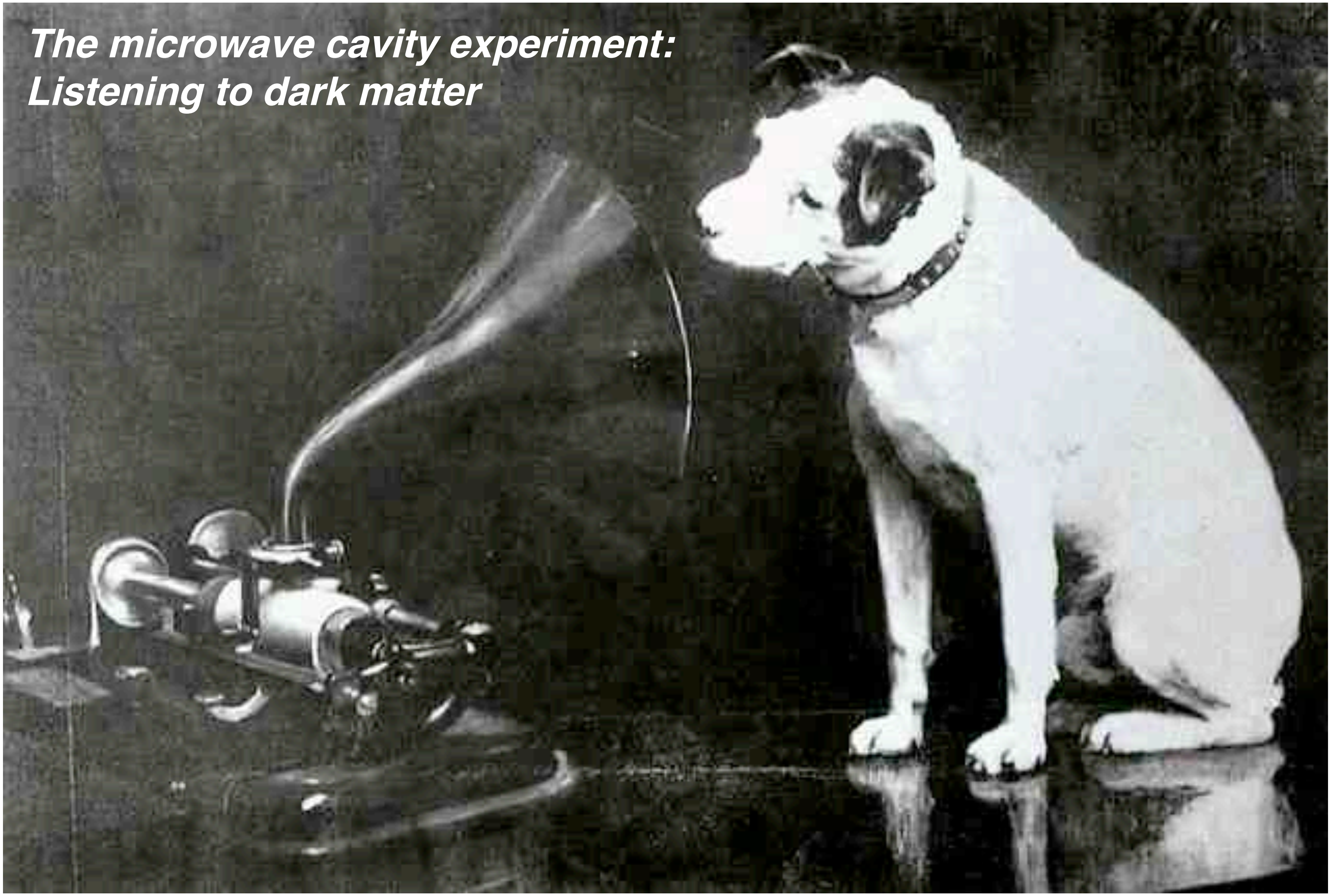
The microwave cavity experiment: Listening to dark matter



Joint ILIAS-CAST-CERN Axion Training – Karl van Bibber, LLNL – 2 December 2005

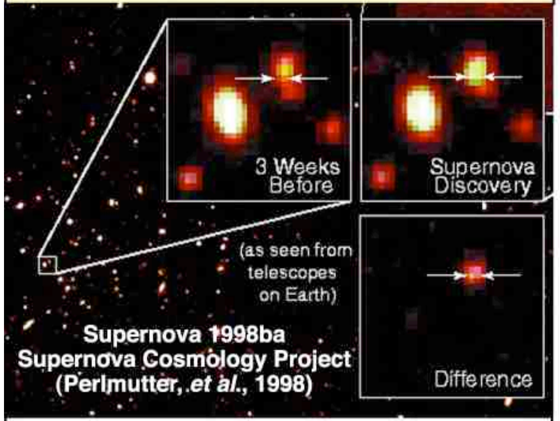
AXION

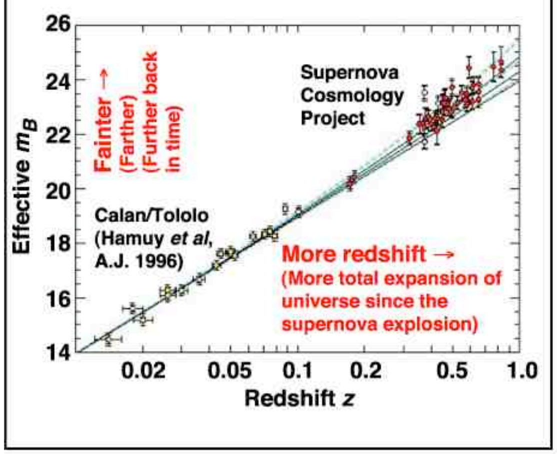
Outline

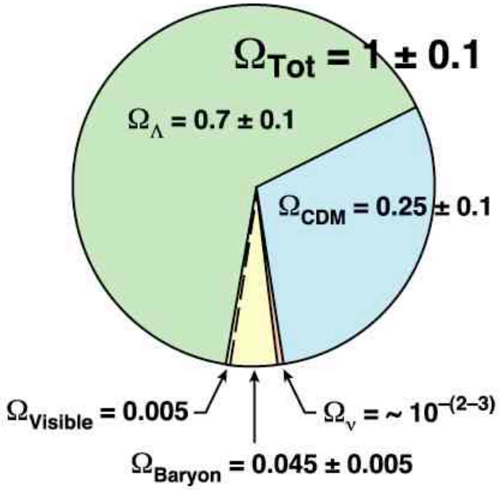
- Brief review of dark matter
- Principle of microwave cavity experiment
- Technical implementation
  - Magnet
  - Microwave cavities
  - Amplifier and receiver
- Data analysis
- Results
- Future developments
  - SQUID amplifiers
  - Rydberg-atom single-quantum detectors
  - Challenge of higher frequencies
- Summary, conclusions
- Final remarks

The advent of "precision cosmology"

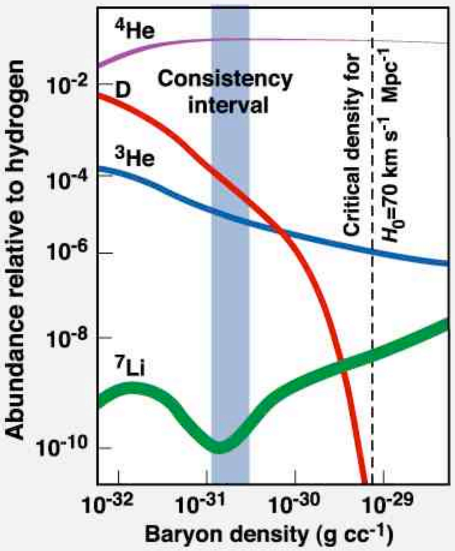
Sn-Ia: $\Omega_\Lambda - \Omega_M$



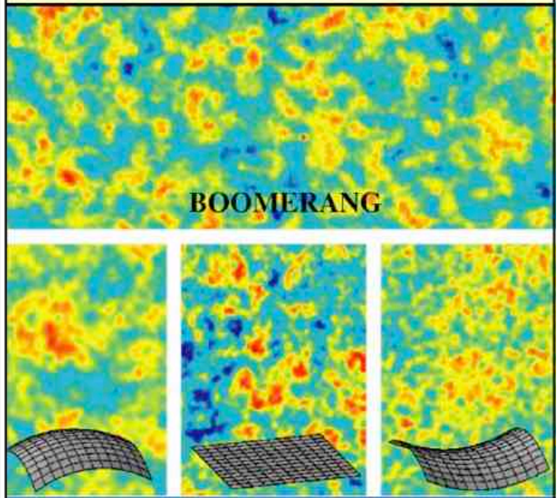




Primordial Nucleosynthesis

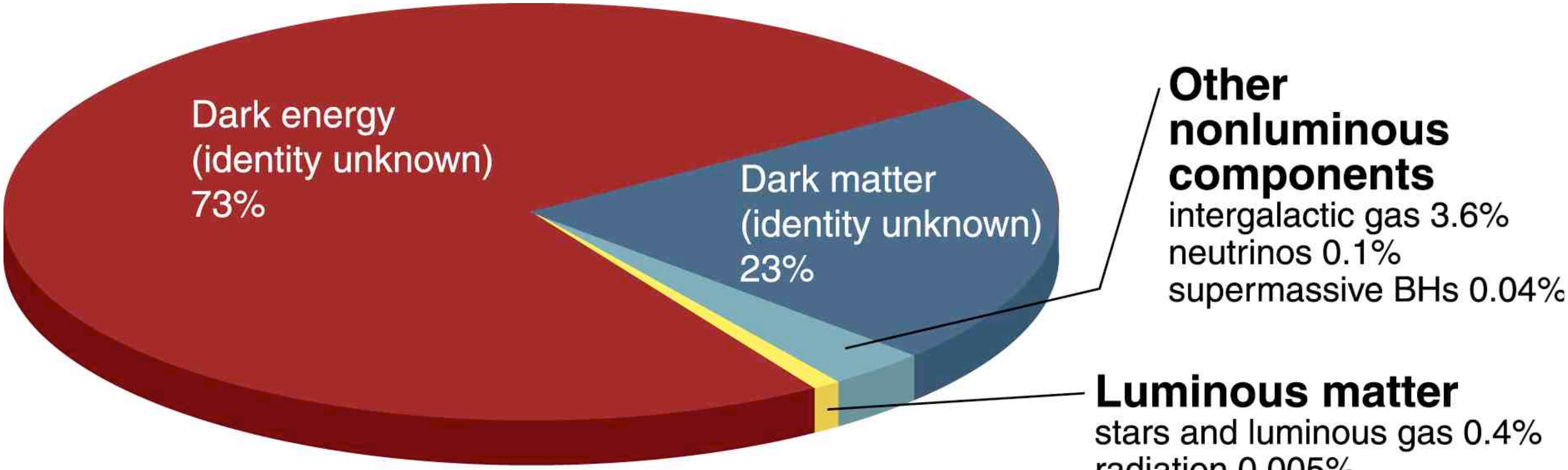


CMBR: $\Omega_\Lambda + \Omega_M$



The cosmological inventory is now well-delineated

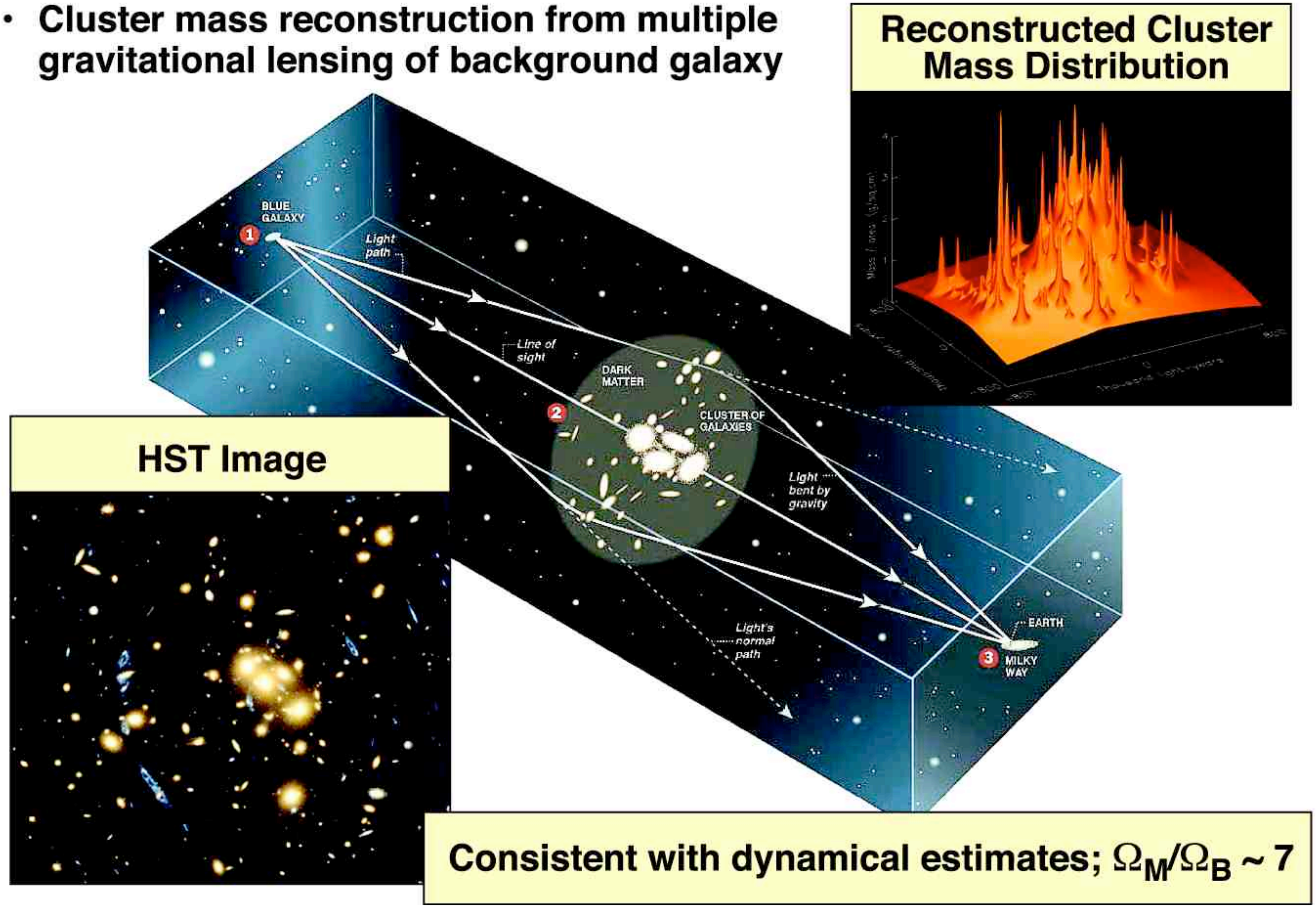
- **But we know neither what the "dark energy" or the "dark matter" is**
- **A particle relic from the Big Bang is strongly implied for DM**
  - **WIMPs ?**
  - **Axions ?**



Science (20 June 2003)

Cluster lensing of background galaxy

- **Cluster mass reconstruction from multiple gravitational lensing of background galaxy**

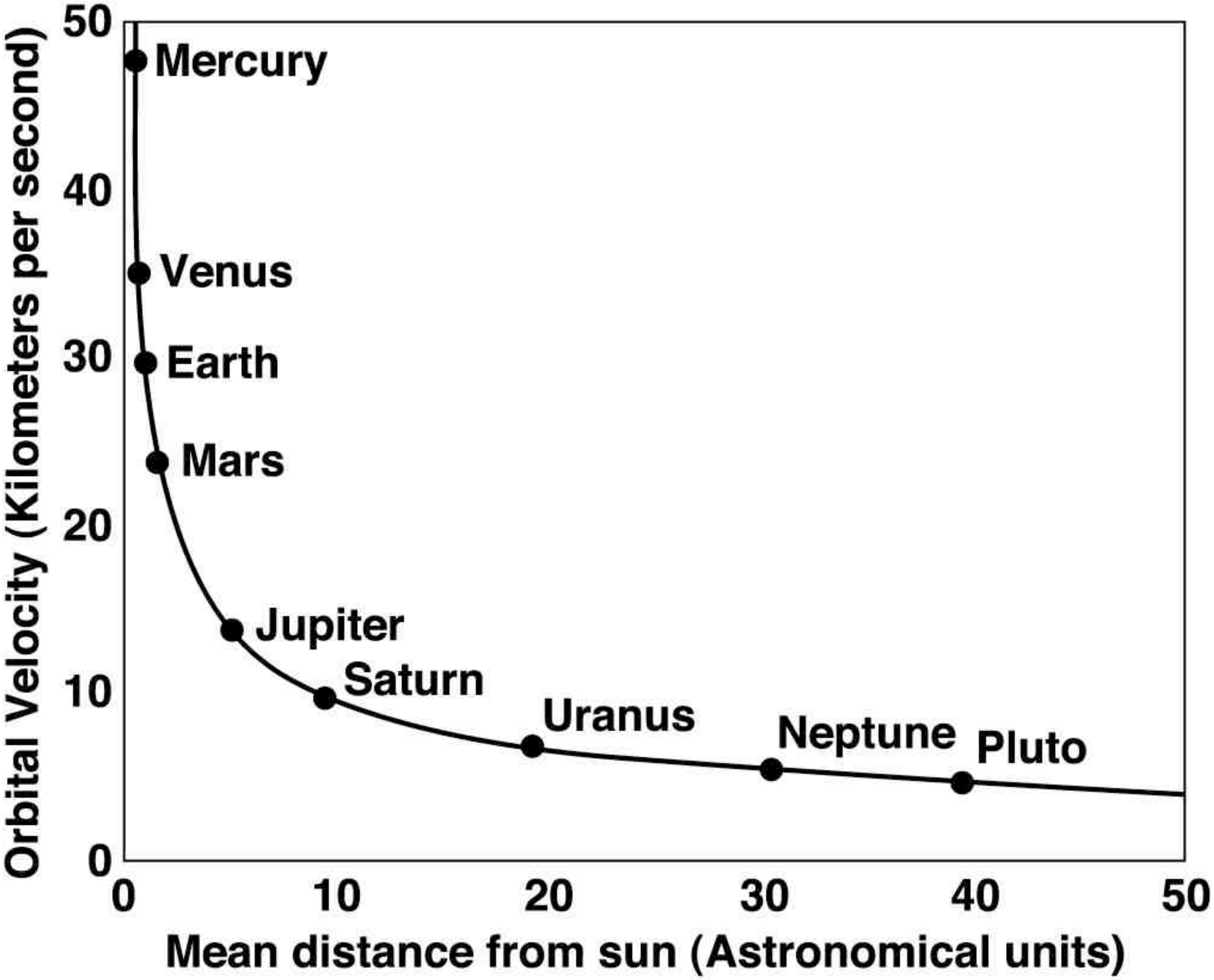


Reconstructed Cluster Mass Distribution

HST Image

Consistent with dynamical estimates; $\Omega_M/\Omega_B \sim 7$

“Rotation Curve” for our solar system



Rotation Curves — Galactic Dark Matter

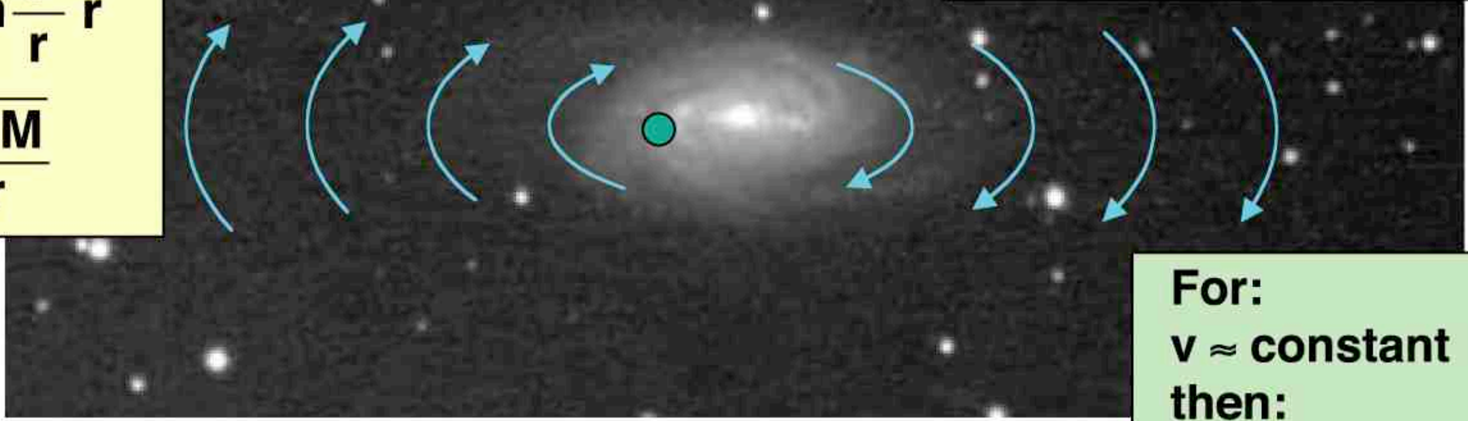
- **Galaxies have constant rotation curves**

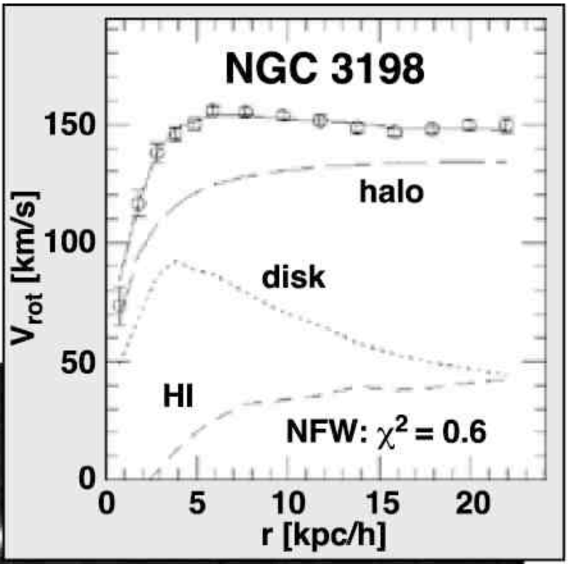
If mass were localised

$$F = -\frac{G M m}{r^2}\hat{r}$$

$$= -m\frac{v^2}{r}\hat{r}$$

$$v = \sqrt{\frac{G M}{r}}$$





For:
$v \approx$ constant
then:

$$M(r) \propto r$$

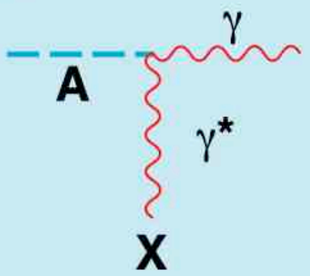
$$M_{dark} \geq 10 M_{lum}$$

- **Dark Matter is right in our own Milky Way!**
- **Maximum likelihood local density $\rho \sim 450\ \mathrm{MeV/cm^3}$**

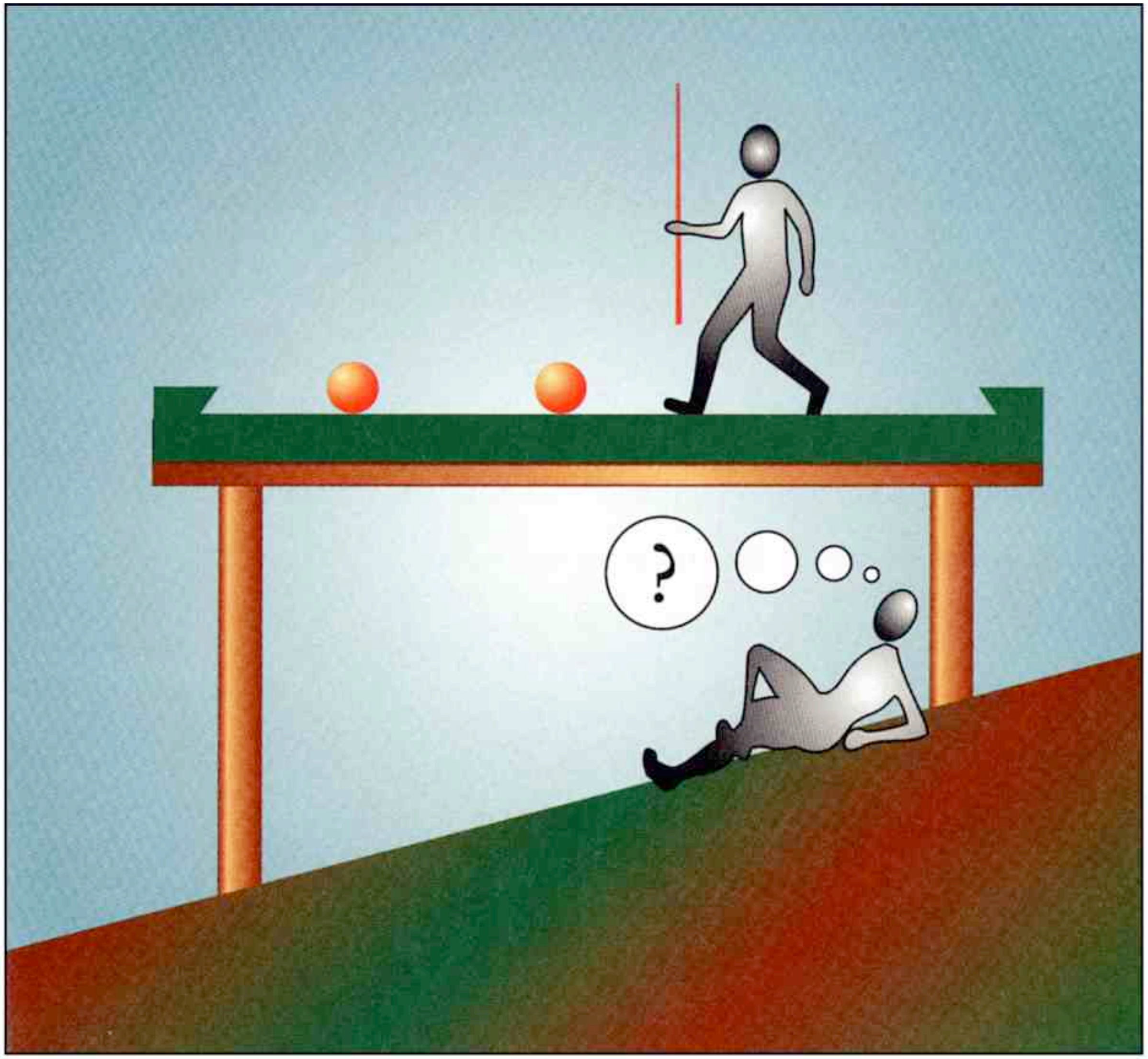
Particle physics provides 3 dark-matter candidates

- Neutrinos
- WIMPs
- **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

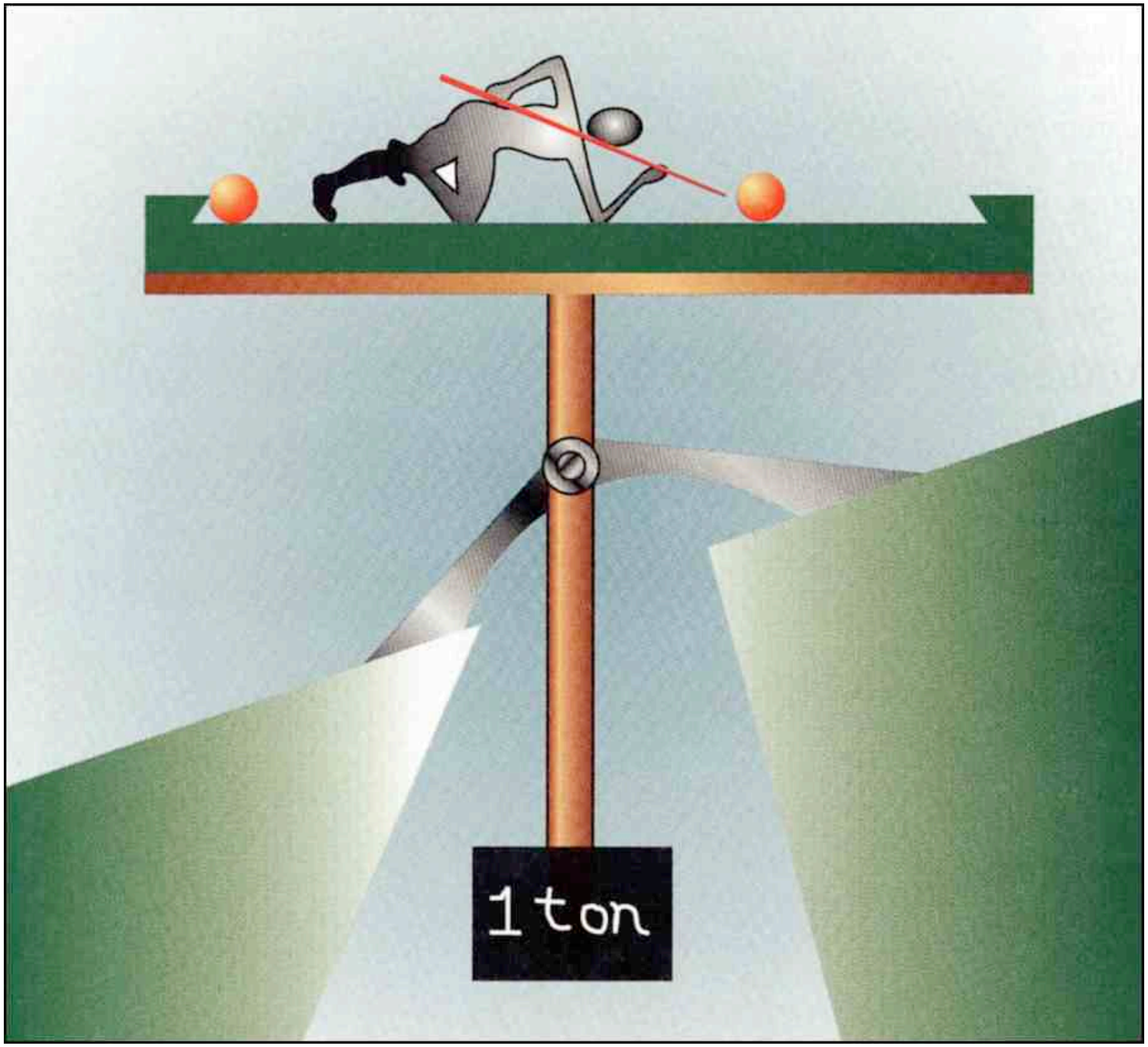


TSP’s* fine-tuning problem

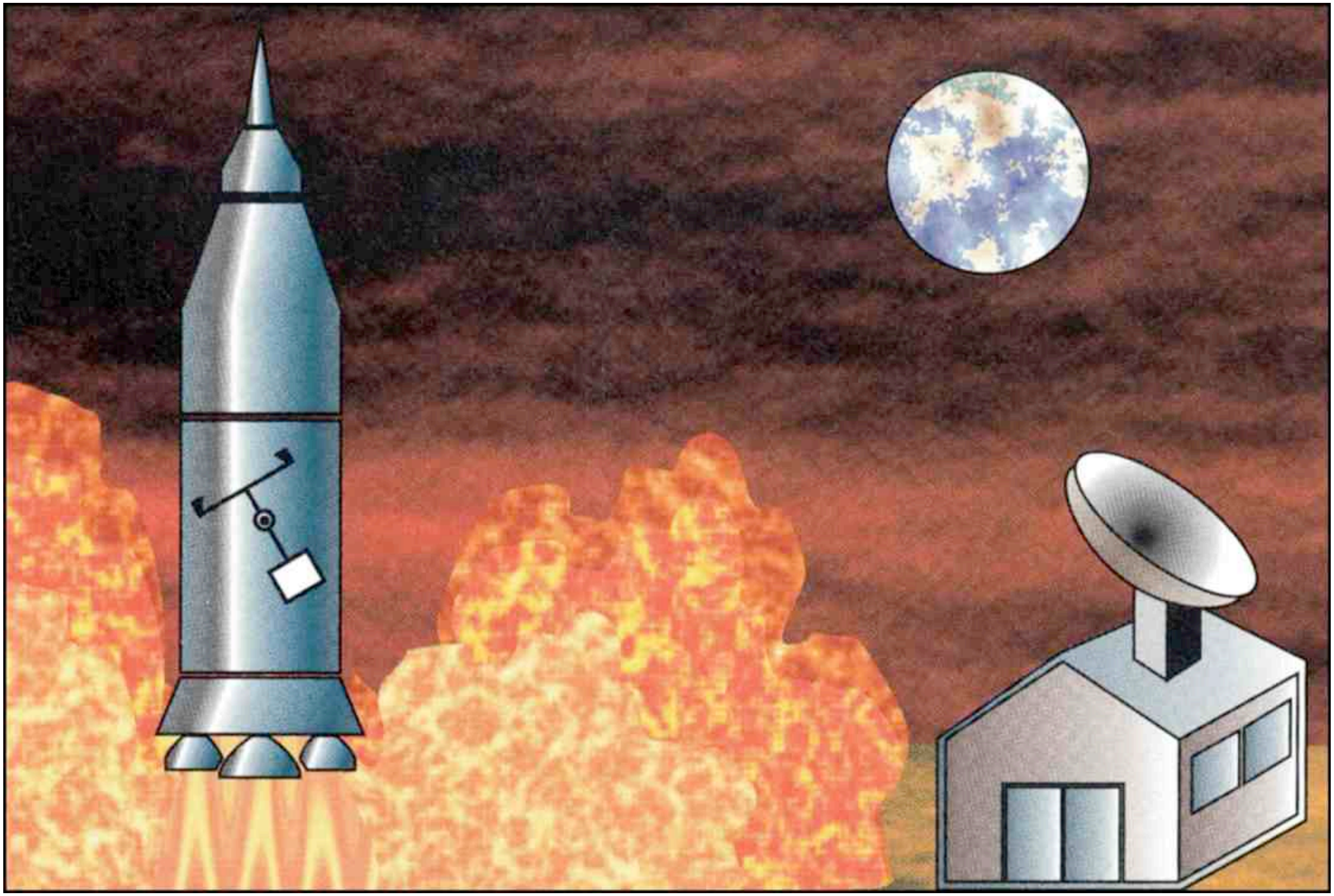


*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)

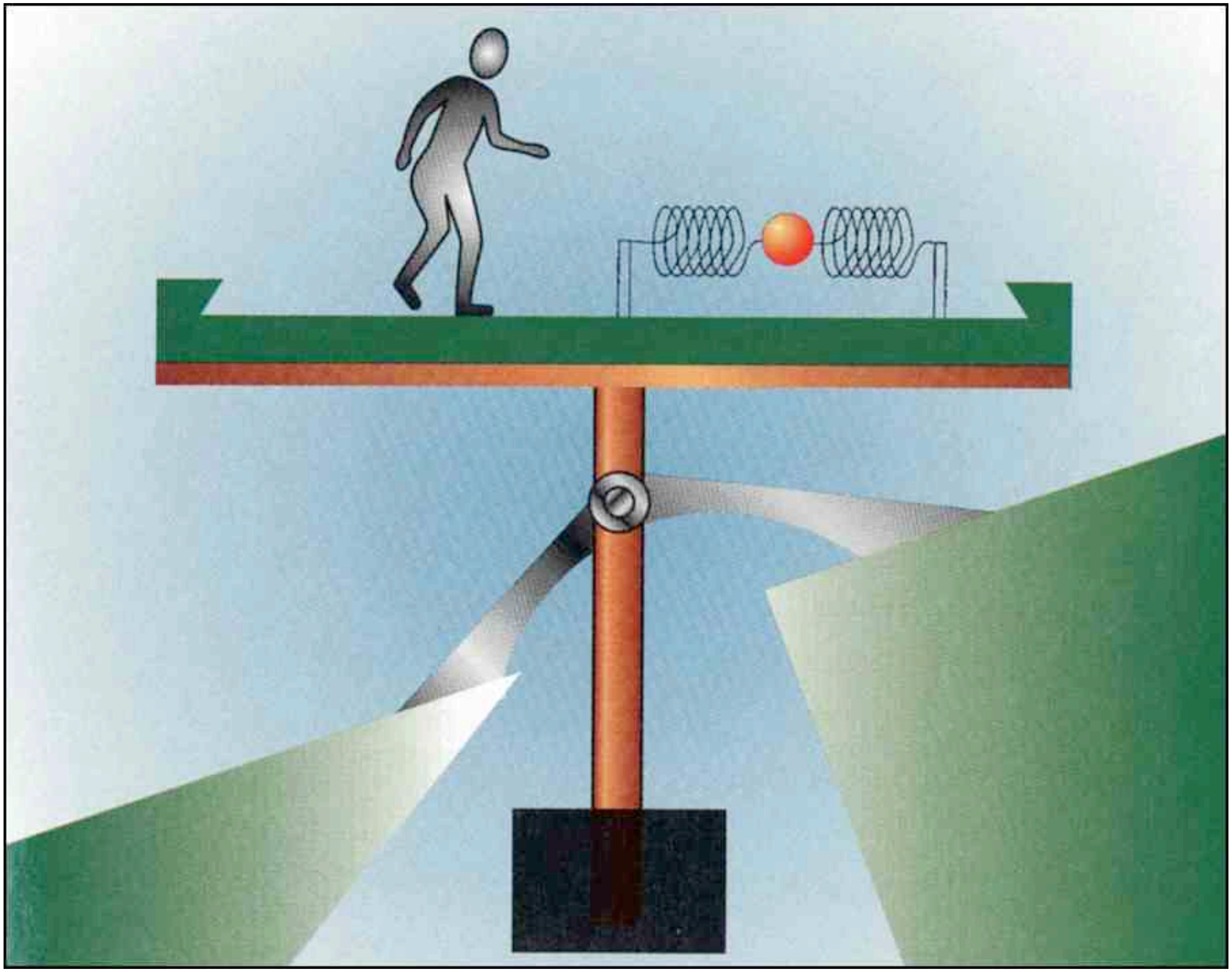
TSP's hypothesis, and first unsuccessful experiment



The key insight



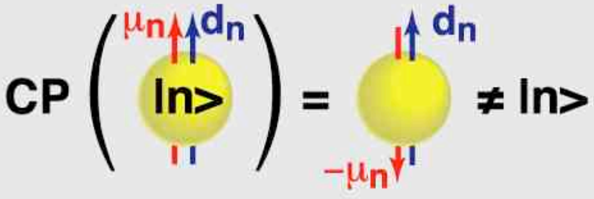
A high-Q search for relic oscillations



The Axion

The Strong-CP Problem

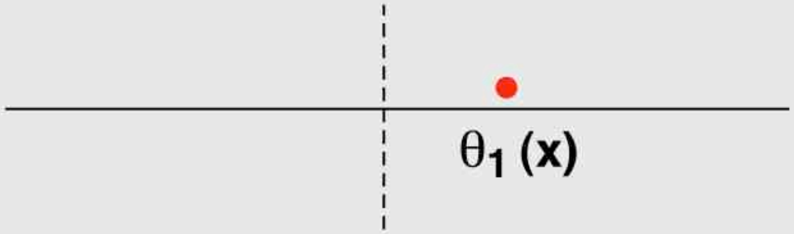
- $\mathcal{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



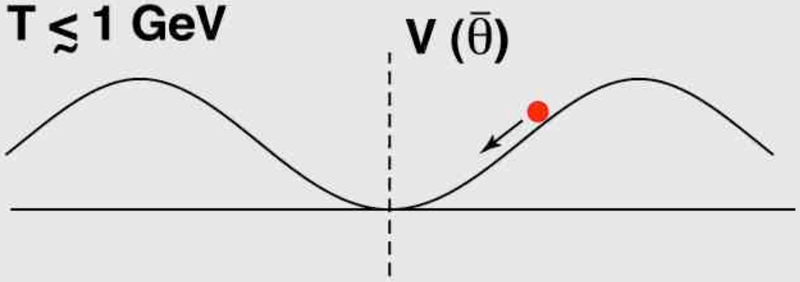
- Why?

Peccei-Quinn / Weinberg-Wilczek

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



- $T \lesssim 1$ GeV



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

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

Generically, all couplings

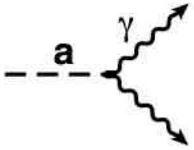
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

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

(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'

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

(Overclosure) (SN1987a)

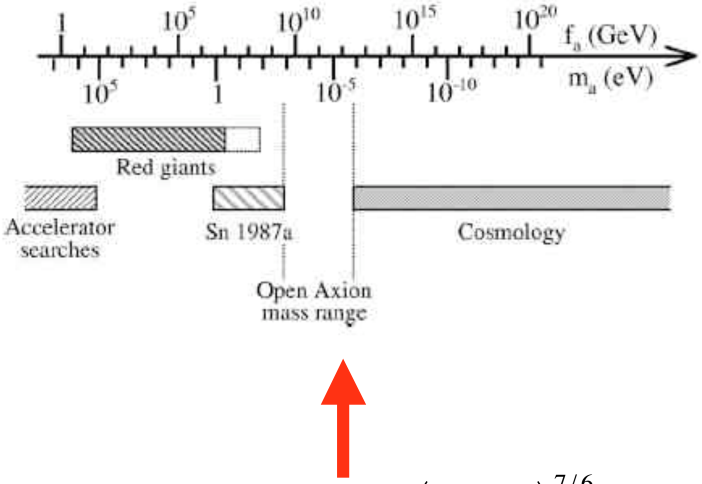
With lower end of window preferred if $\Omega_{CDM} \sim 1$

Completing the analogy f ⟷ l

	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)	$\sim f^{7/6}$	$\sim l$

The axion as dark matter candidate

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**

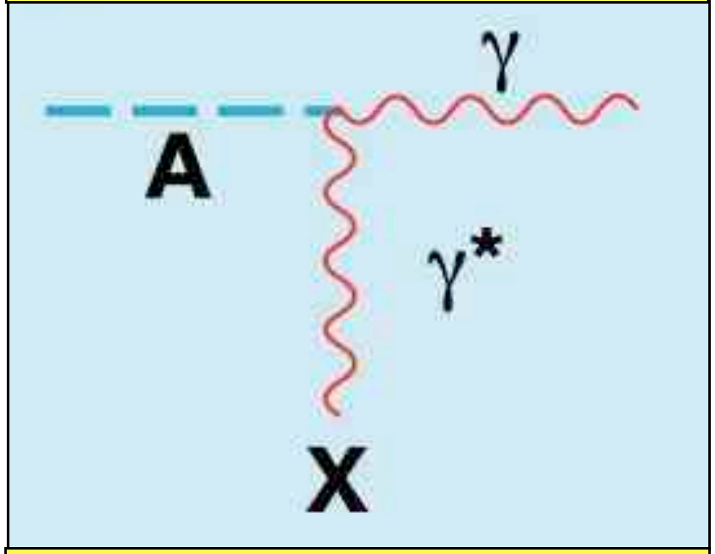
Gates, E.J., G. Gyuk, M.S. Turner, Ap.J. Lett. 449 L123 (1995)

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

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

Axion-photon coupling $g_{a\gamma\gamma}$

Primakoff interaction



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

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

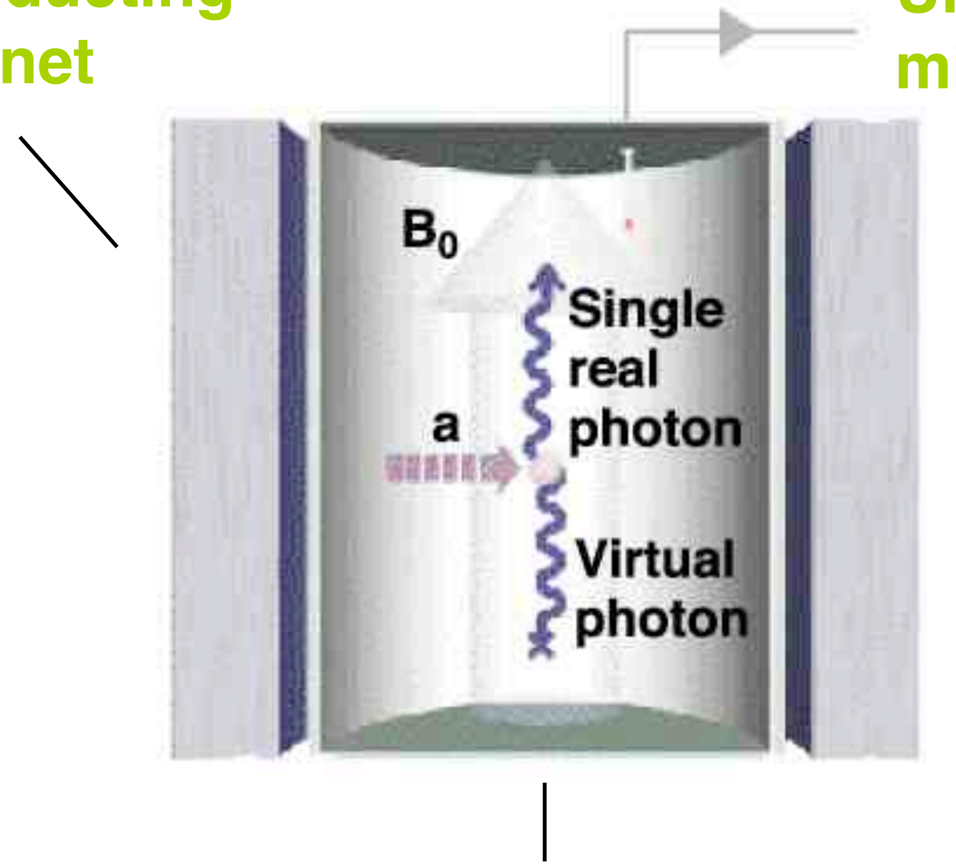
This photon then carries the *total energy* of the axion

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

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

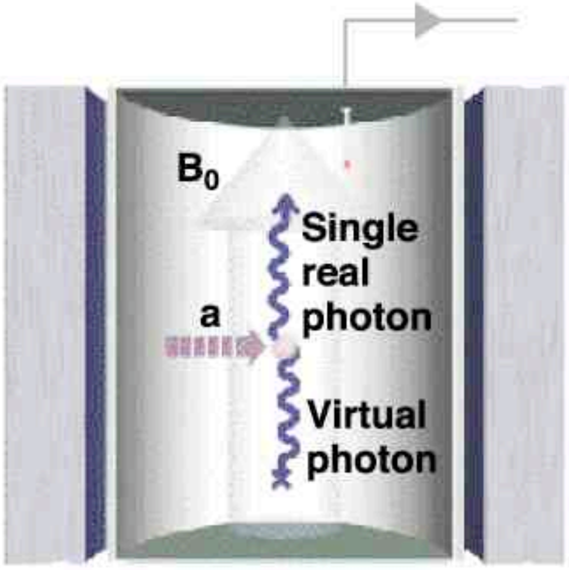
Superconducting magnet

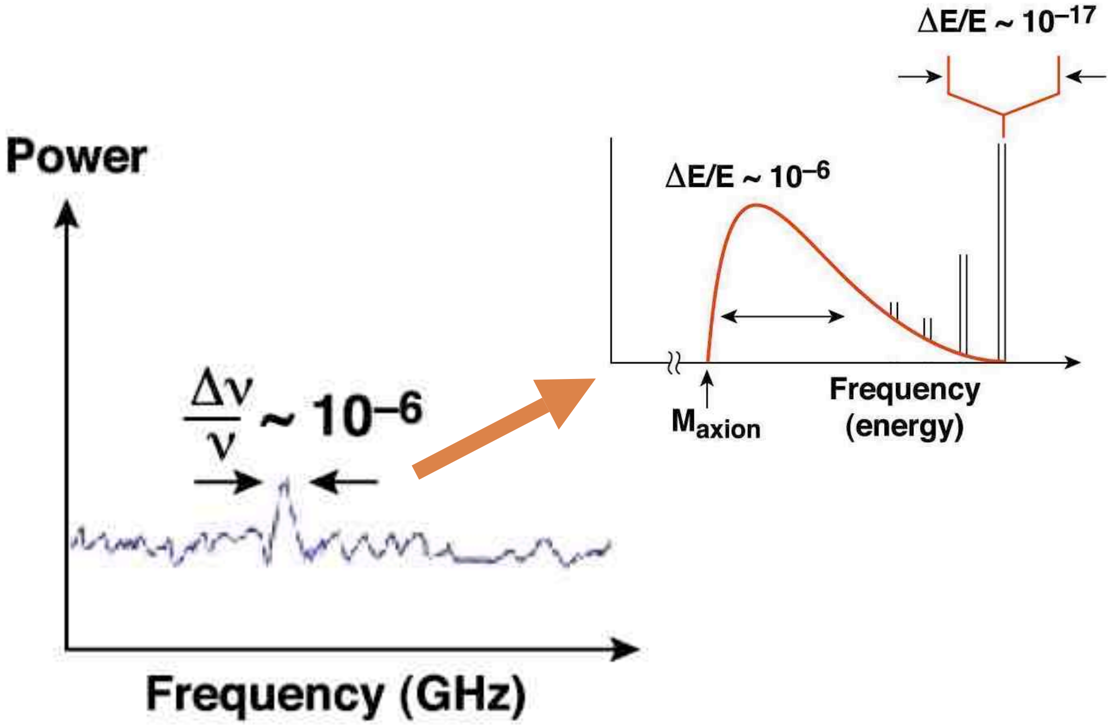
Ultra-low noise microwave receiver



High-Q microwave cavity

The signal is the *total energy* of the axion



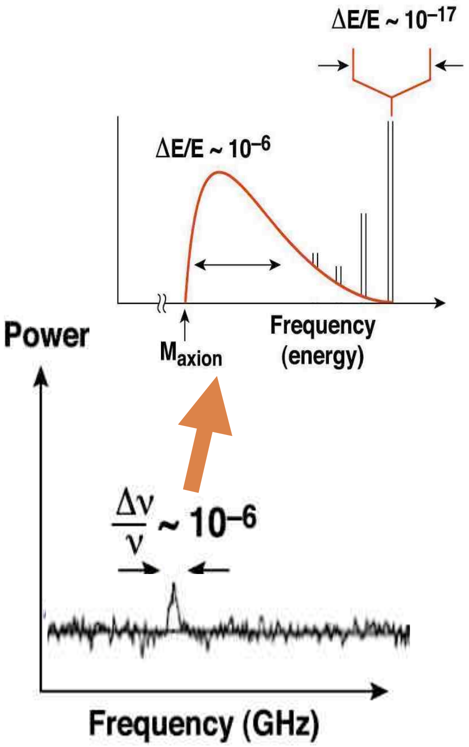


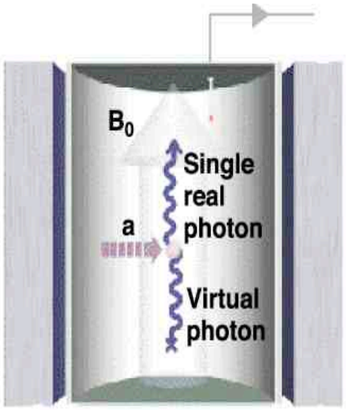
The axion mass range is scanned by tuning the cavity

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

There may be fine structure in the axion signal

Axionic halo dark matter – a unique quantum system





Axionic dark matter is very dense

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

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

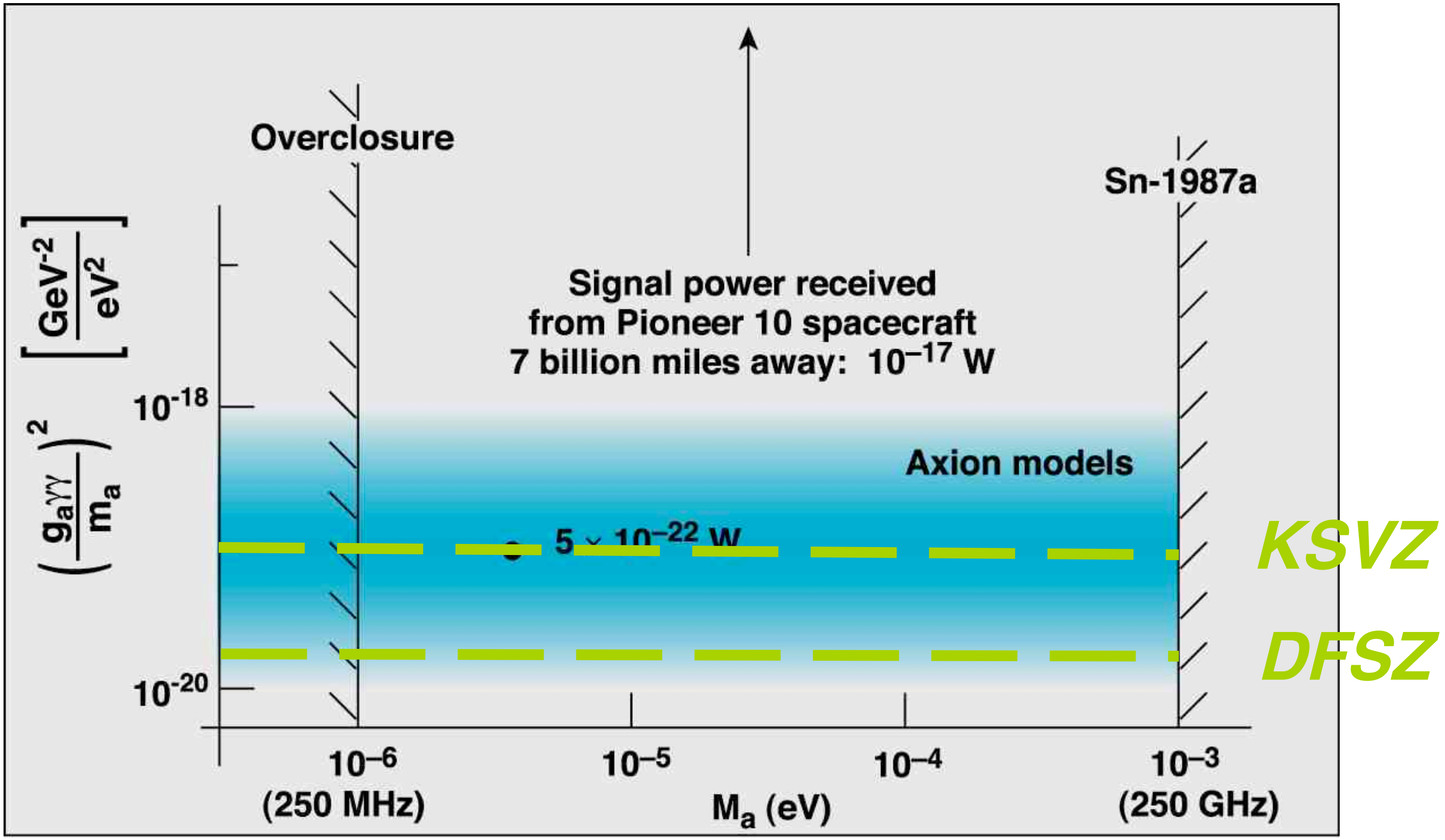
Axionic dark matter is highly coherent

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

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

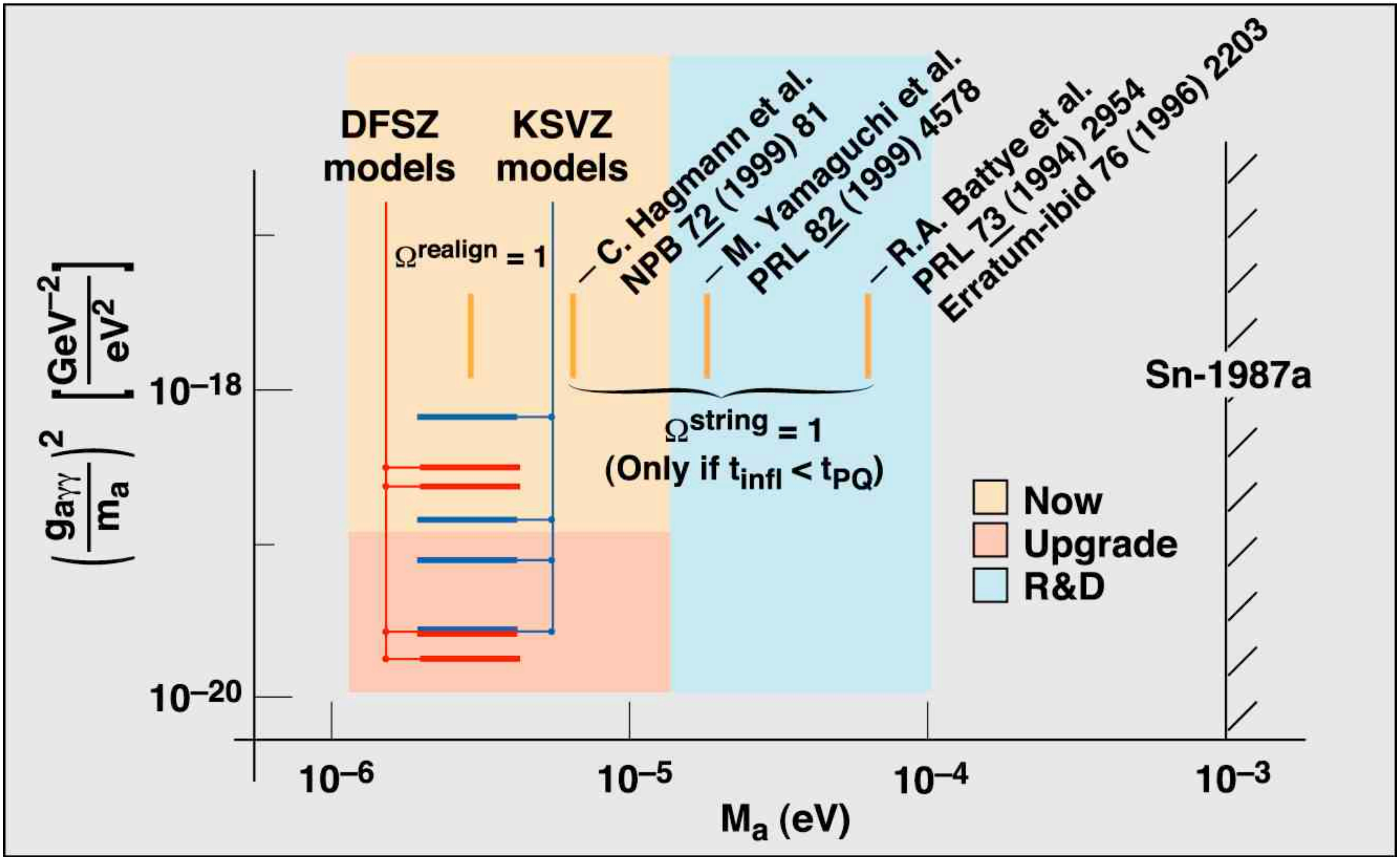
The microwave cavity experiment measures the *total energy* of the axion, thus revealing both Doppler motion and coherence of the axion fluid

The parameter space is bounded



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

The parameter space



The radiometer eqn.* dictates the strategy

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

But integration time limited to ~ 100 sec

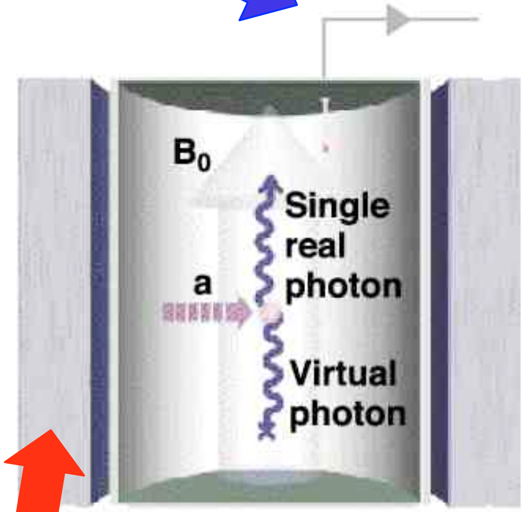
** Dicke, 1946*

System noise temp. now

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

But $T_{Quant} \sim 30$ mK

INVEST HERE!



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

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

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

Basic formulae

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*

$\delta f = f - f_0$ *Offset from central*

C_{lmn} *Cavity form-factor*

Δf	*Cavity bandwidth*
f_{step}	*Frequency tuning steps*
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:

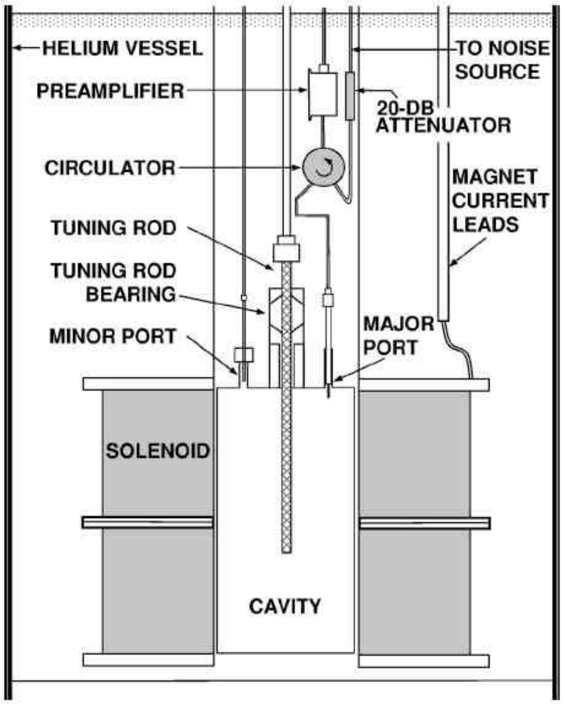
(i) Be sensitive to the most pessimistic model axion (e.g. DFSZ)

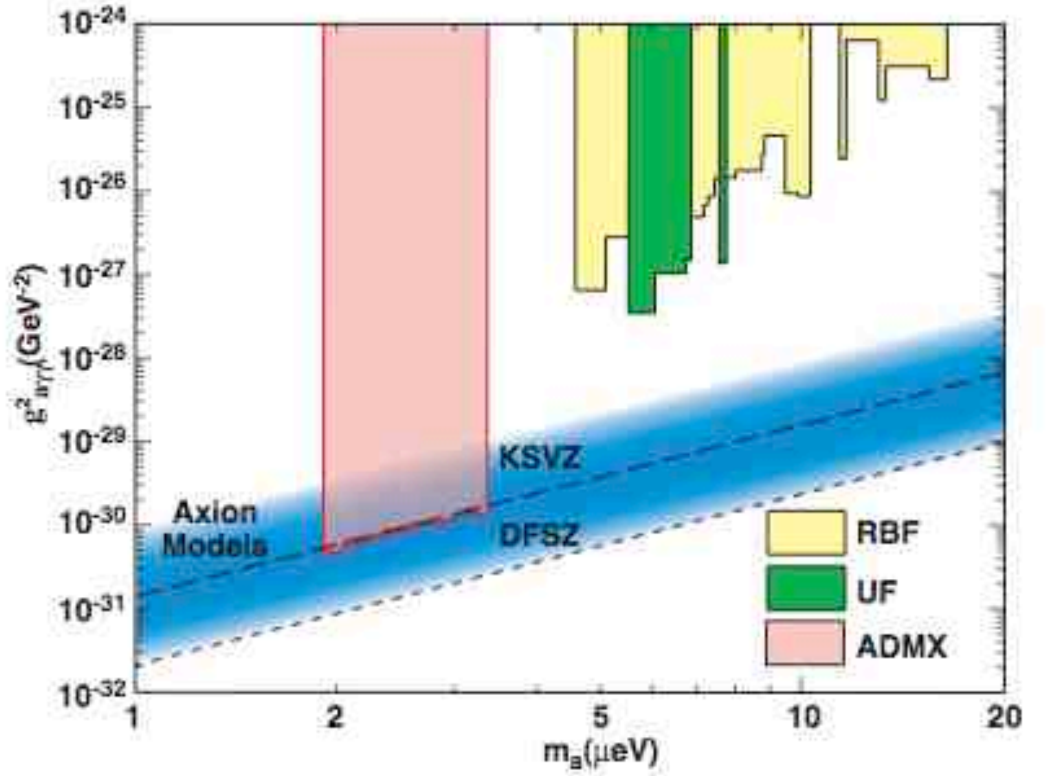
(ii) Which only occupies a fraction of the halo density (e.g. 10%)

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

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

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



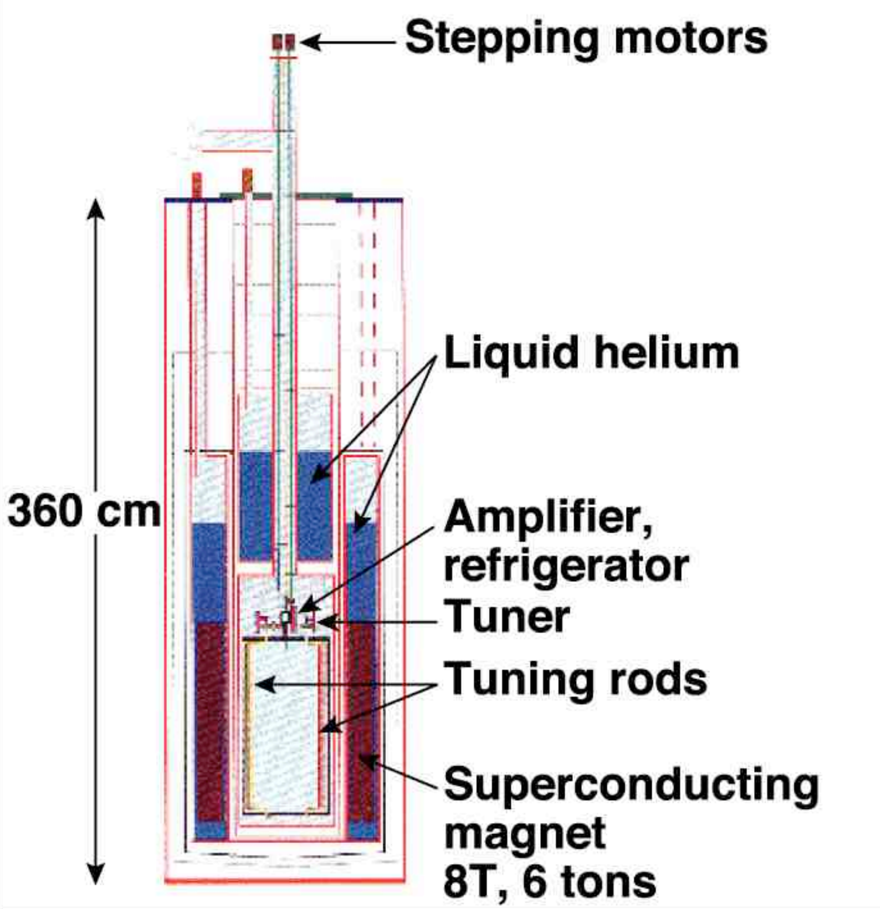


The first-generation experiments already came within a factor of 100-1000 of the desired sensitivity – a stunning achievement

Axion hardware

ADMX LLNL-Florida-Berkeley-NRAO

Magnet with Insert (side view)



Stepping motors

Liquid helium

360 cm

Amplifier, refrigerator

Tuner

Tuning rods

Superconducting magnet
8T, 6 tons

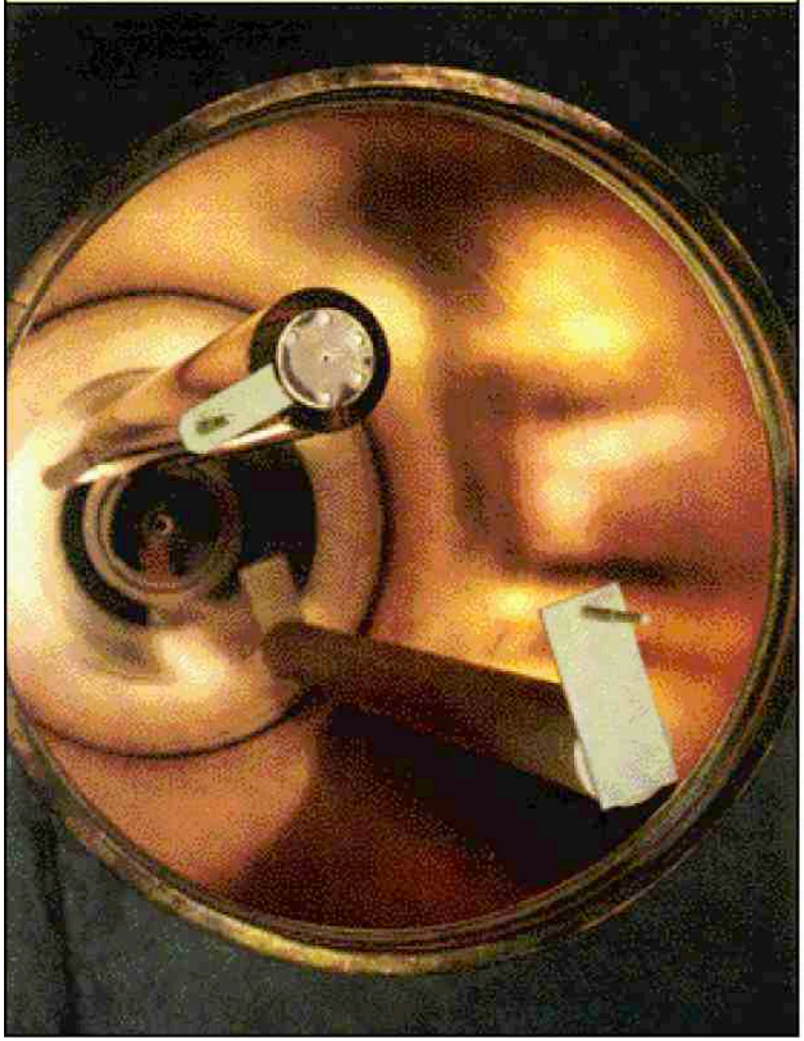
Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

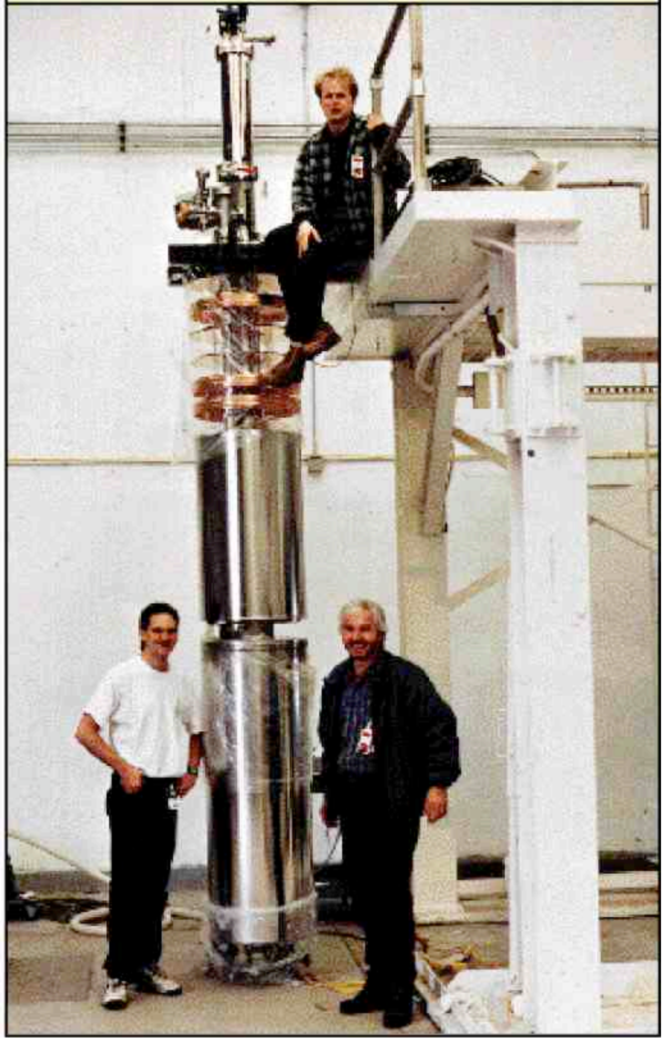
8 T, 1 m × 60 cm ∅

Axion hardware (cont'd)

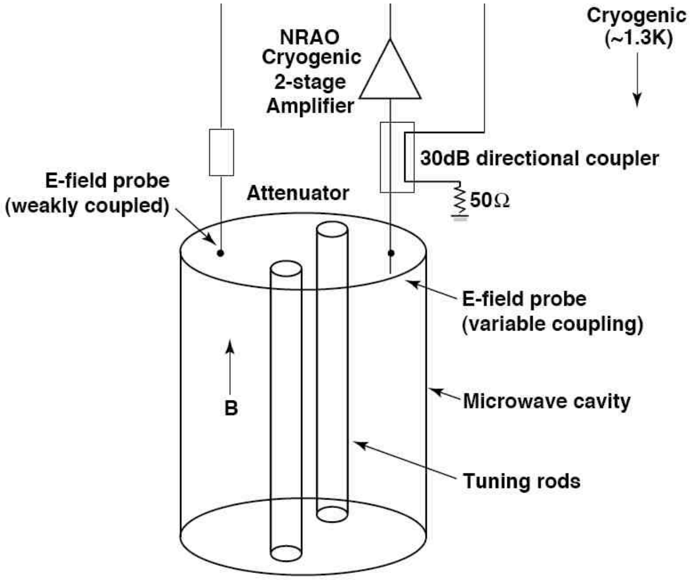
High-Q Cavity (~200,000)

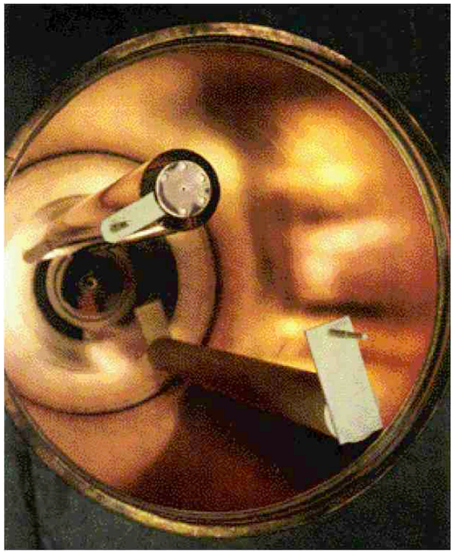


Experimental Insert



Microwave cavity basics (I)





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)*
- $f_0 = 0.115\ \text{GHz} / R[\text{m}]$
- $C_{010} = 0.69$

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

Microwave cavity basics (II)

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

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

For uniform B = B_0:

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

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

Cavity quality, Q_{lmn}:

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

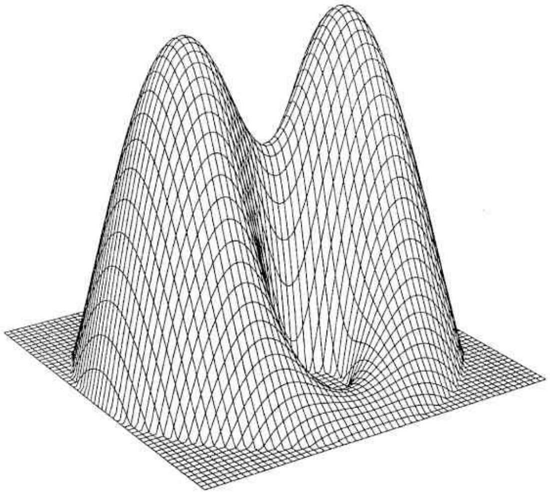
In high B-field, low-T:

- *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

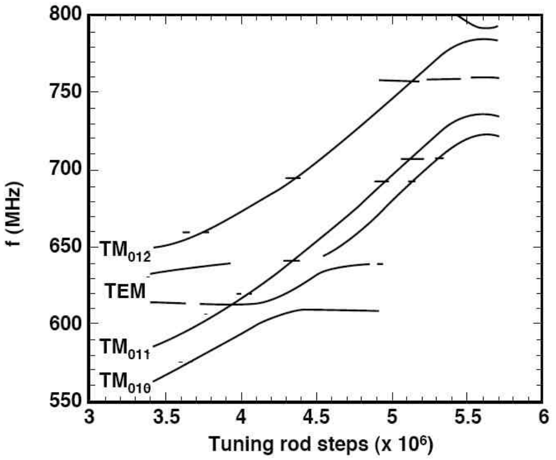
Tuning rods, radial offset

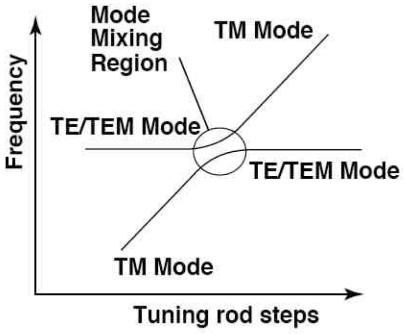


E_z for TM_{010} mode; two metal rods half-way from center

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

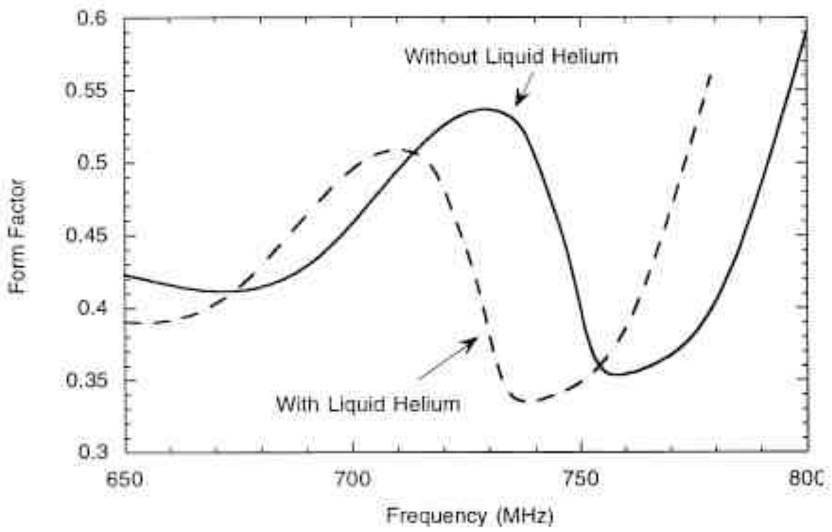
Mode-crossings



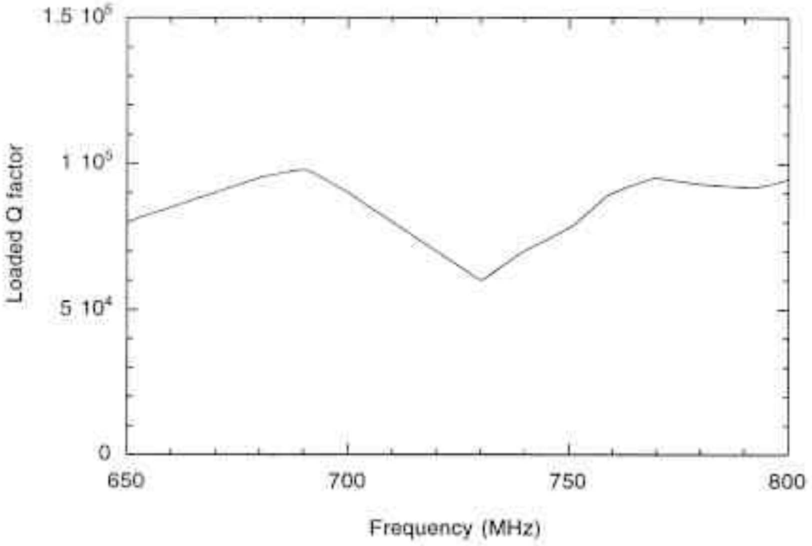


- *Keep cavity aspect ratio L/R low*
- *But can ‘walk-around’ crossings*

Real-life form-factors, Q vs. frequency



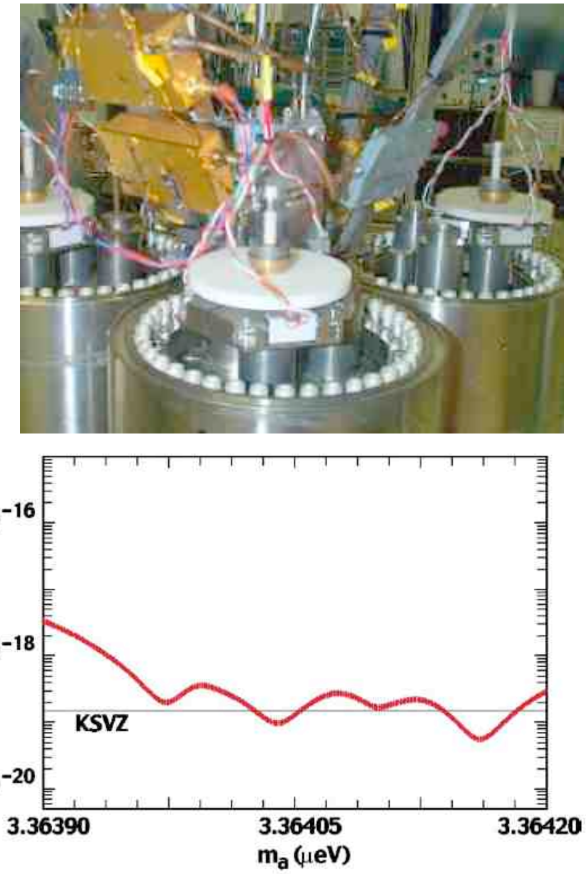
C_{010} vs. frequency, for cases of cavity filled with 1-torr He gas (solid); and SHe filled (dashed)



Q_L vs. frequency for case of two copper rods

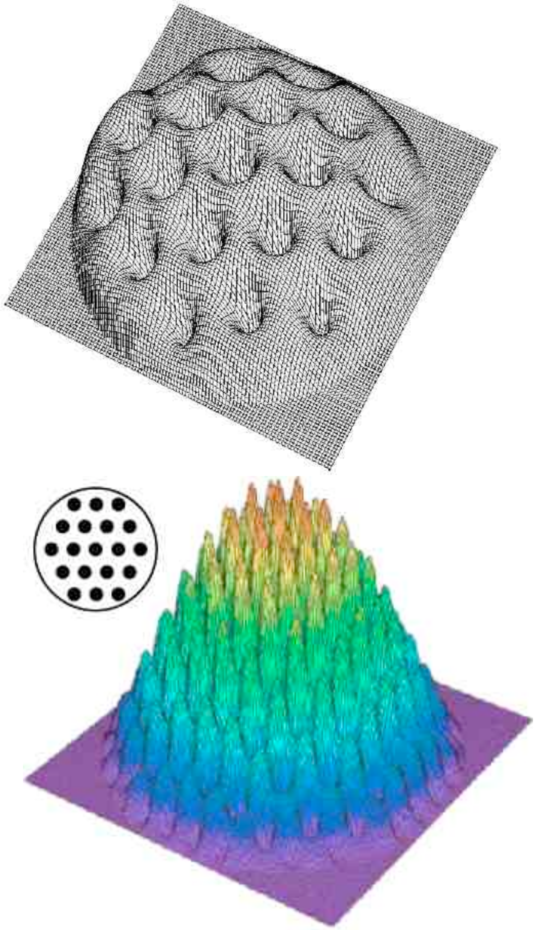
Options for higher frequency cavities

Power-combine multiple cavities (1-10 GHz)



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

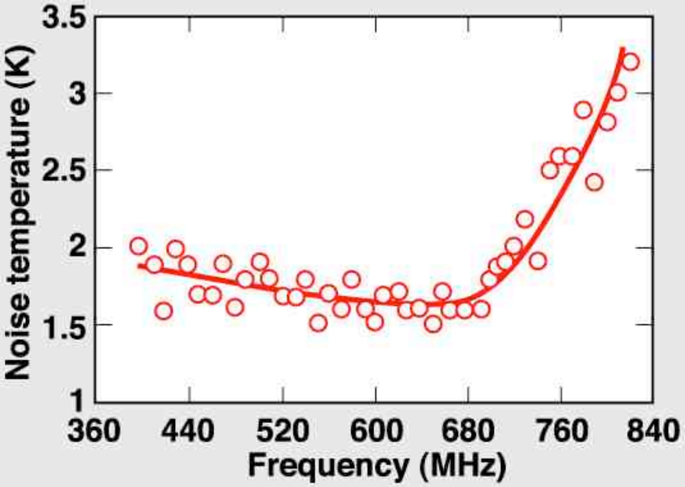
Periodic-post resonators (10-100 GHz)



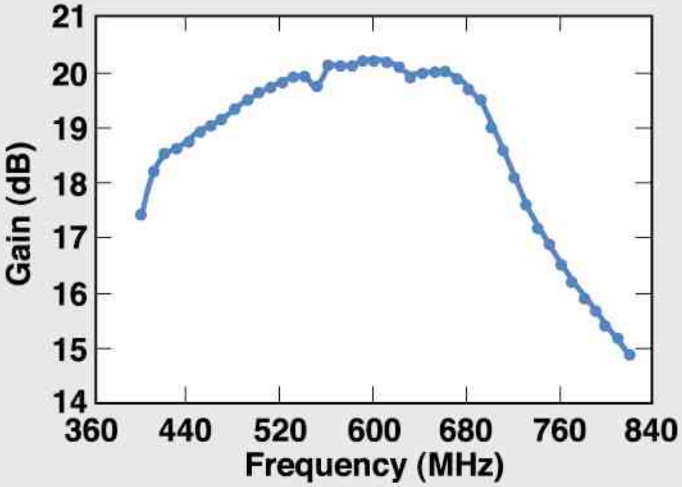
Microwave amplifiers

AXION

Noise Temperature



Gain

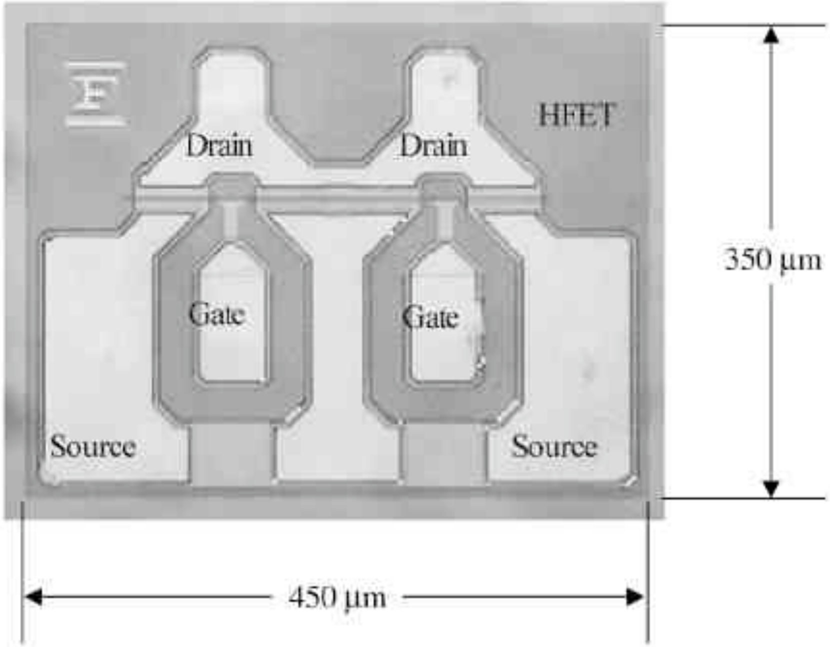


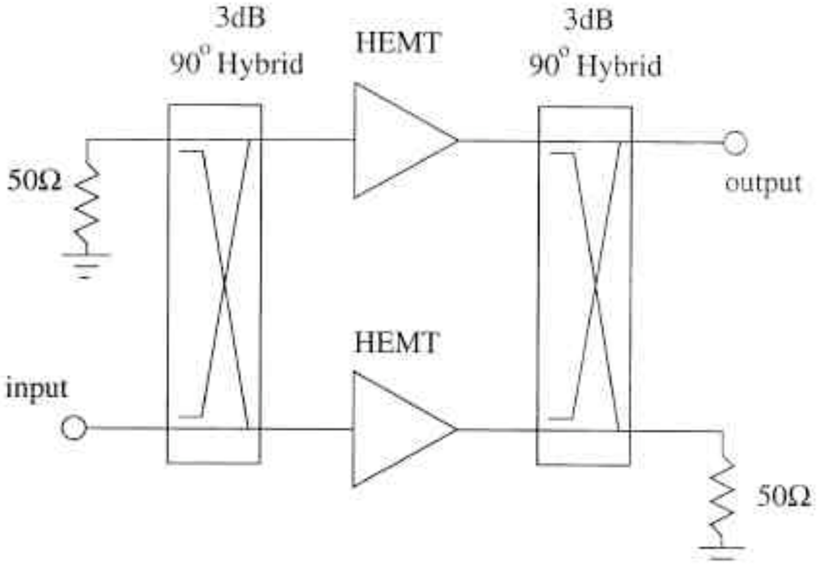
- Currently HFET amplifiers (Heterojunction Field-Effect Transistor)
  - A.k.a. HEMT™ (High Electron Mobility Transistor)
  - Workhorse of radio astronomy, military communications, etc.
- Best to date $T_N \gtrsim 1$ K
  - Independent of T
  - Works in magnetic field

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





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

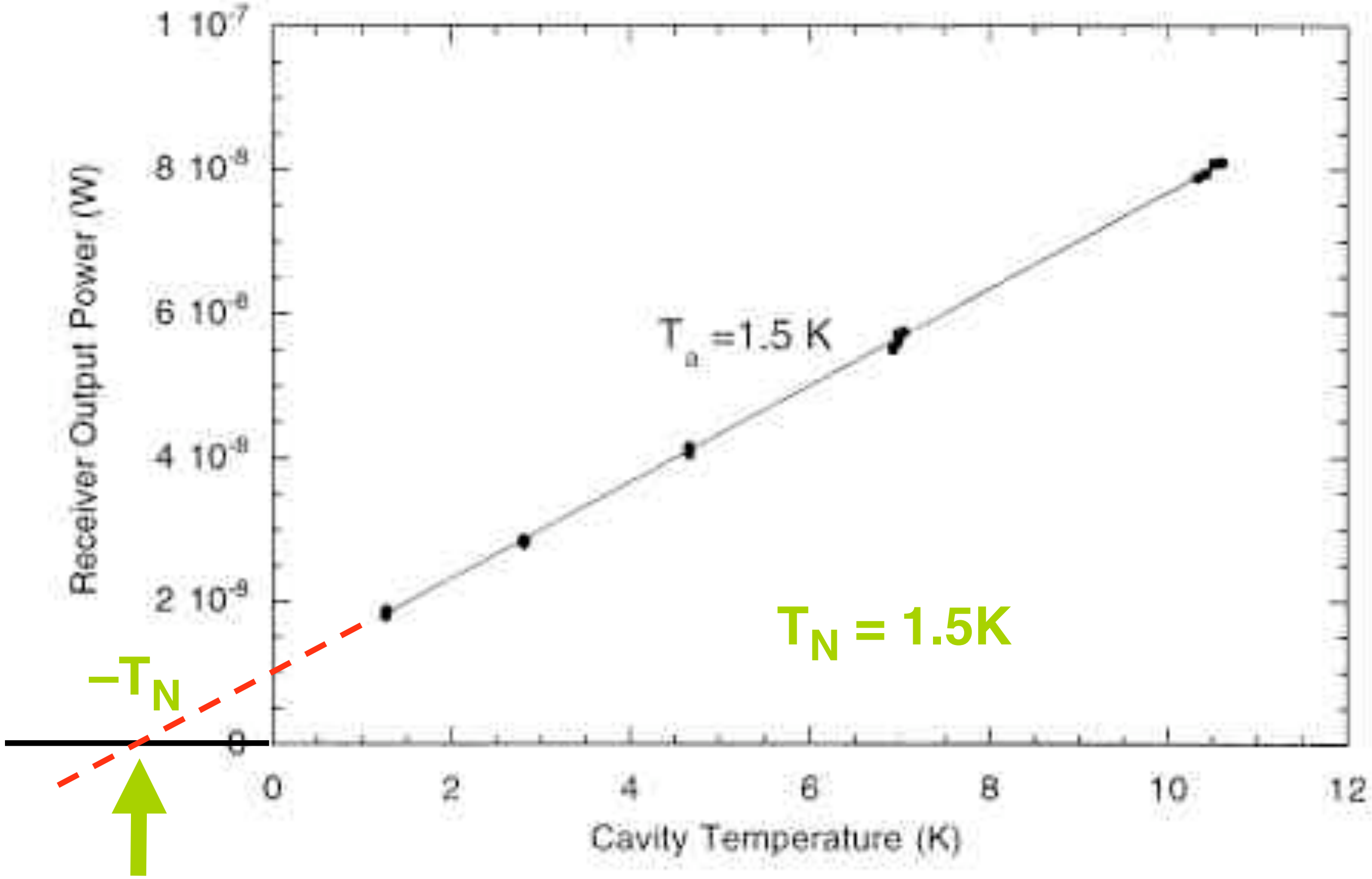
Resonant cavities represent a complex frequency dependent input impedance $Z_0(w-w_0)$

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

There is a small penalty in noise

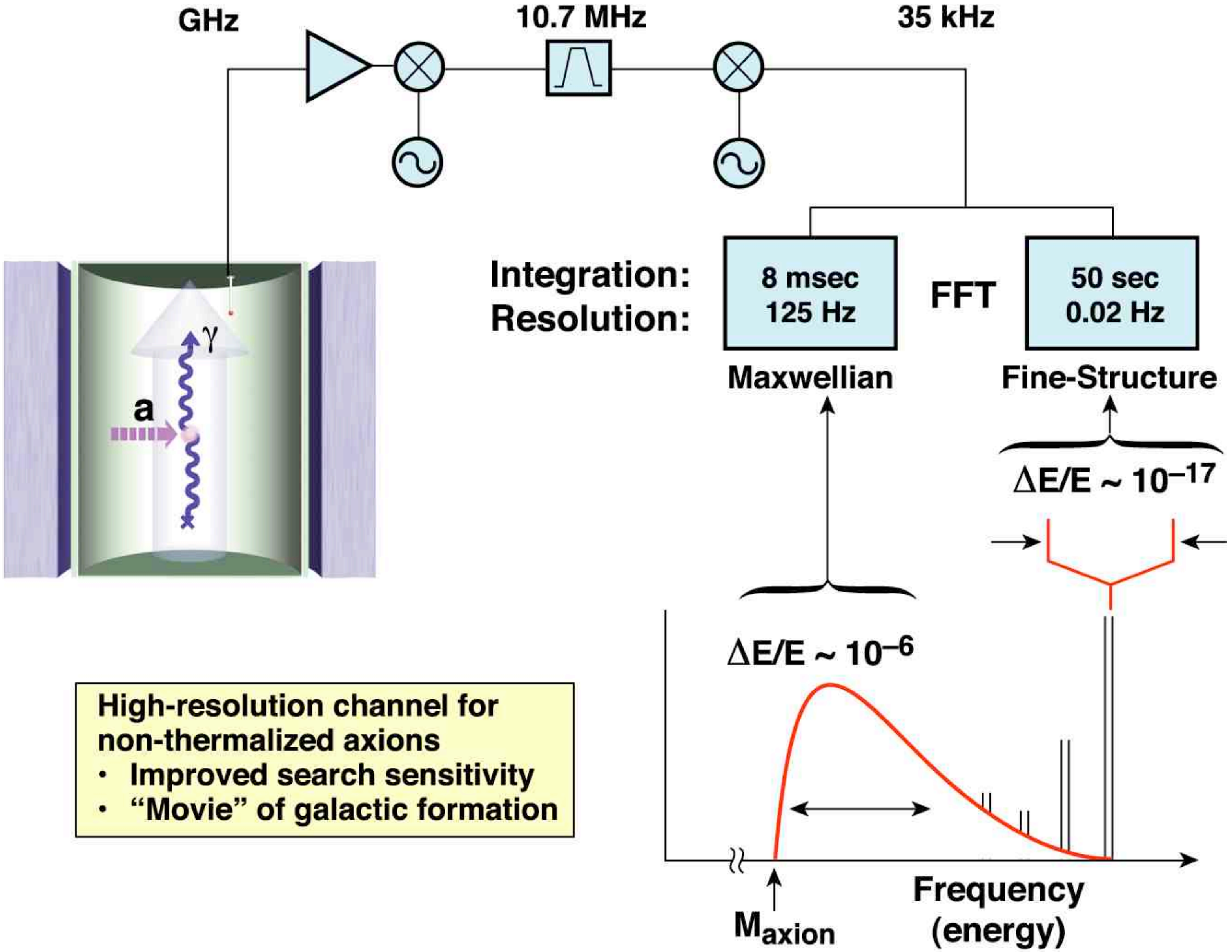
How do you measure the noise temperature of the amplifier *in situ* ?

The “hot-cold” method



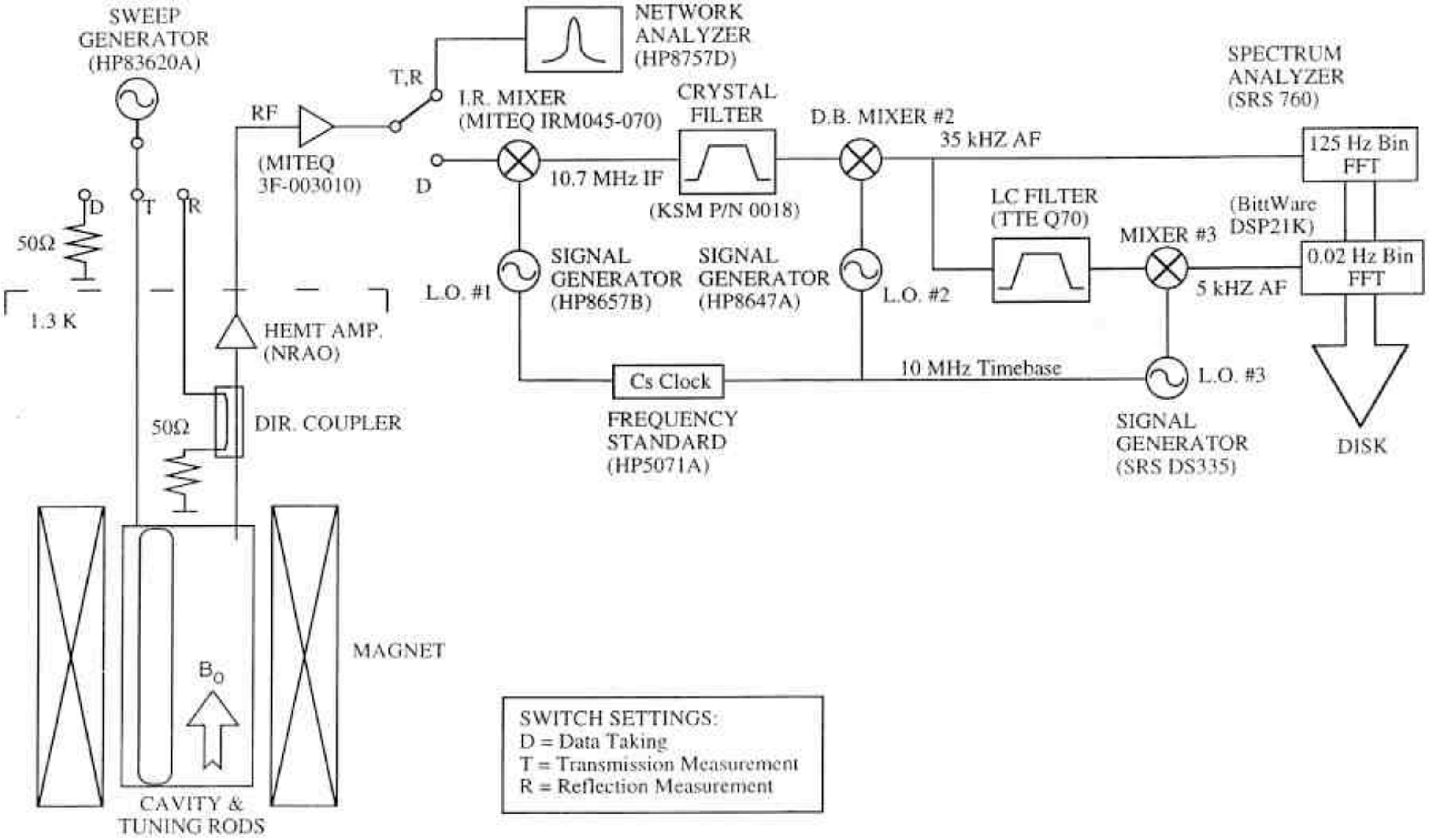
(The intrinsic noise of the HEMT amplifiers are not appreciable functions of temperature below 15K or so)

The axion receiver, and high-resolution search



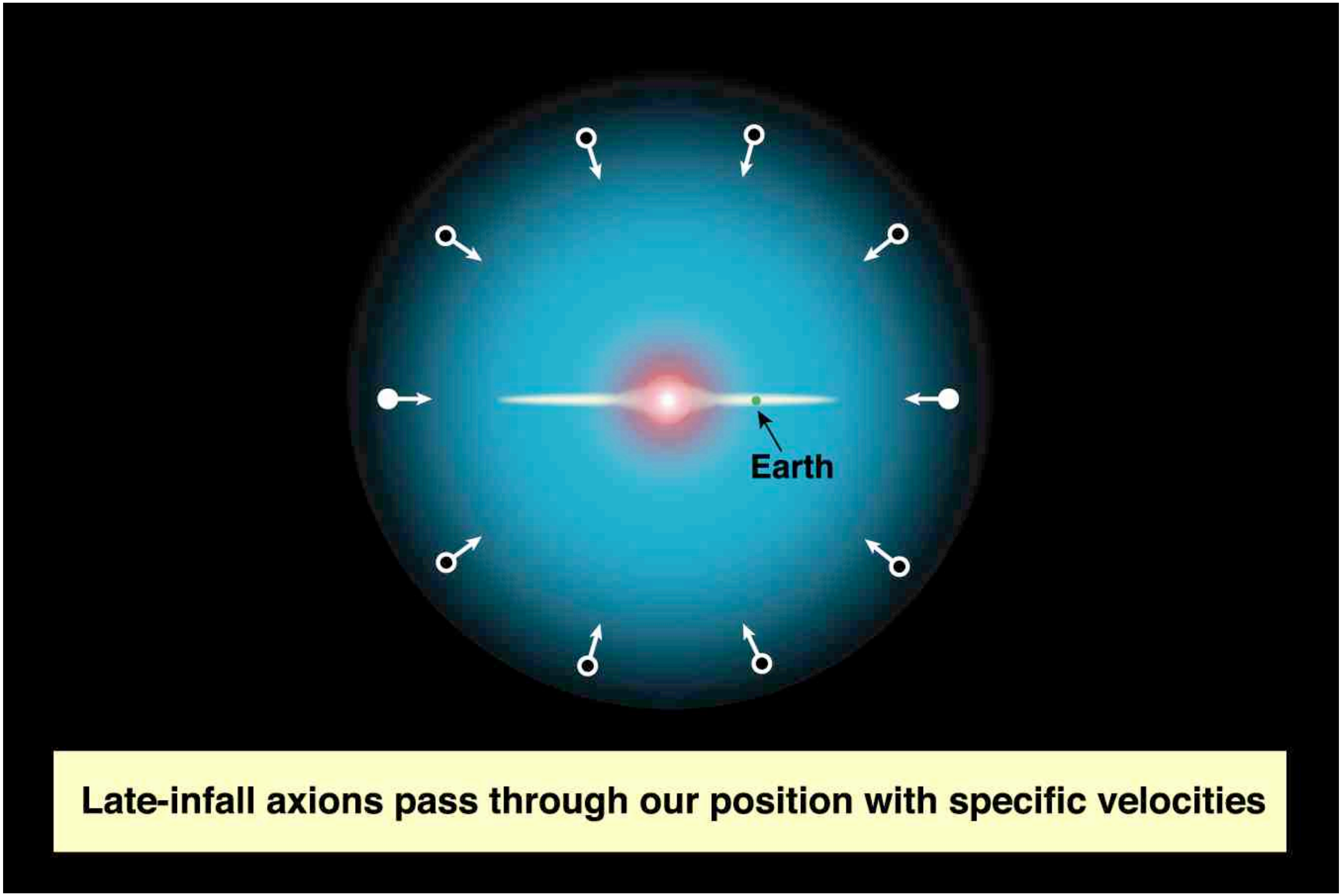
High-resolution channel for non-thermalized axions
- Improved search sensitivity
- "Movie" of galactic formation

The real receiver



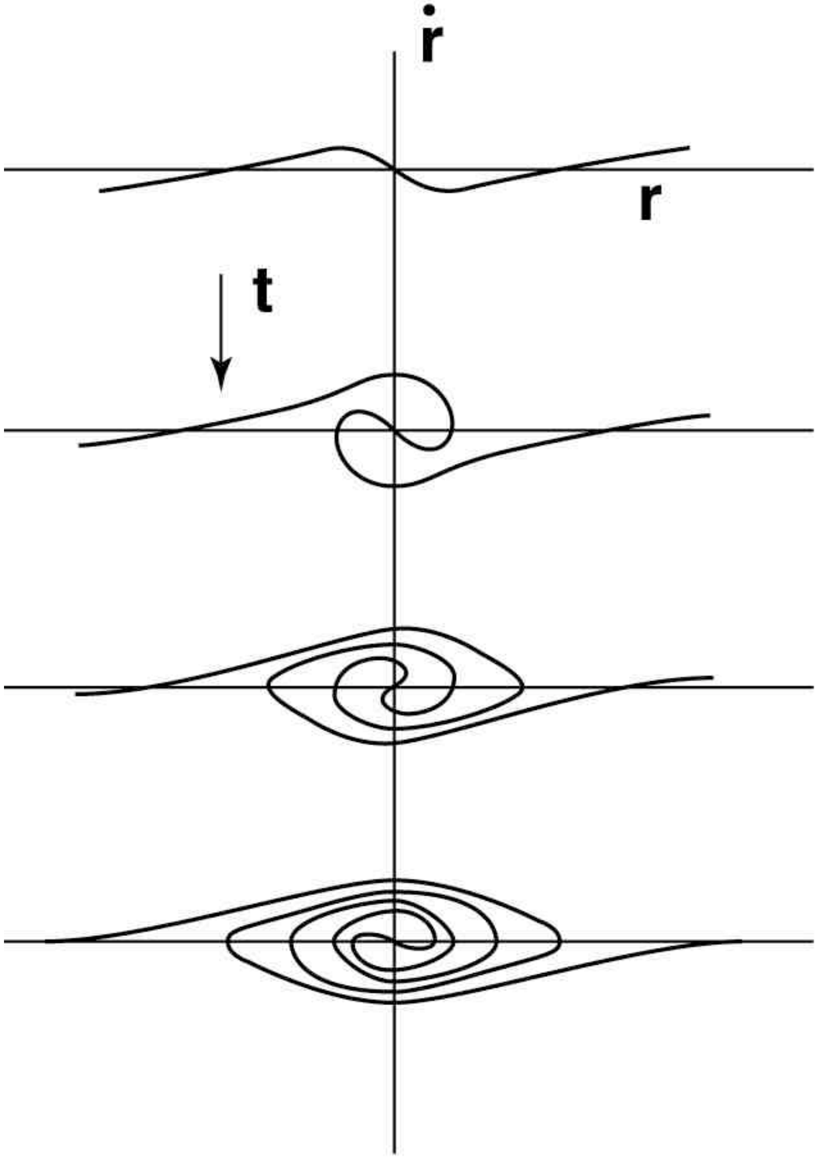
SWITCH SETTINGS:
D = Data Taking
T = Transmission Measurement
R = Reflection Measurement

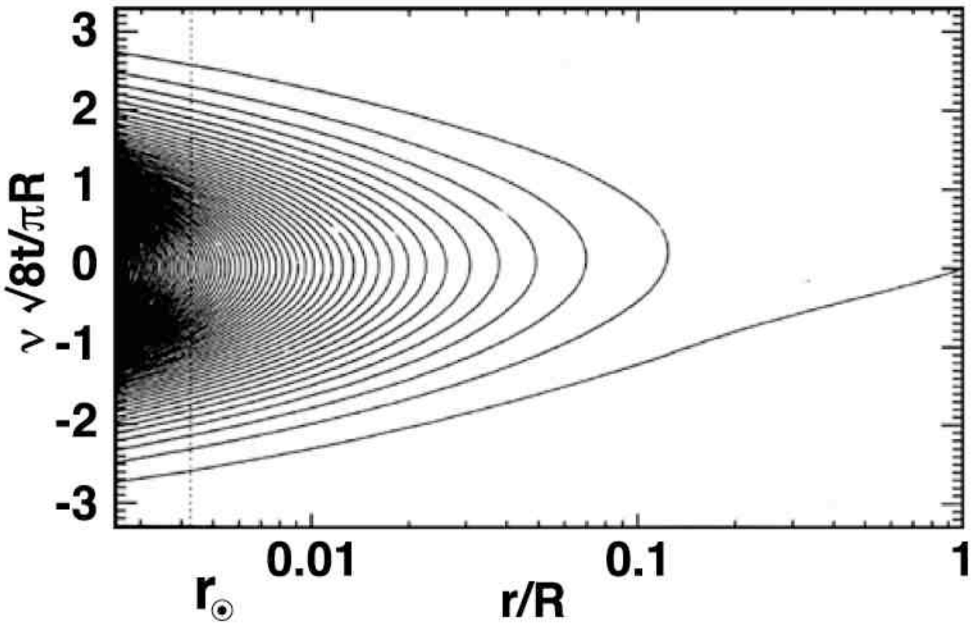
Origin of the non-thermalized component



Late-infall axions pass through our position with specific velocities

1-D infall, and the "folding" of phase space

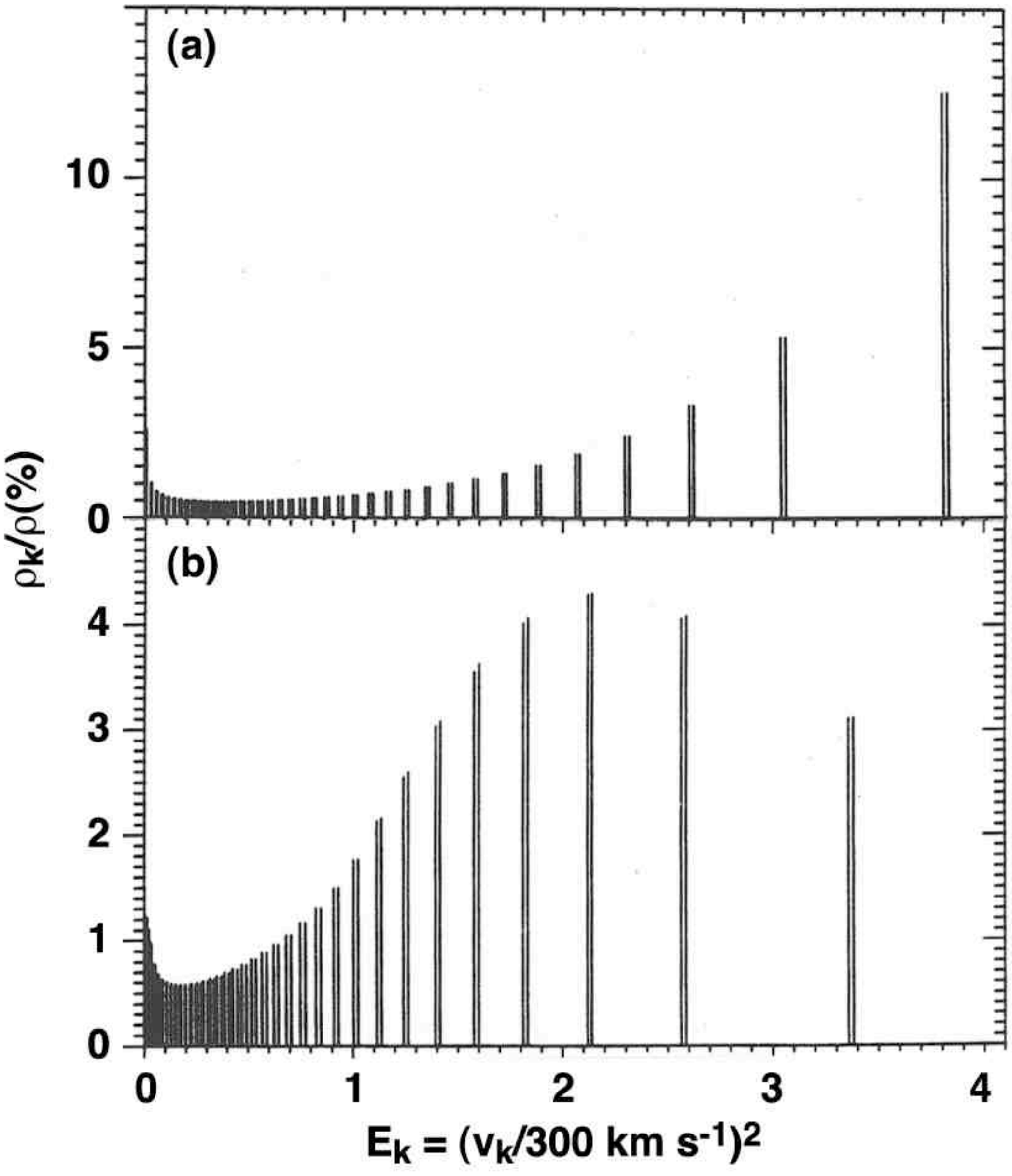




- Model begins with
  - Zero Temperature CDM
  - Hubble expansion
  - Initial density perturbation r = o

- Grows self-consistent potential

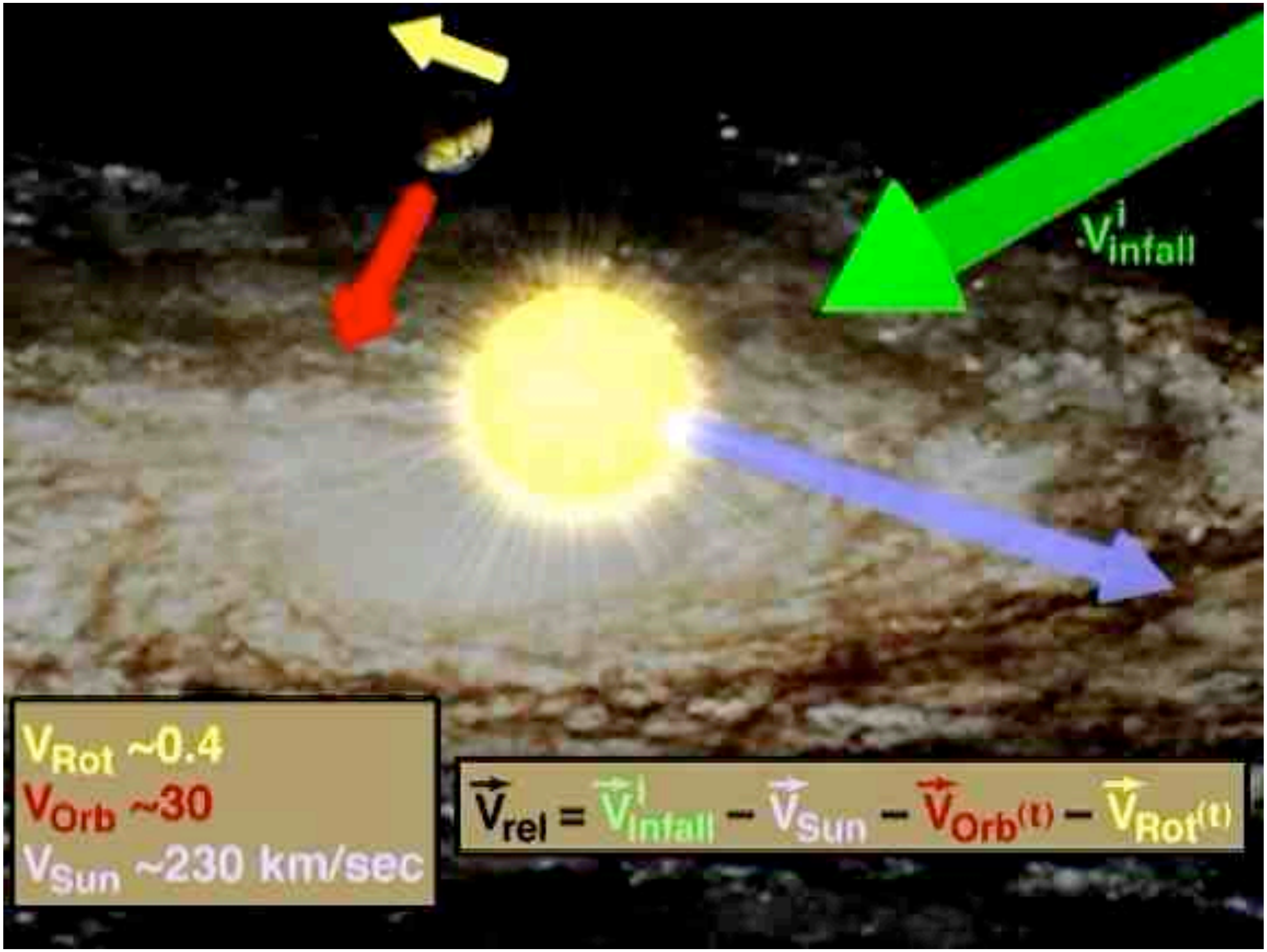
Velocity spectrum of axions at our solar system



(a) No angular momentum

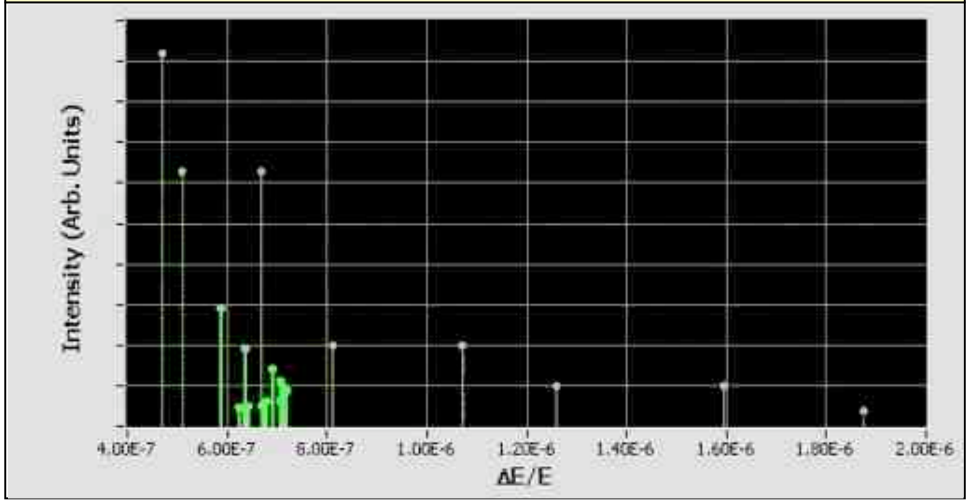
(b) Finite angular momentum

Diurnal and sidereal oscillation of the fine-structure

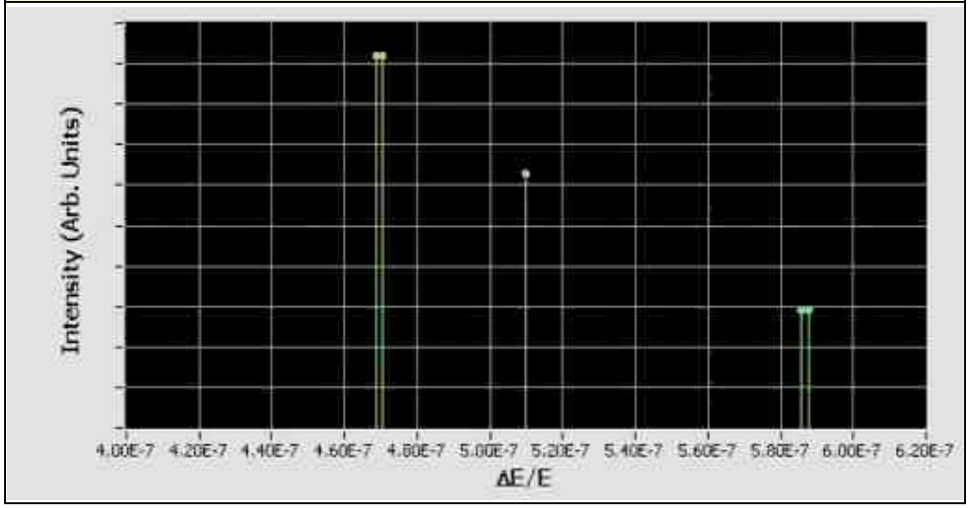


Simulation of one infall model

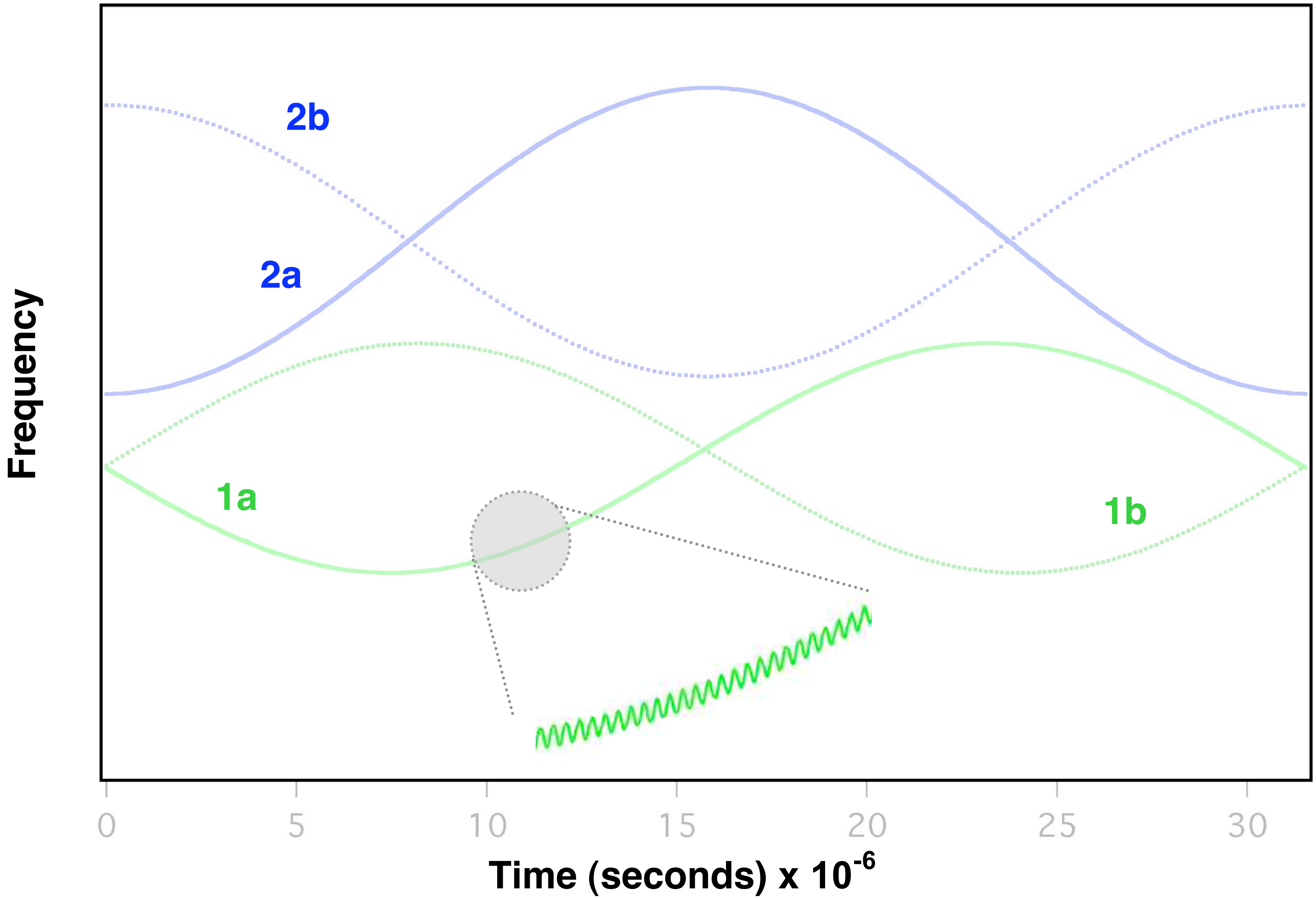
Annual



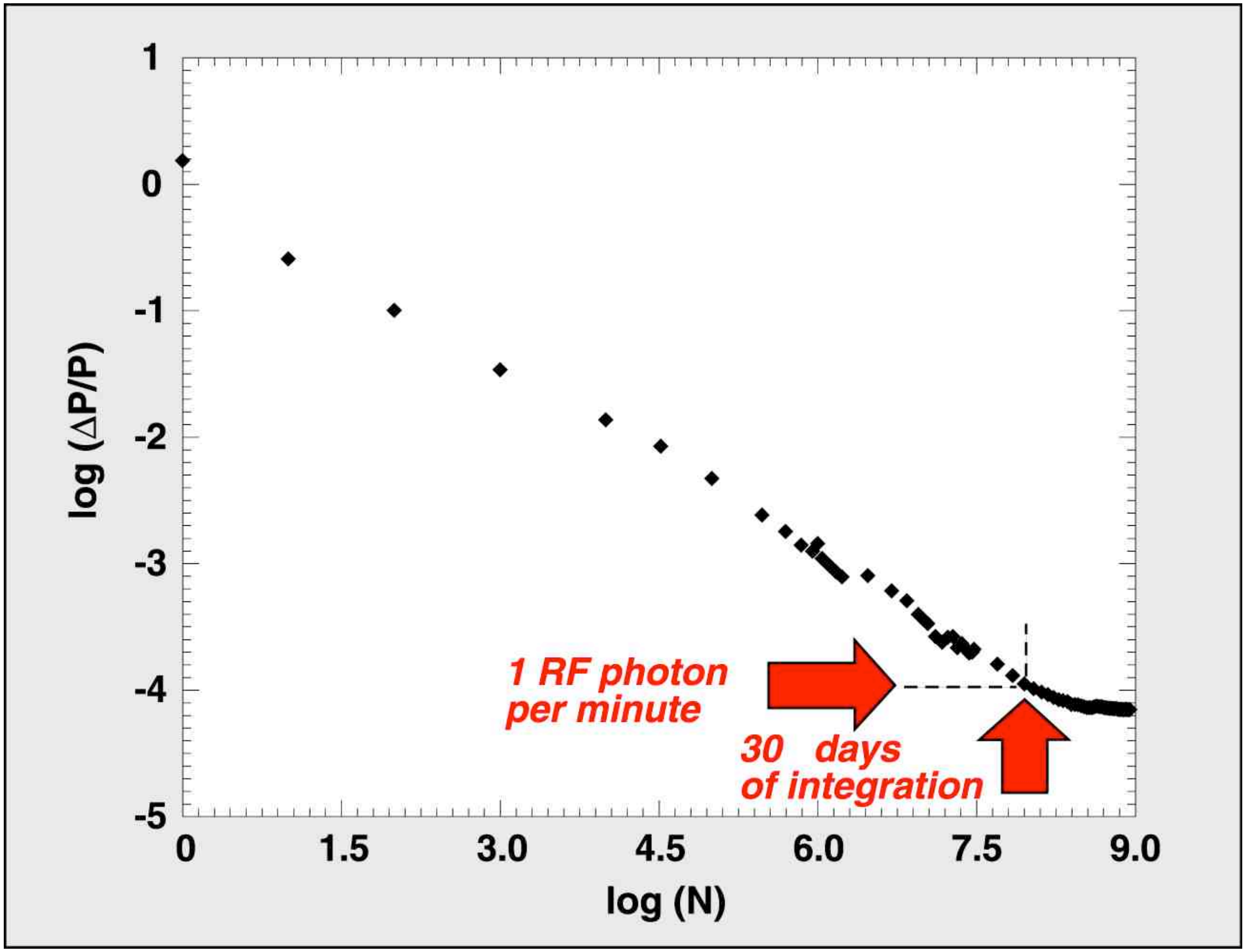
Daily



Diurnal and sidereal oscillation of late-infall axion peaks

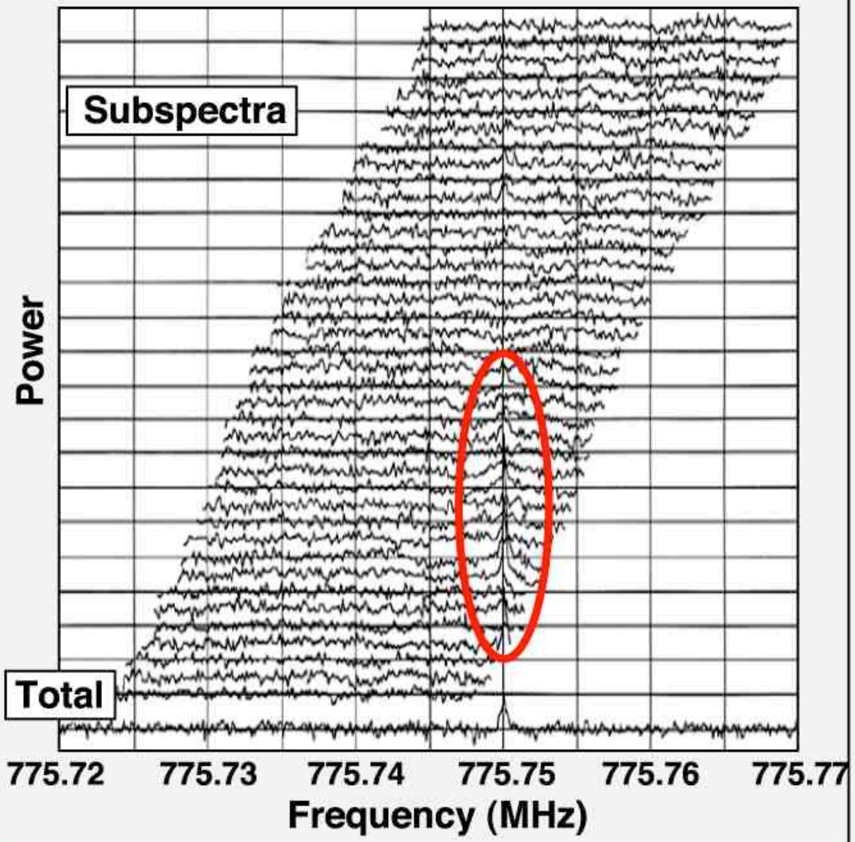
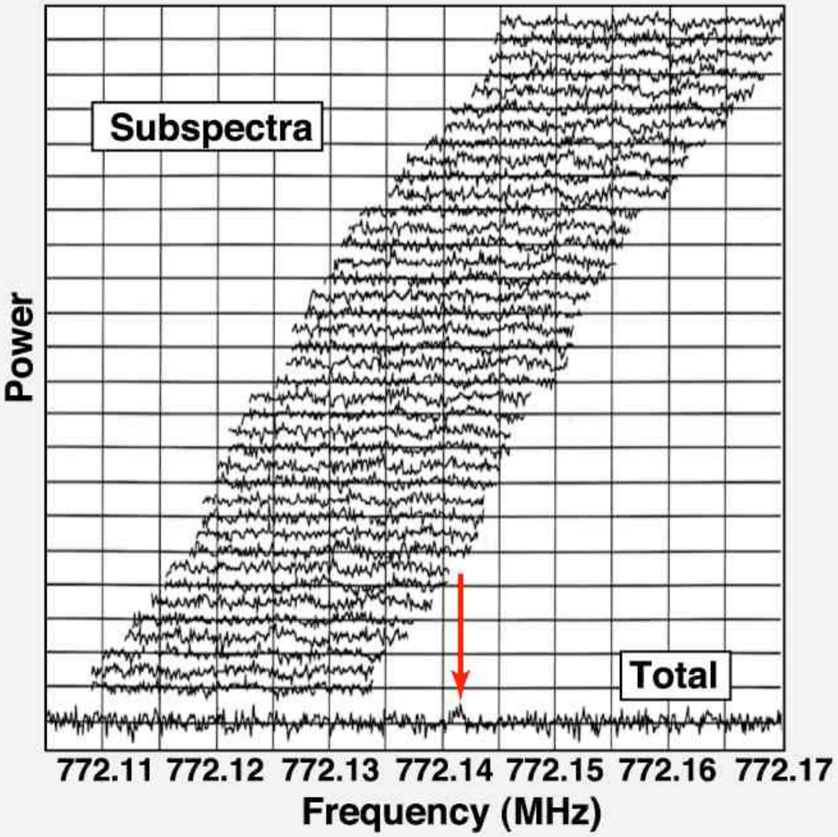


The world's quietest receiver — by 10^4!



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

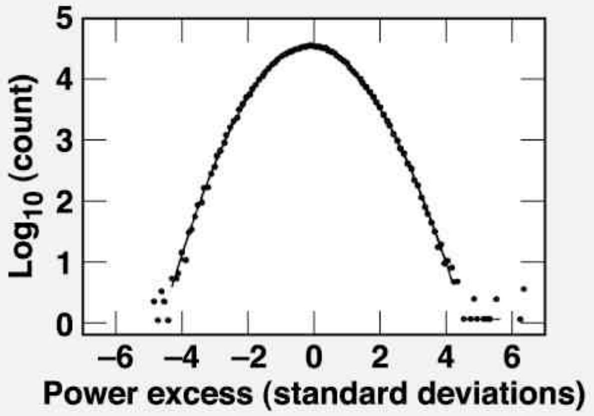
Sample data and candidates

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

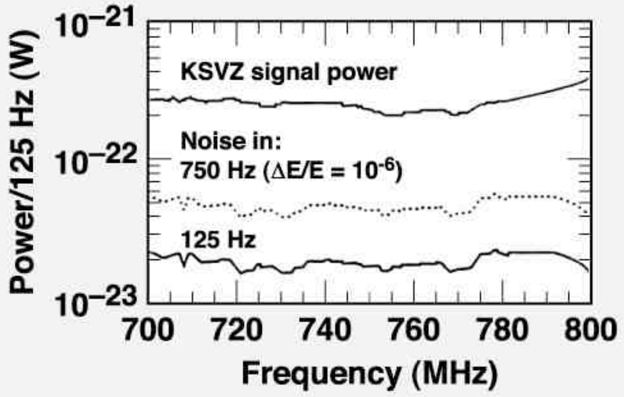
Brief outline of analysis — 100 MHz of data

Data, with Theoretical Curve

(Gaussian noise through receiver and analysis)



S/N > 4 for Thermalized KSVZ Axion

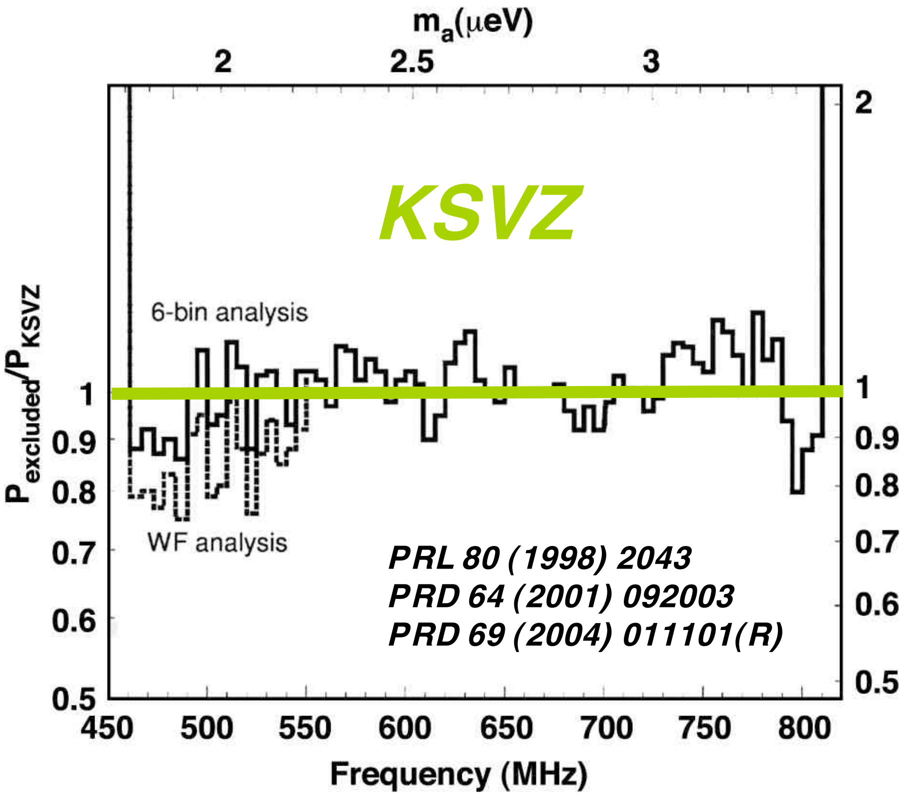


- Each frequency appears in >45 subspectra
- Weighted and co-added to produce spectrum
- 800,000 bins (125 Hz)/100 MHz

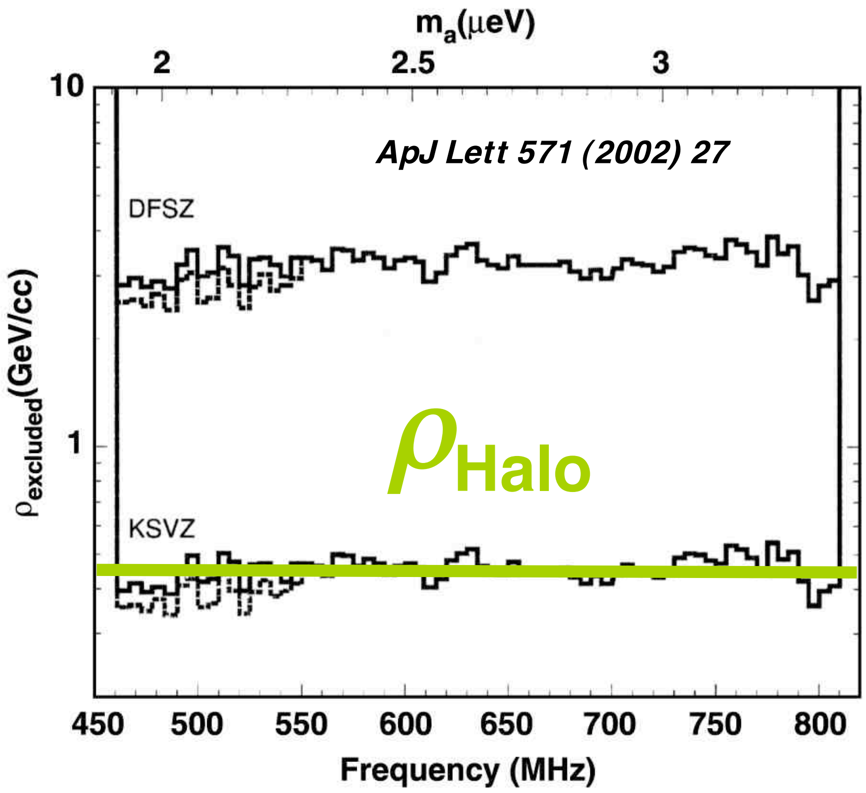
→ 6535 candidates > $2.25\sqrt{6}\,\overline{\sigma}$ (95% C.L.)
→ Rescan all to same sensitivity
→ 23 candidates (Net 90% C.L.)
→ Each examined: radio peaks

For a persistent peak, the ultimate test is to turn off the magnet!

Limits on axion models and local axion halo density



PRL 80 (1998) 2043
PRD 64 (2001) 092003
PRD 69 (2004) 011101(R)

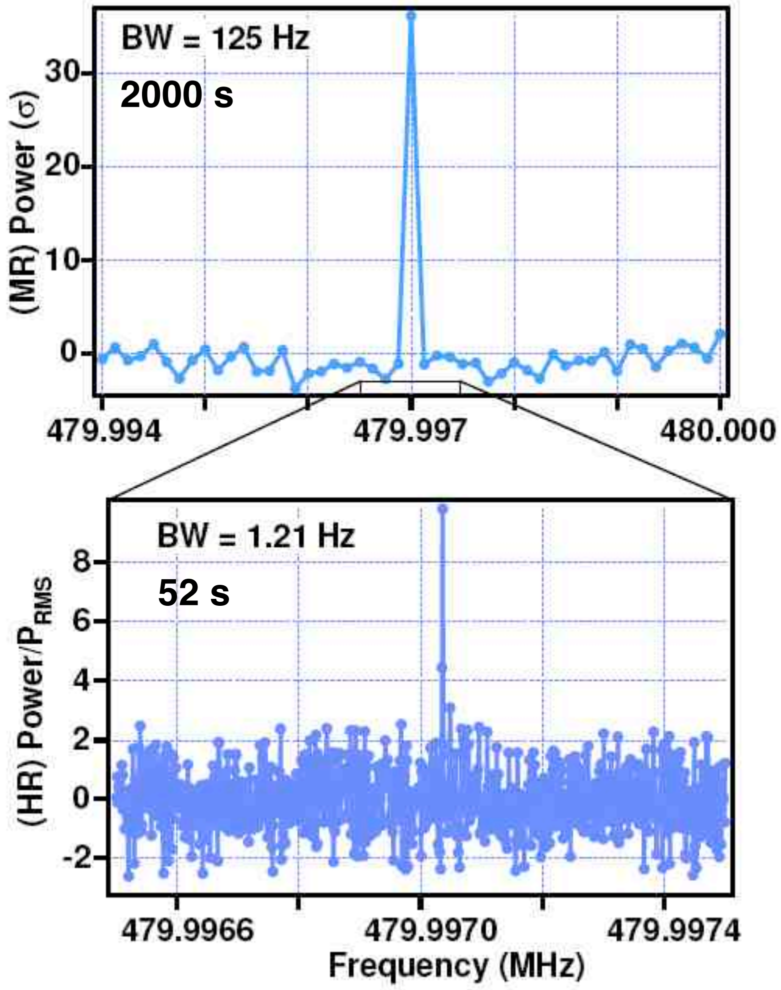


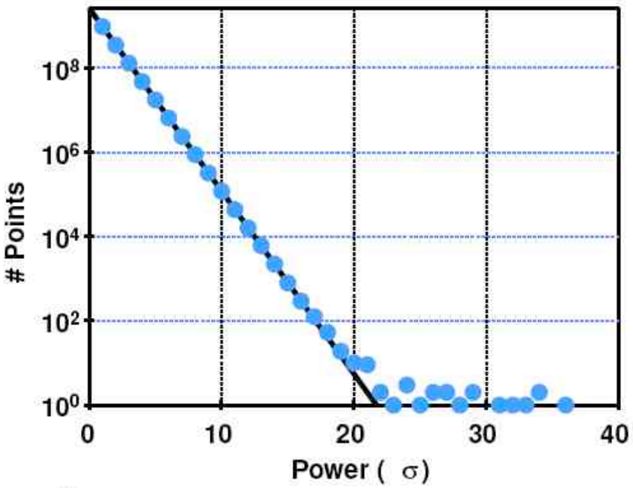
ApJ Lett 571 (2002) 27

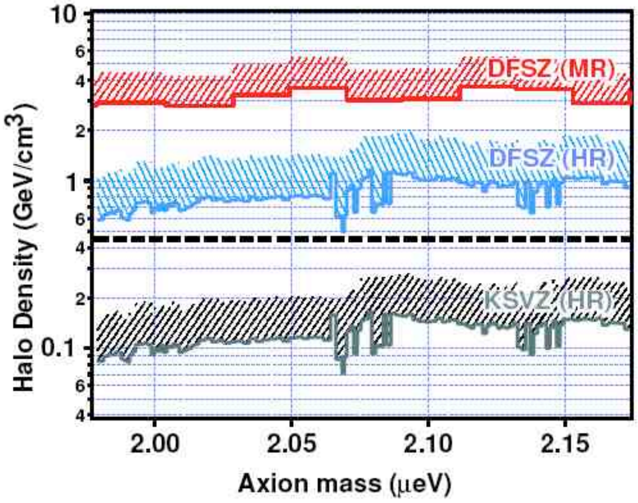
Plausible models have been excluded at the halo density over an octave in mass range

Results of a high-resolution analysis

PRL 95 (9) 091304 (2005)

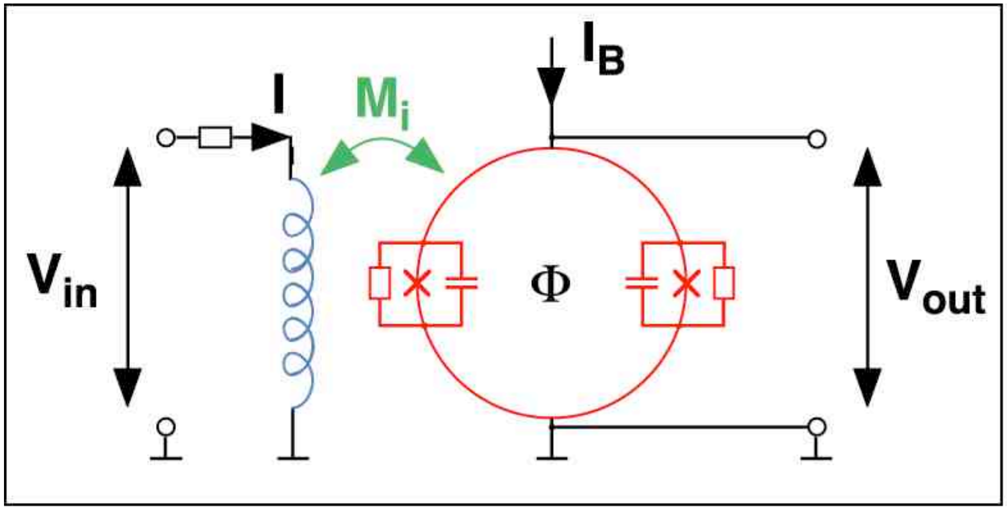


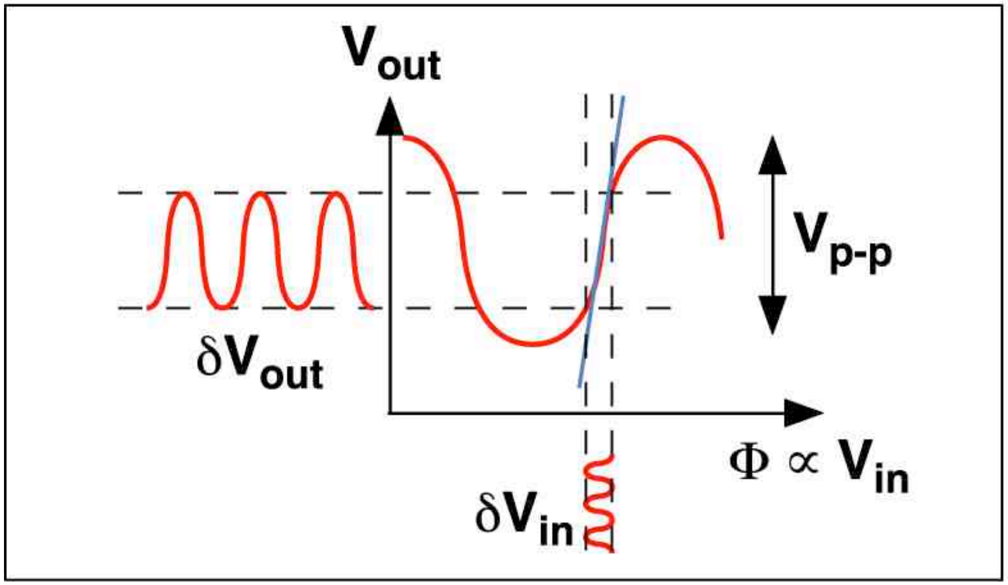




Measured power in environmental (radio) peak same in Med- & Hi-Res

Our future — SQUID amplifiers



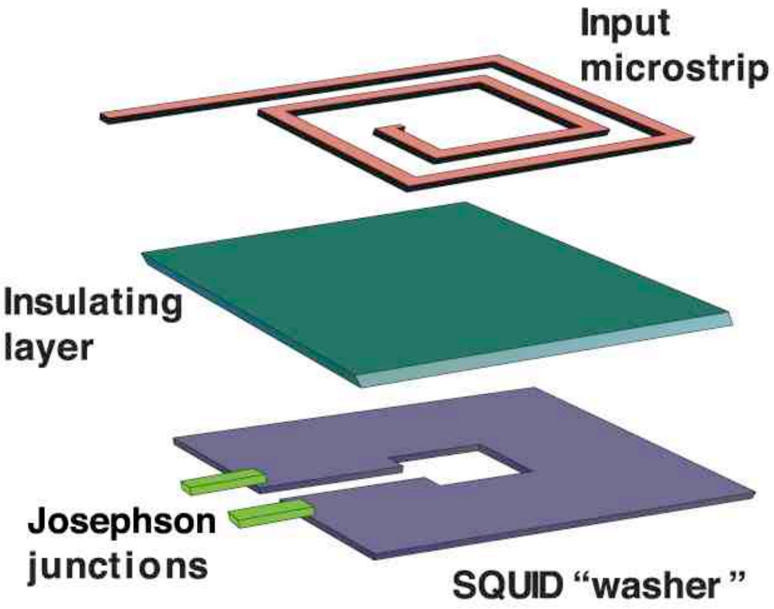


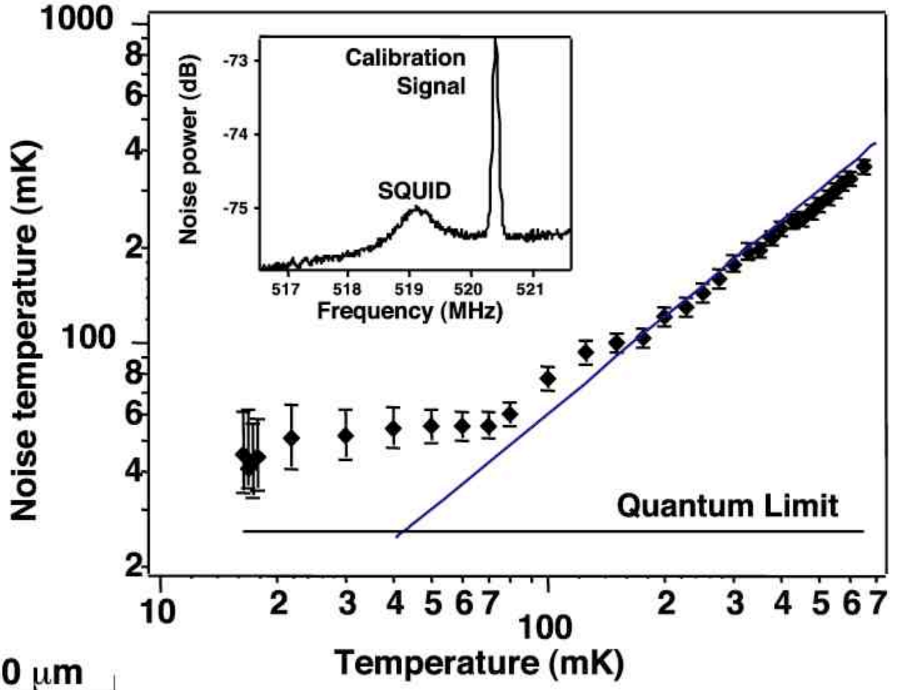
- The basic SQUID amplifier is a flux-to-voltage transformer

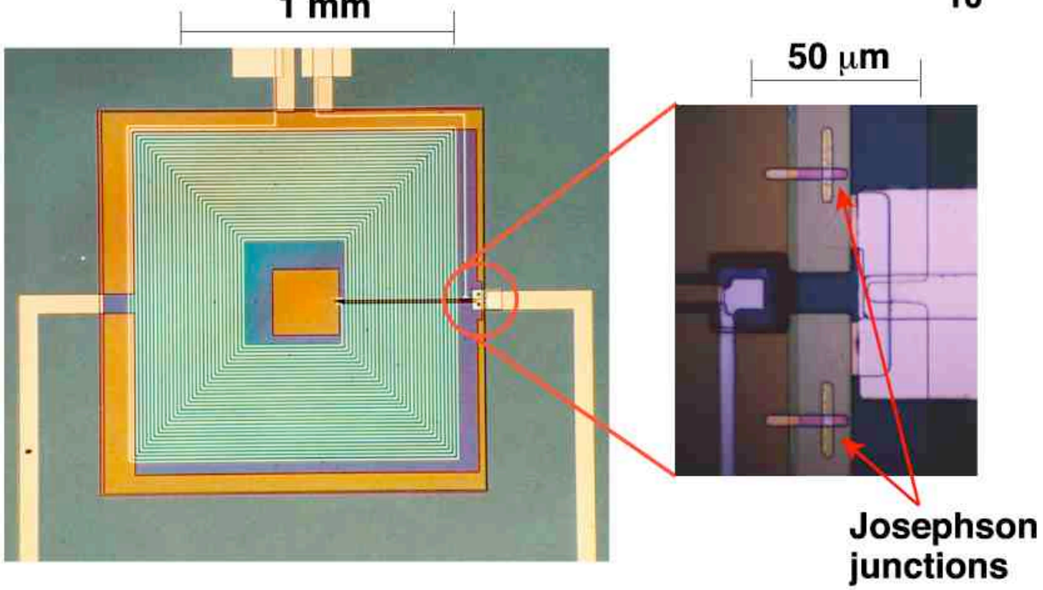
- SQUID noise arises from Nyquist noise in shunt resistance
  - Thus it scales linearly with T

- However, SQUIDs of conventional (inductively coupled) design are poor amplifiers above 100 MHz

Upgrade underway – Microstrip-coupled SQUIDs

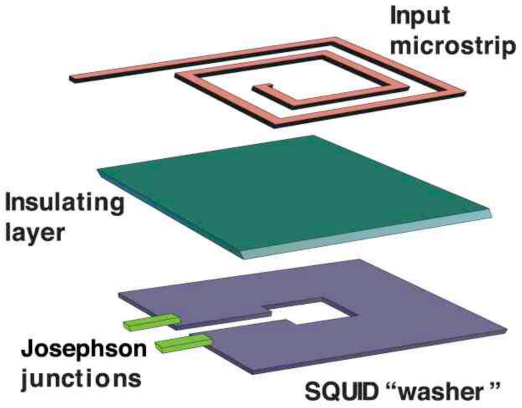


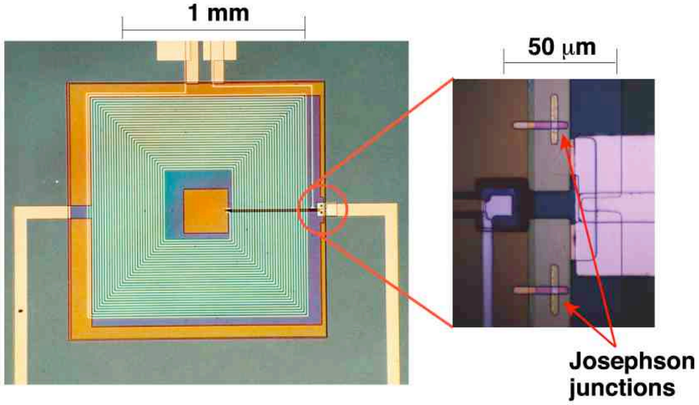


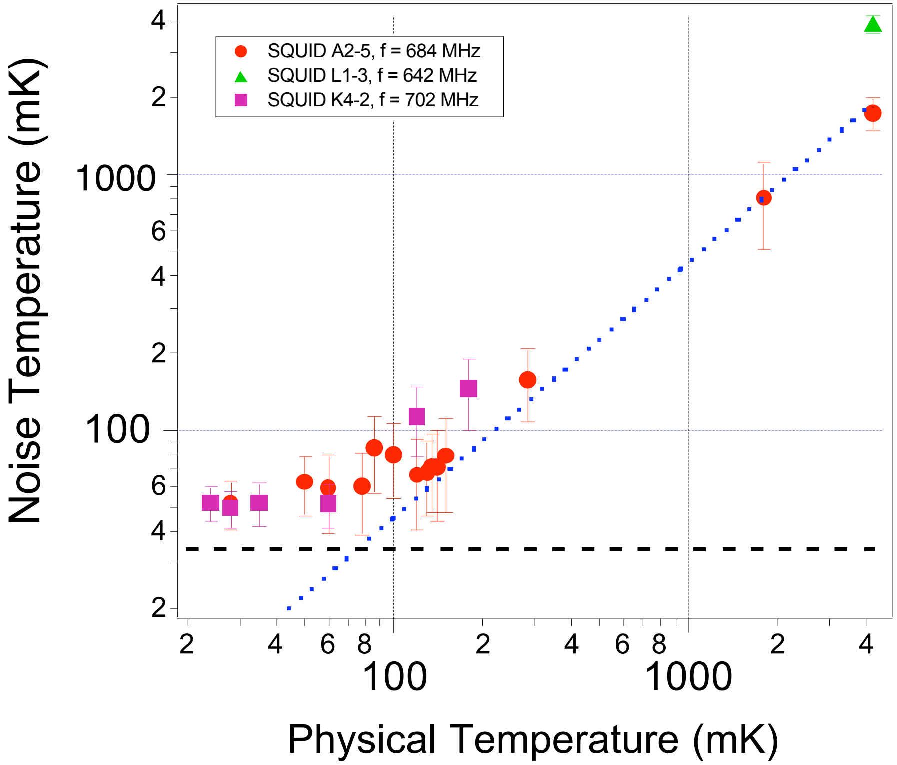


(J. Clarke *et al.*, U.C. Berkeley)

Upgrade well underway to GHz SQUID amplifiers

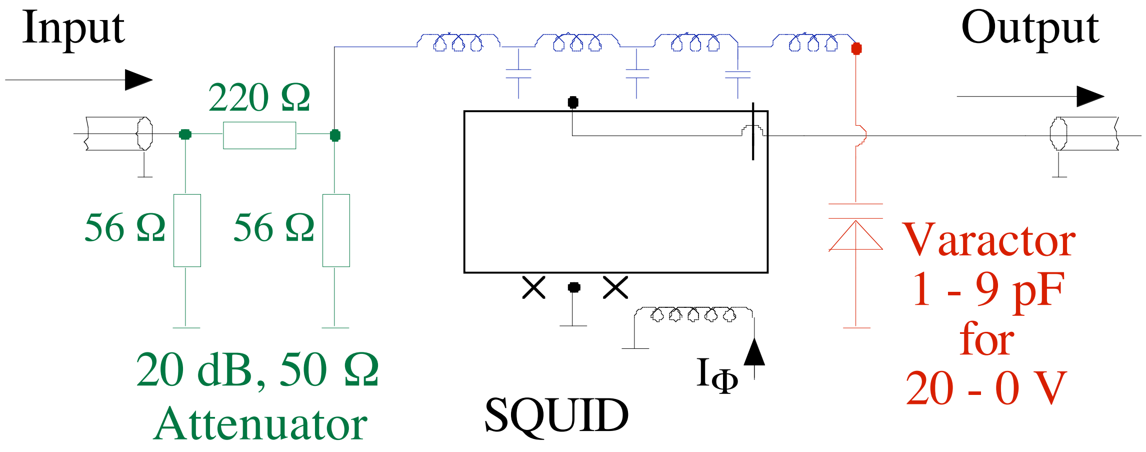


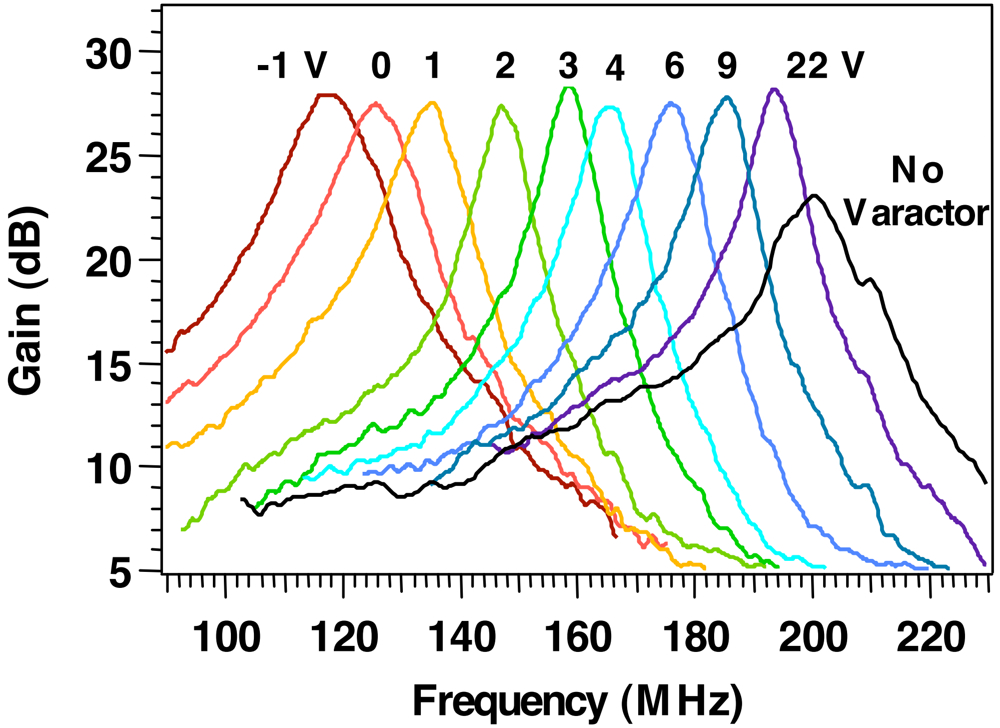




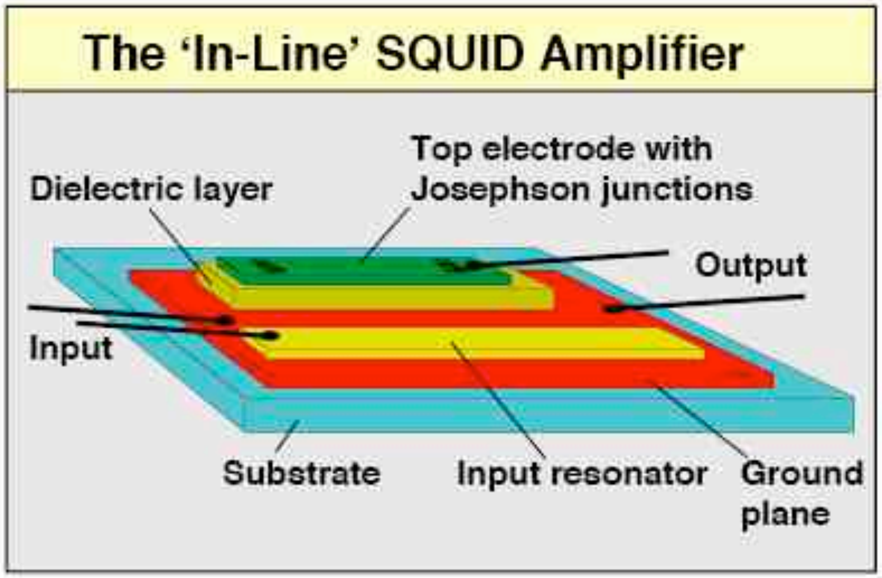
Latest SQUIDs are now within 30% of the Standard Quantum Limit

Varactor tuning of microstrip SQUID





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

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).

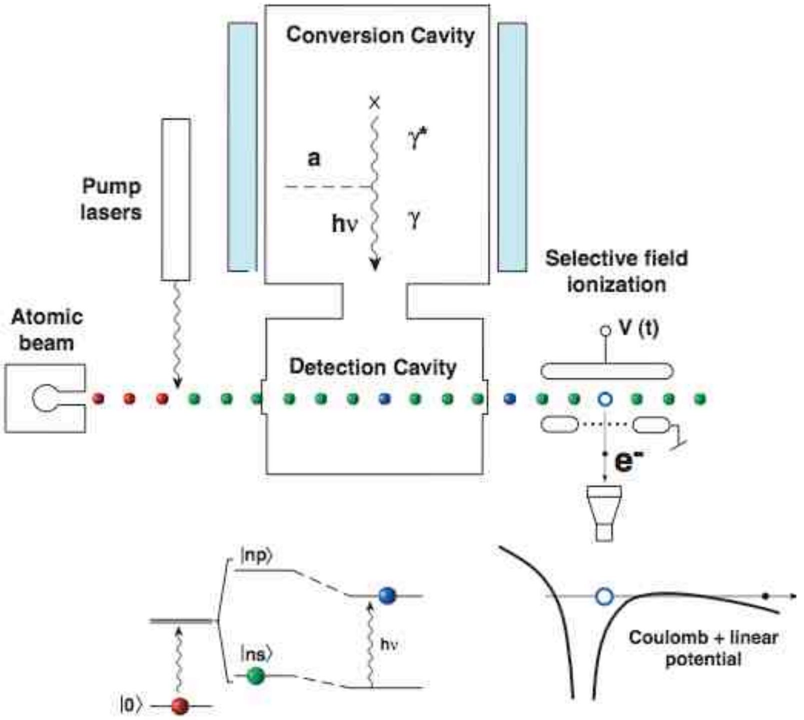
Potential for highly sensitive microwave photon detectors ("RF photo-multiplier tubes") realized by Kleppner and others in the1970's. The axion experiment is an ideal application for Rydberg atoms:

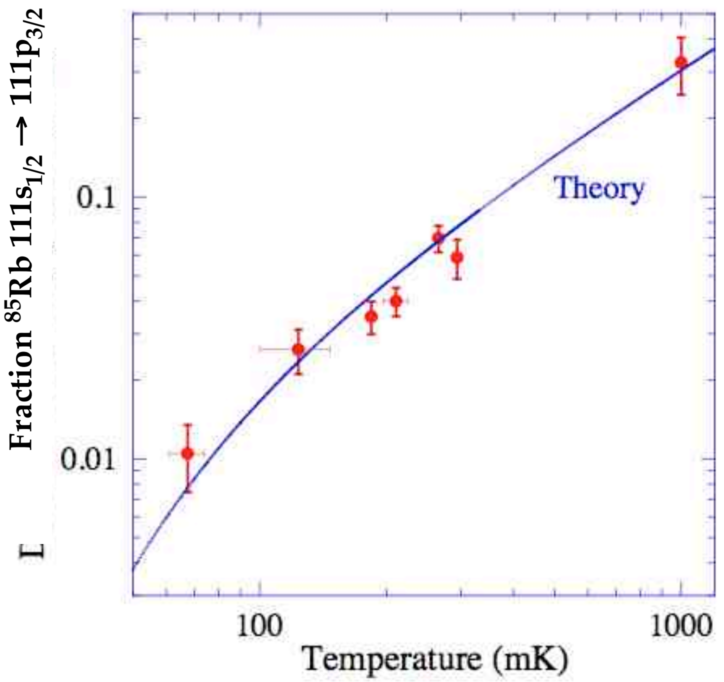
- ***Large transition dipole moments*** $\langle n \pm 1 | er | n \rangle \propto n^2 a_0$
- ***Long liftetimes*** $\tau_n \propto n^3 \quad (l << n); \quad \tau_{100} \approx 1\, m\sec$
- ***Transitions span microwave range*** $\Delta E_n = E_{n+1} - E_n \approx 2R/n^2\ ; \quad \Delta E_{100} \approx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

Most importantly, being a phaseless detector (photons-as-particles), the Rydberg-atom detector can evade the standard quantum limit:

$$h\nu = kT$$

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



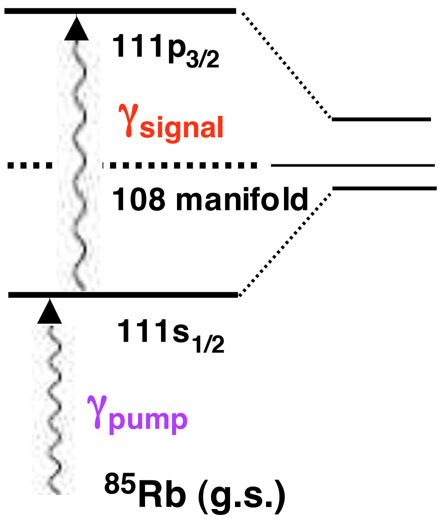


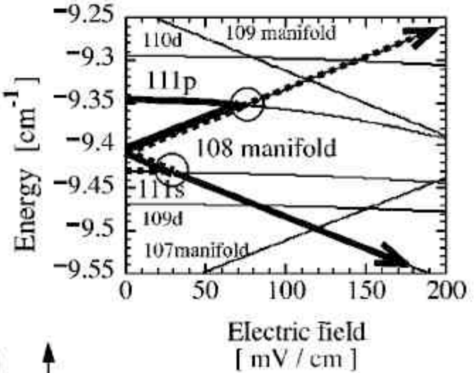
M. Tada et al., Phys. Lett. A (accepted)

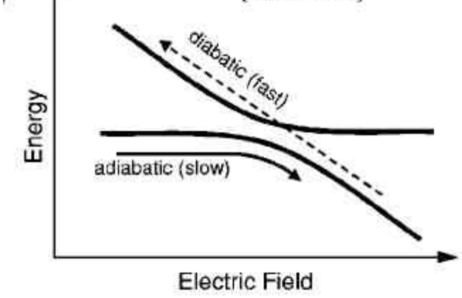
The blackbody spectrum has been measured at 2527 MHz a factor of ~2 below the standard quantum limit (~120mK)

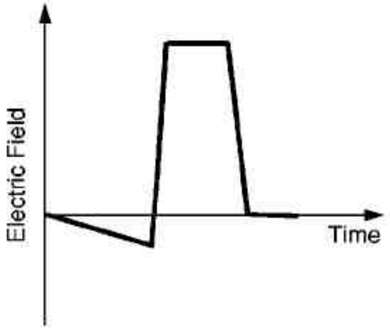
Selective field ionization

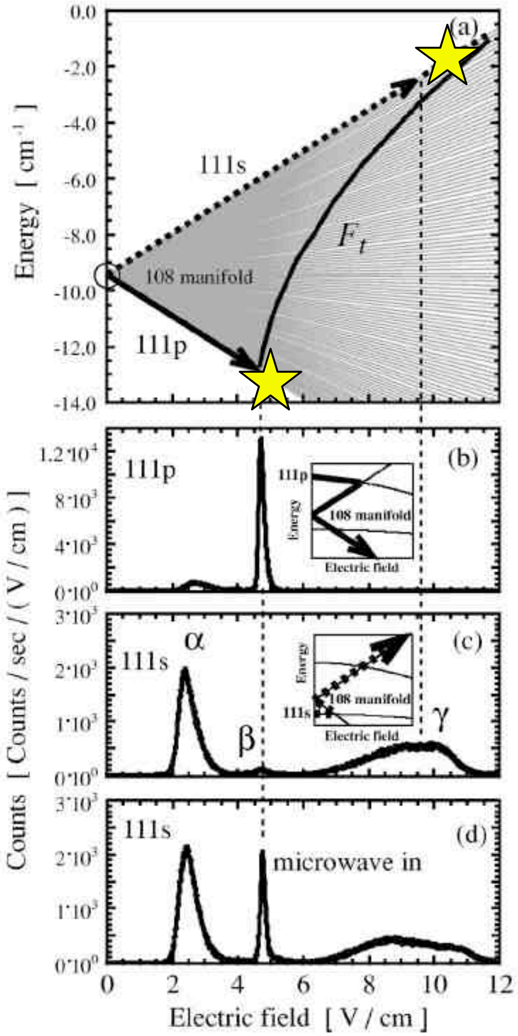
Y. Kishimoto et al., Phys. Lett. A 303 (2002) 279
M. Tada et al., Phys. Lett. A 303 (2002) 285
R. Bradley et al., Rev. Mod. Phys. 75 (2003) 777









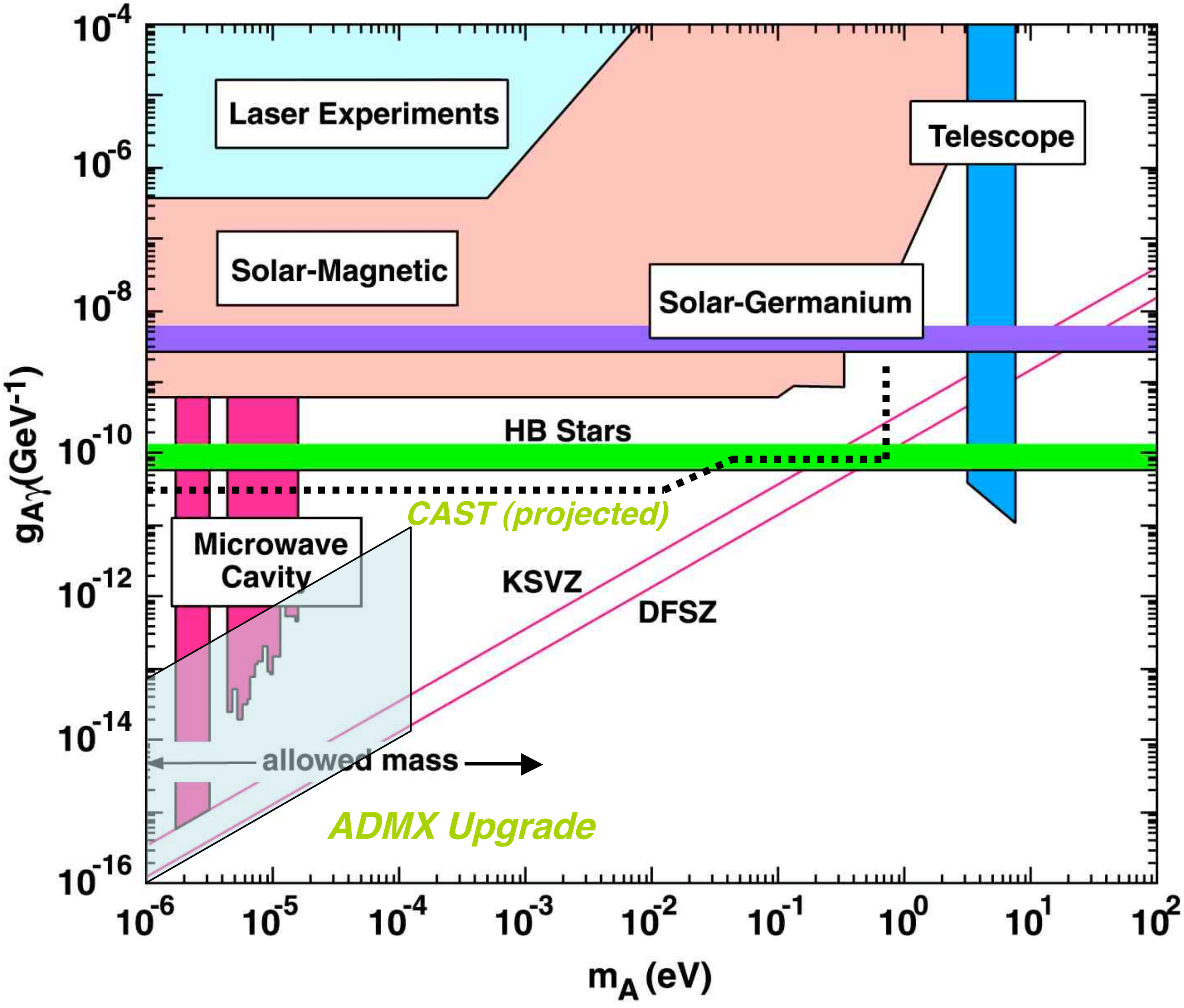


Rydberg "railroad switchyard" enables very high selectivity for ionization of the excited state (111p) with virtually no contamination of the prepared state (111s)

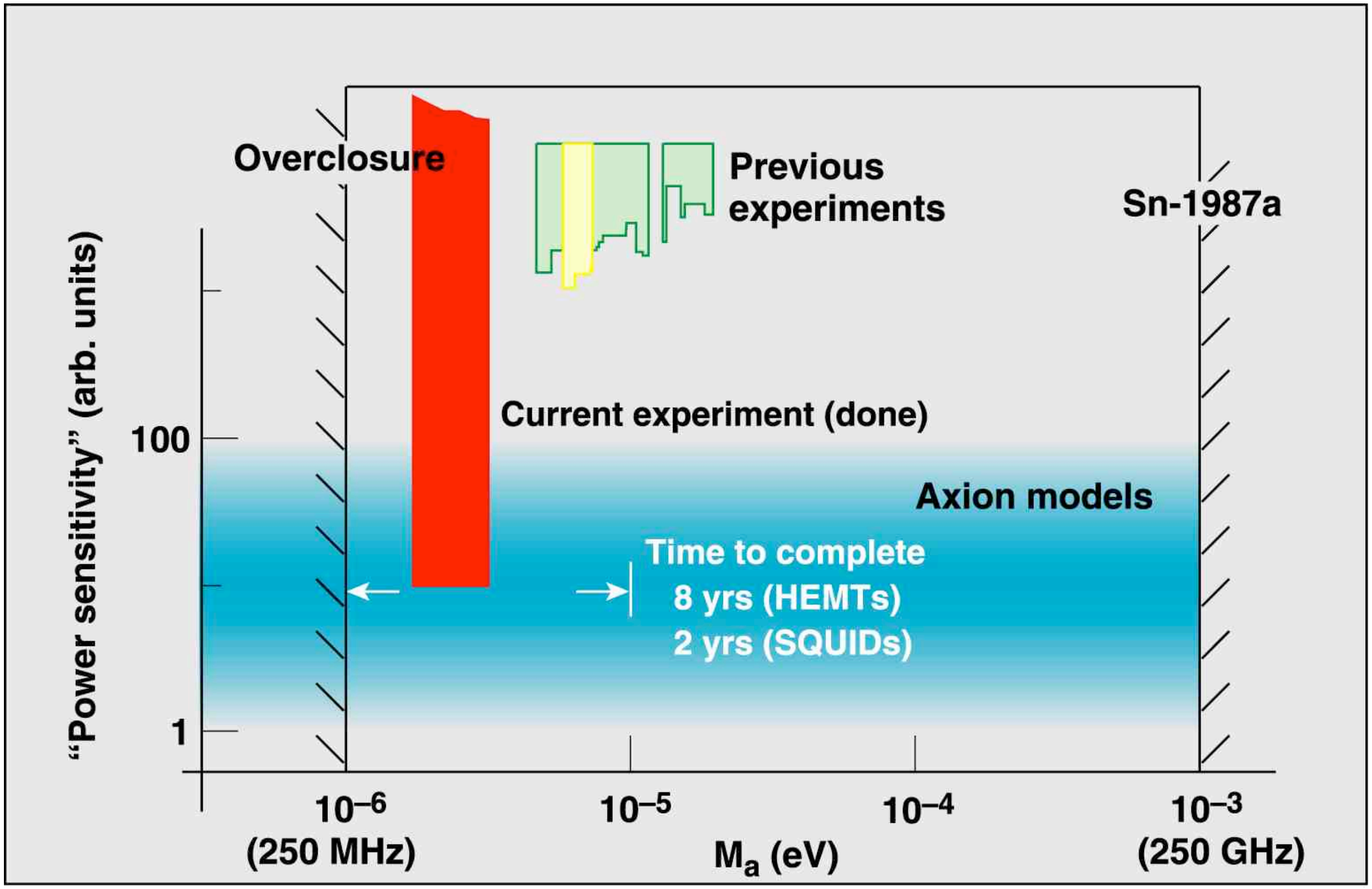
Quiz question: Why does the *lower energy state* ionize at a *lower electric field*?

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

AXION

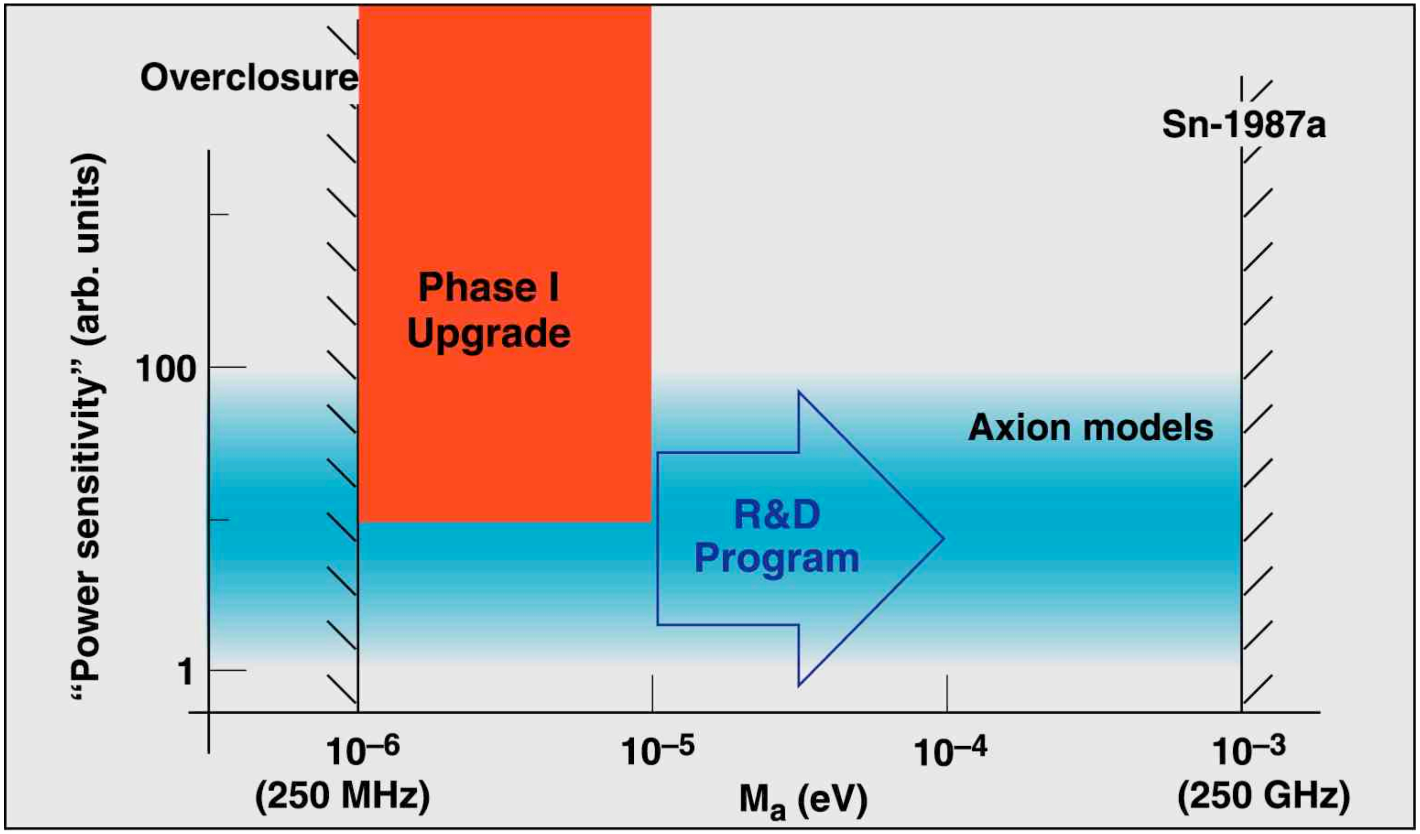


The current experiment and Phase I Upgrade



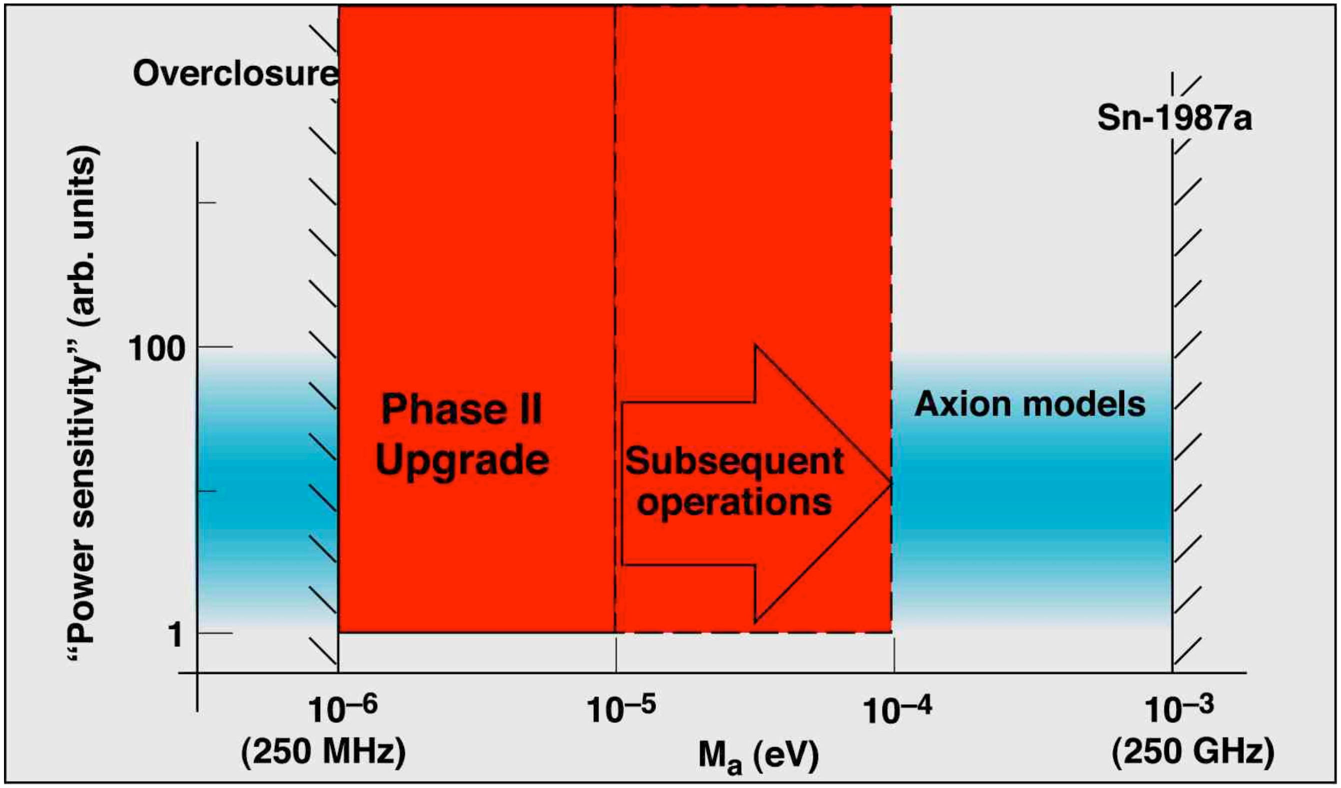
- **The current experiment is based on conventional heterojunction technology (HEMTs)**
- **The physical temperature is T = 1.3 K, and the total system noise temperature is $T_s \gtrsim 3K$**

The Phase I upgrade (ongoing – run mid-2006)



- 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

The Phase II upgrade (next proposal)



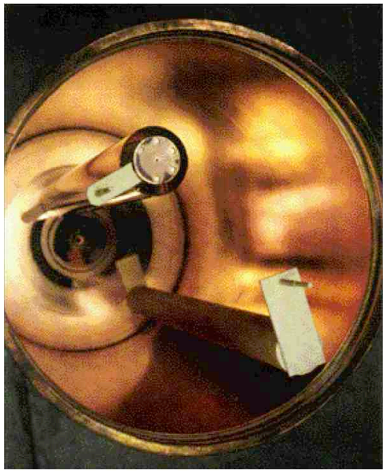
- The Phase II upgrade will add a dilution refrigerator
    - — T ~ 100 mK, $T_S \lesssim 200$ mK
- We will achieve definitive sensitivity over the lowest decade in mass
- And — depending on our R&D success — we will finally cover 2/3 of the mass range

Opportunity for a new collaborating institution in ADMX to develop the microwave cavities!

The ideal group might be an accelerator lab:

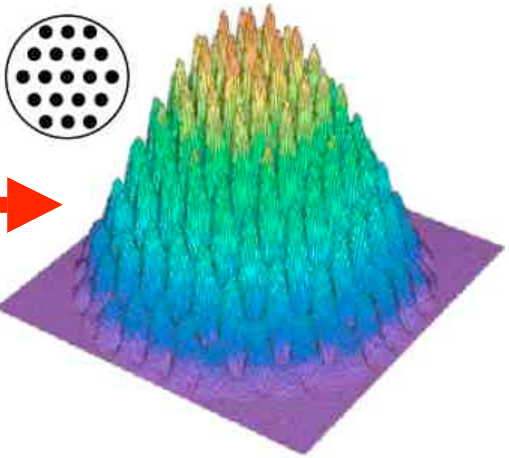
- Electromagnetic modeling
- Prototyping
- RF microwave diagnostics
- Precision metal fabrication, etc.

1 GHz



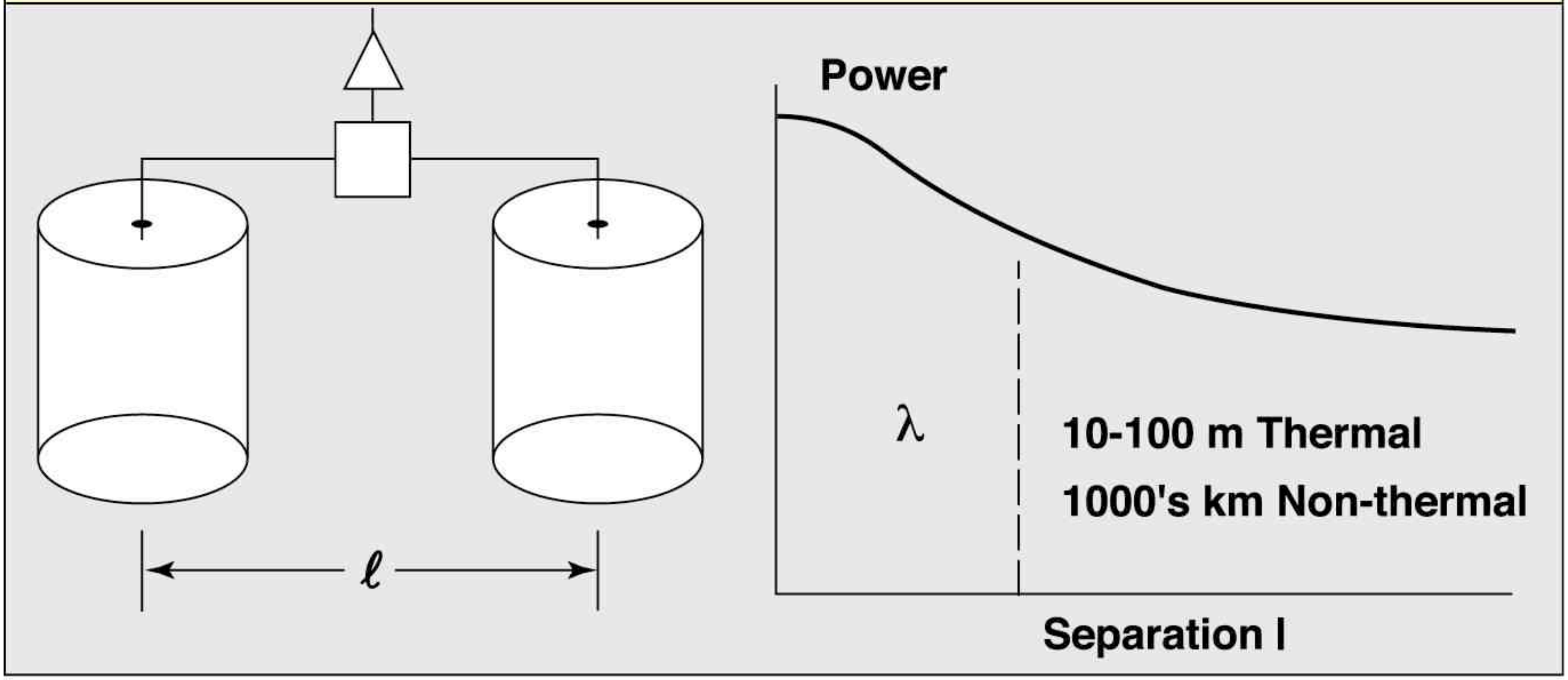
10 GHz

100 GHz



What if the axion is found?

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

Summary & conclusions

- 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
  - The experiment measures E_{tot}, thus potentially revealing extraordinary detail of galactic formation & dynamics through fine-structure and their Doppler modulation
- Experiments are making excellent progress
  - Driving two remarkable technologies: SQUIDs, Rydberg atoms
  - The one DM game where sensitivity will *not* be the issue
  - Scanning in mass *is*; opportunity for a new group to join ADMX
- Axionic dark matter would be a unique Bose system for study

We're all rooting for Supersymmetry at the LHC, but we should root for Axions as the Dark Matter!

Did we forget anything?

Two decades afterwards and the experimental campaign to find the axion is *exclusively* focused on its two-photon coupling, and even that through the Primakoff interaction.

Pierre's insight (PRL 1983) that employing the coherent mixing of axions with photons in a strong magnetic field over a large spatial volume, is very likely the absolutely correct strategy. However, it is difficult to articulate or quantify why that is the case.

It was not always so. In the 1980's schemes were examined to look for the axion through its spin coupling (e.g. coherent magnon production in thin ferrite layers), but gained no traction.

It would seem prudent to examine our assumptions periodically, lest we overlook some other opportunity