Review of Dark-Matter Axion Experiments

Neutrino 2000 Conference

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AXION

P01645-kvb-u-009

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Outline

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- Brief review of the axion
- The Sikivie microwave cavity technique
- The U.S. large-scale experiment* (HEMTs, SQUIDs)
- The Kyoto experiment (Rydberg-atom single quantum detection)
- Summary

*MIT-LLNL-Florida-Berkeley-LBNL-Chicago-FNAL-INR

Brief summary of the Axion

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- The Axion is a light pseudoscalar resulting from the PQ-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

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

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

Cosmological Abundance

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

(Vacuum misalignment mechanism)

Axion Mass 'Window'

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

(Overclosure) (SN1987a)

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

The parameter space

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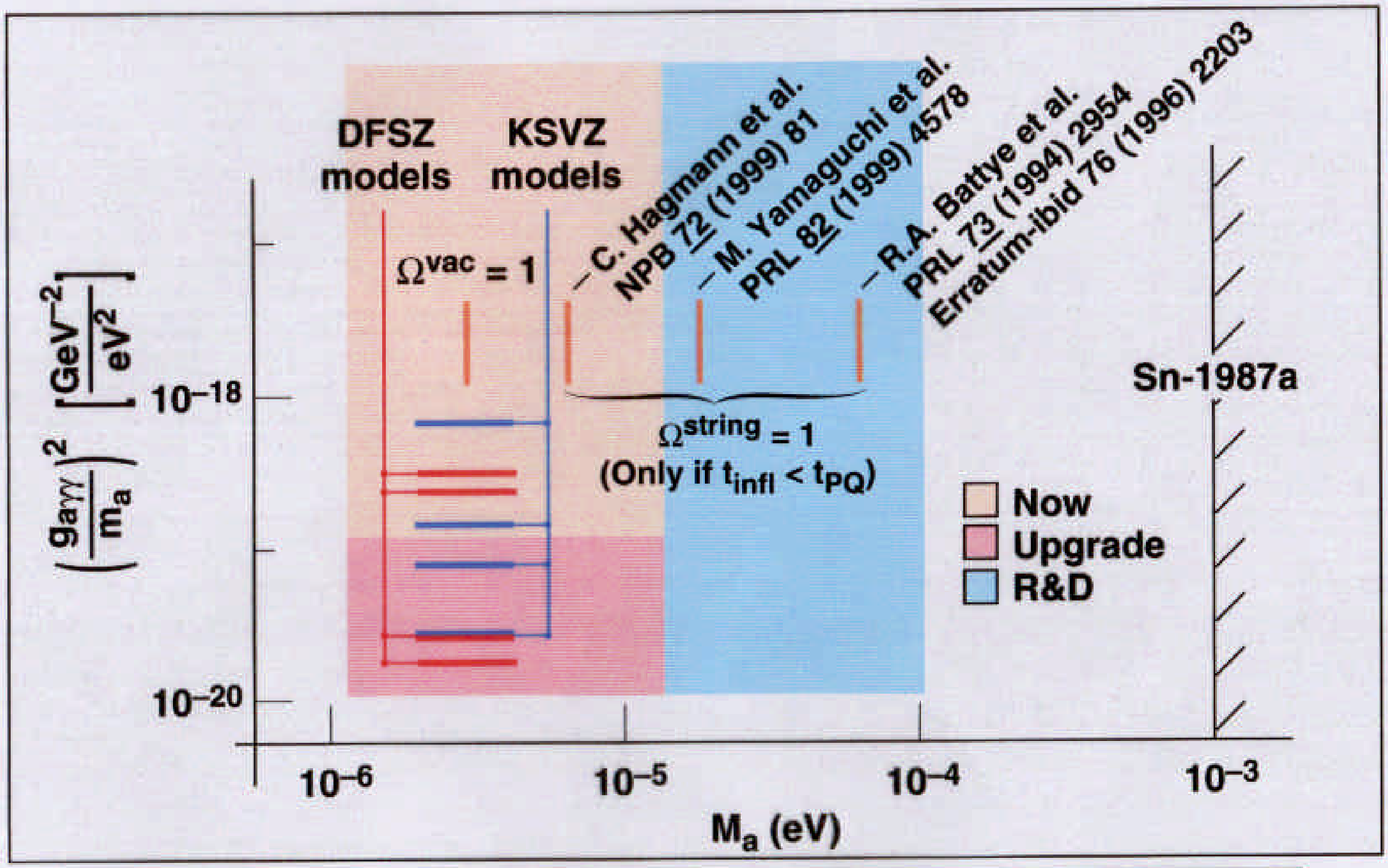

- There is a definitive sensitivity in axion searches
- Large theoretical uncertainties in $\Omega = 1$ all around
- Nevertheless, we can cover a lot of ground!

How to detect dark-matter axions (Sikivie, 1983)

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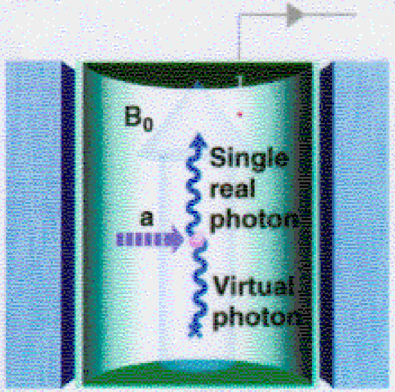
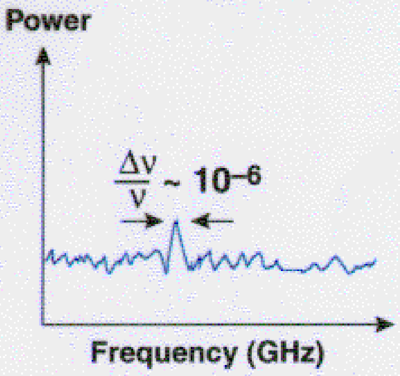
Primakoff Conversion



Signal



Resonant Conversion: $h\nu = m_a c^2[1 + O(\beta^2)]$

$$P_{sig} \sim (5\times10^{-22}\mathrm{W}) \cdot \left(\frac{B}{7.6\mathrm{T}}\right)^2 \cdot \left(\frac{V}{220\ell}\right) \cdot \left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\right) \cdot \left(\frac{m_a}{3\ \mu\mathrm{eV}}\right)$$

Dicke's Radiometer Eqn. → Integration Time

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}} \quad ; \quad T_S = T + T_N$$

Present exp't: $T \sim T_N \sim 1.5$ K

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 $\frac{d\nu}{dt}$

This is a narrow-band experiment. There is no other way to get the required sensitivity!

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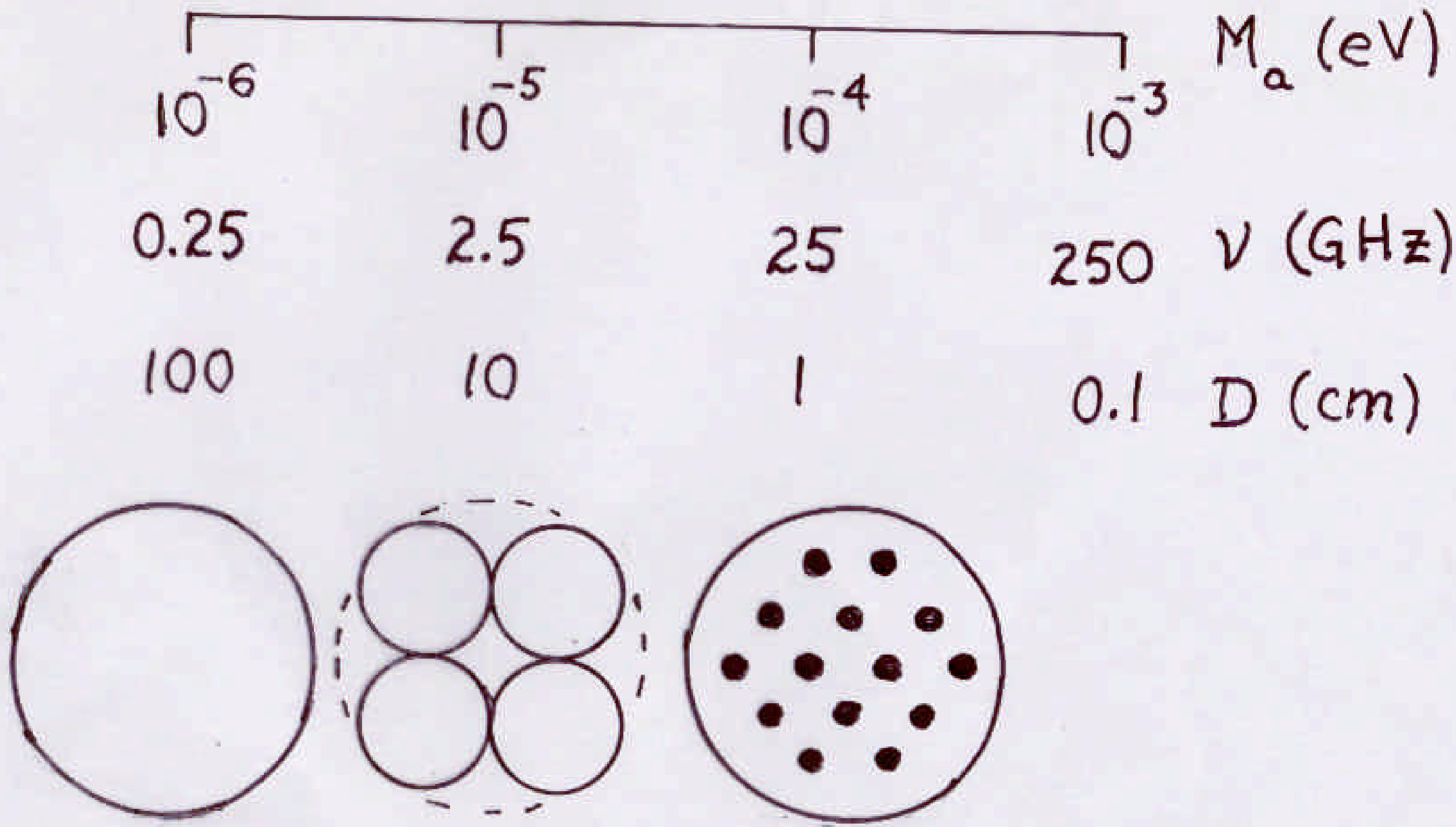

M_a (eV)
10^{-6} 10^{-5} 10^{-4} 10^{-3}
0.25 2.5 25 250 ν (GHz)
100 10 1 0.1 D (cm)

Axion hardware

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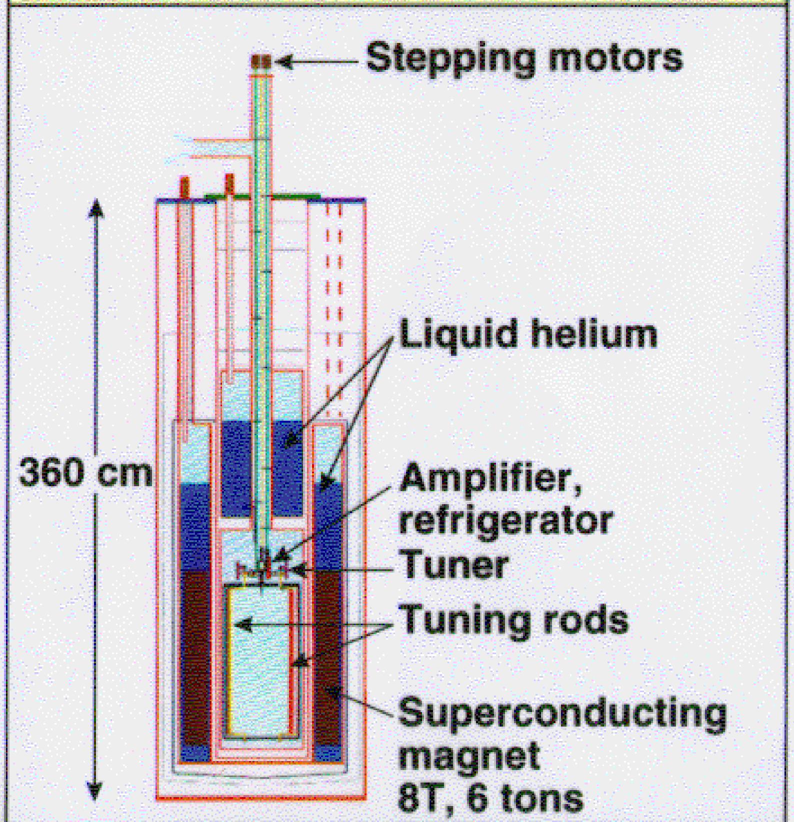
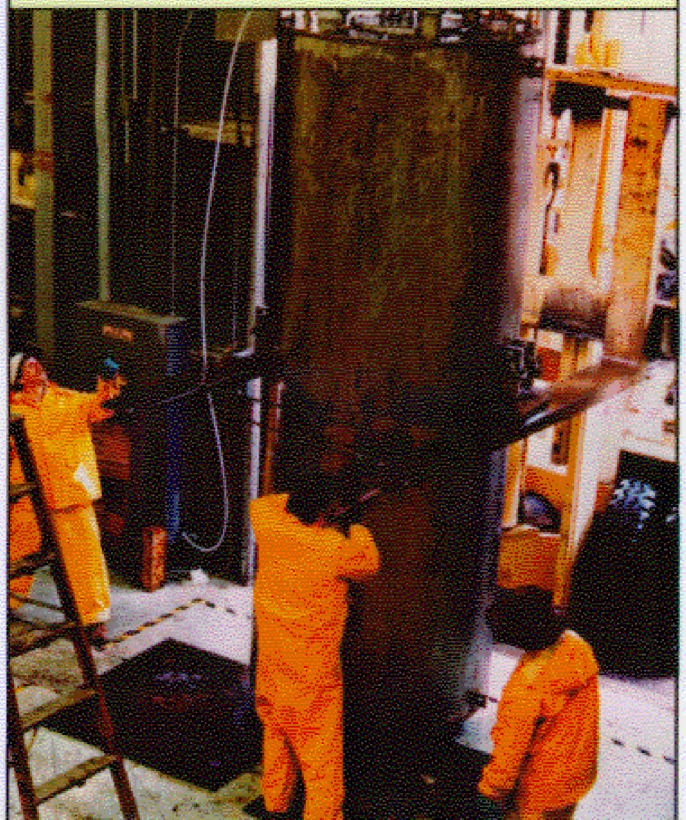
Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)



8 T, 1 m × 60 cm ∅

Axion hardware (cont'd)

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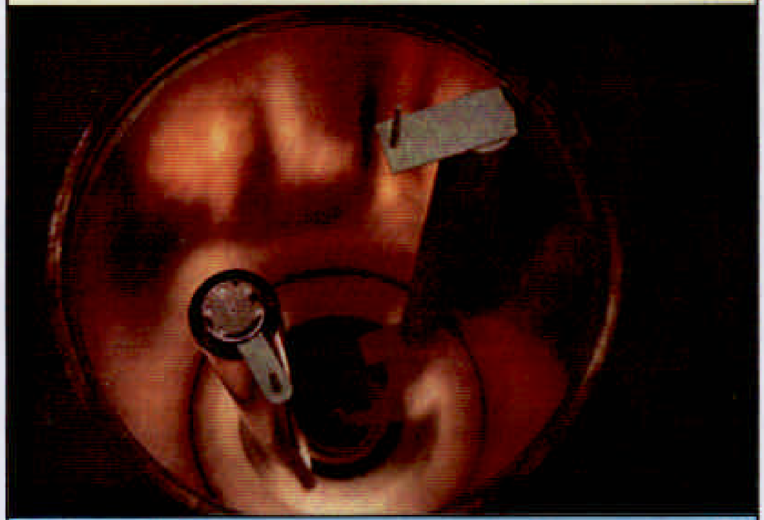
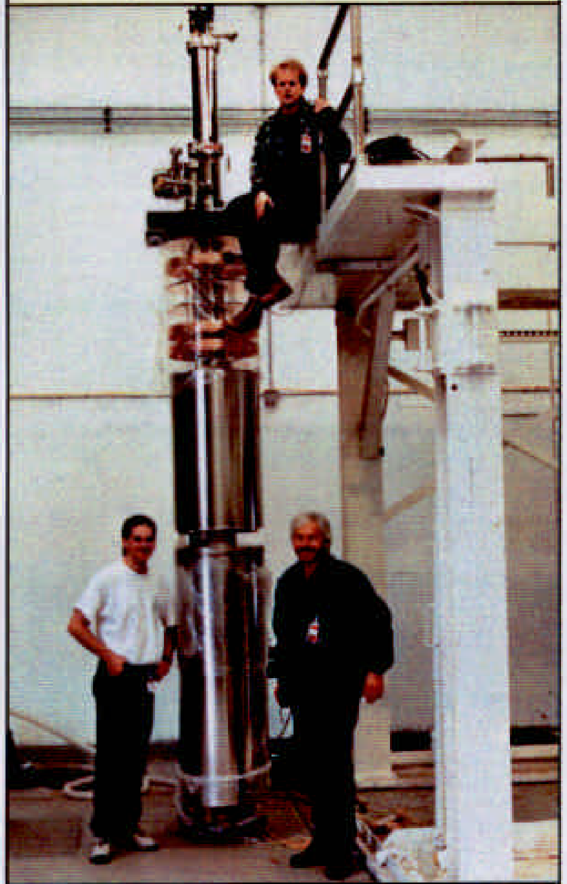
Tunable Microwave Cavity



300–800 MHz, Q ~ 200,000

Construction completed November, 1995. Routine operation began February, 1996; >90% duty factor during single-cavity operation.

Ed Daw (PhD MIT 2/98)



Darin Kinion (PhD UC/LLNL 9/00)
Chris Hagmann (Term, LLNL)

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The axion receiver

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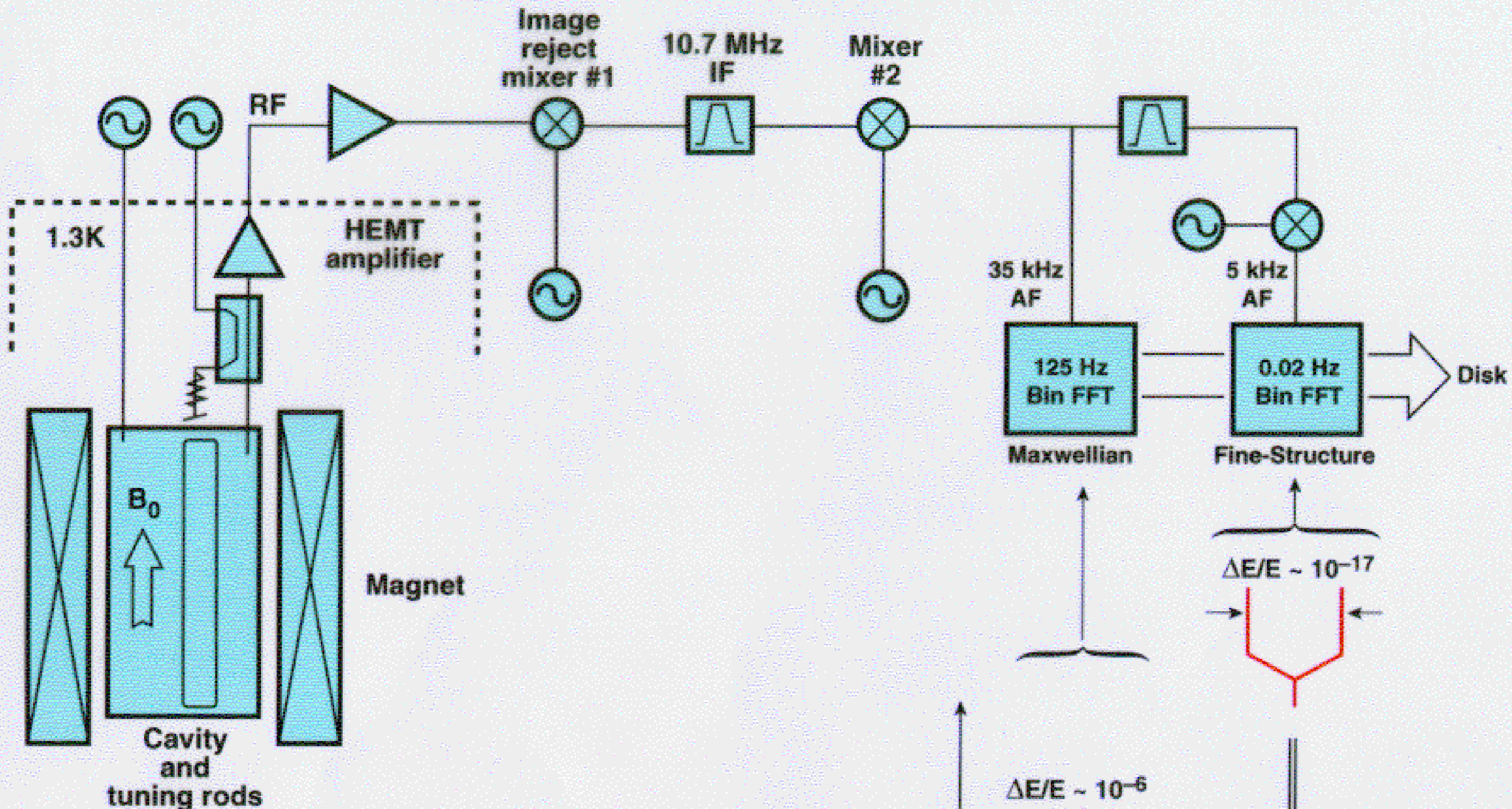

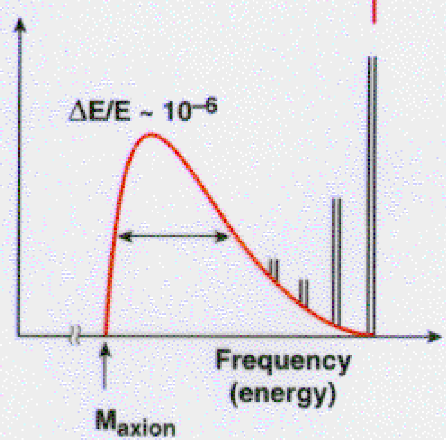

Experiment also instrumented to look for predicted non-thermalized components

- **Increases sensitivity of search**
- **Time-ordered history of galactic formation if found**

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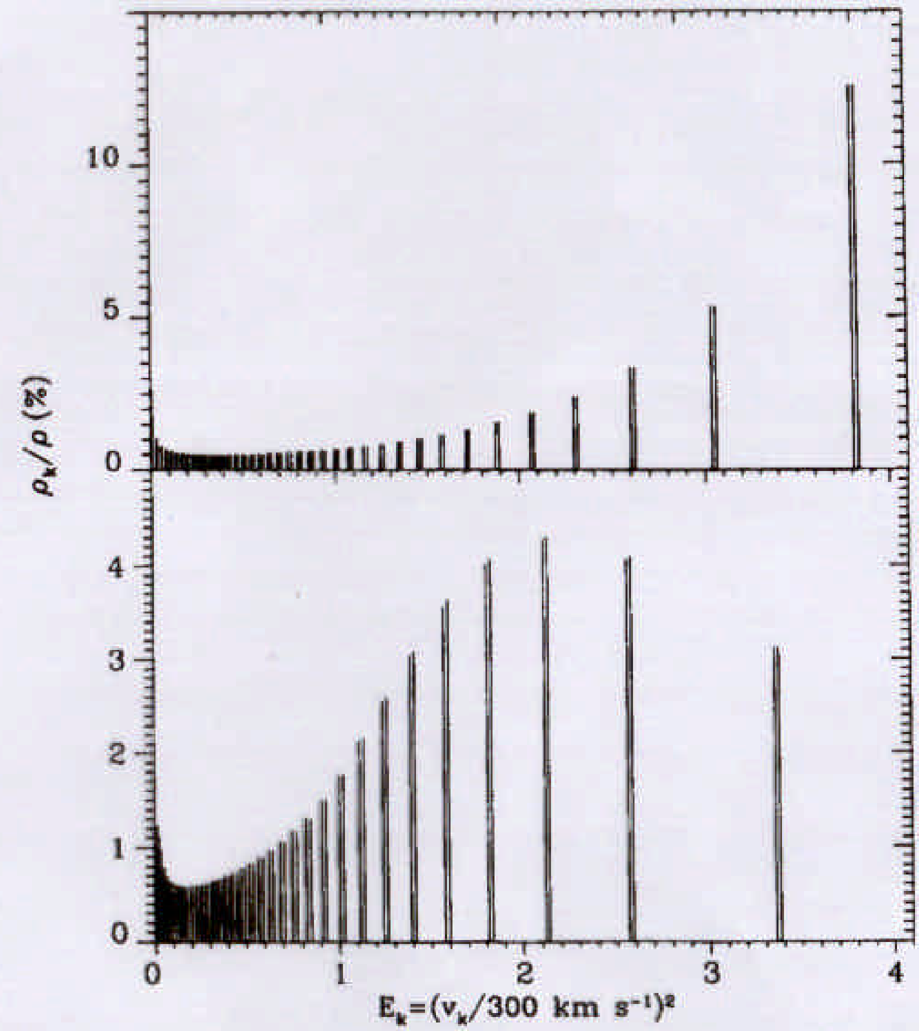

Fig. 4. The velocity spectrum of axions at our solar system, predicted in the model of Refs. [47,48]. (Upper panel) No initial angular momentum. (Lower panel) Finite initial angular momentum. Scattering processes are expected to eventually thermalize the spectrum, leading to the lower energy lines being subsumed into a Maxwellian-like distribution of width $\Delta E_A/E_A \sim 10^{-(6-7)}$.

Sikivie, Tkachev, Wang

Sample data and candidates

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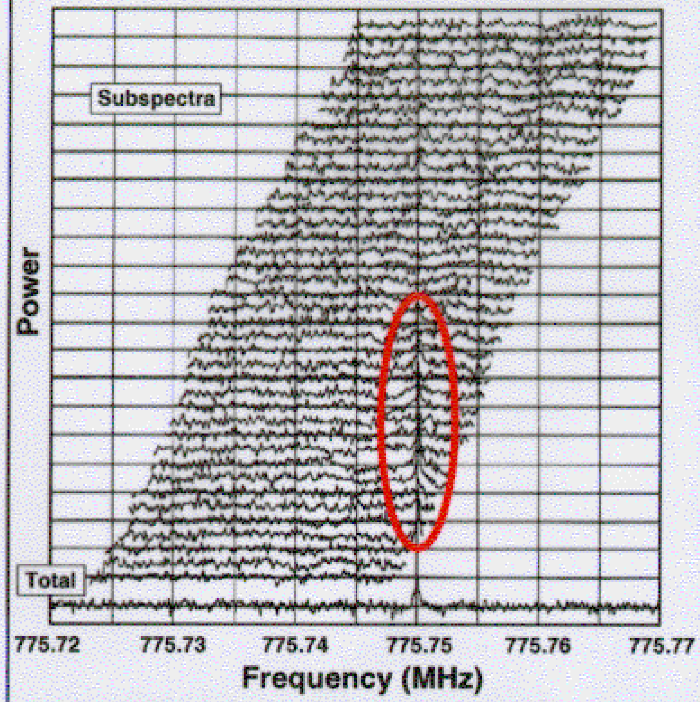
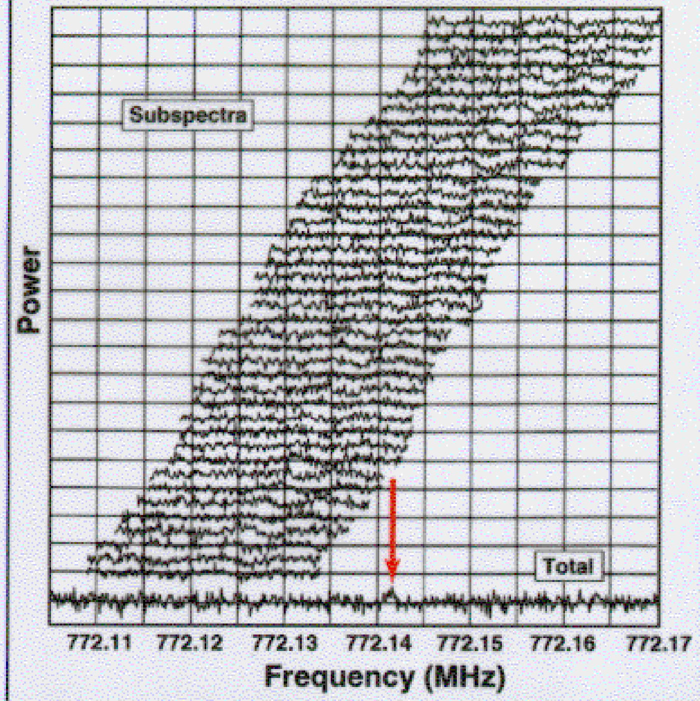
Environmental



Signal maximizes off-resonance: Radio peak

Statistical



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

- **High-resolution data analyzed similarly**
- **Also looked for 'coincidences' between high and medium resolution data**

Brief outline of analysis

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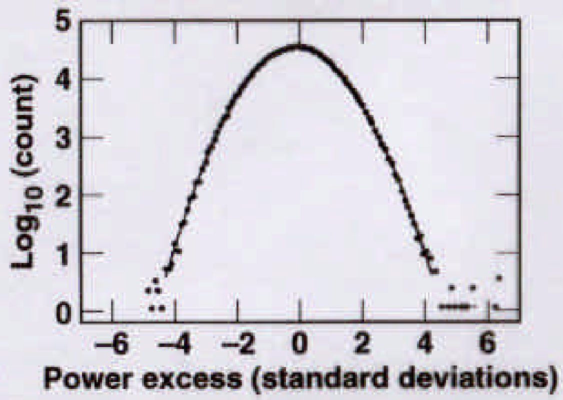
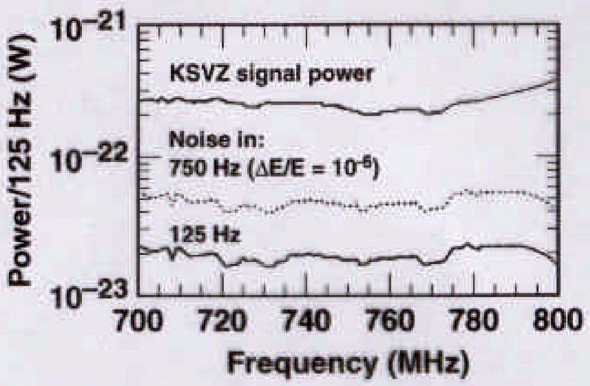
Data, with Theoretical Curve
(Gaussian noise through receiver and analysis)



S/N > 4 for Thermalized KSVZ Axion



- Each frequency appears in >45 subspectra
- Weighted and co-added to produce spectrum
- 800,000 bins (125 Hz)/100 MHz

→ 6535 candidates > $2.25\sqrt{6}\,\sigma$ (95% C.L.)
→ Rescan all to same sensitivity
→ 23 candidates (Net 90% C.L.)
→ Each examined: radio peaks

For a persistent peak, the ultimate test is to turn off the magnet!

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Cosmic axion exclusion plot

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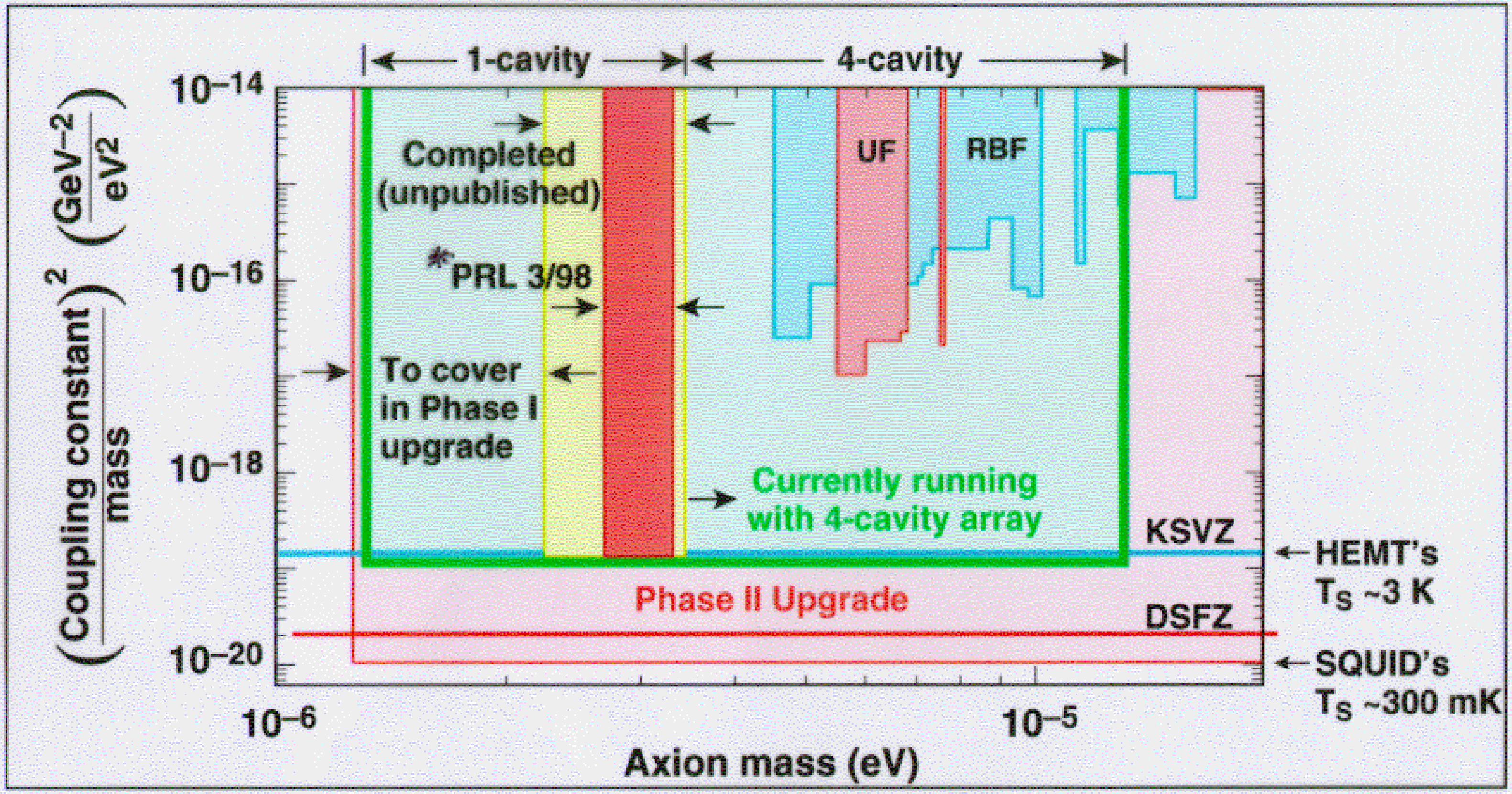

- Phase I Upgrade: SQUIDs at 1.3 K will allow us run at KSVZ 4 times faster than with HEMTS
- Phase II Upgrade: SQUIDs at 200 mK will give us sensitivity to DFSZ axions even if they only constitute 50% of the halo

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* C. Hagmann et al.; Phys. Rev. Lett. 80 2043 (1998)

The 4-cavity array is now running

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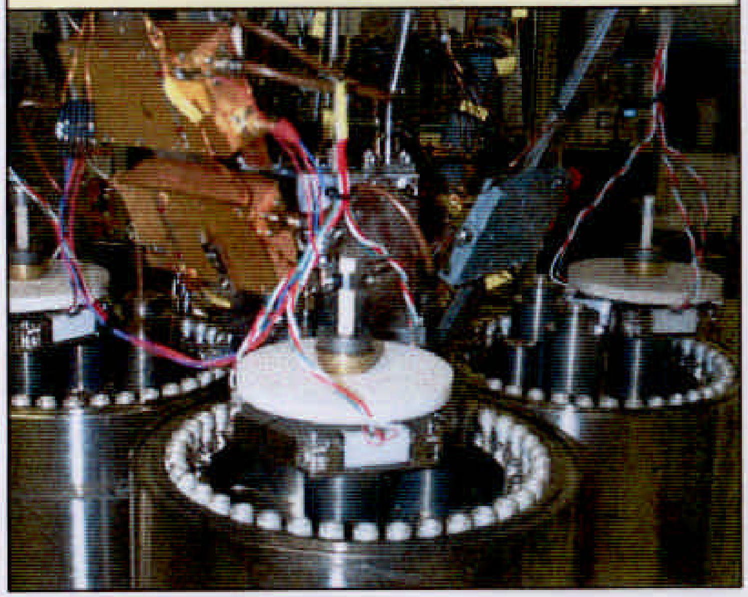
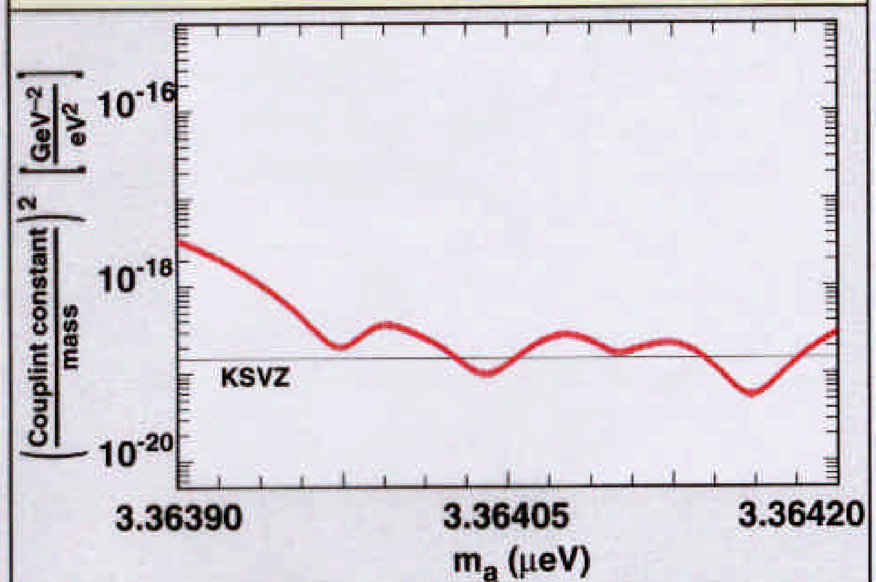
Axion 4-Cavity Array



First 4-Cavity Data



- **Multiple-cavity arrays required for higher frequencies**
- **Required development of cryogenic piezoelectric motors**

SQUID basics

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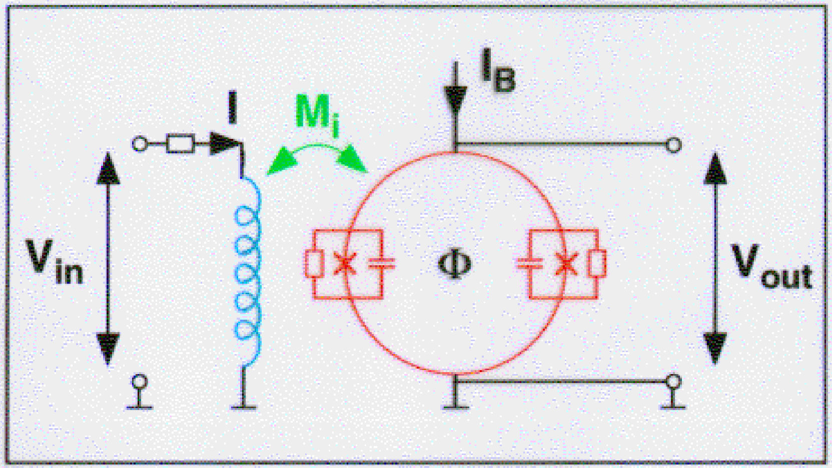

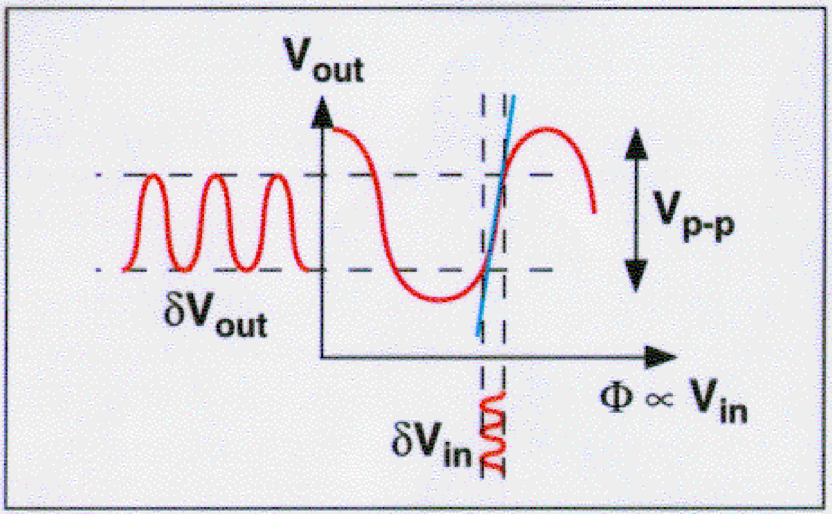

- SQUID noise arises from Nyquist noise in shunt resistance

- Thus it scales linearly with T

What the device looks like

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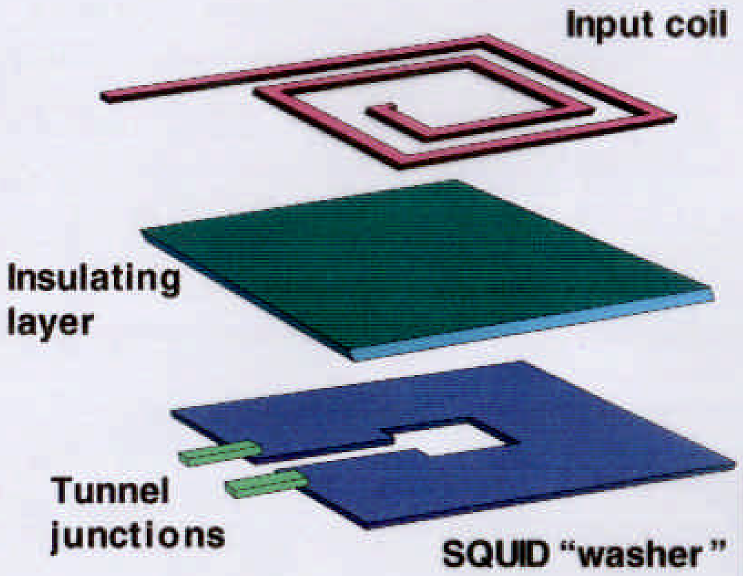

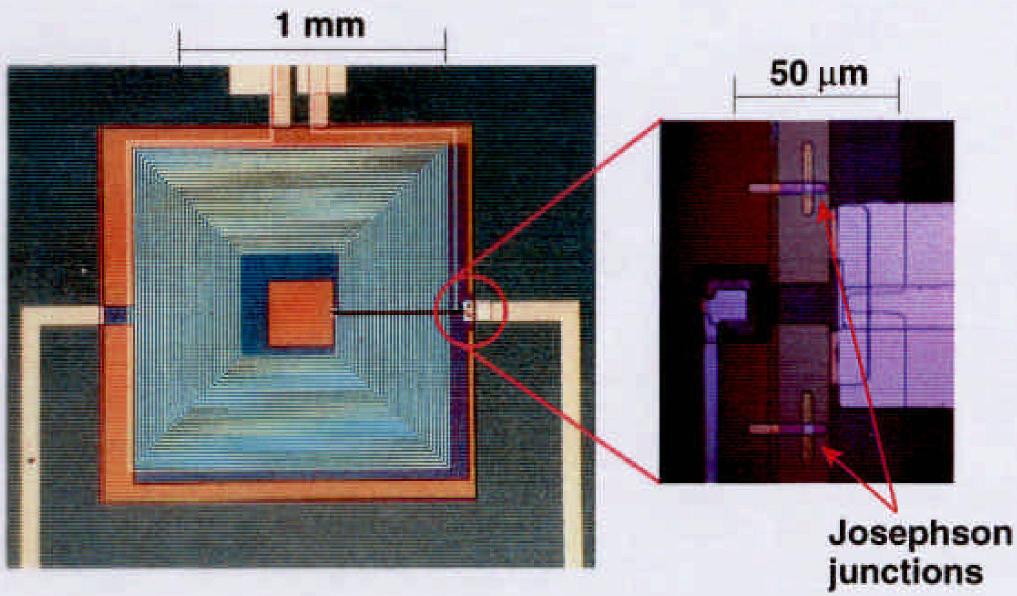

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SQUID performance near quantum limit

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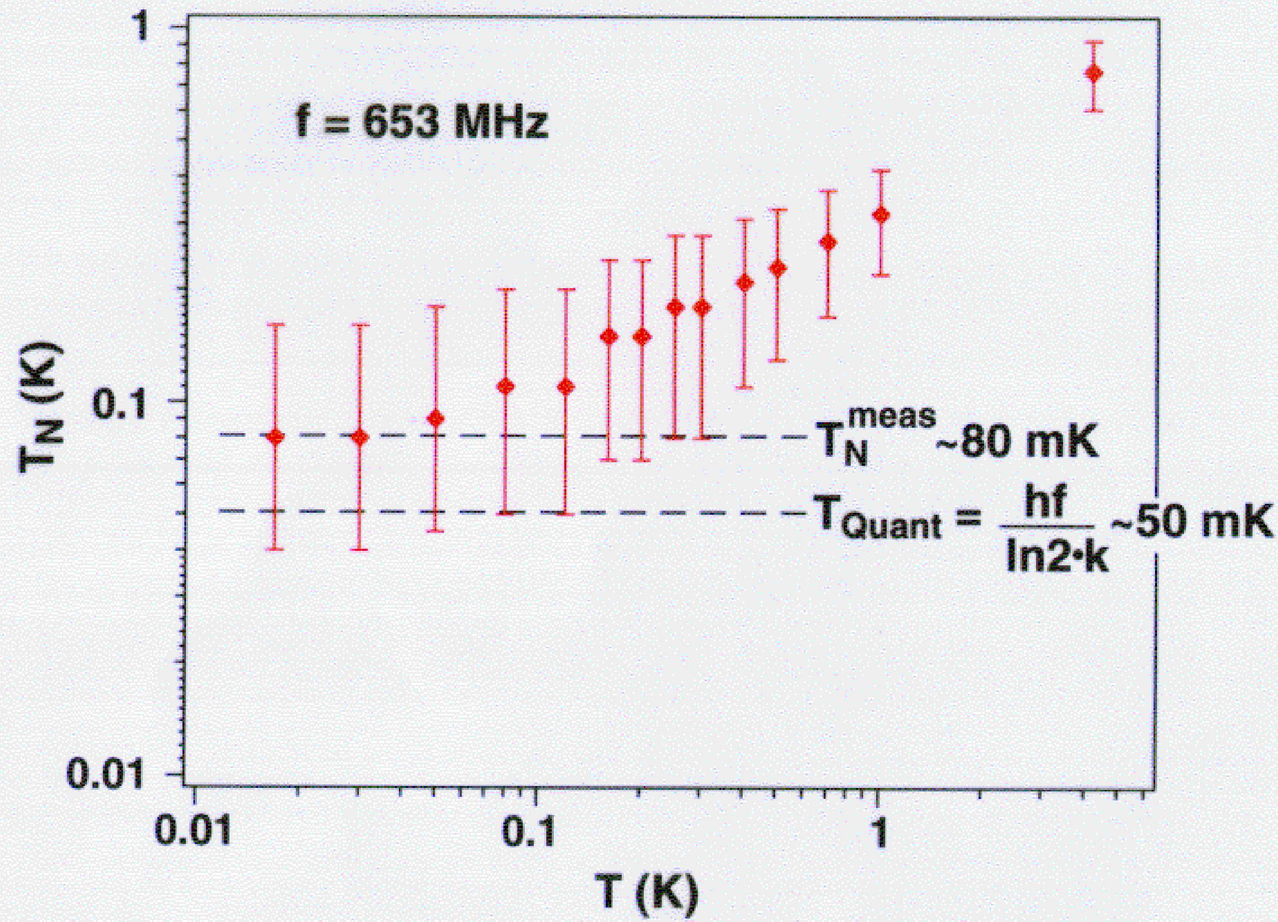

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Highest frequency SQUID amplifier to date: 3 GHz

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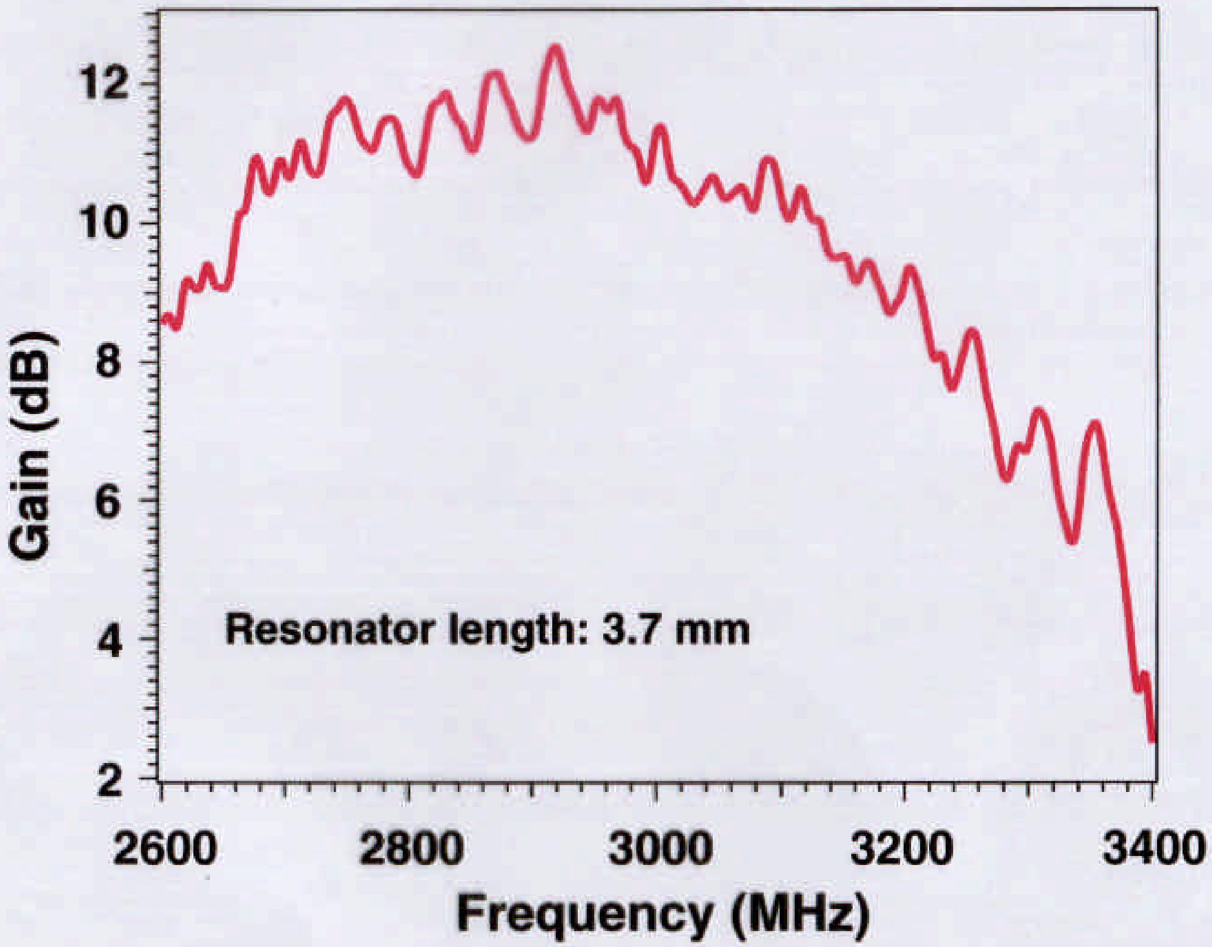

In-situ amplifier tuning

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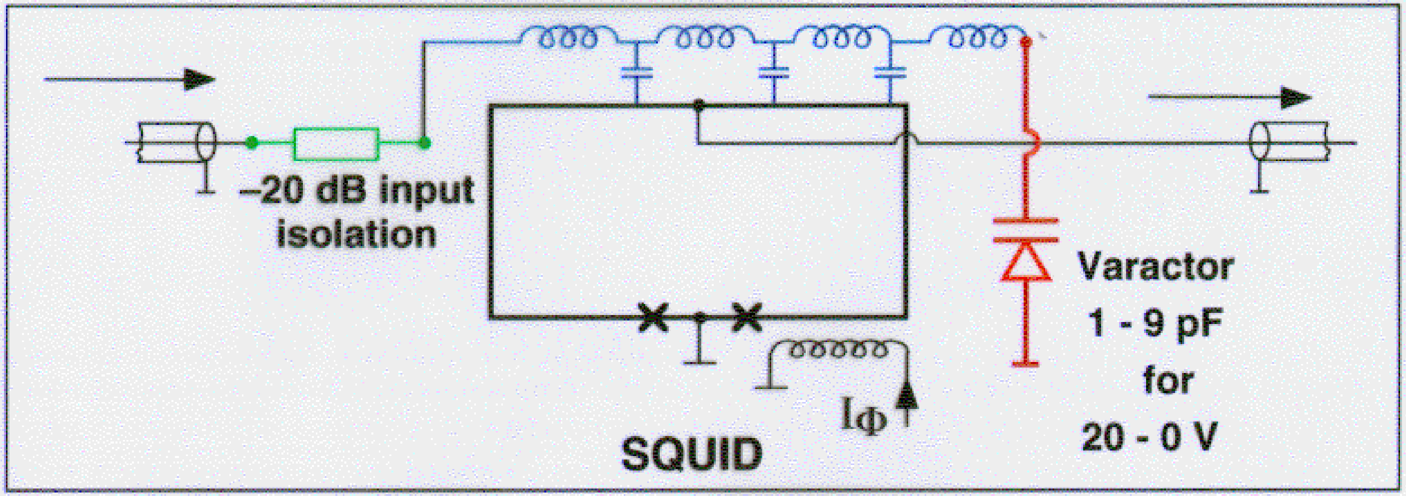

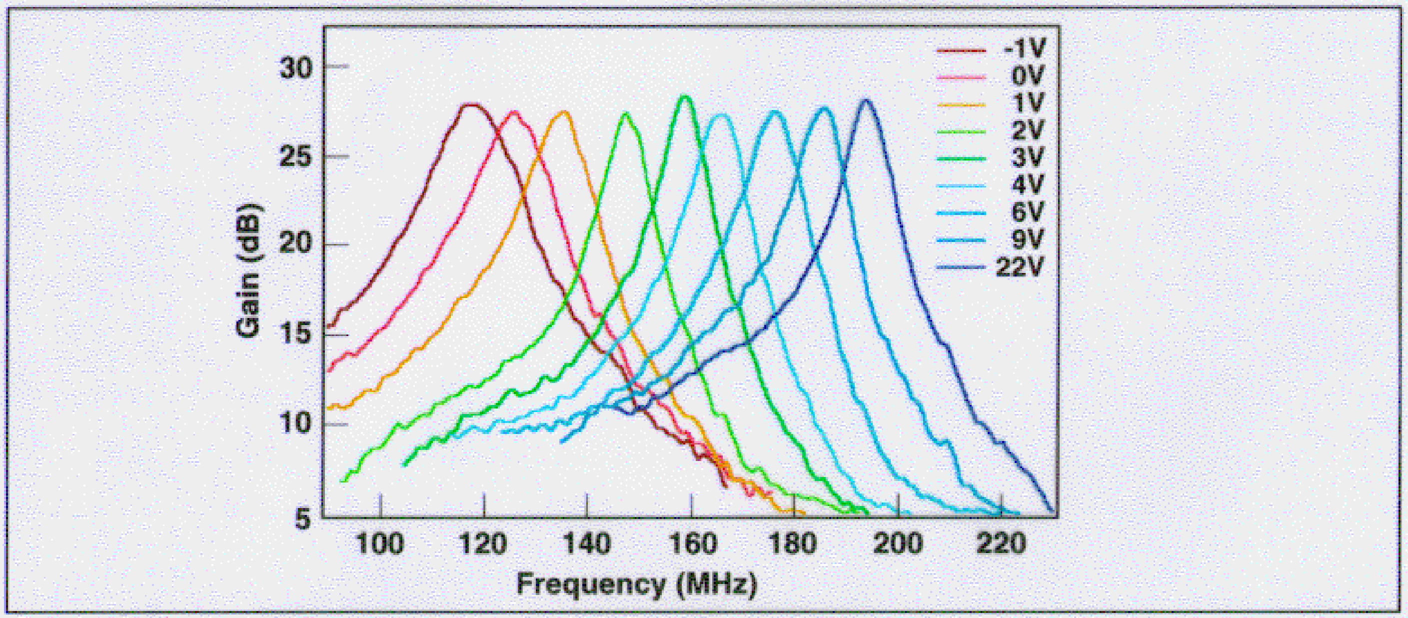

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SQUID postamplifier

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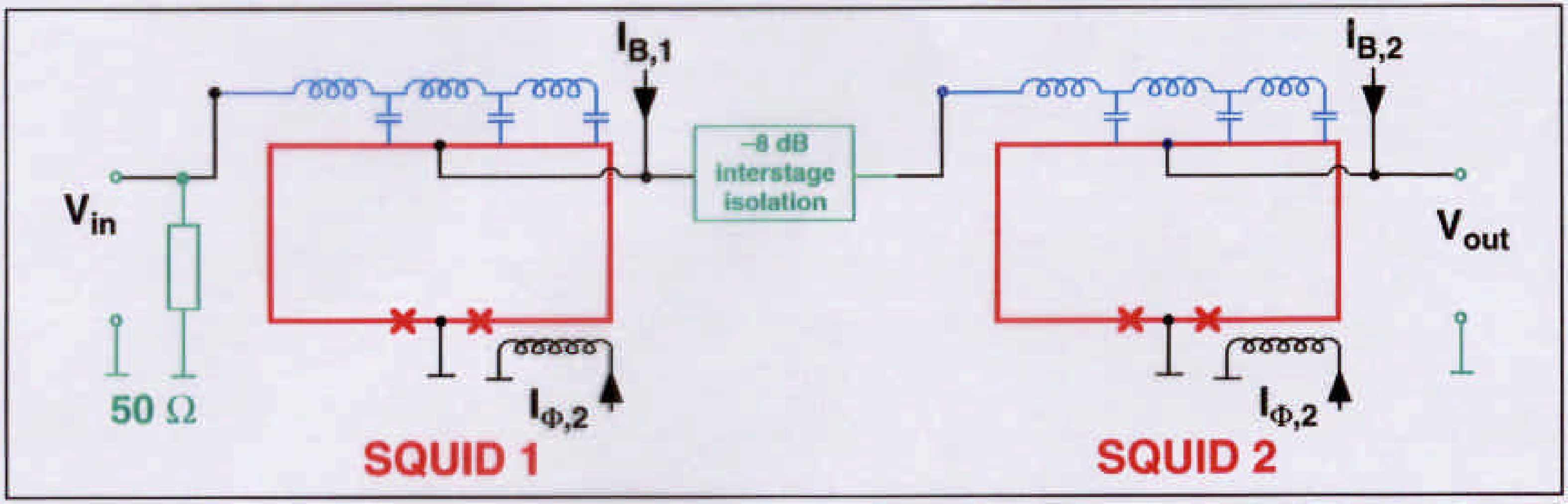

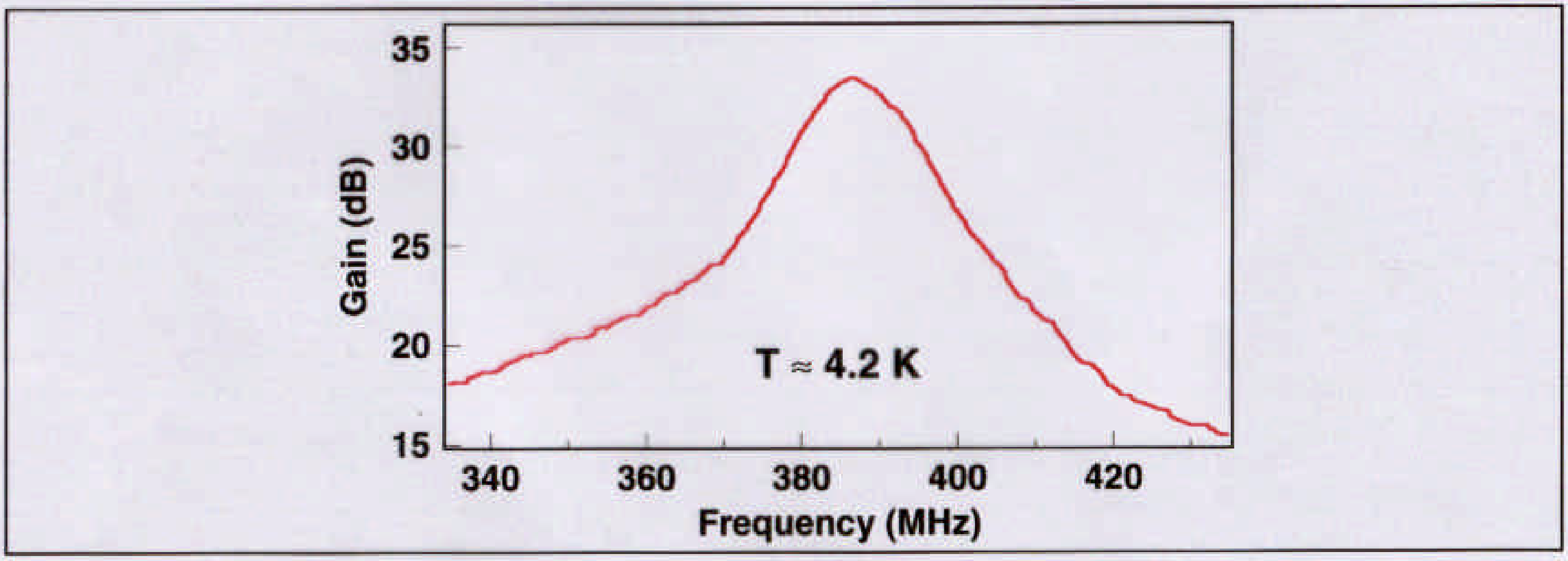

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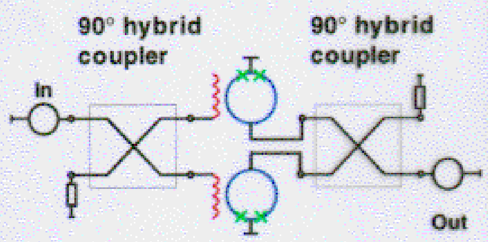
Recent results (II): A balanced SQUID amplifier

Balanced SQUID Amplifier



Gain vs. Frequency

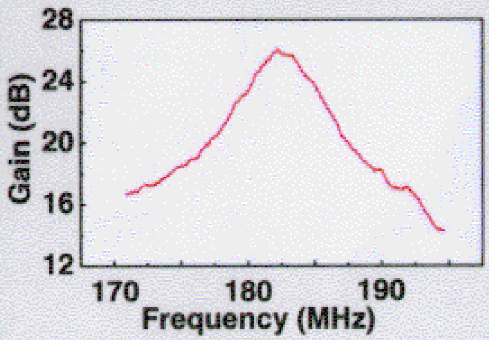
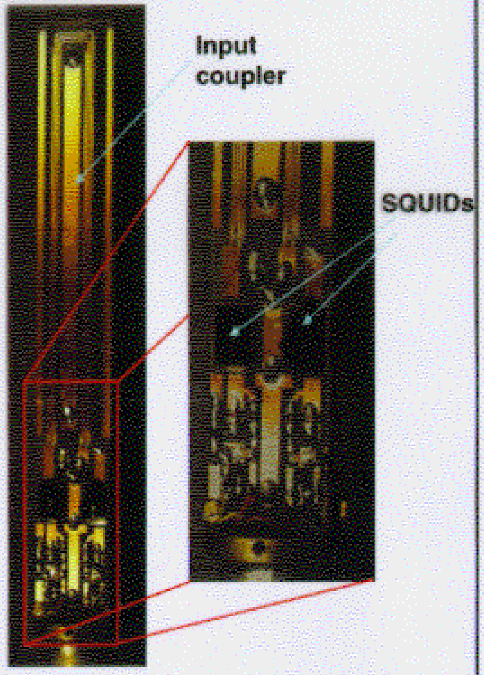


Photo of Balanced SQUID Amplifier



- The input and output impedance of a SQUID amplifier is different from 50 Ω
- An improved impedance match will be obtained if a *balanced amplifier* is used
  - — Balanced HEMT amplifiers are used in the present experiment
- A 90° hybrid coupler divides the input signal into two equal-amplitude components with a 90° phase difference. A second coupler recombines the output.

Balanced amplifiers greatly simplify the experiment, insofar as the cavity impedance is a strong complex function over the cavity resonance.

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R&D towards 100 μeV (25 GHz) — SQUIDs

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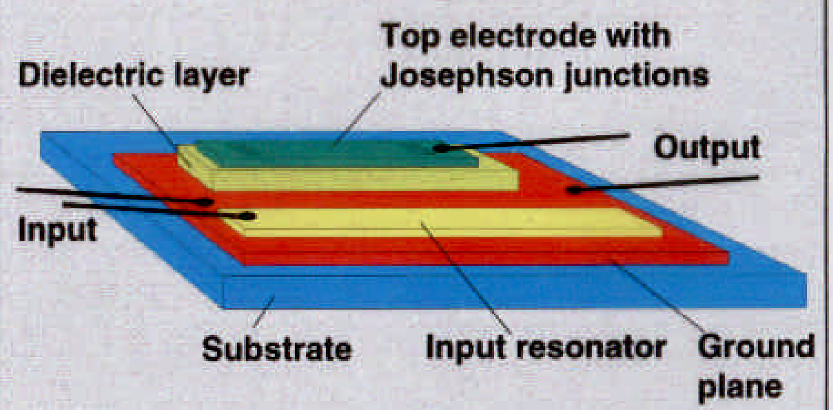
The 'In-Line' SQUID Amplifier



There is strong interest world-wide to develop X-band SQUIDs as IF amplifiers for IR and sub-mm astronomy

- SQUID amplifiers should be made to work >10 GHz
  - Josephson frequency >100 GHz
- The 'in-line' SQUID design appears attractive
  - The SQUID loop consists of two piggy-back superconducting strips, closed by the Josephson junctions on either end
- The key question is how to couple to it
  - A close-by microstrip line will be tried first
- UCB R&D effort will increase, as amplifier production winds down

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R&D towards 100 μeV (25 GHz) — Resonators

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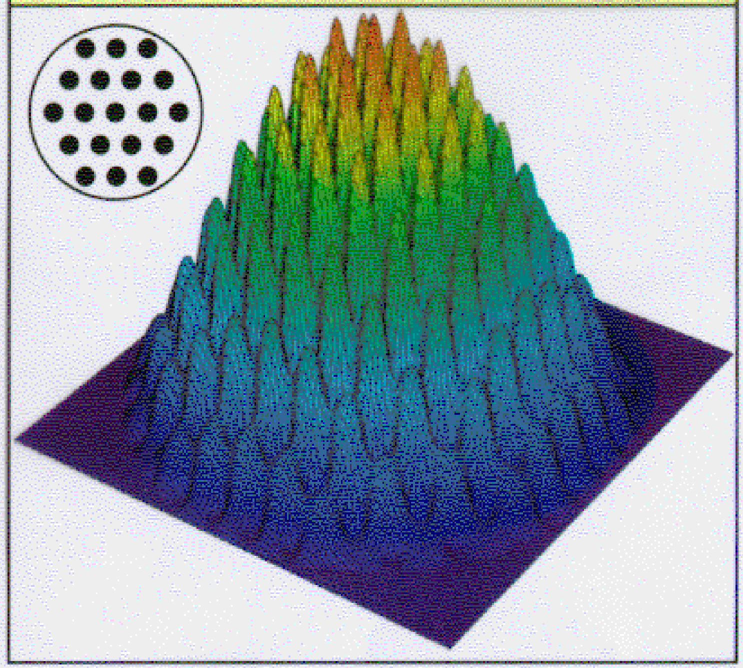
TM_{010} Electric Field for 96-post Array



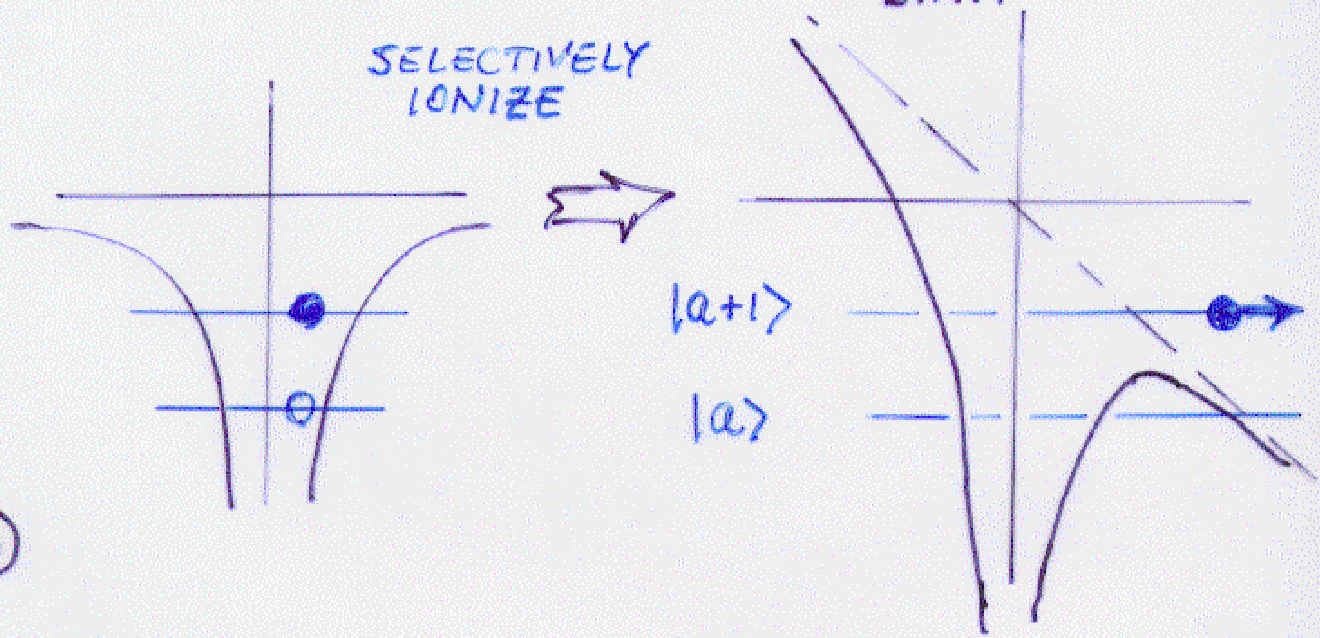
- Single cavity TM_{010}:
  - — Number $\propto f^3$ in fixed volume
    - – To minimize TE, TEM intruders
- Periodic Post Resonators can have very high TM_{010} frequencies
  - — Number $\propto f$
    - – Height $\propto f^{-1}$ to minimize mode crossings
    - – Tuned by global shift of alternate posts
    - – Stacked as pans
- Modeling begun; first warm prototype being designed

We believe this is a promising avenue to the next decade in mass

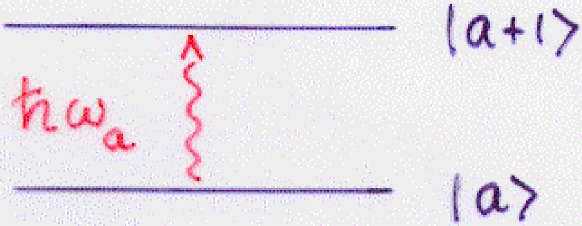
KYOTO UNIVERSITY AXION SEARCH USING RYDBERG ATOM SINGLE QUANTUM DETECTOR

"RF PHOTOTUBE" PHASELESS → EVADES QUANTUM LIMIT

③



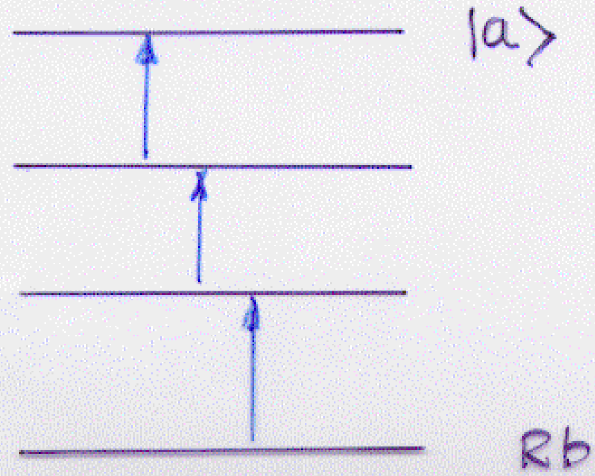
②



ABSORB PHOTON FROM CONVERTED AXION

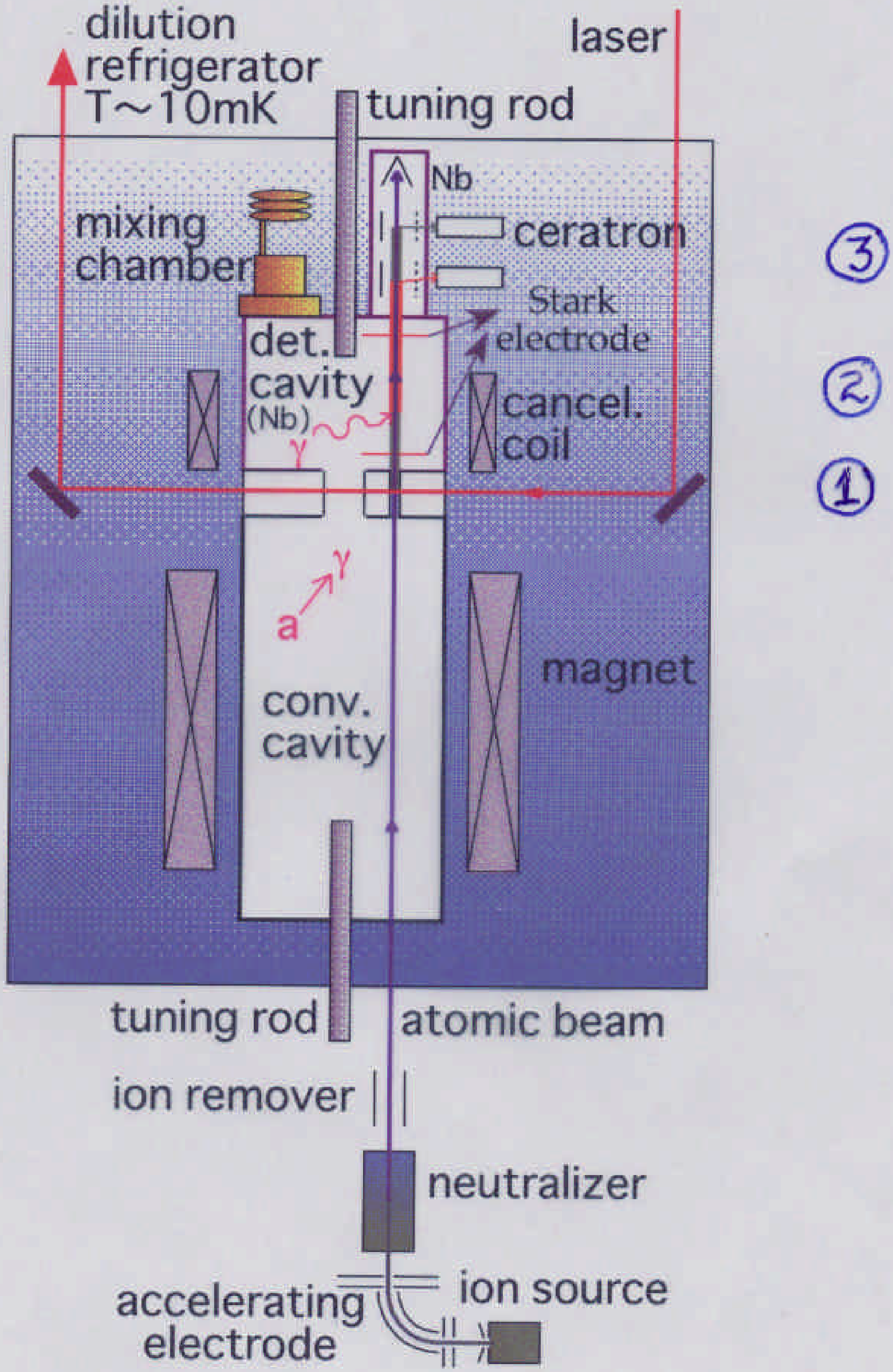
($E_{a+1} - E_a$ MATCHED TO CAVITY FREQ.)

①



PREPARE RYDBERG STATE |a⟩

CARRACK – Kyoto



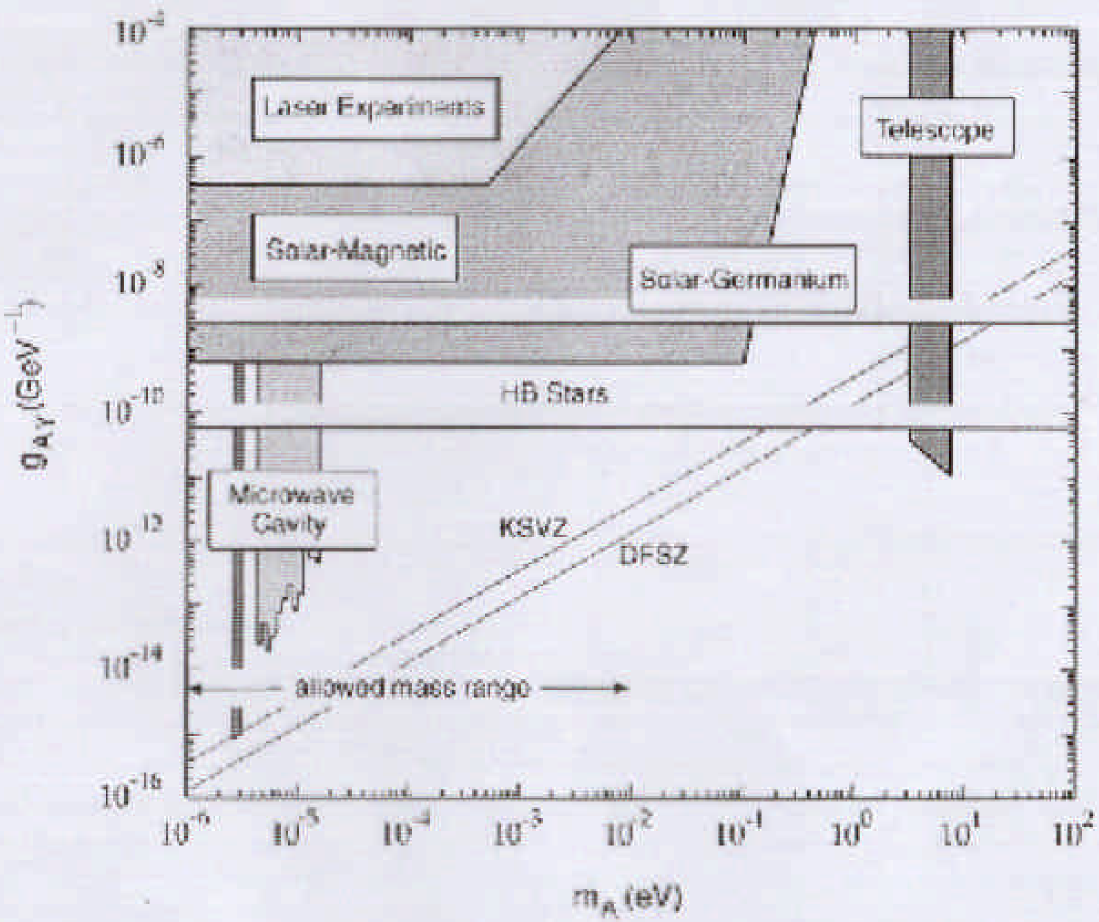


Fig. 26. Plot of excluded $g_{A\gamma\gamma}$ vs. m_A with all experimental and observational constraints, along with predicted couplings for KSVZ and DFSZ models.

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Summary

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- The axion is well-motivated in particle physics and a very credible dark-matter candidate
- The parameter space (mass, coupling) is bounded and present experiments have already scanned well into this region
- Near-quantum-limited SQUID amplifiers are the enabling technology for a truly definitive search
- Rydberg atom single-quantum detection promise the ultimate sensitivity, if high operational reliability can be achieved