Microwave Cavity Searches for Axions

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Outline

Axions and dark matter

The Axion Dark-Matter eXperiment (ADMX)
Original (transistor amplifier) experiment (completed),
sensitive to plausible D.M. masses & couplings

"Phase I" upgrade (SQUID amplifier w/o dilution refrigerator) experiment
(completed), incorporate SQUID amplifiers

"Phase II" (SQUID amplifier with dilution refrigerator) experiment
(under construction), incorporate dilution refrigerator
The "definitive" experiment

The Kyoto Experiment (CARRACK), Rydberg-atom-based photon
counting (in development), potential to evade Standard Quantum
Limit to amplifier noise.

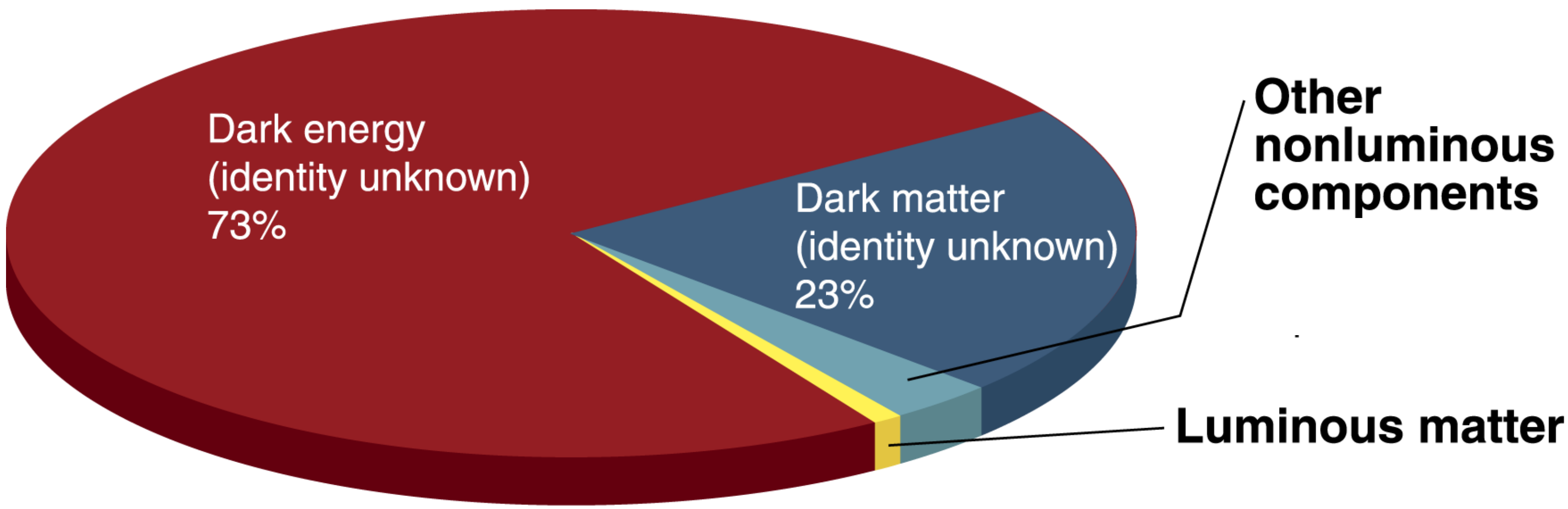
Summary and prospects

RF cavity experiments address the question: Does our local dark matter halo consist of Peccei-Quinn axions?

We know neither what the “dark energy” or the “dark matter” is

A particle relic from the Big Bang is strongly implied for DM

- **WIMPs ?**
- **Axions ?**



Science (20 June 2003)

Peccei-Quinn axions: constrained mass and coupling

- **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

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

Generically, all couplings

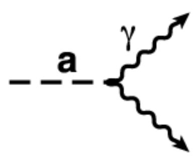
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

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

(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'

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

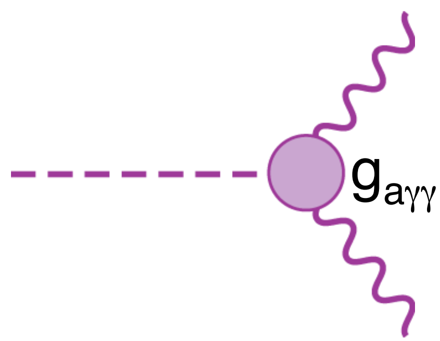
(Overclosure) (SN1987a)

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

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

The axion couples (very weakly, indeed) to normal particles.

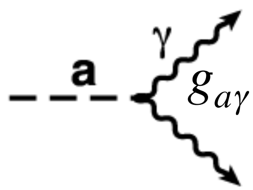
But it happens that the axion 2γ coupling has relatively little axion-model dependence



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

Pierre Sikivie's RF-cavity idea (1983):
Axion and electromagnetic fields exchange energy

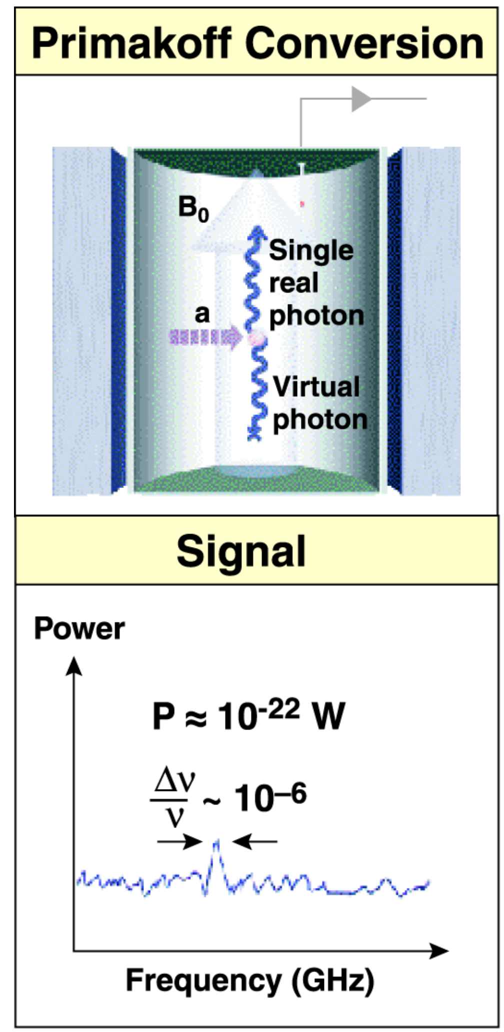
The axion-photon coupling…



…is a source term in Maxwell's Equations

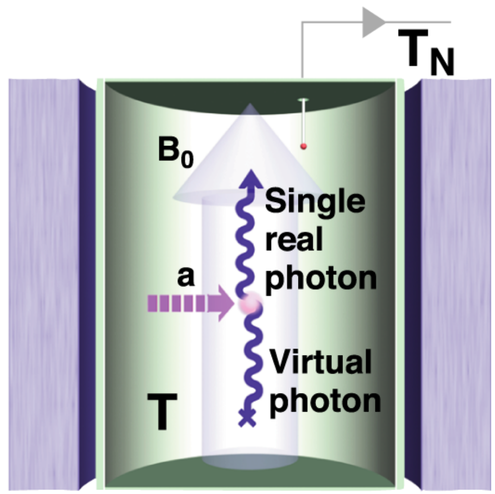
$$\frac{\partial\left(\mathbf{E}^2/2\right)}{\partial t} - \mathbf{E}\cdot\left(\nabla\times\mathbf{B}\right) = g_{a\gamma}\dot{a}\left(\mathbf{E}\cdot\mathbf{B}\right)$$

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



Some experimental details of the RF-cavity technique

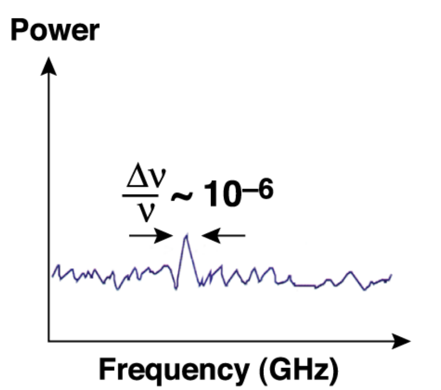
Primakoff Conversion



- **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

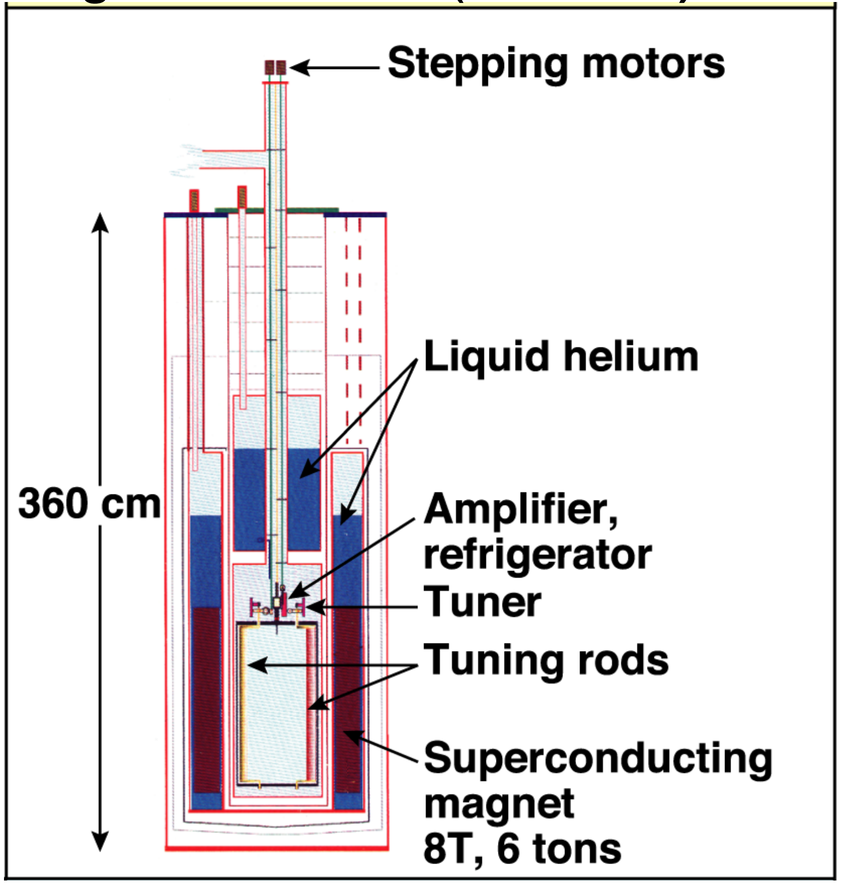


Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	**For fixed scan rate $\frac{d\nu}{dt}$**

ADMX: Axion Dark-Matter eXperiment

U of Washington, LLNL, University of Florida, UC Berkeley, National Radio Astronomy Observatory, Sheffield University

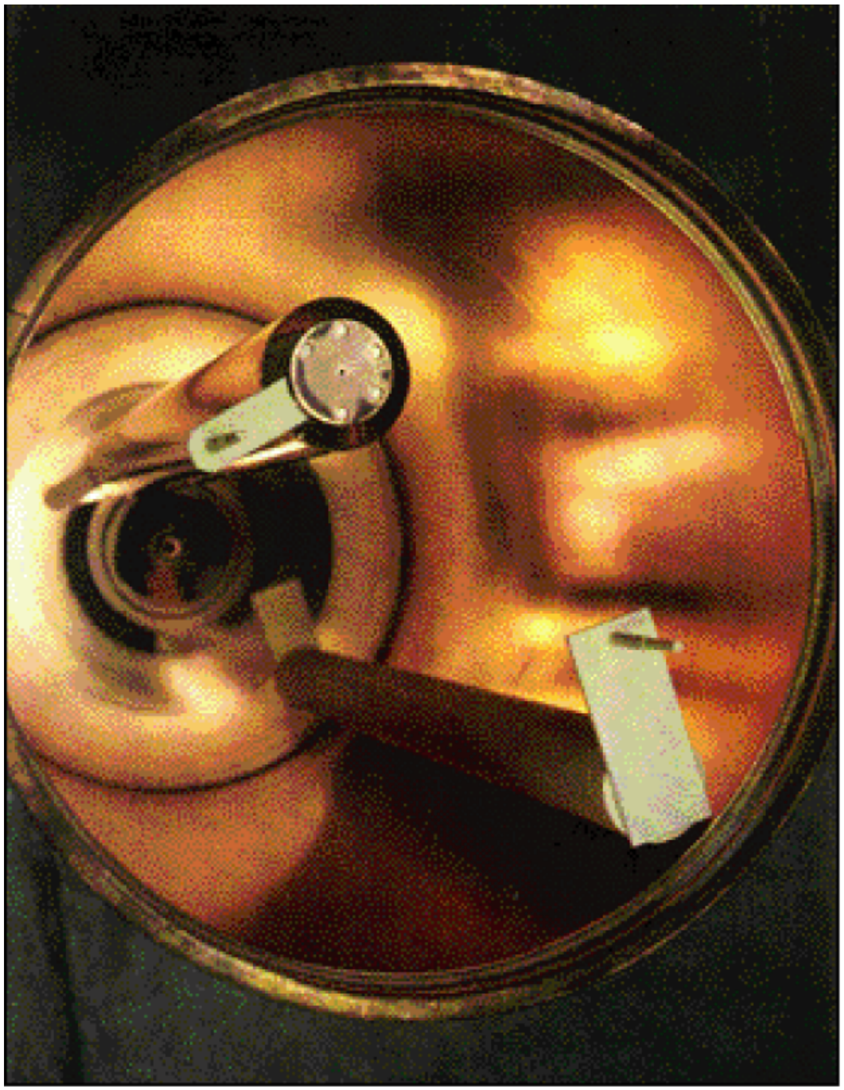
Magnet with insert (side view)



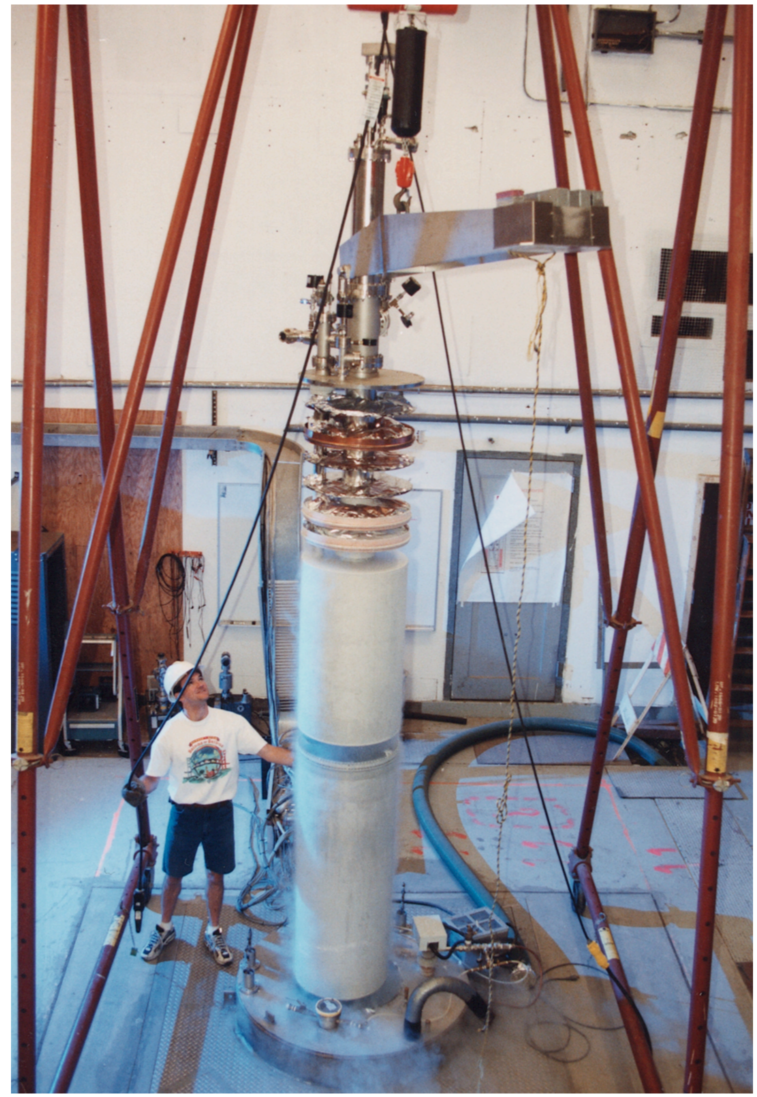
Magnet cryostat

ADMX hardware

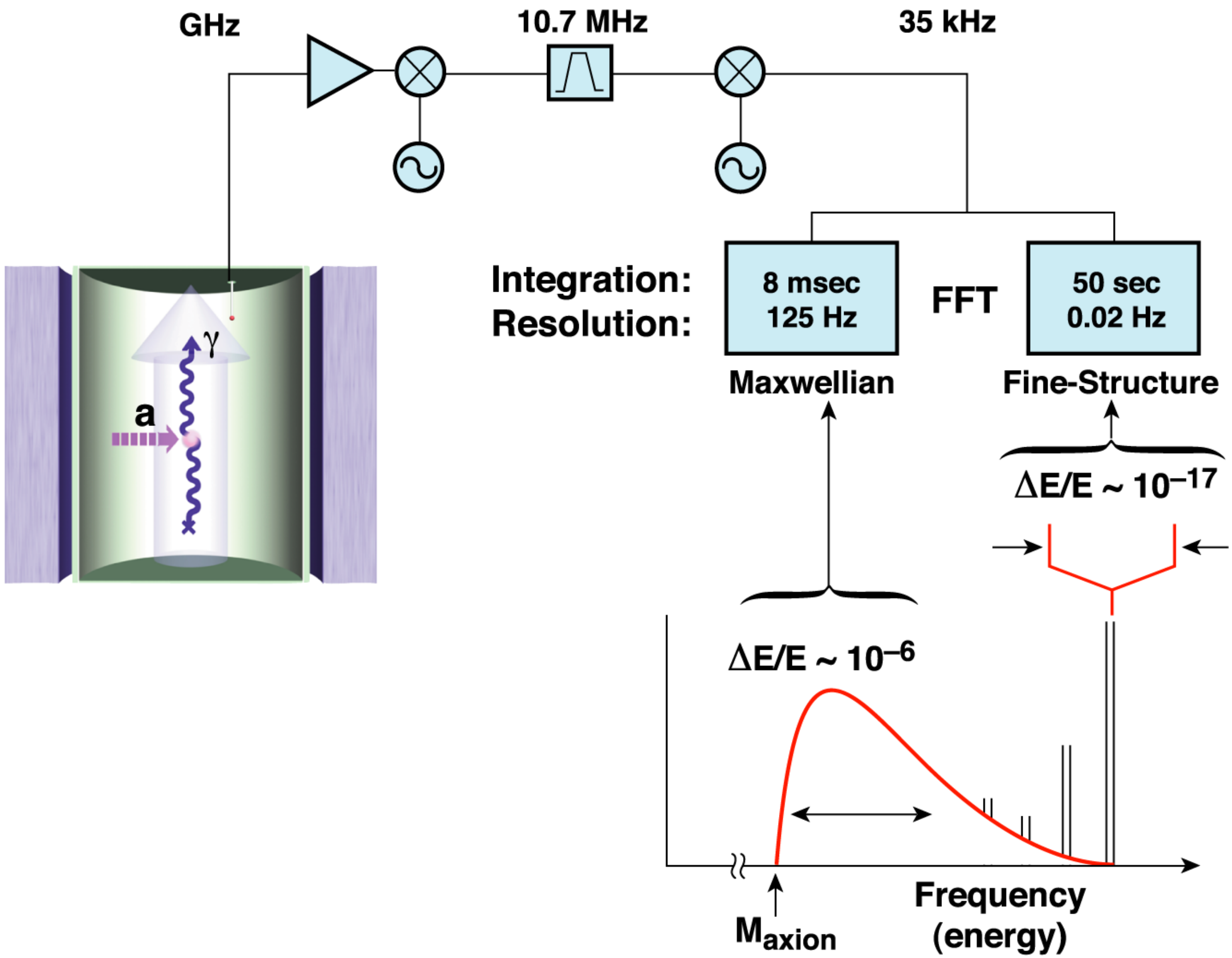
high-Q cavity



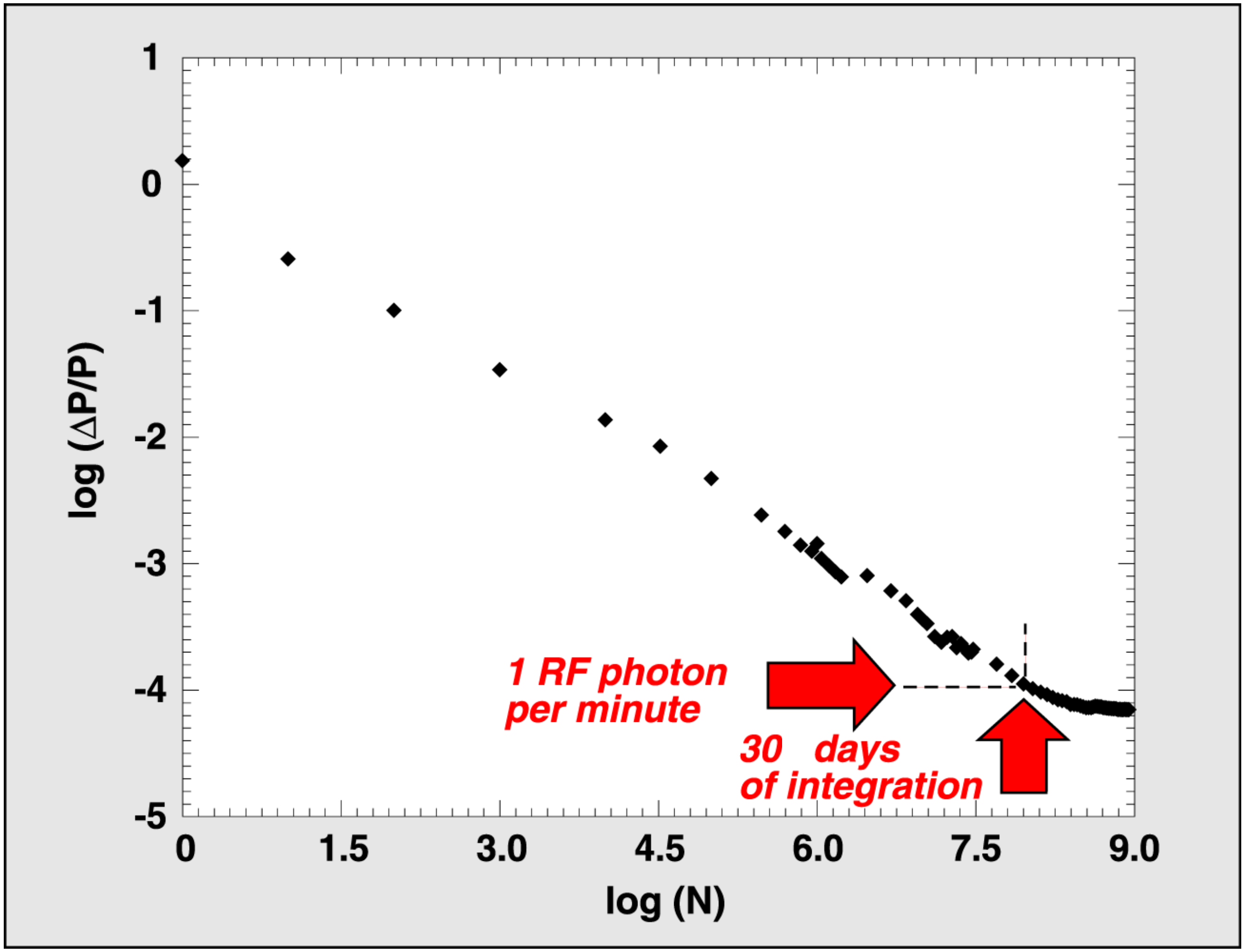
experiment insert



ADMX axion receiver

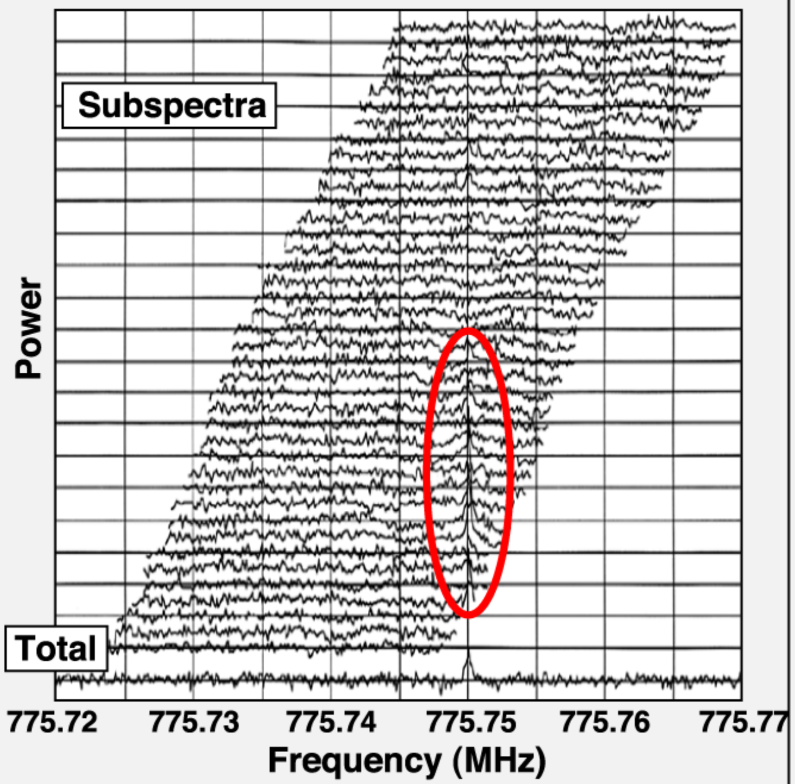
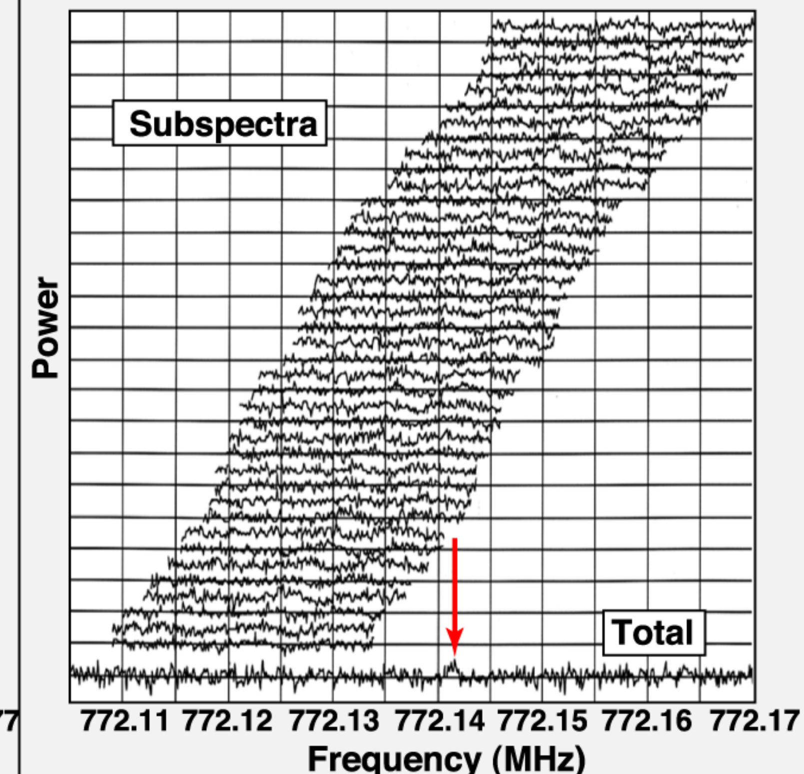


Converted microwave photons are detected by the world's quietest radio receiver

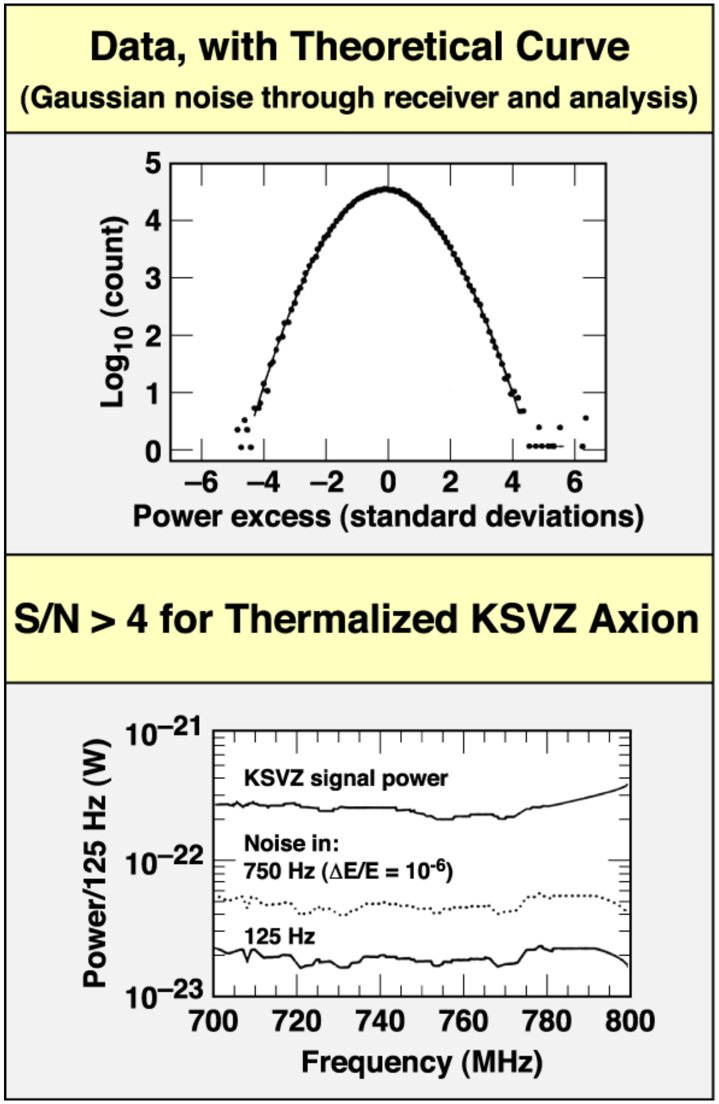


Systematics-limited for signals of 10^{-26} W
~10^{-3} of "DFSZ" axion power (1/100 yoctoWatt).

Sample data and candidates

Environmental	Statistical
	
Signal maximizes off-resonance: Radio peak	**Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)**

Brief outline of analysis — 100 MHz of data

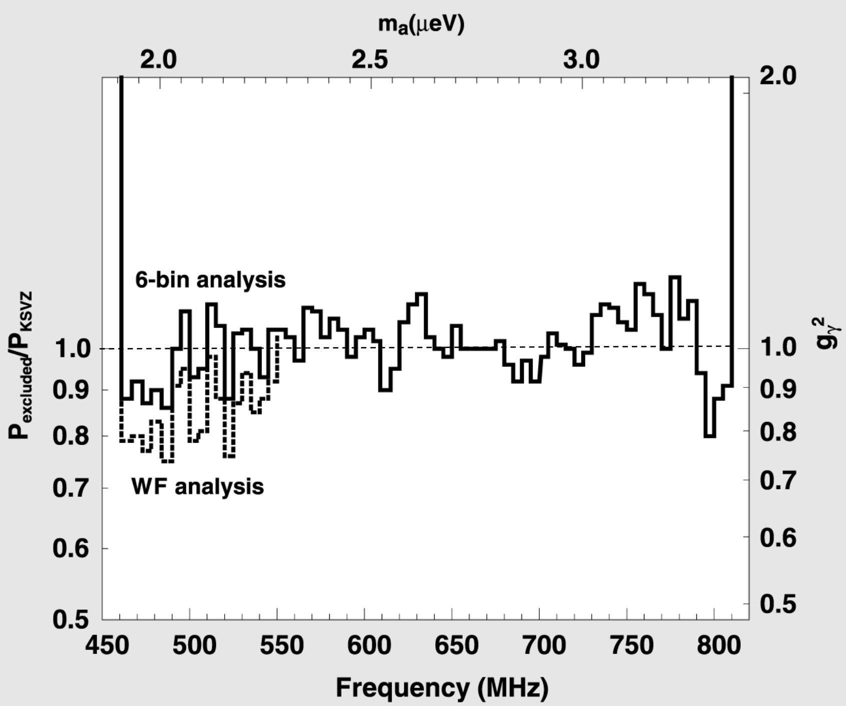


- Each frequency appears in >45 subspectra
- Weighted and co-added to produce spectrum
- 800,000 bins (125 Hz)/100 MHz

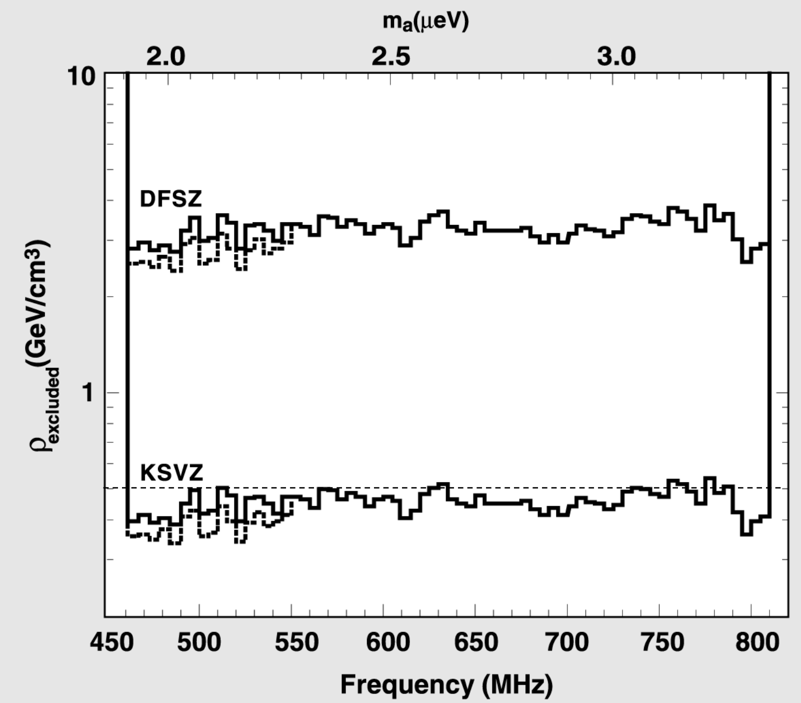
→ 6535 candidates > $2.25\sqrt{6}\,\overline{\sigma}$ (95% C.L.)
→ Rescan all to same sensitivity
→ 23 candidates (Net 90% C.L.)
→ Each examined: radio peaks

Results from the decade of the original ADMX

Particle Physics



Astrophysics



These are interesting regimes of particle and astrophysics: probe realistic DM axion couplings and halo densities

Summary of original (transistor amplifier) ADMX results

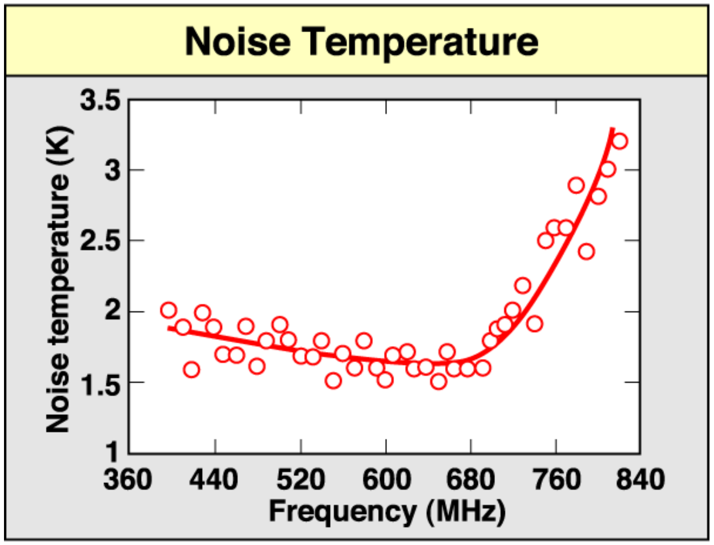
- Scanned $461 < f_0 < 810$ MHz in ~ 10 years
  - Net scan rate ≤ 0.5 MHz/day (at optimal f_0)

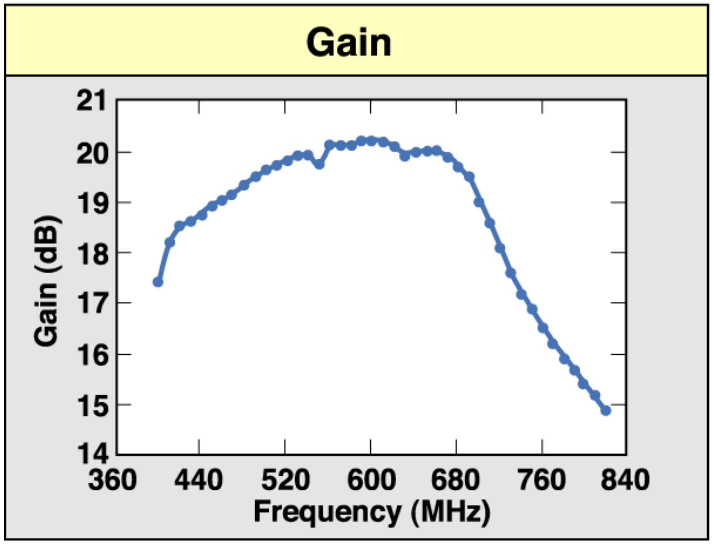
- But, the lowest (and attractive) decade of “standard” axion mass spans $300 < f_0 < 3000$ MHz

- …and the “DFSZ” models (weak, but plausible) are another factor of 7 lower in conversion power

Scanning the attractive axion-mass decade and models
In a reasonable amount of time requires a speed-up

A slight digression on Microwave amplifiers





HFET amplifiers (Heterojunction Field-Effect Transistor)

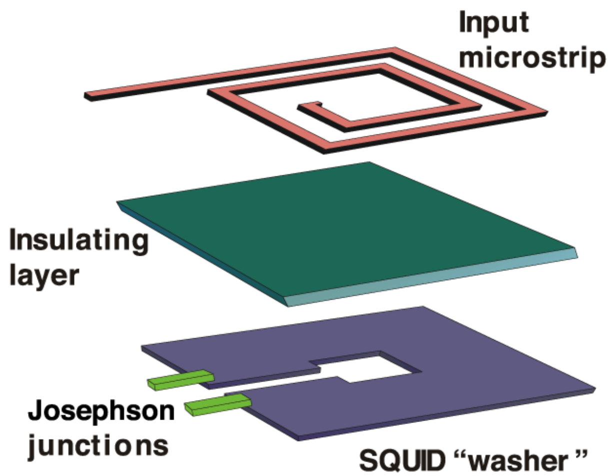
- **A.k.a. HEMT™ (High Electron Mobility Transistor)**
- **Workhorse of radio astronomy, military communications, etc.**

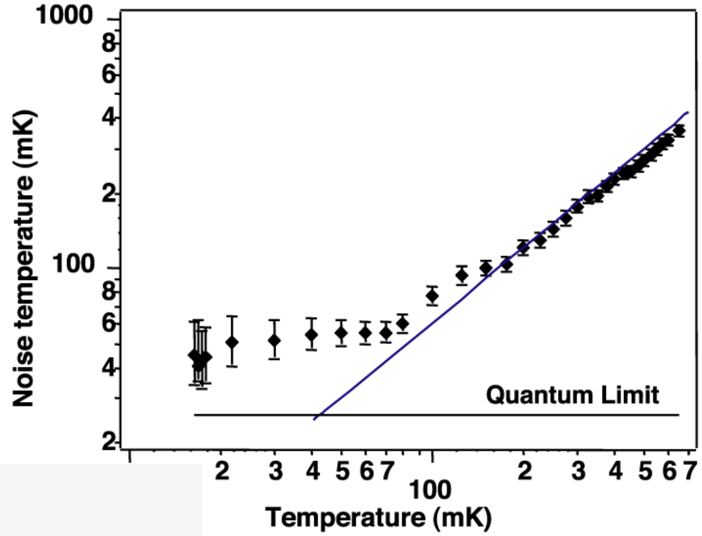
- **Best to date $T_N \gtrsim 1$ K**

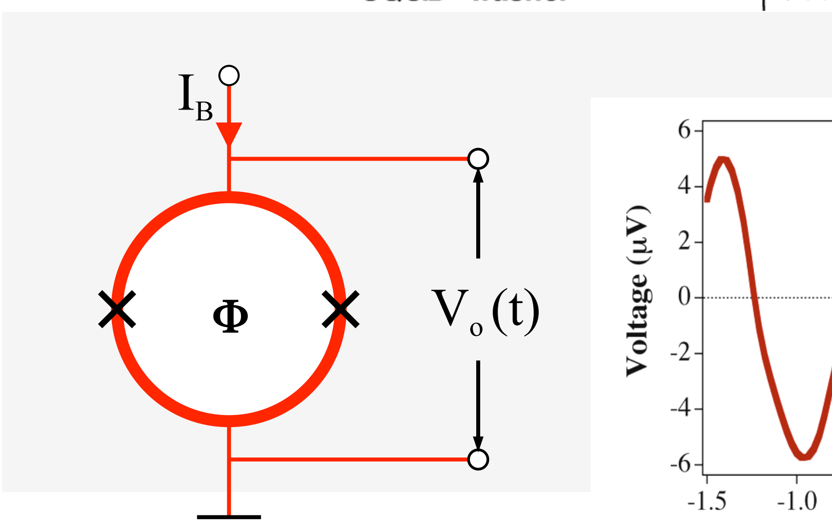
But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!

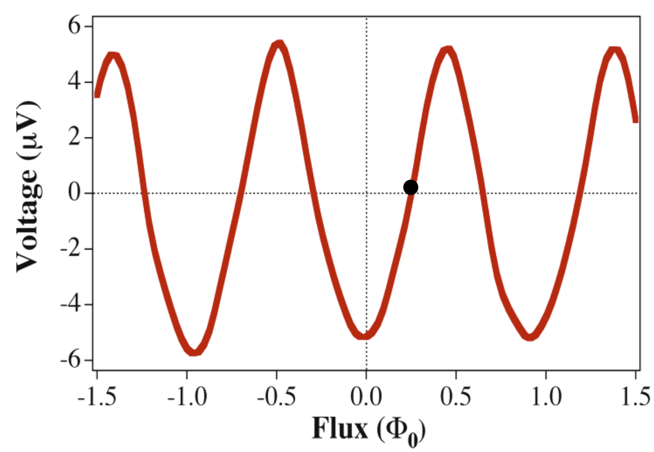
A quantum-limited amplifier would both give us definitive sensitivity, *and* dramatically speed up the search!

Phase I & II Upgrade path:
Quantum-limited SQUID-based amplification









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

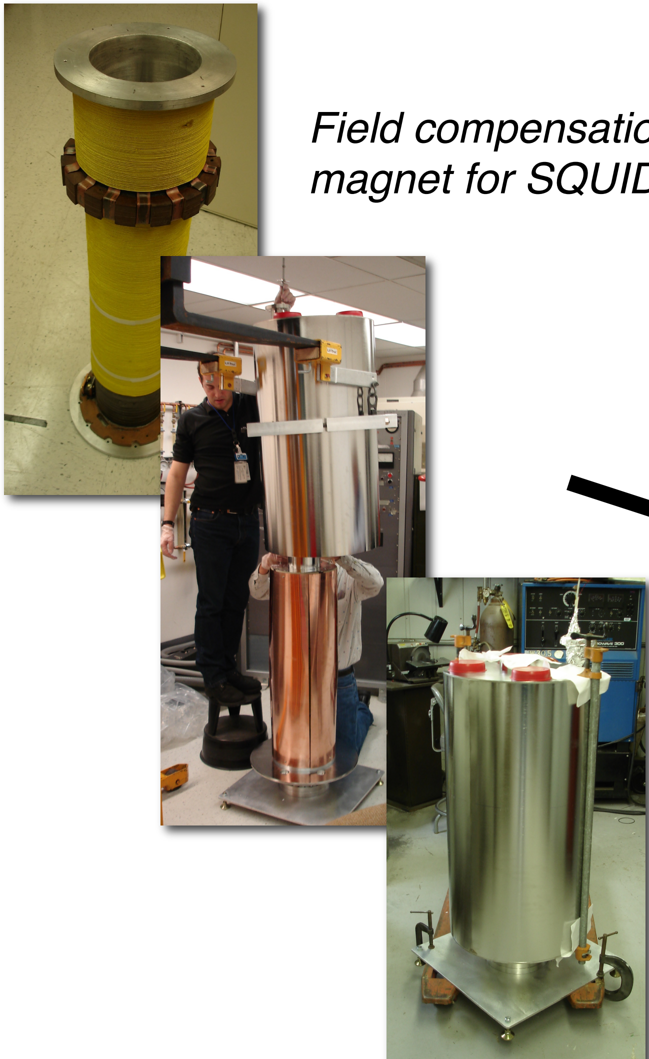
ADMX “Phase I” and “Phase II” upgrades

The ADMX SQUID upgrade proceeds in two phases:

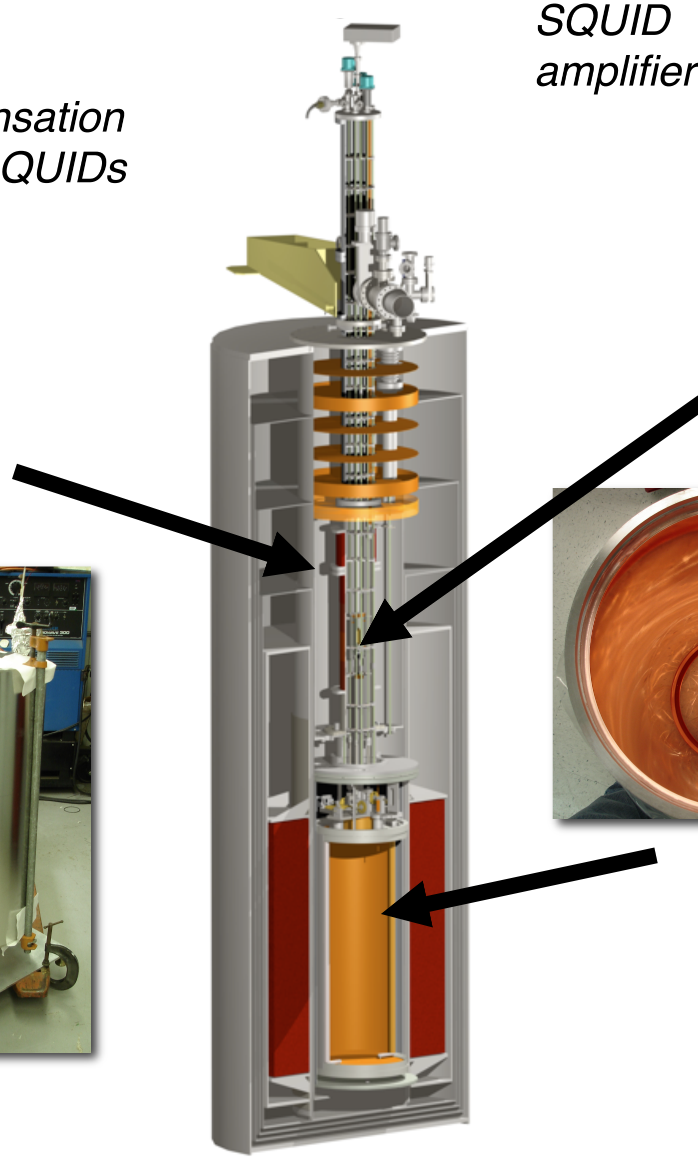
Phase I: Retrofit SQUID amplifiers first, but stay at 2K physical temperature (data-taking completed)

Phase II: Once SQUIDs work in situ, retrofit with the dilution refrigerator for 100 mK physical temperature (x20 lower temperature) (under construction)

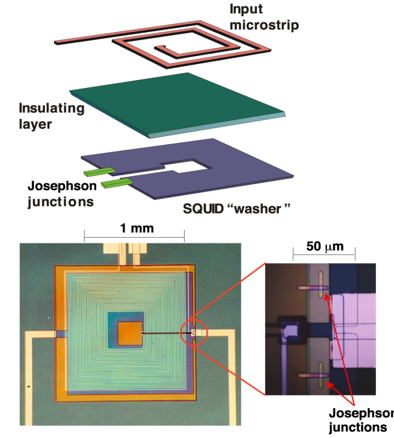
Phase I Upgrade construction finished late 2007 and then entered commissioning, operated into 2010



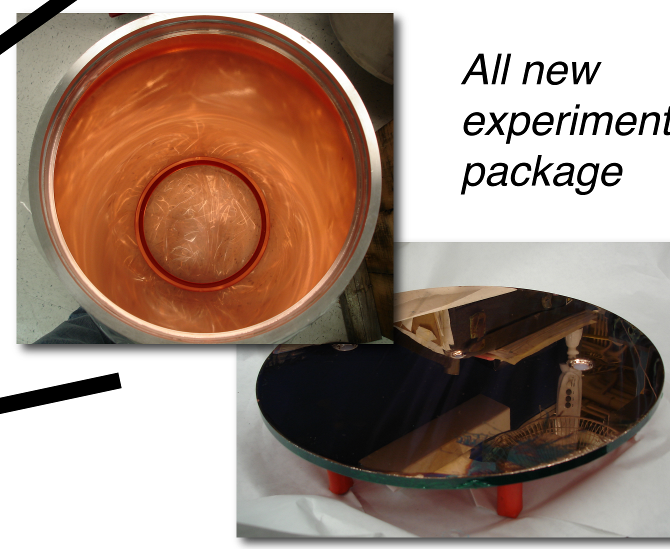
Field compensation magnet for SQUIDs



SQUID amplifier



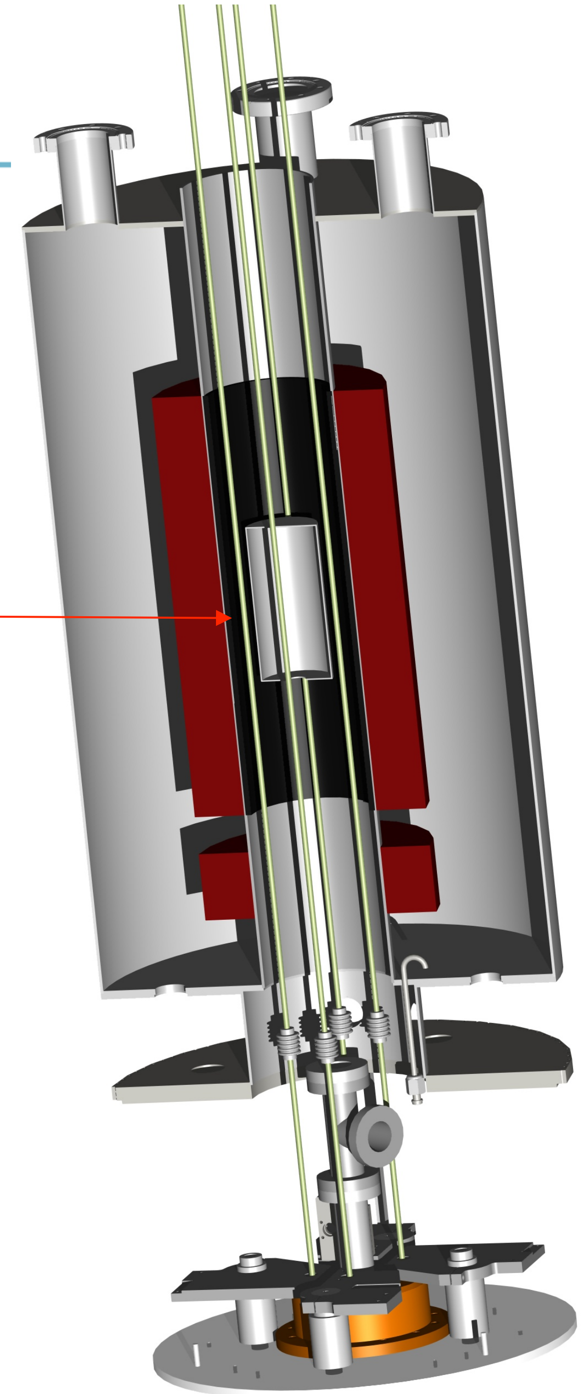
All new experiment package



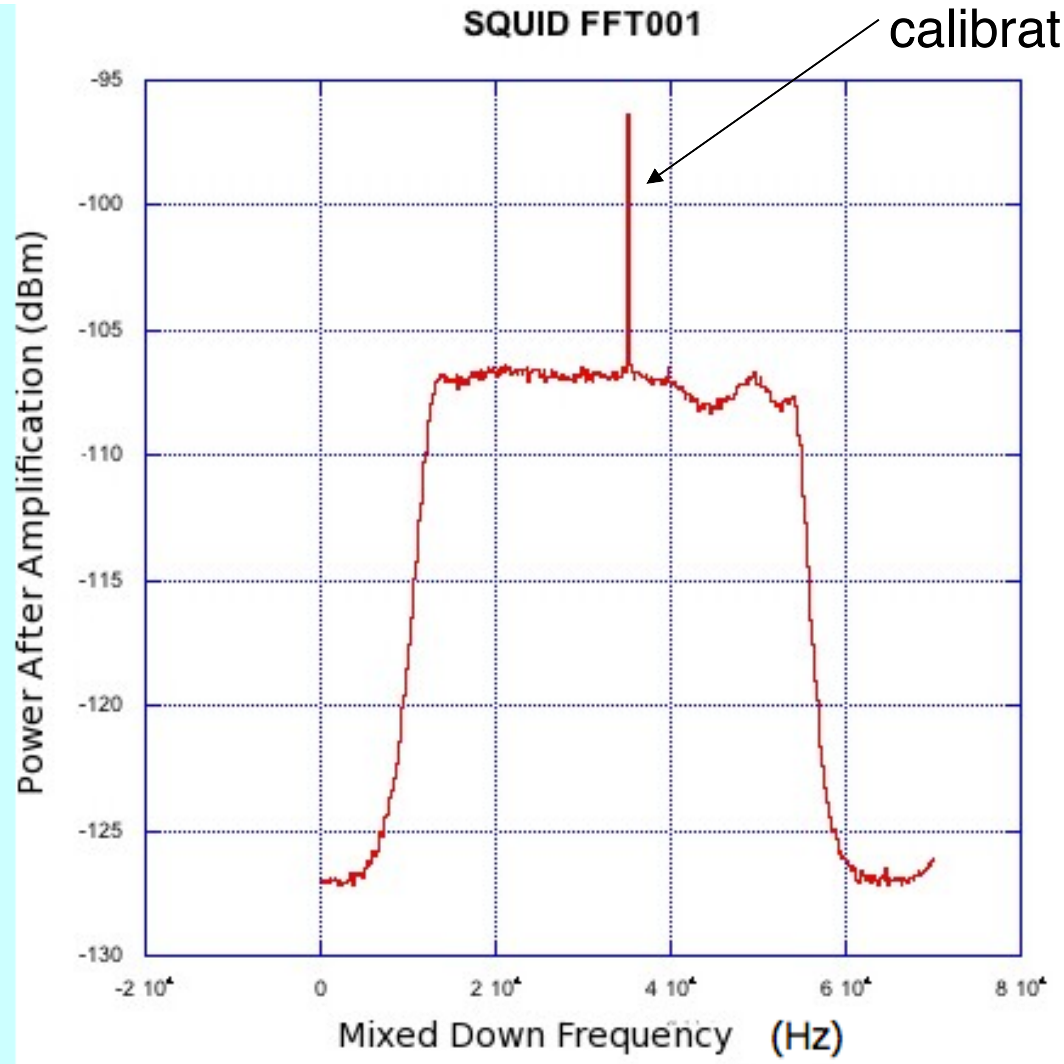
The SQUIDs sit well above the cavity

From outwards-in:

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



Phase I commissioning: SQUID amplifier



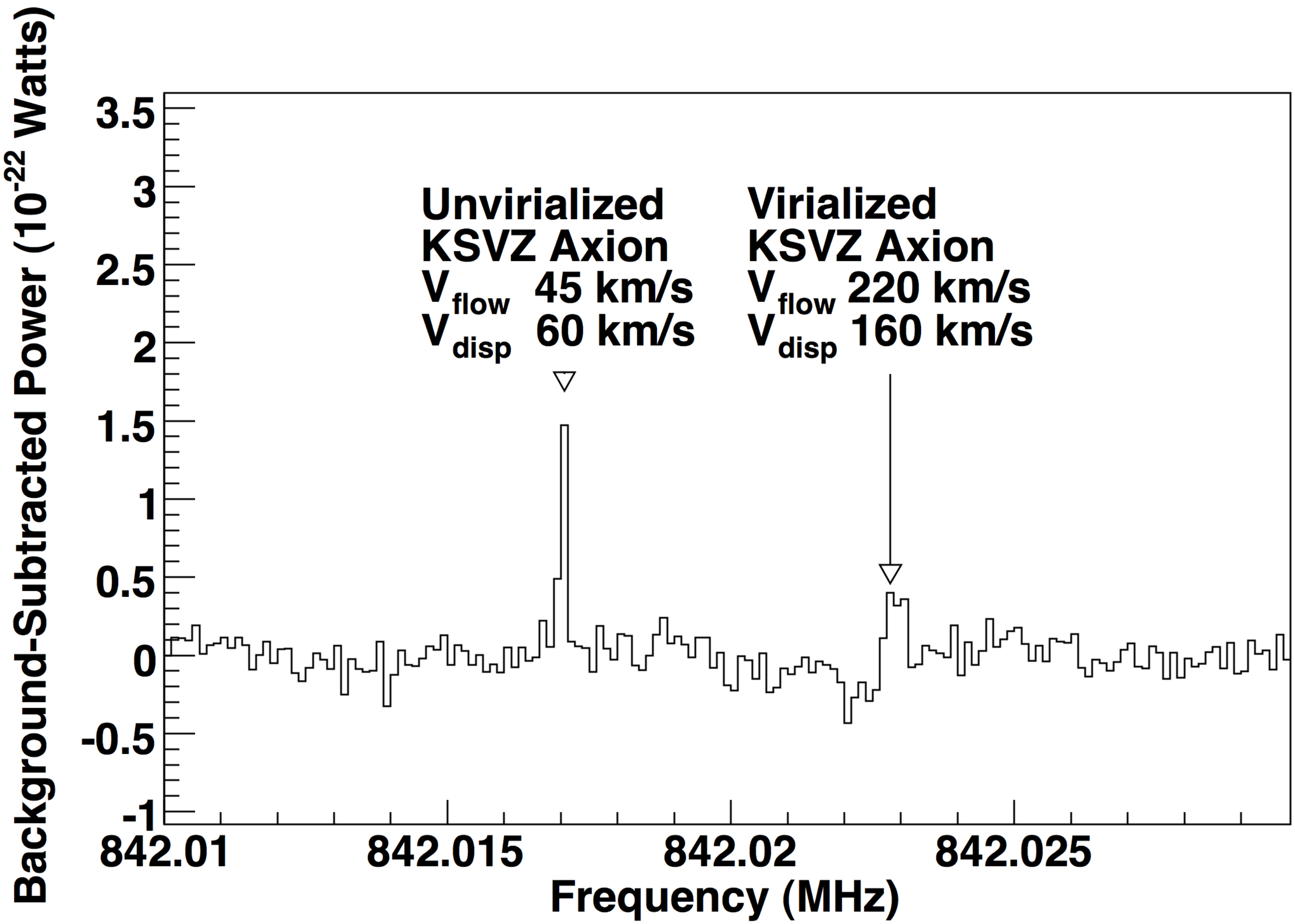
January 25, 2008:

Temperature ~ 4K

Bucking coil active

SQUID functioning as amplifier

What would a signal look like in ADMX?



Phase I operations: First-year science data

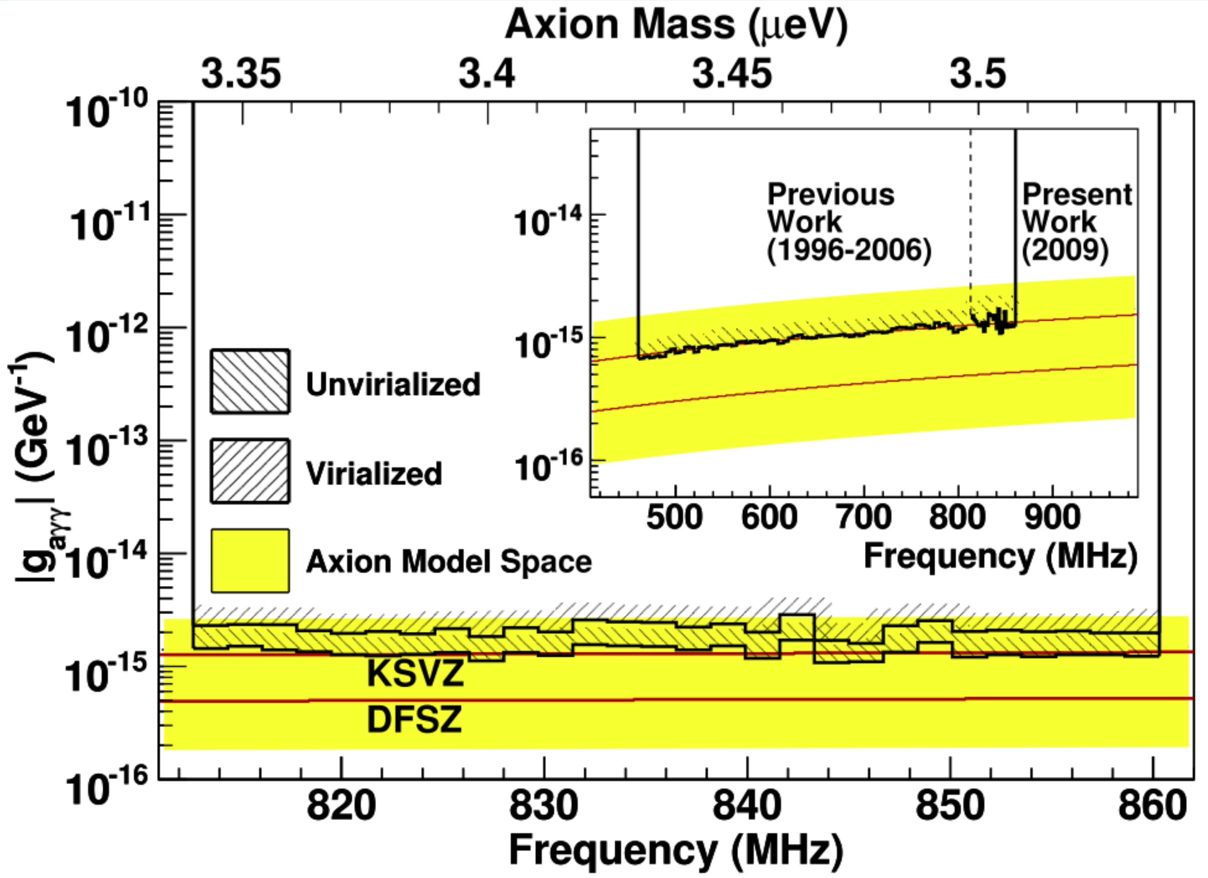
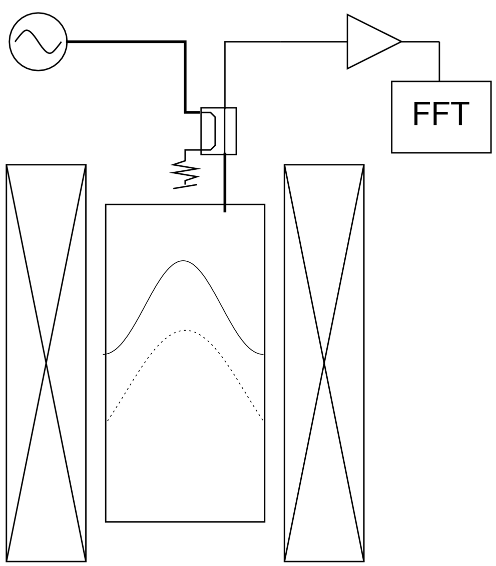


FIG. 5: Axion-photon coupling excluded at the 90% confidence level assuming a local dark matter density of 0.45 GeV/cm^3 for two dark matter distribution models. The shaded region corresponds to the range of the axion photon coupling models discussed in [23].

Phase I operations include exotics "Chameleons"& hidden-sector photons

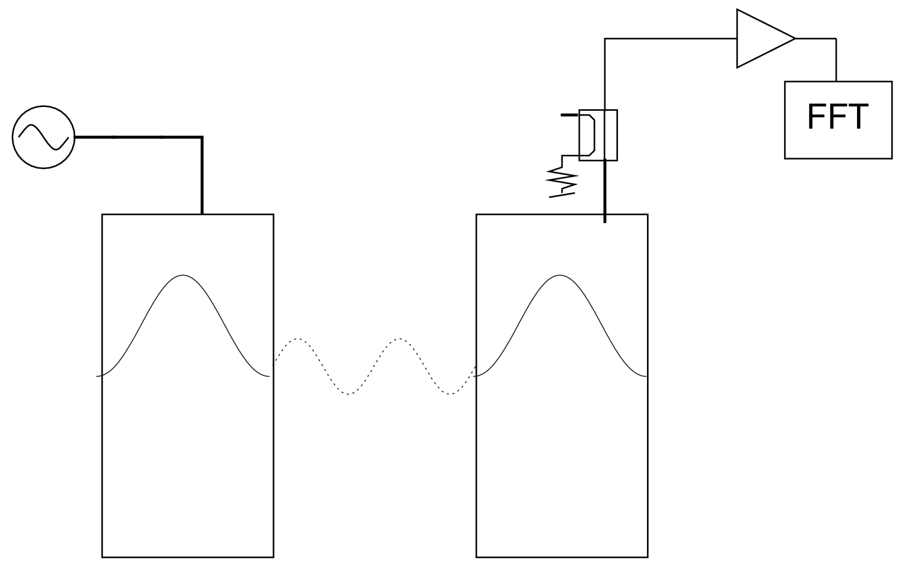
Chameleons

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

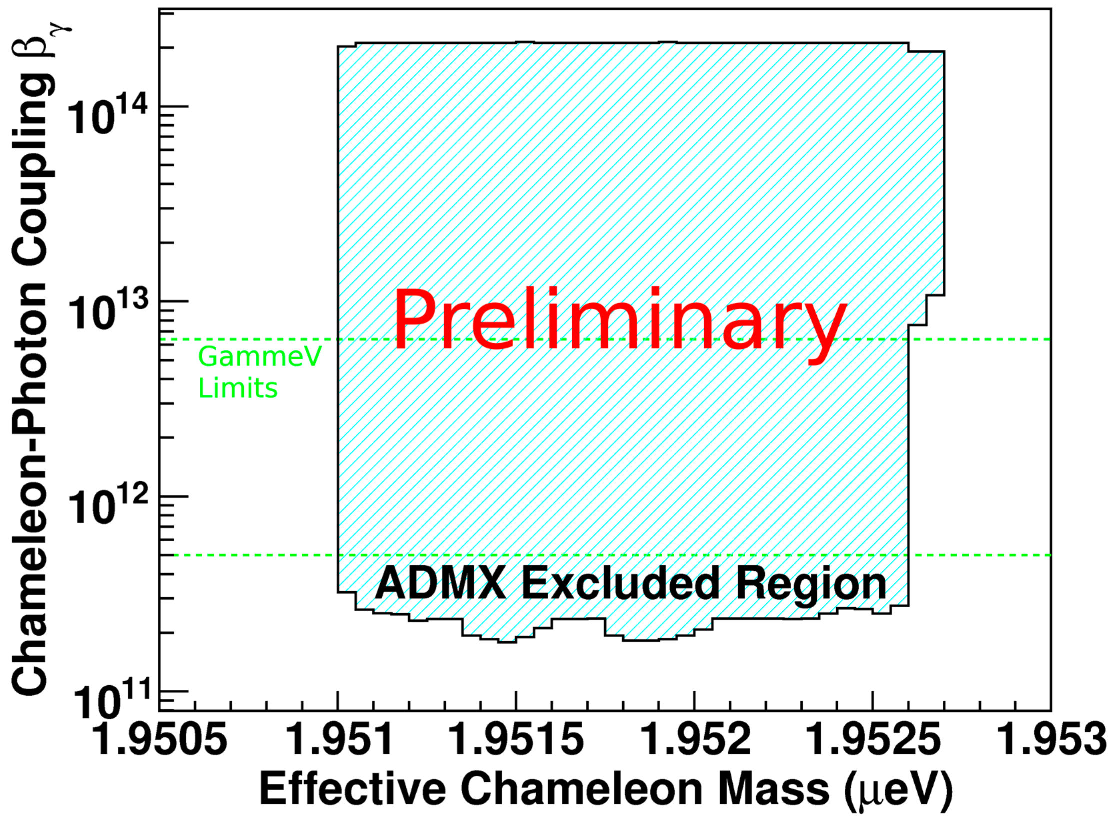


Hidden-sector photons

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

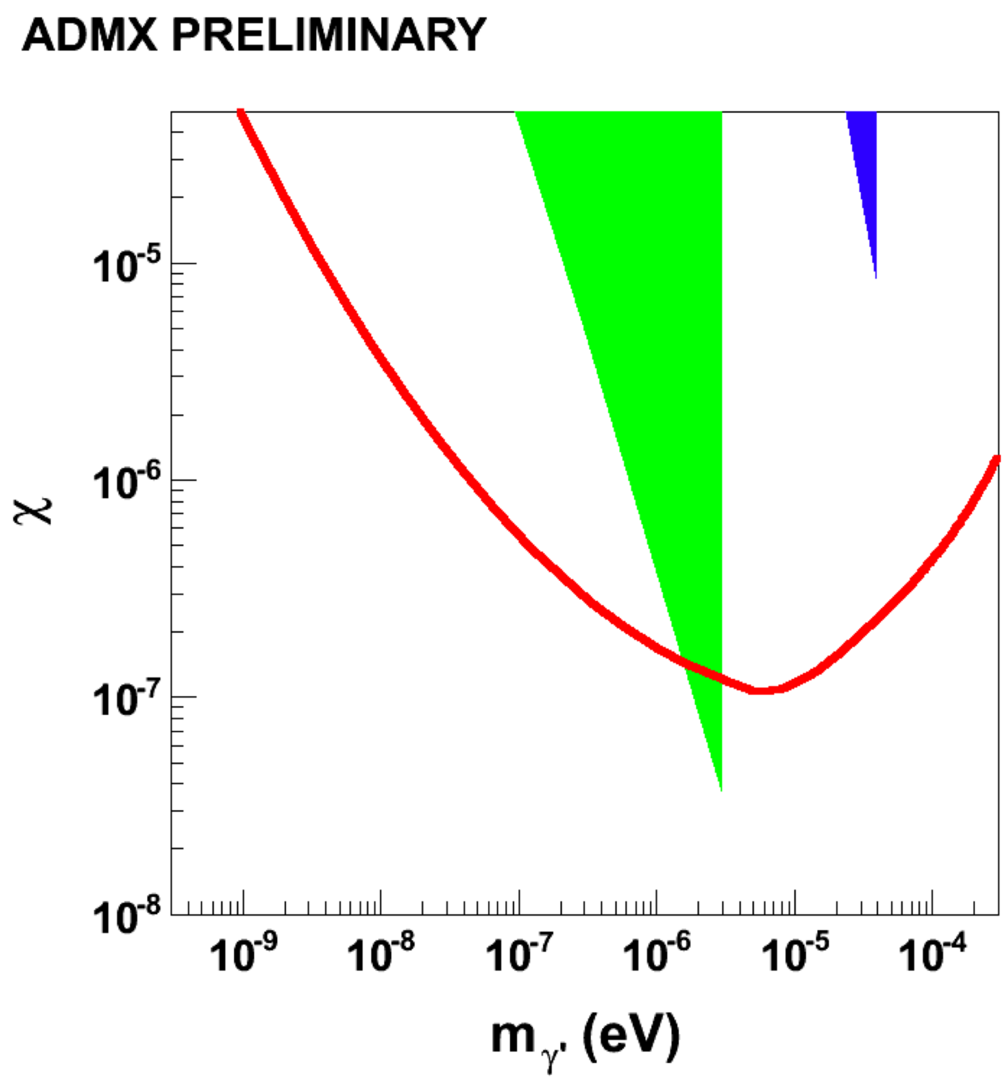


Chameleons

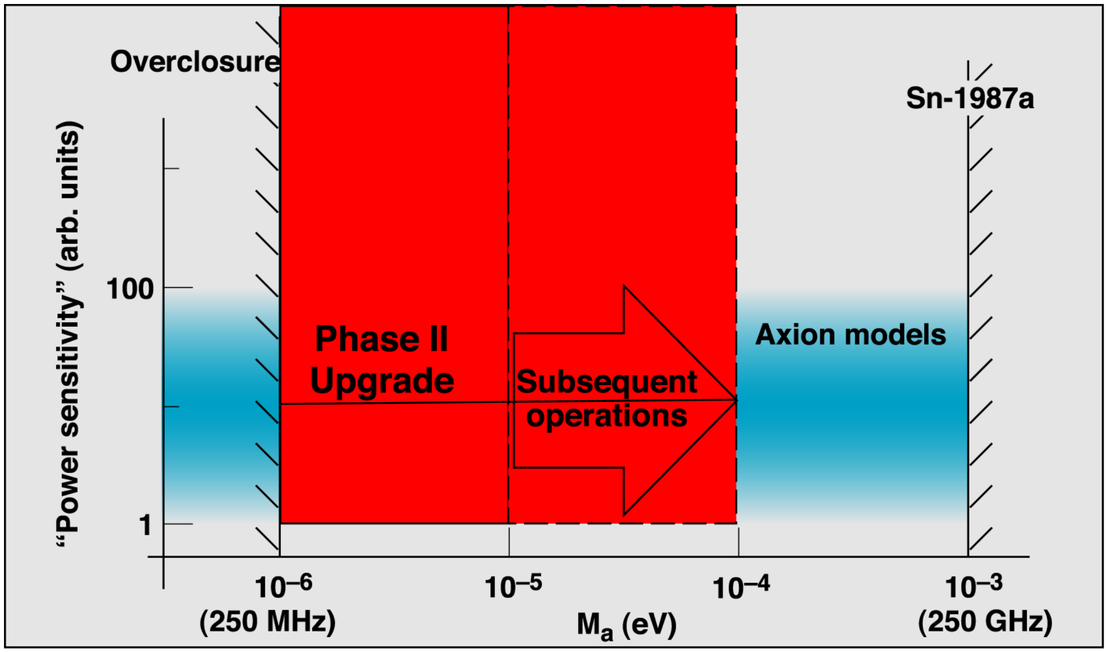


Chameleon-Photon Coupling β_γ
10^{14}
10^{13}
10^{12}
10^{11}
GammeV
Limits
Preliminary
ADMX Excluded Region
1.9505
1.951
1.9515
1.952
1.9525
1.953
Effective Chameleon Mass (μeV)

Hidden Sector Photons



Phase II ADMX: Construction starting now. Adds dilution-refrigerator cooling



Phase II will scan the lower-mass decade at or below DFSZ sensitivity at fractional dark-matter halo density, then continue upward in frequency
This is the "definitive" search for standard axions

New thread: Non-classical photon states

Single microwave-photon detection: a RF-photon phototube

For any detector of electromagnetic radiation, there's a number-of-quanta, phase-of-radiation uncertainty relation:

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

Evading the "Standard Quantum Limit":
If you don't measure the electromagnetic phase ϕ,
you can measure the number of quanta n to arbitrarily high precision.
(We do this all the time in the optical with photomultiplier tubes.)

This is a "phototube" for microwave photons.

RF Phototube: Rydberg-atom microwave-photon detection

Rydberg atoms are alkali metals in high states of excitation

Small energy difference between n and n+1 levels

$\Delta W_n \sim 1/n^3$

$\Delta W_{100} \approx 7$ GHz

Large E1 transition between n and n+1 levels

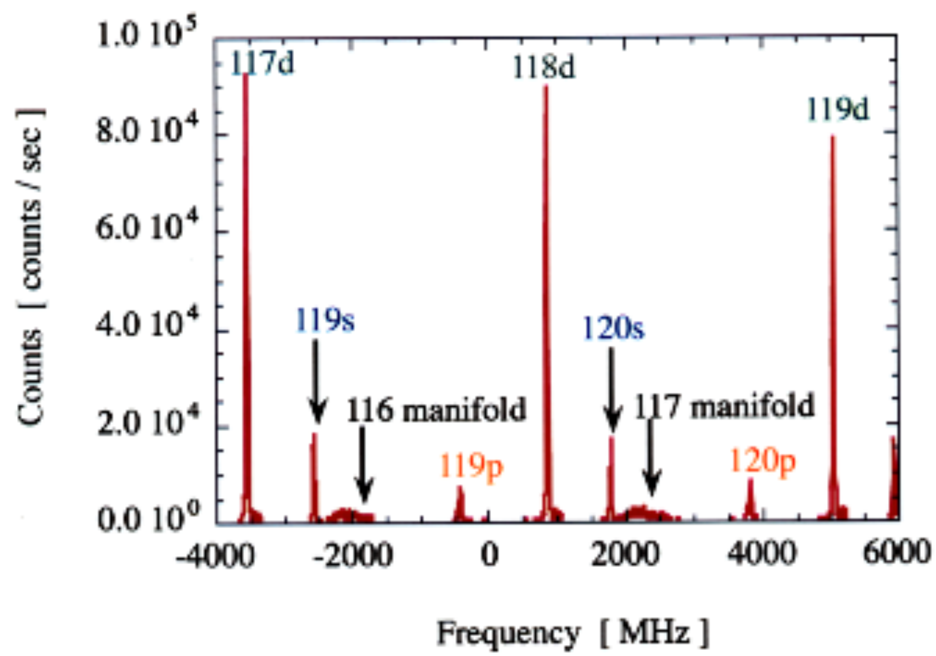
$\langle n+1 | er | n \rangle \sim n^2$, $\Gamma_n \sim n^4$

$\Gamma_{100} \approx 3\times10^4$/sec

Long life time

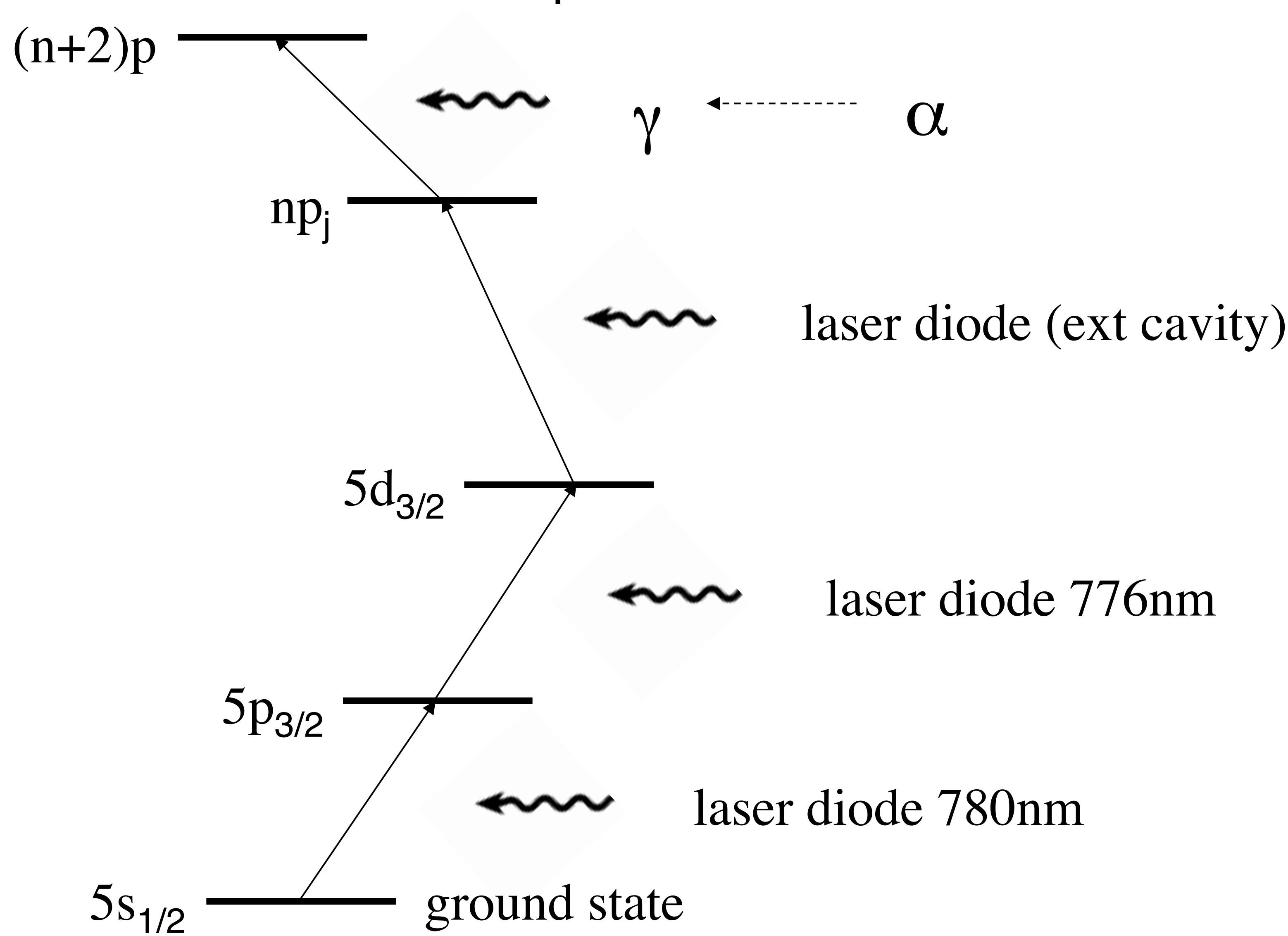
$\tau_n \sim n^3$

$\tau_{100} \approx 1$ msec

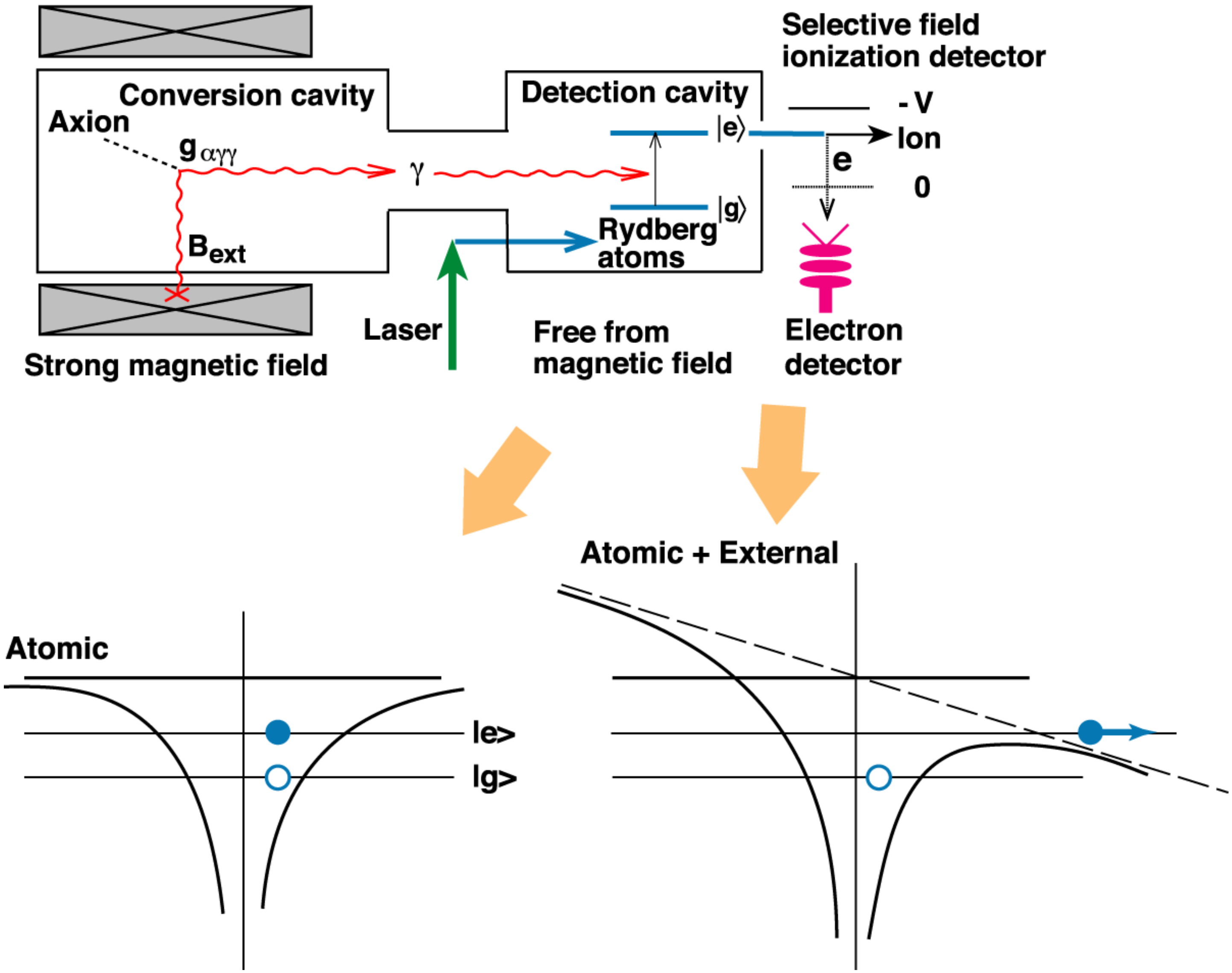


Preparing the Rydberg state

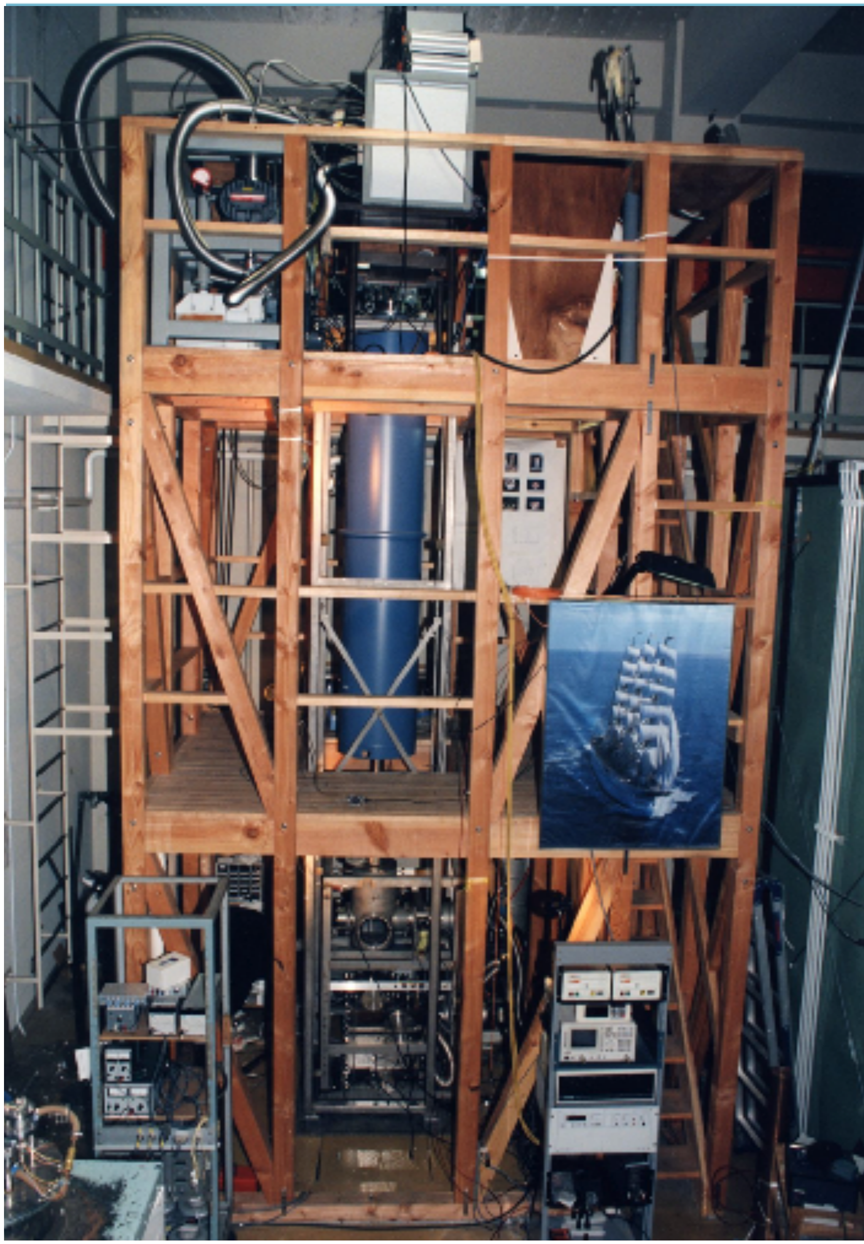
Laser diodes make this semi-practical

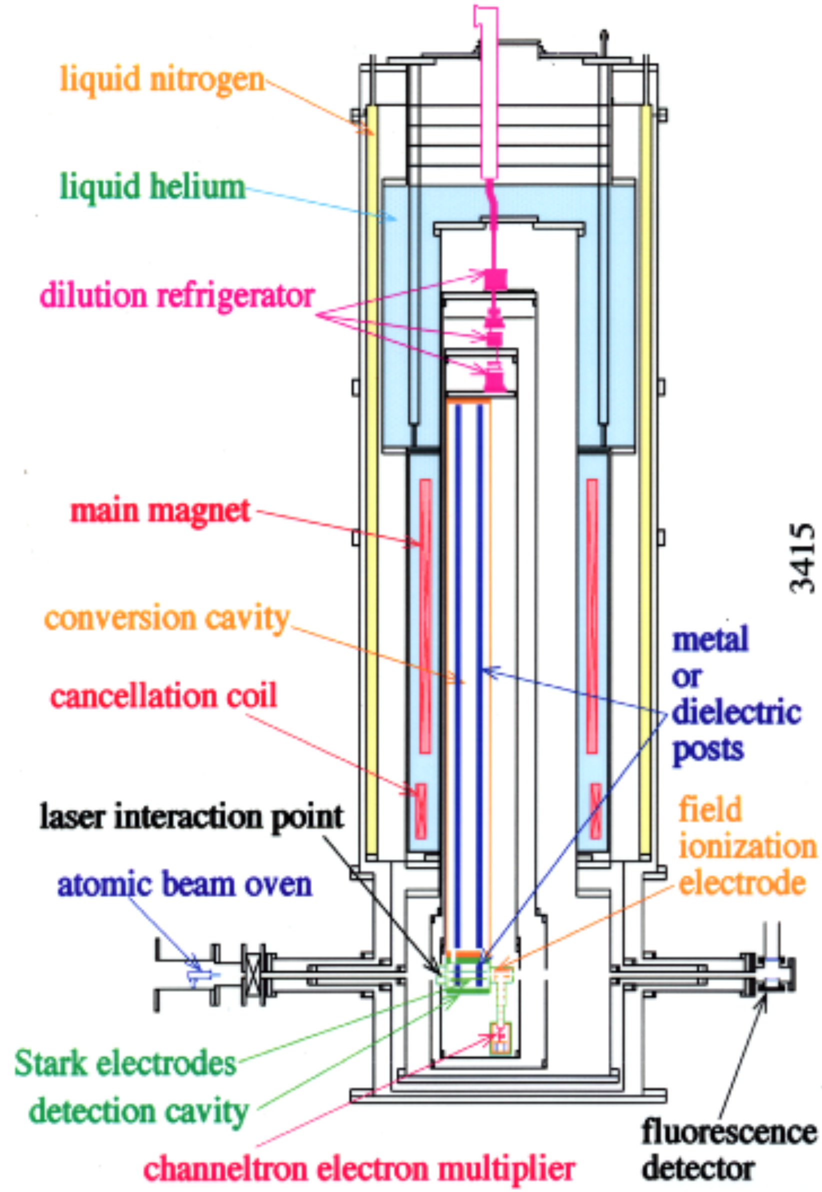


Principle of Rydberg-atom-based axion detector

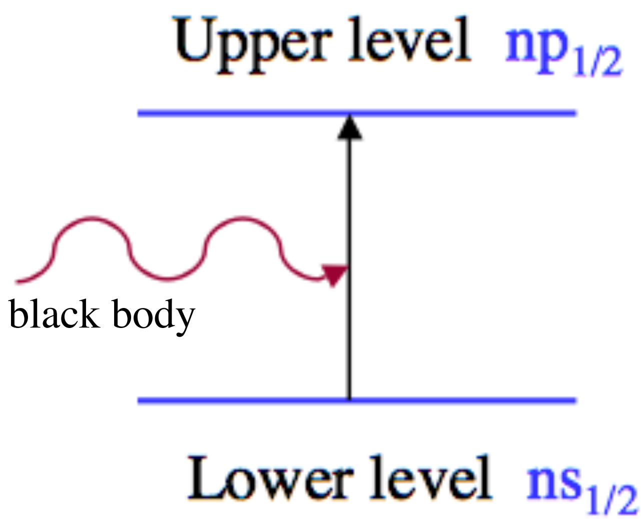


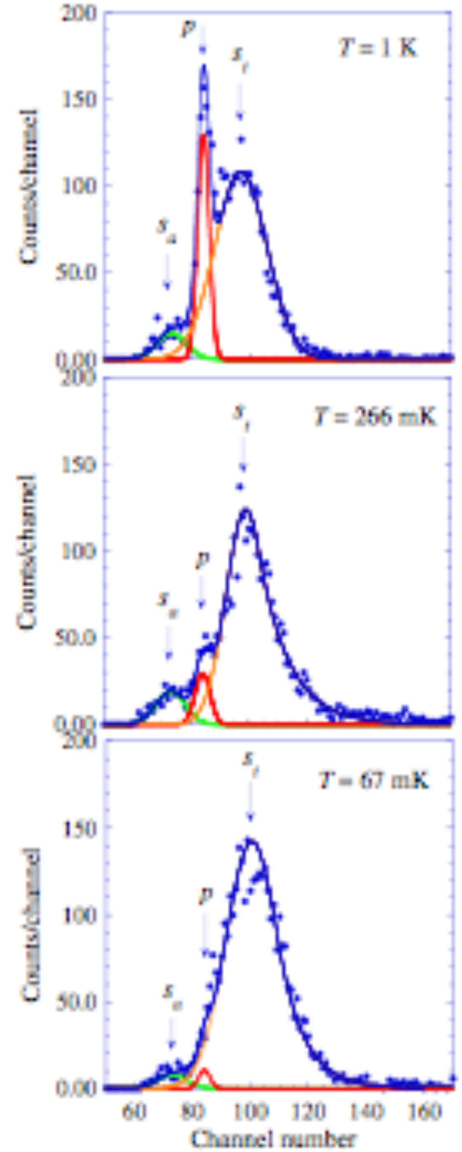
CARRACK: Cosmic Axion Research with Rydberg Atoms in resonant Cavities in Kyoto





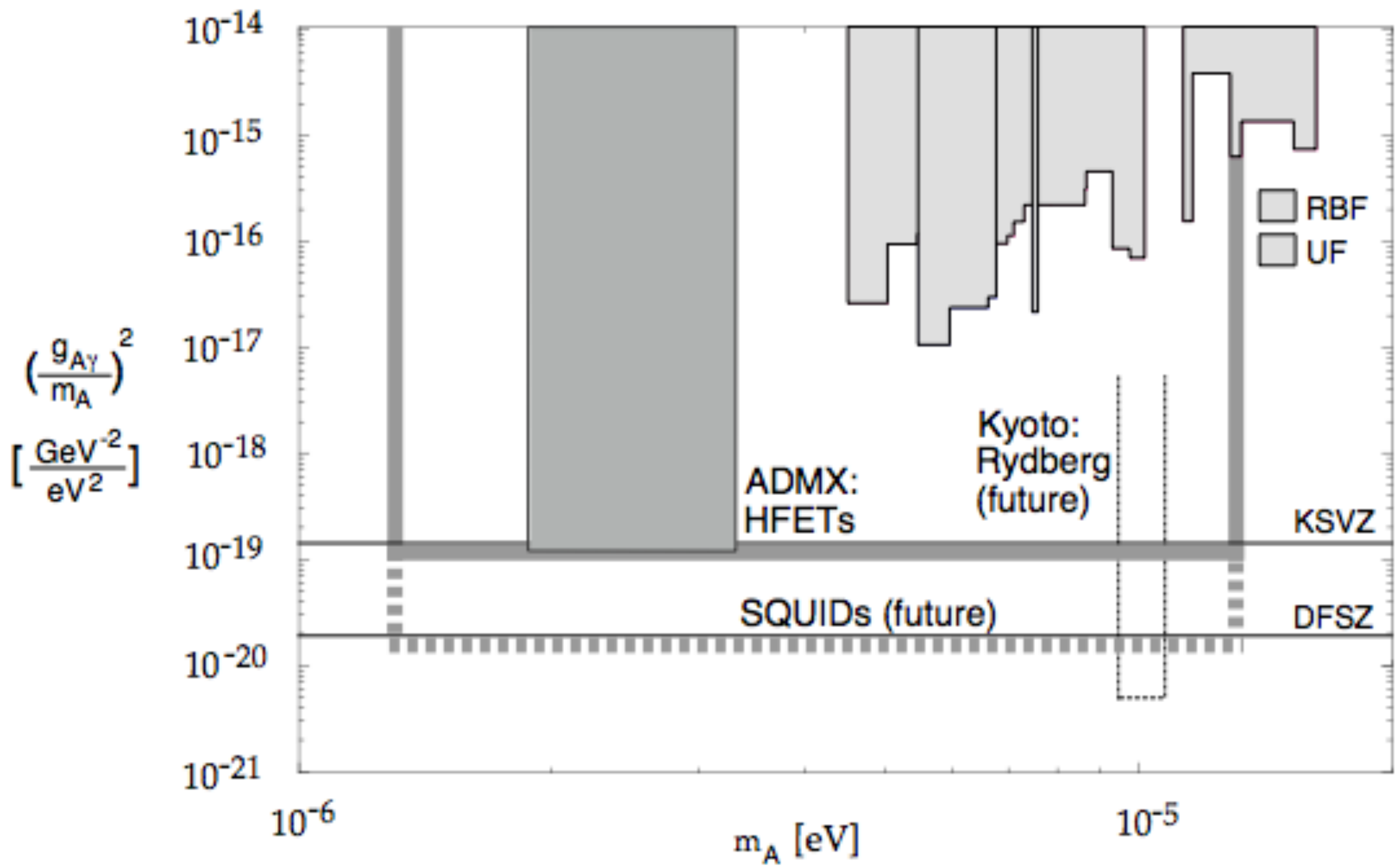
Ionization spectra: detection of single black-body photons



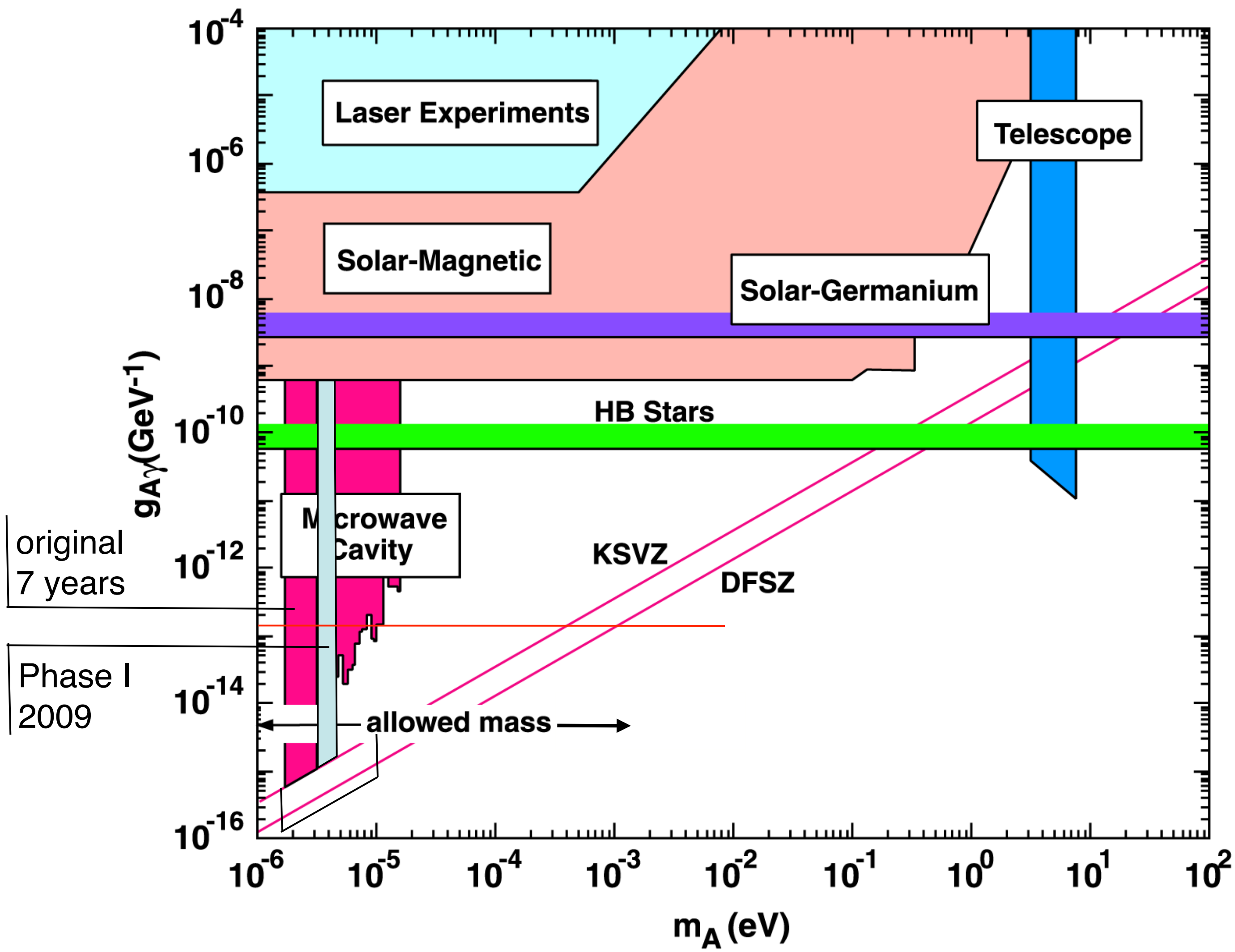


Tada et al., Phys.Lett.A

CARRACK sensitivity



Various axion limits: Why RF cavities?



Conclusions

The original ADMX achieved sensitivity to plausible PQ DM axions
using transistor HFET amplifiers.

The ADMX Phase I SQUID Upgrade :
Science: 1st year “medium-resolution” results published, “high-resolution” analysis in progress; exotics (Chameleons & hidden-sector photons).

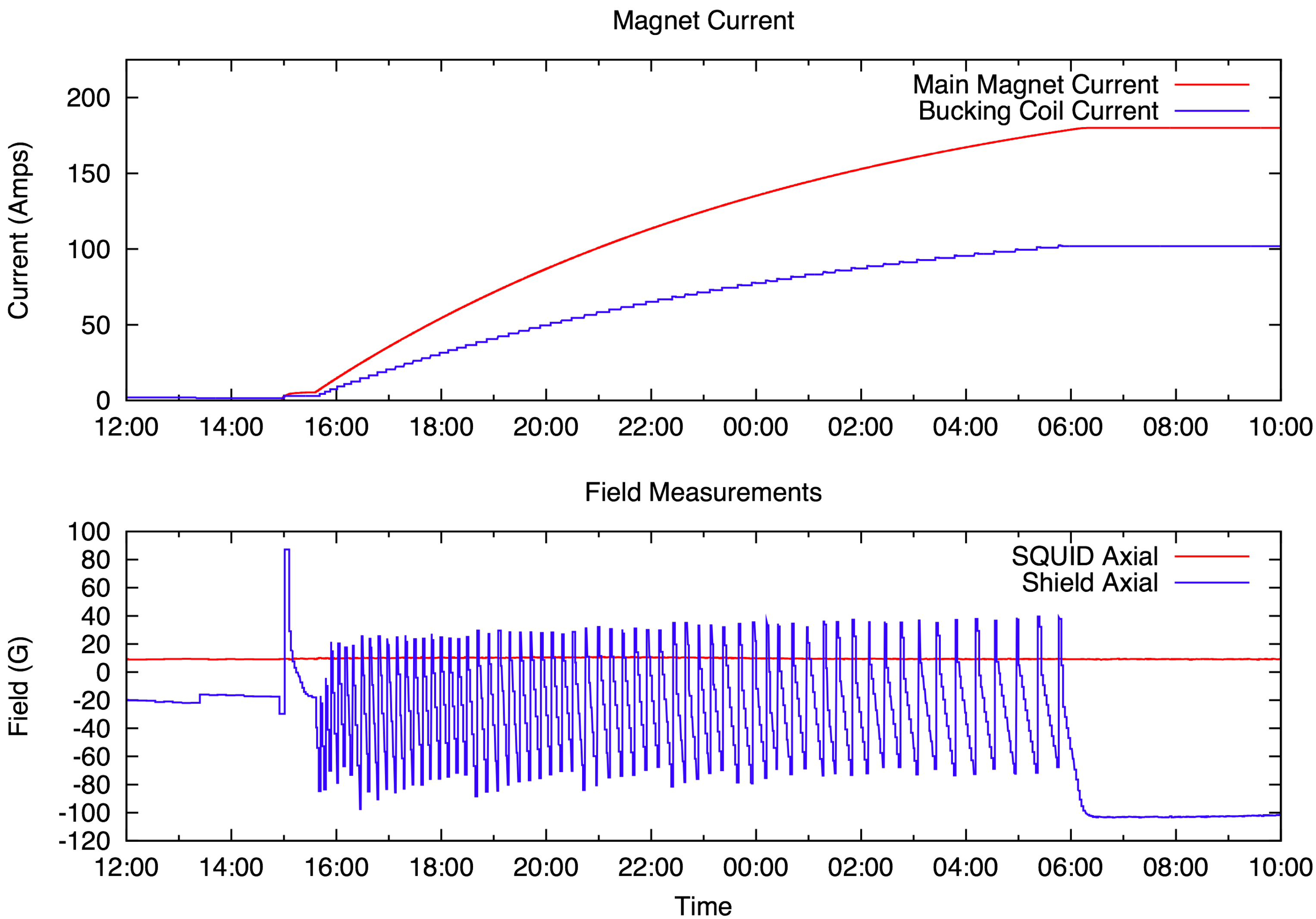
ADMX Phase II SQUID & Dilution Refrigerator Upgrade
Construction takes 3 years with commissioning into year 4.
Simultaneous higher-frequency R&D on amplifiers & resonant structures

This final ADMX phase or CARRACK in operations will be sensitive to even the more pessimistically-coupled axions at fractional halo density

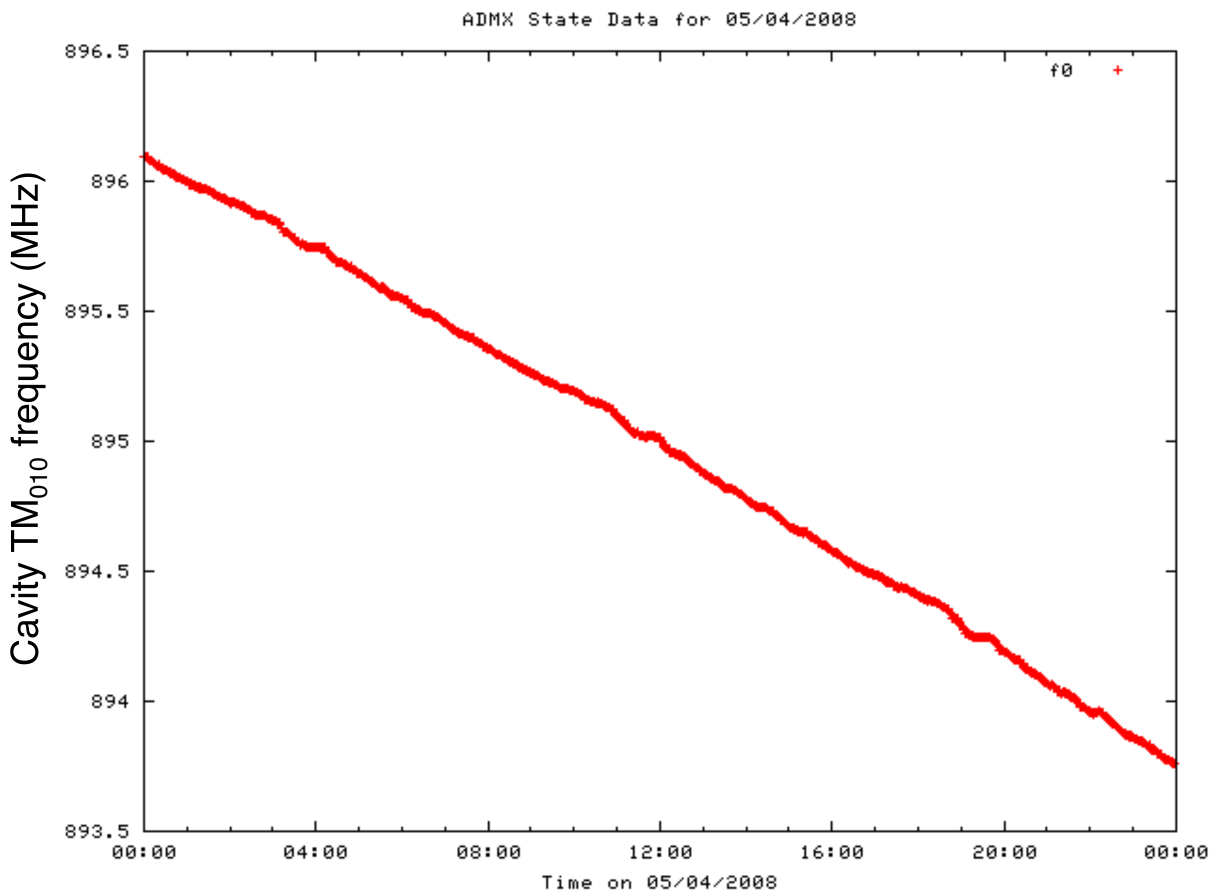
Quite starkly: These experiments have the sensitivity and mass reach to either detect or rule out PQ DM axions at high confidence.

Back-up slides

Phase I operations:
Automated bucking-coil field control

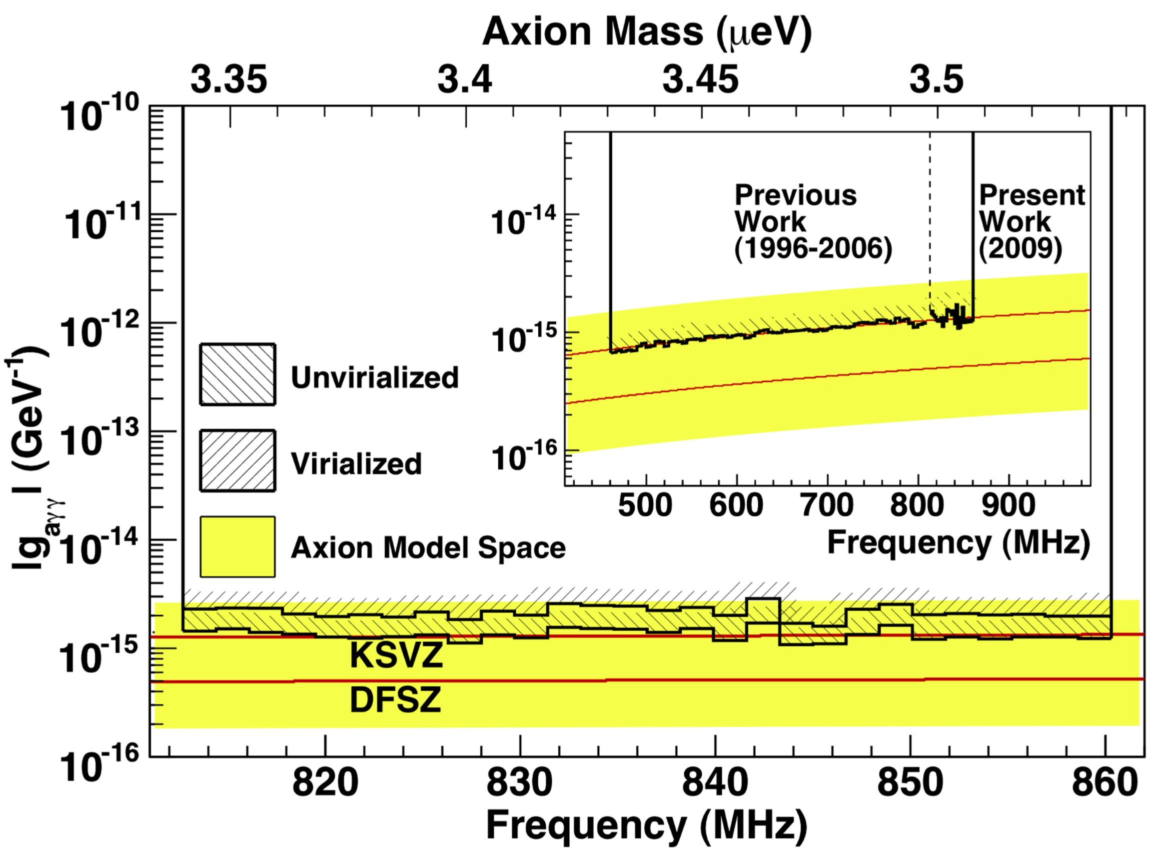


Phase I operations: Tuning during smooth operations



Smooth operations gives ~1 MHz/day net scan rate

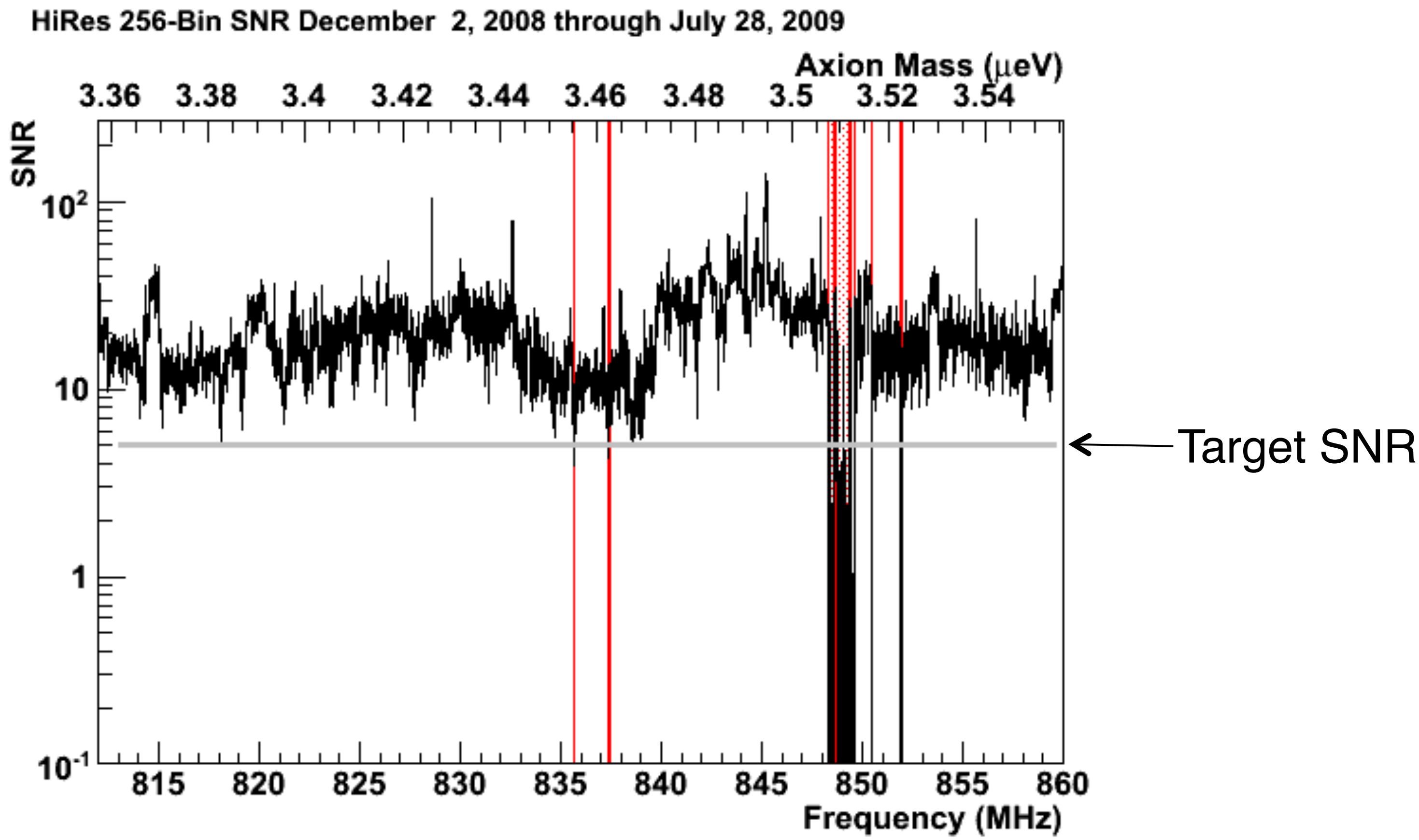
Medium-Resolution Phase I Limit



Brief timeline of ADMX Phase I upgrade (SQUIDS w/o dilution refrigerator)

- Original ADMX scanned 460 – 812 MHz (1.86 – 3.26 μeV) @ KSVZ
- Down-time for Phase I Upgrade (SQUIDS) (2004-2008)
- First cool-down of Phase I Upgrade (fall 2007)
- Sept 2008-Dec 2008 Operations
- Jan 2009 – Feb 2009 Access to fix thermal issues
- March 2009 – onwards Major Operations:
  Milestones achieved:
  (1) Heat load at design value
  (2) Magnetic field bucking system operational
  (3) SQUID receiver chain operational
  (4) Production data-taking
- PRL published on first-year operations
- Spring 2010: Phase I stops for Phase II construction

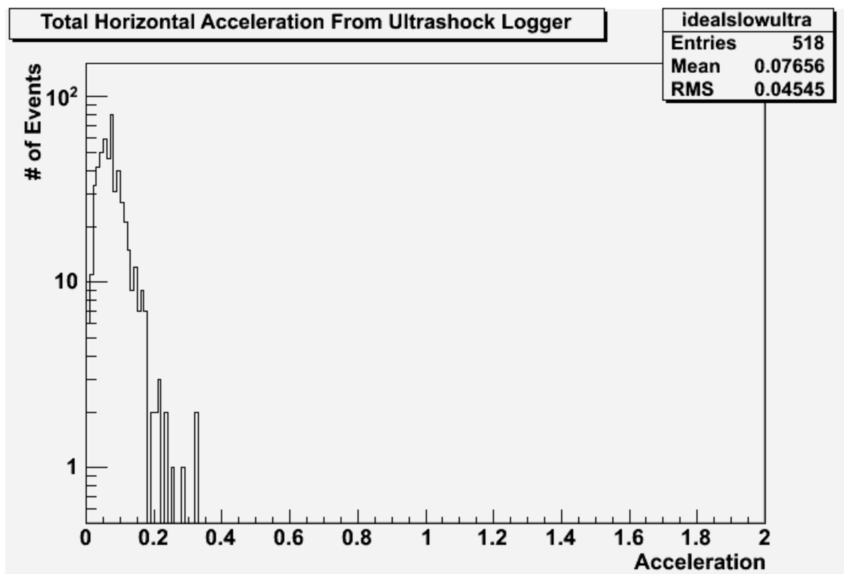
Phase I operations: Hi-Resolution Science data (c.f., poster Jeff Hoskins and talk Leanne Duffy)



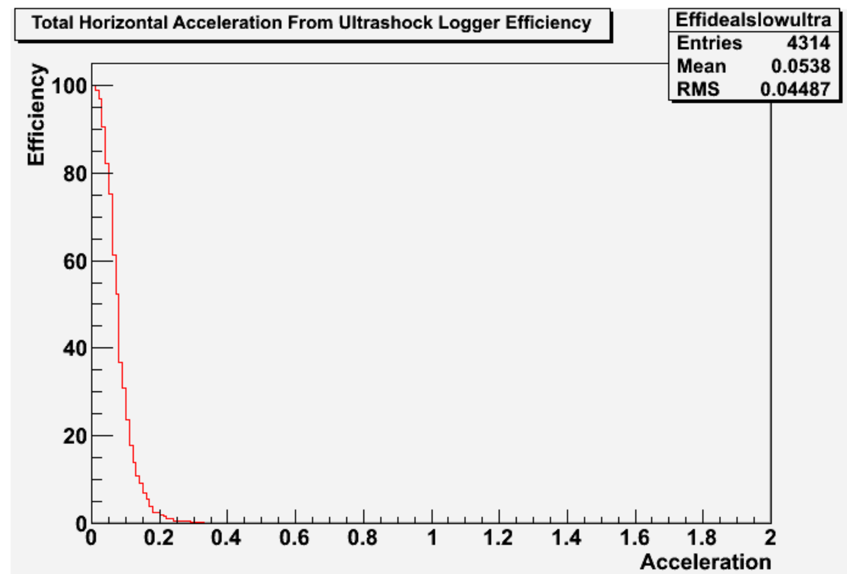
Analysis is in progress:
High resolution channel potentially gives greatly increased sensitivity

Phase II: Data from test move (c.f., poster Kyle Tracy & Jesse Heilman

20 minutes at 20-30 mph on a bad road



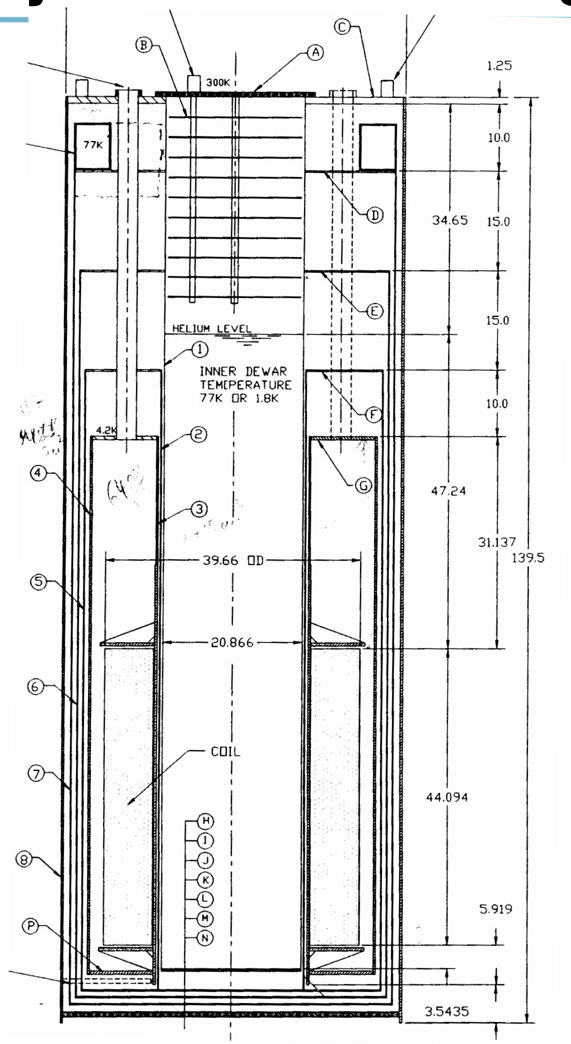
Data was binned by the maximum acceleration logged each second



Acceleration vs. percentage of counts above that acceleration

Scheduling cryostat move for spring 2010

Early Phase II challenge: Move cryostat to U of Washington



coil ~ 6 tons, cryostat & coil ~ 12 tons, height ~ 3.5 m

Magnet coil suspension is delicate and welded shut