A Large-scale Search for Dark-Matter Axions

ICHEP 2000

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AXION

Outline

AXION

- Brief review of the axion
- The Sikivie microwave cavity technique
- The U.S. large-scale experiment*
- R&D on SQUID amplifiers
- 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

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

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

Cosmological Abundance

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

(Vacuum misalignment mechanism)

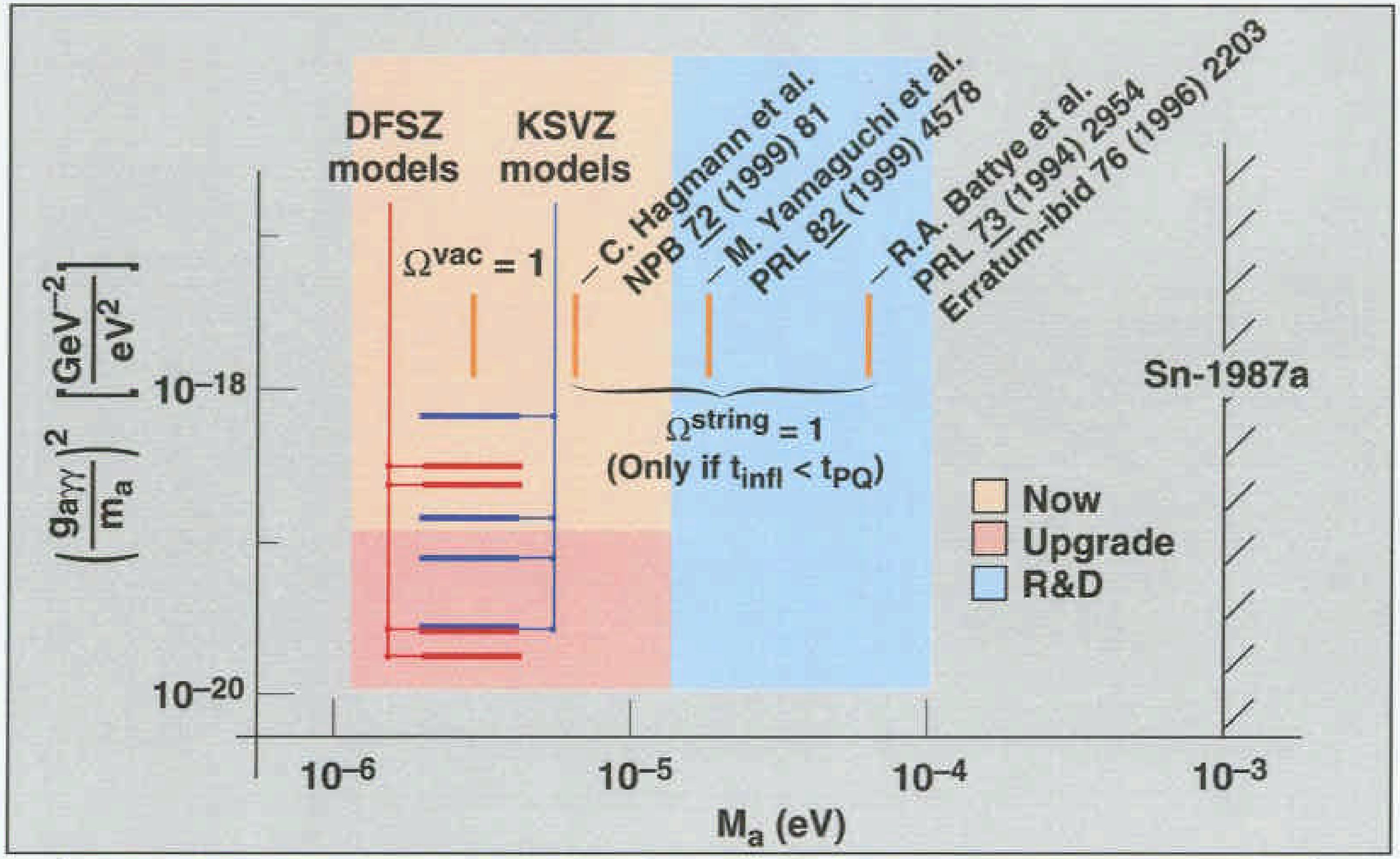
Axion Mass 'Window'

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

(Overclosure) (SN1987a)

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

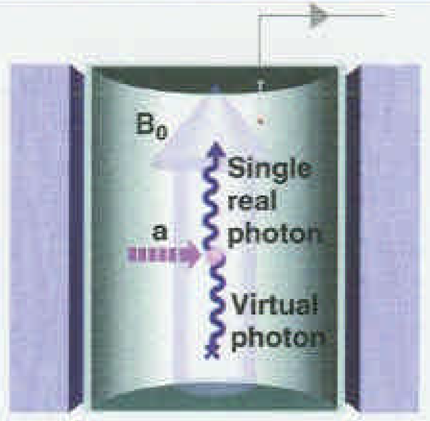
The parameter space



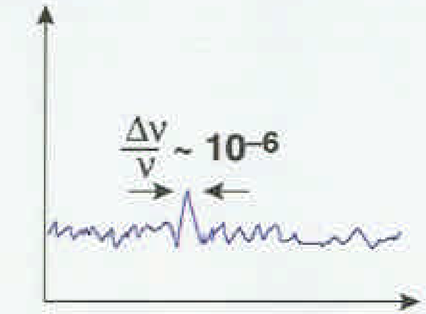
- There is a definitive sensitivity in axion searches
- Large theoretical uncertainties in $\Omega = 1$ all around
- Nevertheless, we can cover a lot of ground!

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

Primakoff Conversion



Signal



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

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

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!

Overall program direction

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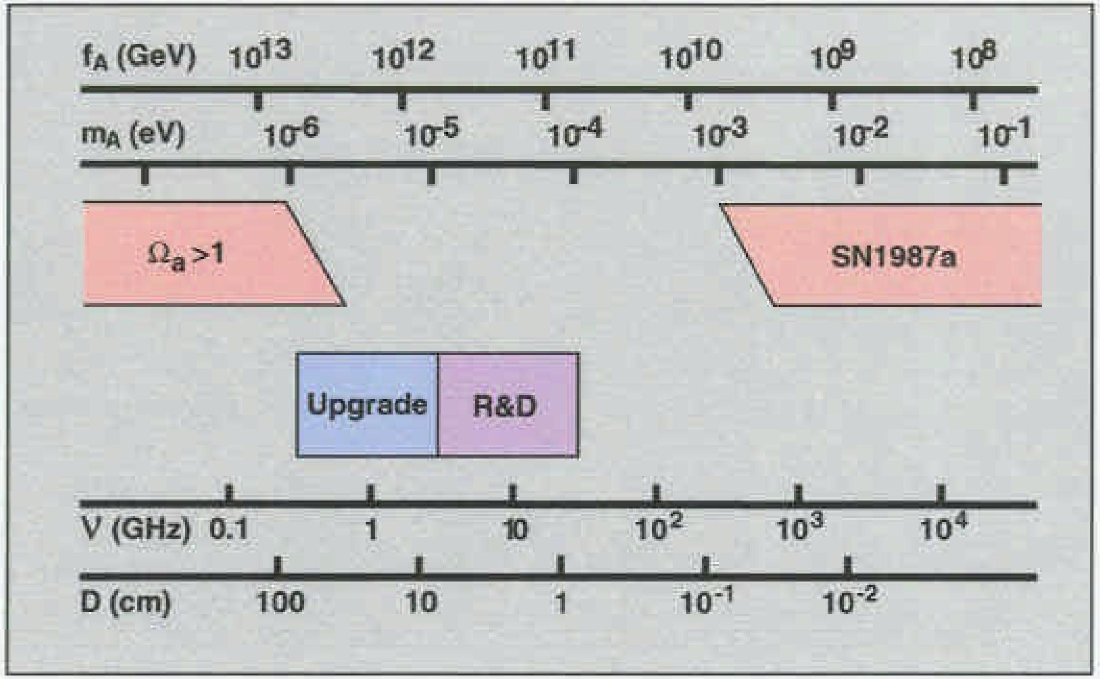
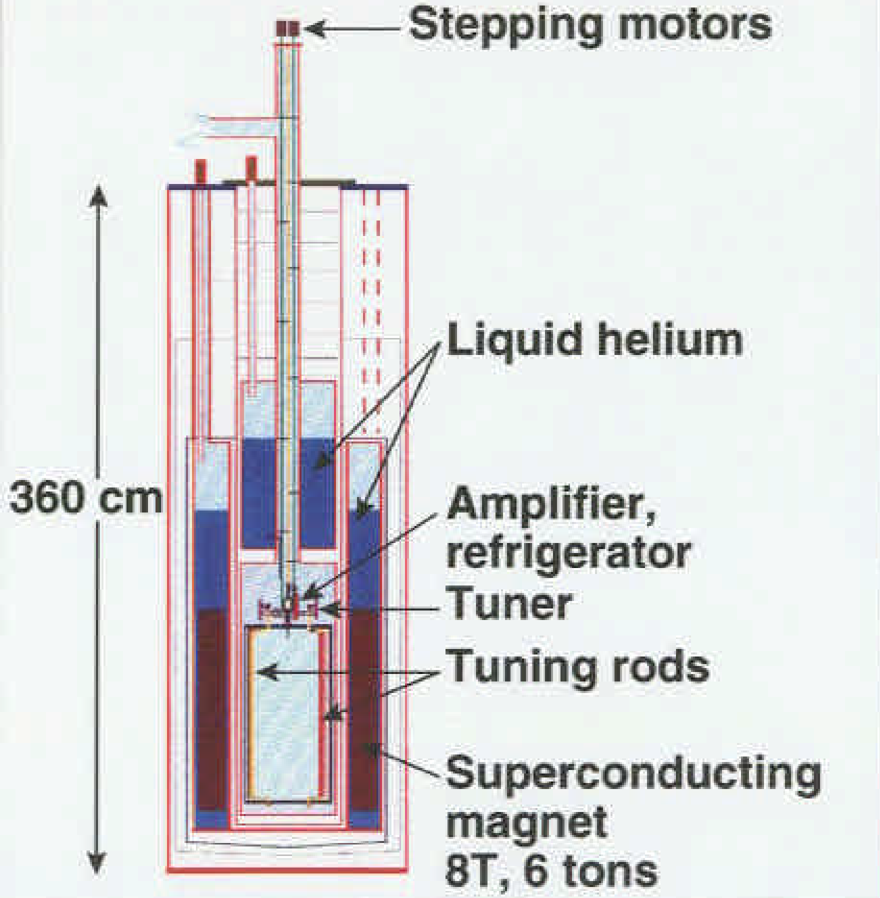


- Currently taking data in 1-10 μeV range
- Beginning in 2001, Upgrade and Operations to ultimate sensitivity, over 1-10 μeV
  - — In two steps
- Concurrent R&D on SQUIDs and resonators to $\gtrsim$100 μeV (25 GHz)
  - — Incorporate and extend mass range

- The upgrade in sensitivity will allow us to answer ***decisively*** whether axions constitute the dark matter, over the mass range covered.
- The R&D program may allow us to cover 2/3 of the open mass range or more.

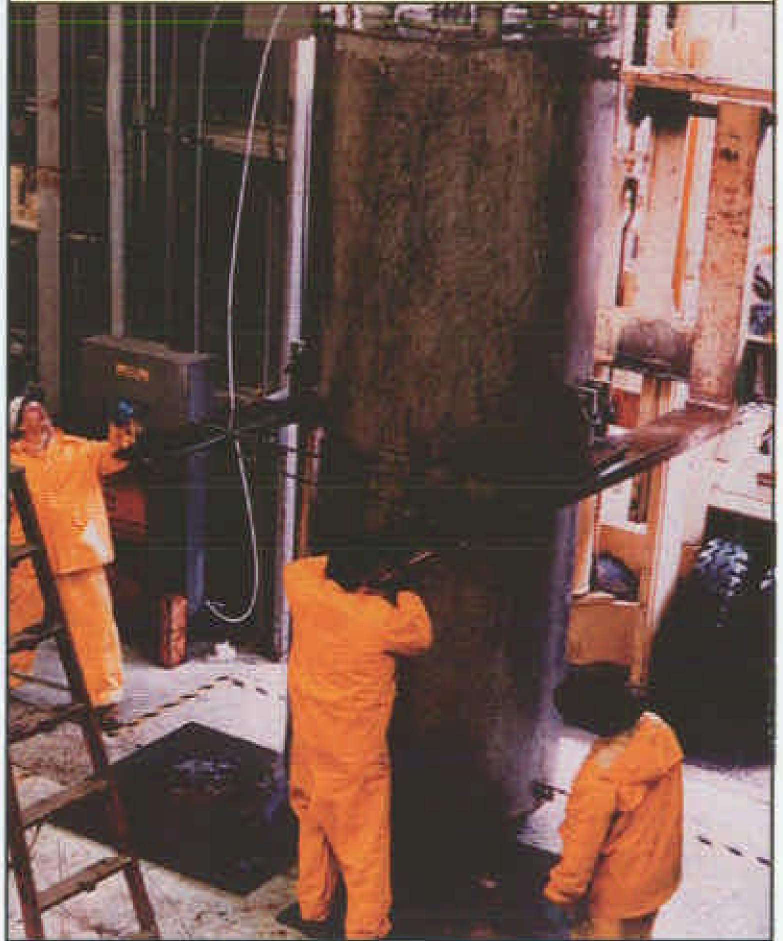
Axion hardware

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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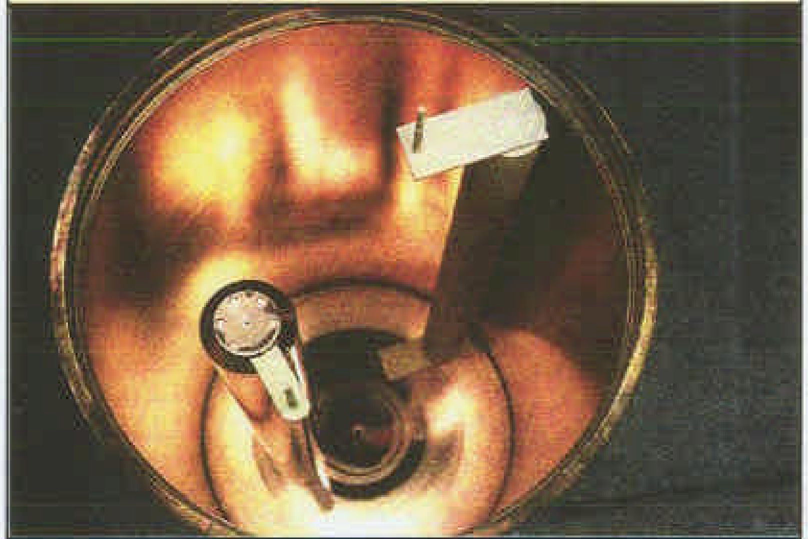
Tunable Microwave Cavity



300–800 MHz, Q ~ 200,000

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

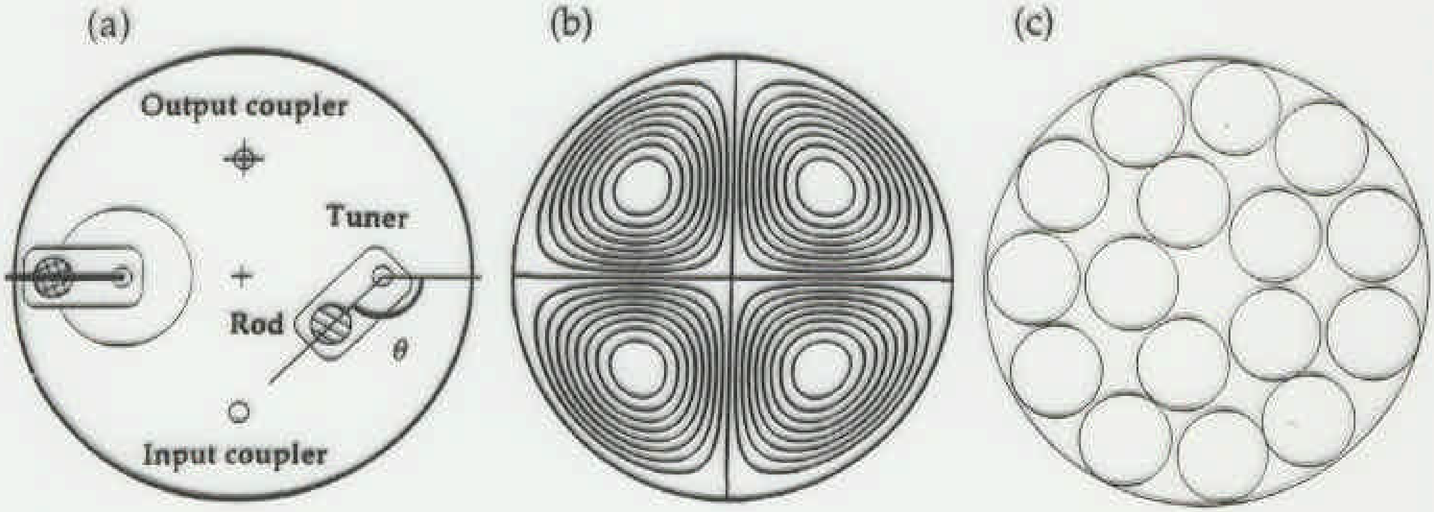
Ed Daw (PhD MIT 2/98)

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

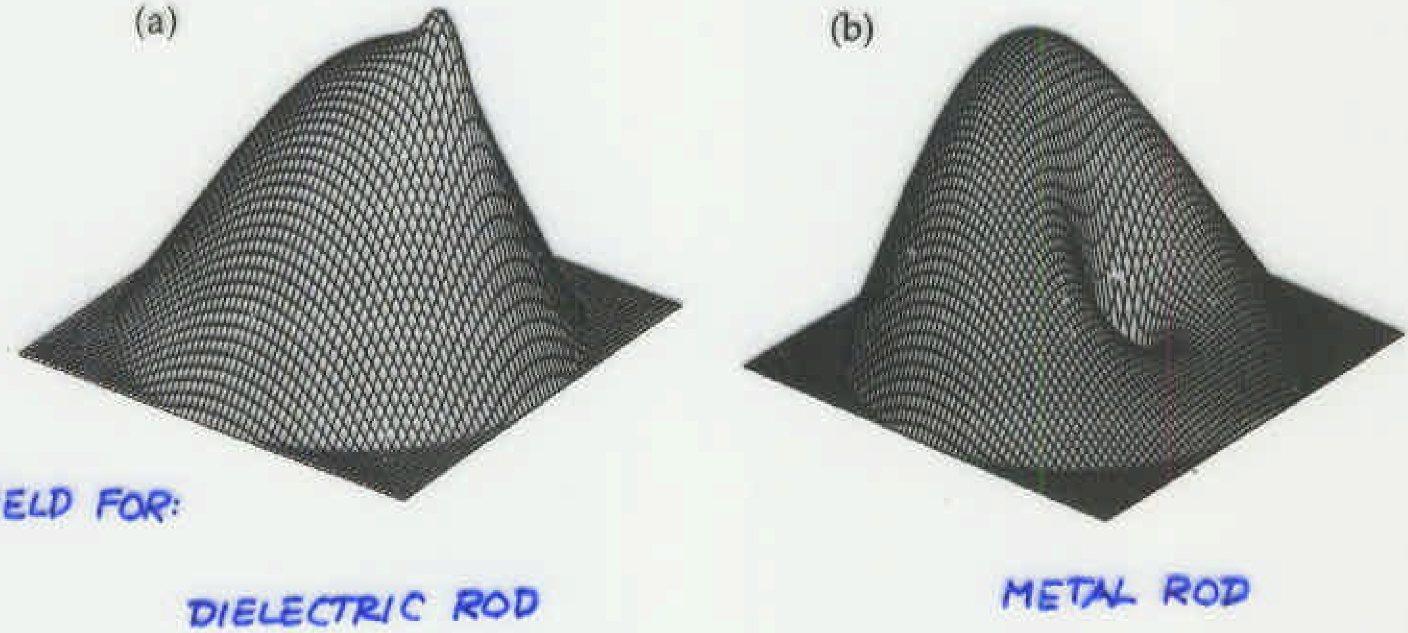
HOW THE EXPERIMENT IS TUNED

MULTIPLE CAVITY ARRAYS:

f $\sim 2.1 \cdot f$ $\sim 4.4\,f$



TUNING OF CAVITIES BY METAL, DIELECTRIC RODS:
A RANGE OF −30%, +50% IS FEASIBLE

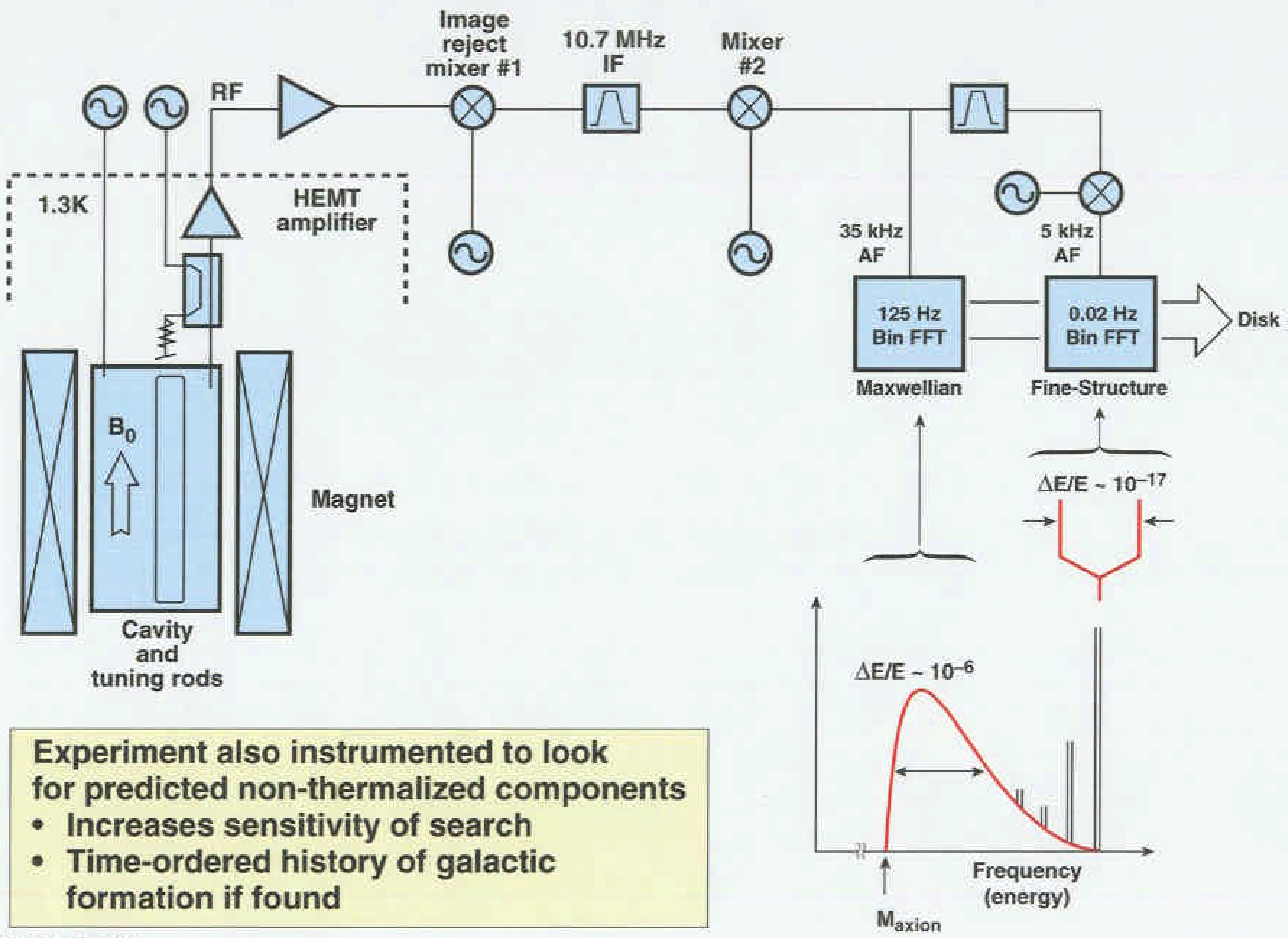


E-FIELD FOR:

DIELECTRIC ROD METAL ROD

(BOTH, $d/D \sim 0.1$)

The axion receiver



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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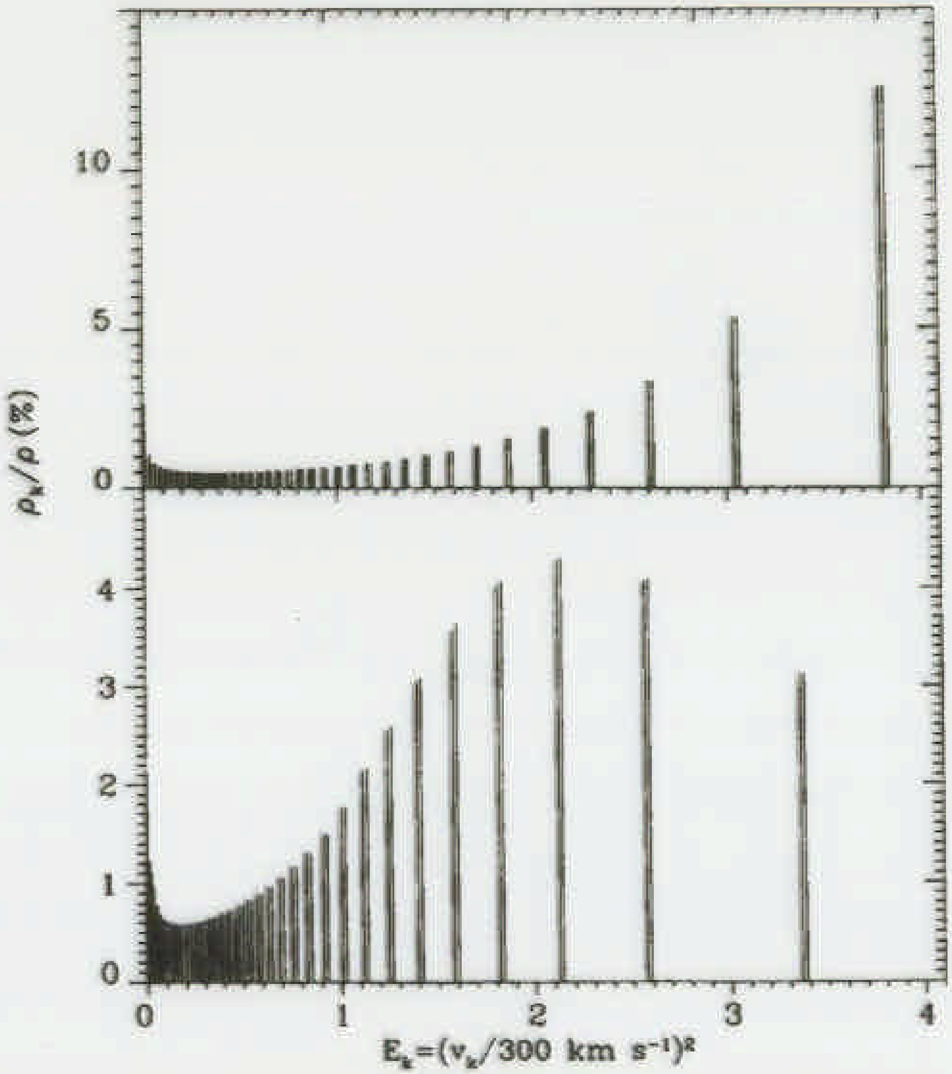

Fig. 4. The velocity spectrum of axions at our solar system, predicted in the model of Refs. [47,48]. (Upper panel) No initial angular momentum. (Lower panel) Finite initial angular momentum. Scattering processes are expected to eventually thermalize the spectrum, leading to the lower energy lines being 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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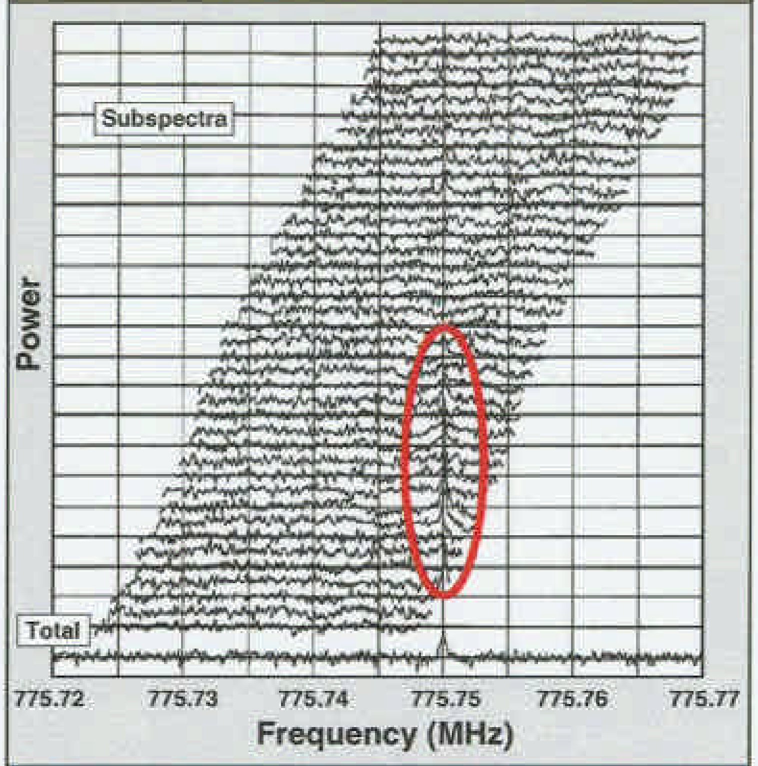
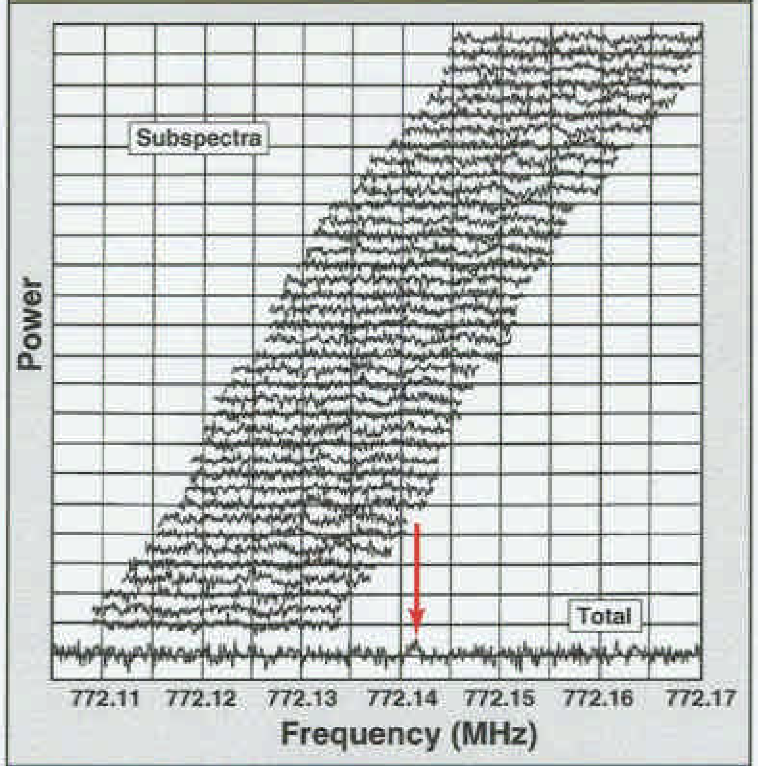
Environmental



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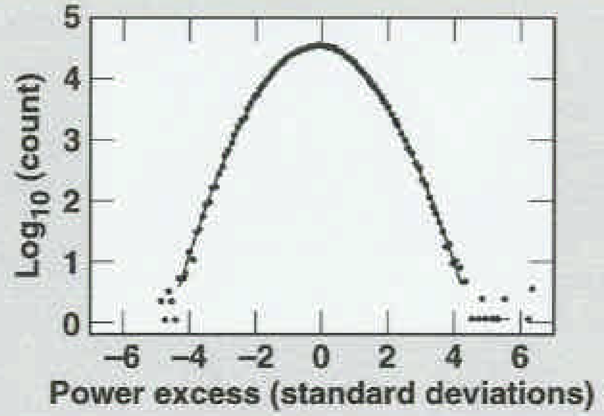
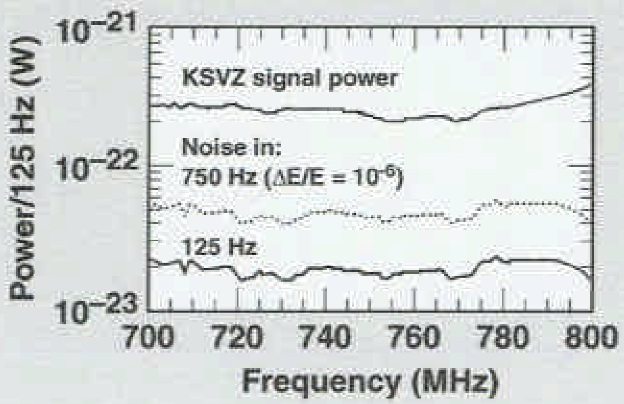
Data, with Theoretical Curve
(Gaussian noise through receiver and analysis)



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!

Cosmic axion exclusion plot

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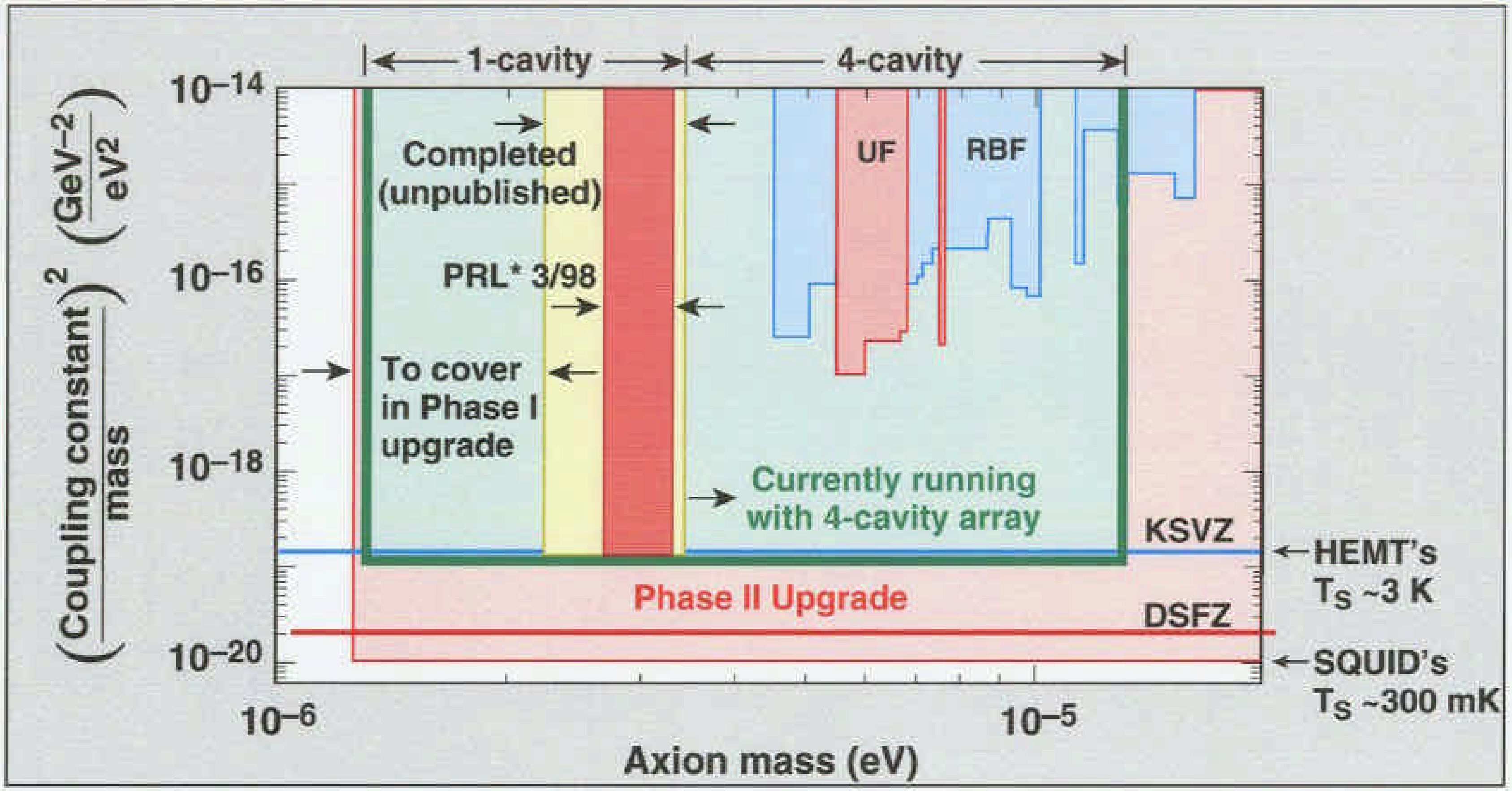

- Phase I Upgrade: SQUIDs at 1.3 K will allow us run at KSVZ 4 times faster than with HEMTS
- Phase II Upgrade: SQUIDs at 200 mK will give us sensitivity to DFSZ axions even if they only constitute 50% of the halo

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

The 4-cavity array is now running

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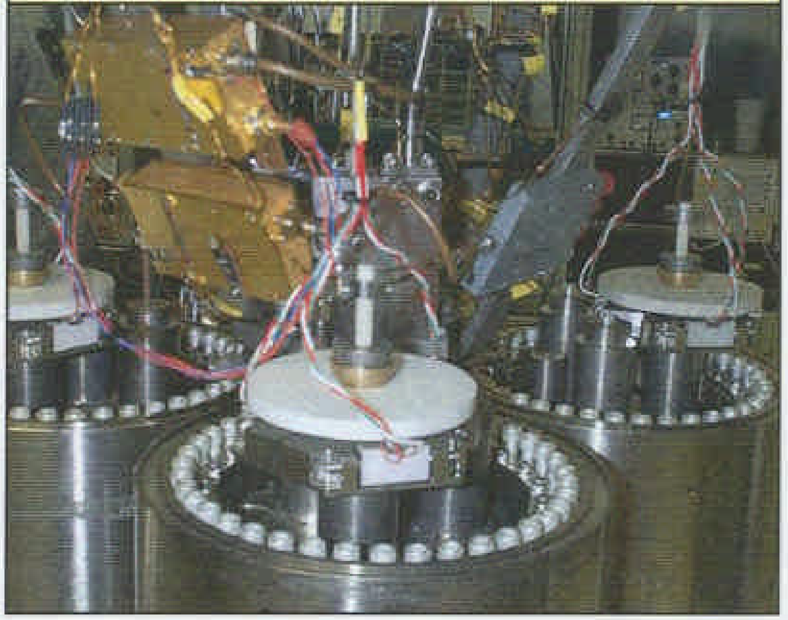
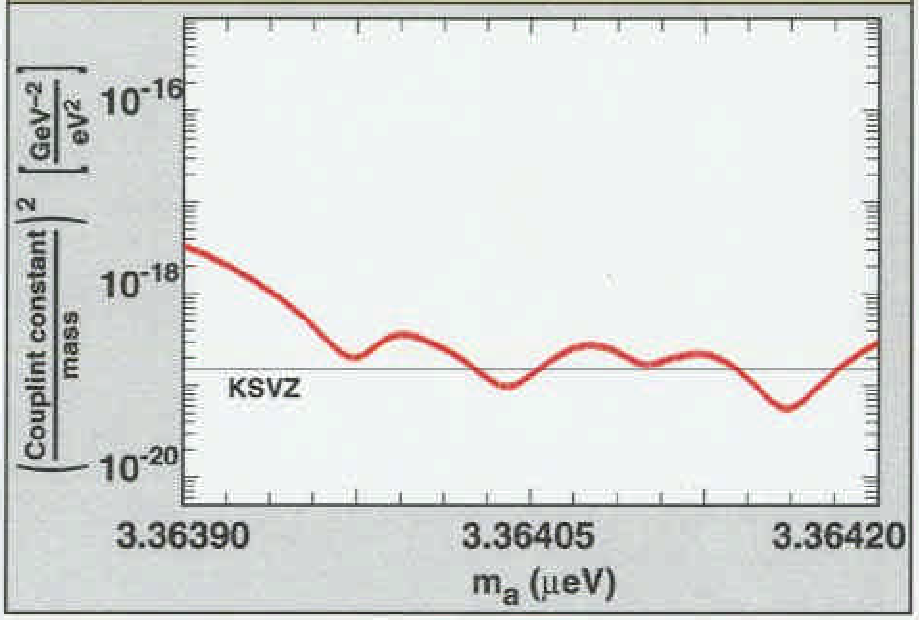
Axion 4-Cavity Array

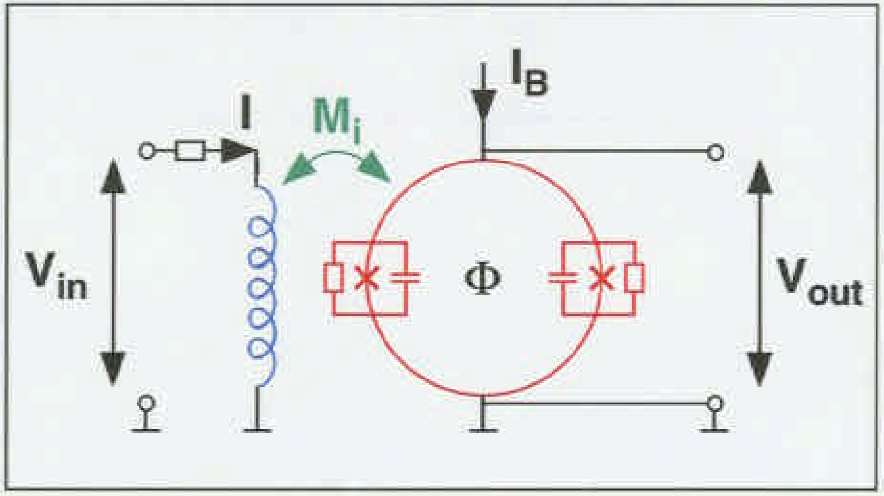


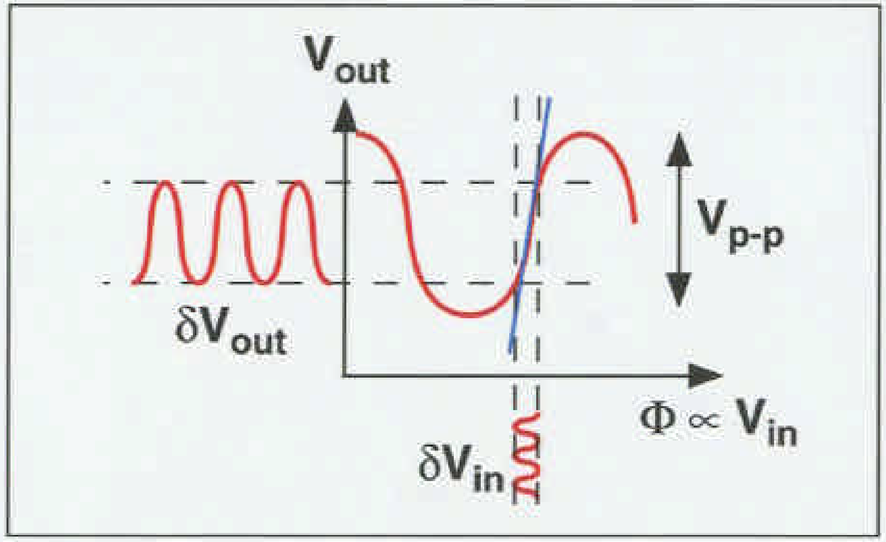
First 4-Cavity Data



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

SQUID basics





- SQUID noise arises from Nyquist noise in shunt resistance

- Thus it scales linearly with T

What the device looks like

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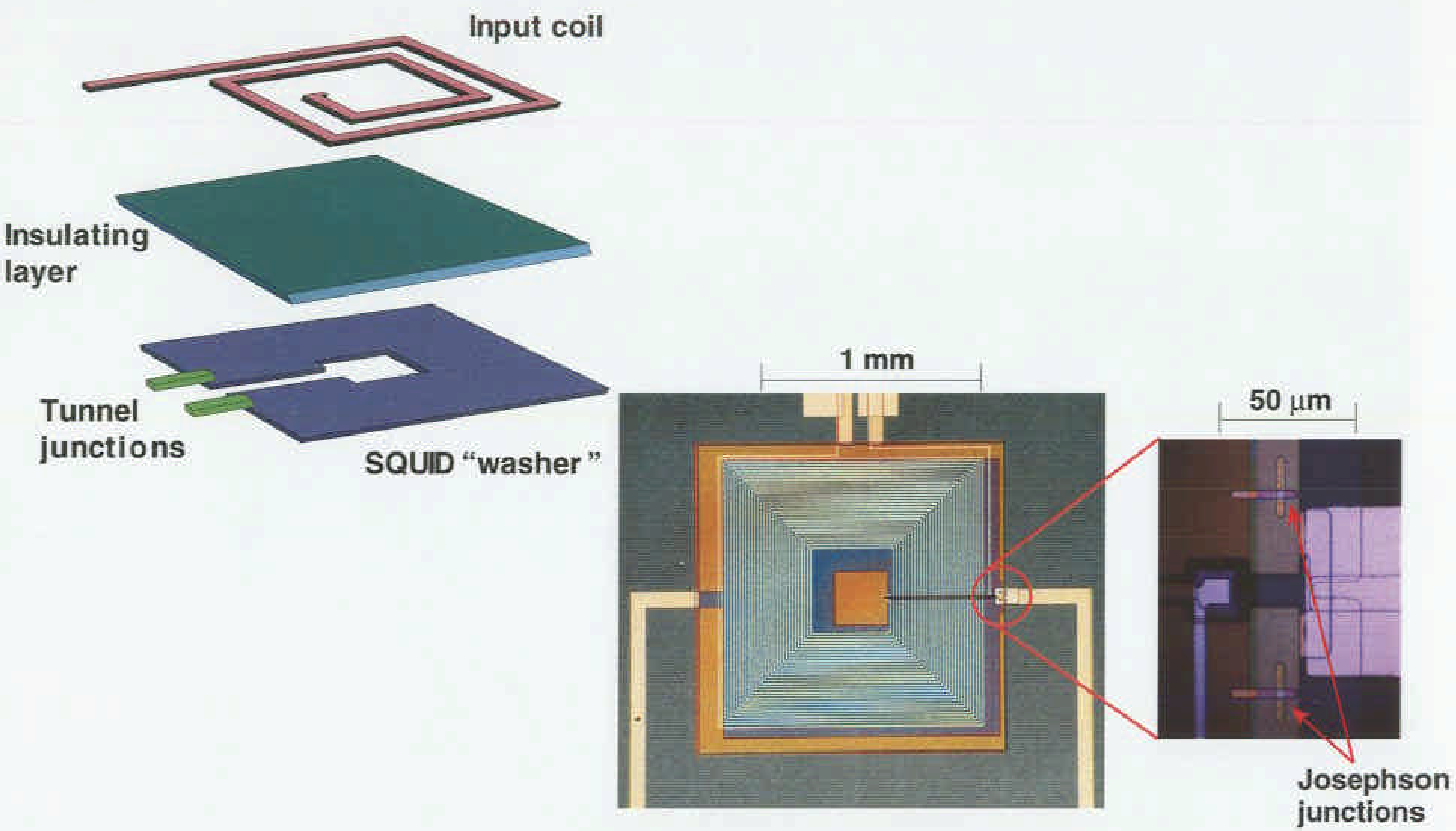

SQUID performance near quantum limit

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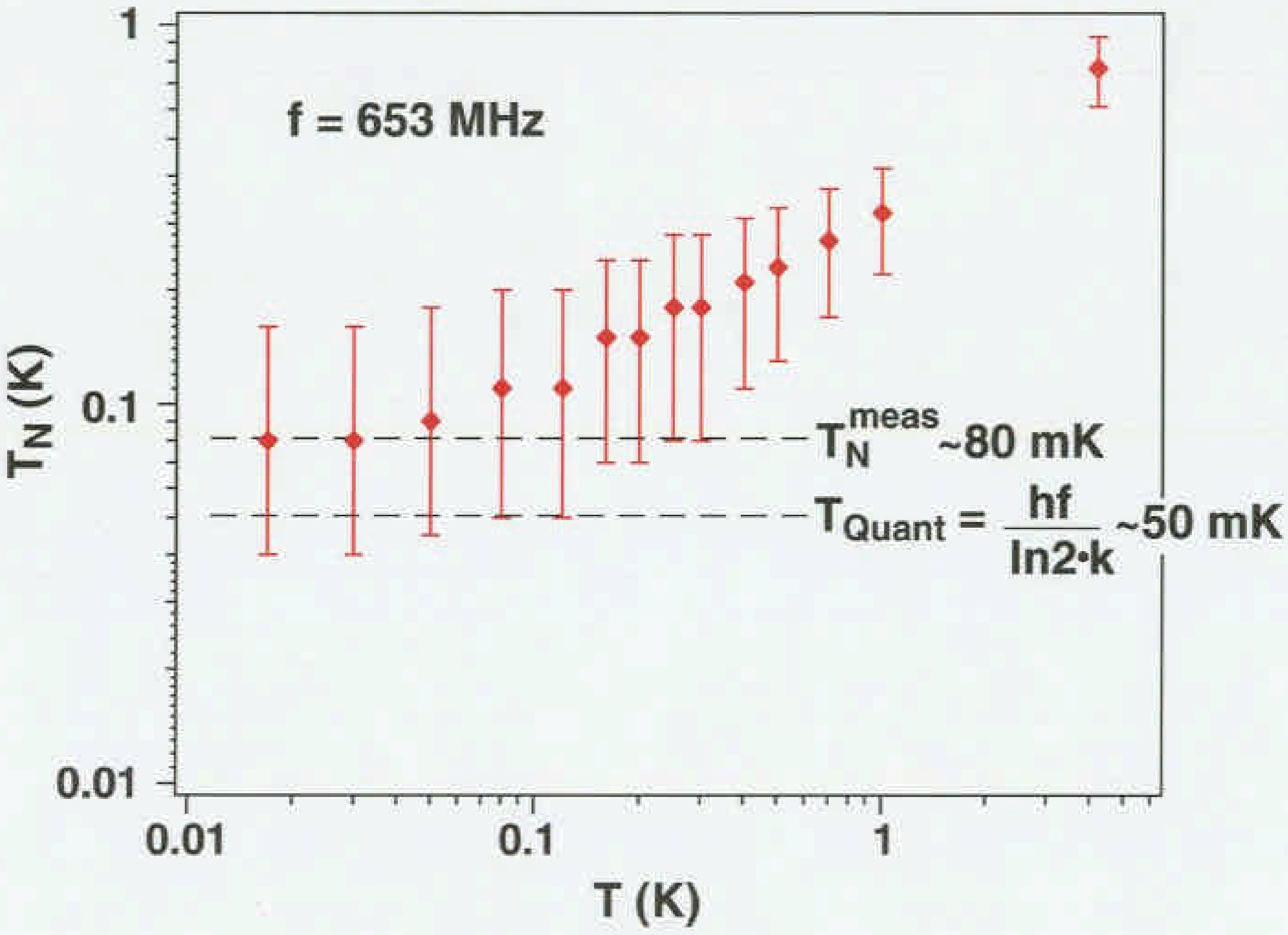


LATEST RESULT FROM THE CLARKE GROUP

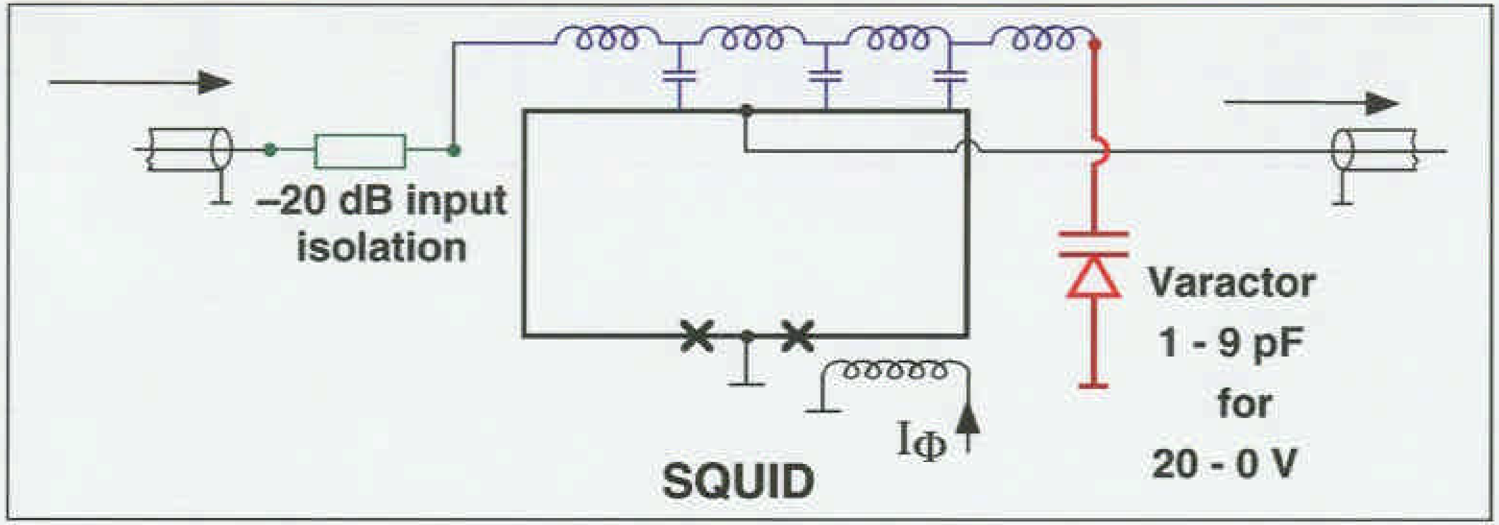
$$T_N = 50 \text{ mK}$$
@
$$f = 550 \text{ MHz}$$

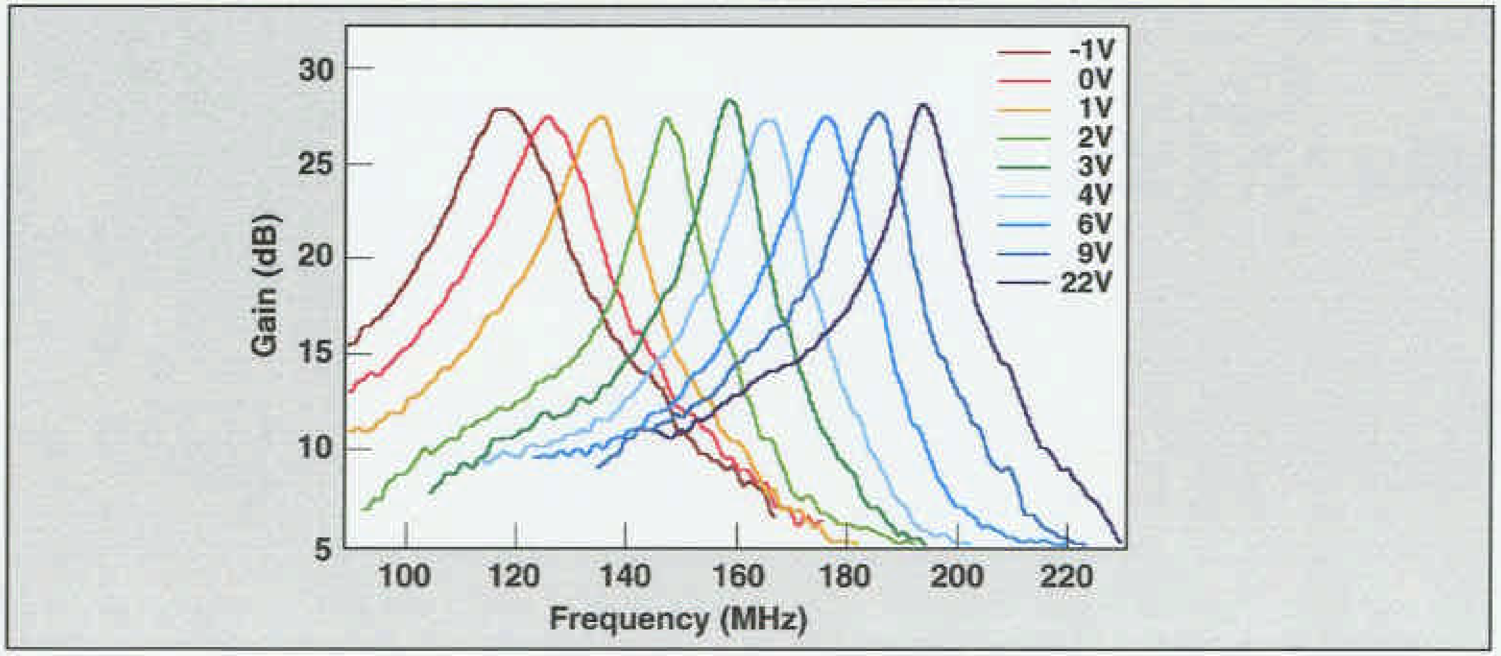
N.B.:

$$T_{QUANT} \sim \frac{hf}{k} = 29 \text{ mK}$$

(U.C. BERKELEY, 7/00)

In-situ amplifier tuning





SQUID postamplifier

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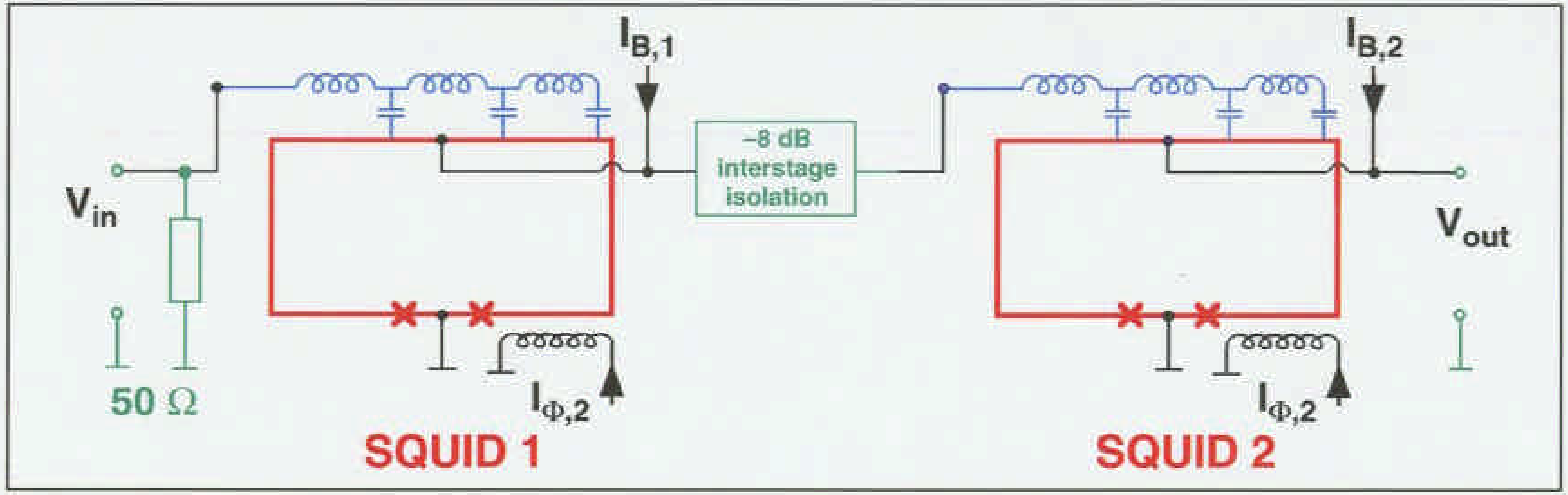

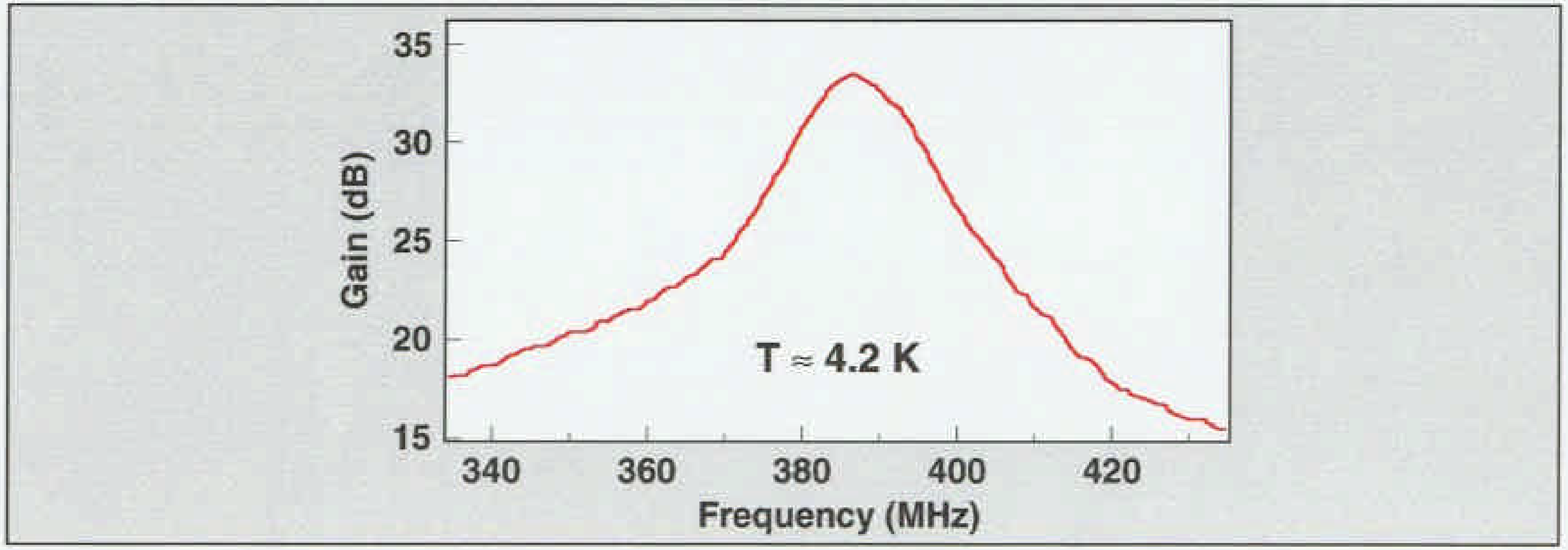

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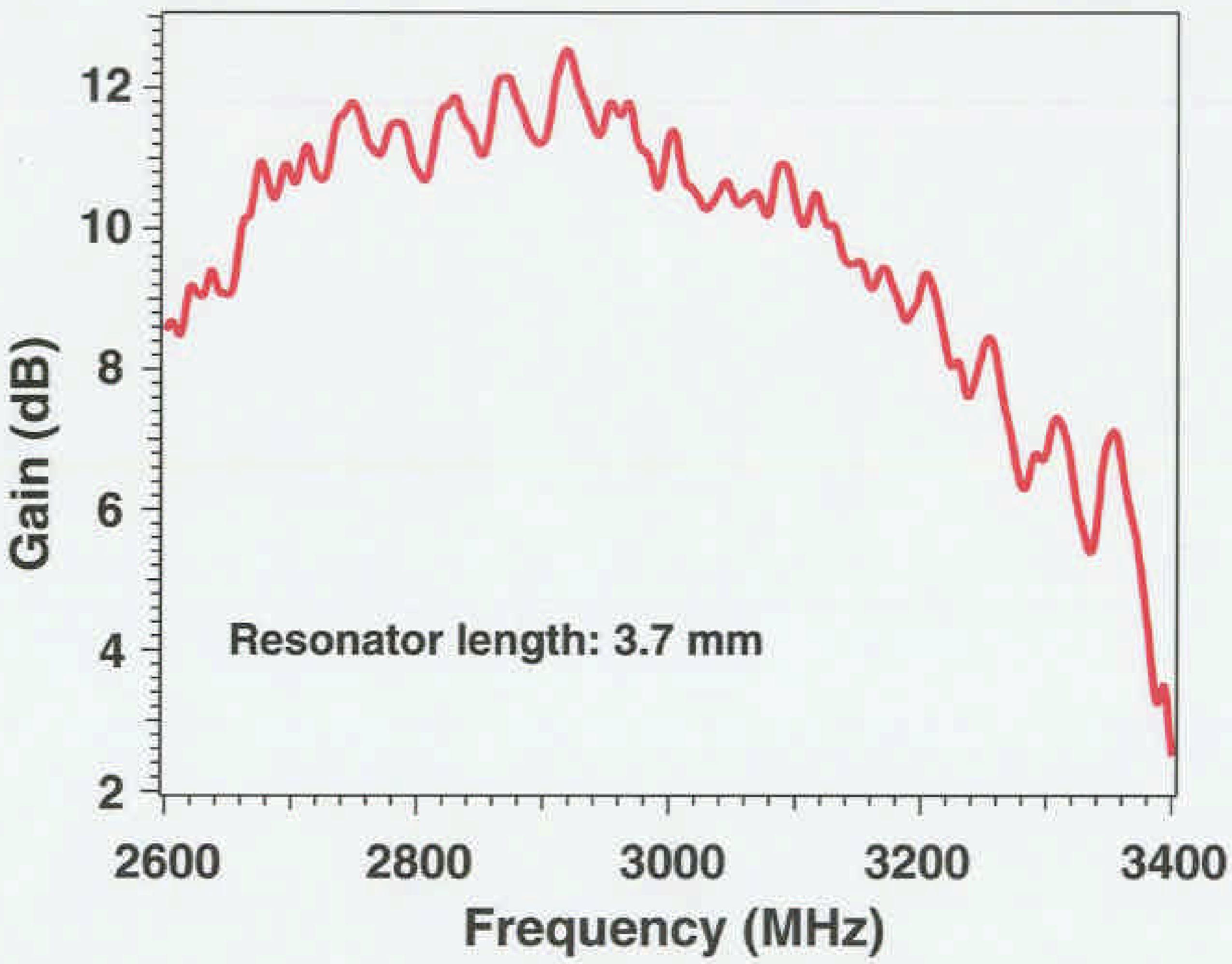
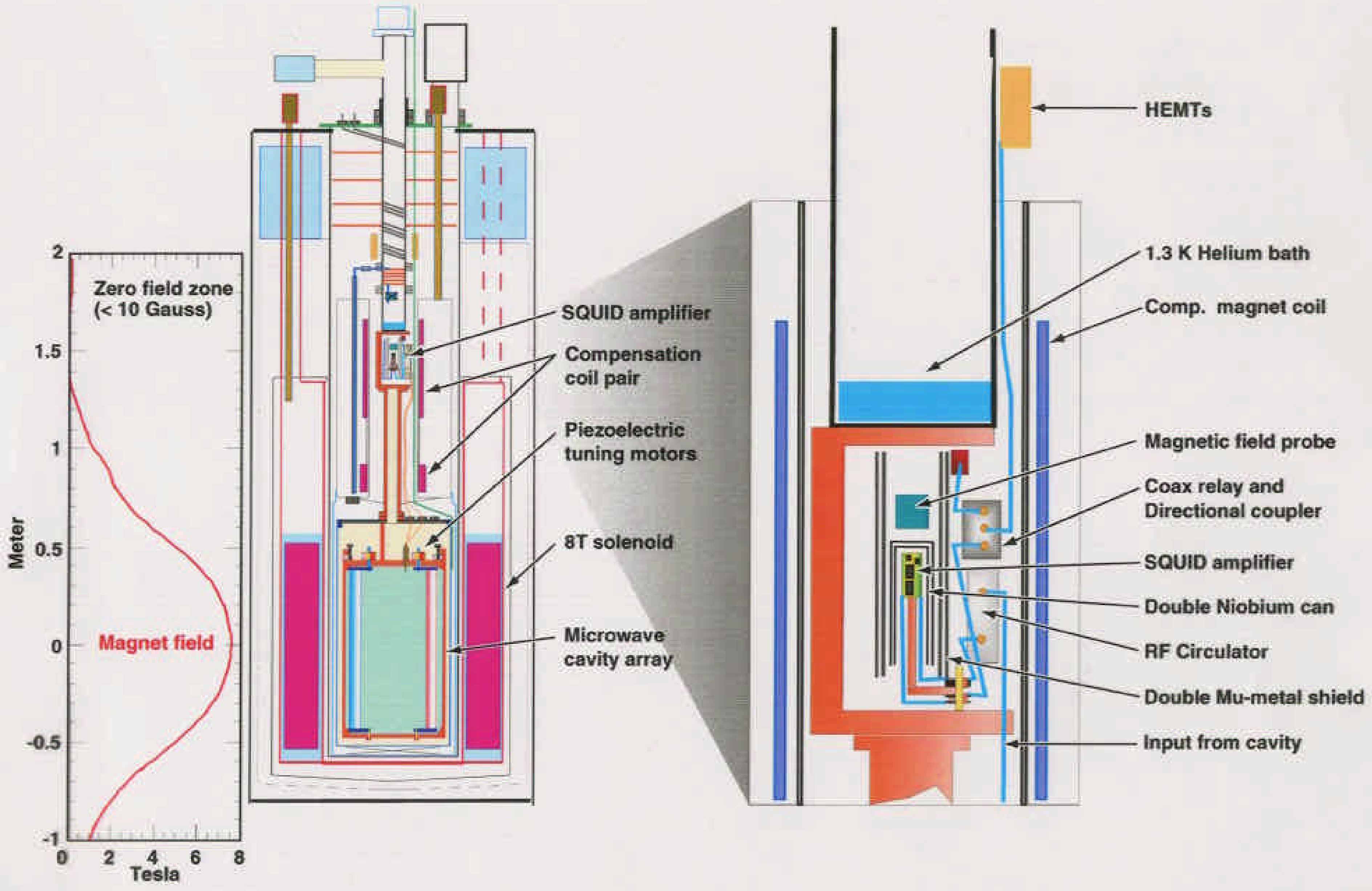
Highest frequency SQUID amplifier to date: 3 GHz





P01484-kvb-u-001

R&D towards 100 μeV (25 GHz) — SQUIDs

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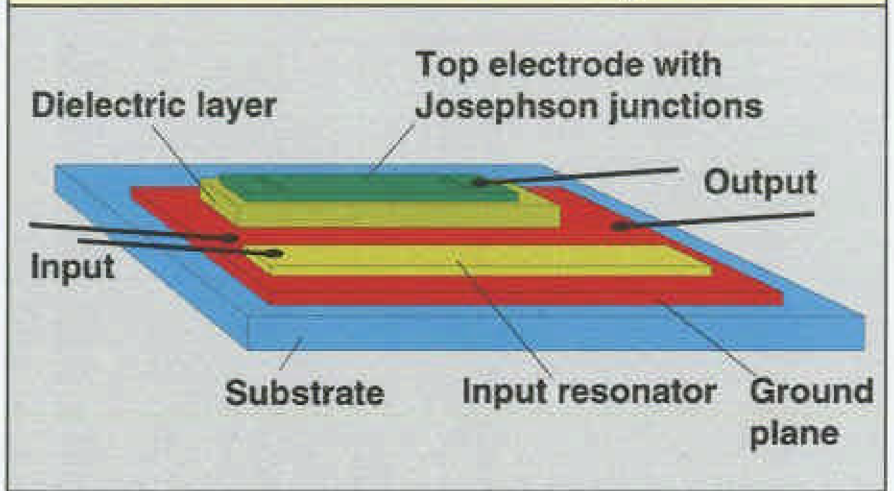
The 'In-Line' SQUID Amplifier



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

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

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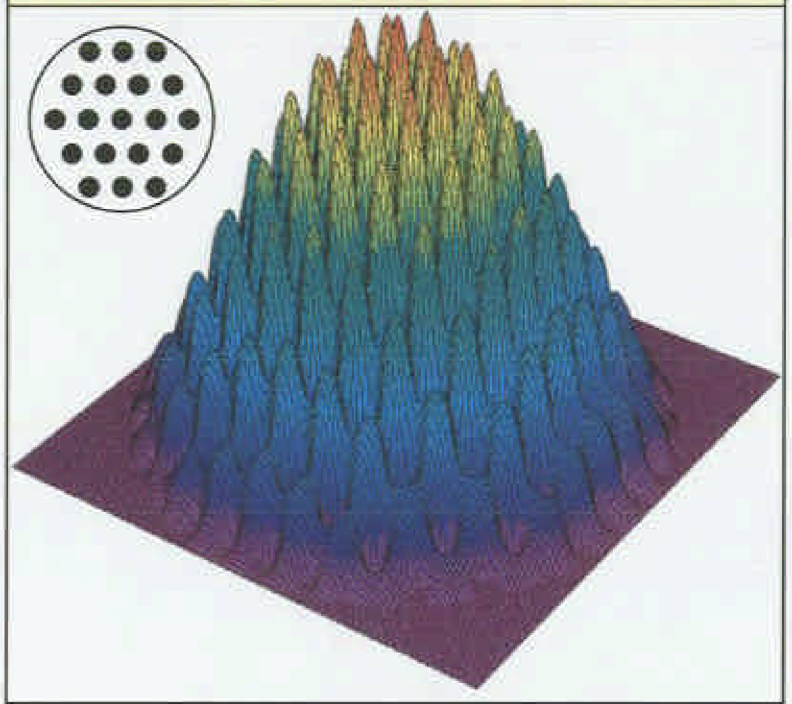
TM$_{010}$ Electric Field
for 96-post Array



- 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 is being tested

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

Summary

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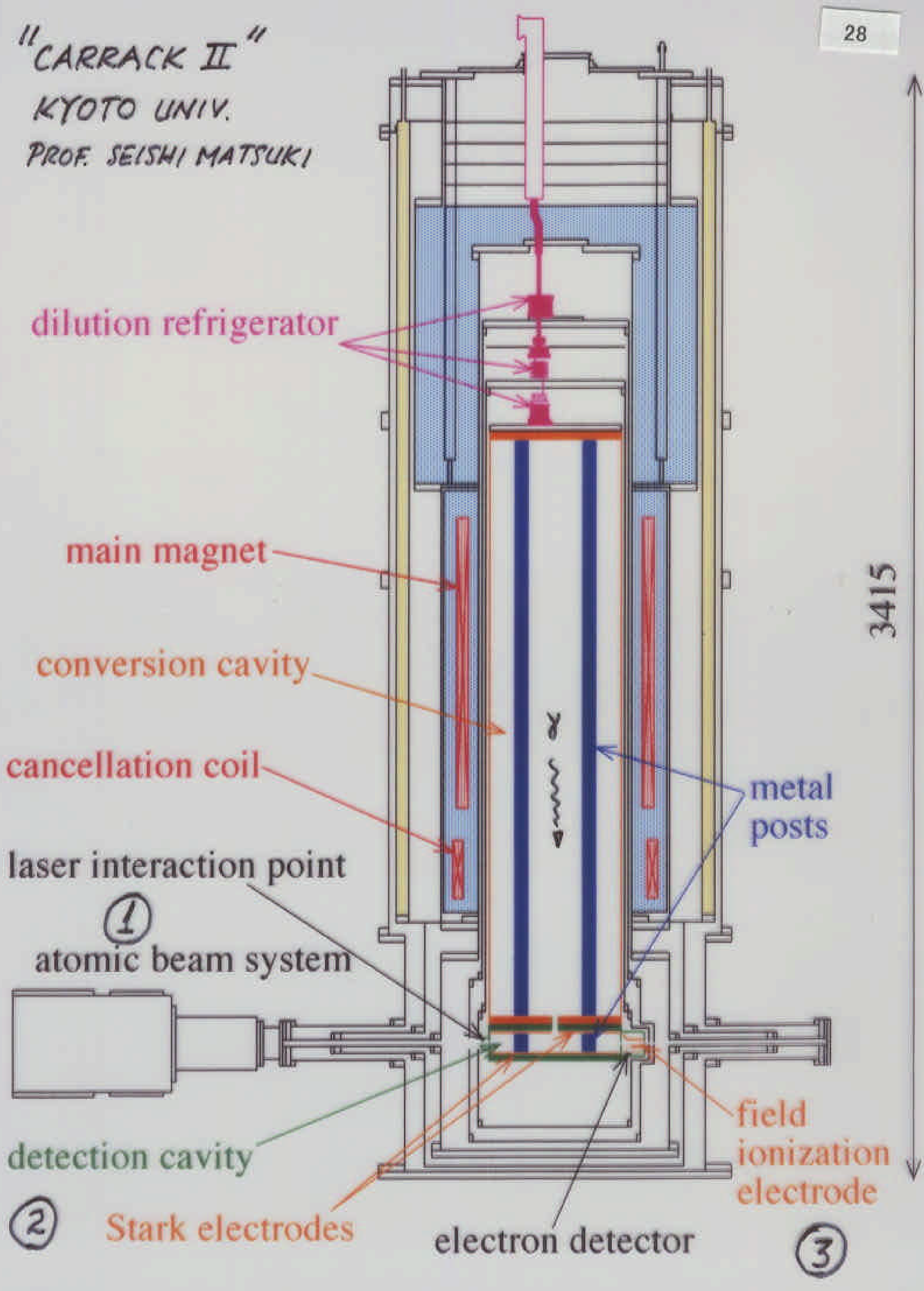
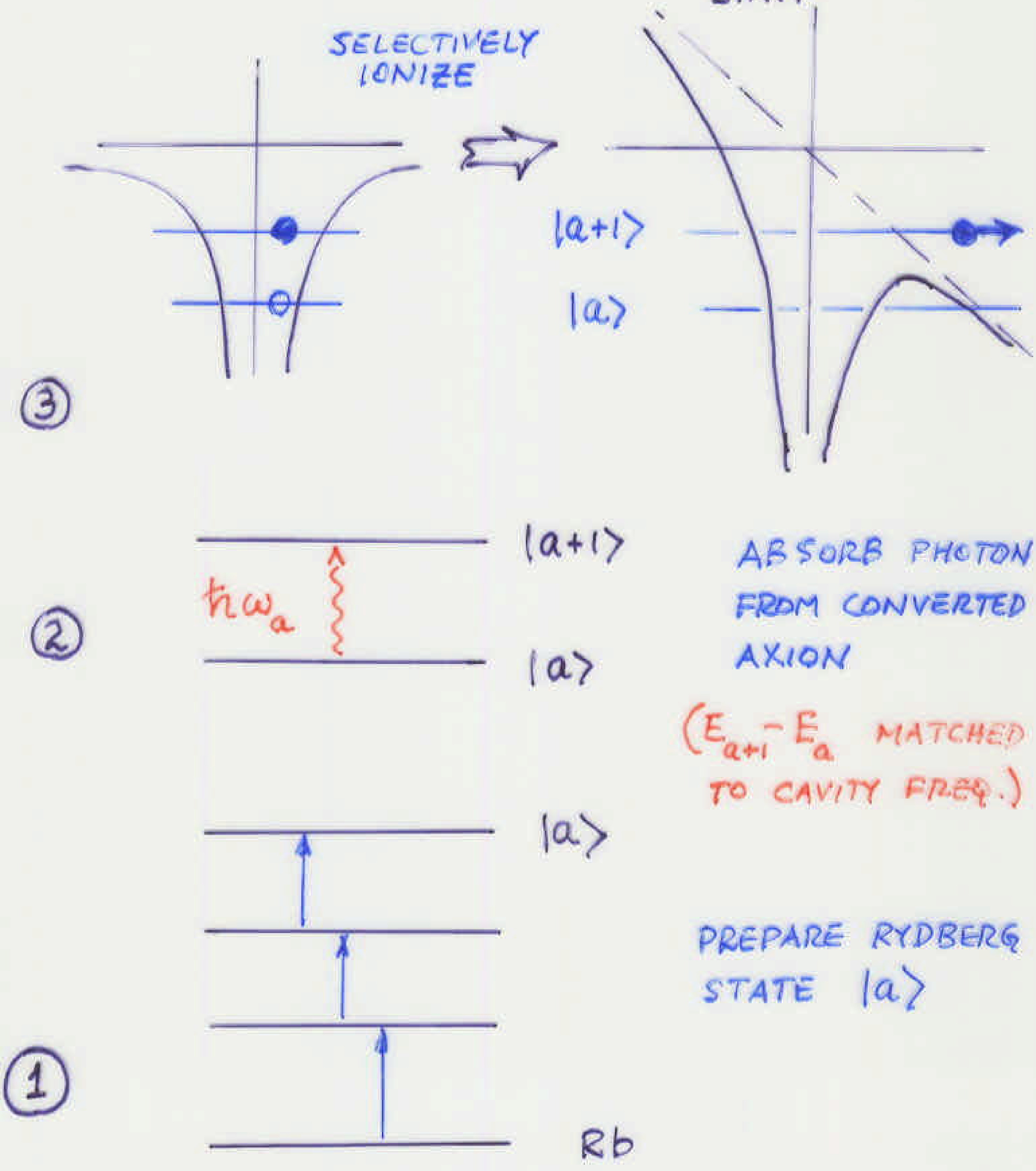
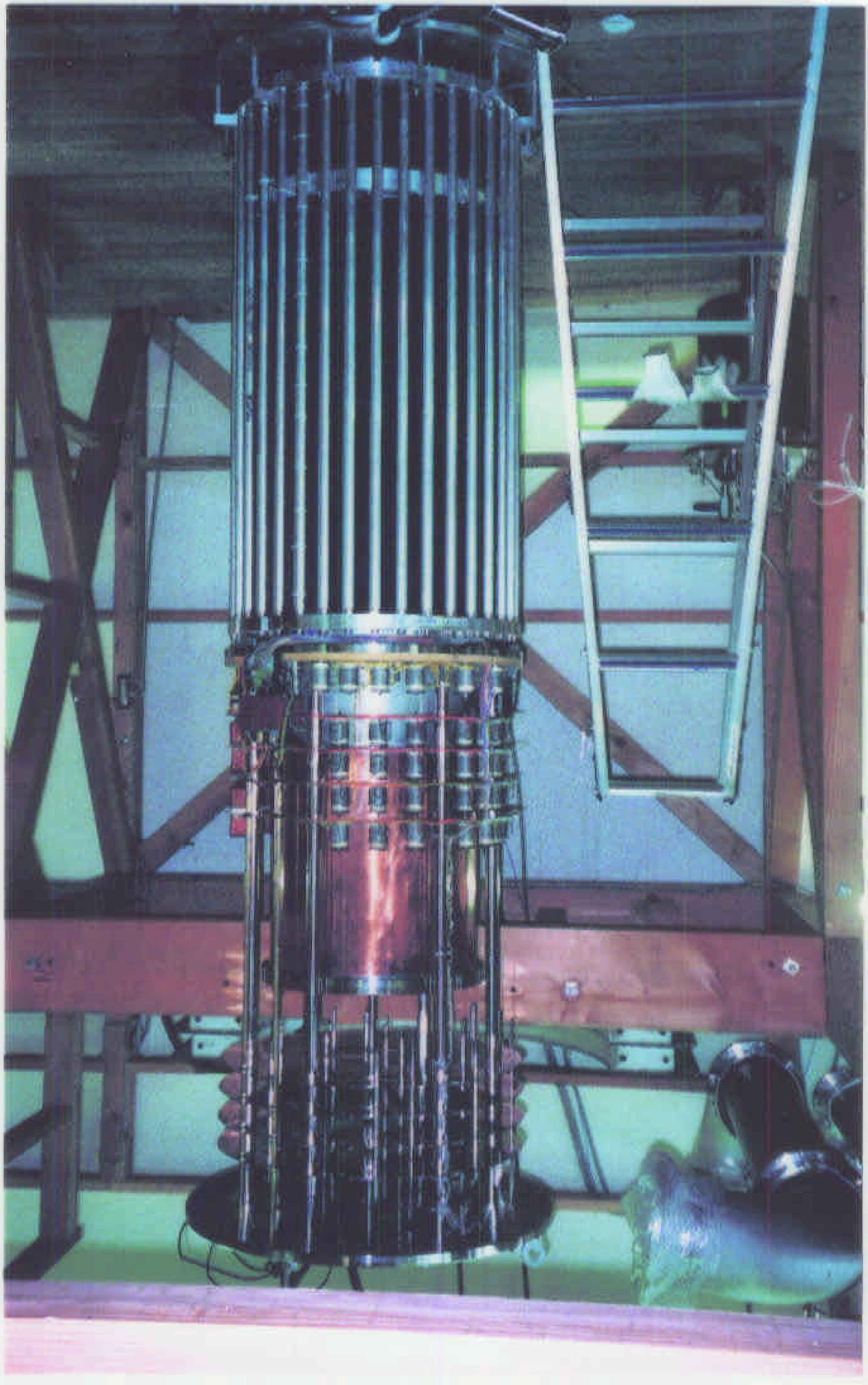
- The axion is well-motivated in particle physics and a very credible dark-matter candidate
- The parameter space (mass, coupling) is bounded and present experiments have already scanned well into this region
- Near-quantum-limited SQUID amplifiers are an enabling technology for a truly definitive search
- R&D effort underway to extend the search into the second decade in frequency

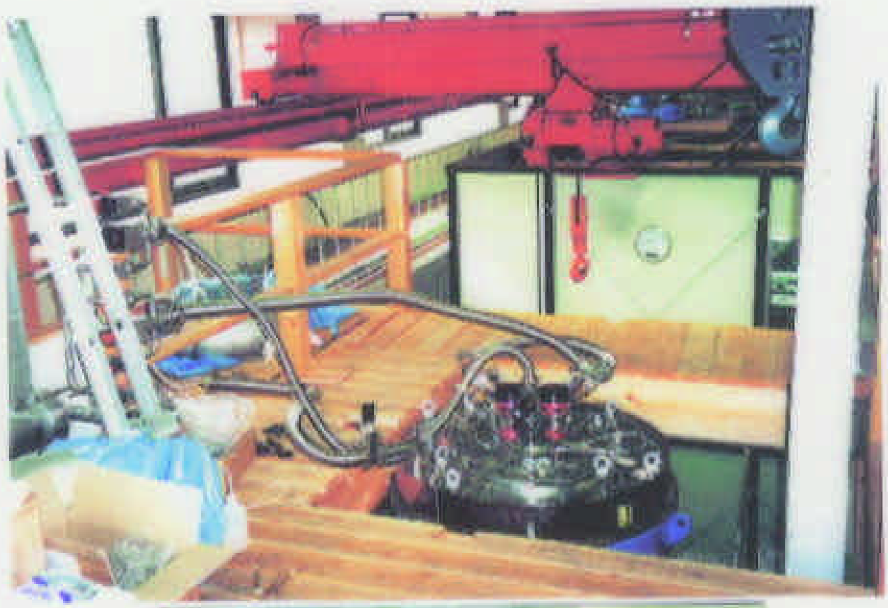

"CARRACK II"
KYOTO UNIV.
PROF. SEISHI MATSUKI
dilution refrigerator
main magnet
conversion cavity
cancellation coil
metal
posts
laser interaction point
①
atomic beam system
3415
detection cavity
field
ionization
electrode
②
Stark electrodes
electron detector
③

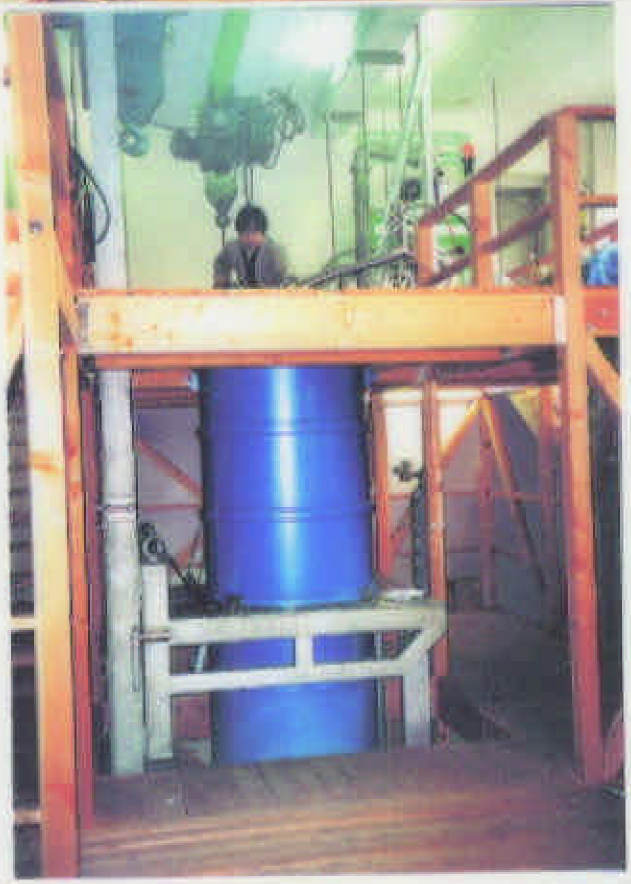
KYOTO UNIVERSITY AXION SEARCH USING RYDBERG ATOM SINGLE QUANTUM DETECTOR

"RF PHOTOTUBE" PHASELESS → EVADES QUANTUM LIMIT









CARRACK2
Axion
探索装置