3rd Joint ILIAS–CERN–DESY Axion–WIMPs

Chasing Axions to the Quantum-Limit and Beyond

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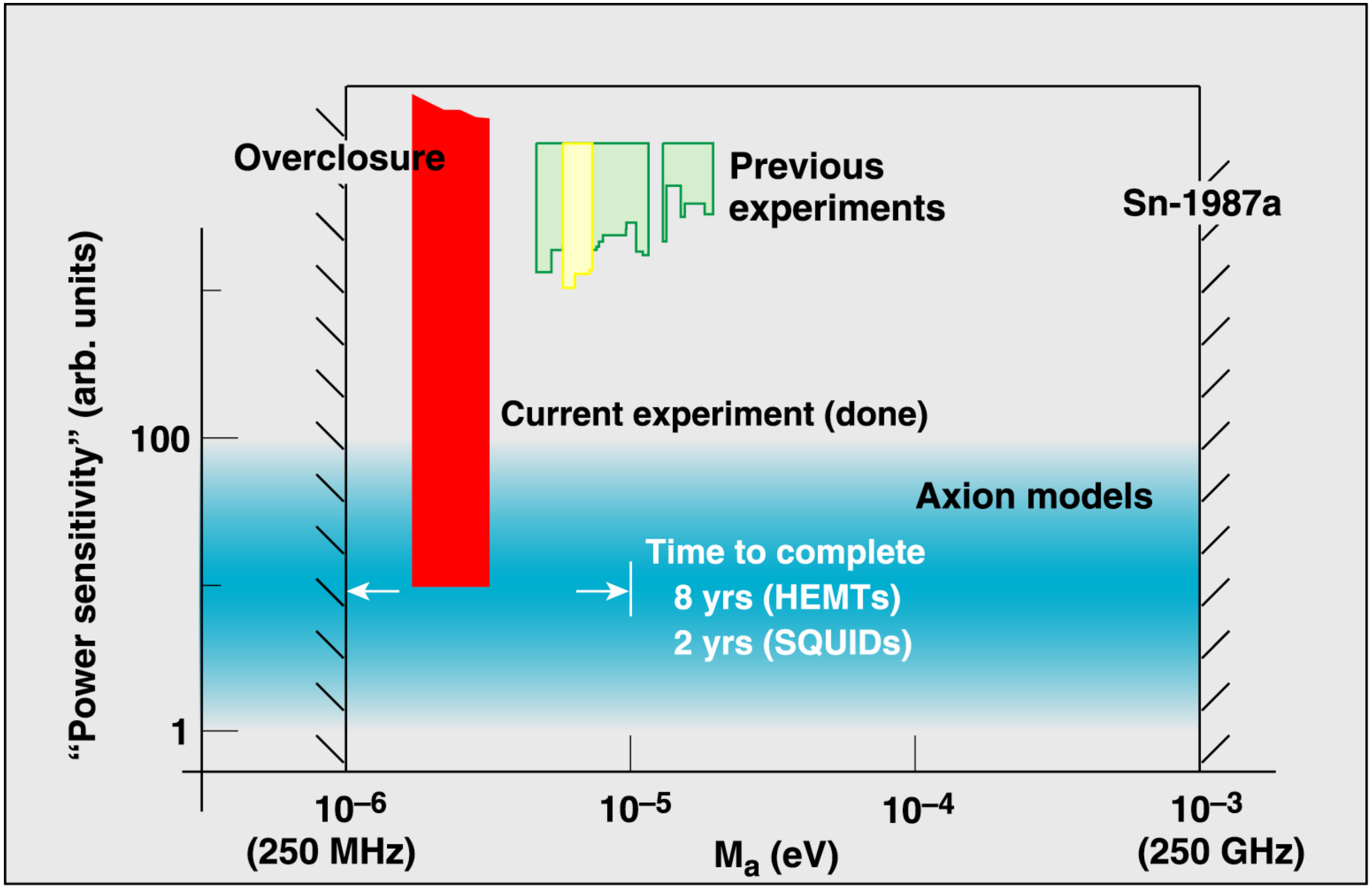
June, 2007

Phase 0 recap

ADMX



- **The current experiment is based on conventional heterojunction technology (HEMTs)**
- **The physical temperature is T = 1.3 K, and the total system noise temperature is $T_S \gtrsim 3K$**

How Can We Improve?

- Present experiment acquires data at a rate of ~ 1 MHz/day.

- 10+ years we've managed to acquire an octave of data (478 < f < 810 MHz).

- Allowable phase space spans 300 MHz to at least 300 THz

How will we ever discover/rule-out the axion???

Review search parameters

- Recall the search rate at fixed SNR:

$$\frac{dv}{dt} \propto \frac{B^2V^2}{T_S^2}$$

- Increase B,V; or decrease T_N:

🚫 •bigger B: 10-12 Tesla $5M+

🚫 •bigger V: larger center bore magnet

➡ •*smaller* T_N: better amplifiers!

Temperature offers the best promise for radical advances.

Lower temperature approaches

- Consider what a factor of 10 in improvement in temperature buys
  - Factor of 100 in scan speed, or a
  - Factor of 10 in sensitivity
- Noise in our first stage Ga-As FET comes from channel impurities (scattering) and does not fall much below $T_P \sim 14K$

Must consider new amplification technology.

New thread: Non-classical photon states

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- Any detector of electromagnetic radiation must obey the number-of-quanta, phase-of-radiation uncertainty relation:

$$\Delta n \cdot \Delta \phi \geq 1$$

- Amplifiers which interact with electromagnetic radiation in a classical manner obey the above relationship with equal uncertainty contribution from each factor. The quantum object (photon) is said to be in a **coherent state**.

- Amplifiers which interact with electromagnetic radiation in a non-classical manner also obey the above relationship, but non necessarily with equal uncertainty contributions from each factor. The quantum object (photon) is said to be in a **squeezed state**.

See R. Bradley, *et al.* RMP 75 (2003) for a thorough discussion.

Quantum limit or not

- When an amplifier is forced to behave in a classical manner it must obey the standard quantum limit:

$$\hbar\omega = k_B T$$

- SQUIDs, HFETs and the like must obey the standard quantum limit
- When an amplifier no longer behaves as such it is not bound by the standard quantum limit.
- Photomultipliers, bolometers, etc do not have to obey the standard quantum limit.

Next generation of RF cavity based experiments

- The next generation of RF cavity-based axion detection experiments take different approaches to amplification.

- CARRACK uses Rydberg atoms for their detectors and thus evades the quantum limit.

CARRACK: Cosmic Axion Research with Rydberg Atoms in resonant Cavities in Kyoto

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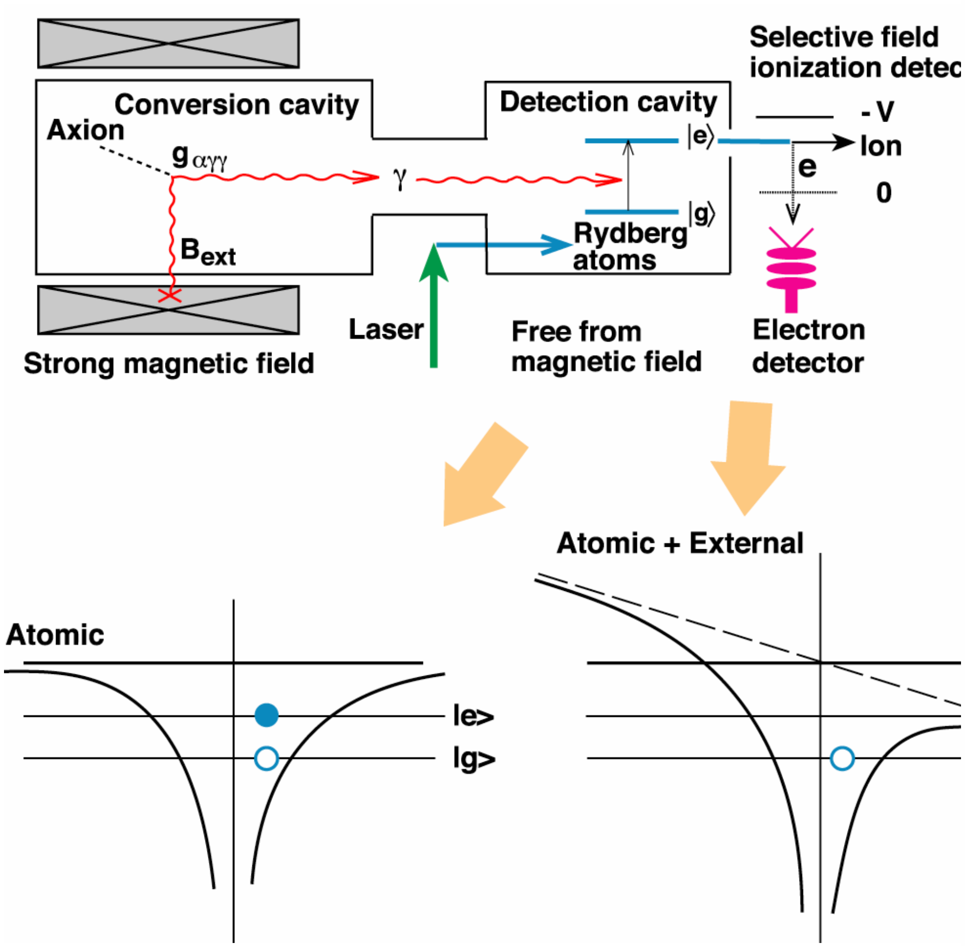
Rydberg-atom single-quantum detectors

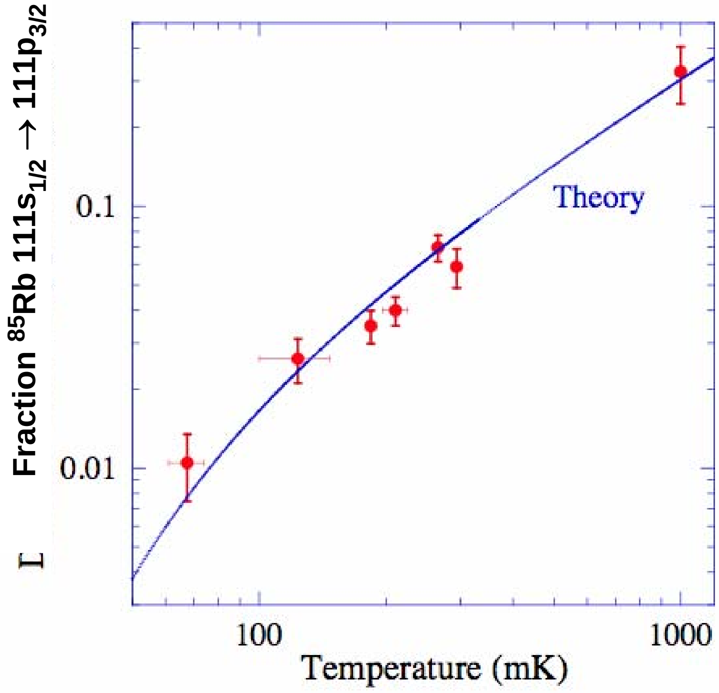
•Atoms with a single electron promoted to a large principal quantum number, n >> 1. Superposition of Rydberg states yields “classical atoms” with macroscopic dimensions (e.g. ~ 1 mm).

• Potential for highly sensitive microwave photon detectors (“RF photo-multiplier tubes”) realized by Kleppner and others in the1970’s. The axion experiment is an ideal application for Rydberg atoms:

- ***Large transition dipole moments*** $\langle n \pm 1 | er | n \rangle \propto n^2 a_0$
- ***Long liftetimes*** $\tau_n \propto n^3 \quad (l << n); \quad \tau_{100} \approx 1\, m\sec$
- ***Transitions span microwave range*** $\Delta E_n = E_{n+1} - E_n \approx 2R/n^2; \quad \Delta E_{100} \approx 7\ GHz$

Rydberg single-quantum detection *(S. Matsuki et al., Kyoto)*





M. Tada et al., Phys. Lett. A (accepted)

The blackbody spectrum has been measured at 2527 MHz a factor of ~2 below the standard quantum limit (~120mK)

Selective field ionization

Y. Kishimoto et al., Phys. Lett. A 303 (2002) 279
M. Tada et al., Phys. Lett. A 303 (2002) 285
R. Bradley et al., Rev. Mod. Phys. 75 (2003) 777

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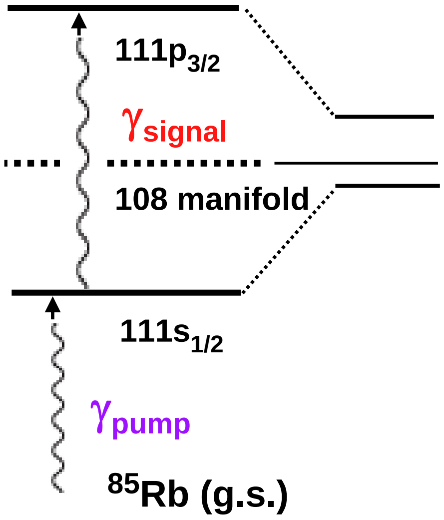
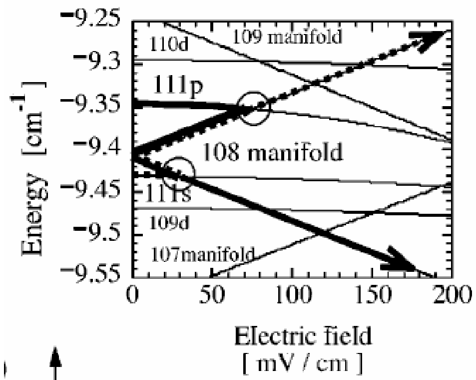
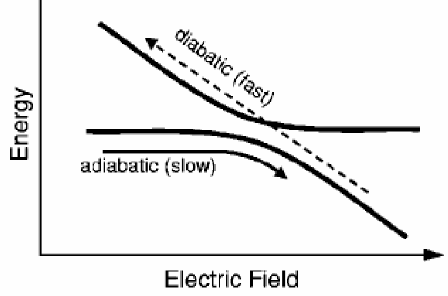
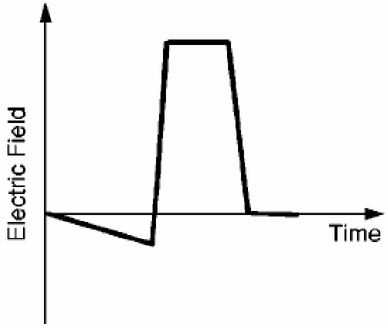
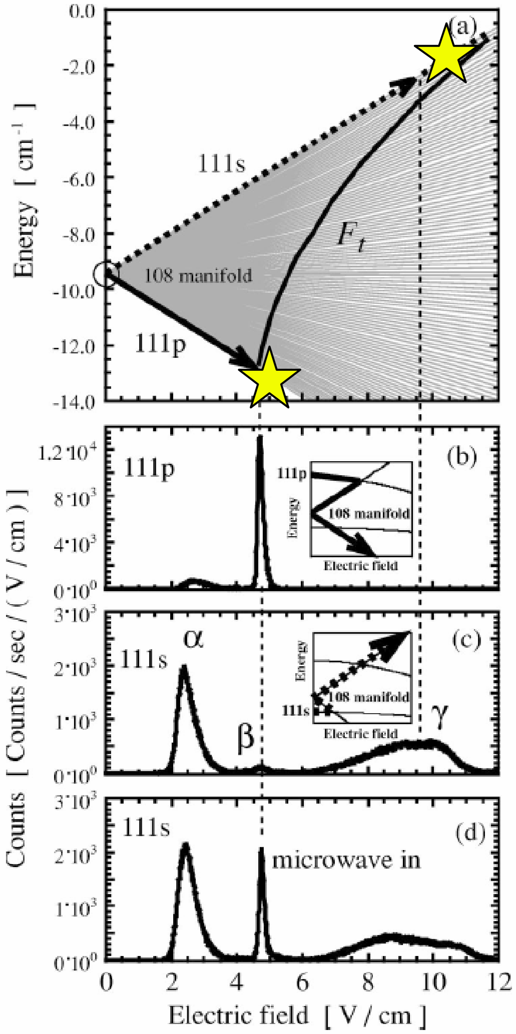






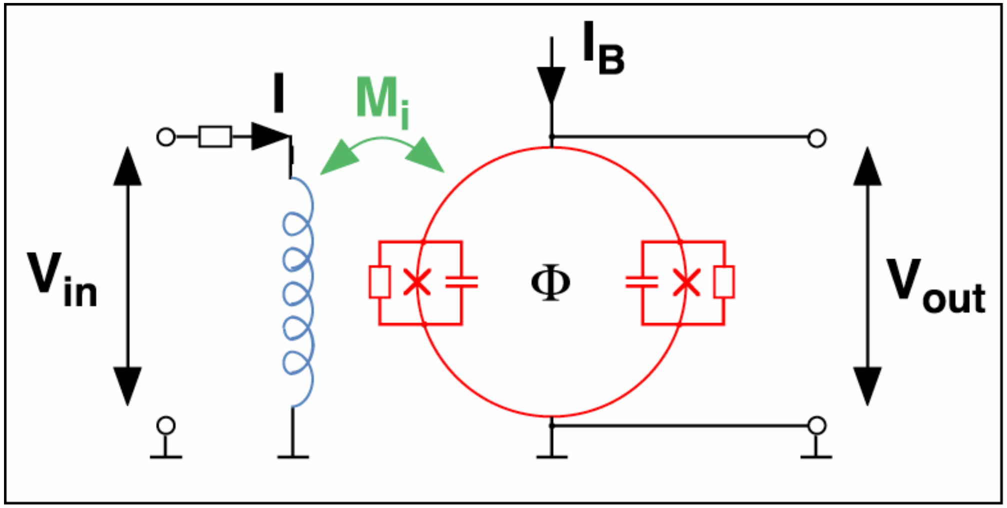


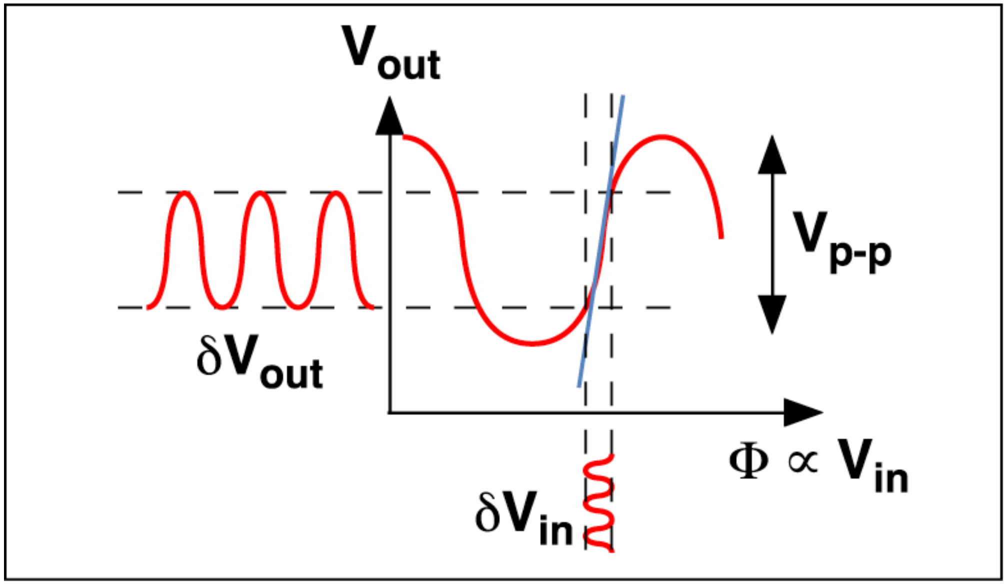


Rydberg "railroad switchyard" enables very high selectivity for ionization of the excited state (111p) with virtually no contamination of the prepared state (111s)

Our future — SQUID amplifiers

ADMX





- **The basic SQUID amplifier is a flux-to-voltage transformer**
- **SQUID noise arises from Nyquist noise in shunt resistance**
  - **Thus it scales linearly with T**
- **However, SQUIDs of conventional (inductively coupled) design are poor amplifiers above 100 MHz**

Phase I of the Axion Dark Matter eXperiment *ADMX*

- ADMX Phase I relies on SQUID based amplification, and is thus quantum-limited.

- However, the temperature at which this limit is attained is around 40mK.

GHz SQUID amplifiers

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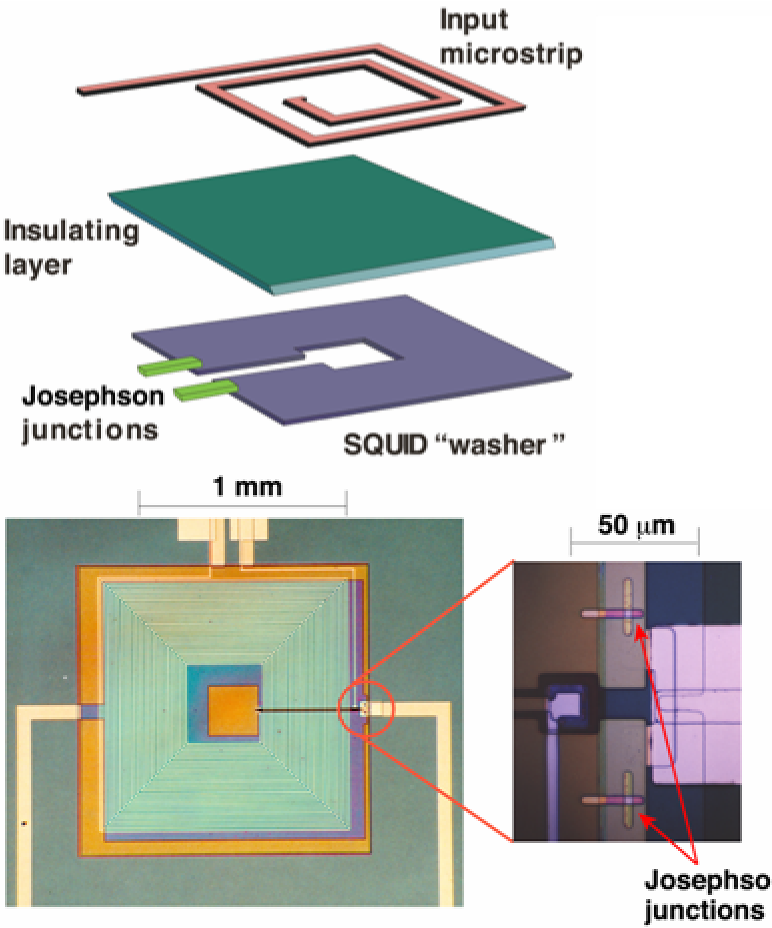
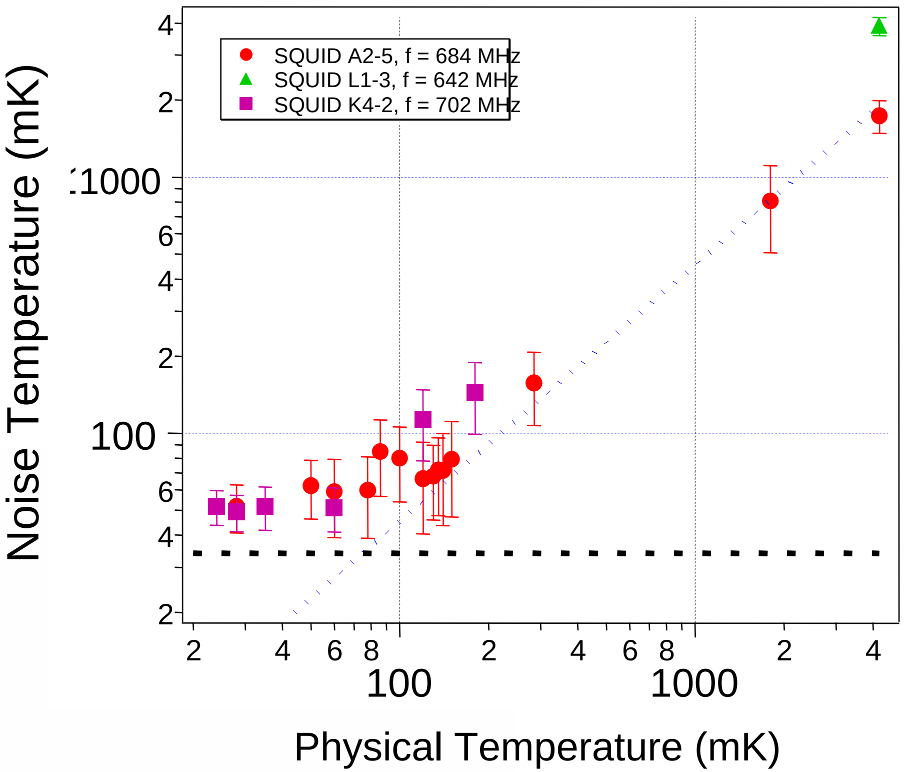
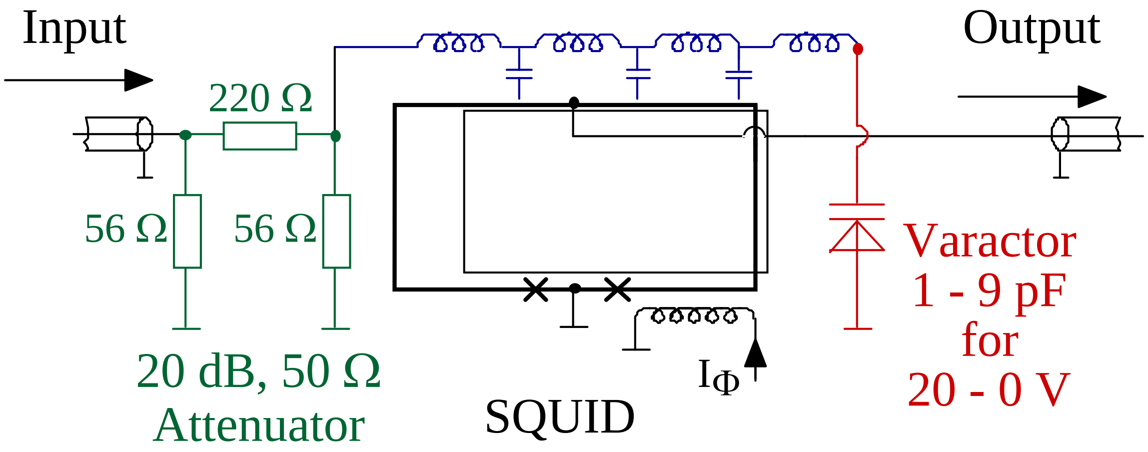


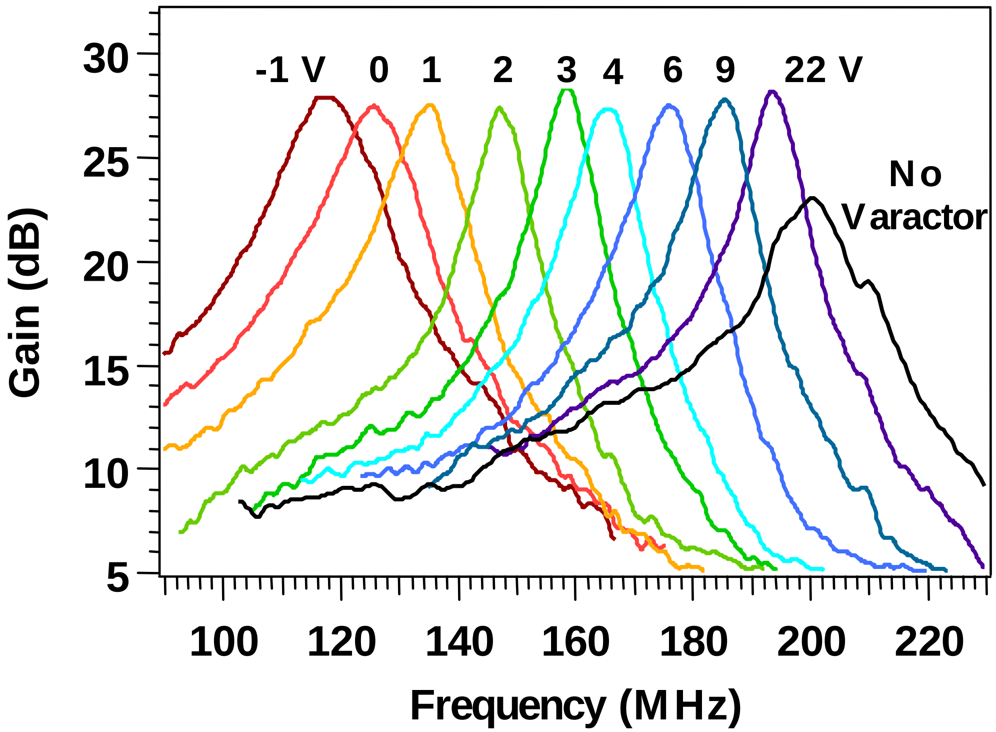


Latest SQUIDs are now within 30% of the Standard Quantum Limit

Varactor tuning of microstrip SQUID

ADMX

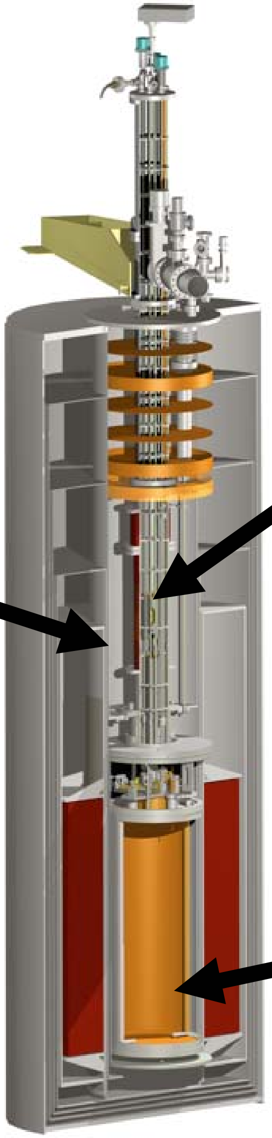




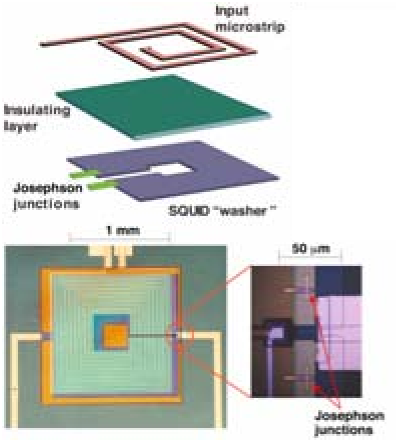
SQUIDs drive our Phase I upgrade

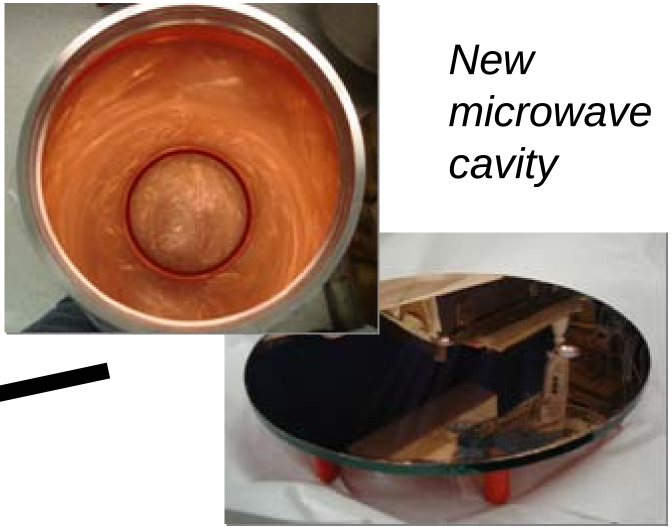
ADMX

Field compensation magnet for SQUIDs



SQUID amplifier





New microwave cavity

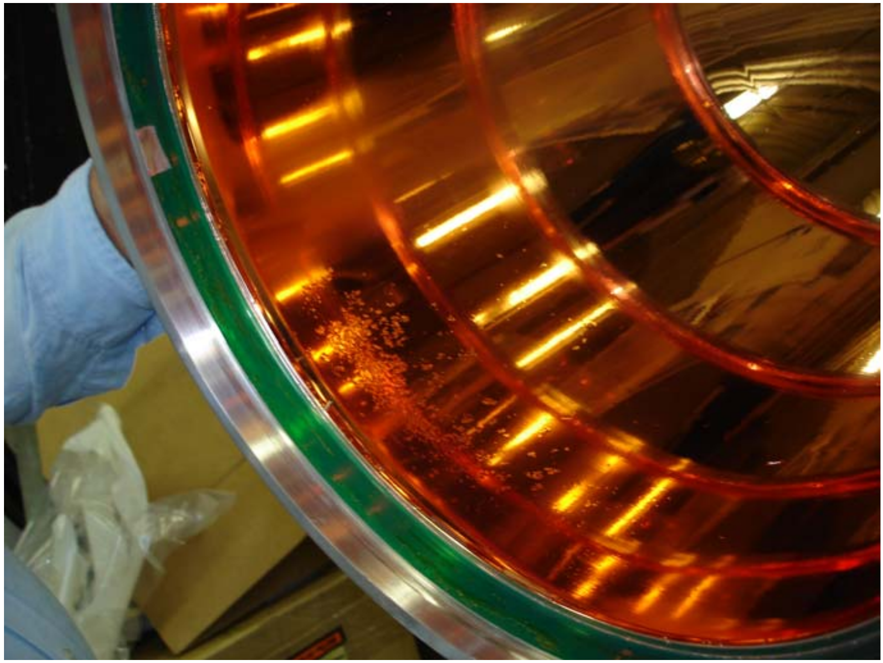
Phase I Upgrade (SQUIDs @ 1.3K) is nearly complete

What improvements did we make to our Phase 0 design?

- Reduce field in vicinity of SQUID amplifier
  - Physically move
  - Buck fringe field
  - Shield amplifier
- Replaced “wet” system with “dry” system
  - Reduce heat load on experimental insert
- Shrunk cavity dimensions
  - Access higher frequencies
  - Better physical fit within main magnet bore

High-Q cavity

- Axion conversion scales with Q – the cavity quality factor
- The quality factor itself is inversely dependent on the skin depth
- The skin depth is inversely proportional to frequency
- $Q \sim \delta^{-1} \sim f$



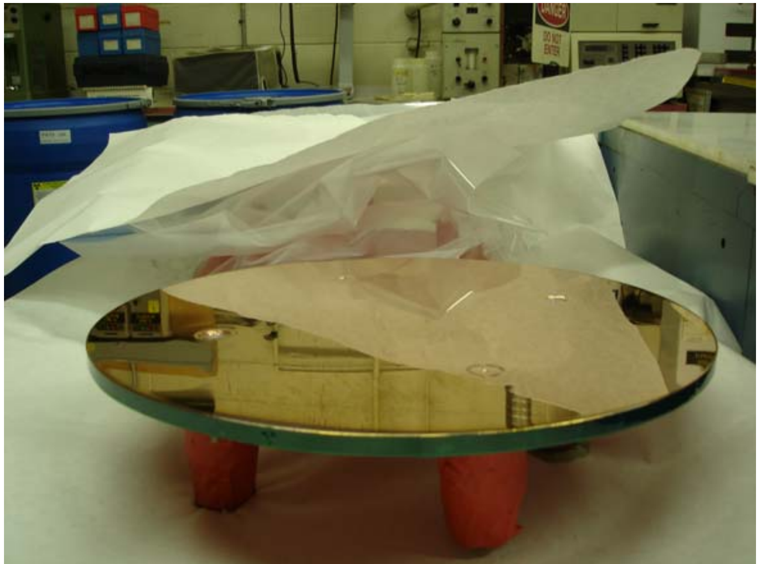
High-Q cavity

- At high frequencies and low temperatures the classical skin depth is replaced by the anomalous skin depth $\delta \propto (\omega\sigma)^{-1/3}$
- Since this dimension is on order of 20 microns, no need to make entire cavity out of high conductivity material

- As with LINAC cavities we plate Cu on a metal that is more readily machinable. Don’t want large conductive masses, either, since this leads to eddy current dissipation

High-Q cavity

- The plating process is called UBAC and employs oxygen-free copper (99.99% pure Cu with 0.0005% O to improve conductivity)
- With this level of attention we manage to achieve near-theoretical Q-values (~2x10^5 unloaded at 1.3K)



Main Magnet

- Our main magnet is constructed from Nb_3Ti – a Type II superconductor

$$B_c = B_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

- With T_c ~ 10K and $B_c(0)$ ~ 15T, at an operating temperature of 4K B_c ~ 12T. The 226 A (max) that is needed to fully charge the magnet comes nowhere close to generating this critical field

Main magnet

- The stored energy is more problematic
- U/V = $1/2LI^2$ L ~ 500H and I ~ 226A
- Should the magnet coils go normal ~ 12MJ needs to be dissipated. We have two diode protection circuits to safely release this energy: cold and warm. The cold diodes conduct ~ 5V and a quench would quickly vaporize all the LHe.

Bucking Coil

- Whereas our HFET amplifiers work admirably in a 6T field (though orientation effects are critical), the SQUID cannot function if δB is an appreciable fraction of a Weber

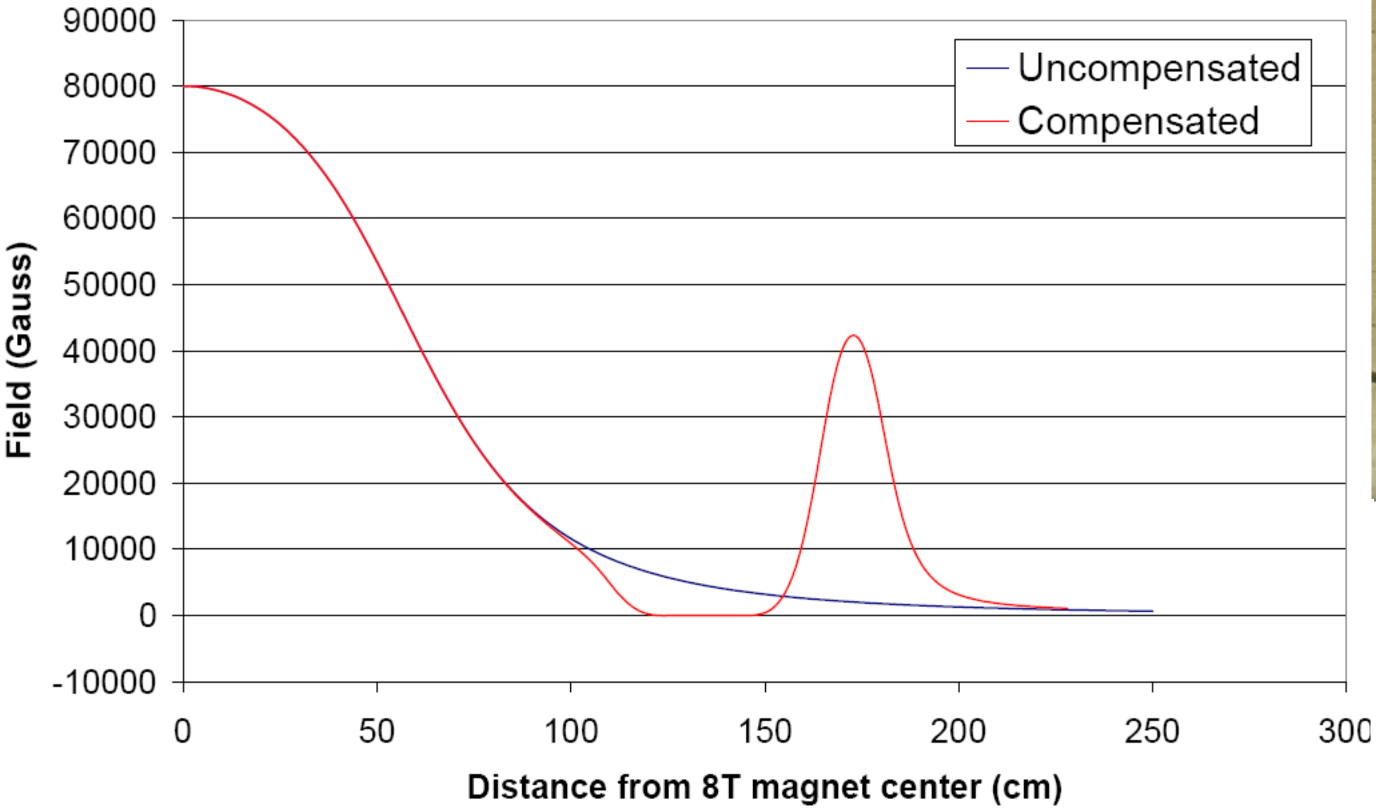
  $\delta\Phi = \delta BA << 1\text{x}10^{-15}$,

  thus $\delta B < 10\text{nT}$

- Must buck the field in the vicinity of the SQUID by 8 orders of magnitude

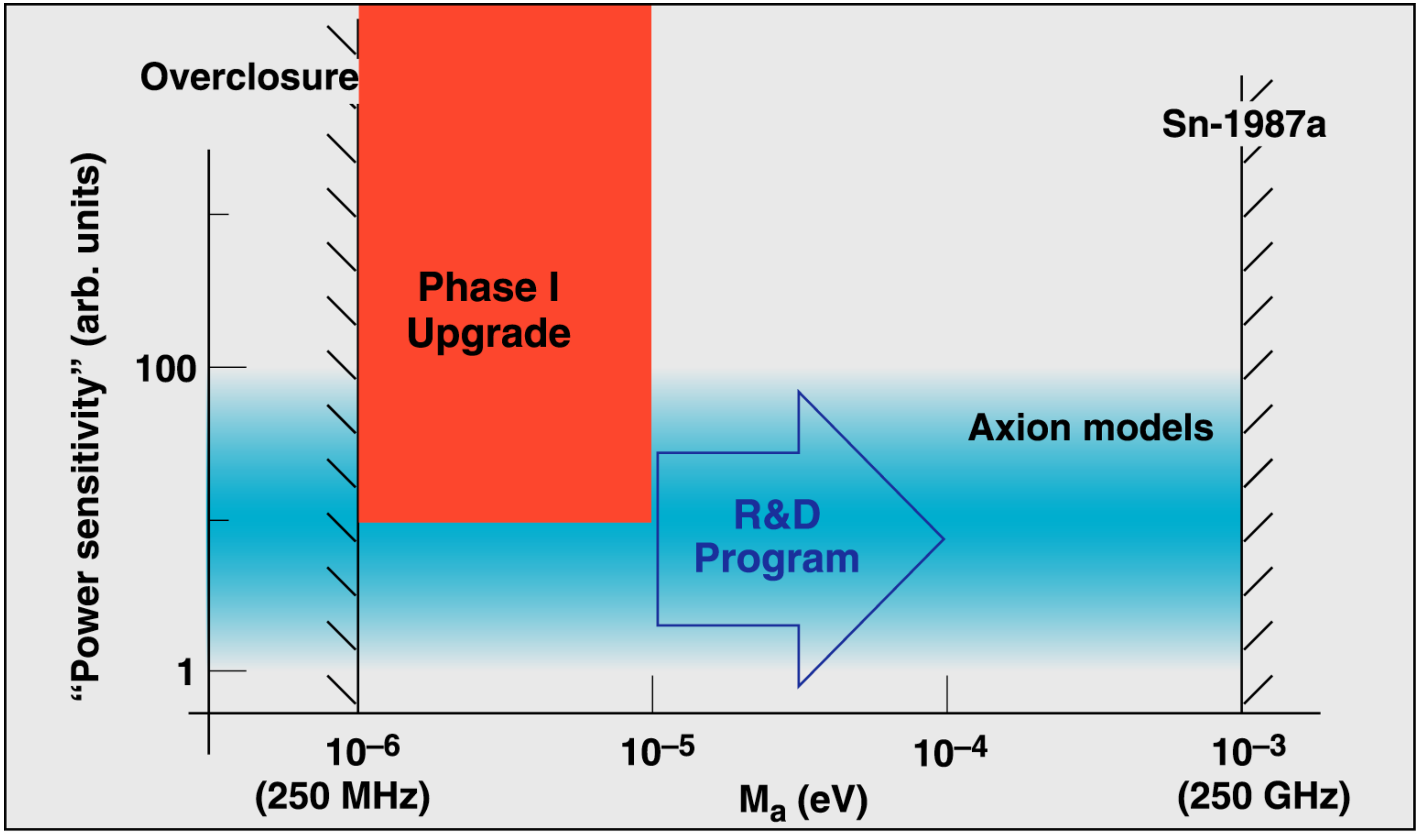
Bucking Coil

ADMX



The Phase I upgrade (ongoing – run mid-2007)

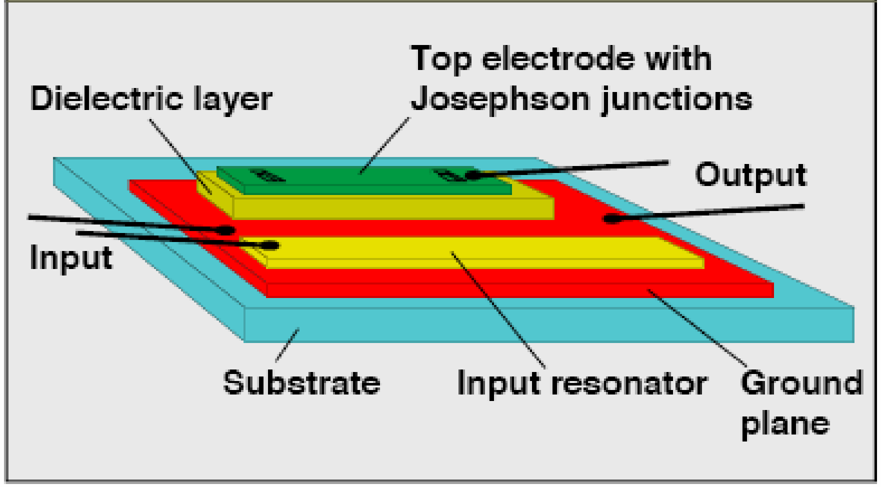
ADMX



- Phase I will incorporate SQUIDs for the first time
- The physical temperature will remain T = 1.3 K, but the system noise temperature will be $T_S \sim 1.5$ K
- We will scan at the current sensitivity faster by x4!
- We will scan new mass range and publish physics
- R&D will open up the next decade in mass

Concept for SQUID amplifiers towards 100 μeV (25 GHz)

The 'In-Line' SQUID Amplifier

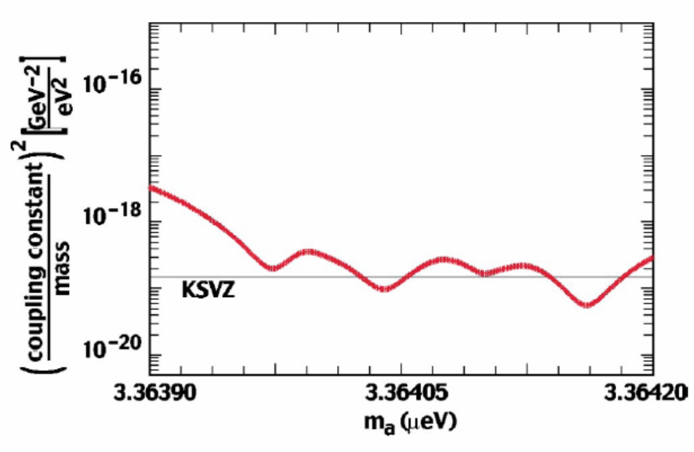


There is strong interest world-wide to develop X-band SQUIDs as IF amplifiers for IR and sub-mm astronomy

- 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

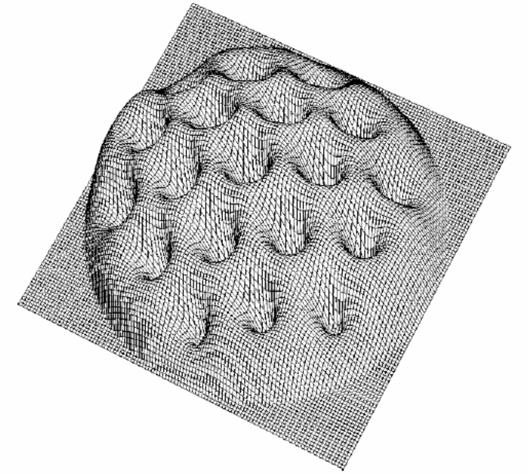
Options for higher frequency cavities

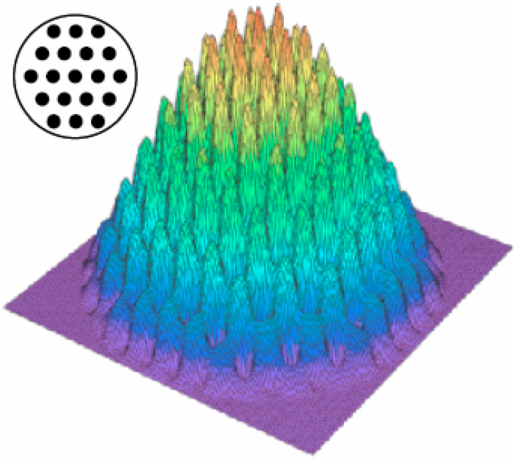
Power-combine multiple cavities (1-10 GHz)



“The Gang of Four”; Darin Kinion, Thesis, UC Davis (2000)

Periodic-post resonators (10-100 GHz)





The Phase II upgrade (planned)

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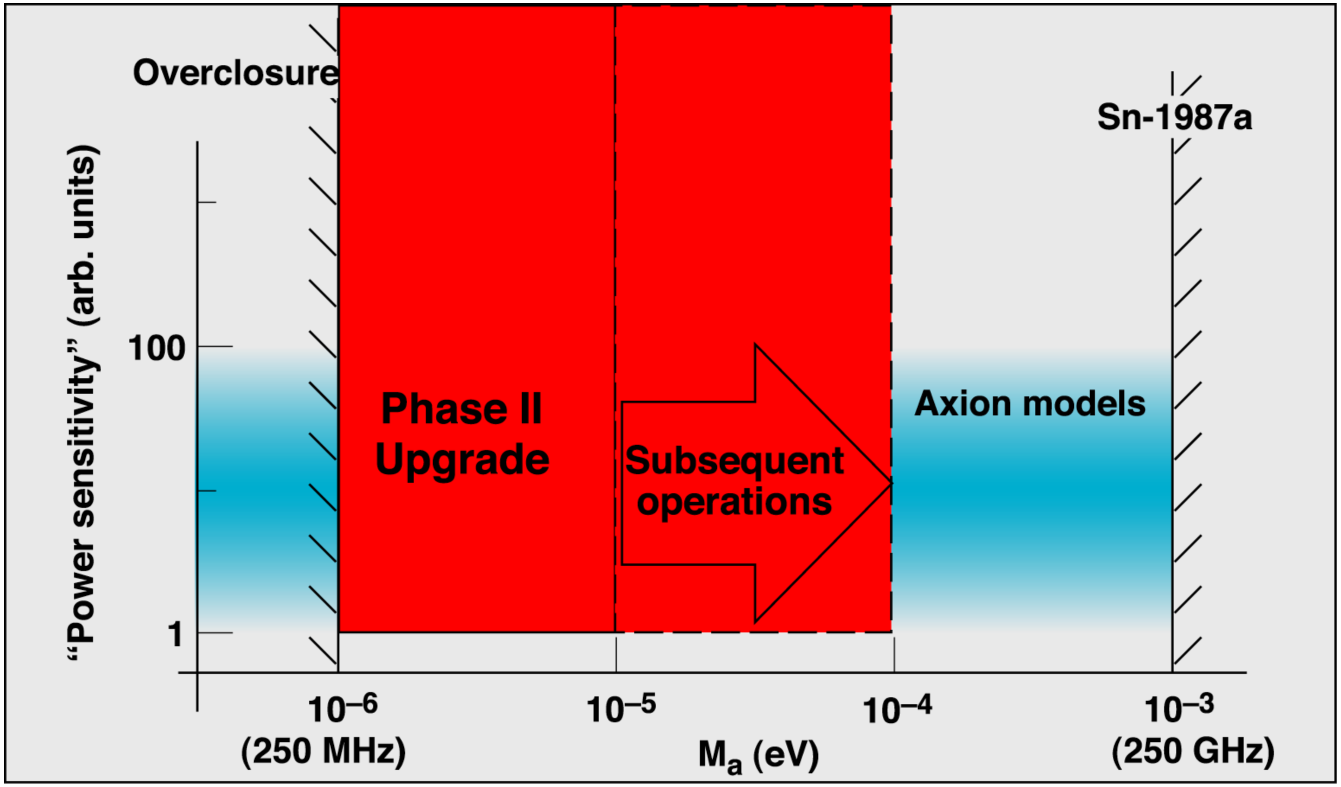

- The Phase II upgrade will add a dilution refrigerator
  - $T \sim 100$ mK, $T_S \lesssim 200$ mK
- We will achieve definitive sensitivity over the lowest decade in mass
- And — depending on our R&D success — we will finally cover 2/3 of the mass range