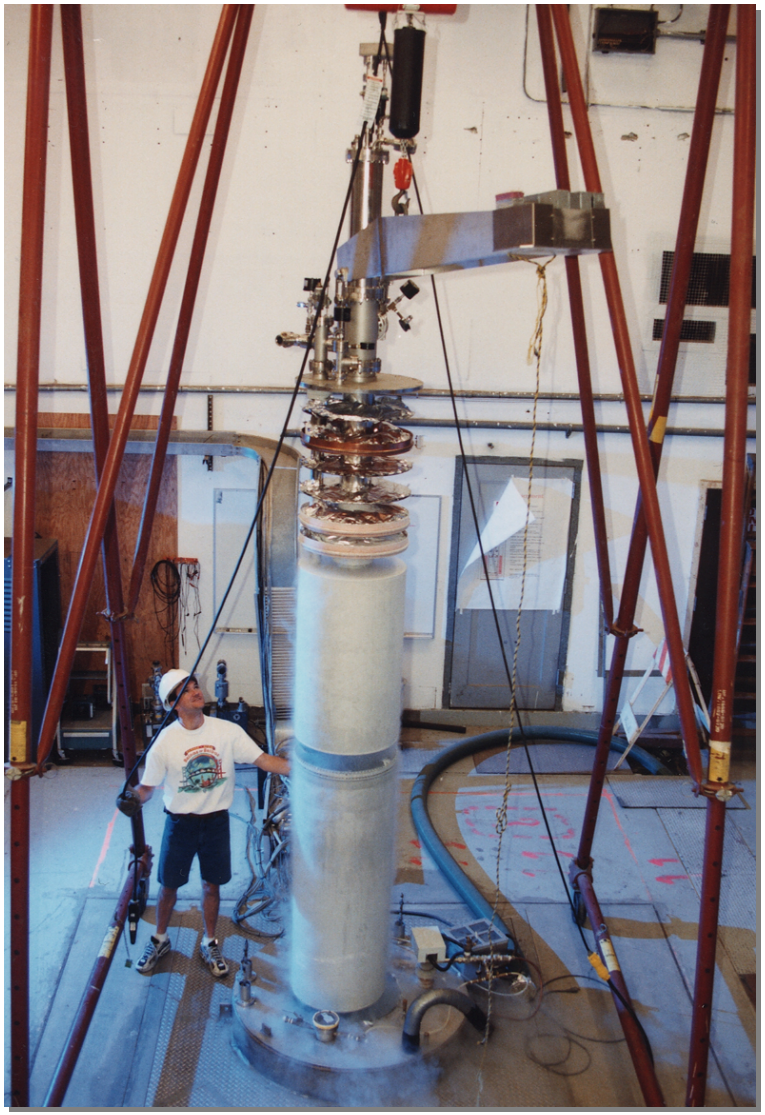


Finding the Axion

The Search for the Dark Matter of the Universe

Gianpaolo Carosi
Lawrence Livermore National Laboratory, USA

The Hunt for Dark Matter Symposium
May 11th, 2007

ADMX

Outline

- Evidence for Dark Matter
- Where the Axion came from and how it can solve DM problem
- The **A**xion **D**ark **M**atter e**X**periment (ADMX) at LLNL
- Status of the search
- Future

Evidence for Dark Matter

ADMX

- **Fritz Zwicky (1933):**
- **Galactic Dynamics (Coma Cluster)**

Evidence

•Spiral Galaxy Rotation Curves

•Clusters of Galaxies

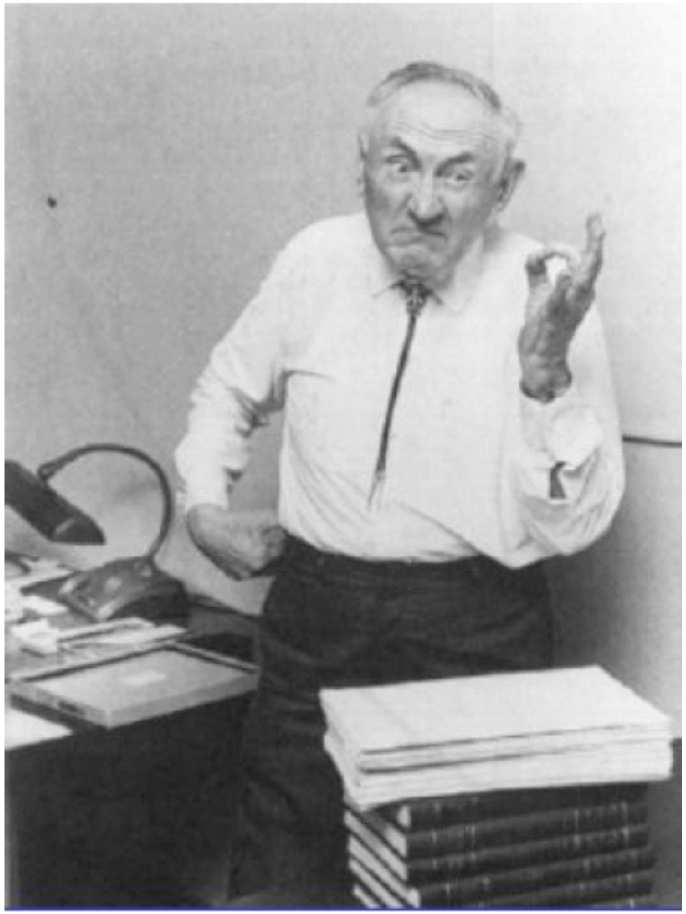
-X-ray gas temperatures

-Gravitational Lensing

-Motion of member galaxies (Virial Theorem)

•Large Scale Flows

•Structure formation and the CMB



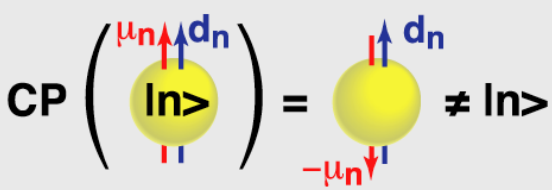
The Axion

Peccei & Quinn, PRL 38 (77) 1440; Weinberg, PRL 40 (78) 227; Wilczek PRL 40 (78) 279

ADMX

The Strong-CP Problem

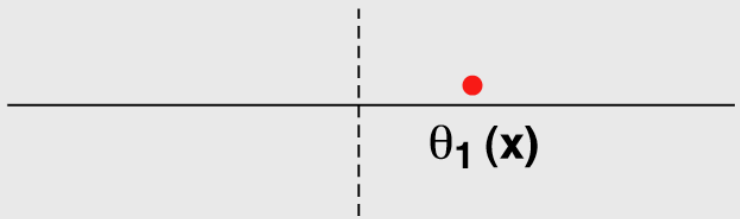
- $\mathcal{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



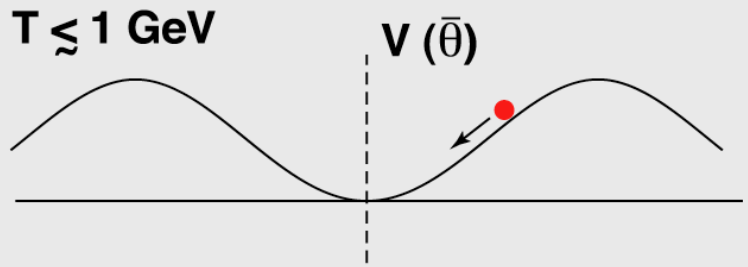
- Why?

Peccei-Quinn / Weinberg-Wilczek

- θ a dynamical variable
- T = f_a spontaneous symmetry breaking



- T $\lesssim$ 1 GeV



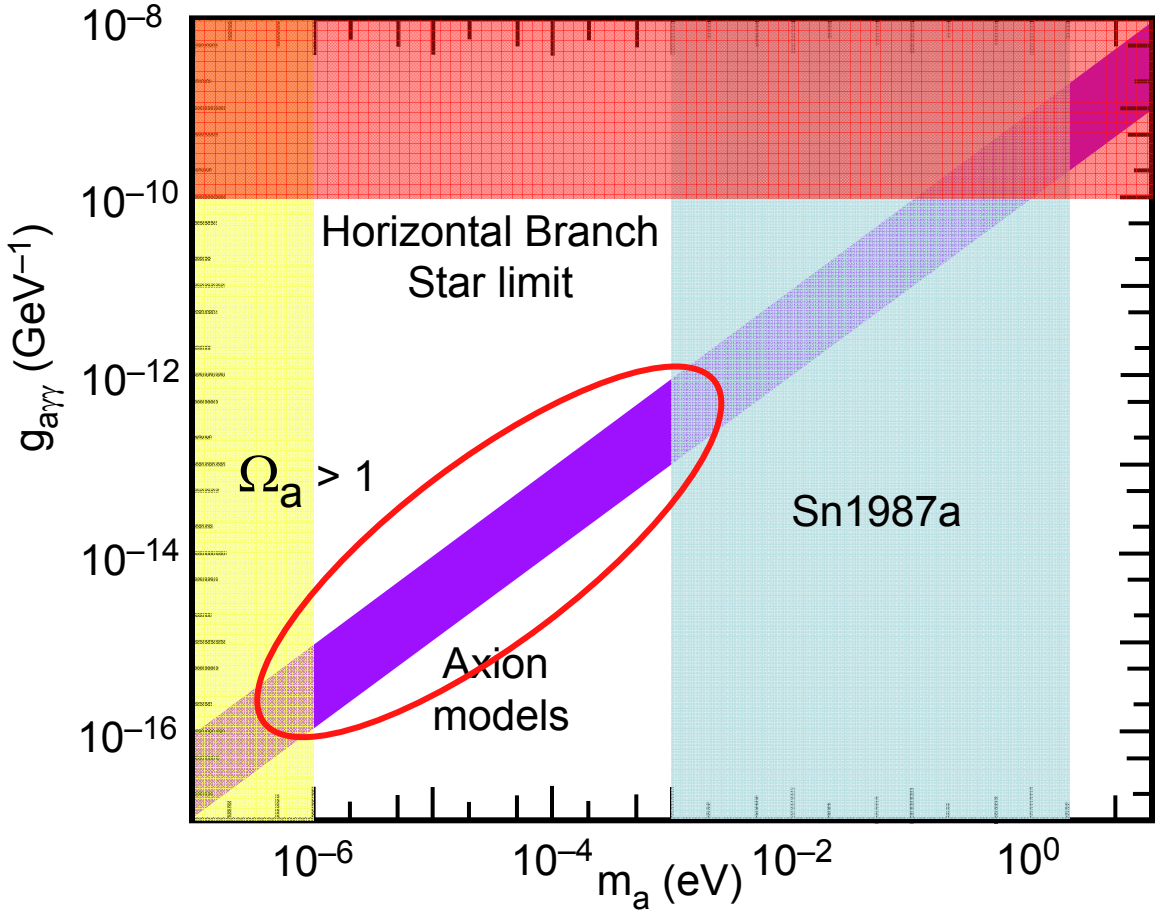
  - $\bar{\theta}$ dynamically $\rightarrow$ 0
  - Remnant oscillation = Axion

Axions have also recently been realized to be a generic feature of string theories

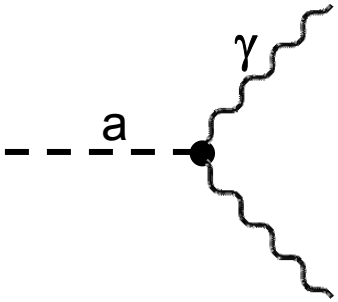
Srvck & Witten hep-th/0605206

Axion basics

ADMX



Light cousin of π^0: $J^\pi = 0^-$



m_a , $g_{aii} \propto f_a^{-1}$ $\therefore$ $g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6}$ $\rightarrow$ $m_a > 1\ \mu\text{eV}$

Sn1987a ν pulse precludes NN→NNa for $m_a \sim 10^{-(3-0)}$ eV

Red giant evolution precludes $g_{a\gamma\gamma} > 10^{-10}$ GeV^{-1}

Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

Who we are (ADMX, Phase I Operations)

ADMX

Initial operations: Took data from 1996 - 2004

University of California, Berkeley
John Clarke

University of Florida
Leanne Duffy, David Tanner, Pierre Sikivie

Lawrence Livermore National Laboratory
Stephen Asztalos *, Gianpaolo Carosi, Christian Hagmann, Darin Kinion, Karl van Bibber +

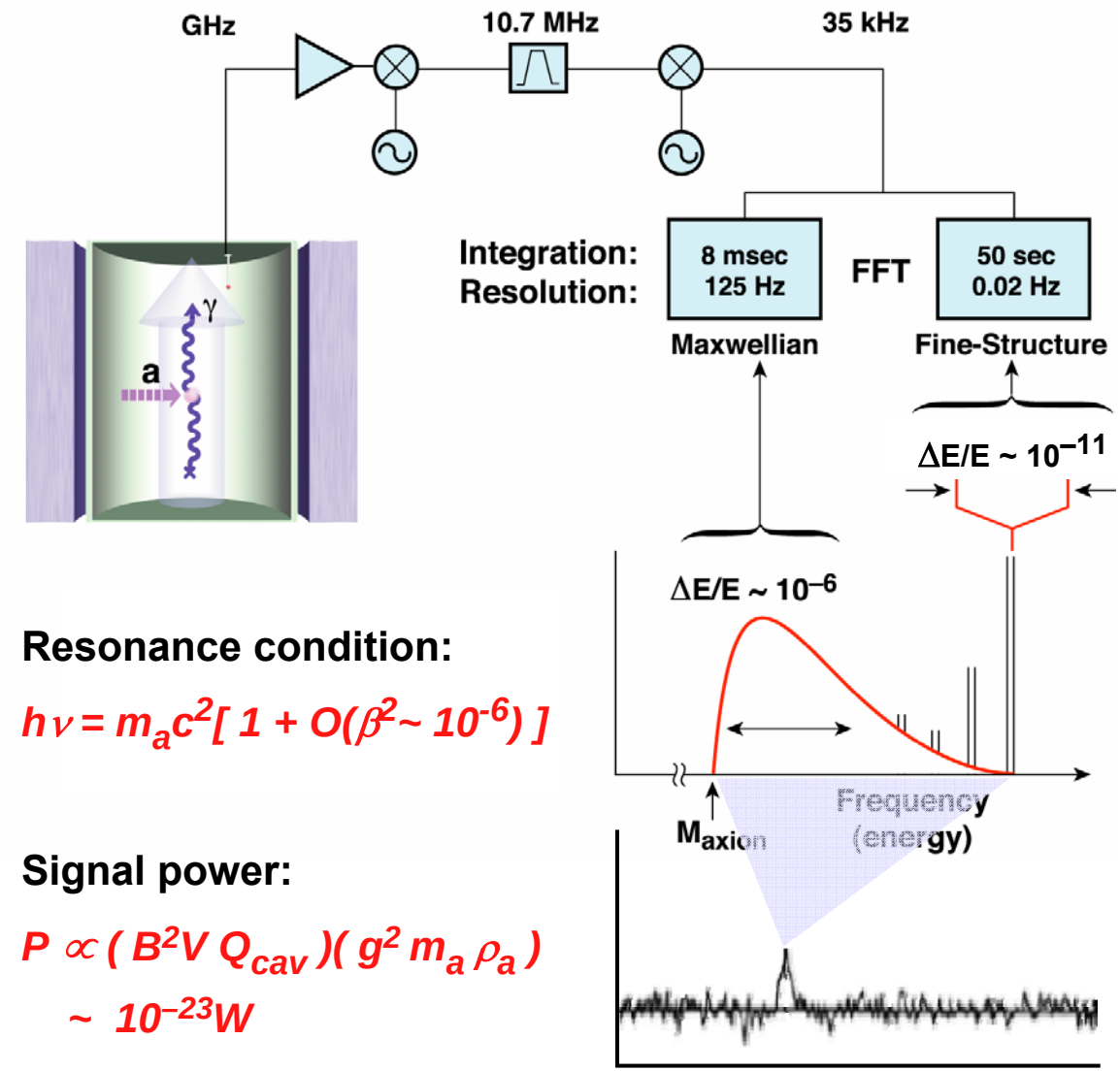
National Radio Astronomical Observatory
Richard Bradley

University of Washington
Leslie Rosenberg +

* ***Project Manager***
\+ ***Co-spokesperson***

Nature of axionic dark matter, and principle of the microwave cavity experiment *[Pierre Sikivie, PRL 51, 1415 (1983)]*

ADMX



Local Milky Way density:

$\rho_{halo} \sim 450\ MeV/cm^3$

Thus for $m_a \sim 10\ \mu eV$:

$\rho_{halo} \sim 10^{14}\ cm^{-3}$

Resonance condition:

$h\nu = m_a c^2 [\, 1 + O(\beta^2 \sim 10^{-6}) \,]$

Signal power:

$P \propto (\, B^2 V\, Q_{cav}\,)(\, g^2\, m_a\, \rho_a\,)$

$\sim 10^{-23} W$

$\beta_{virial} \sim 10^{-3}$:

$\lambda_{De\ Broglie} \sim 100\ m$

$\Delta\beta_{flow} \sim 10^{-11}$:

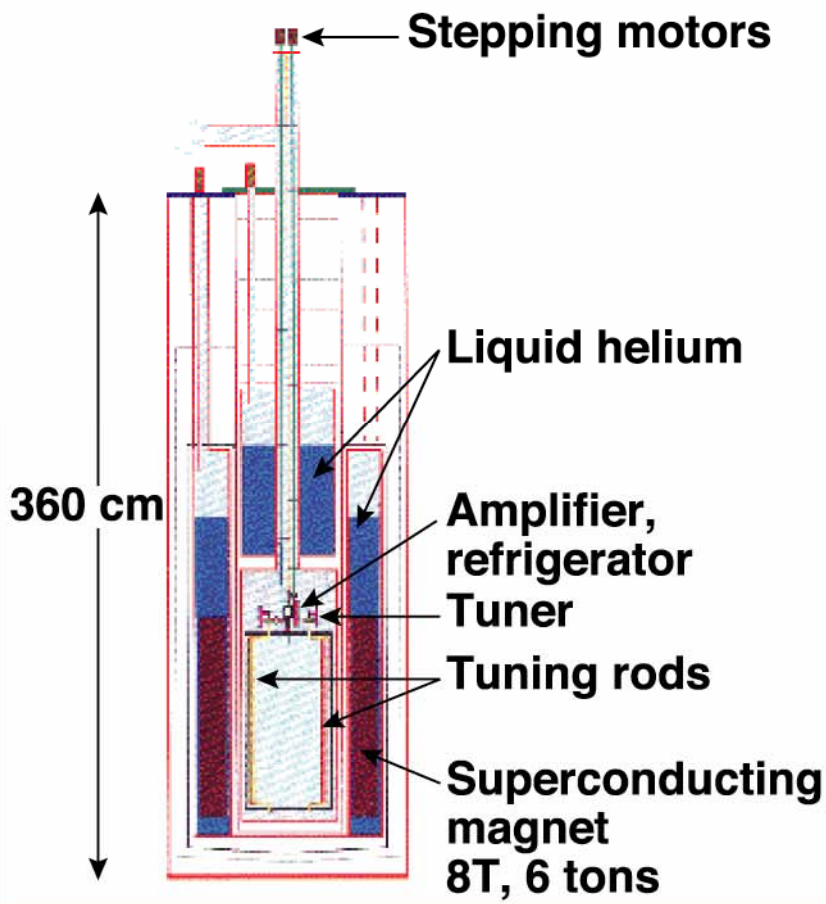
$\lambda_{Coherence} \sim 1000\ km$

Axion hardware

ADMX LLNL-Florida-Berkeley-NRAO

ADMX

Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

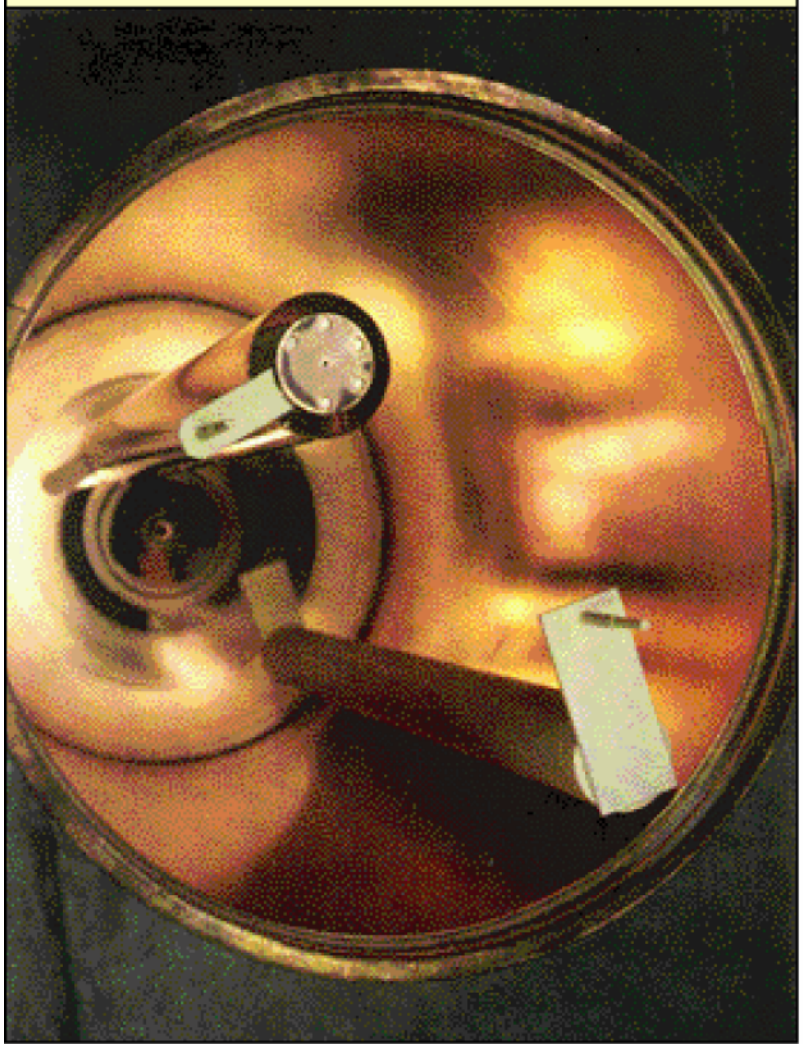
Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm ∅

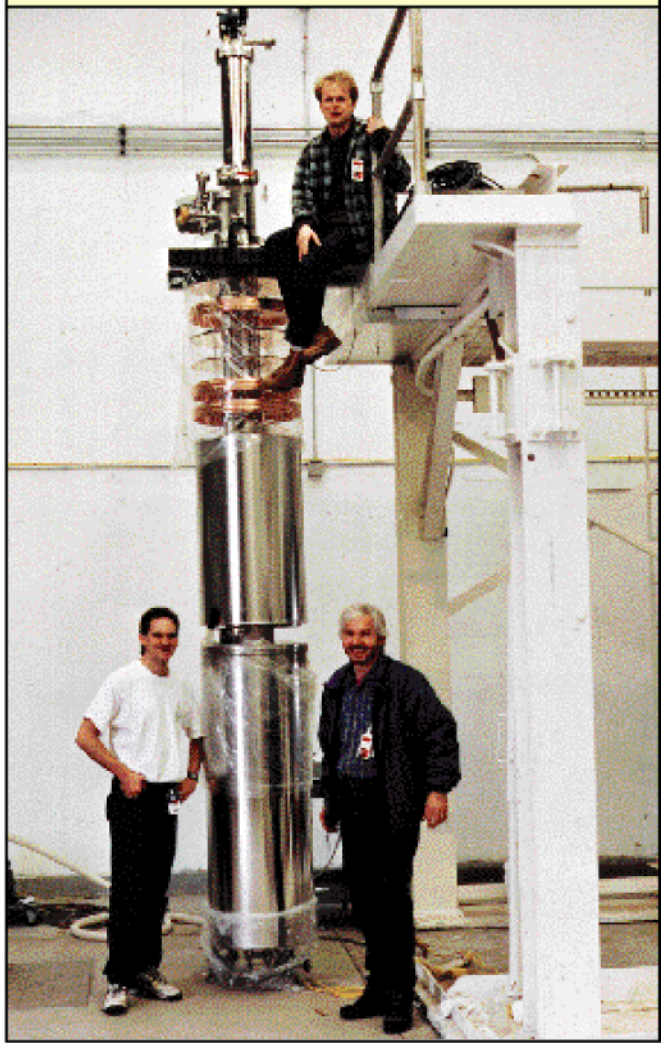
Axion hardware (cont'd)

ADMX

High-Q Cavity (~200,000)

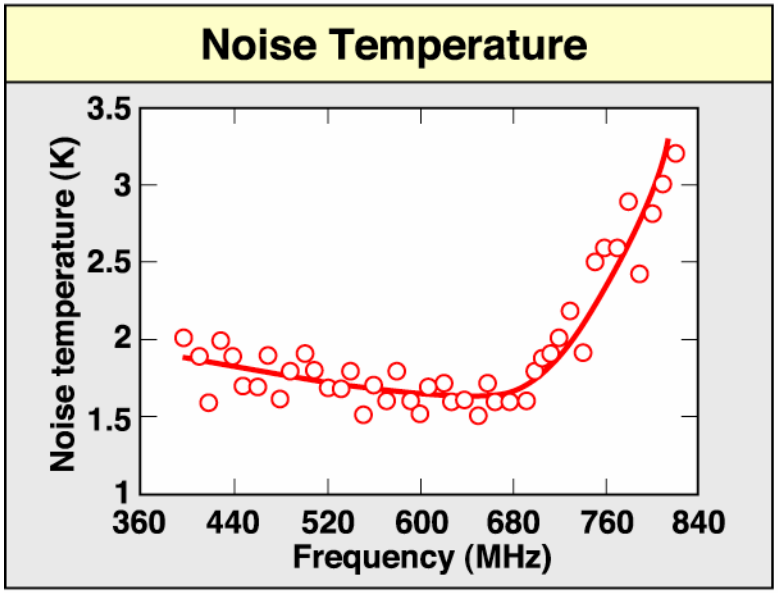


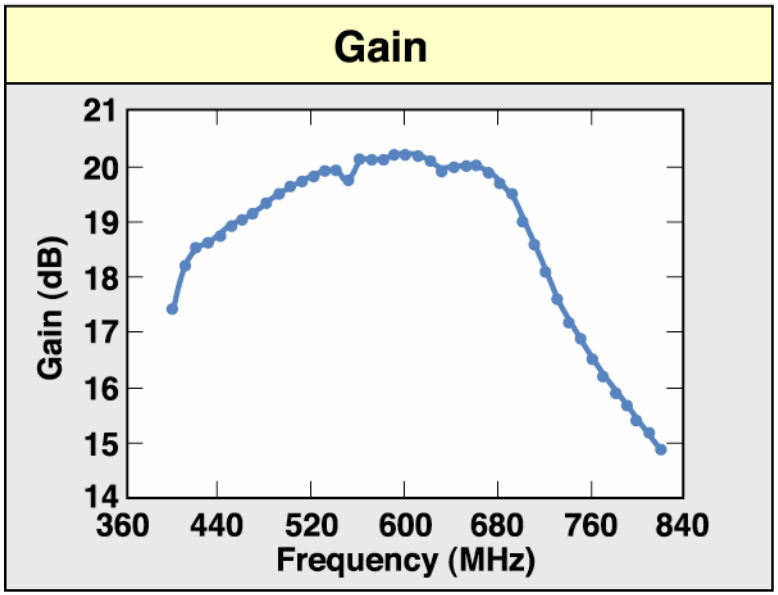
Experimental Insert



Microwave amplifiers

ADMX





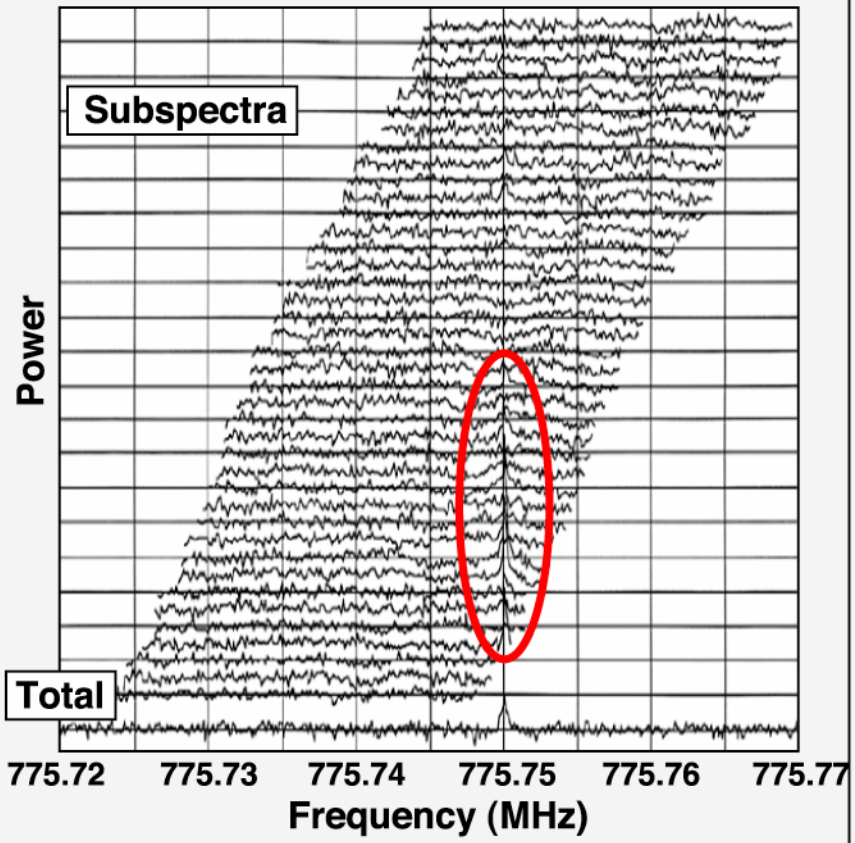
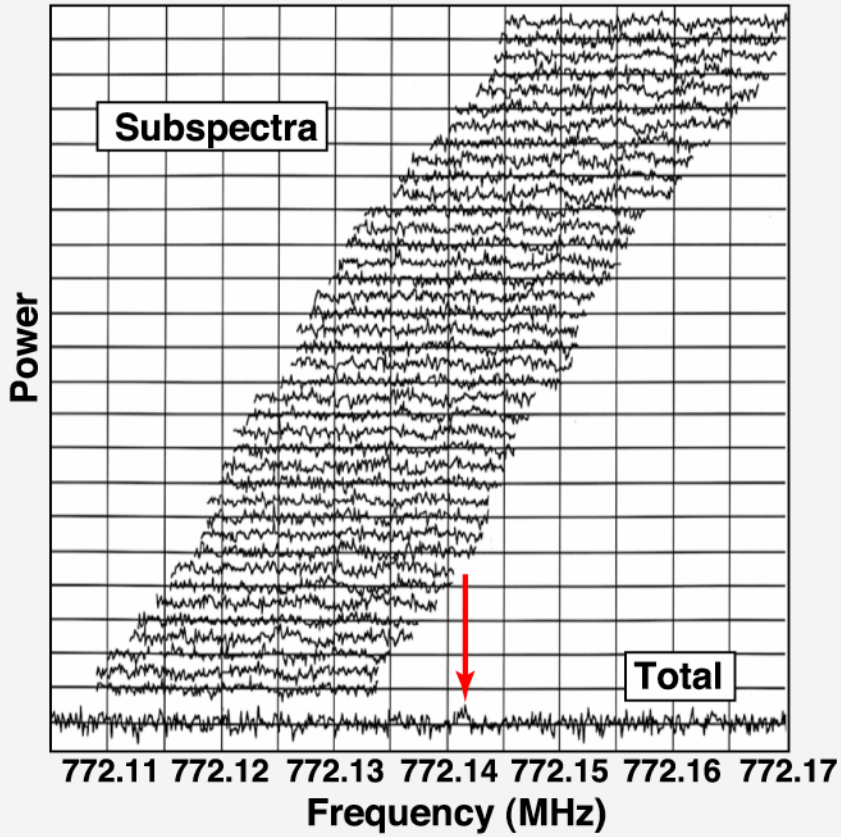
- Currently HFET amplifiers (Heterojunction Field-Effect Transistor)
  - A.k.a. HEMT™ (High Electron Mobility Transistor)
  - Workhorse of radio astronomy, military communications, etc.
- Best to date $T_N \gtrsim 1$ K
  - Independent of T
  - Works in magnetic field

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!

Sample data and candidates

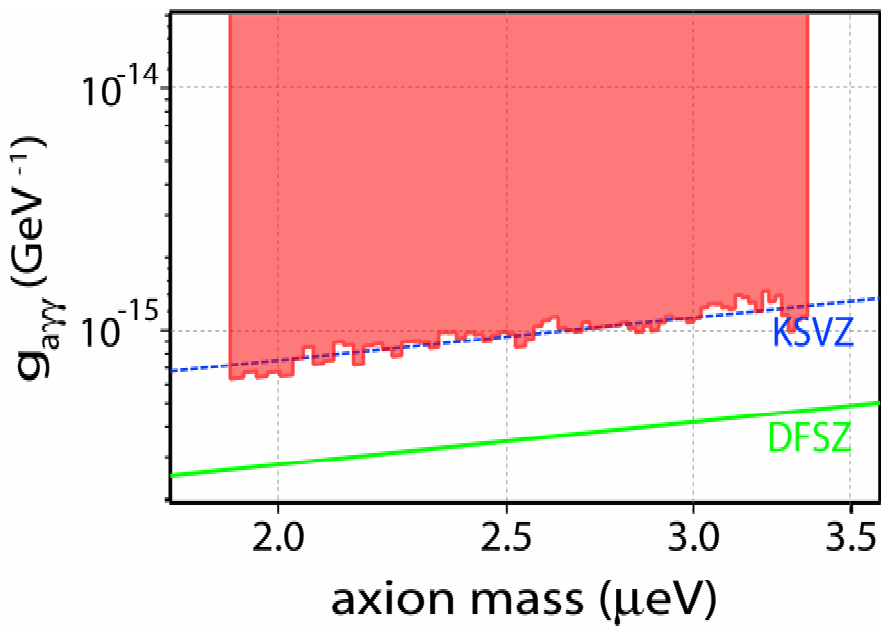
ADMX

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

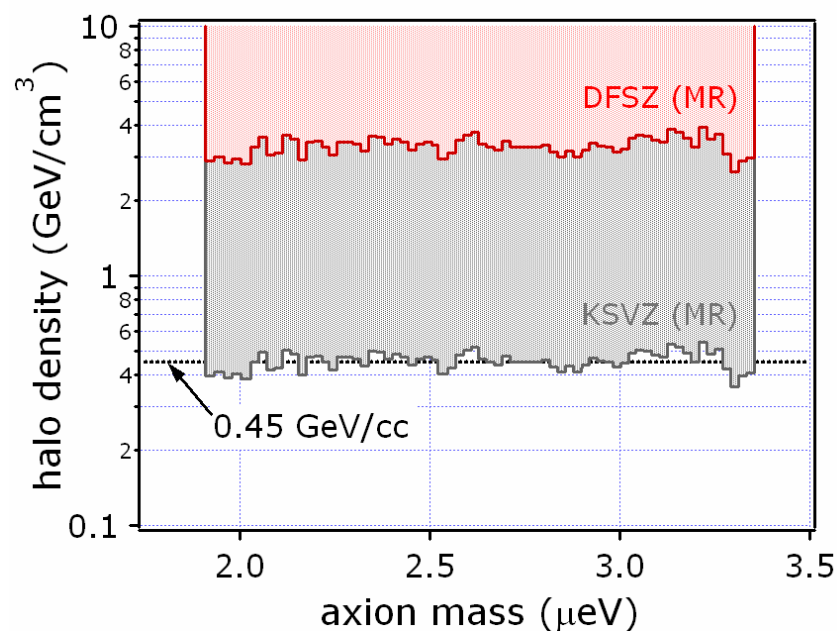
Current ADMX MedRes limits

ADMX

Particle Physics
(limits in coupling assuming 450 MeV/cc density)



Astrophysics
(limits in density with set couplings)



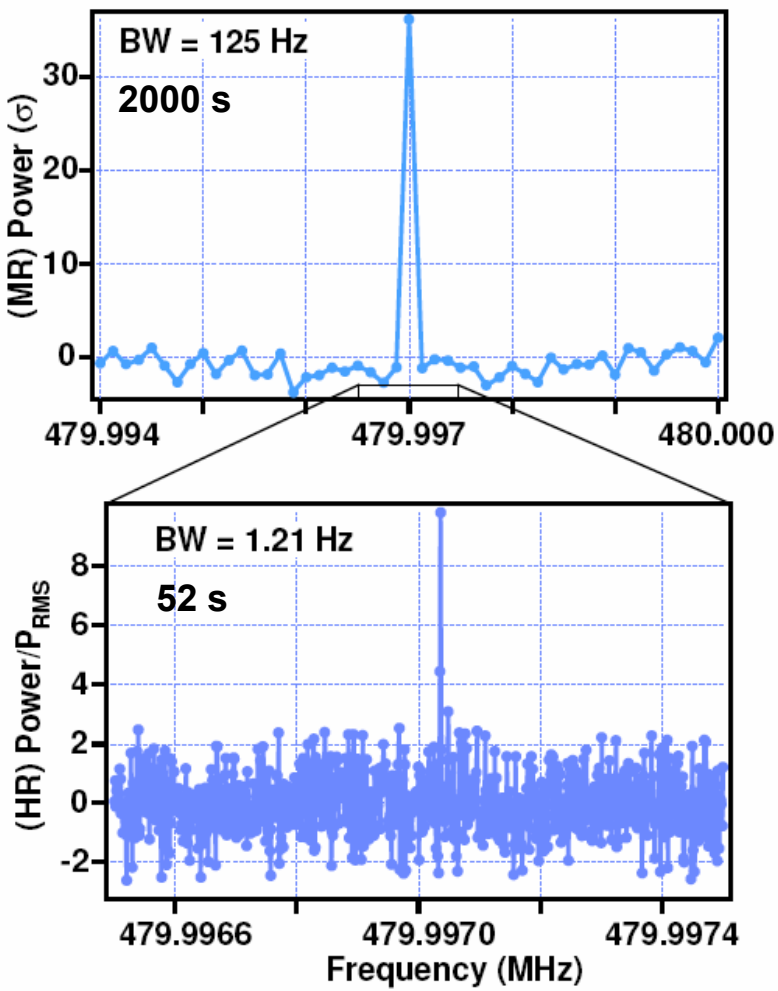
S.J. Asztalos *et al.*, Astrophys. J. Lett. **571**, L27 (2002)

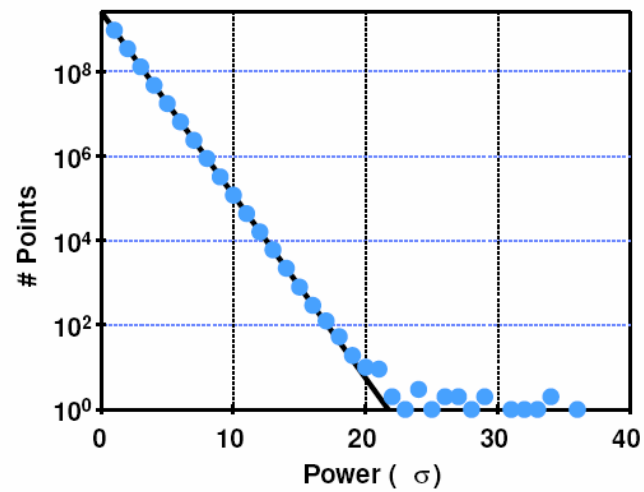
Definitive experiment requires achieving sensitivity to DFSZ model axions at fractional halo densities (ρ < 450 Mev/cc).

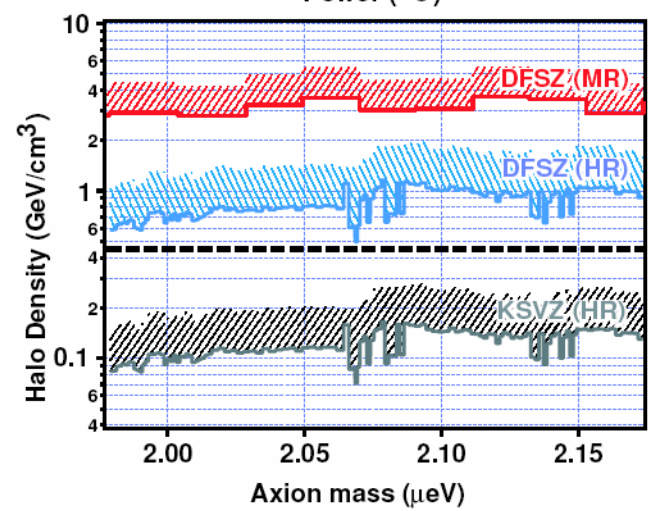
Results of a high-resolution analysis

PRL 95 (9) 091304 (2005)

ADMX







Measured power in environmental (radio) peak same in Med- & Hi-Res

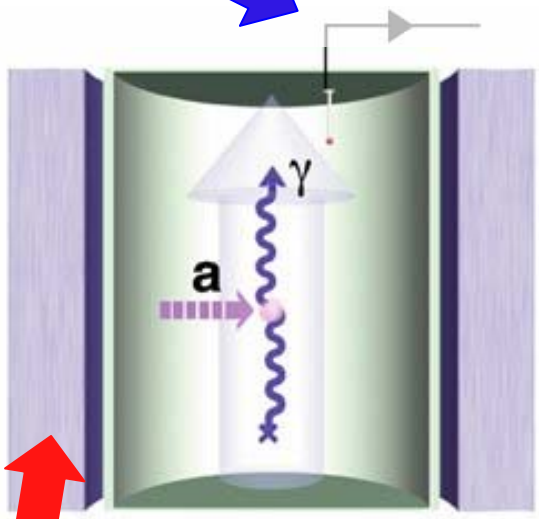
The radiometer eqn.* dictates the strategy

ADMX

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

But integration time limited to ~ 100 sec

** Dicke, 1946*



System noise temp. now

$T_S = T + T_N \sim 1.5 + 1.5\ K$

But $T_{Quant} \sim 30\ mK$

INVEST HERE!

$$P_{sig} \sim (B^2 V\, Q_{cav})(g^2 m_a \rho_a)$$
$$\sim 10^{-22}\ watts$$

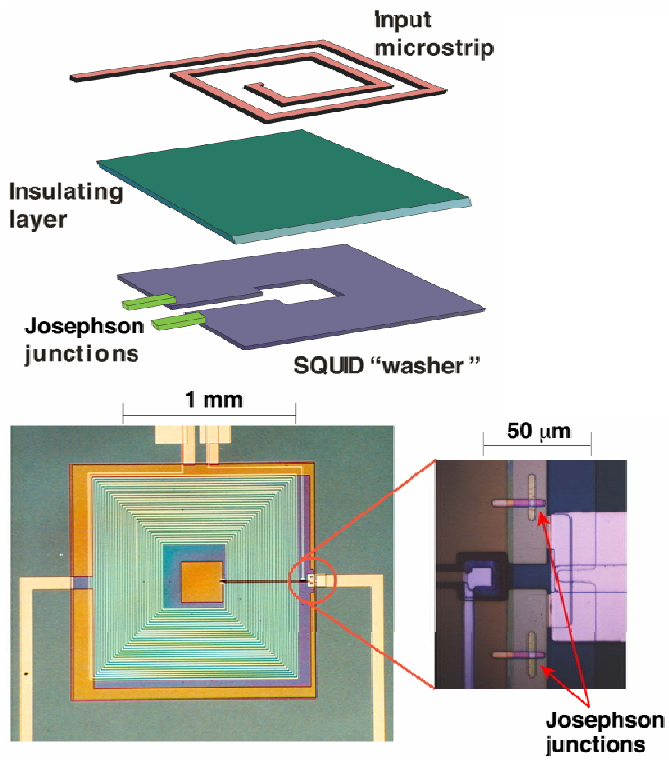
But magnet size, strength $B^2V \sim \$$

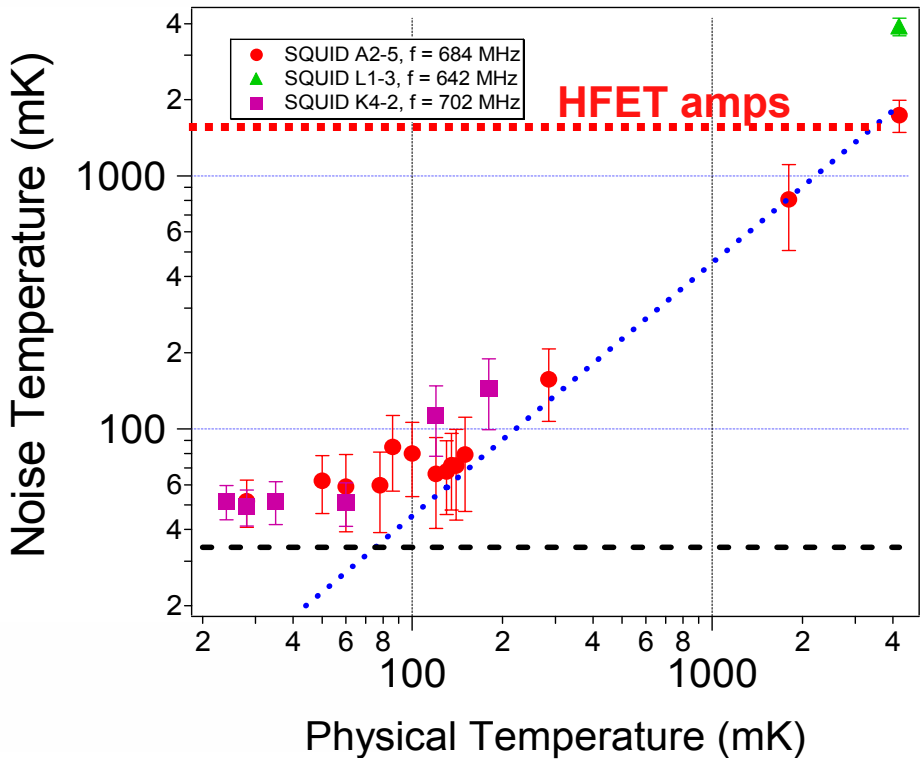
The enabling technology – GHz SQUID amplifiers* ADMX

Presently the noise temperature of our HFET amps is ~ 1.5K

But the quantum limit at 1 GHz is ~ 50 mK

*Prof. John Clark and Dr. Darin Kinion (UC Berkeley)

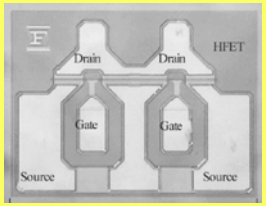
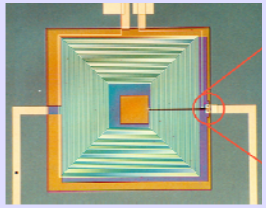




Our latest SQUIDs are now within 15% of the Standard Quantum Limit

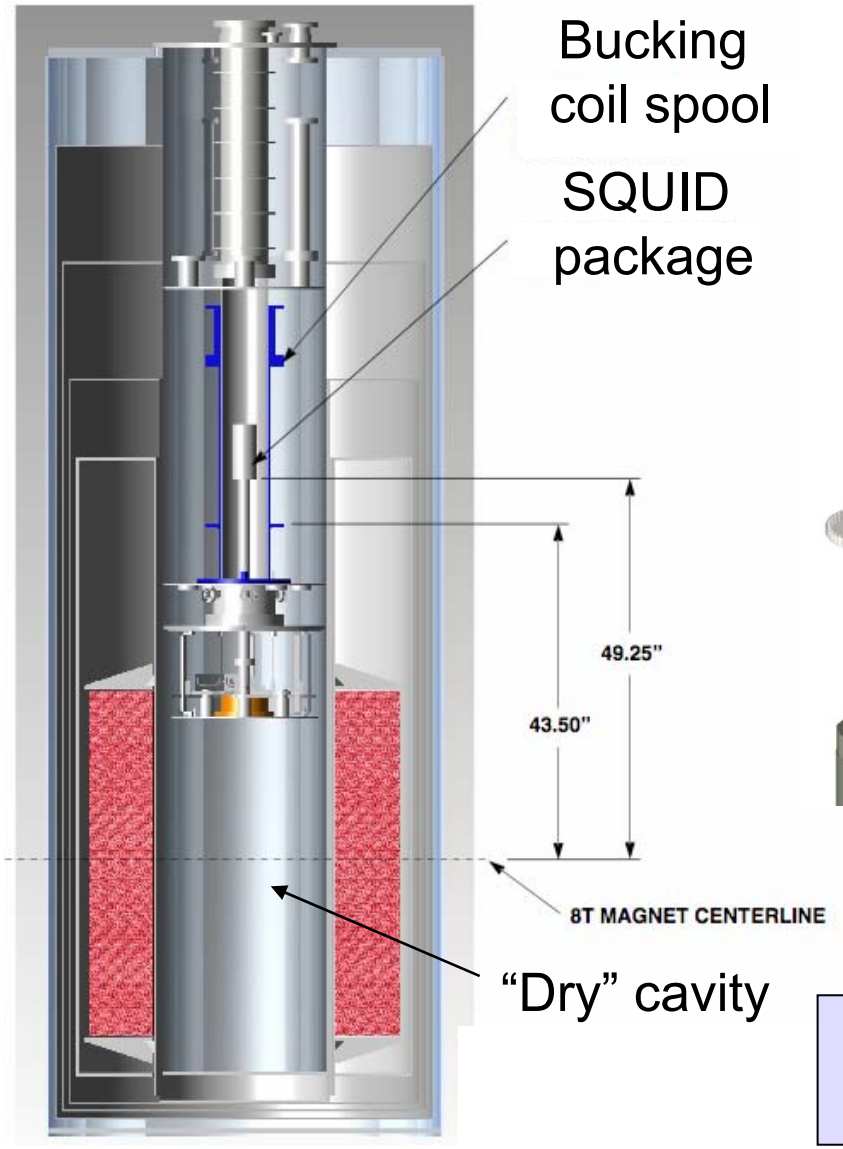
Phase I / Phase II Upgrades in detail

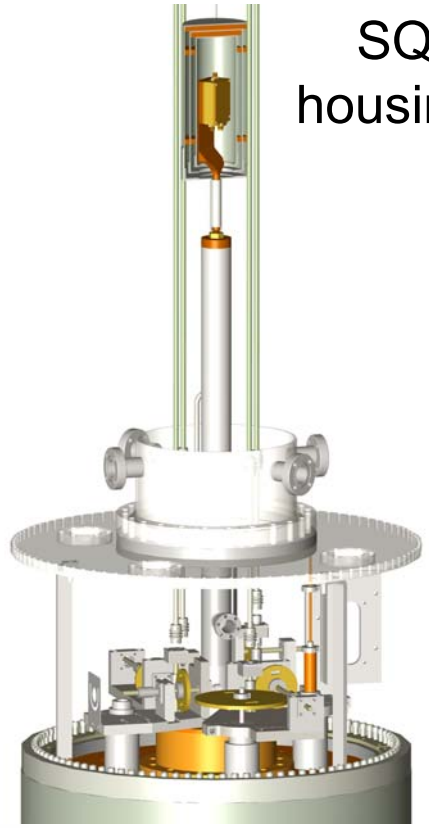
ADMX

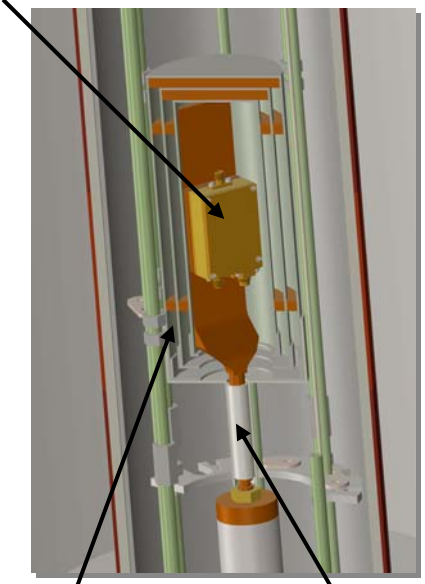
Stage	**ADMX Now**	**Phase I**	**Phase II**
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Fridge
T_{phys}	1.3 K	1.3 K	100 mK
T_{amp}	2	0.4	100
$T_{sys} = T_{phys} + T_{amp}$	3.3	1.7	200
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	4 @ KSVZ	5 @ DFSZ
		OR	***AND !***
Sensitivity Reach $g^2 \propto T_{sys}$	KSVZ	0.5 x KSVZ	DFSZ

The Phase I Upgrade is deep into execution

ADMX







SQUID housing (Nb)

Cold finger

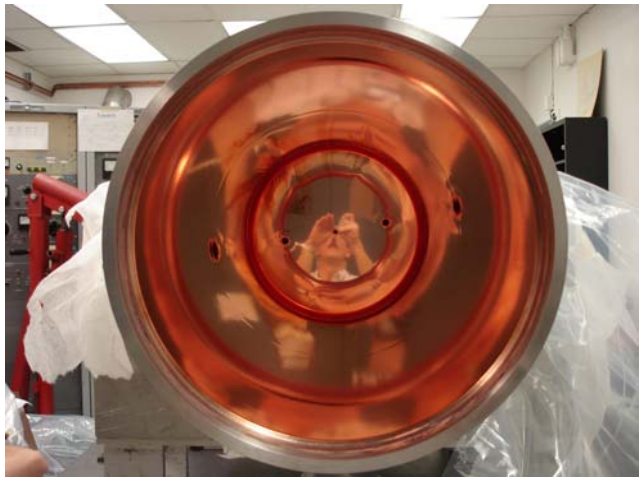
Nb & Cryoperm magnetic shields

All design work was completed long ago & on schedule

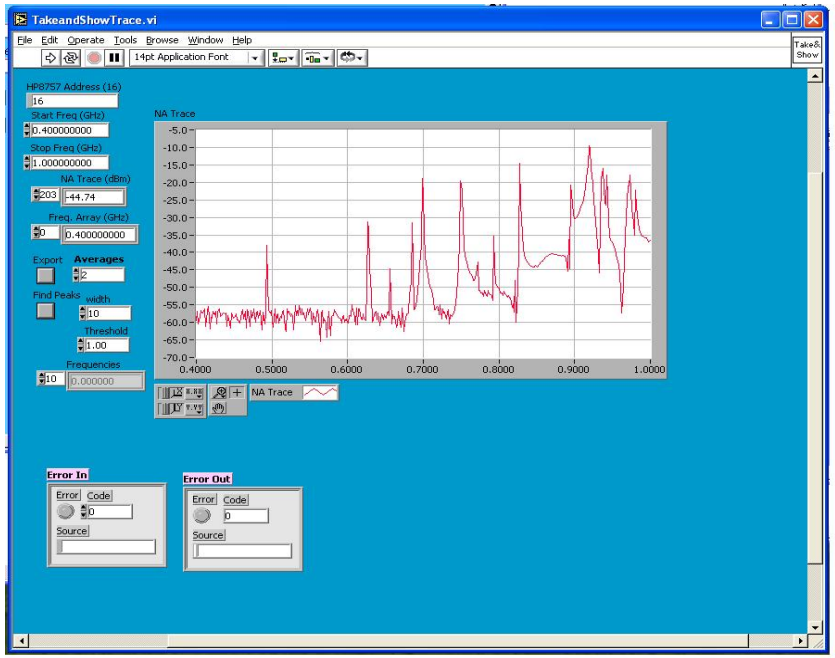
Phase I Upgrade Status

ADMX

Cavity plating 05/06



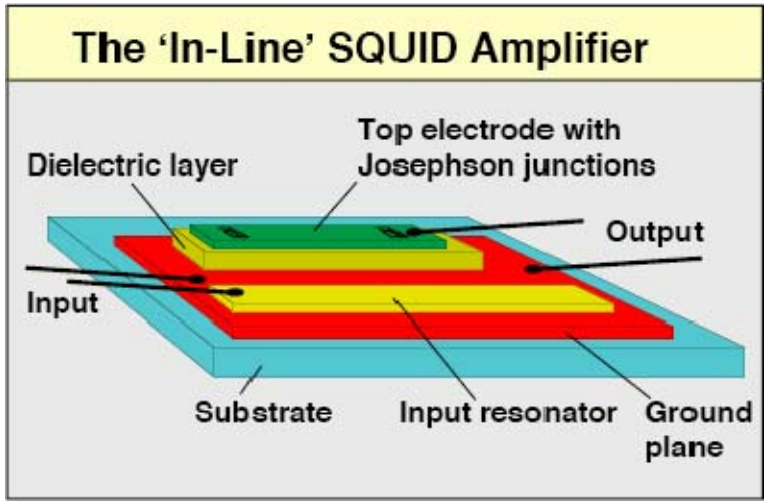
Bucking coil integrated into LHe reservoir 04/06



Cavity response 07/06

To complete the job, ADMX needs concurrent R&D

ADMX



To get to 10, and then 100 GHz, we need to:

- Develop new RF cavity geometries
- Develop new SQUID geometries

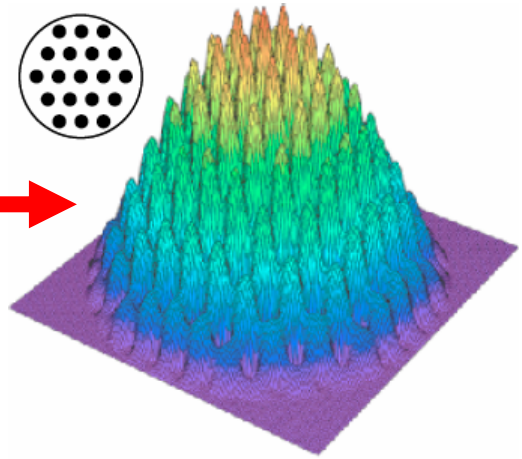
We know what to do, but have bootlegged as far as we can; now it needs real attention

Our Road-Map includes support for R&D

1 GHz

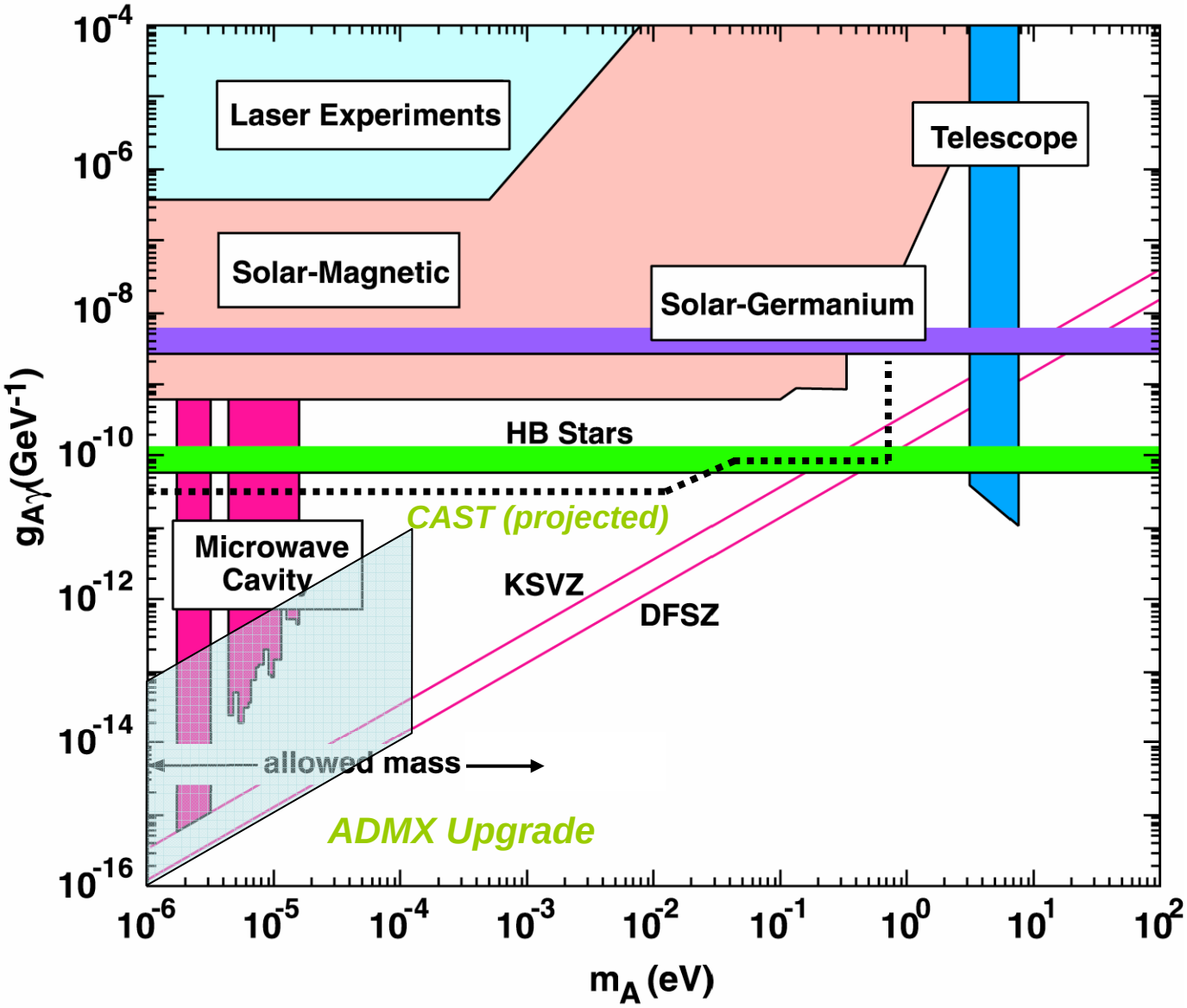
10 GHz

100 GHz



Excluded $g_{A\gamma\gamma}$ vs. m_A with all experimental and observational constraints

ADMX



P02459-ljr-u-04

Summary & conclusions

ADMX

- Favorable situation – constrained search space in m_a, $g_{\alpha\gamma\gamma}$

- The Primakoff interaction is the master key
  - Discovery would be definitive; signal can be toggled on-off with B-field
  - The experiment measures E_{tot}, thus potentially revealing extraordinary detail of galactic formation & dynamics through fine-structure and their Doppler modulation

- ADMX upgrade proceeding on schedule
  - Currently being reconstructed with SQUID amplifiers.
  - Commissioning of experiment expected end of June.
  - Data taking expected beginning of Fall.

Should be able to probe the most pessimistic axion couplings (DFSZ) at fractional halo density over 2 decades in mass over the next 10 years

Additional Slides

Particle physics provides 3 classes of dark-matter candidates

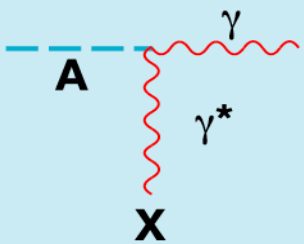
ADMX

General requirements:

- **Interacts extremely weakly with standard model particles**
- **Non-relativistic (required for structure formation)**
- **Local density ~ 450 MeV/cm^3**

- **Neutrinos** ← Standard 3 generations are too light
  Possible heavy (>45 GeV) 4th generation
- **WIMPs** ← SUSY neutralino, Kaluza-Klein particles
- **Axions**

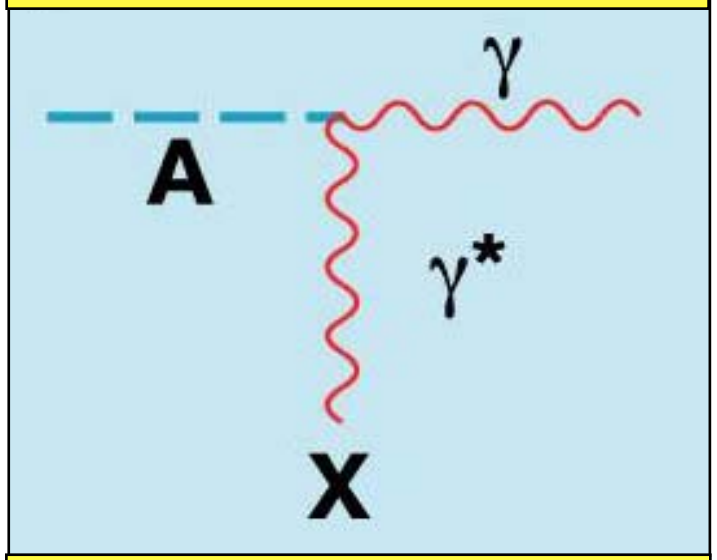
- **The Axion is a very light pseudoscalar ($J^{\pi} = 0^{-}$), like the neutral pion, π°**
- **Like the π°, it has a two-photon coupling**
  - **One of the photons can be virtual**



Key to Detection: Axion-photon coupling $g_{a\gamma\gamma}$

ADMX

Primakoff interaction



$J^{\pi} = 0^{-} \rightarrow L \sim E \bullet B$

The axion, like the π^0, has a two-photon coupling

The free-space ($\gamma\gamma$) lifetime is irrelevantly long:

$\tau \sim 10^{50}$ sec for ~ 1 μeV axion

But it more readily converts to a *single real photon* in EM field

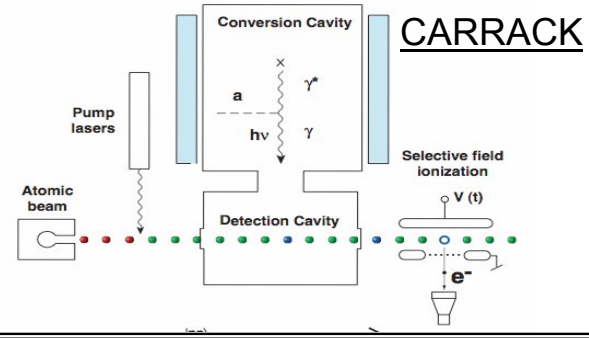
This photon then carries the *total energy* of the axion

This Primakoff interaction is the basis for the most sensitive experiments to search for the axion

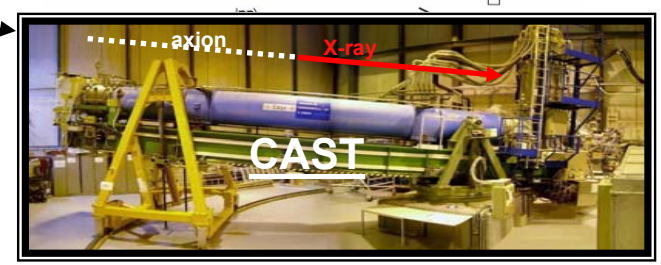
Variety of experiments*…

ADMX

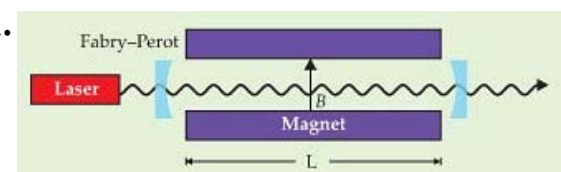
- **Microwave Cavities**
  - Low noise amplifiers (**ADMX**) and Rubidium Atoms (**CARRACK**)
    - Look for dark matter axions (low mass) converting to photons in B-Field
    - **Will focus today on ADMX project.**

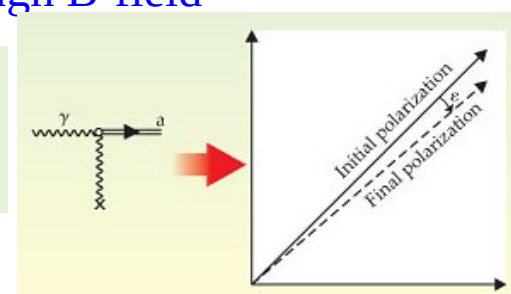


- Solar Observatories
  - X-Ray (**CAST**) and Germanium detectors
    - Look for axions generated from the sun
    - Higher coupling required than for DM axions.



- Lab experiments
  - Photon regeneration and polarization changes (**PVLAS**)
    - Look for production of axions from light passing through B-field
    - Higher coupling required.





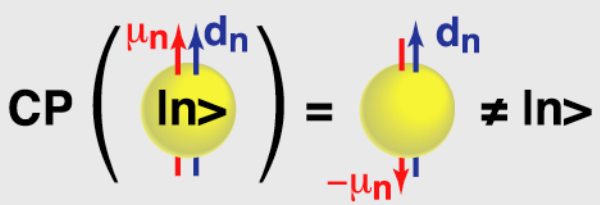
***See August Physics Today for experimental overview**

Where did the Axion come from?

ADMX

The Strong-CP Problem

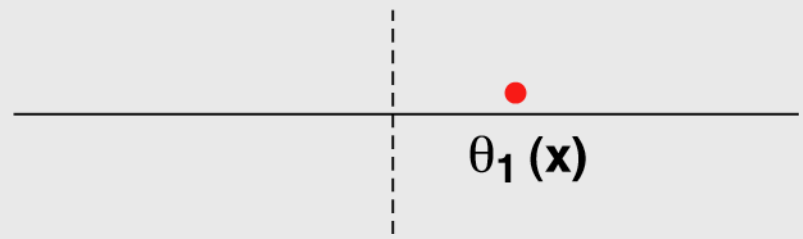
- $\mathcal{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G\tilde{G}$
  - — Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - — $\bar{\theta} < 10^{-10}$
  - — Strong-CP preserving



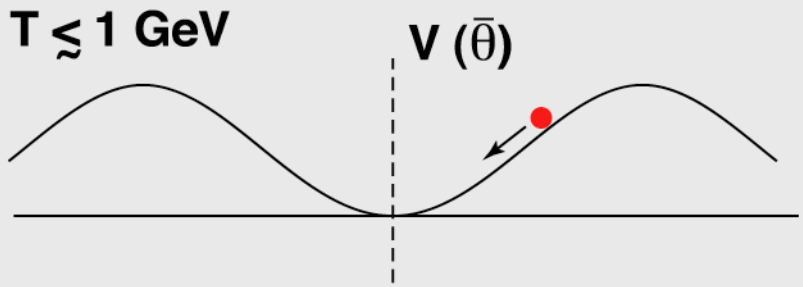
- Why?

Peccei-Quinn / Weinberg-Wilczek

- θ a dynamical variable
- T = f_a spontaneous symmetry breaking



- T $\lesssim$ 1 GeV



  - — $\bar{\theta}$ dynamically $\rightarrow$ 0
  - — Remnant oscillation = Axion

Properties of the Axion

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- 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

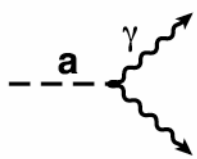
Mass and Couplings

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

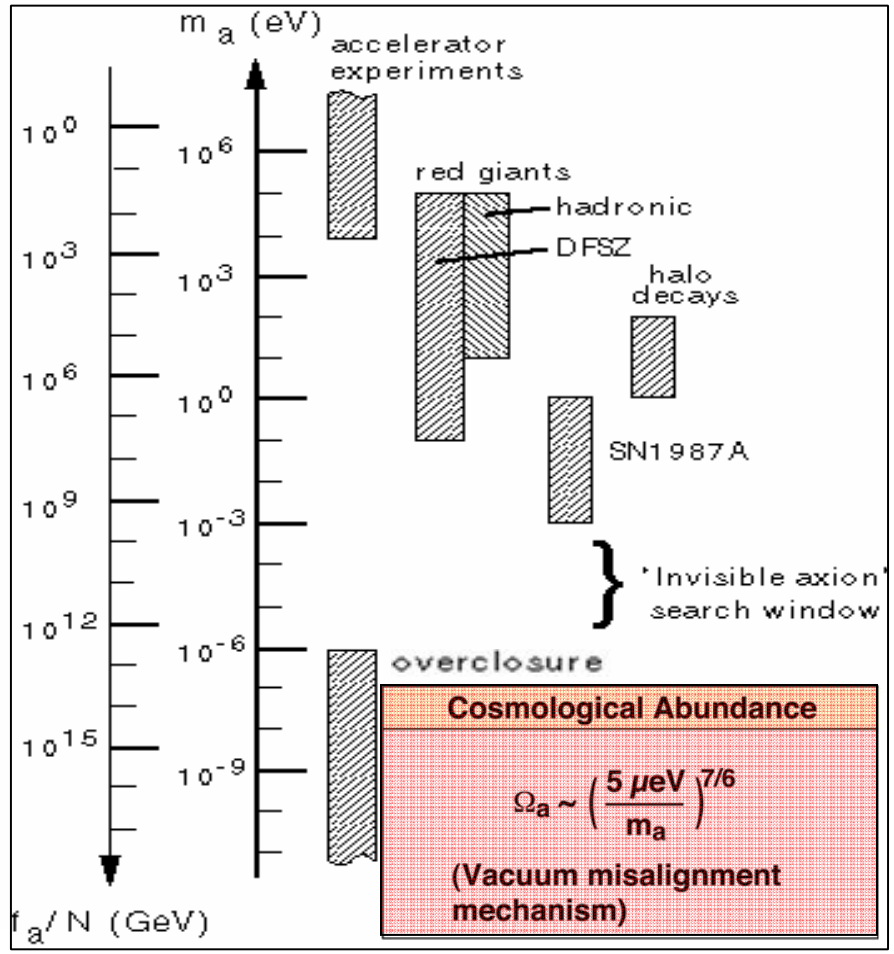
Generically, all couplings

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

Coupling to Photons



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



Principle of the microwave cavity experiment to search for dark-matter axions *[Pierre Sikivie, PRL 51, 1415 (1983)]*

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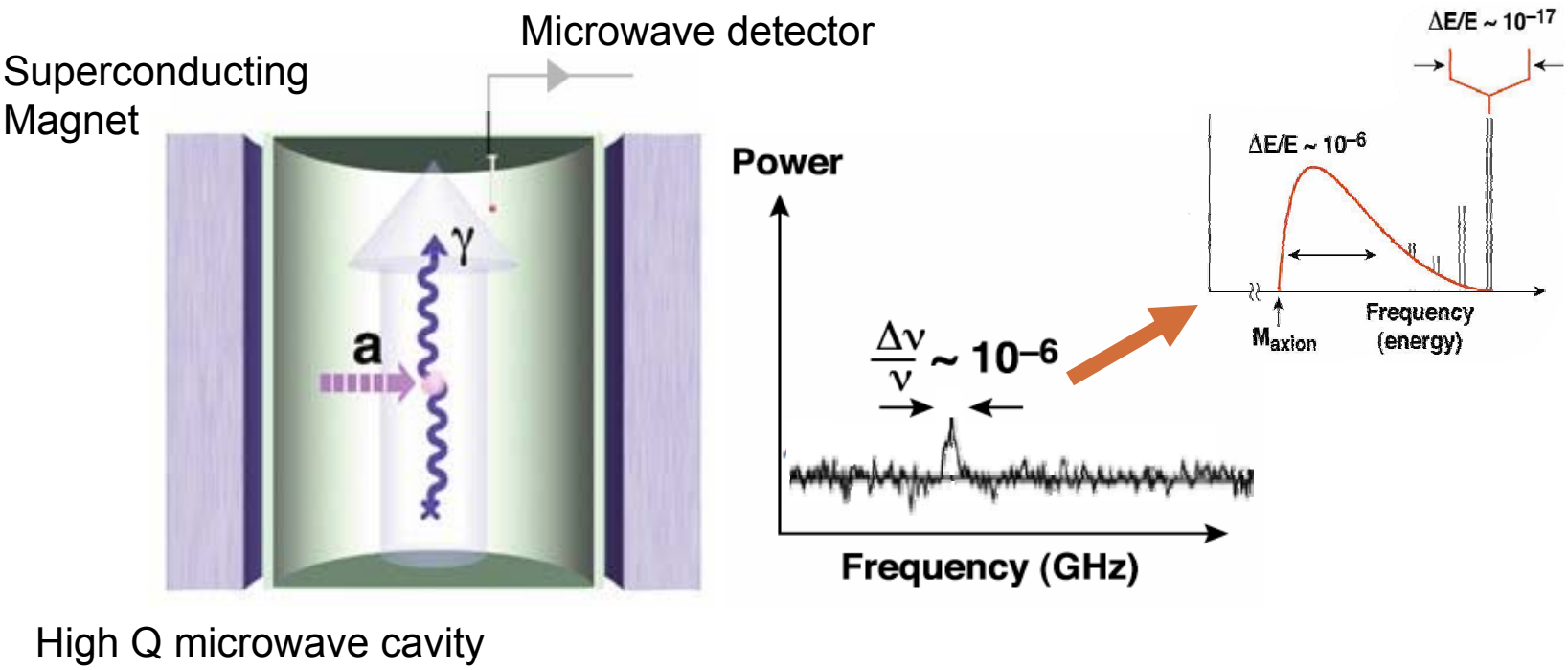

The axion mass range is scanned by tuning the cavity

Resonance condition: $h\nu = m_a c^2[1 + O(\beta^2 \sim 10^{-6})]$

Signal power: $P \propto (B^2 V Q_{cav})(g^2 m_a \rho_a) \sim 10^{-23}$ *watts*

There may be fine structure in the axion signal

The axion receiver, and high-resolution search

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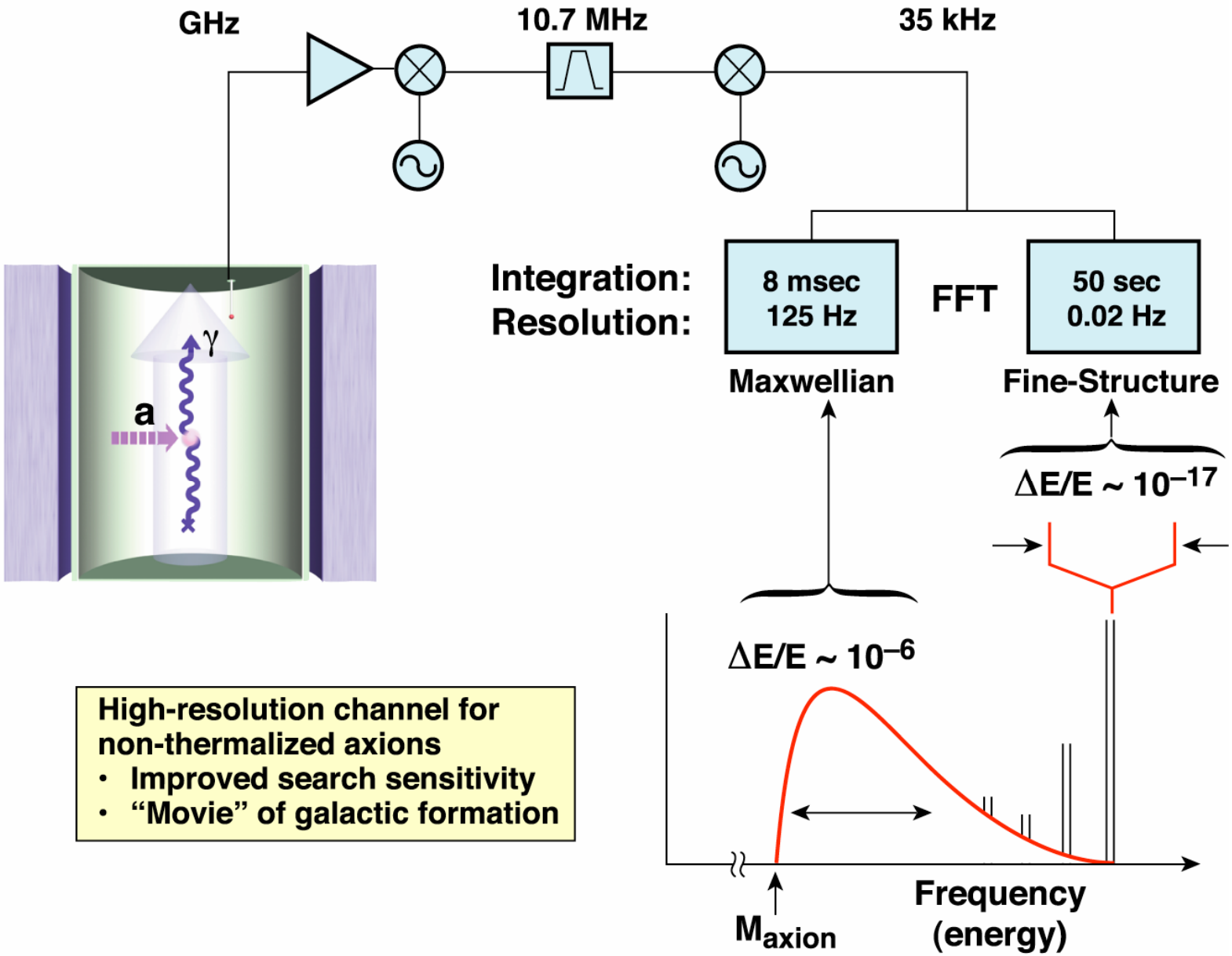

High-resolution channel for non-thermalized axions

- **Improved search sensitivity**
- **"Movie" of galactic formation**

The parameter space is bounded

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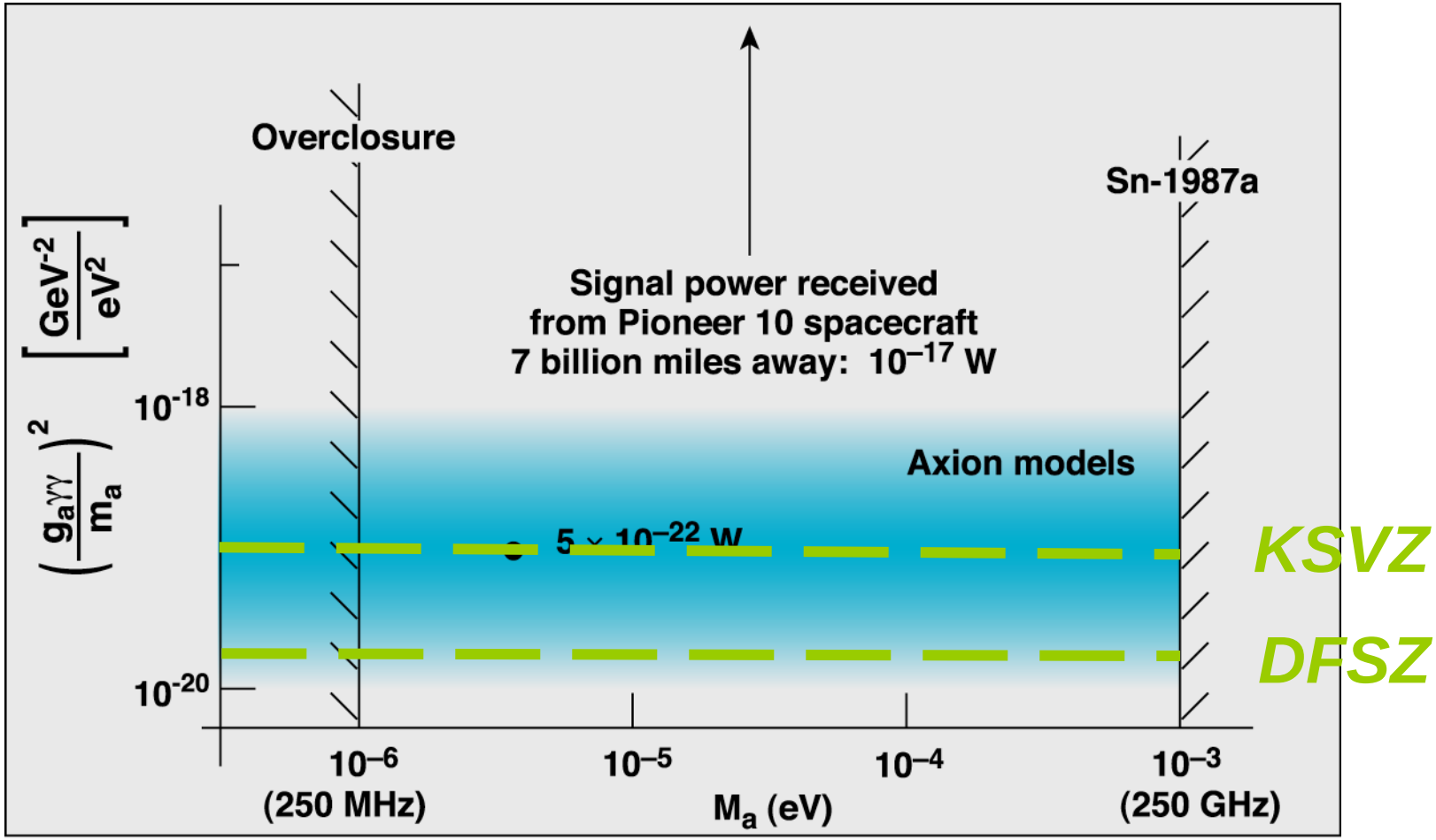
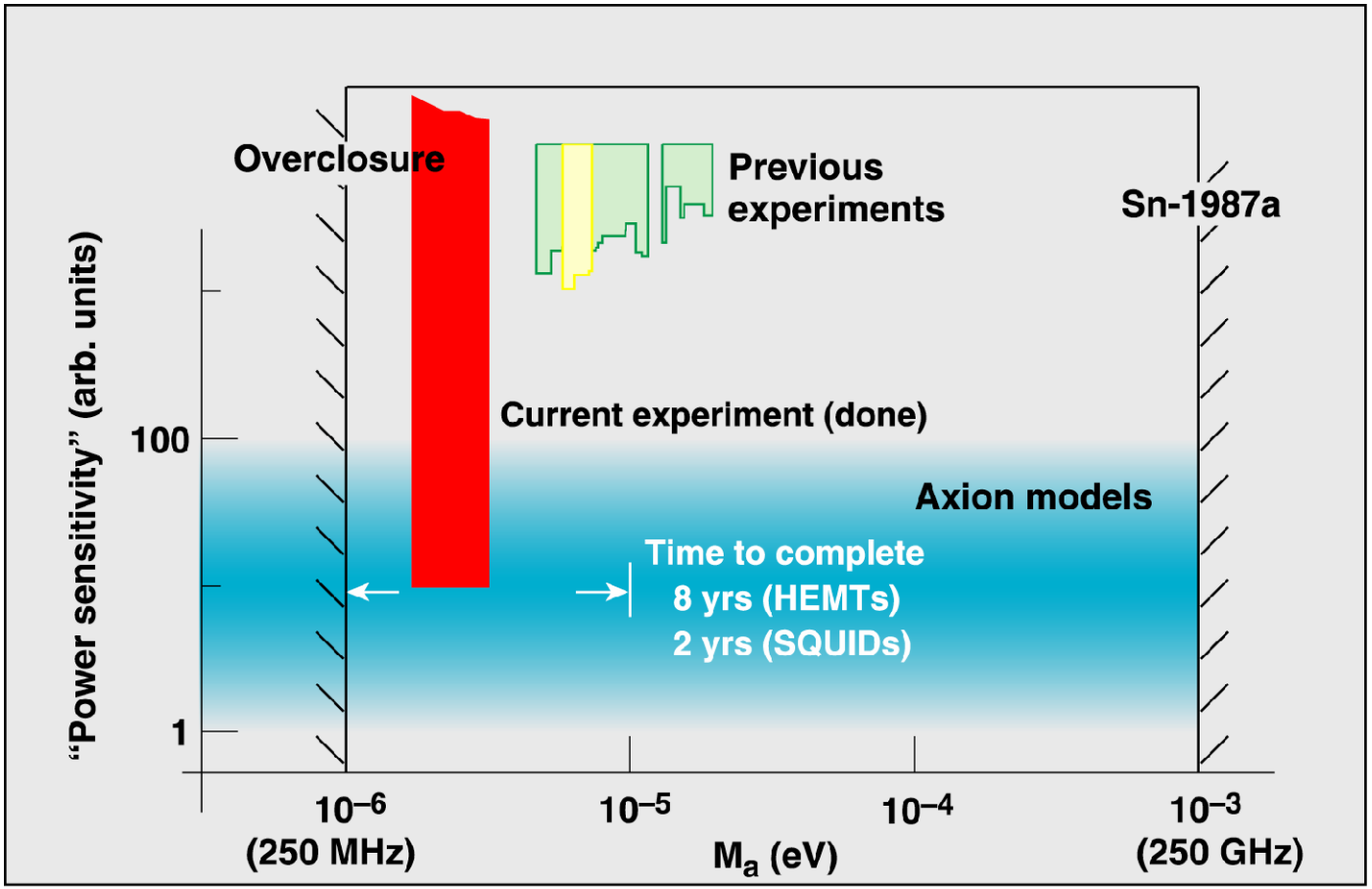


- The axion is bounded in both coupling and mass!
- But the expected signals are tiny

The scientific deliverable of the Phase I Upgrade

ADMX



The Phase I run will cover 800 - 900 MHz, utilizing only one cavity, and one SQUID amplifier (T_{phys} ~ 1.3 K, T_{amp} ~ 0.4 K)

The ADMX R&D program

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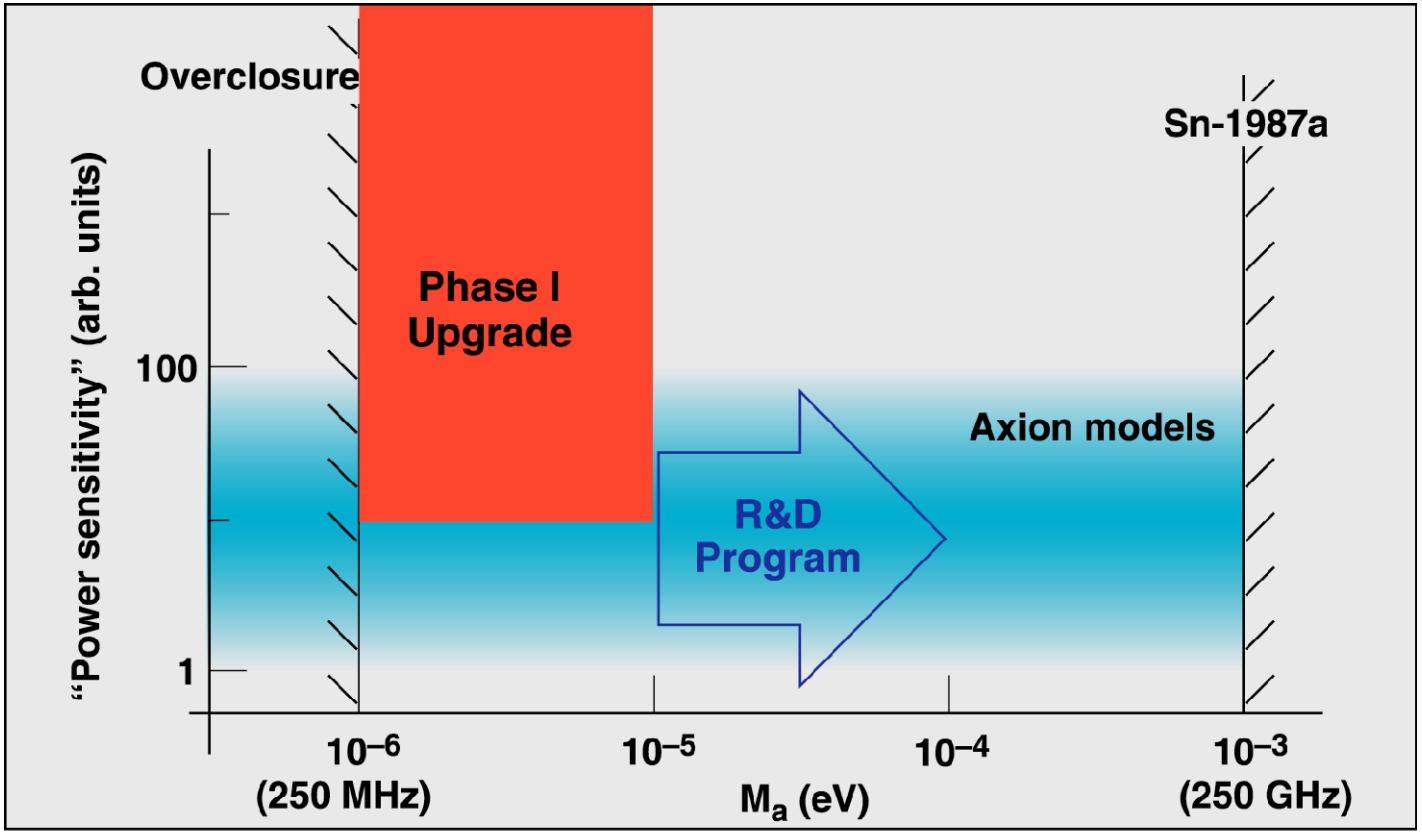
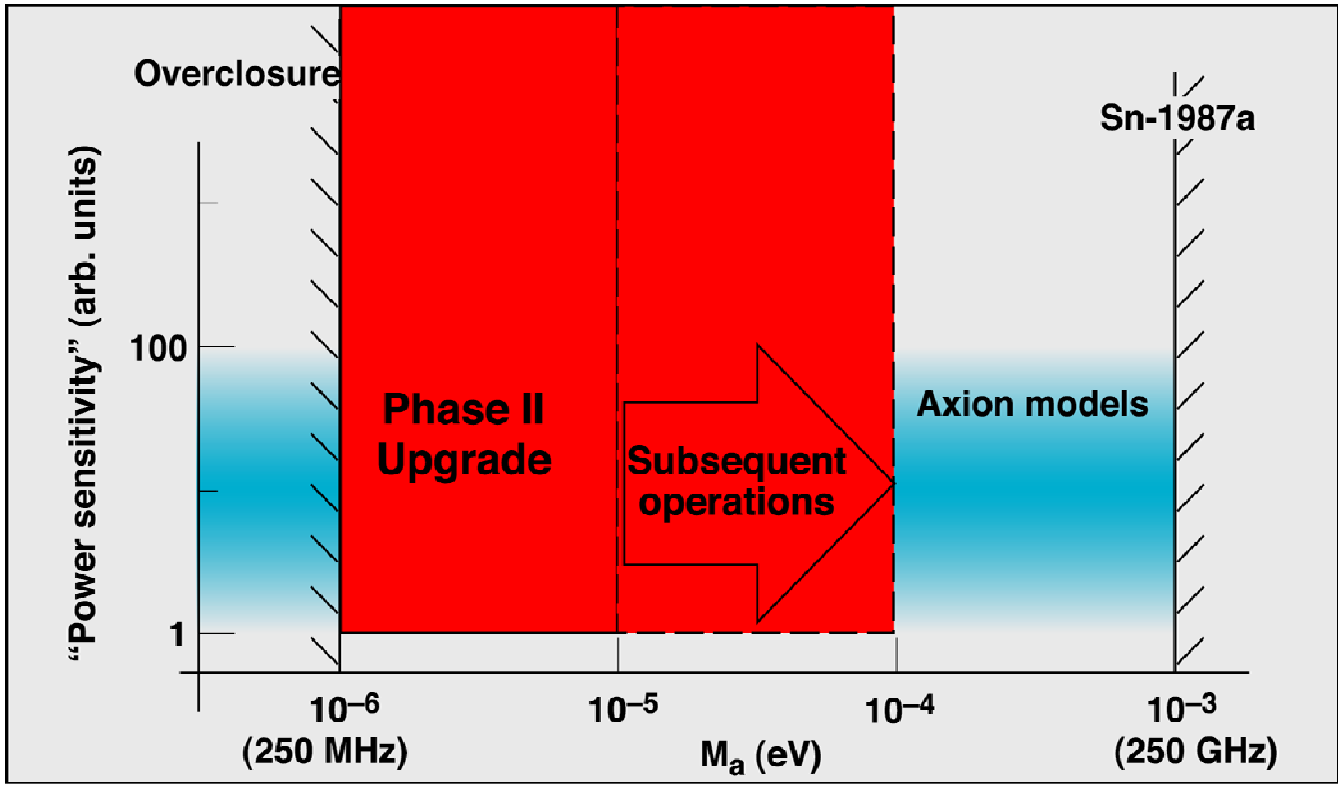


A concurrent high-frequency R&D program is needed to complete the program within a decade, and should begin soon

The Phase II upgrade and beyond

ADMX



Phase II will rescan the lowest mass decade at or below DFSZ, then continue upward *(if prepared by the R&D)*