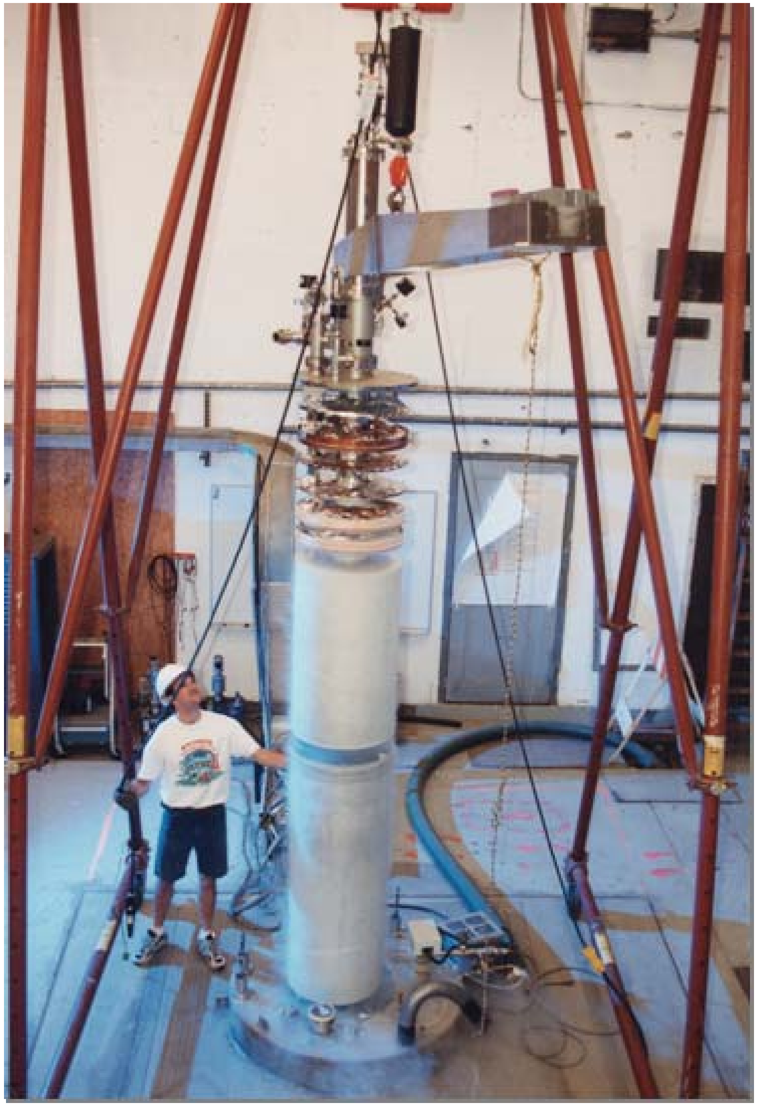


3rd Joint ILIAS–CERN–DESY Axion–WIMPs

The Axion Dark Matter eXperiment (ADMX) Phase 0

Steve Asztalos, LLNL

June, 2007

Collaboration

ADMX

- ADMX is a five institution collaboration
  - Lawrence Livermore National Laboratory
    - Co-spokesperson (K. van Bibber)
    - Staff scientist (D. Kinion)
    - Post doc (G. Carosi), Principal Investigator (S. Asztalos)
  - University of Washington
    - Co-spokesperson (L. Rosenberg)
    - Graduate student (M. Hotz), post doc (G. Rybka - summer '07)
  - University of Florida
    - D. Tanner and P. Sikivie
    - Former graduate student (L. Duffy now at LANL)
  - University of California – Berkeley
    - J. Clarke
  - National Radio Astronomy Observatory
    - R. Bradley

Collaboration expertise

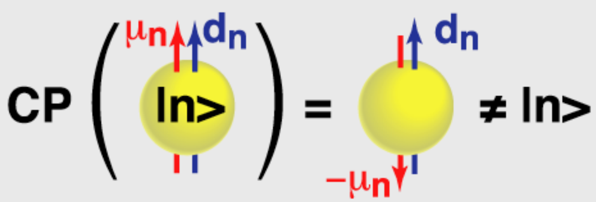
ADMX

- Lawrence Livermore National Laboratory
  - Experimental site since 1995
  - Operations
  - Phase I design
  - SQUID development
- University of Washington
  - Operations
  - Analysis
- University of Florida
  - Theoretical guidance
  - Cryogenic engineering
  - High resolution analysis
- University of California – Berkeley
  - Ground-breaking SQUID design
- National Radio Astronomy Observatory
  - Low-noise amplifiers

The Axion

The Strong-CP Problem

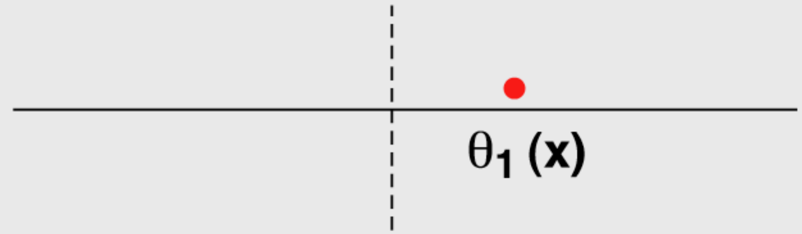
- $\mathcal{L}_{QCD} = \;....\; + \dfrac{\theta}{32\pi^2}\, G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m.
  $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



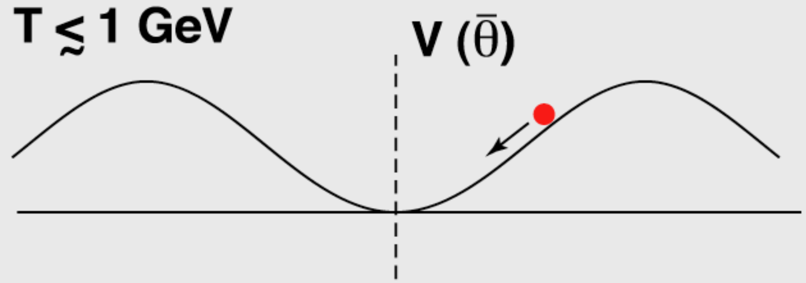
- Why?

Peccei-Quinn / Weinberg-Wilczek

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



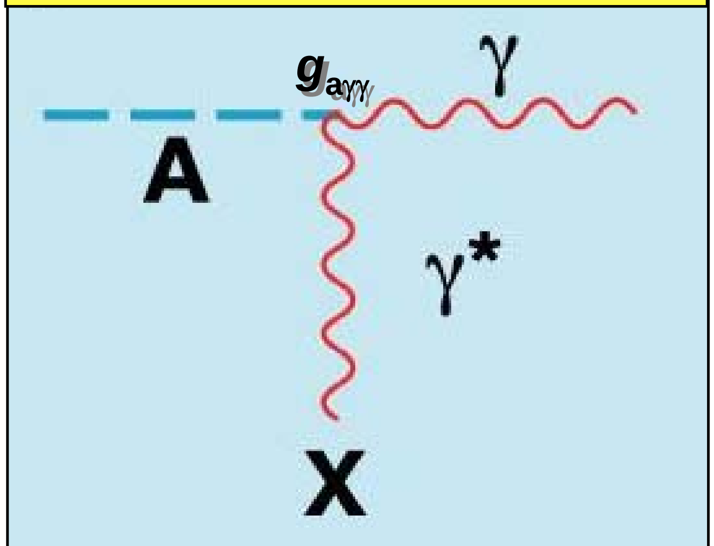
- $T \lesssim 1$ GeV



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

Axion-photon coupling

Primakoff interaction



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

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)

But it can also be converted into 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

Properties of the Axion

- 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

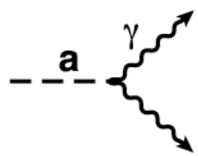
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

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

(Vacuum misalignment mechanism)

Coupling to Photons



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

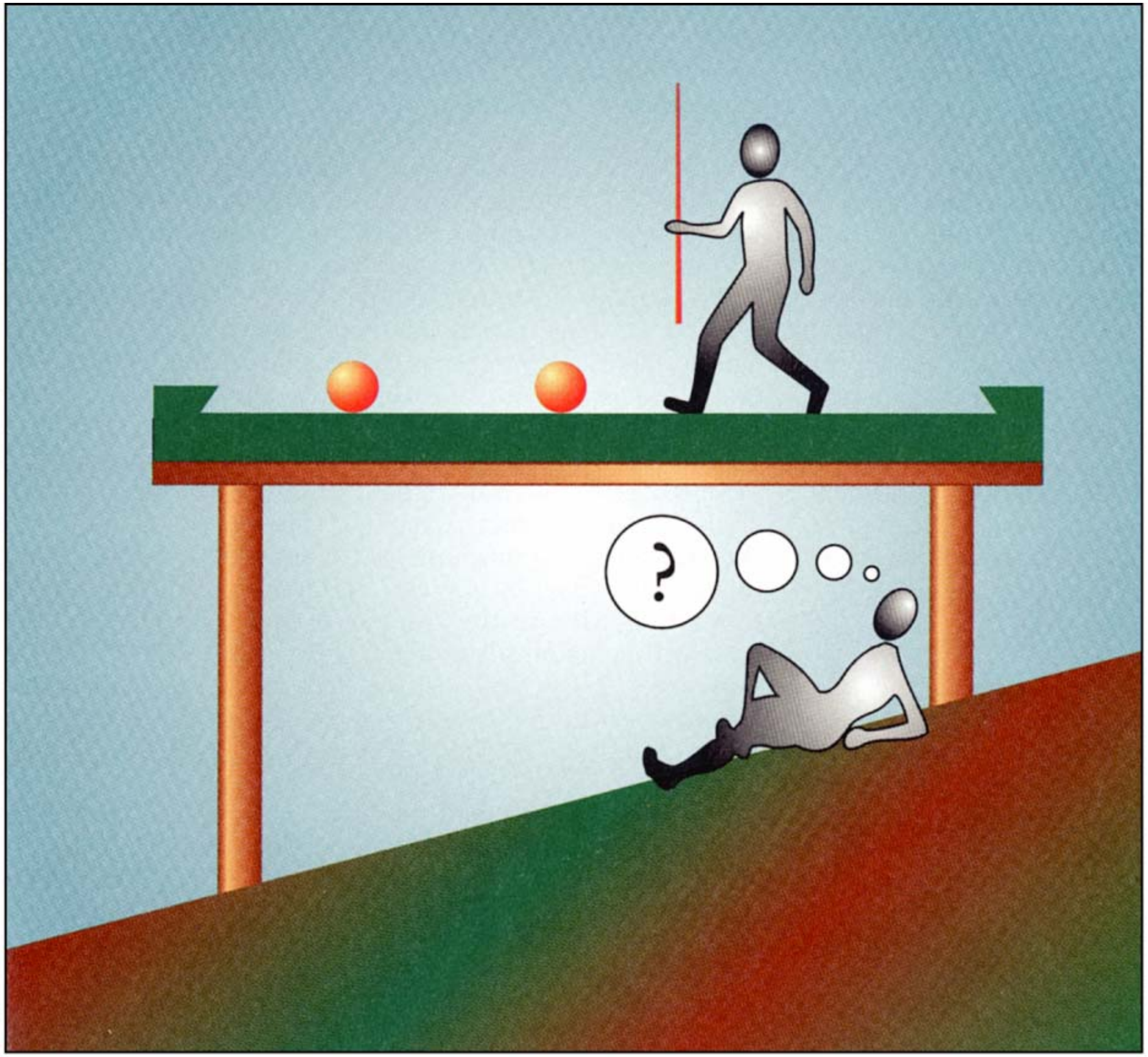
Axion Mass 'Window'

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

(Overclosure) (SN1987a)

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

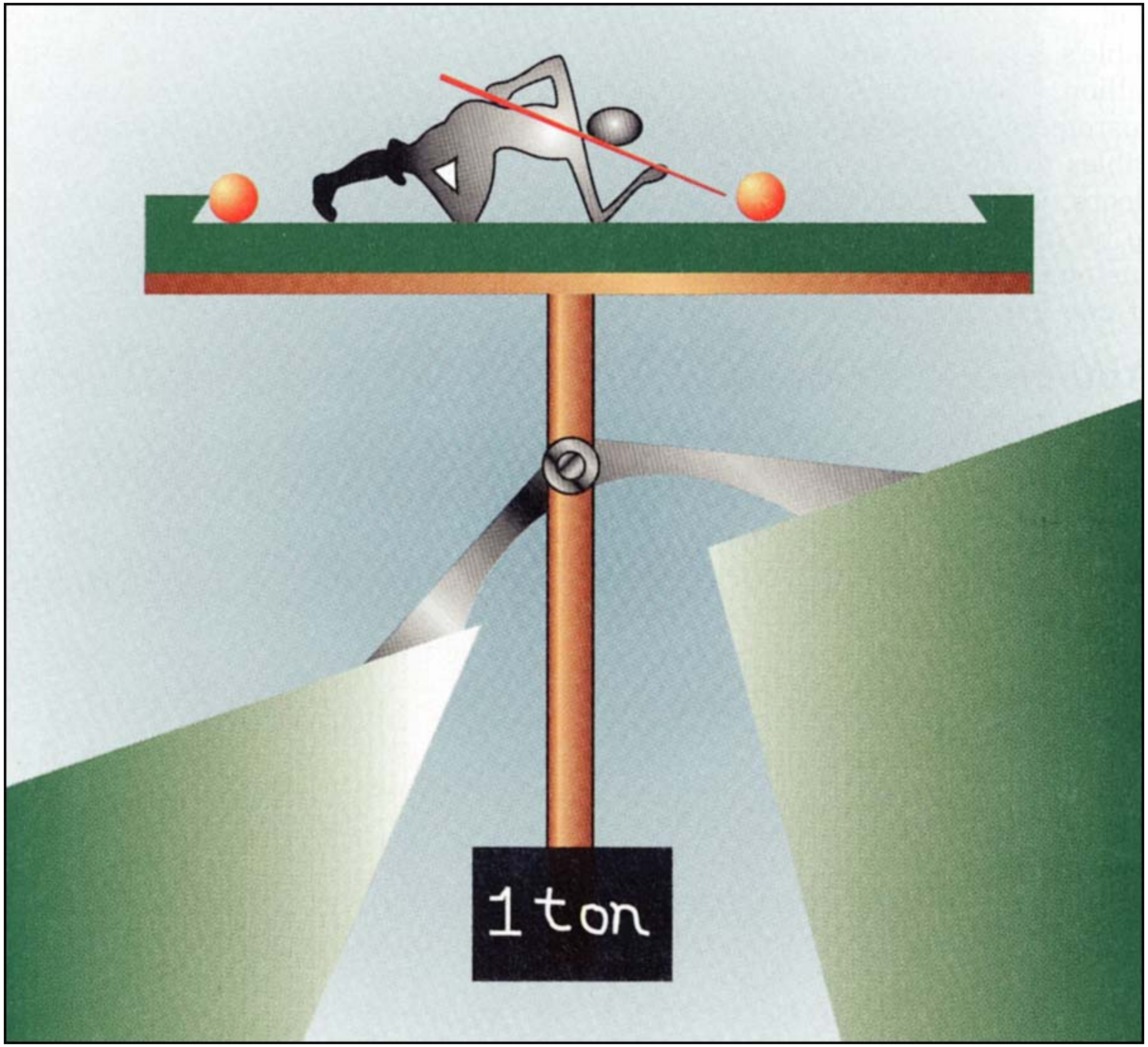
TSP's* fine-tuning problem



*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)

TSP's hypothesis, and first unsuccessful experiment

ADMX

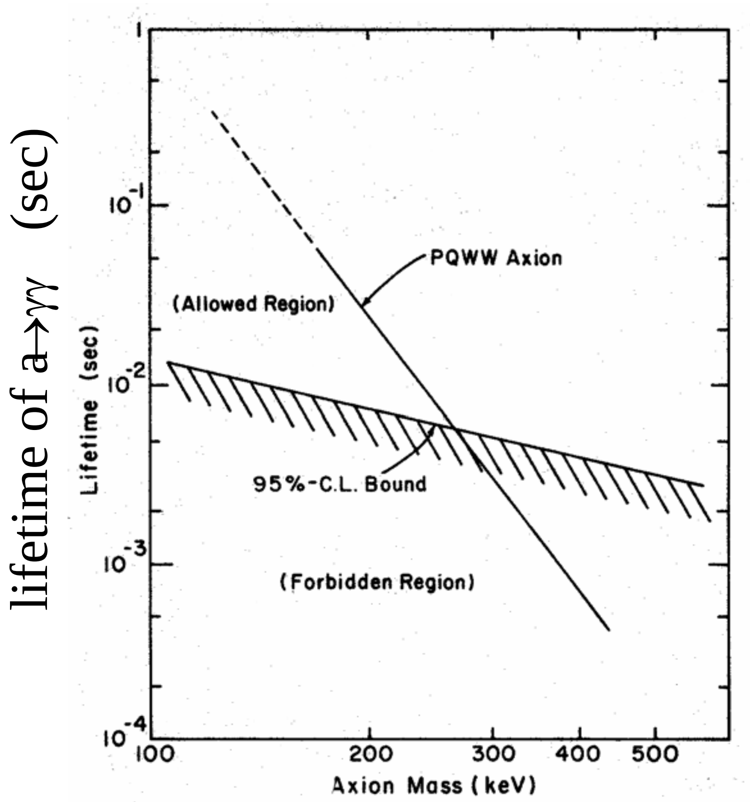


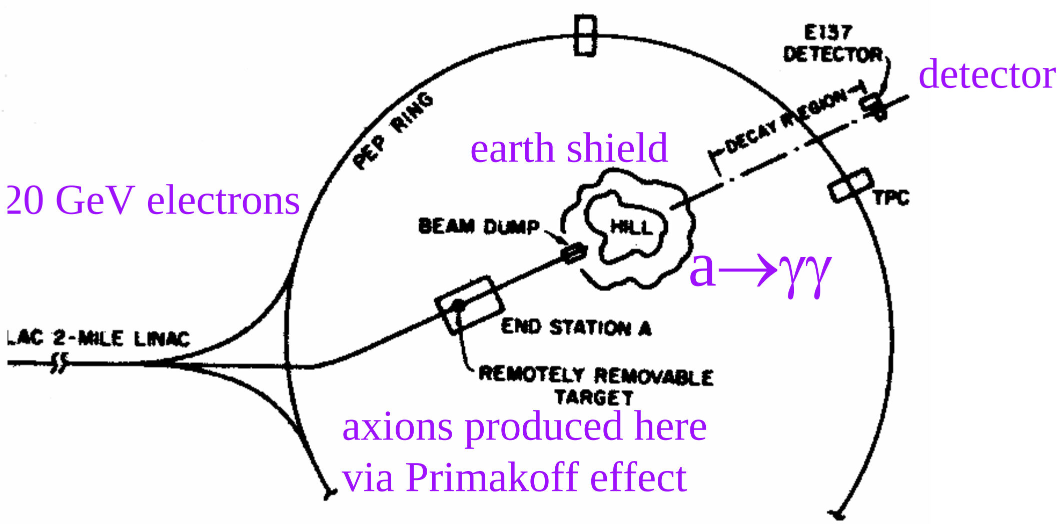
"invisible pooltable straightening mechanism"

Summary of past laboratory searches: A heavy axion is excluded

ADMX

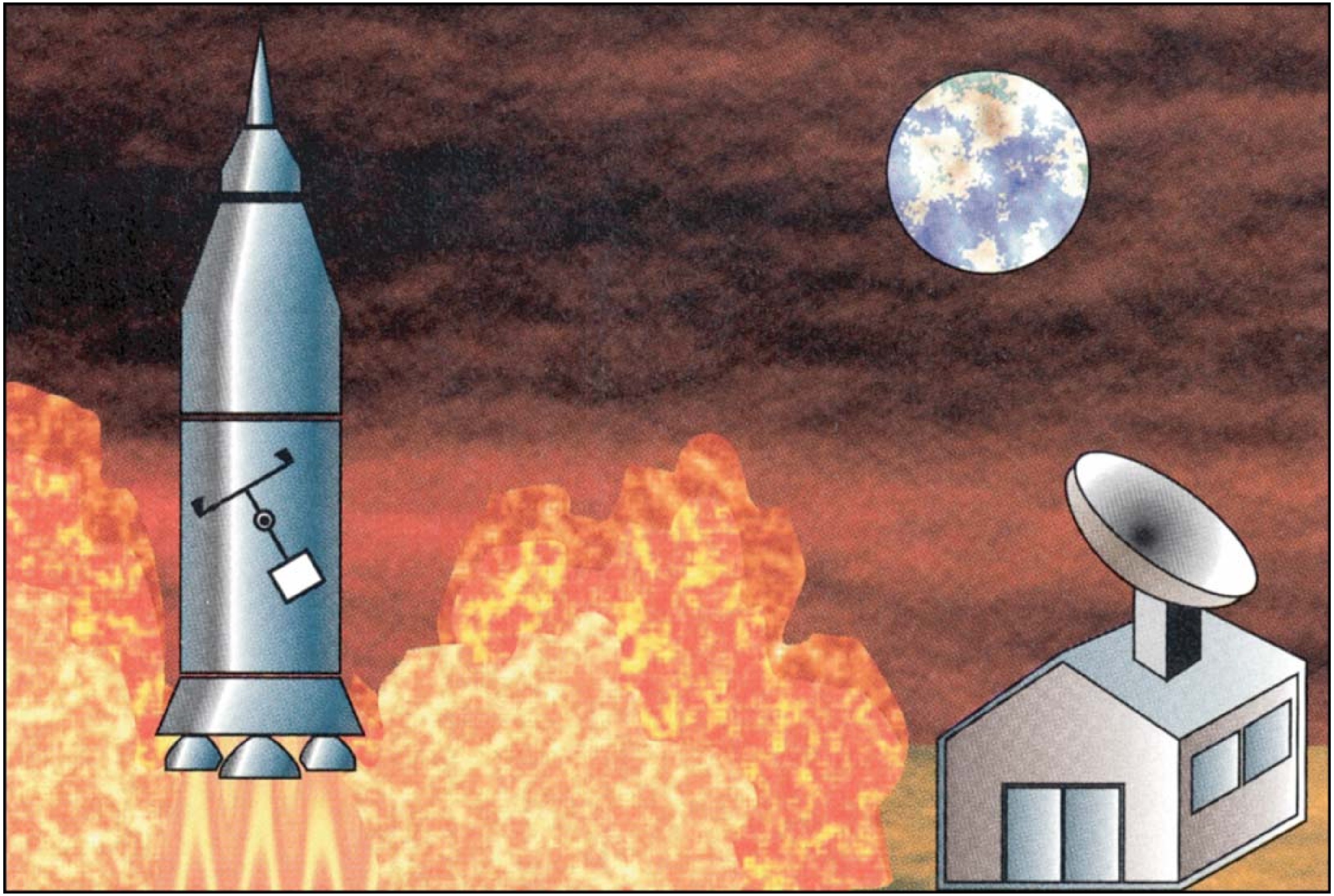
For example: SLAC E137 (Bjorken et al.)



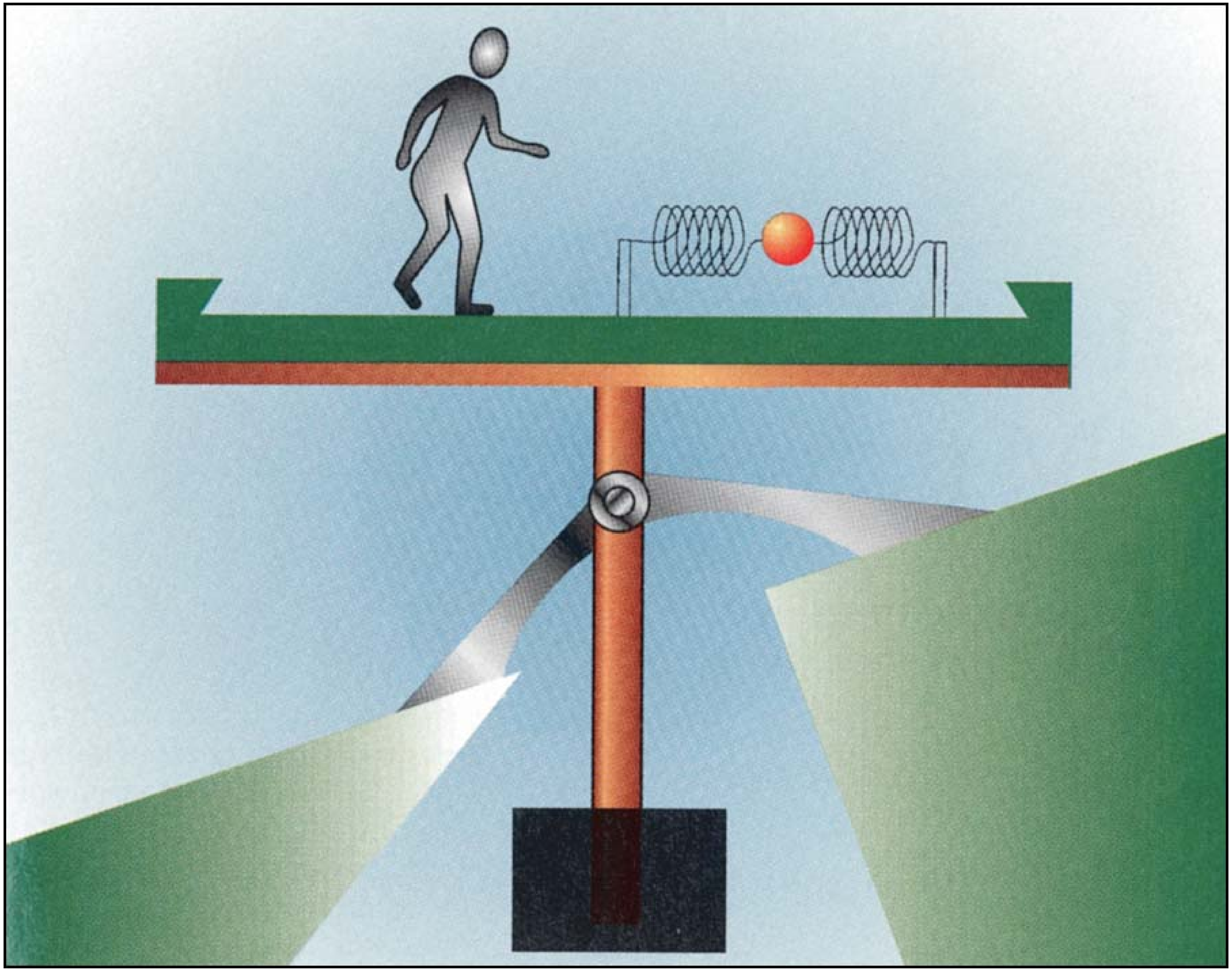


f_{PQ} must be considerably greater than the weak scale

A key insight



A high-Q search for relic oscillations



Completing the analogy $f \longleftrightarrow l$

ADMX

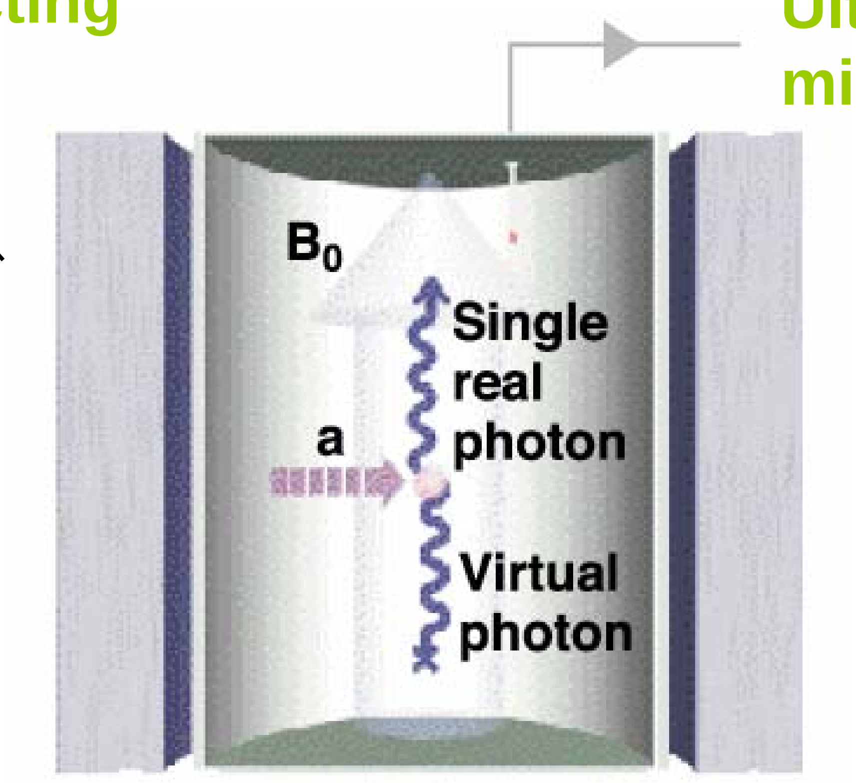
	PQ-symmetry breaking scale	Pendulum length
Quanta m_a (ω)	$\sim f^{-1}$	$\sim l^{-1/2}$
Couplings g	$\sim f^{-1}$	$\sim l^{-1}$
Total energy Ω_a (E)	$\sim f^{7/6}$	$\sim l$

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

ADMX

Superconducting magnet

Ultra-low noise microwave receiver

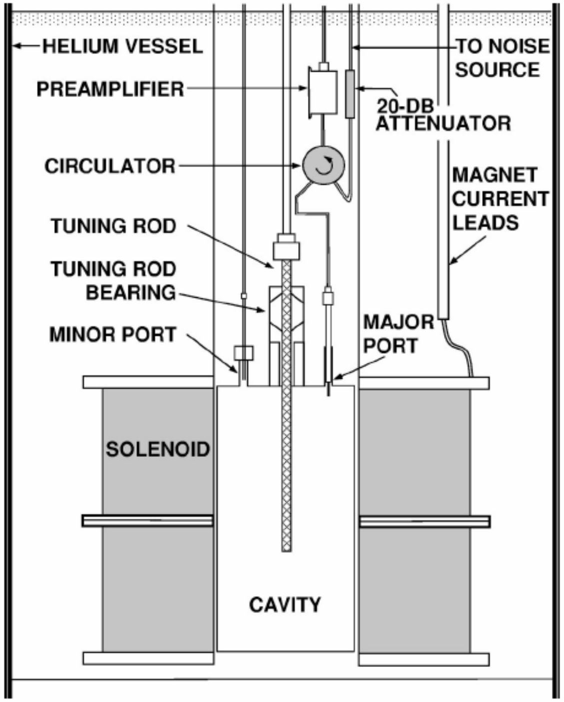


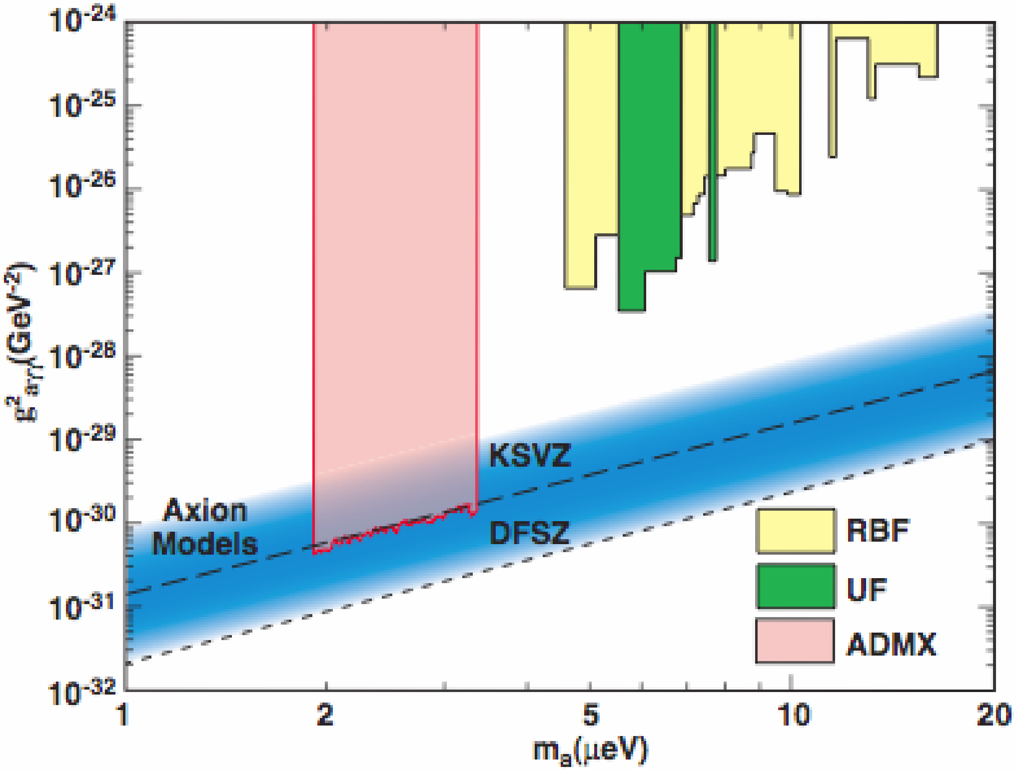
High-Q microwave cavity

The first-generation experiments RBF, UF – 1980's

ADMX

From W. Wuensch *et al.*, Phys. Rev. D40 (1989) 3153



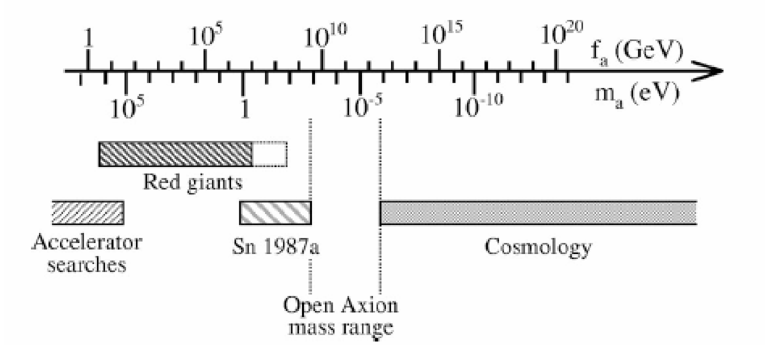


The first-generation experiments already came within a factor of 100-1000 of the desired sensitivity – a stunning achievement

The axion as dark matter candidate

ADMX

Cosmological abundance



$$\Omega_a = (0.5 - 3.0) \cdot \left(\frac{6\,\mu eV}{m_a} \right)^{7/6}$$

Local halo density

Max. likelihood density to multicomponent Milky Way galaxy with all constraints:

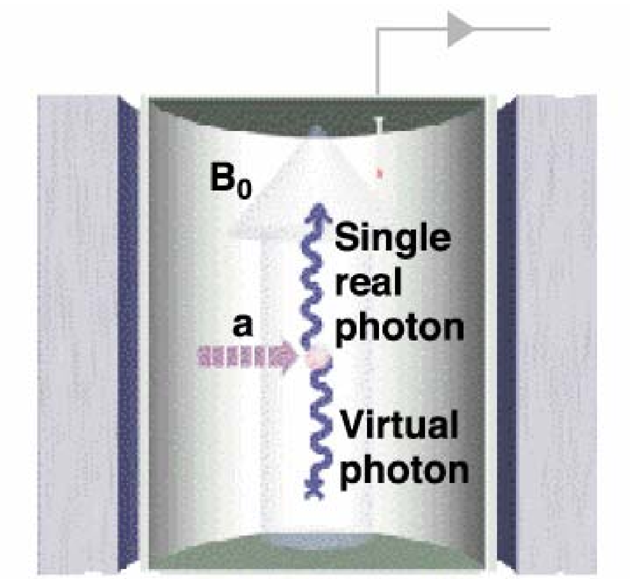
- **Rotation curve**
- **Virial velocity**
- **Projected areal disk density**
- **Microlensing optical depth**

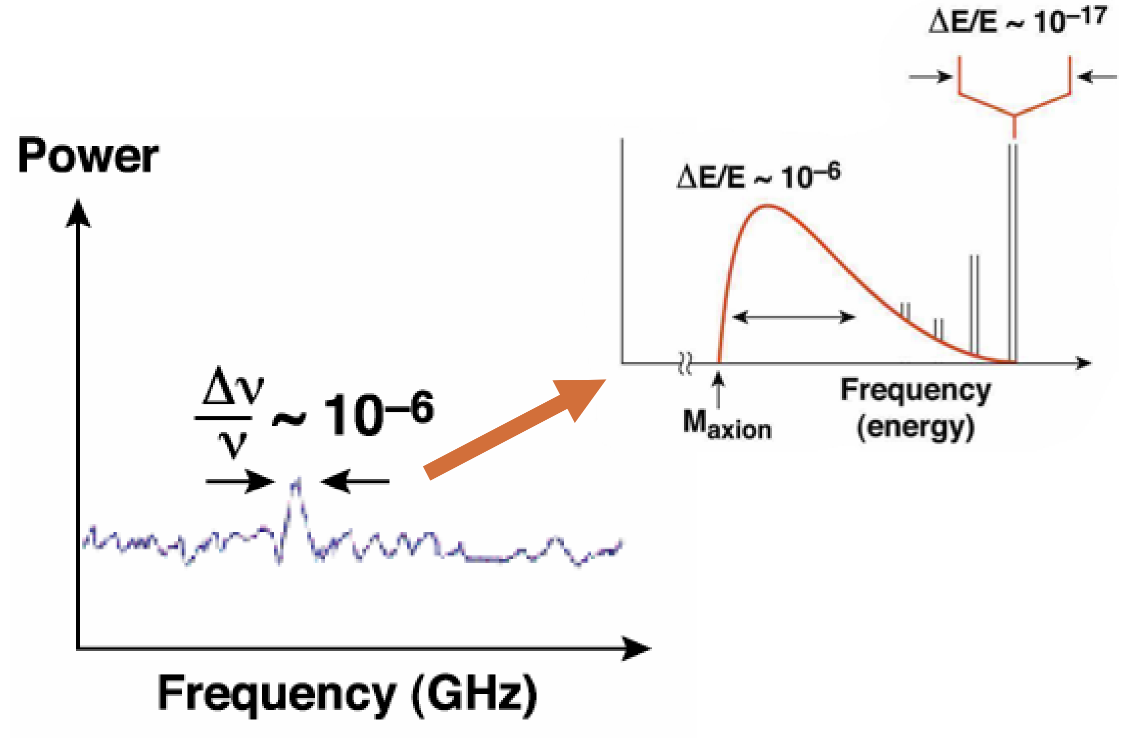
Gates, E.J., G. Gyuk, M.S. Turner, Ap.J. Lett. 449 L123 (1995)

$$\rightarrow \quad \rho_{halo} = 0.45\,^{+0.45}_{-0.15}\; GeV/cm^3$$

The cavity search assumes that axions constitute some or all of the dark matter, but that is a soft assumption for a sufficiently light axion

The signal is the *total energy* of the axion





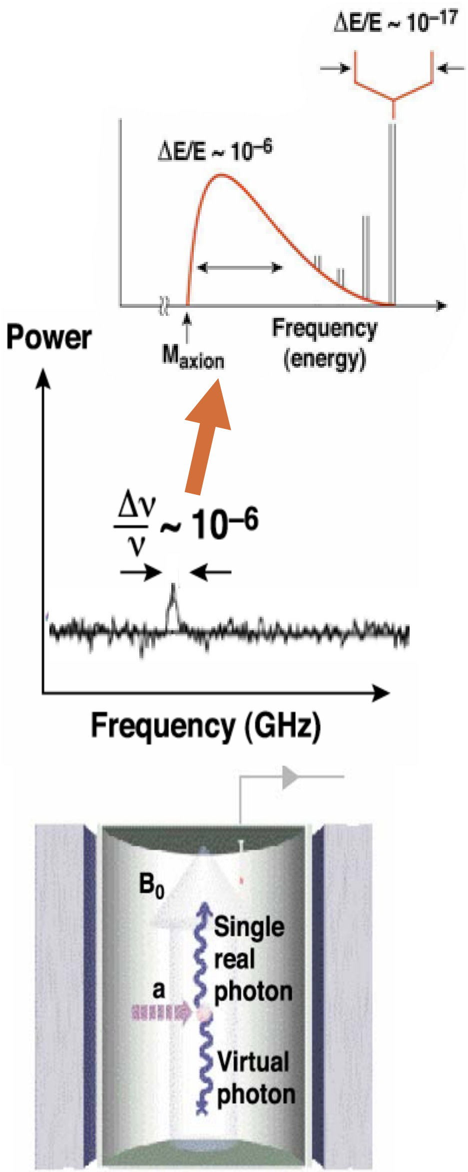
The axion mass range is scanned by tuning the cavity

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

There may be fine structure in the axion signal

Axion halo dark matter – a unique quantum system

ADMX



Axionic dark matter is very dense

Milky Way density: $\rho_{halo} \approx 450\ MeV \cdot cm^{-3}$

Thus if m_a~10μeV: $\rho_{\#} \approx 10^{14}\ cm^{-3}$

Axionic dark matter is highly coherent

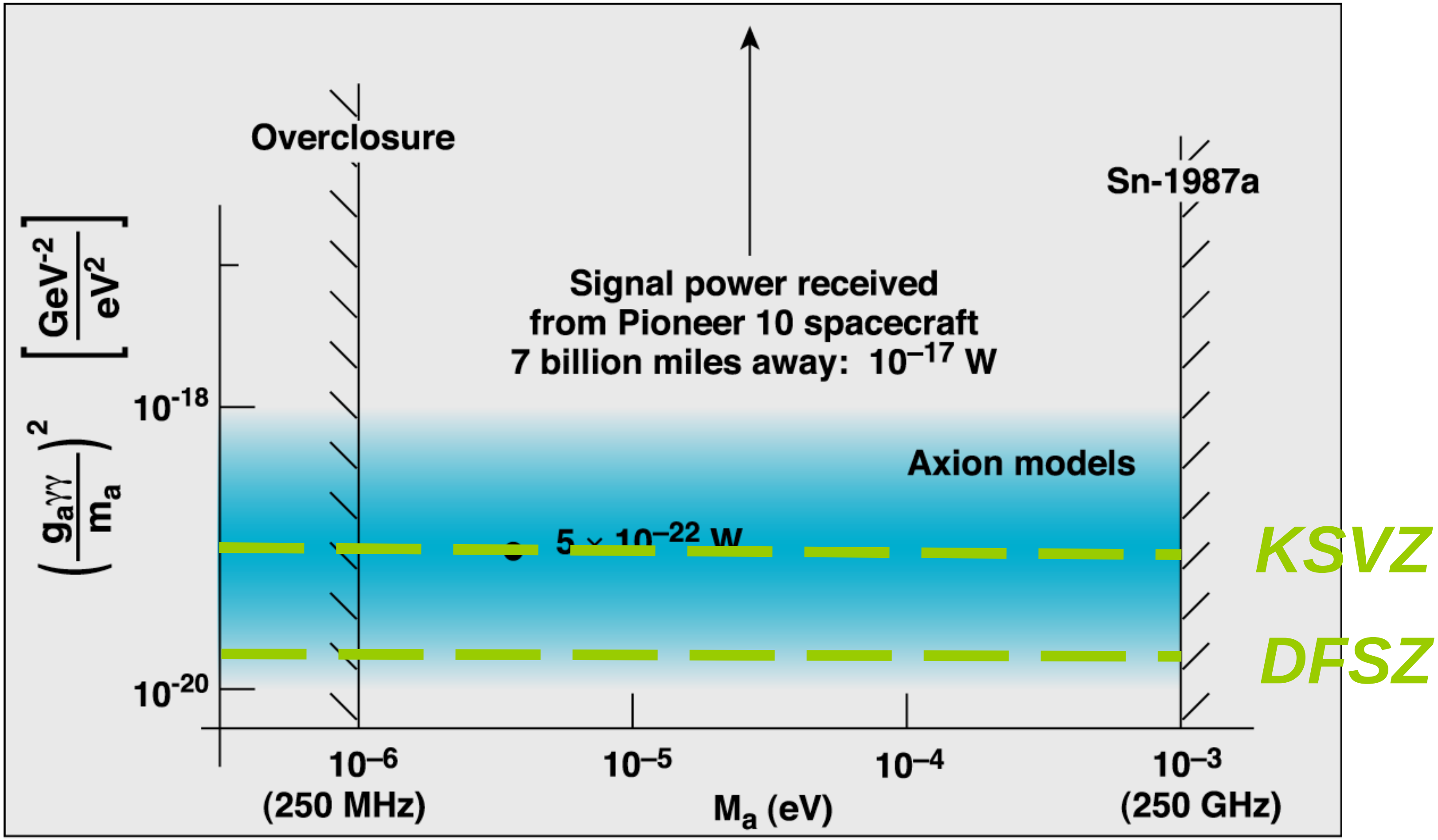
$\beta_{virial} \approx 10^{-3}$ → $\lambda_{De\ Broglie} \approx 100\ m$

$\Delta\beta_{flow} \approx 10^{-7}$ → $\lambda_{Coherence} \approx 1000\ km$

The microwave cavity experiment measures the *total energy* of the axion, thus revealing both Doppler motion and coherence of the axion fluid

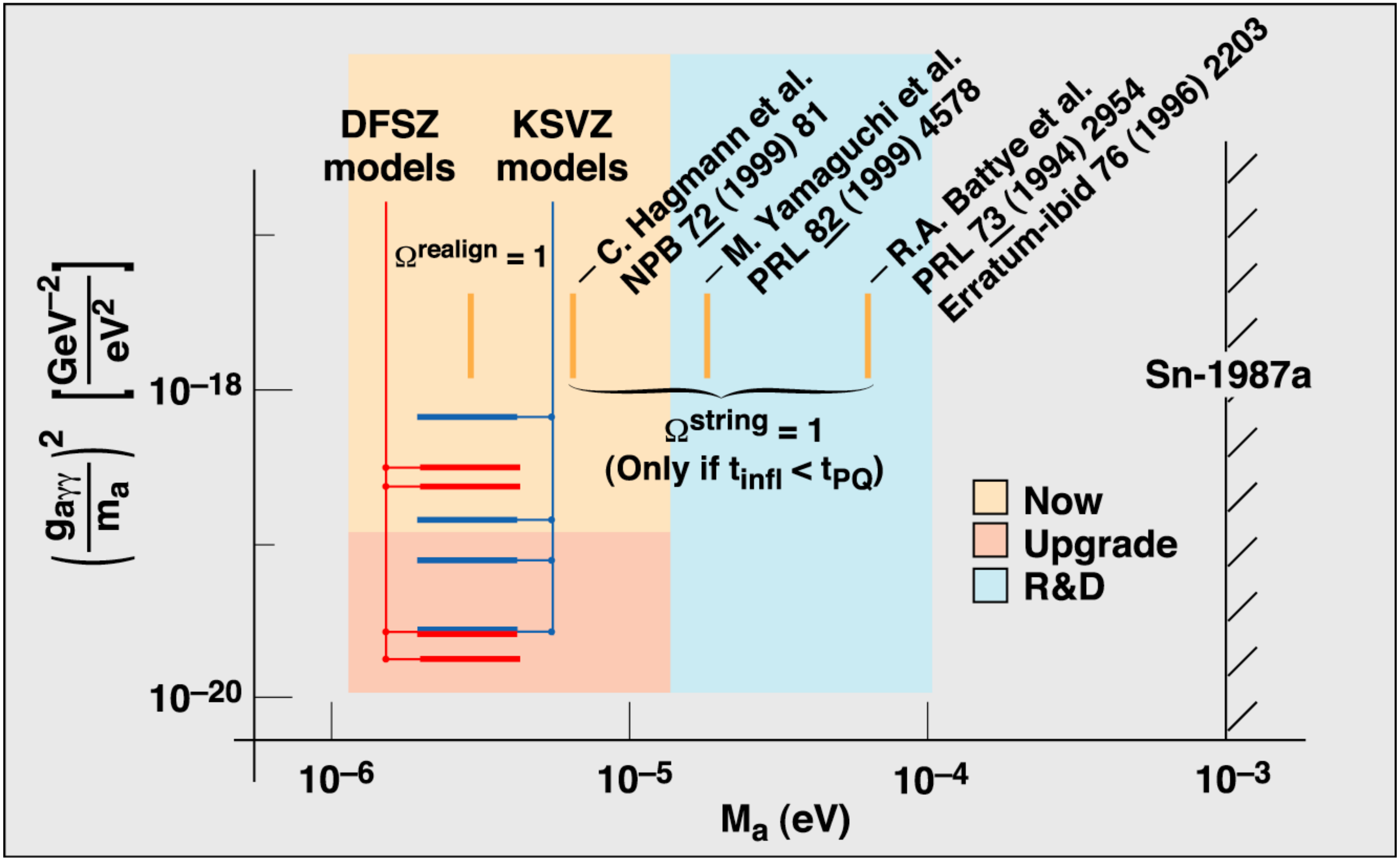
The parameter space is bounded

ADMX



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

The parameter space



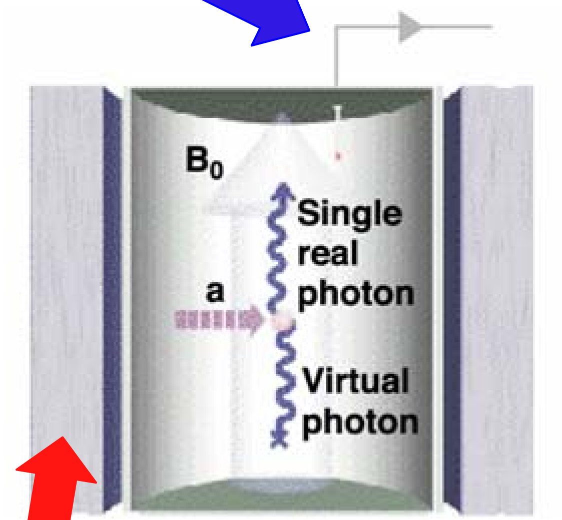
The radiometer eqn.* dictates the strategy

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

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

$P_{sig} \sim (B^2V\ Q_{cav})(g^2 m_a \rho_a)$

$\sim 10^{-22}$ *watts*

Basic formulae

ADMX

Signal power:

$$P_0 = 1.7\times10^{-21}\mathrm{W}\left(\frac{V}{0.2\mathrm{m}^3}\right)\left(\frac{B_0}{7.6T}\right)^2 \times C_{\mathrm{lmn}}\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_\mathrm{a}}{7.5\times10^{-25}\mathrm{g/cm}^3}\right) \times\left(\frac{f}{700\ \mathrm{MHz}}\right)\left(\frac{Q_\mathrm{L}}{90000}\right)\frac{\beta}{(1+\beta)}\frac{1}{1+(2Q_\mathrm{L}\delta f/f_0)^2}$$

Scanning rate:

$$\frac{\mathrm{d}f}{\mathrm{d}t}\approx\frac{15\mathrm{GHz}}{\mathrm{year}}\left(\frac{V}{0.2\mathrm{m}^3}\right)^2\left(\frac{B_0}{7.6T}\right)^4 \times C_{010}^2\left(\frac{g_\gamma}{0.97}\right)^4\left(\frac{\rho_\mathrm{a}}{7.5\times10^{-25}\mathrm{g/cm}^3}\right)^2 \times\left(\frac{f}{700\ \mathrm{MHz}}\right)^2\left(\frac{Q_L}{90000}\right)\frac{\beta^2}{(1+\beta)^2}\left(\frac{5}{\mathrm{SNR}}\right)^2 \times\left(\frac{3K}{T_\mathrm{S}}\right)^2\left(\frac{f_\mathrm{step}}{\Delta f}\right)\sum_{n=-m}^{m}\frac{1}{(1+((2nf_\mathrm{step}/\Delta f))^2)^2}$$

$Q_L = Q_0/(1+\beta)$	*Loaded Q-value; β coupling*	Δf	*Cavity bandwidth*
$\delta f = f - f_0$	*Offset from central*	f_{step}	*Frequency tuning steps*
C_{lmn}	*Cavity form-factor*	n	*Overlapping tuning steps*

Note both the power and scanning rate depend linearly on Q_L

Rules-of-thumb for optimizing the experiment

For scanning at a fixed coupling $g_{a\gamma\gamma}$	$$\frac{1}{f}\frac{df}{dt} \propto (B^2 V)^2 \cdot \frac{1}{T_S{}^2}$$
For scanning at a fixed sweep rate	$$g \propto \frac{1}{B^2 V} \cdot T_S$$

Ideally one wants sufficiently low temperature such that one can:

(i) Be sensitive to the most pessimistic model axion (e.g. DFSZ)

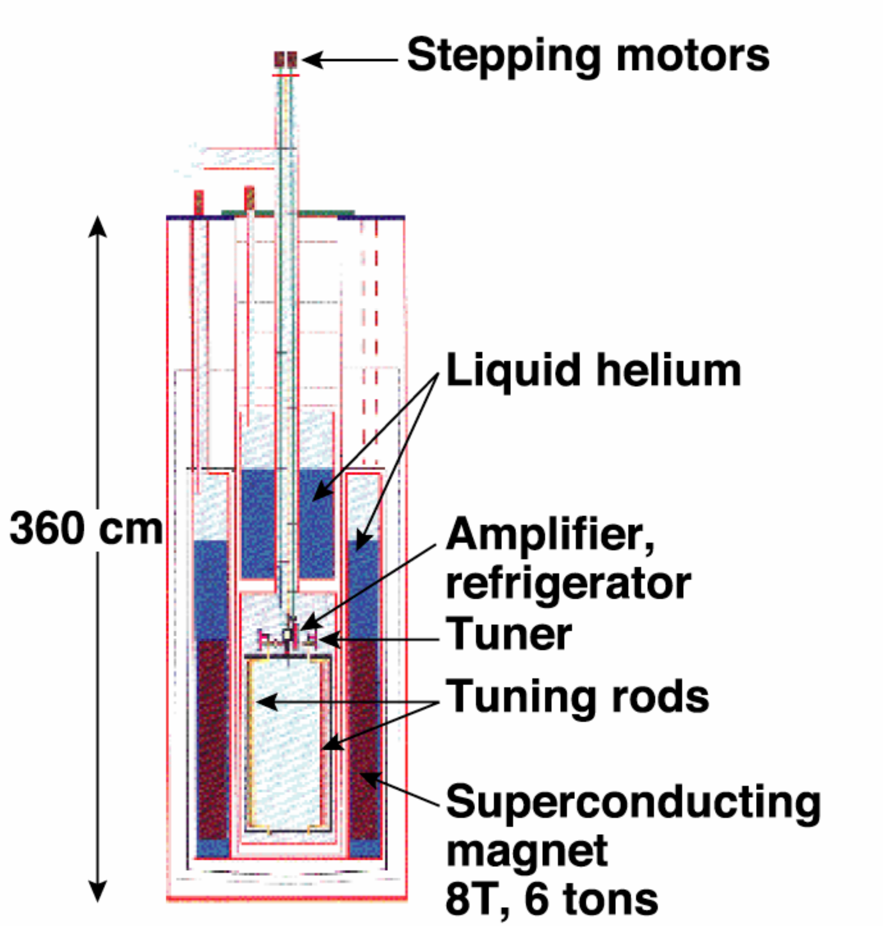
(ii) Which only occupies a fraction of the halo density (e.g. 10%)

(iii) Finish the whole works in a tractable time (e.g.10 yrs)

Axion hardware

ADMX

Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

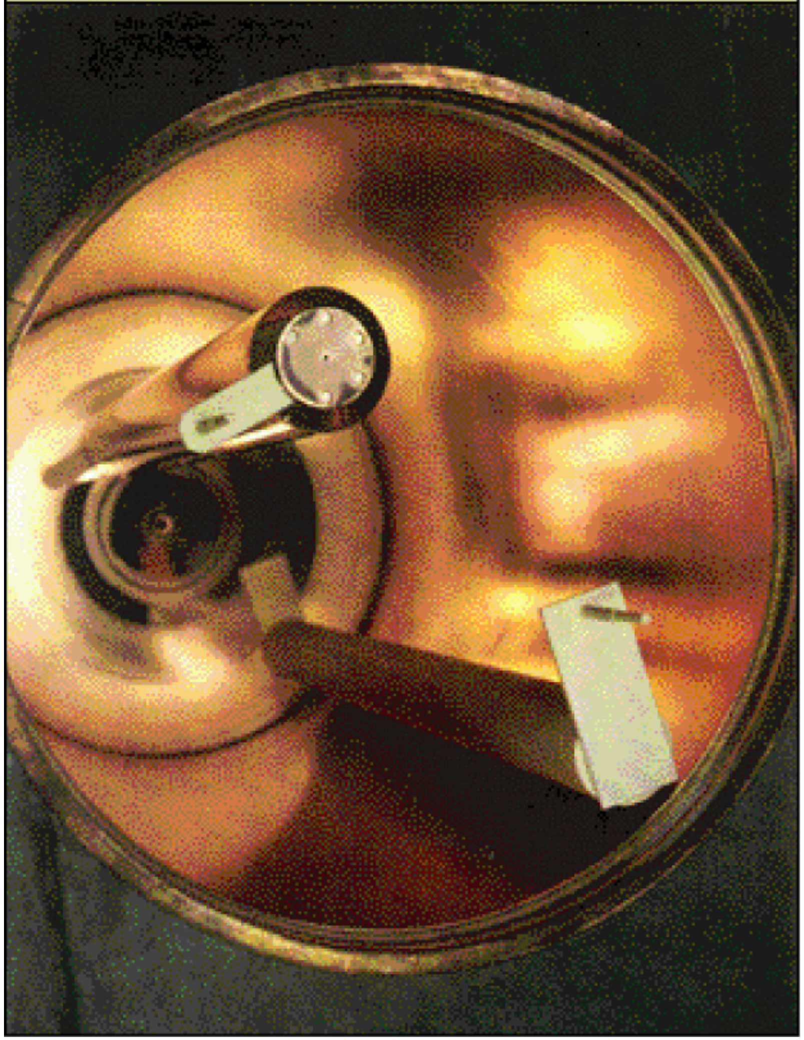
Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm ∅

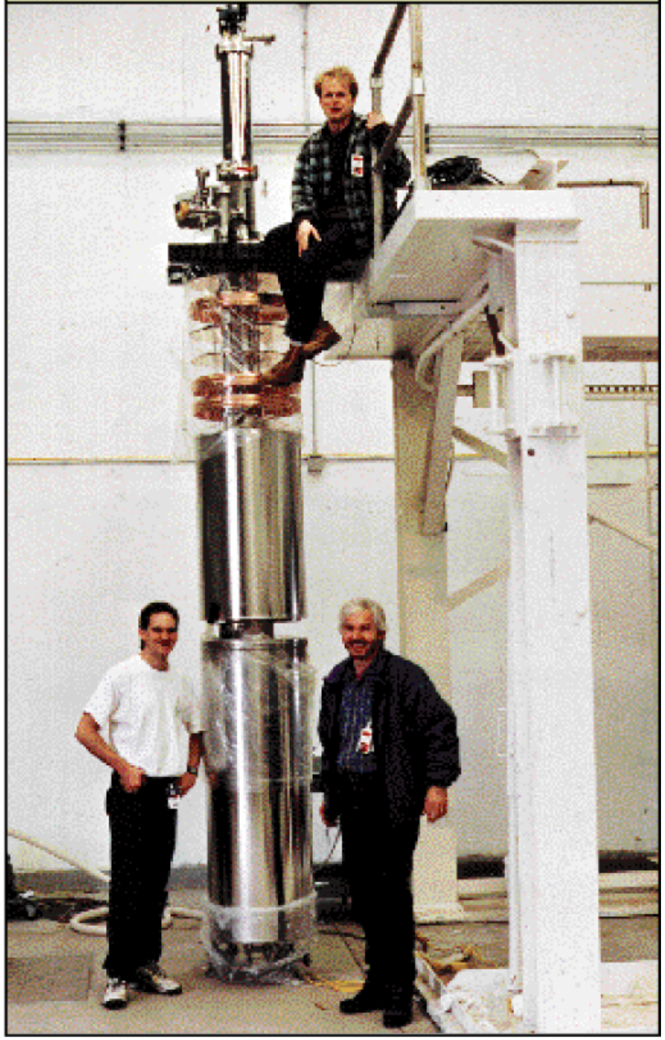
Axion hardware (cont'd)

ADMX

High-Q Cavity (~200,000)

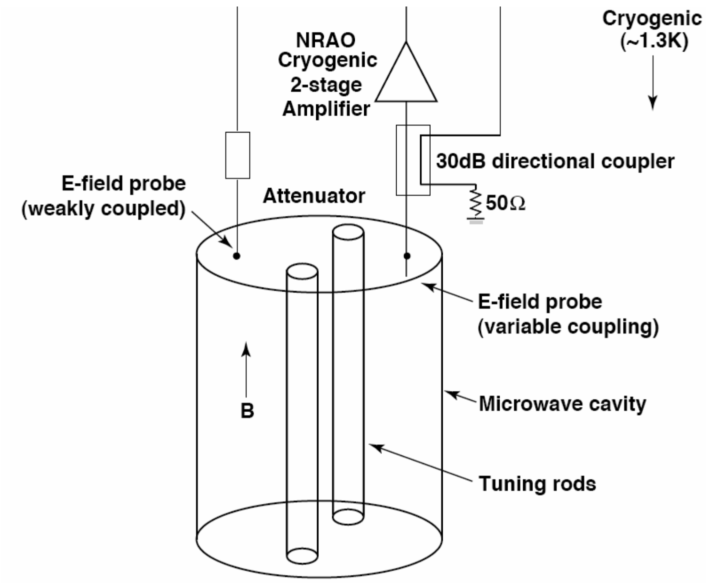


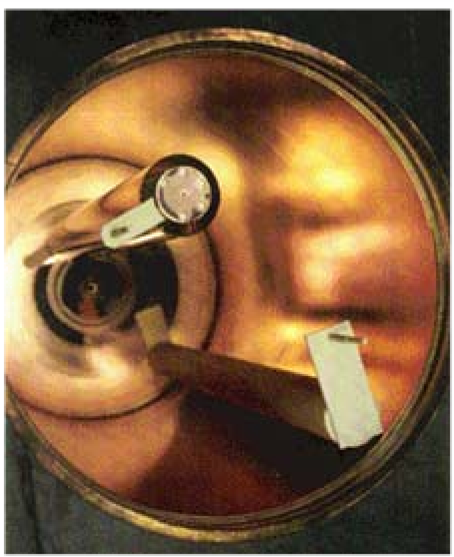
Experimental Insert



Microwave cavity basics (I)

ADMX





Required/desired features:

- ***Cover ~100 MHz to ~100 GHz***
- ***Practical tuning, ± 50%***
- ***High quality factor, $Q \sim 10^5$***
- ***High cavity form-factor, C = O(1)***
- ***Minimal mode-crossings***
- ***Minimal mode-localization***

Simplest – right circular cavity, TM_{010}:

- $E_z = J_0(kr)$ ***(empty)***
- $f_0 = 0.115$ ***GHz / R[m]***
- $C_{010} = 0.69$

$h\nu = mc^2 \longrightarrow m_a = 4.136\ \mu eV \cdot f[GHz]$

Microwave cavity basics (II)

ADMX

Cavity form-factor C_{lmn} (overlap of E, B_{ext}):

$$C_{1mn} = \frac{\left(\int_V \boldsymbol{B}(\boldsymbol{x}) \cdot \boldsymbol{E}_{lmn}(\boldsymbol{x})\, \mathrm{d}^3 \boldsymbol{x} \right)^2}{B_0^{\,2} V \int_V \varepsilon_r(\boldsymbol{x}) \boldsymbol{E}_{lmn}(\boldsymbol{x})^2\, \mathrm{d}^3 \boldsymbol{x}}$$

For uniform B = B_0:

- *$C(TM_{010})$ ~ 0.69*
- *Much smaller for TM_{0n0}*
- *TE, TEM identically 0*

Try to use the TM_{010}-like mode for all configurations

Cavity quality, Q_{lmn}:

$$Q = O \frac{(Volume)}{(Surface\ Area) \cdot (Skin\ Depth)}$$

In high B-field, low-T:

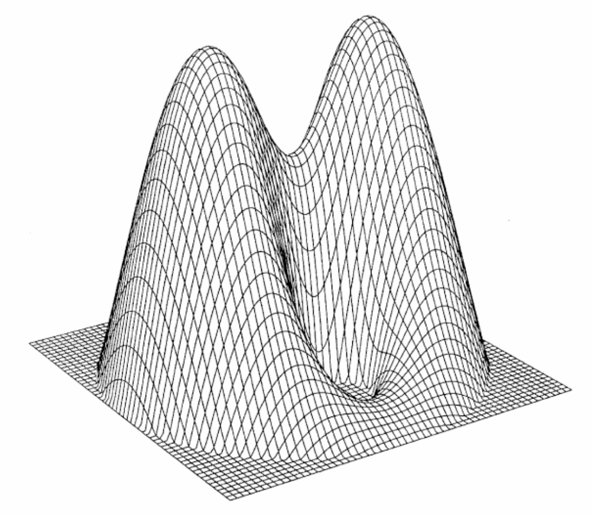
- *Must be copper (not SC!)*
- *Anomalous skin depth limit*

Q limited to few 10^5, but we reach the theoretical max

Microwave cavity basics (III) – Tuning

ADMX

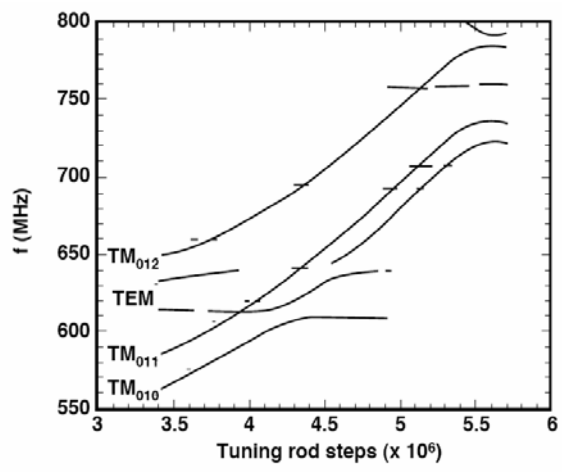
Tuning rods, radial offset

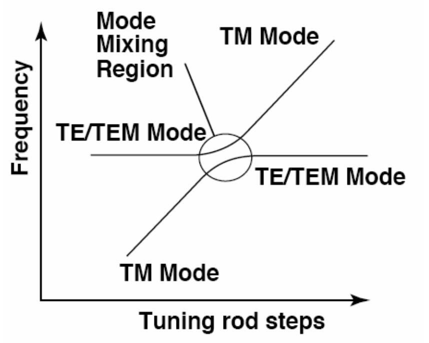


E_z for TM_{010} mode; two metal rods half-way from center

- *Metal - up; dielectric - down*
- *Keep longitudinal symmetry*

Mode-crossings

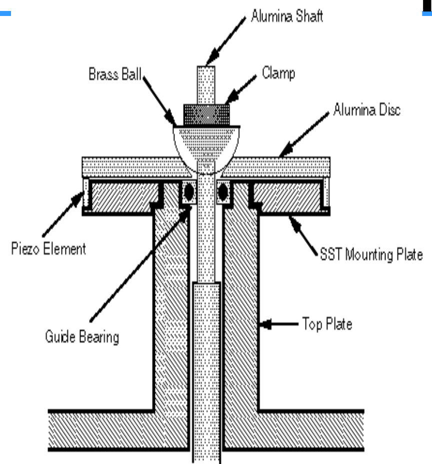


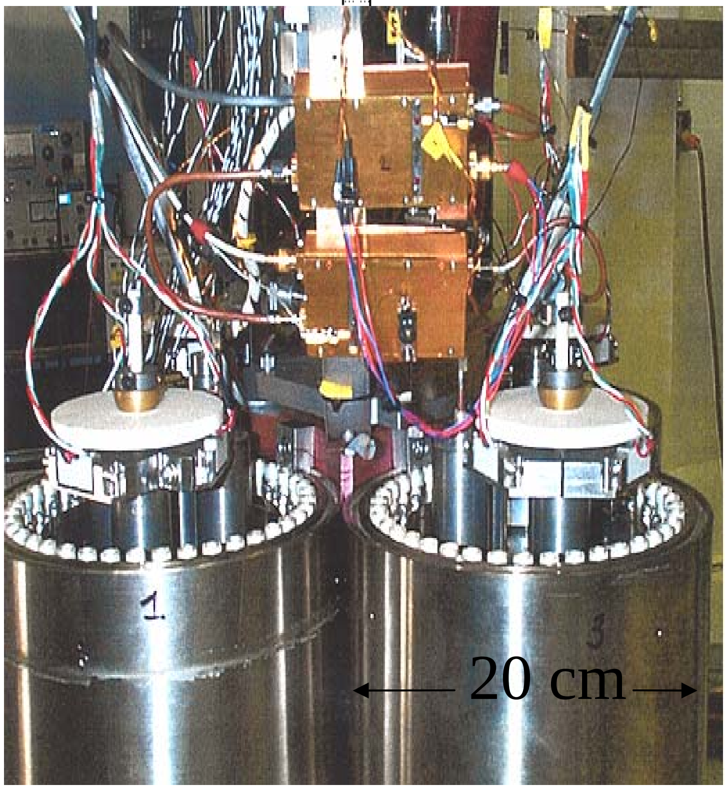


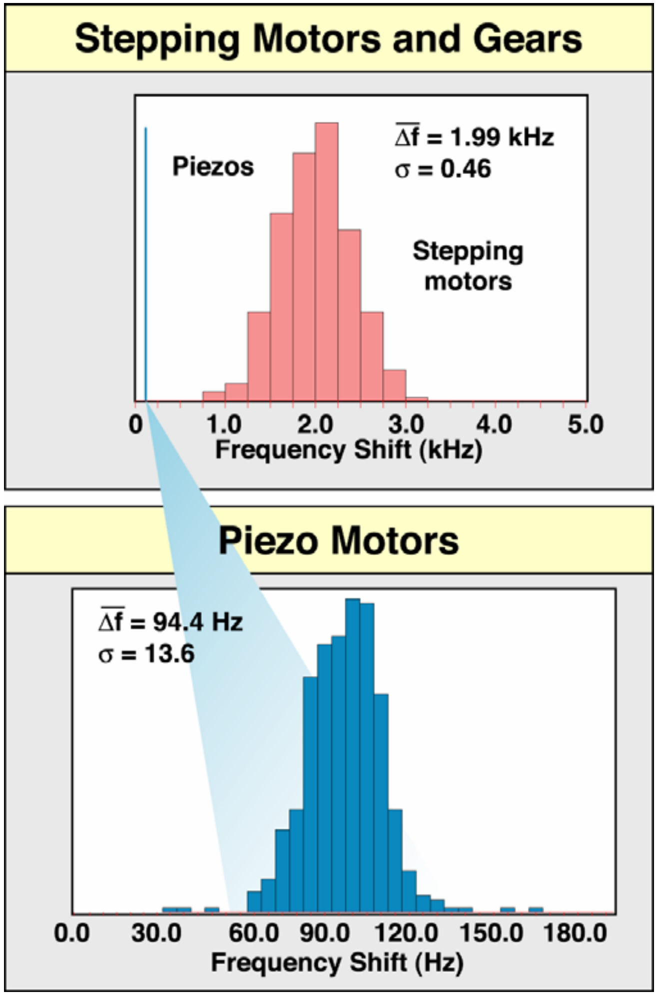
- *Keep cavity aspect ratio L/R low*
- *But can 'walk-around' crossings*

Multiple Cavity Ops

Piezo Tuning System



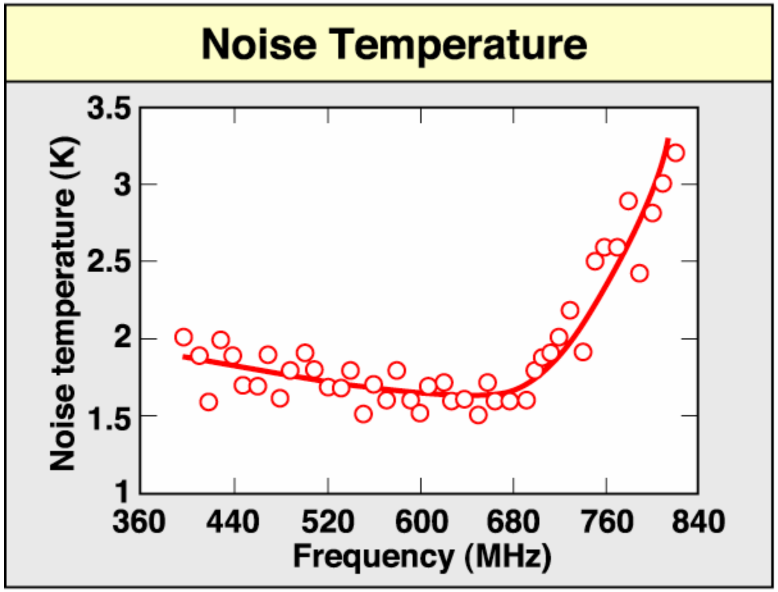


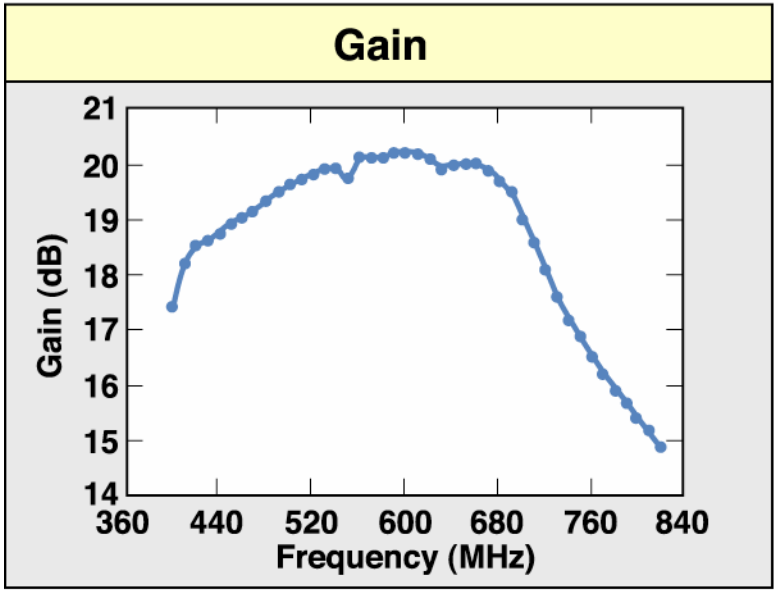


Piezo motors have low power dissipation, work at low temperatures and high magnetic fields

Microwave amplifiers

ADMX





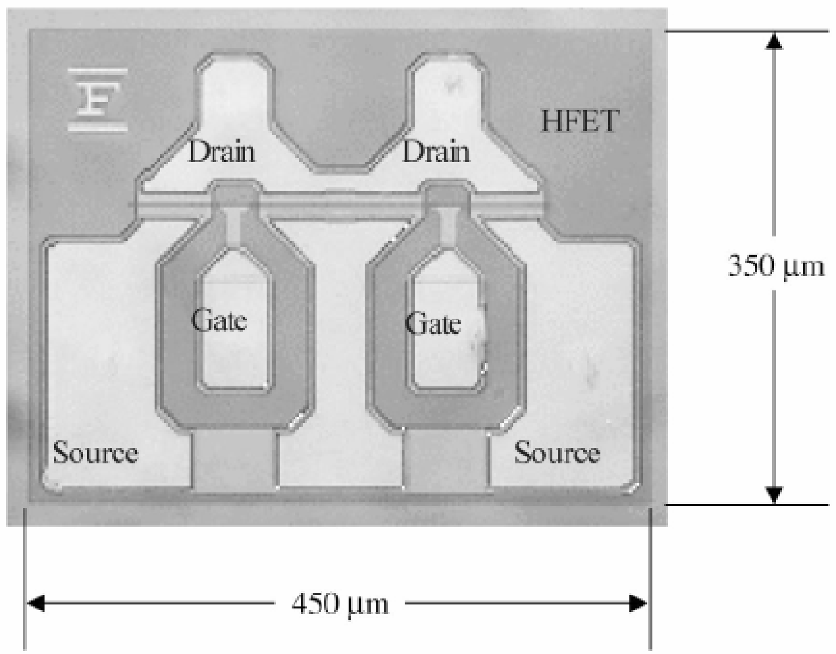
- **Currently HFET amplifiers (Heterojunction Field-Effect Transistor)**
  - **A.k.a. HEMT™ (High Electron Mobility Transistor)**
  - **Workhorse of radio astronomy, military communications, etc.**
- **Best to date $T_N \gtrsim 1$ K**
  - **Independent of T**
  - **Works in magnetic field**

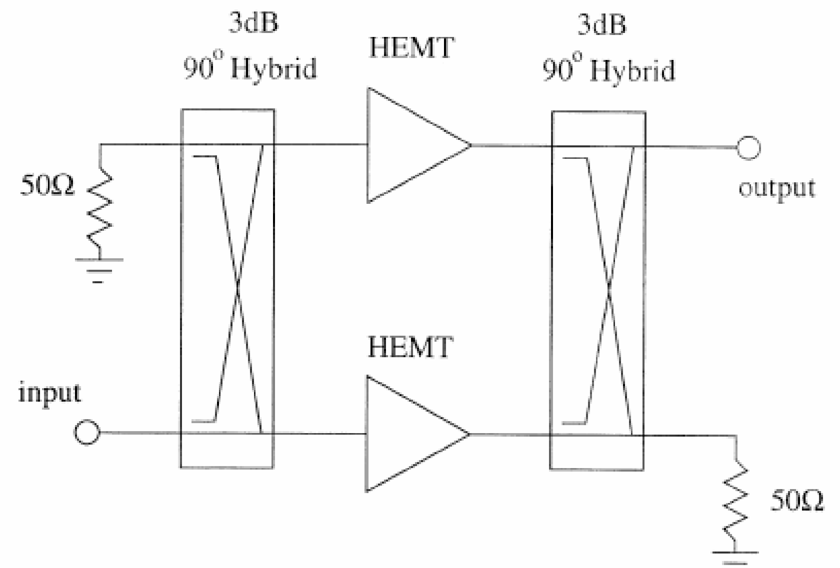
But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!

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

Heterojunction FET (“HEMTs”) & balanced design

ADMX





Donor layer ($Al_xGa_{1-x}As$) separate from gate layer (GaAs), thus eliminating impurity scatterers

Electrons propagate ballistically across the 2D channel (0.25μ length, 300μ wide)

Thus noise is very low

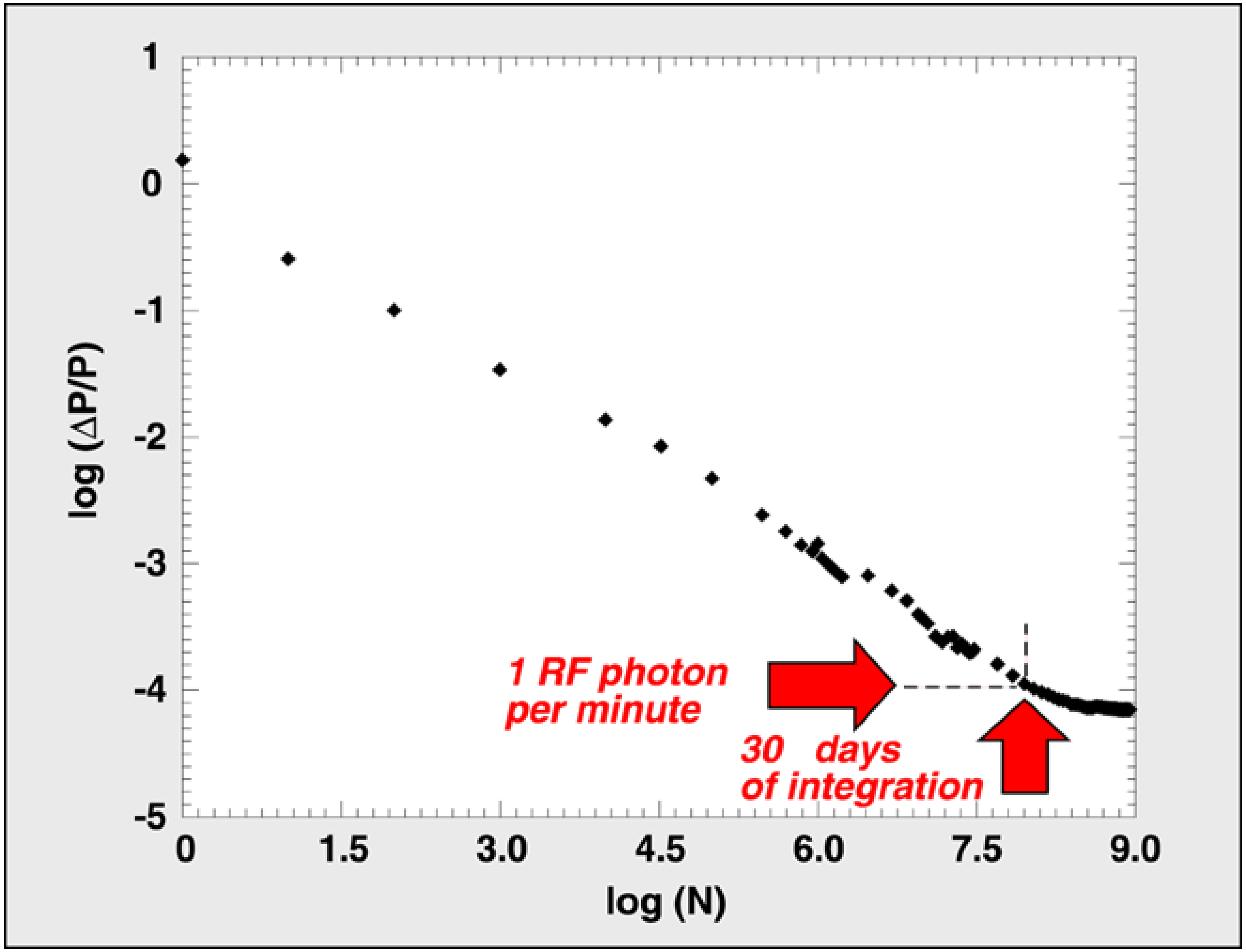
Resonant cavities represent a complex frequency dependent input impedance $Z_0(w-w_0)$

Hybrid design minimizes input reflection, providing broad-band match to the complex cavity load

There is a small penalty in noise

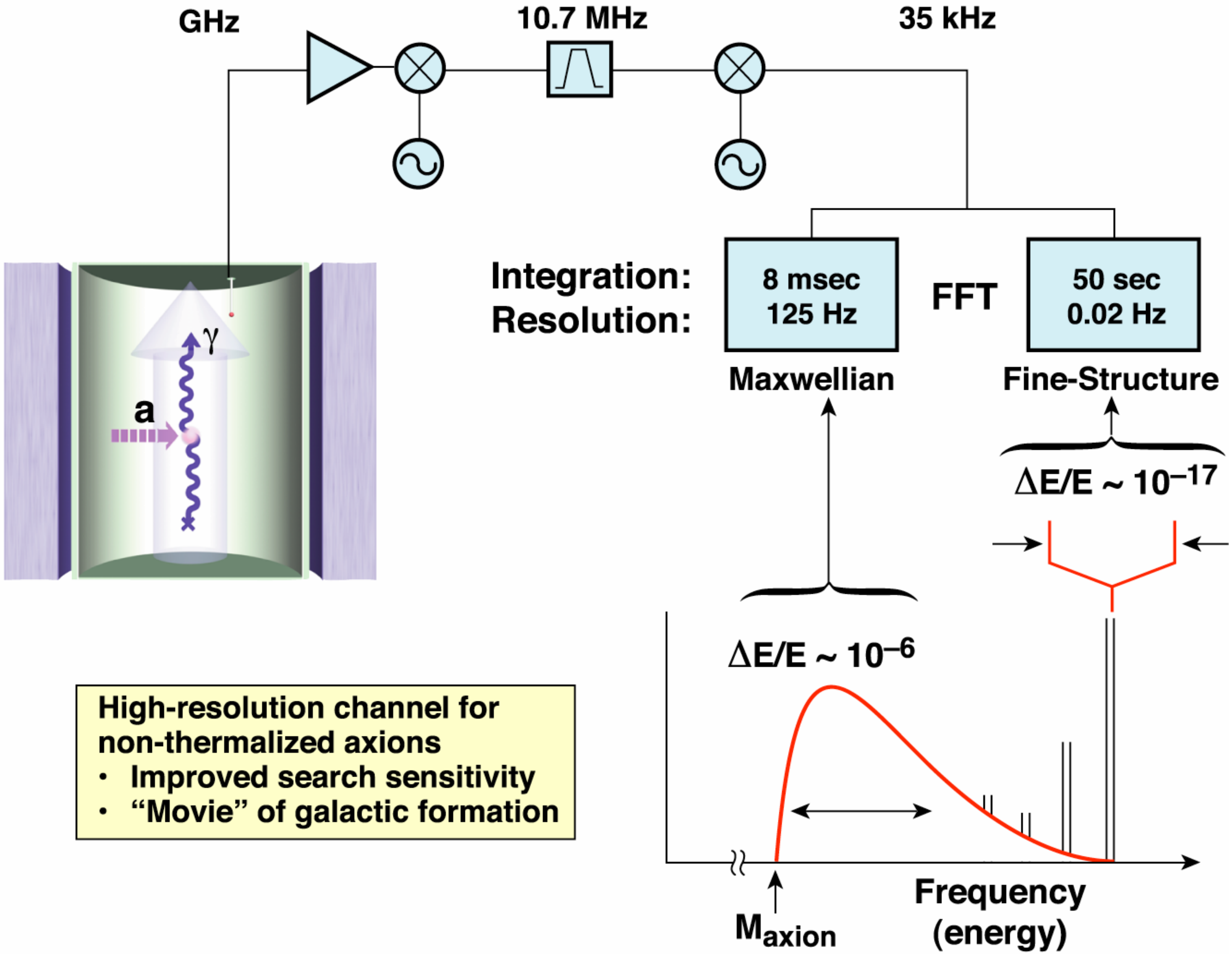
The world's quietest receiver — by 10^4!

ADMX



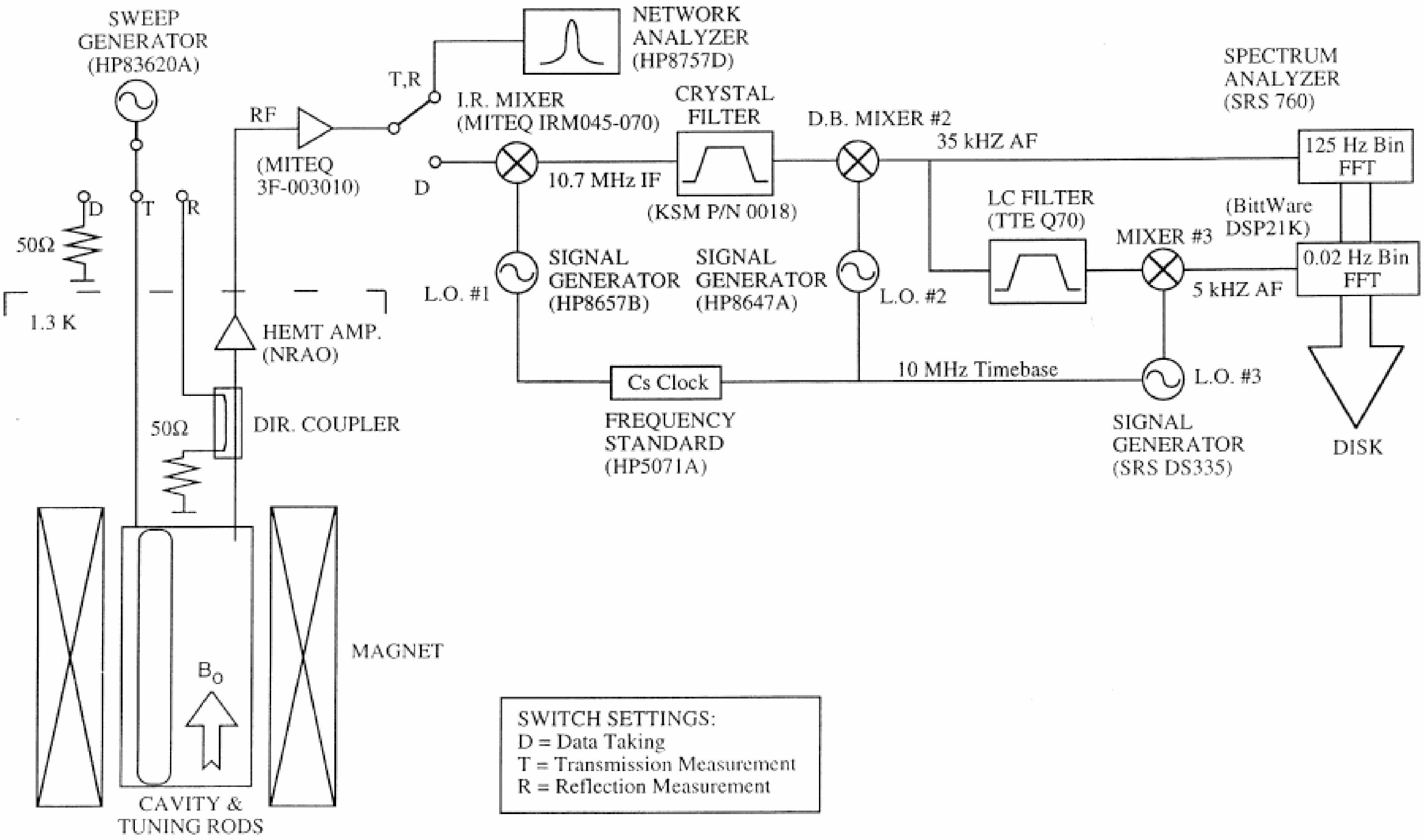
We are systematics-limited for signals of 10^{-26} W — 10^{-3} of DFSZ axion power!

The axion receiver, and high-resolution search *ADMX*



High-resolution channel for non-thermalized axions
- **Improved search sensitivity**
- **"Movie" of galactic formation**

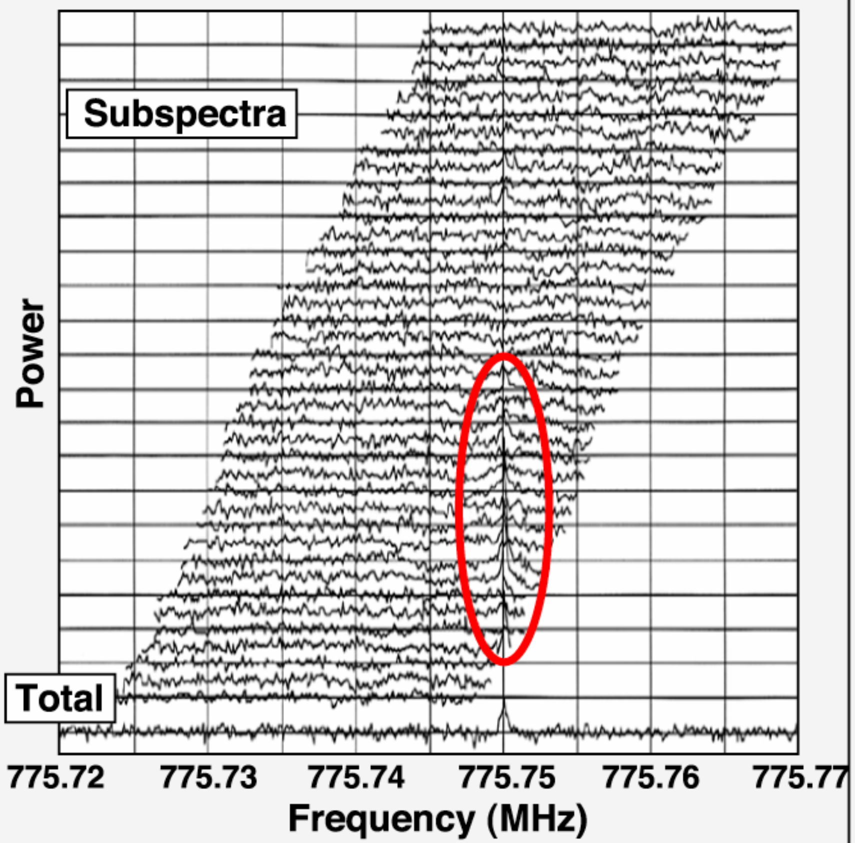
The real receiver



Sample data and candidates

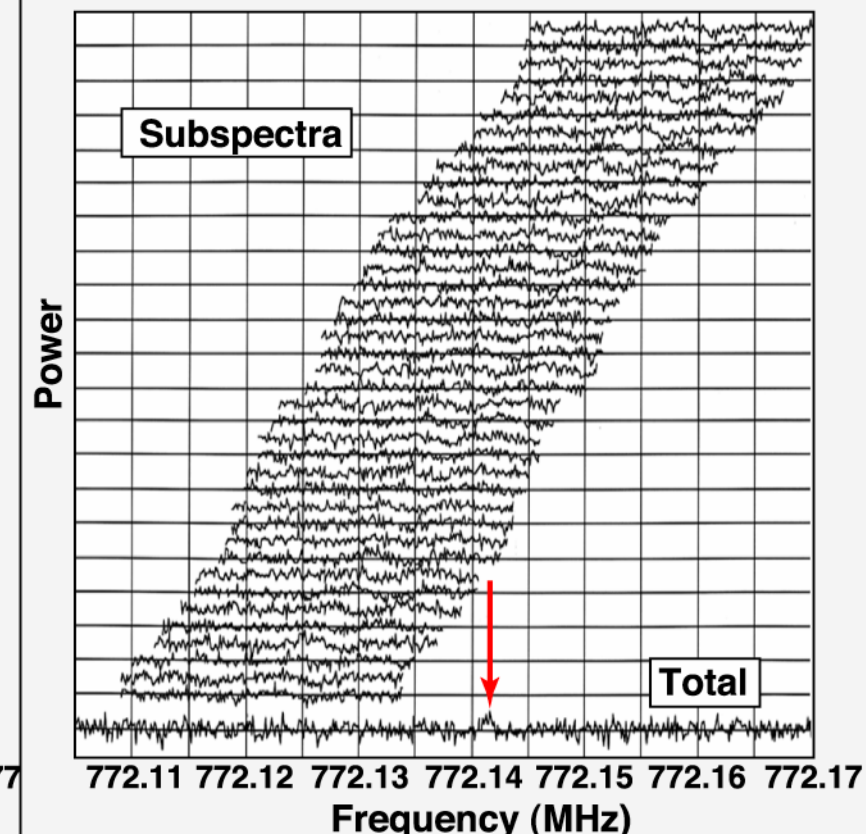
ADMX

Environmental



Signal maximizes off-resonance: Radio peak

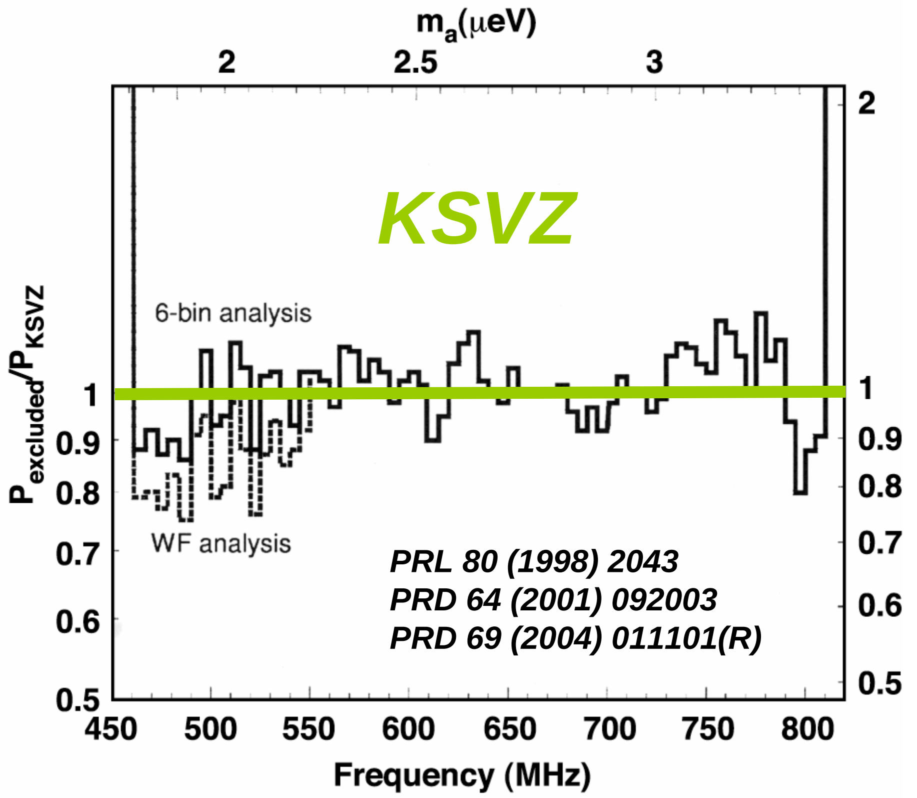
Statistical

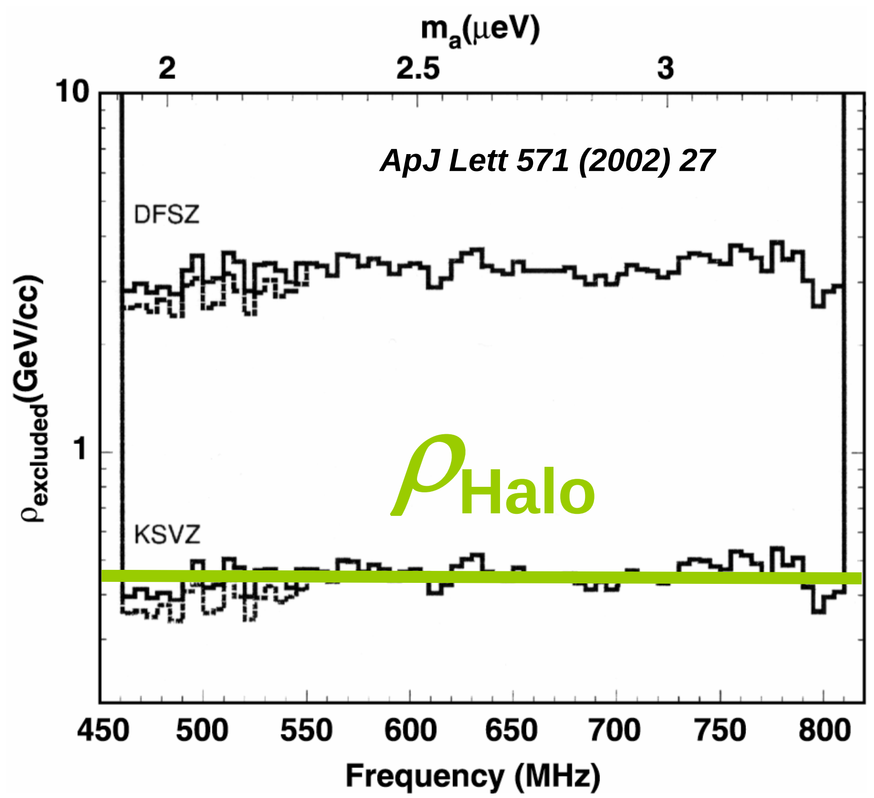


Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

Limits on axion models and local axion halo density

ADMX



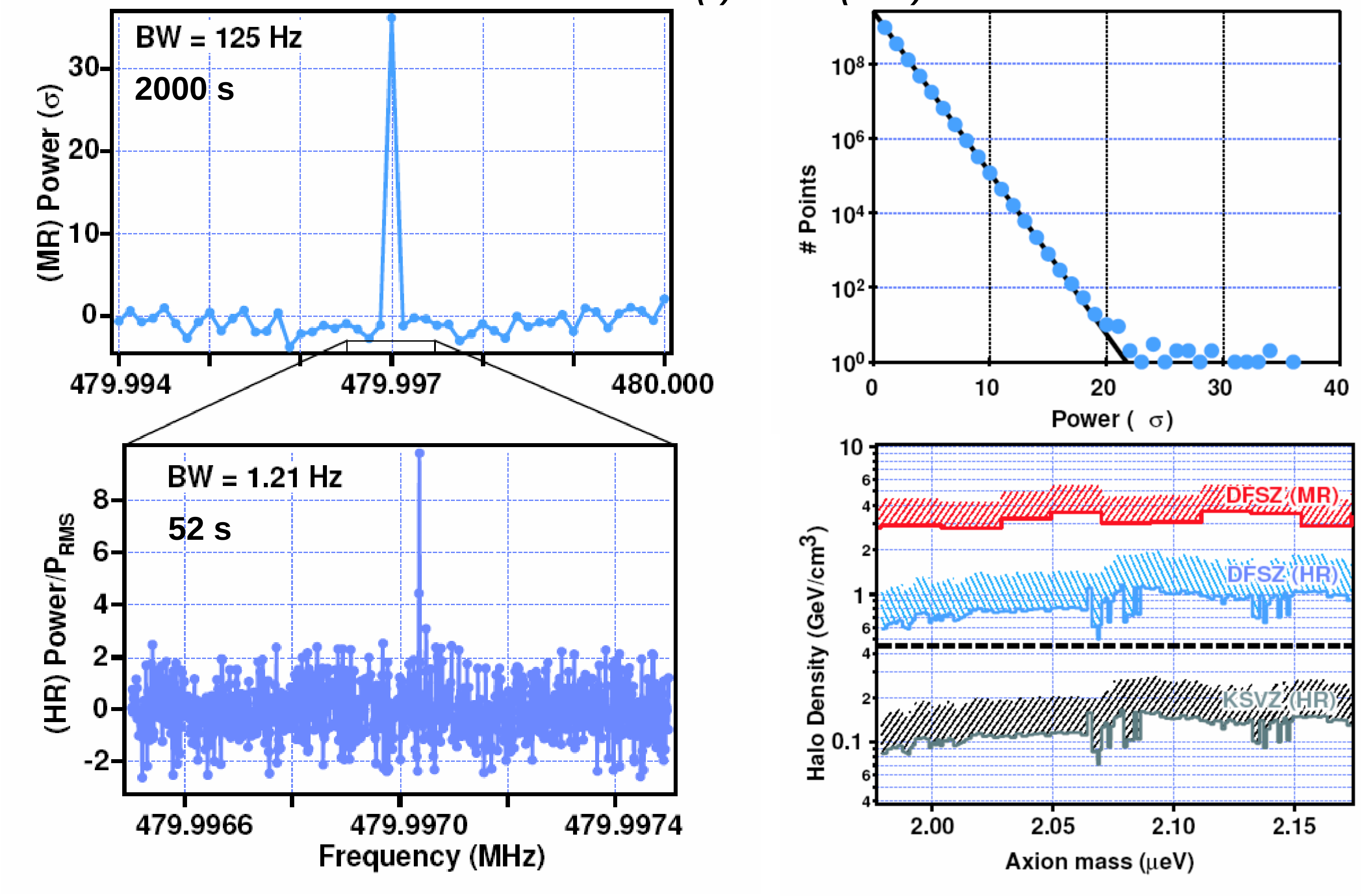


Plausible models have been excluded at the halo density over an octave in mass range

Results of a high-resolution analysis

ADMX

PRL 95 (9) 091304 (2005)

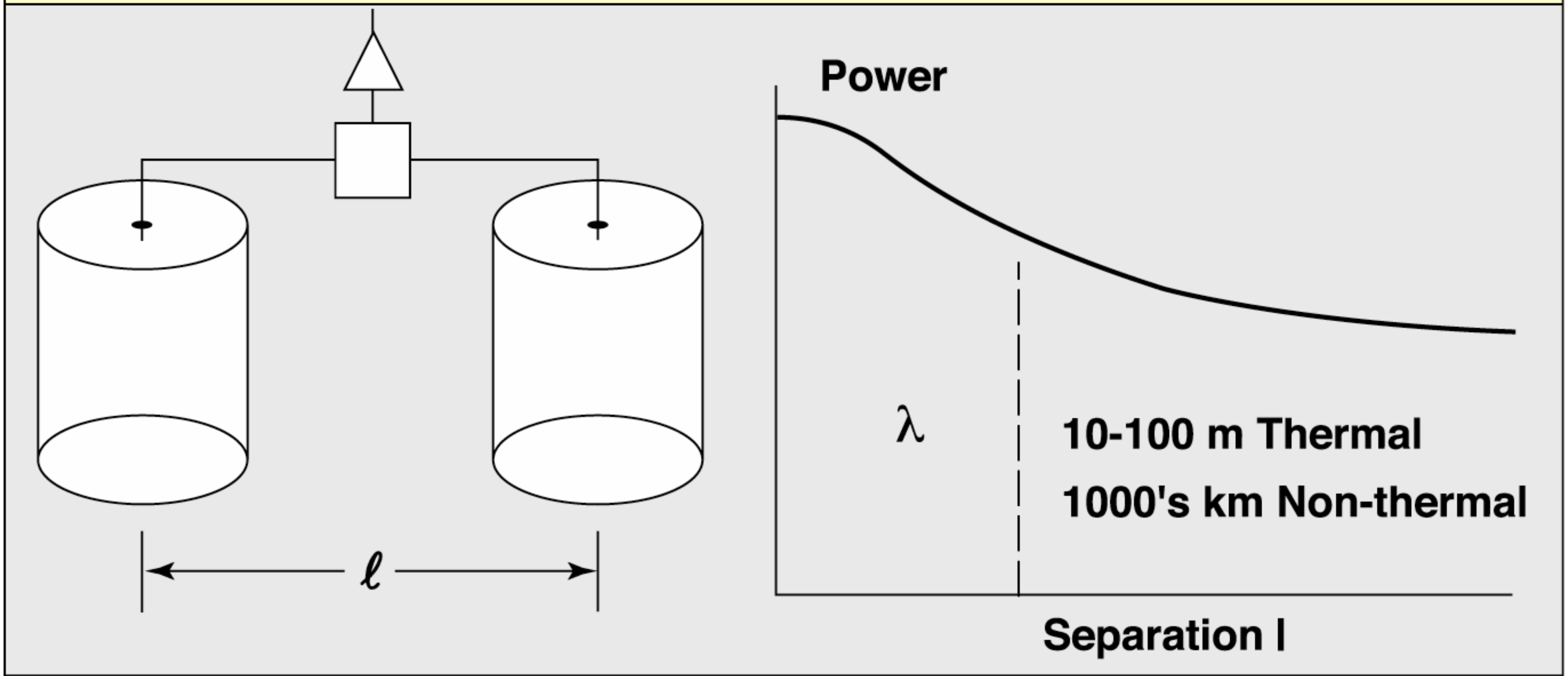


Measured power in environmental (radio) peak same in both channels

What if the axion is found?

ADMX

The Study of Unique Quantum System



And should the axion posses fine-structure, it would constitute a "movie" of the formation of our Milky Way galaxy