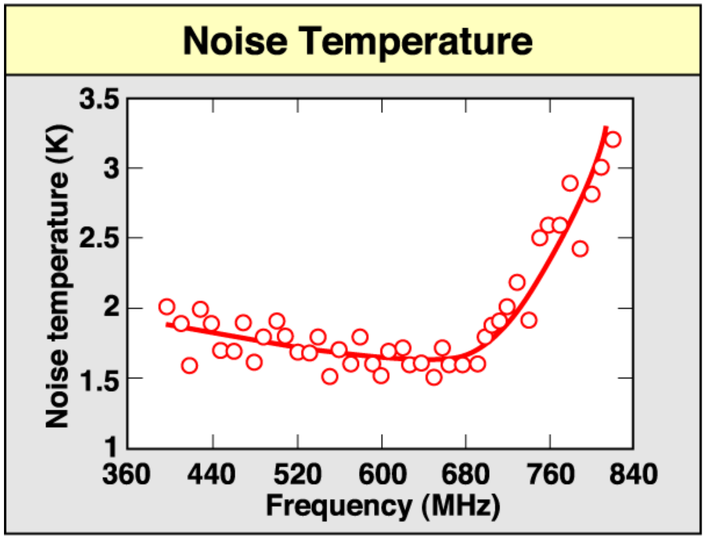
Signal maximizes off-resonance: Radio peak

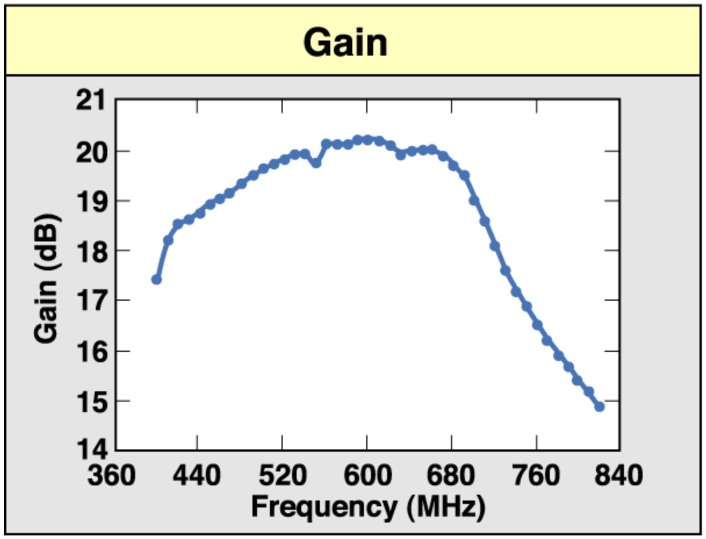
Statistical



Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

A slight digression on microwave amplification


Noise Temperature


Gain

HFET amplifiers
(Heterojunction Field-Effect Transistor)

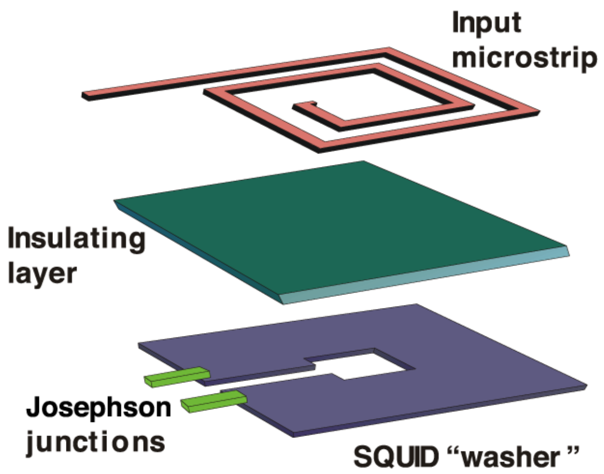
- — A.k.a. HEMT™ (High Electron Mobility Transistor)
- — Workhorse of radio astronomy, military communications, etc.

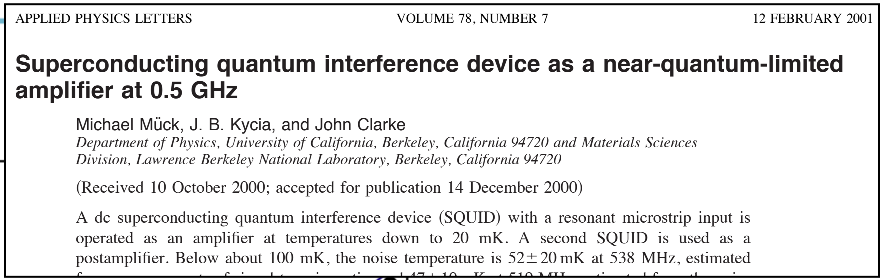
- Best to date $T_N \gtrsim 1$ K

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 (c.f., John Clarke's discussion).





APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 7 12 FEBRUARY 2001

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

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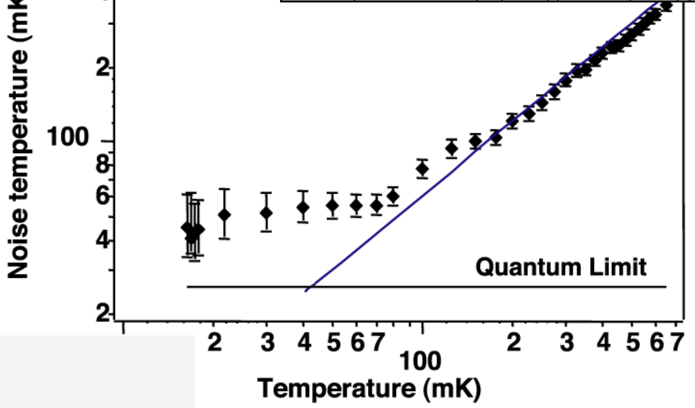
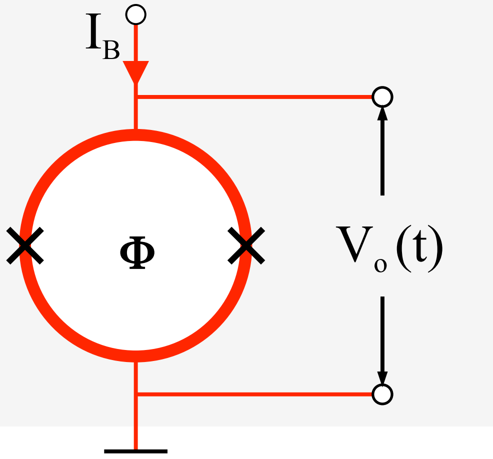
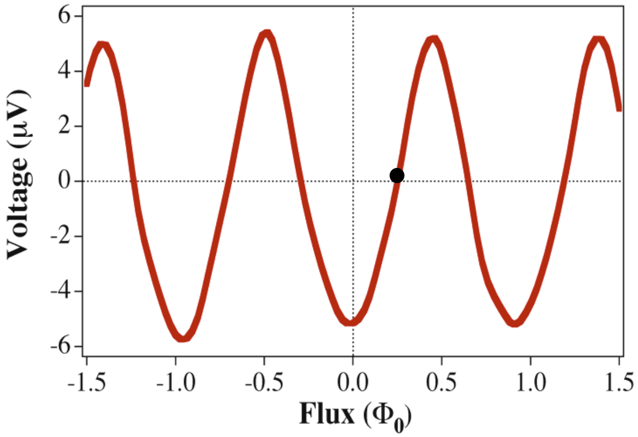
(Received 10 October 2000; accepted for publication 14 December 2000)

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

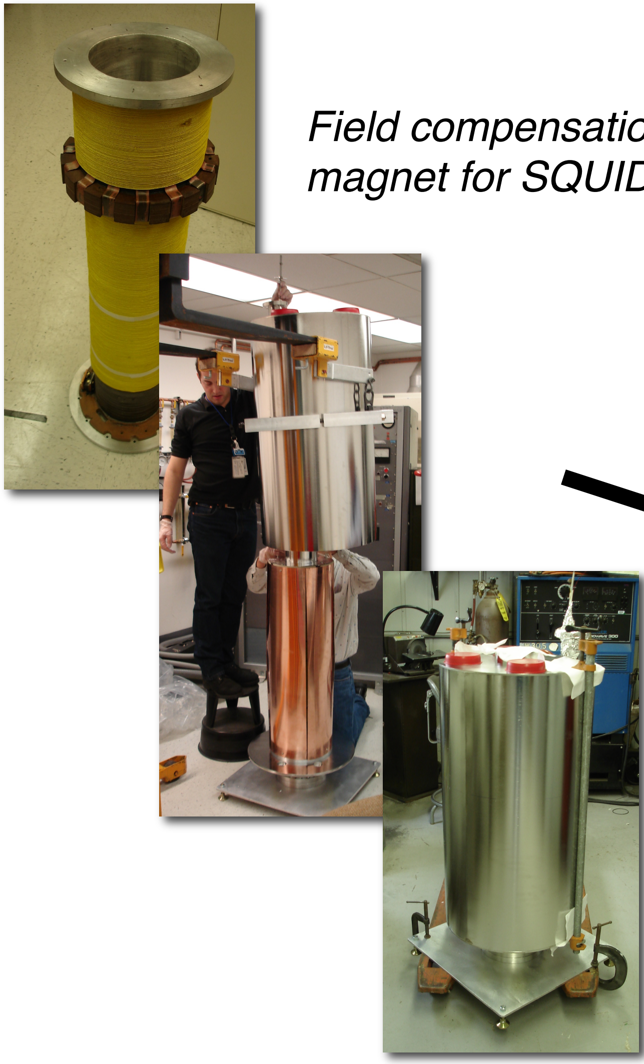


- GHz SQUIDs have been measured with T_N ~50 mK
- Near quantum–limited noise
- This provides an enormous increase in ADMX sensitivity

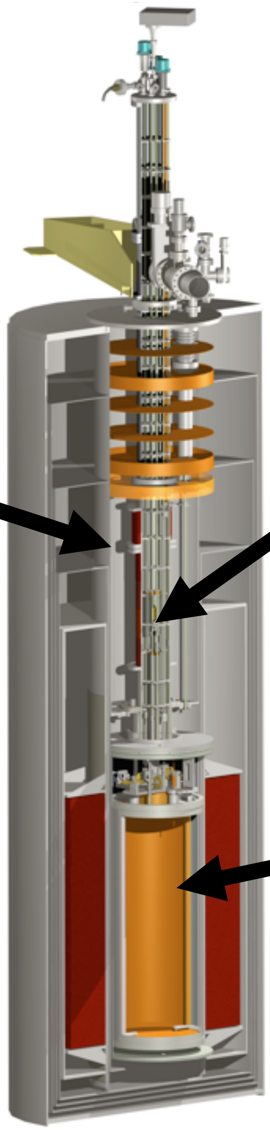




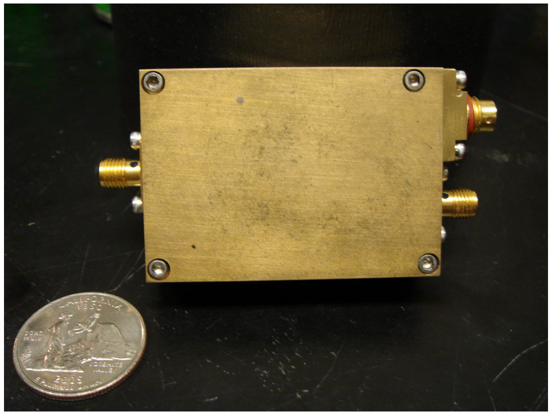
ADMX SQUID upgrade construction finished late 2007 and then entered commissioning, operated into 2010



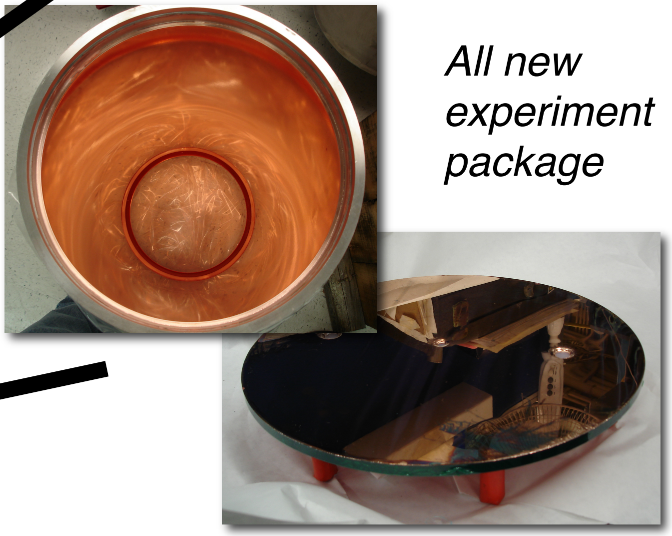
Field compensation magnet for SQUIDs



SQUID amplifier



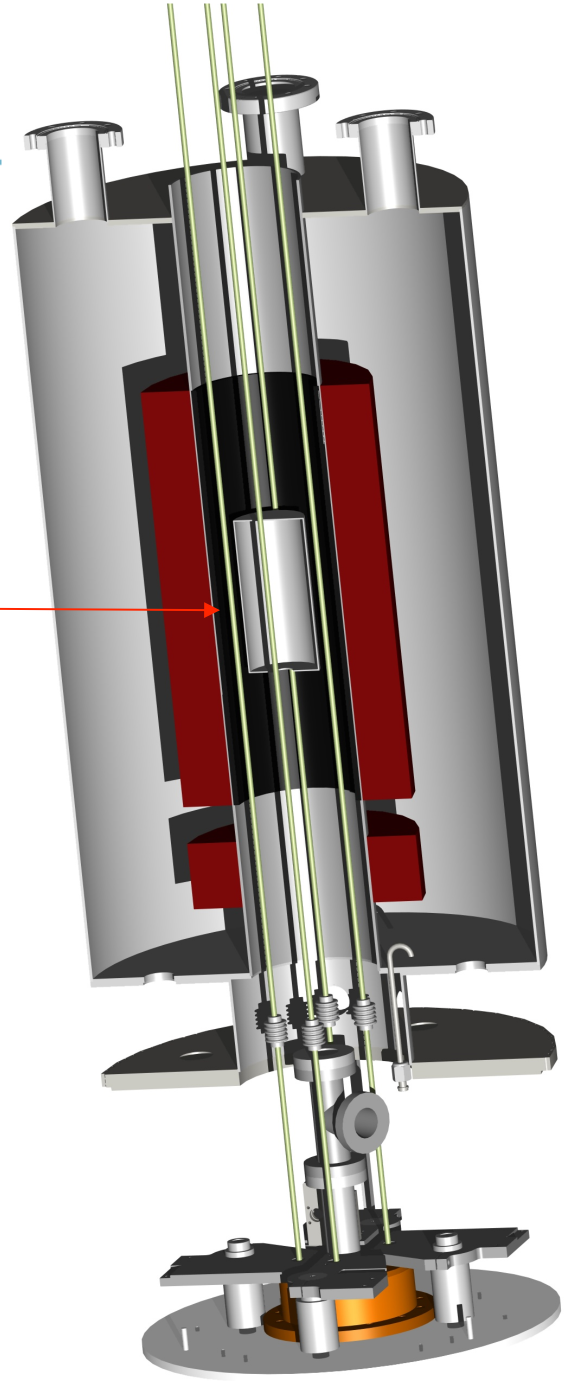
All new experiment package



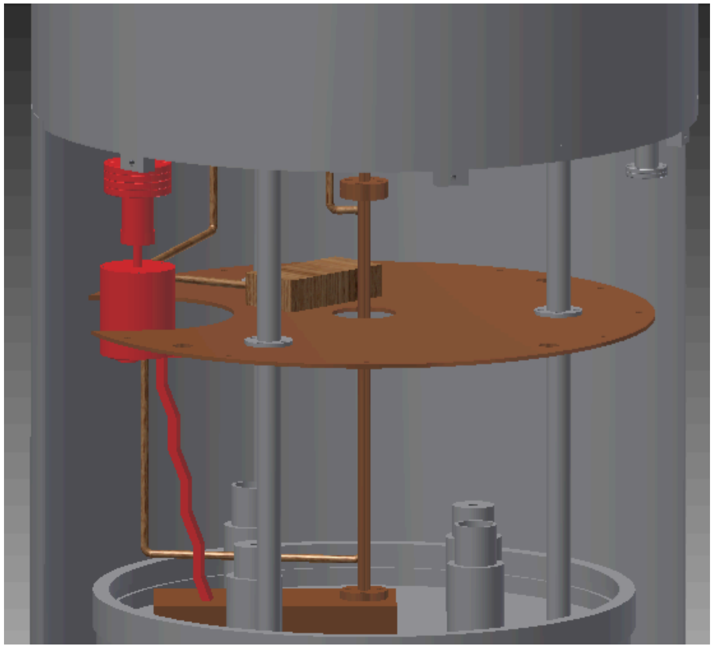
The SQUIDs sit well above the cavity

From outwards-in:

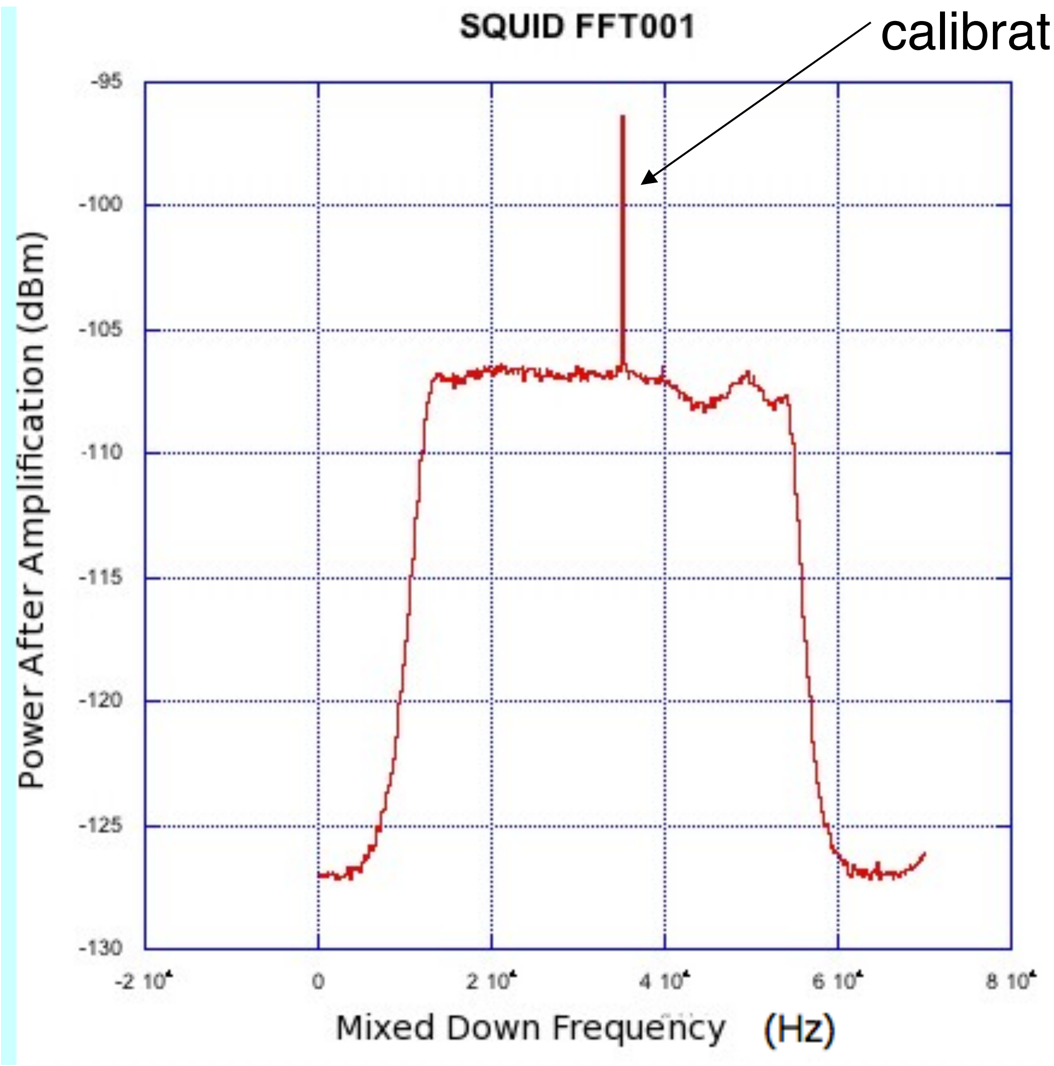
Bucking coil
Iron shield.
Cryoperm (mumetal) shields.
Superconducting shields.
SQUID amplifier package.
SQUIDs.



Refrigerator assembly



First commissioning: SQUID amplifier in ADMX



calibration (about 100 yoctowatts)

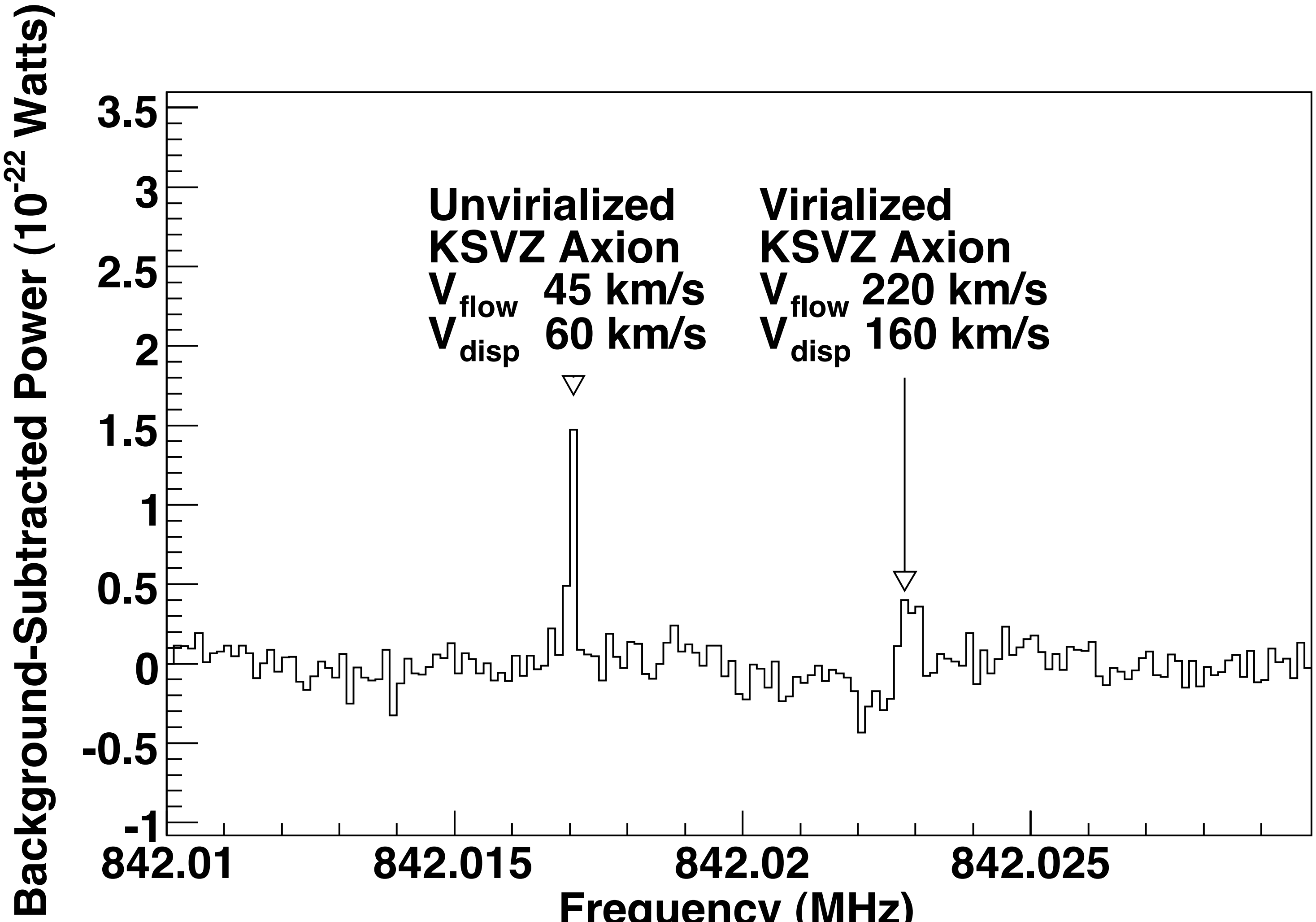
January 25, 2008:

Temperature ~ 4K

Bucking coil active

SQUID functioning as amplifier

What would an axion look like in ADMX? Like the WIMP people, we need to understand the halo.



Initial SQUID-ADMX operations: 1/2-year science data

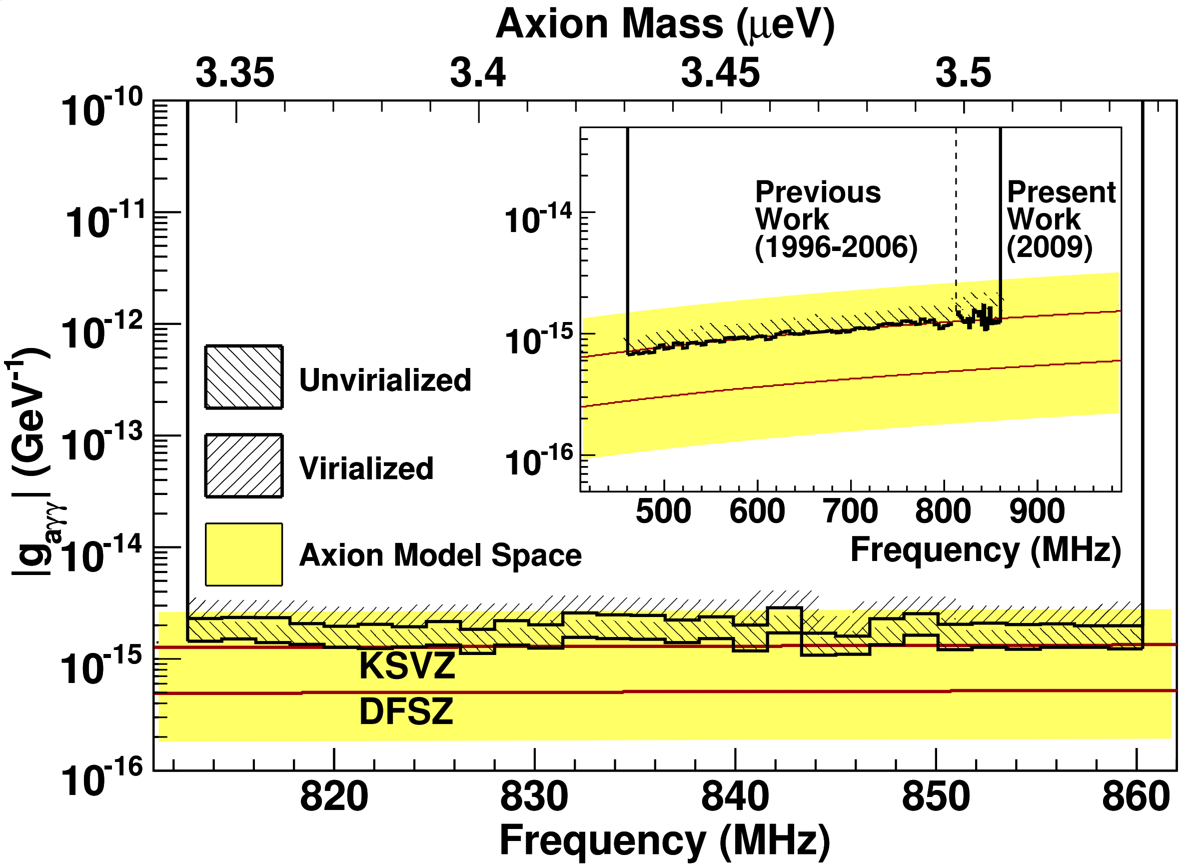
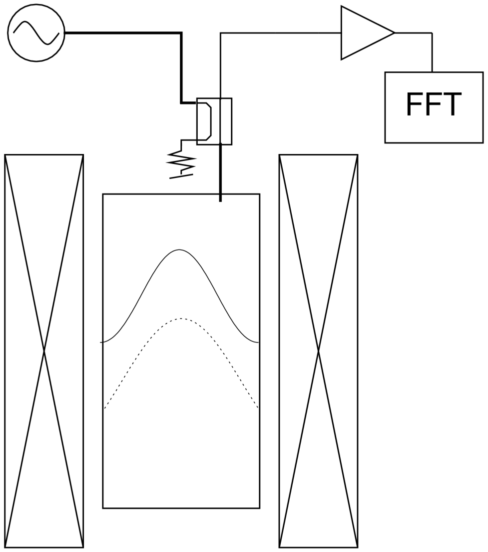


FIG. 5: Axion-photon coupling excluded at the 90% confidence level assuming a local dark matter density of 0.45 GeV/cm^3 for two dark matter distribution models. The shaded region corresponds to the range of the axion photon coupling models discussed in [23].

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

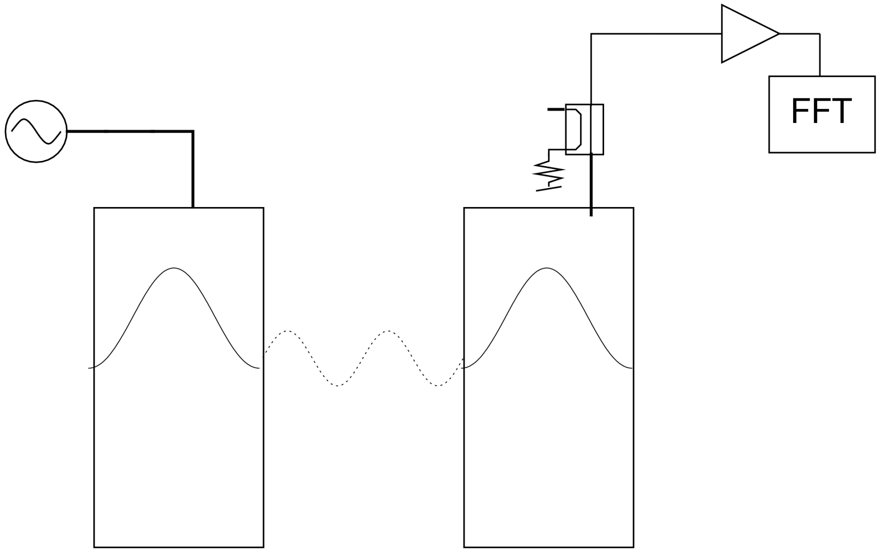
Chameleons

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

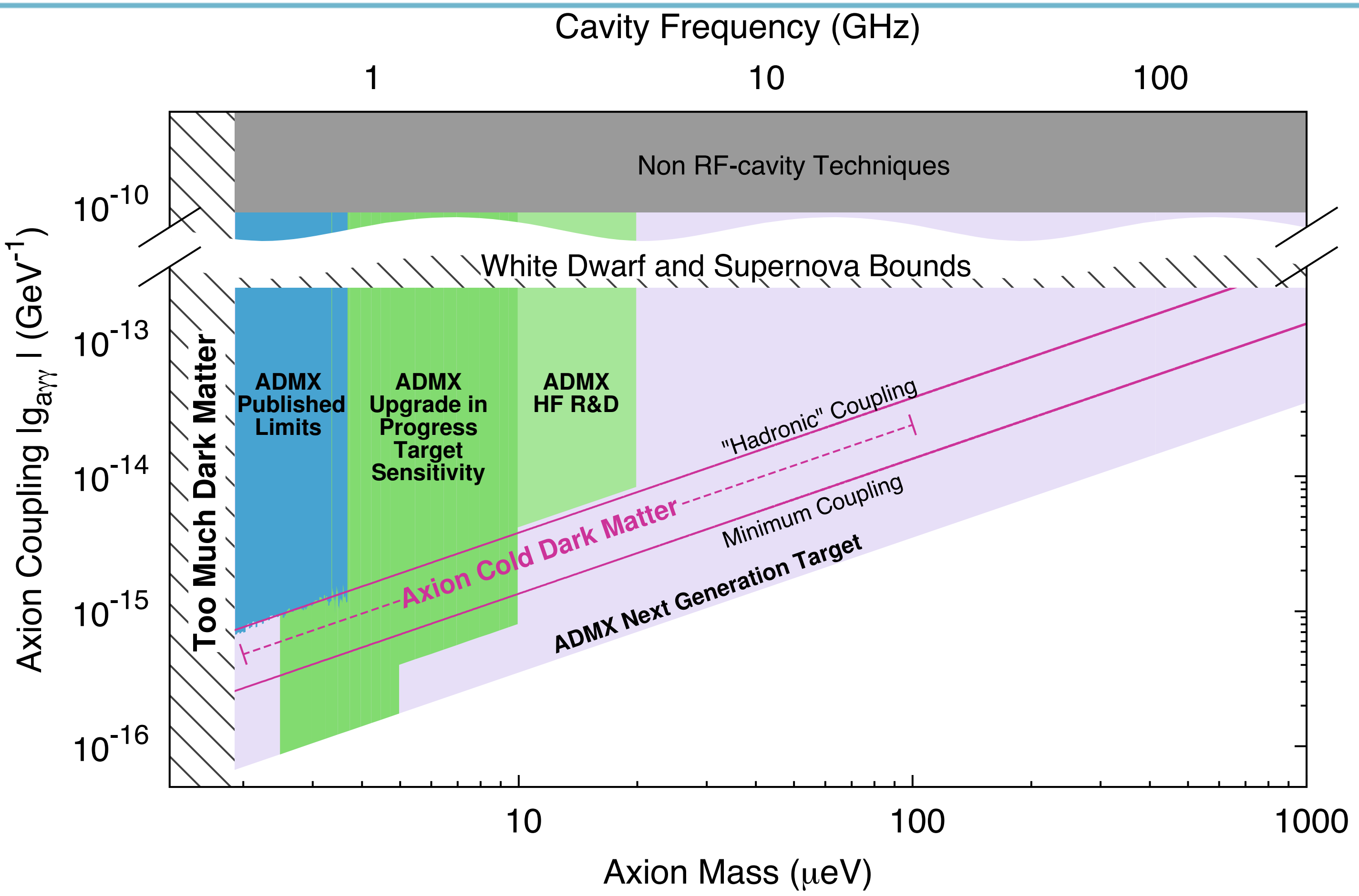


Hidden-sector photons

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



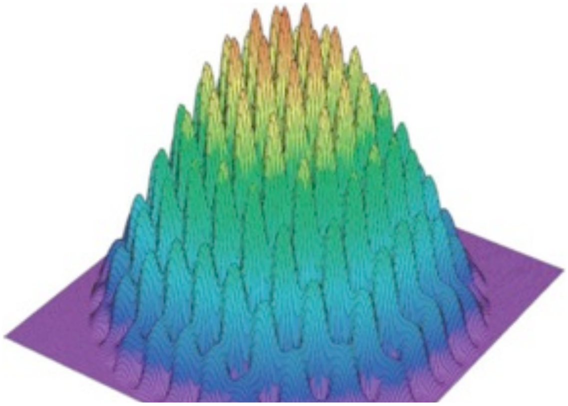
What's happening to ADMX now?
Building final phase: add dilution-refrigerator cooling



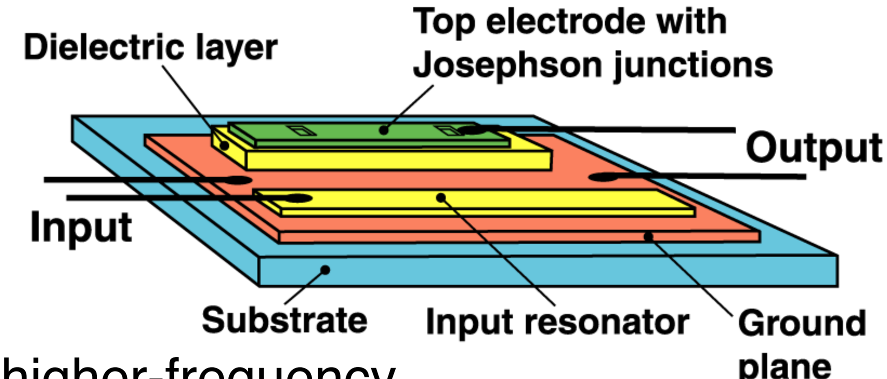
Dilution refrigerator cooled detectors allow scanning at or below DFSZ sensitivity at fractional dark-matter halo density.
This is the "definitive" QCD dark-matter axion search

Can the RF-cavity experiments do better? Higher frequencies, higher Q, squeezed states?

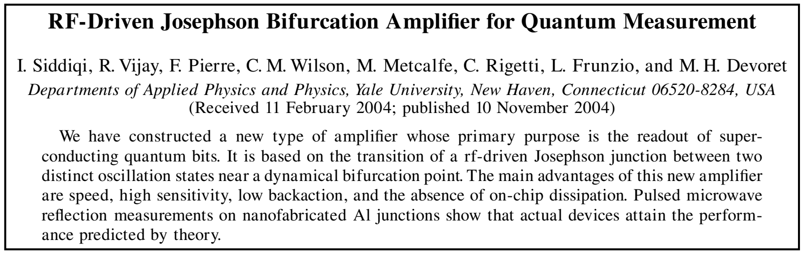
Very active R&D paths.



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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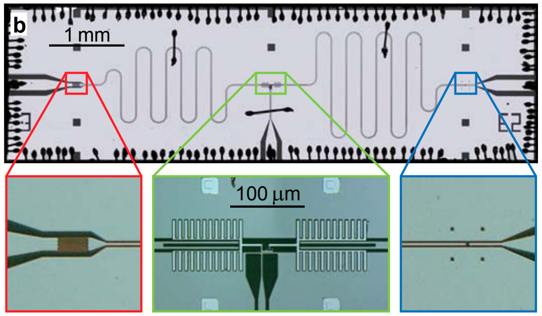
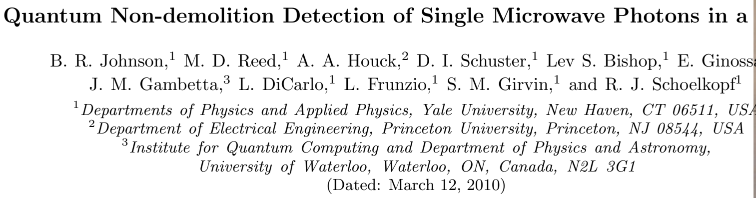
(Received 11 February 2004; published 10 November 2004)

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

B. R. Johnson,[1] M. D. Reed,[1] A. A. Houck,[2] D. I. Schuster,[1] Lev S. Bishop,[1] E. Ginossar,[1]
J. M. Gambetta,[3] L. DiCarlo,[1] L. Frunzio,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]
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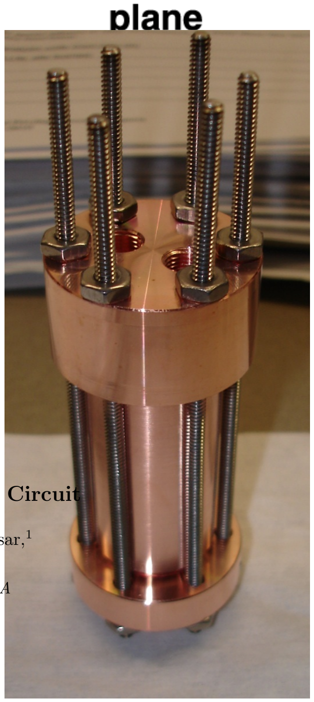
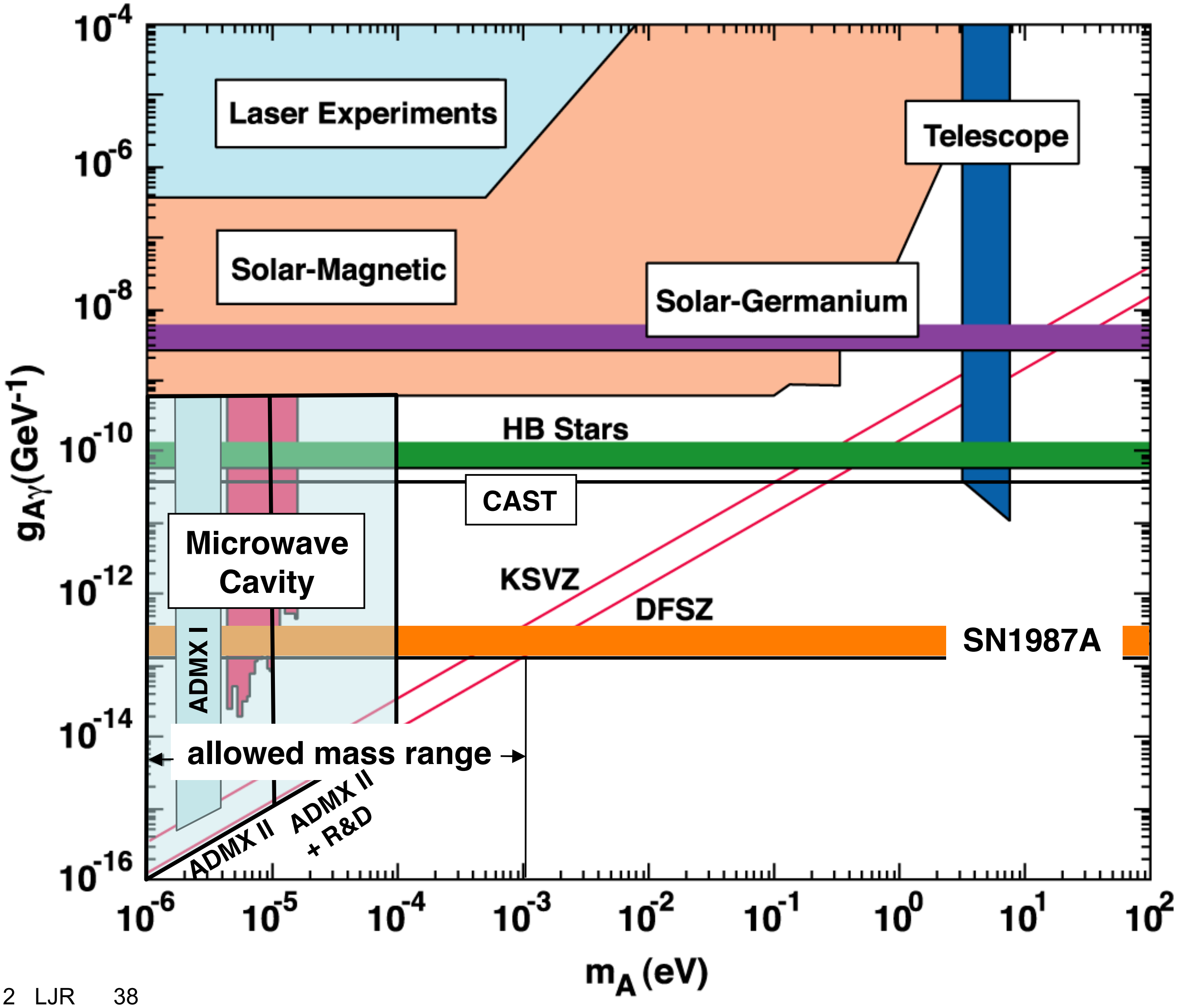
(Dated: March 12, 2010)



“hybrid” superconducting cavities (Yale group)

Selected limits: Revisited showing RF-cavity sensitivity to QCD dark-matter axions



Conclusions: Are we going to find the QCD Dark-Matter axion?

Sure. I have little doubt.

I find the the Strong CP Problem very troubling.
The source of CP violation in the weak interactions should as well induce strong-interaction CP violation: But this isn’t seen.

There’s some reason CP is missing in strong interactions: Hence “QCD axions” are a good bet for the strong CP problem.

These same axions solve the dark matter problem. The particle-physics predictions are sufficiently robust, as are the astrophysics halo models (“How would you keep them out?”).

There are many axion-search technologies. The RF-cavity technique is the only one sensitive to QCD dark-matter axions.

The coming ADMX phases will be sensitive to even the more pessimistically-coupled QCD dark-matter axions at fractional halo density.

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

Thank you

INT Organization.

ADMX Collaborators.

Axion colleagues across the world.

DOE & NSF sponsors of dark-matter research.
(We know the strains you're under and we appreciate the support.
Indeed, this workshop was supported by DOE/NP,HEP and NSF)

And David Schramm.