Microwave Cavity Search for Axions

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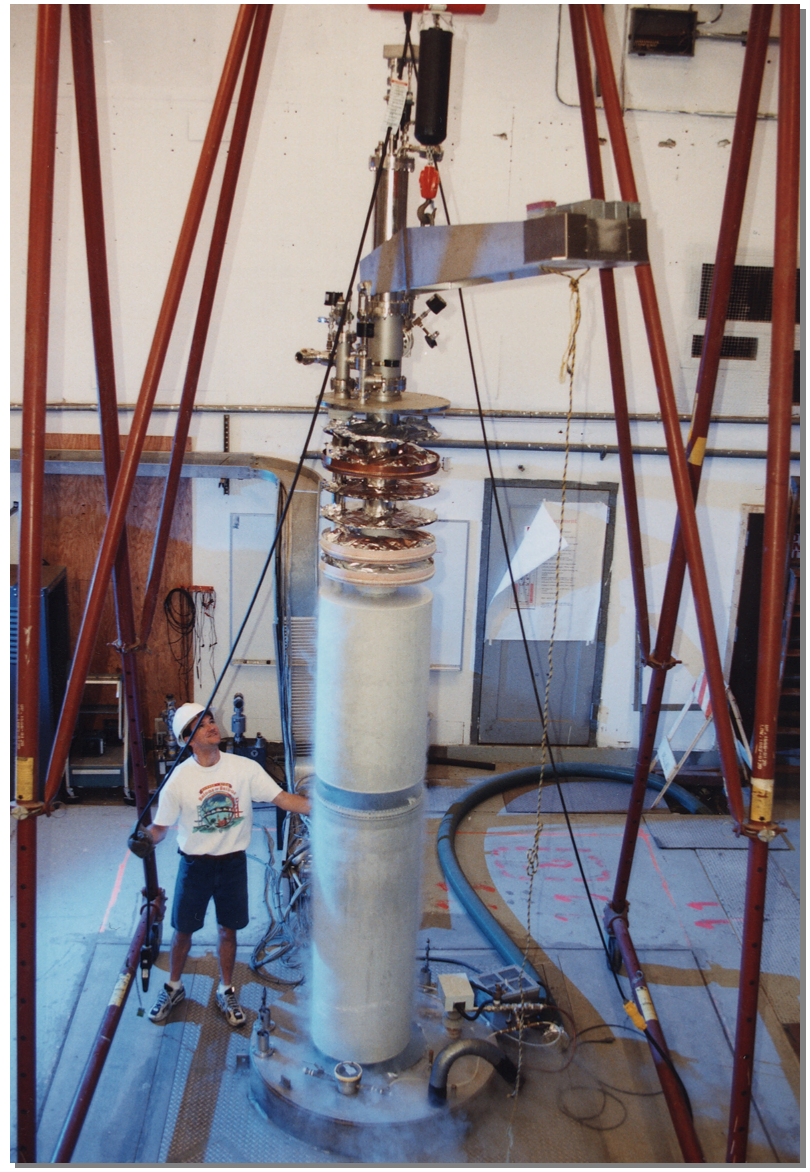

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Outline

- Brief review of the axion and its dark matter implications
- The Sikivie microwave cavity technique
- The Axion Dark-Matter Experiment (ADMX) – Results
- ADMX – Prospects
- Another approach to axion detection – Photon regeneration
- Summary

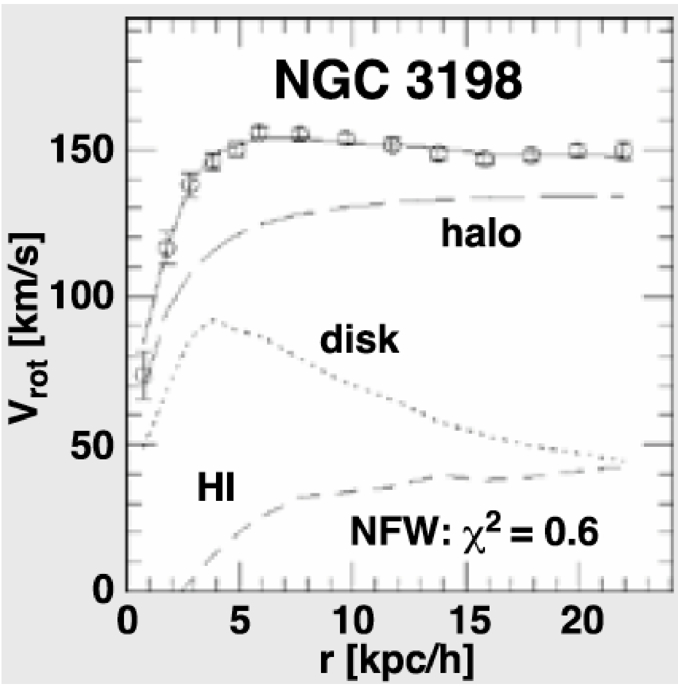
A brief review of the axion

- Peccei-Quinn mechanism for strong CP problem -> a
- Like an ultra-light, ultra-weakly interacting pion π^0
- Decays by two-photon emission $a \to \gamma\gamma$ (but $\tau > \tau_{universe}$)
- All couplings *proportional* to its mass: $g_{aii} \sim m_a$
- Abundance roughly *inverse* to mass: $\Omega_a \sim m_a^{-7/6}$
- Mass limits: $10^{-6} < m_a < 10^{-(2-3)}$ eV

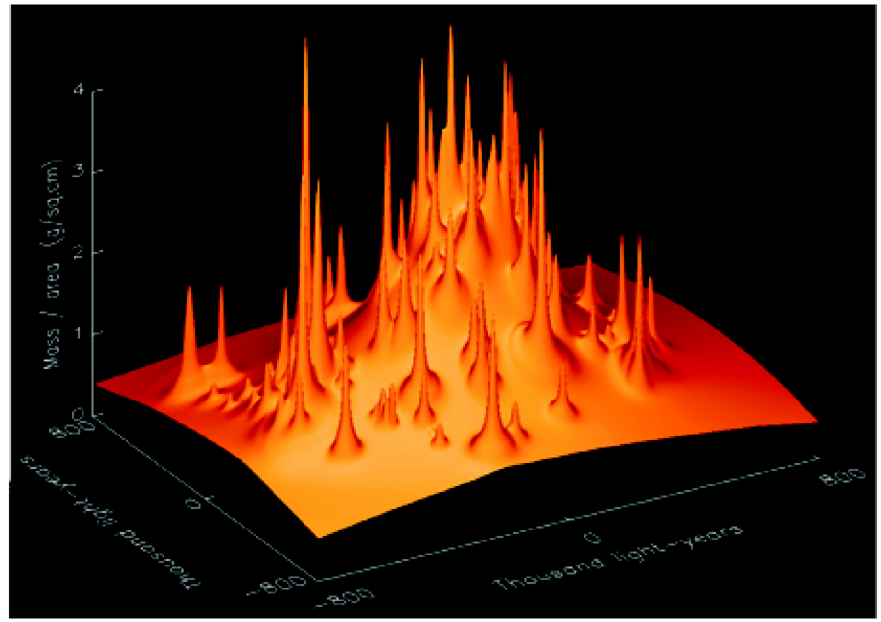
  (*overclosure*) (*SN1987a*)
- Galactic halos may consist of axions (Ipser/Sikivie, PRL 1983)
- At the Earth, $\rho = 0.45$ geV/cm^3

Evidence for dark matter: now very compelling

Dynamics



Lensing of background objects as a probe



"The rotation curves [of all spiral galaxies] remain high even at large radii."

Faber and Gallagher
ARAA 1979

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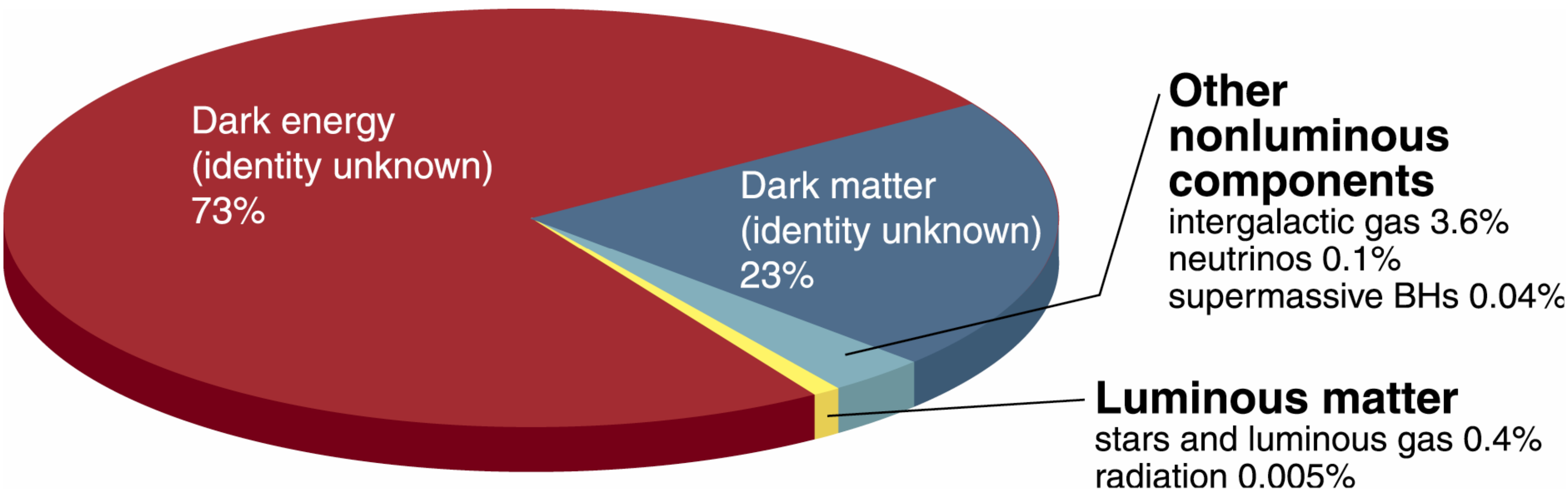
The cosmological inventory is now well-delineated

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



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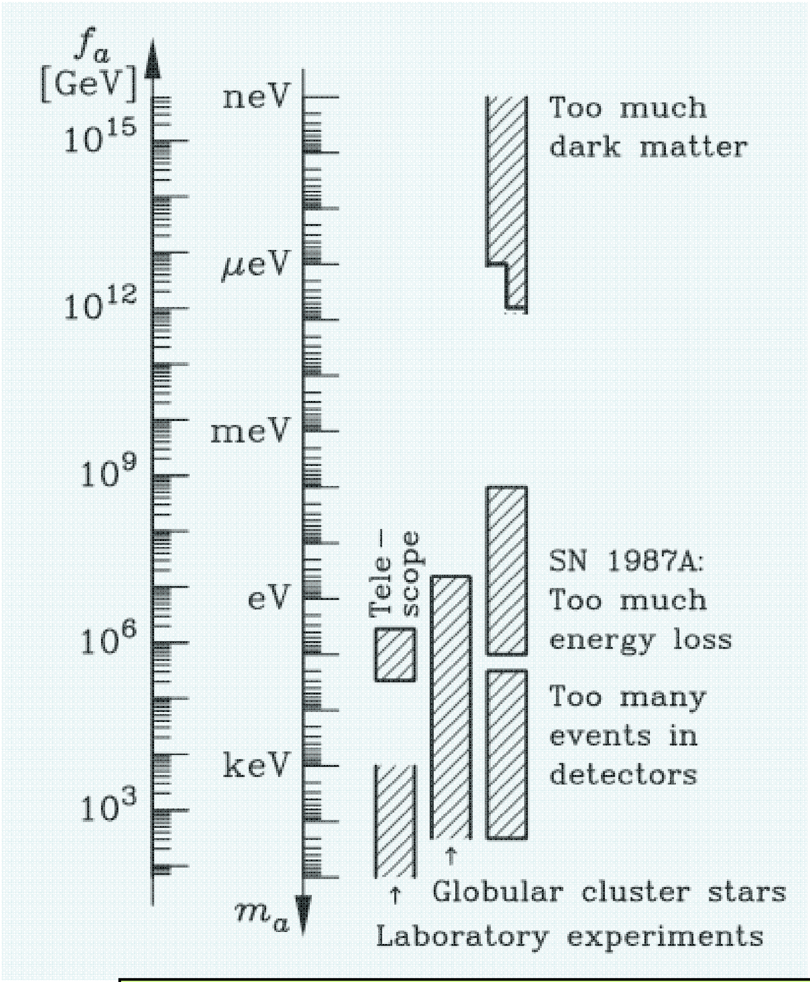
Present window for the axion mass



Very light axions forbidden: else too much dark matter

⇐Dark matter range:“axion window”
very hard to detect
“invisible axions”

Heavy axions forbidden: else new pion-like particle

A very light axion (~10 μeV) would be an ideal dark-matter candidate

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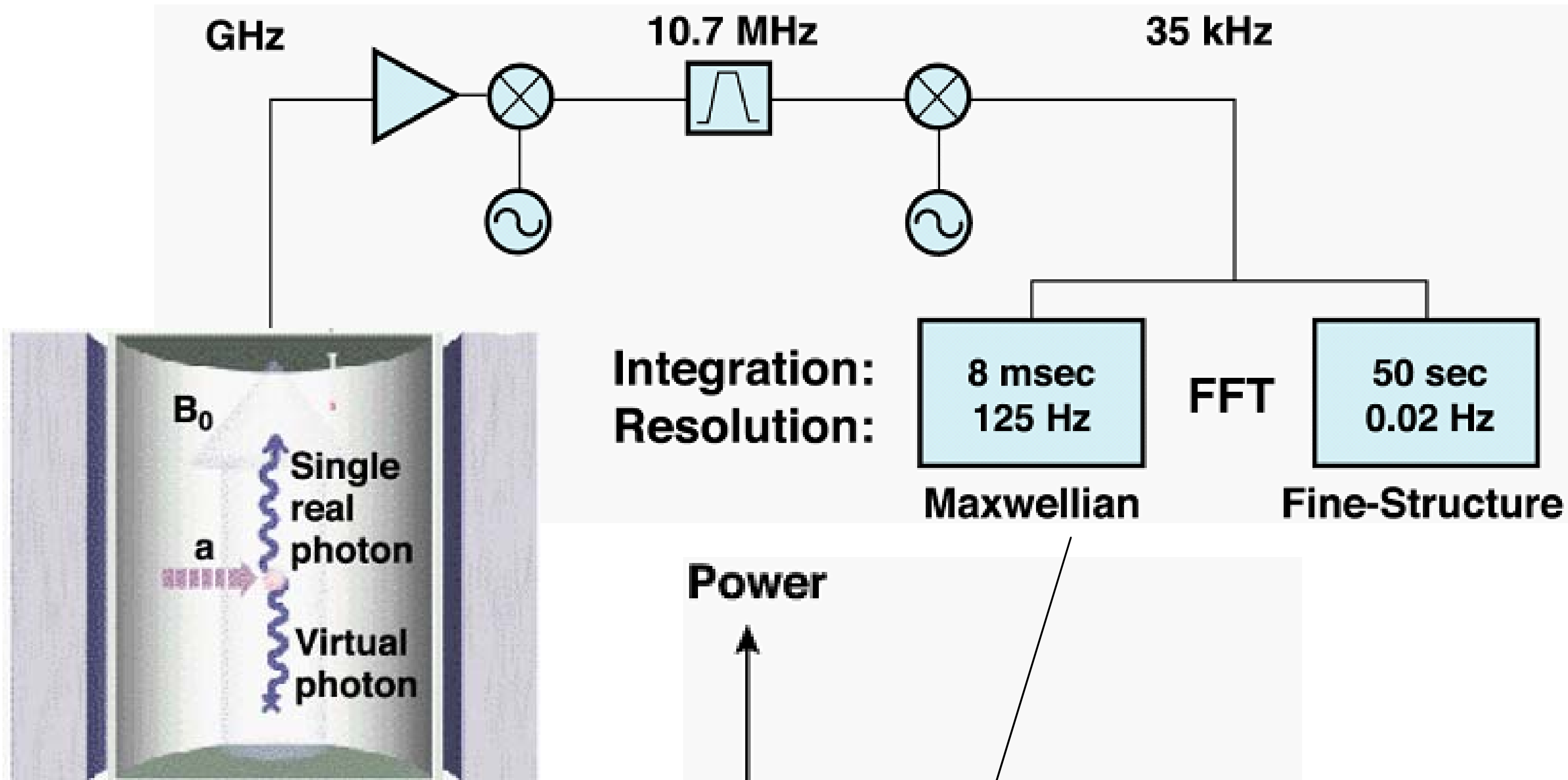
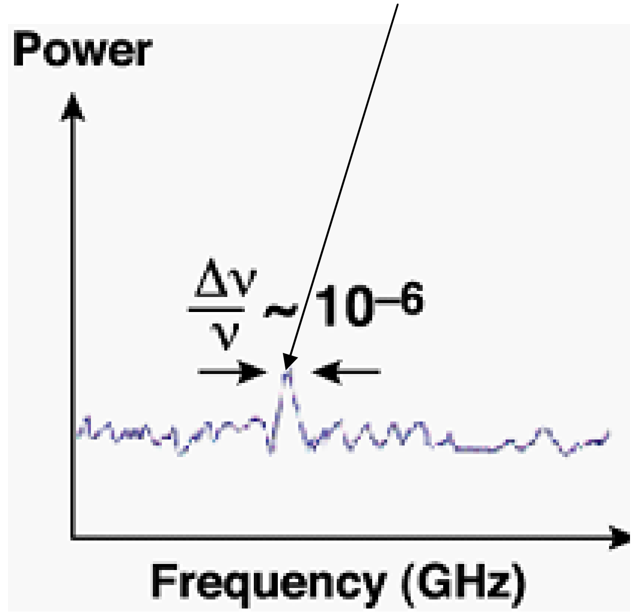
Cavity axion detector (Sikivie, 1983)





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

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Signal strength

- Power from the cavity is

$$P = 2.3 \cdot 10^{-26}\mathrm{Watt}\left(\frac{V}{200\ell}\right)\left(\frac{B_0}{8\mathrm{Tesla}}\right)^2 C_{nl}\left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5\cdot 10^{24}\mathrm{g/cm}^3}\right)\left(\frac{m_\mathrm{a}}{2\pi\mathrm{GHz}}\right)\min(Q_\mathrm{L}, Q_\mathrm{a})$$

- $Q_\mathrm{L} \sim 10^5$ and $Q_a \sim 10^6$

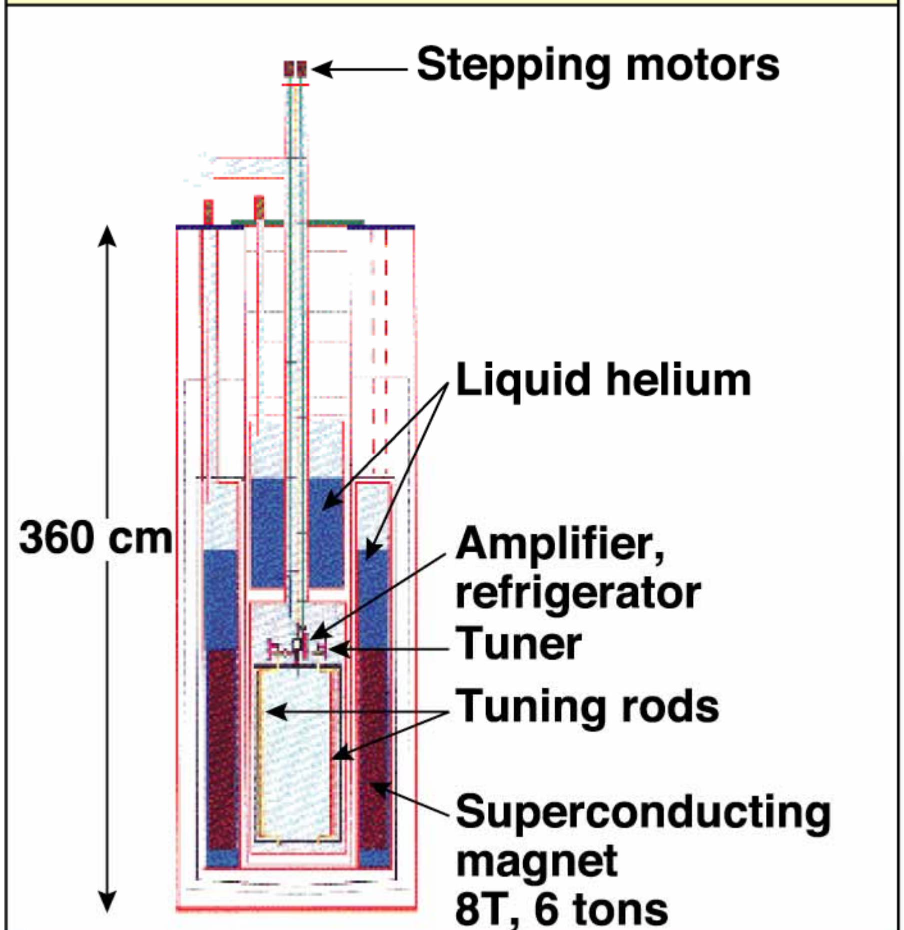
- For KSVZ axions, $g_\gamma \sim 0.97$,[1] whereas for DFSZ axions $g_\gamma \sim 0.36$.[2]

[1] The KSVZ model is one implementation of the 'hadronic axion,' J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. **B166**, 493 (1980).

[2] The DFSZ model is based on a simple GUT scenario M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **B104**, 199 (1981); A.R. Zhitnitsky, Yad. Fiz. **31**, 497 (1980) [Sov. J. Nucl. Phys. **31**, 260 (1980)].

ADMX hardware @ LLNL

Magnet with Insert (side view)



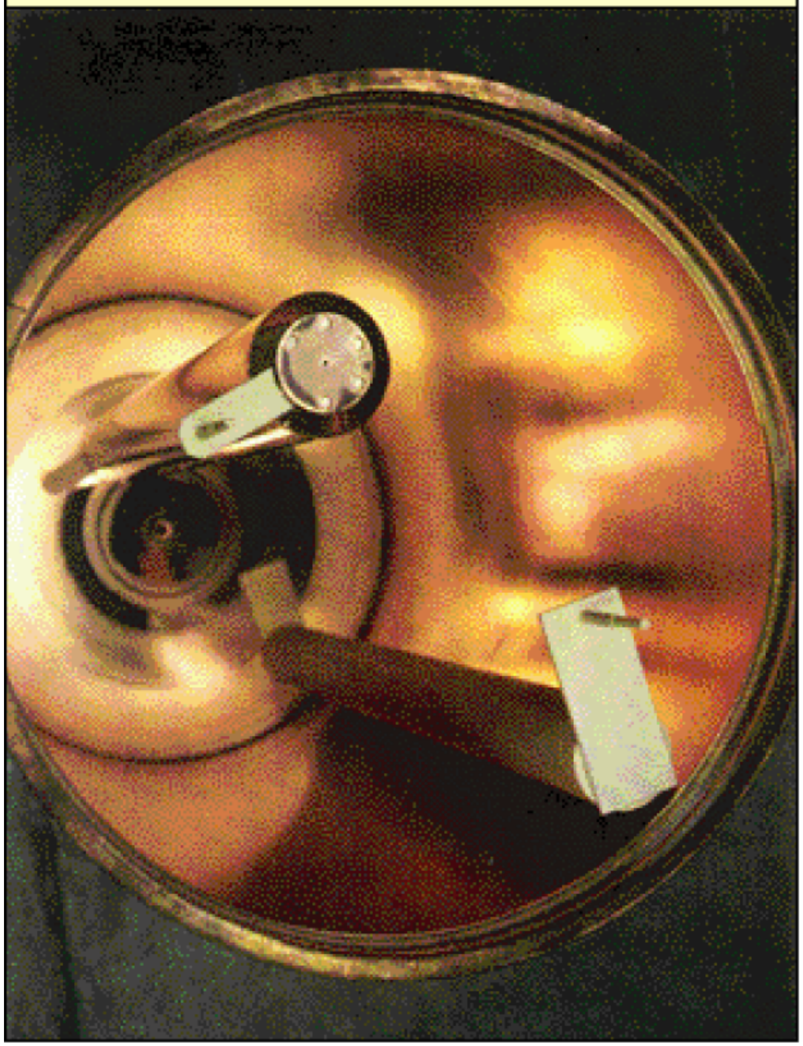
Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

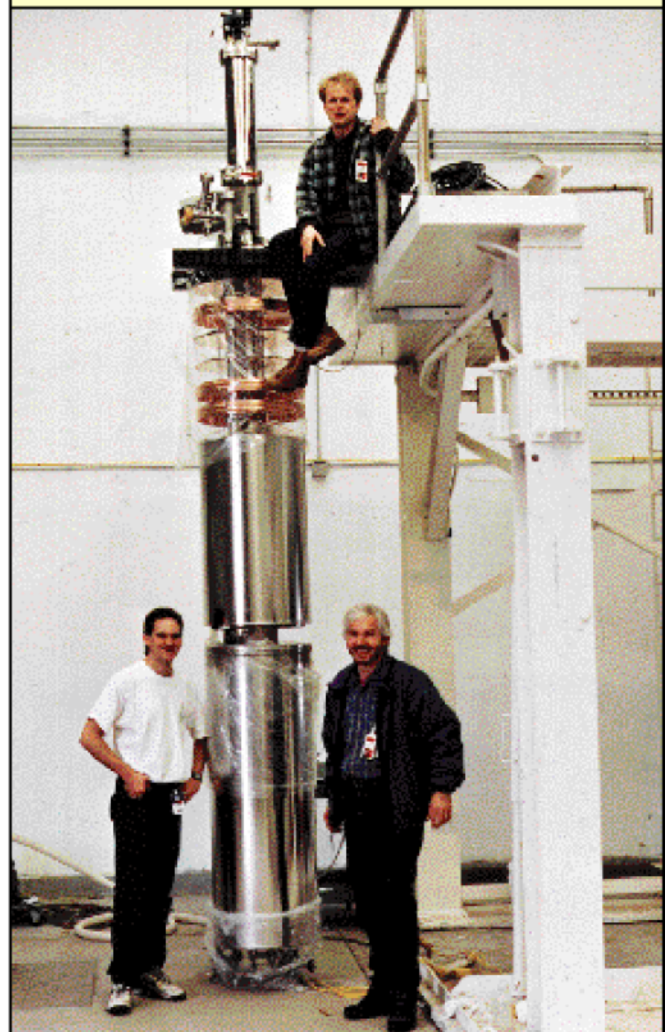
8 T, 1 m × 60 cm ∅

ADMX hardware (cont'd)

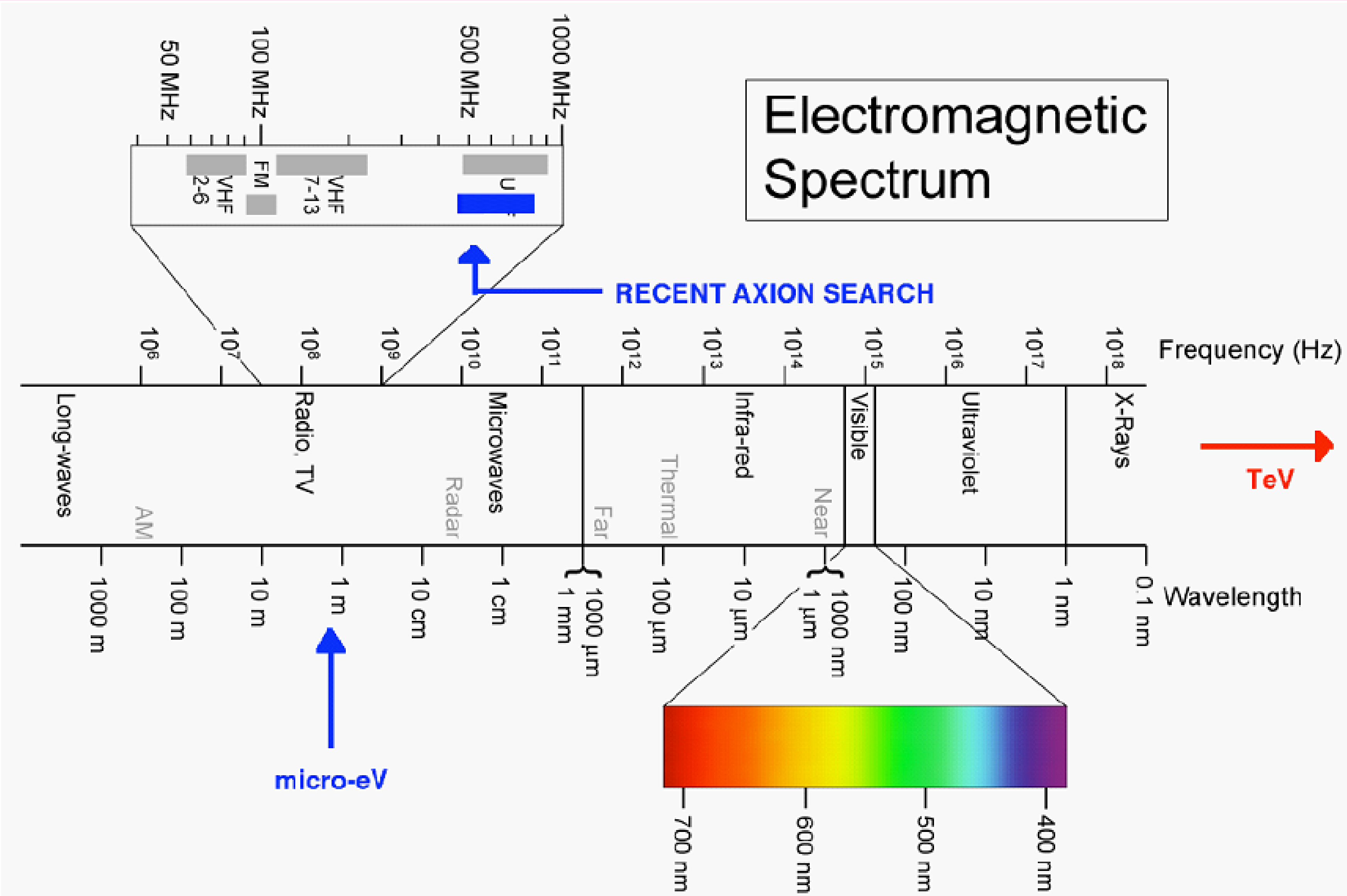
High-Q Cavity (~200,000)



Experimental Insert

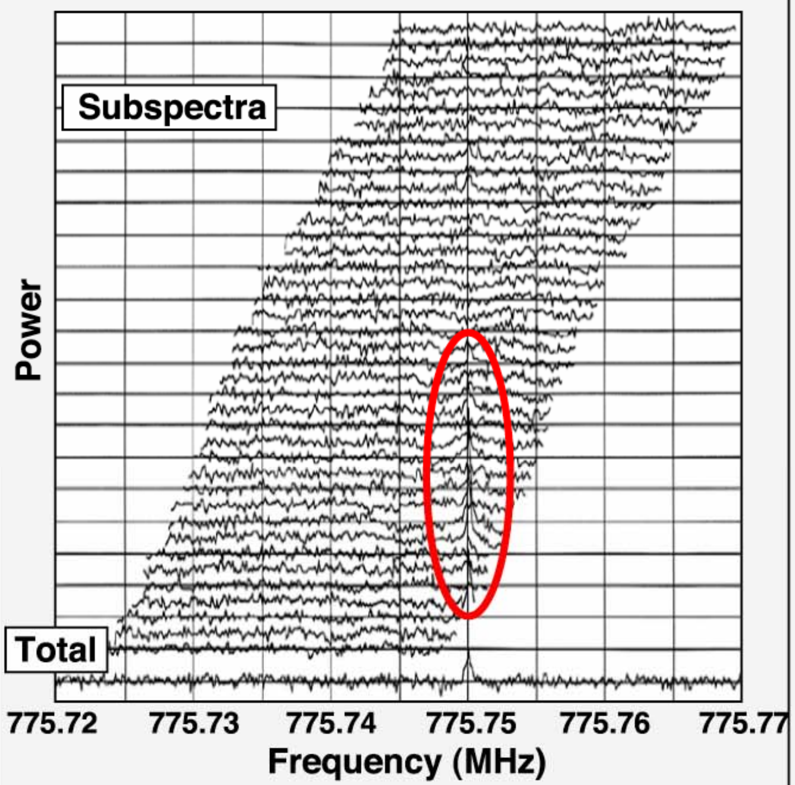


Search spectrum



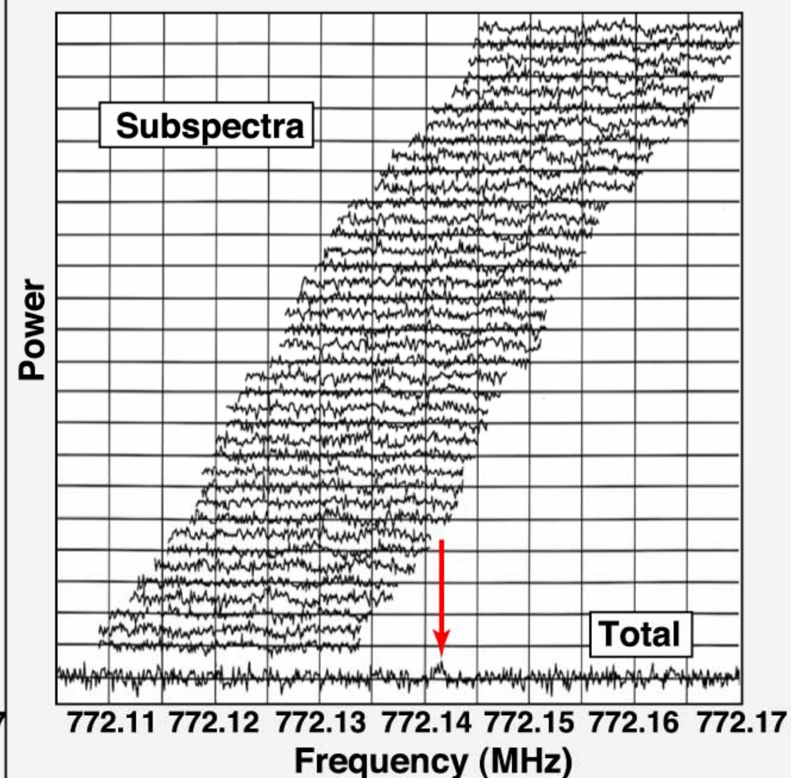
Sample data and candidates

Environmental



Signal maximizes off-resonance: Radio peak

Statistical

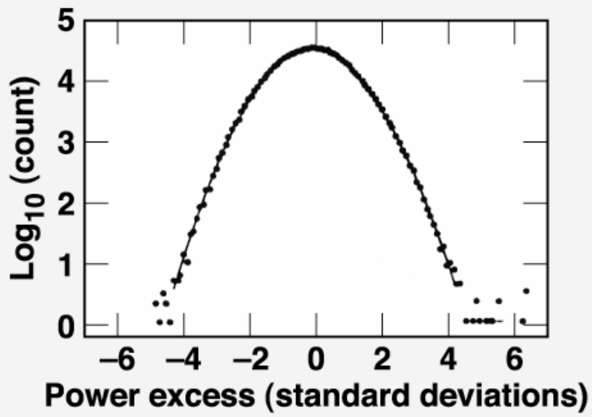


Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

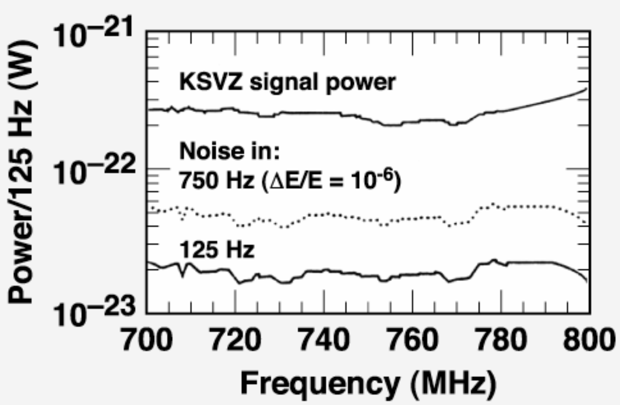
Details of data acq. & analysis

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!

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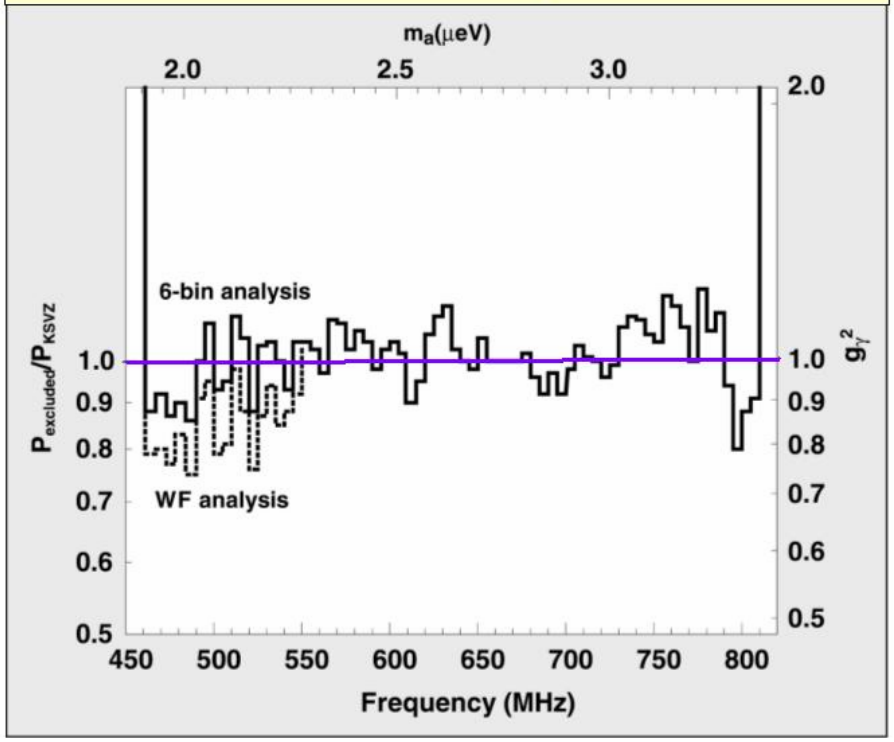
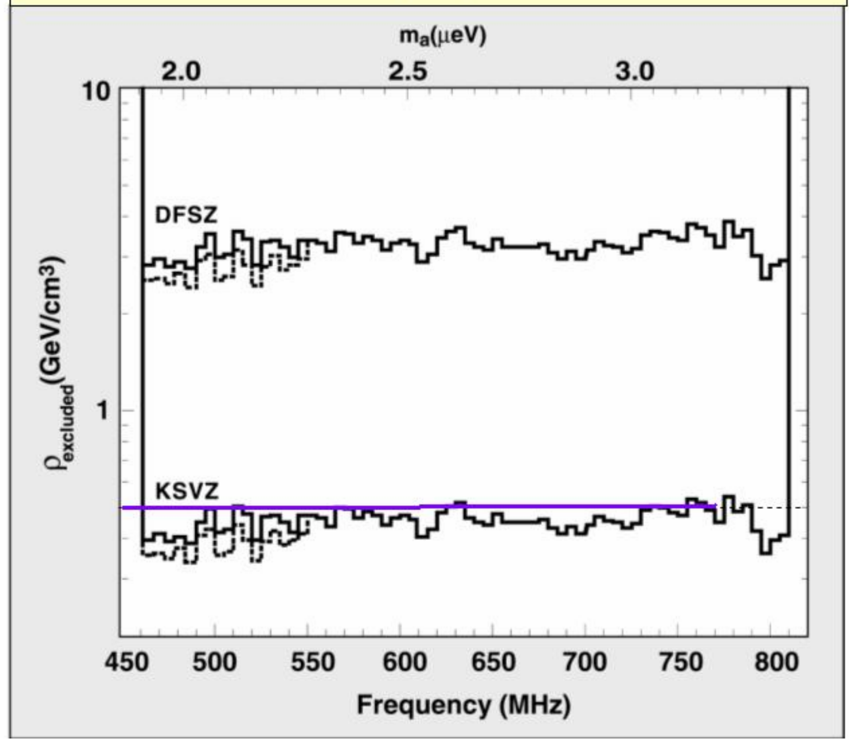
Limits on axion models and local axion halo density

Particle Physics

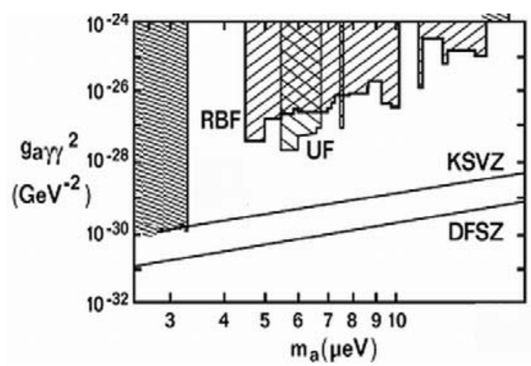


PRL 80 (1998) 2043
PRD 64 (2001) 092003
PRD 69 (2004) 011101(R)

Astrophysics



ApJ Lett 571 (2002) 27



RBF*: PRL 59 (1987) 839*
UF*: PRD 42 (1990) 1297*

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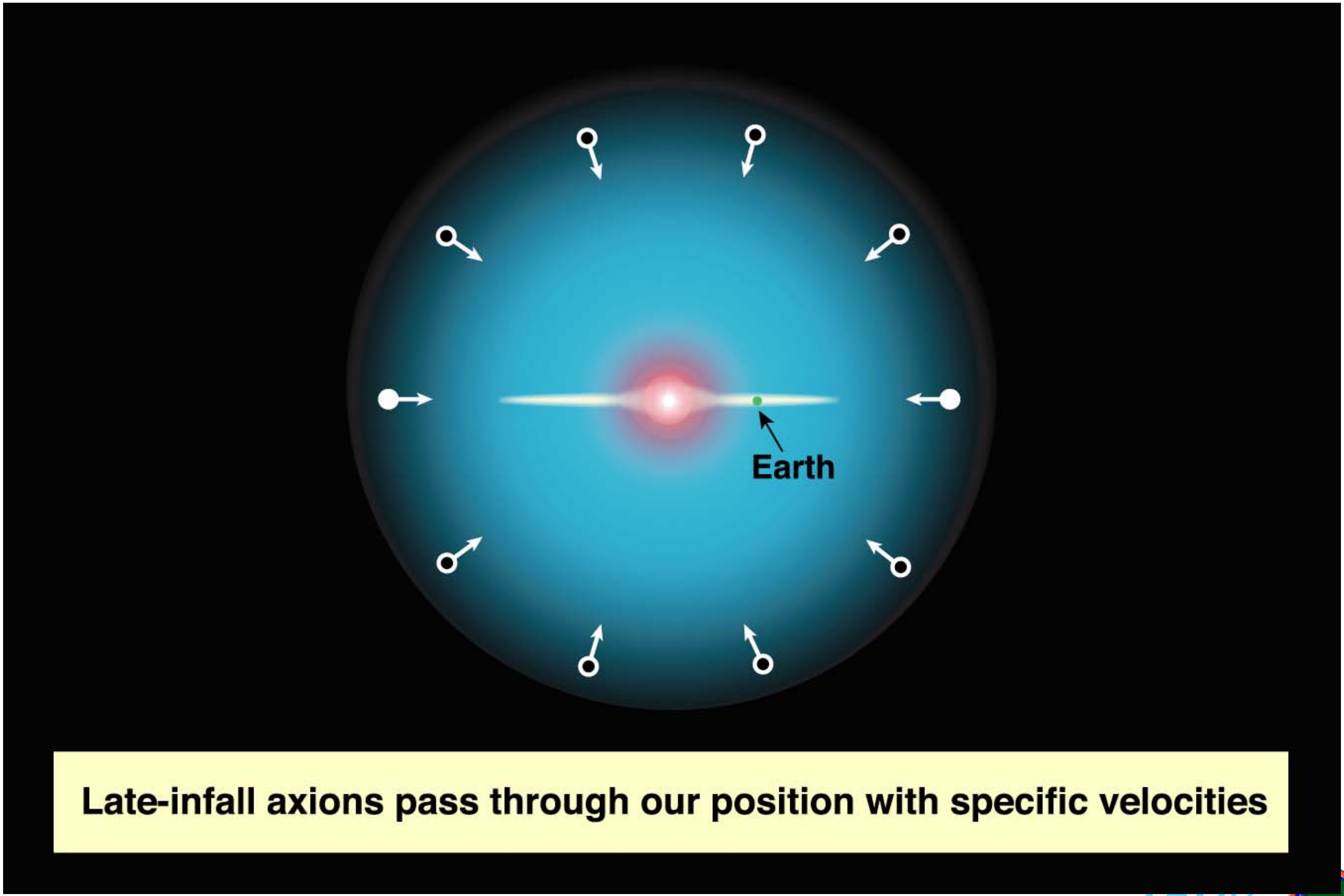
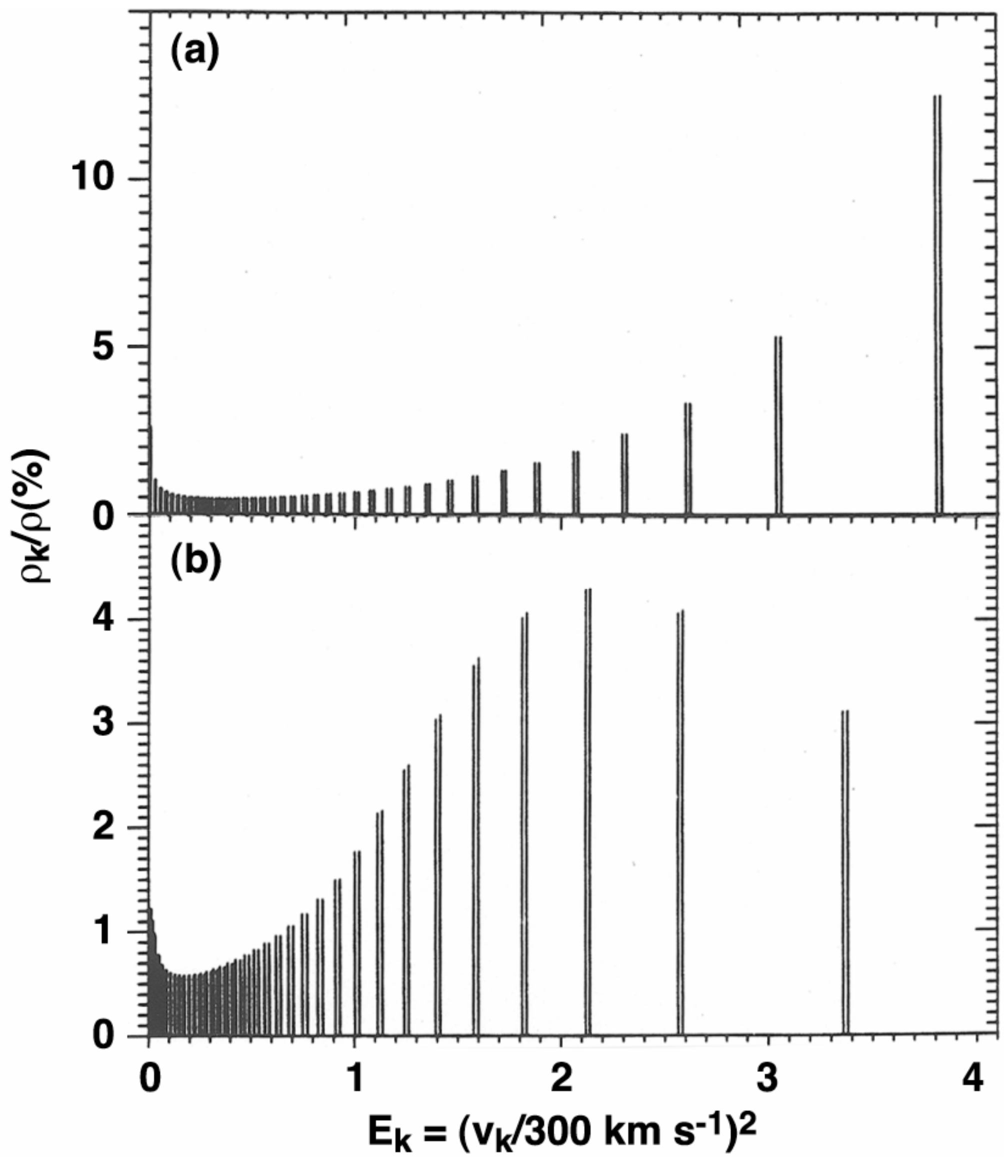
Could there be sharp features in the axion spectrum?



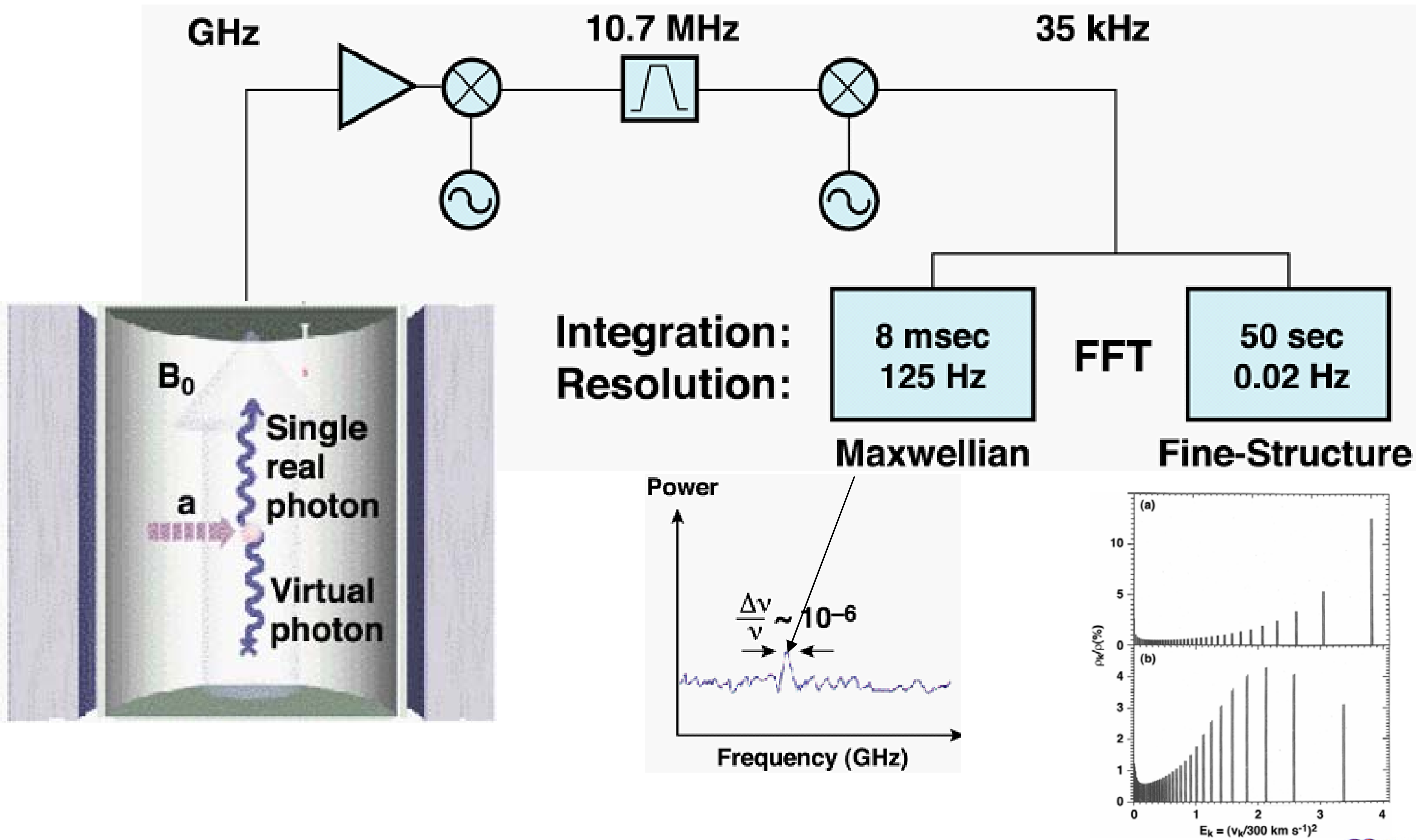
Velocity spectrum of axions at our solar system



(a) No angular momentum

(b) Finite angular momentum

Cavity axion detector (Sikivie, 1983)



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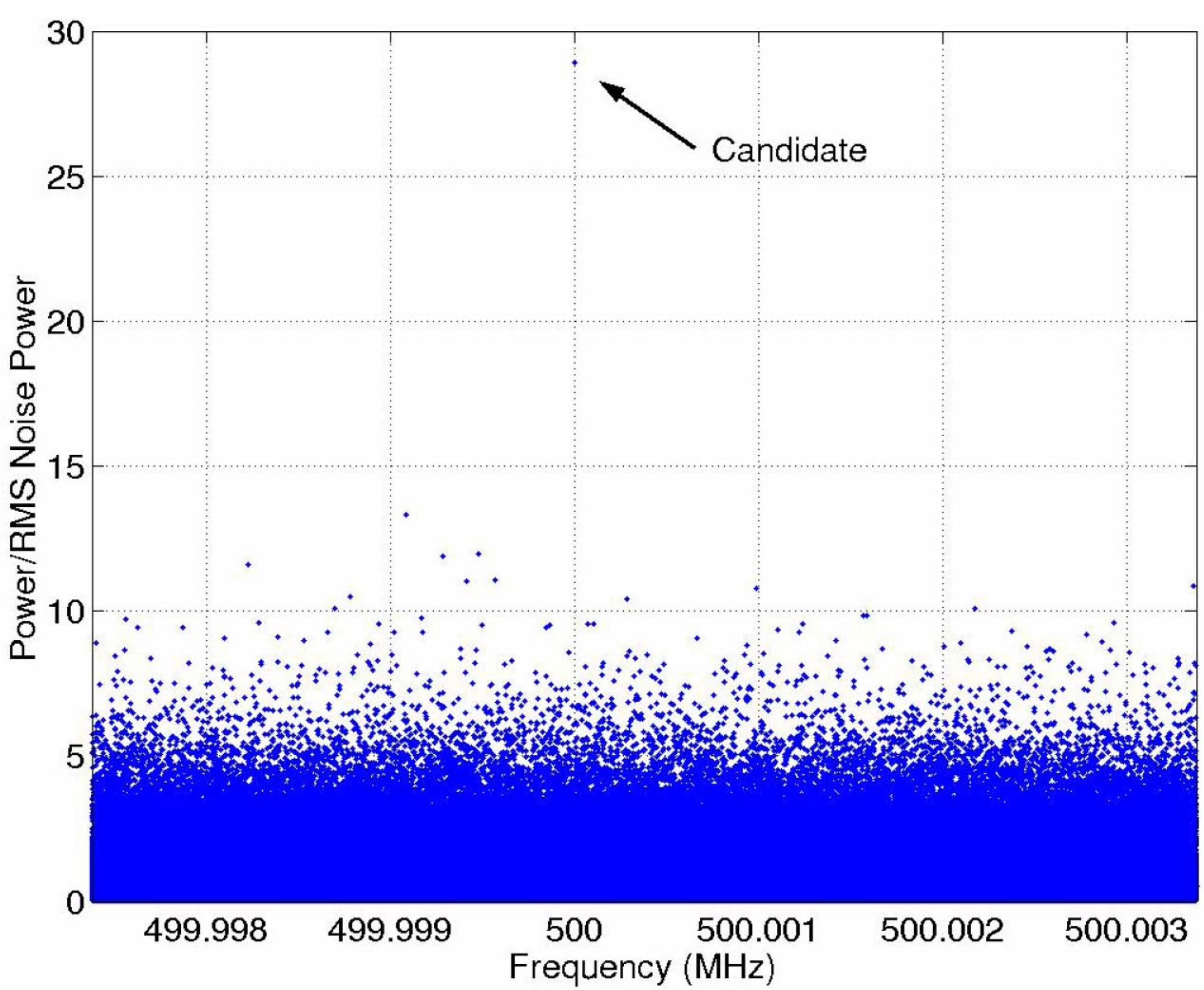
High resolution data – $\delta f \sim 0.02$ Hz



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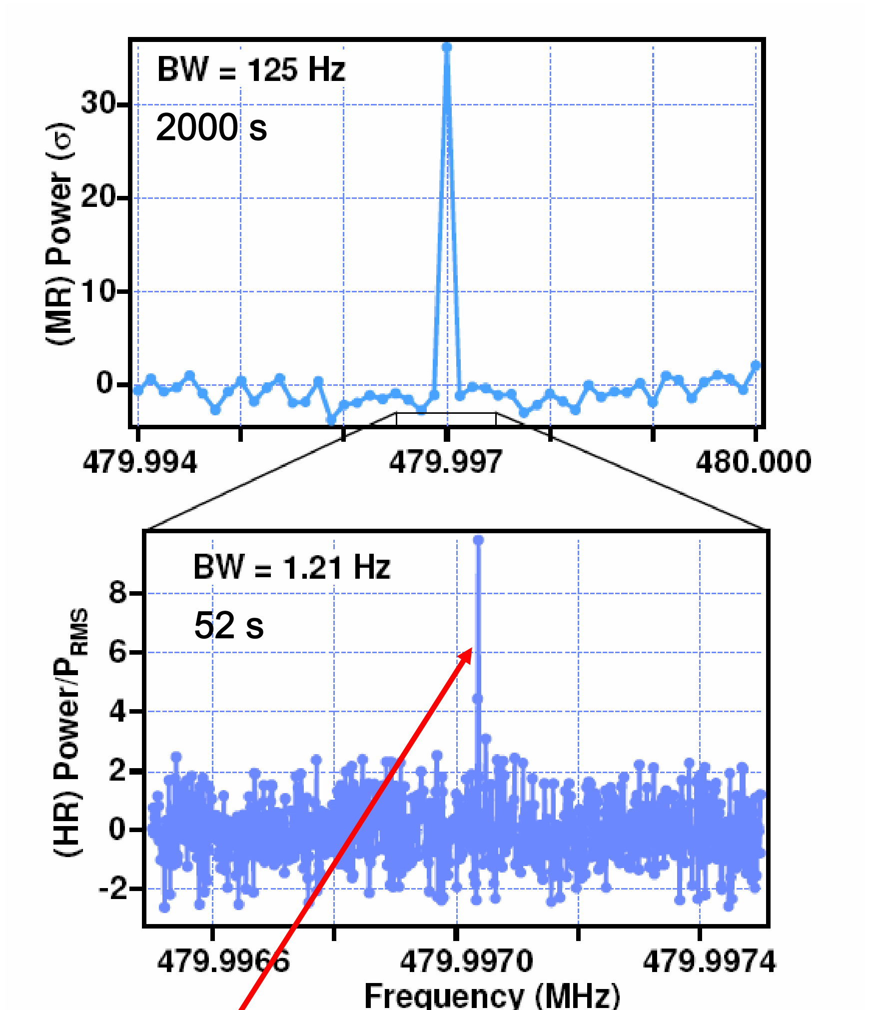
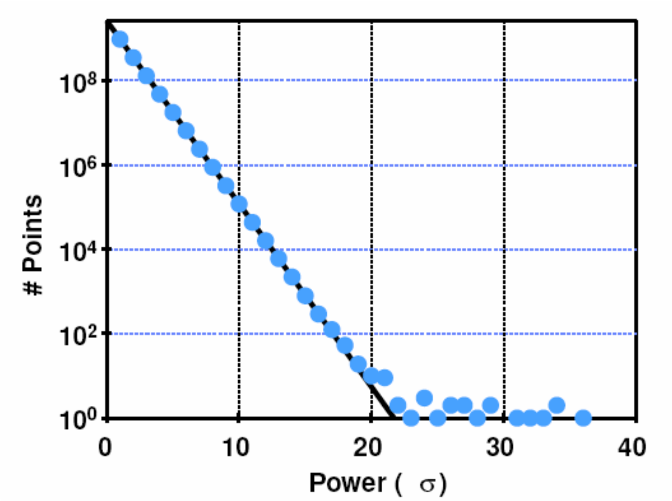
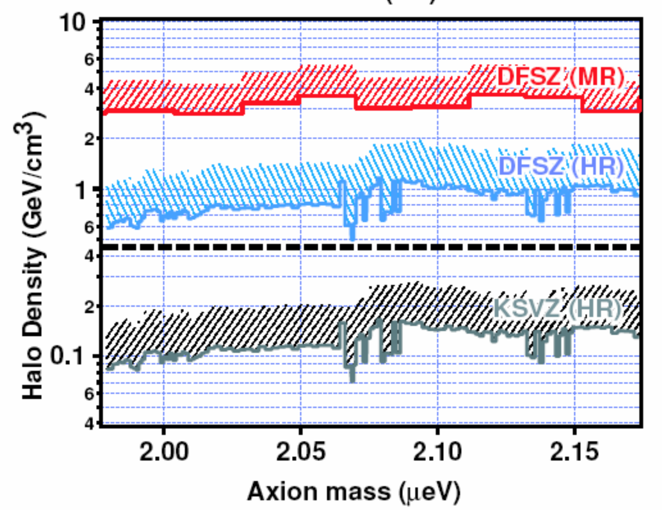
Results of the high-resolution analysis

L Duffy et al., *PRL **95**, 091304 (2005); PRD **74**, 012006 (2006).*







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

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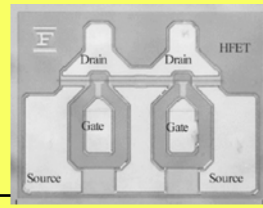
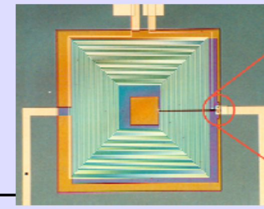
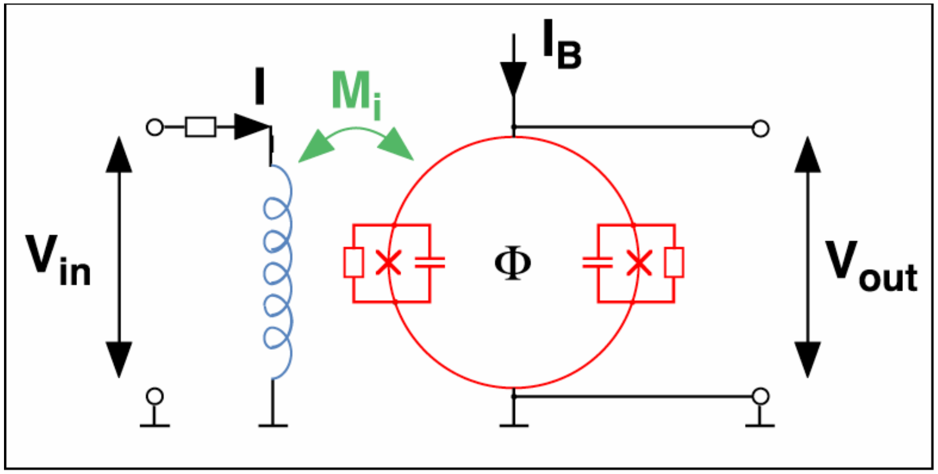
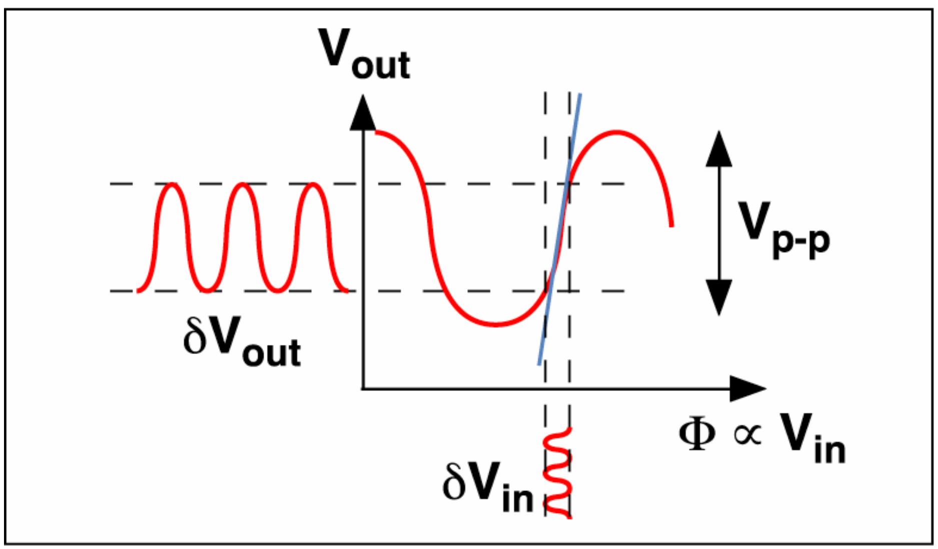
ADMX upgrades

Stage	**ADMX Now**	**Phase I**	**Phase II**
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Dil Fridge 
T_{phys}	1.3 K	1.3 K	50 - 100 mK
T_{noise}	2 K	0.4 K	50 – 100 mK
$T_{sys} = T_{phys} + T_{noise}$	3.3 K	1.7 K	150 mK
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	4 @ KSVZ	10 @ DFSZ
Sensitivity Reach $g^2 \propto T_{sys}$	1 x KSVZ	0.5 x KSVZ	0.3 x DFSZ

"Phase I" upgrade: SQUID amplifiers





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

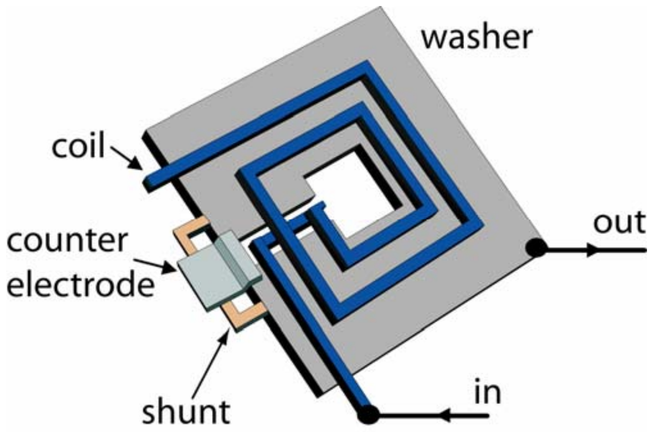
But the quantum limit at 700 MHz is ~ 33 mK

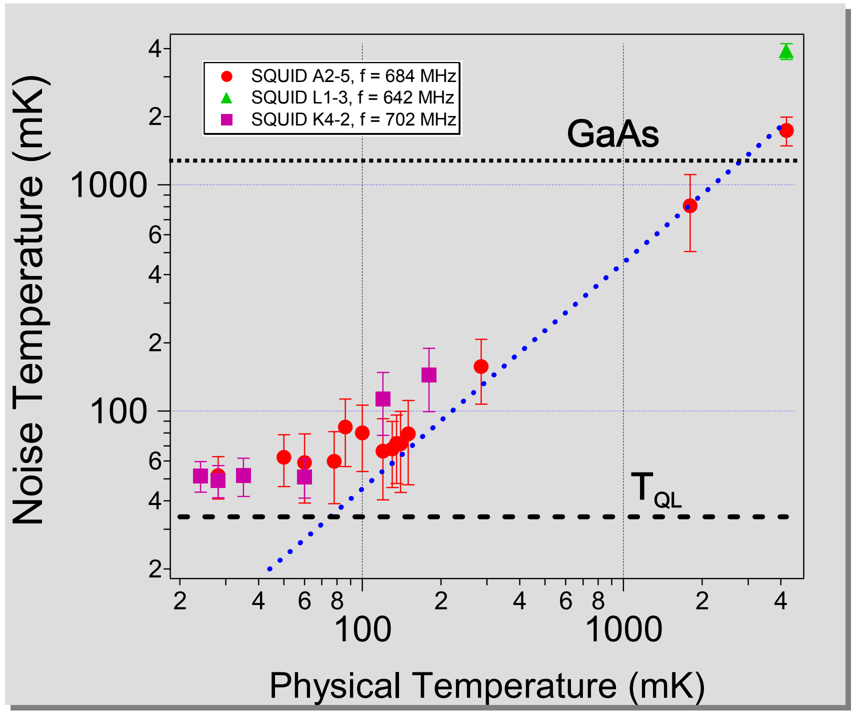
Use SQUID amplifier -- a flux-to-voltage transducer

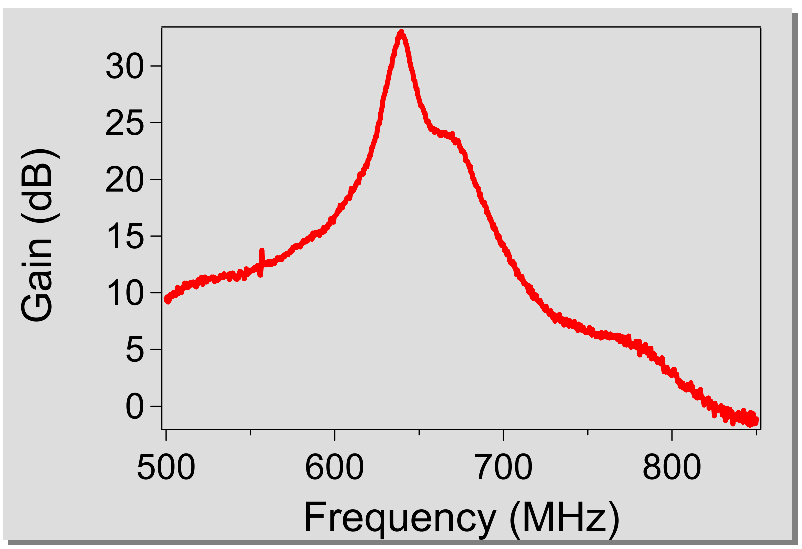
SQUID noise arises from Nyquist noise in shunt resistance - scales linearly with *T*

However, SQUIDs of conventional design are poor amplifiers above 100 MHz (parasitic couplings).

Microstrip SQUID amplifiers







More than an order of magnitude quieter than current GaAs HFET amplifier

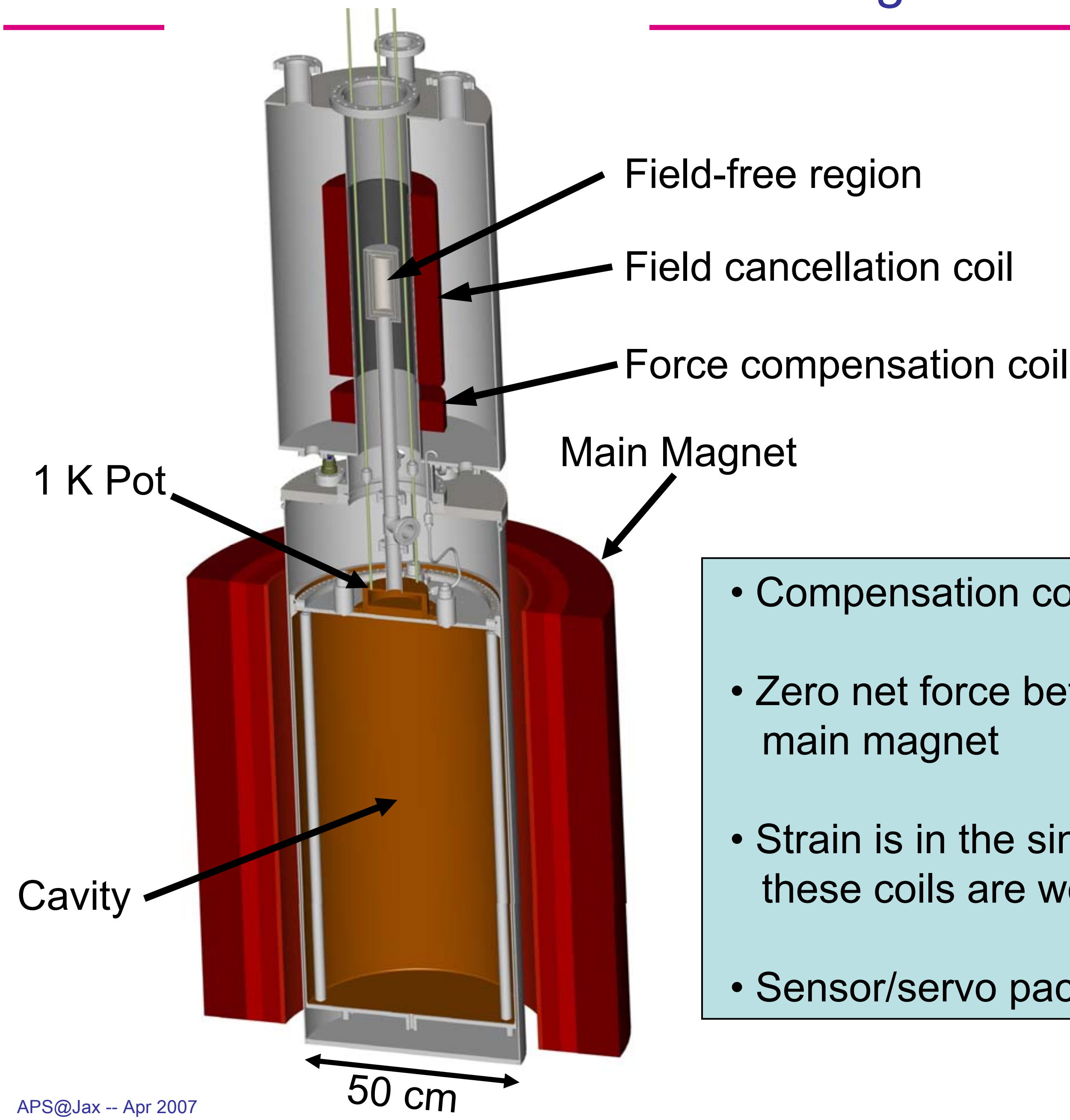
Our latest SQUIDs are now within 15% of the Standard Quantum Limit

ADMX

ADMX is in a Phase I upgrade
Addition of SQUID amplifiers: nearing completion

- A challenge: Zero-field region for the SQUID amplifiers
  - SQUIDS DO NOT LIKE MAGNETIC FIELDS
  - Needed “bucking coil” to reduce field in region of the superconducting electronics
  - Field is a few Gauss
  - Passive shielding can then take over
  - Must manage tons of force between opposed magnets
  - Designed, delivered by AMI, installed

Design



From outwards-in:

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

- Compensation coil has 2 opposed windings
- Zero net force between compensation coil and main magnet
- Strain is in the single-piece mandrill on which these coils are wound
- Sensor/servo package minimizes field at center

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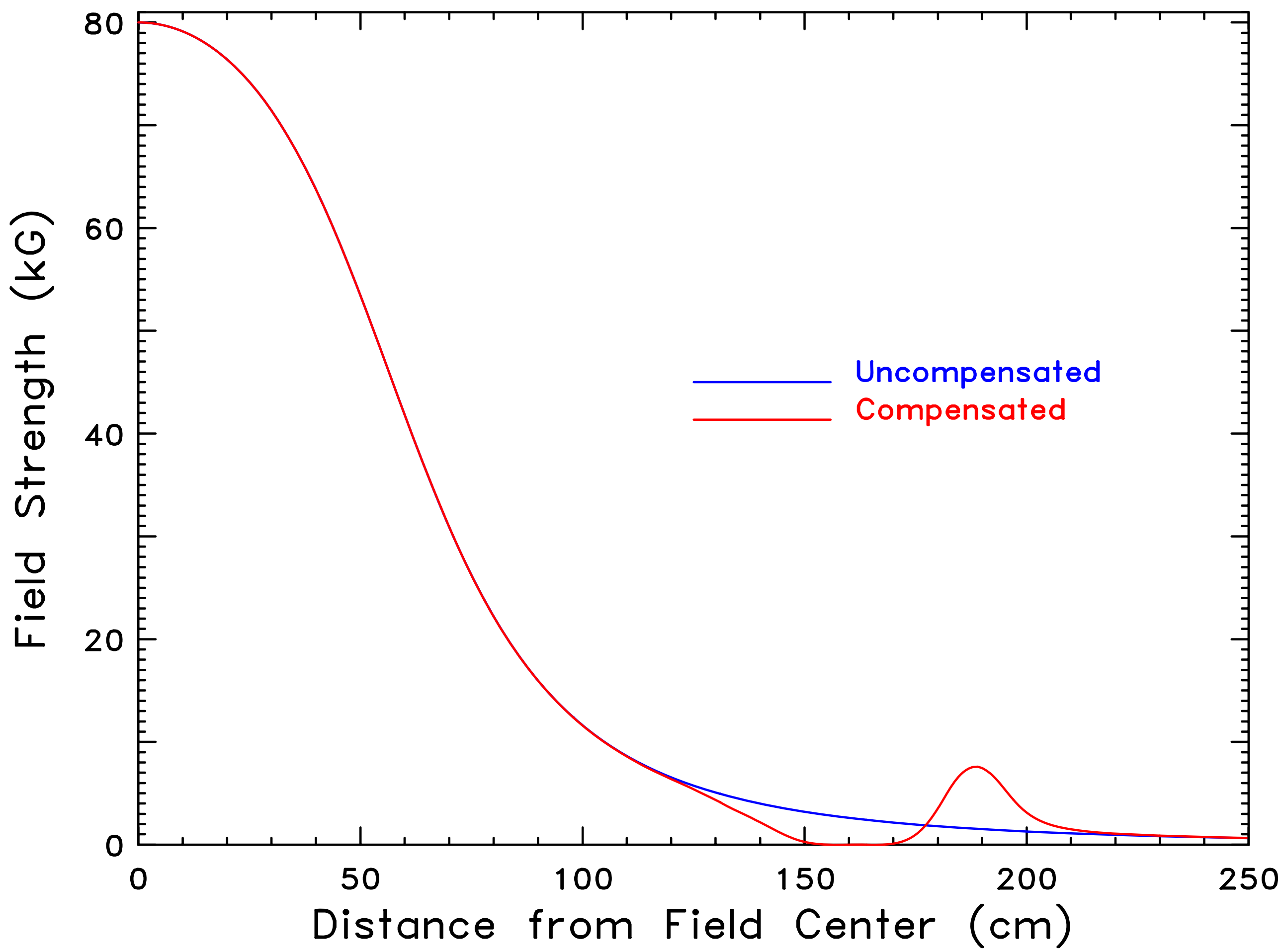
Field profiles, on axis

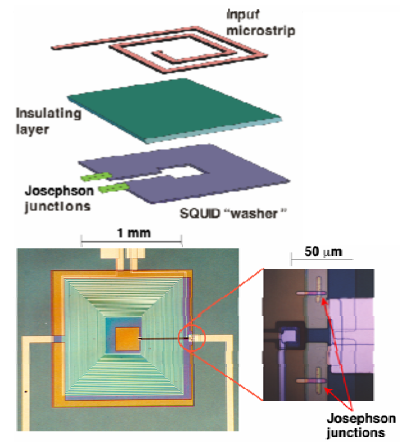


- $|B_{uncomp}|$ ~ 4 kG, far below the 80 kG critical field of NbTi.
- Currents are manageable.

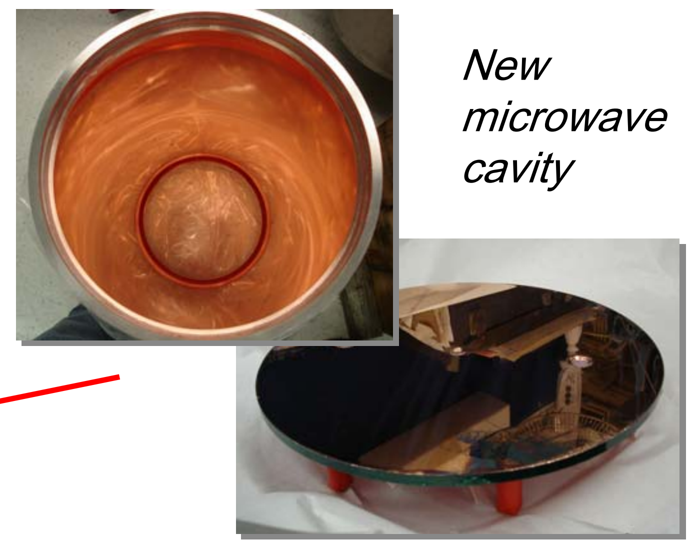
Phase I upgrade nearing completion

Field compensation magnet for SQUIDs

SQUID amplifier



New microwave cavity



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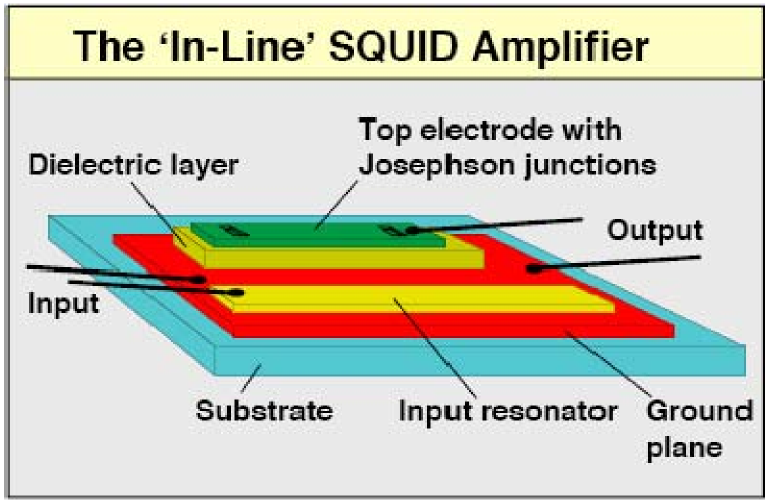
Further upgrade and higher frequencies



Incorporate dilution fridge to reduce cavity Temperature to 50 mK. (Phase II)

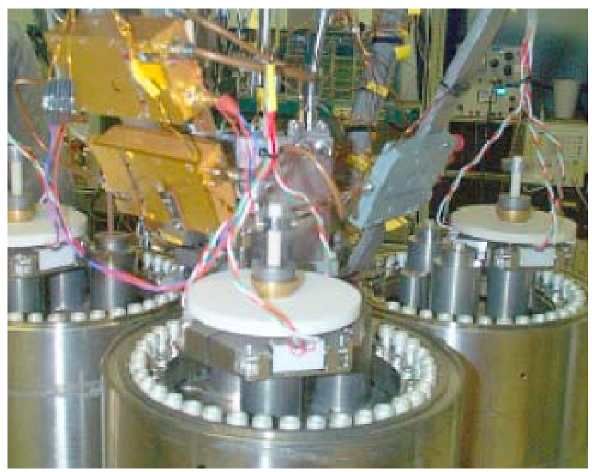
To get to 10 GHz, and then 100 GHz

--- Developing new SQUID geometries

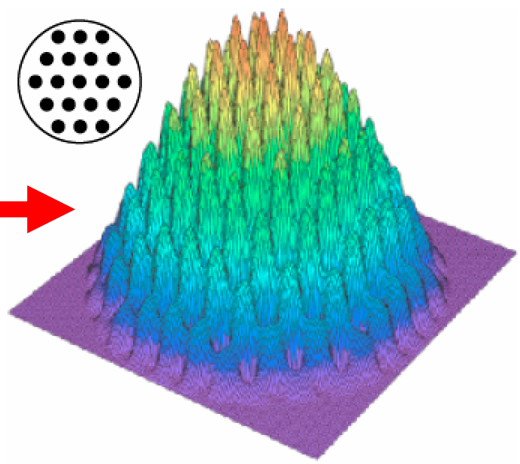
--- Developing new RF cavity geometries

0.3-0.8 GHz

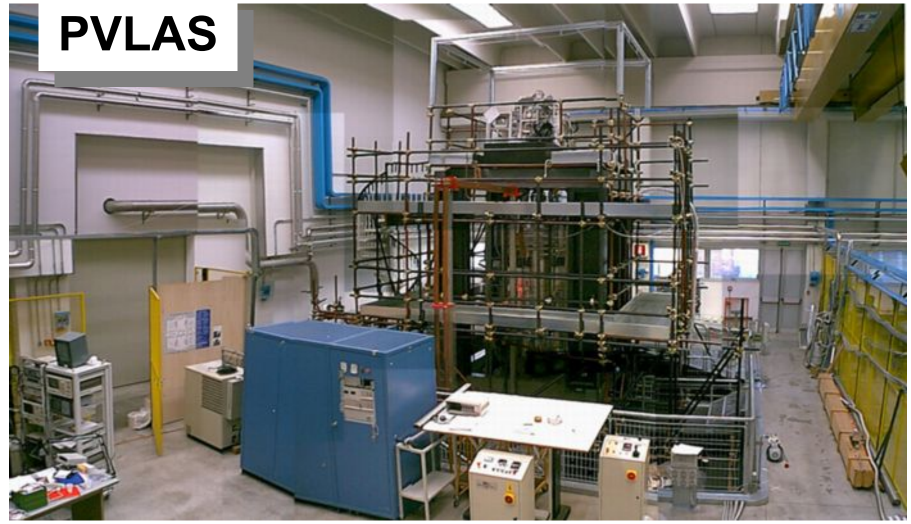
0.8-3 GHz

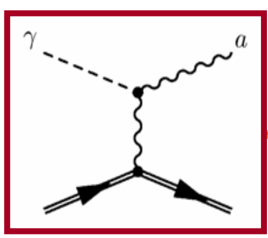


3-30 GHz

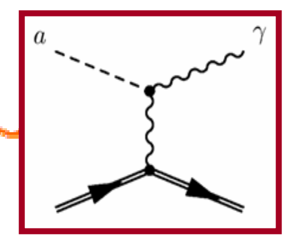


There are several experimental searches for axions





Sun



CERN

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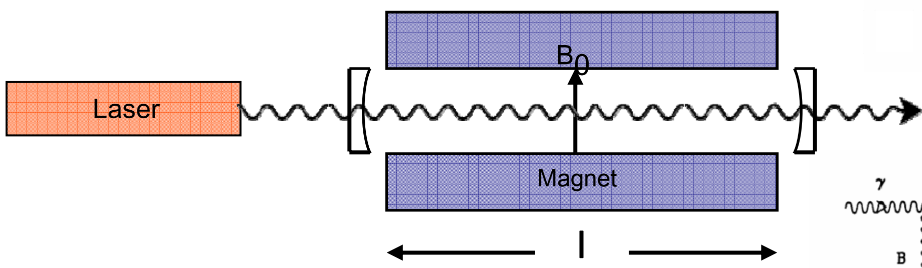
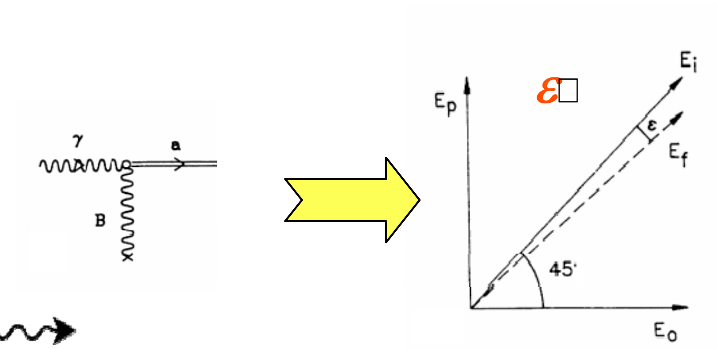
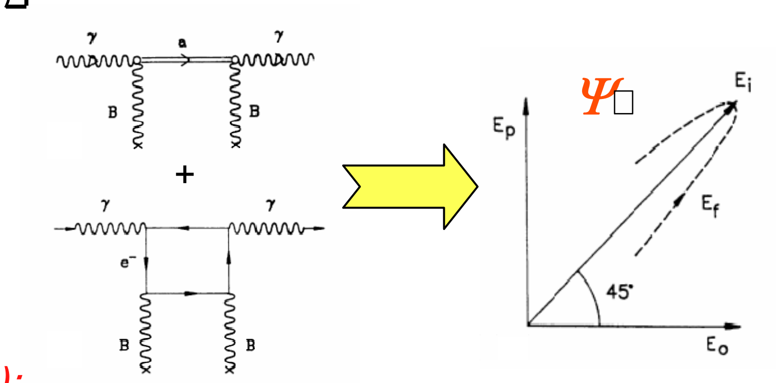
Purely laboratory experiments

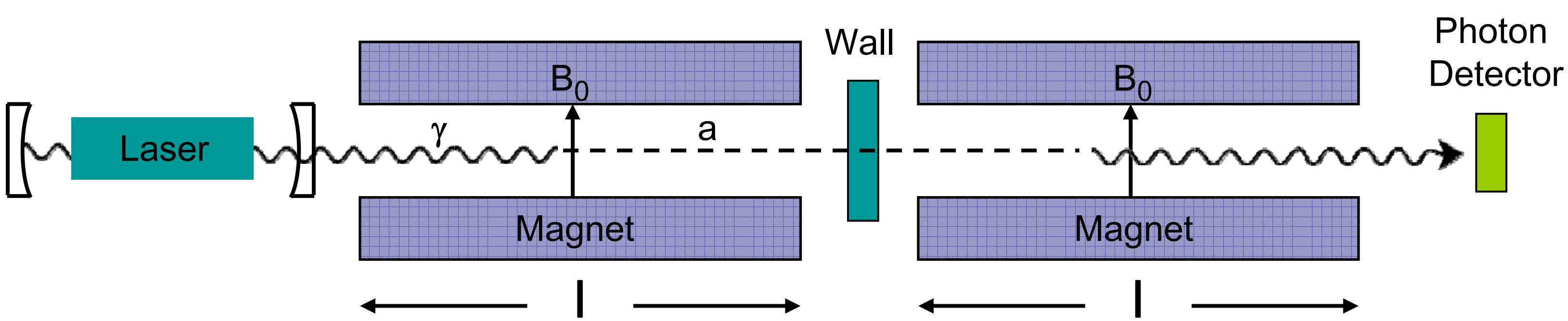
Polarization effects (e.g. PVLAS):
Vacuum dichroism & birefringence







Photon regeneration (JLAB and elsewhere):
"Shining light through walls"



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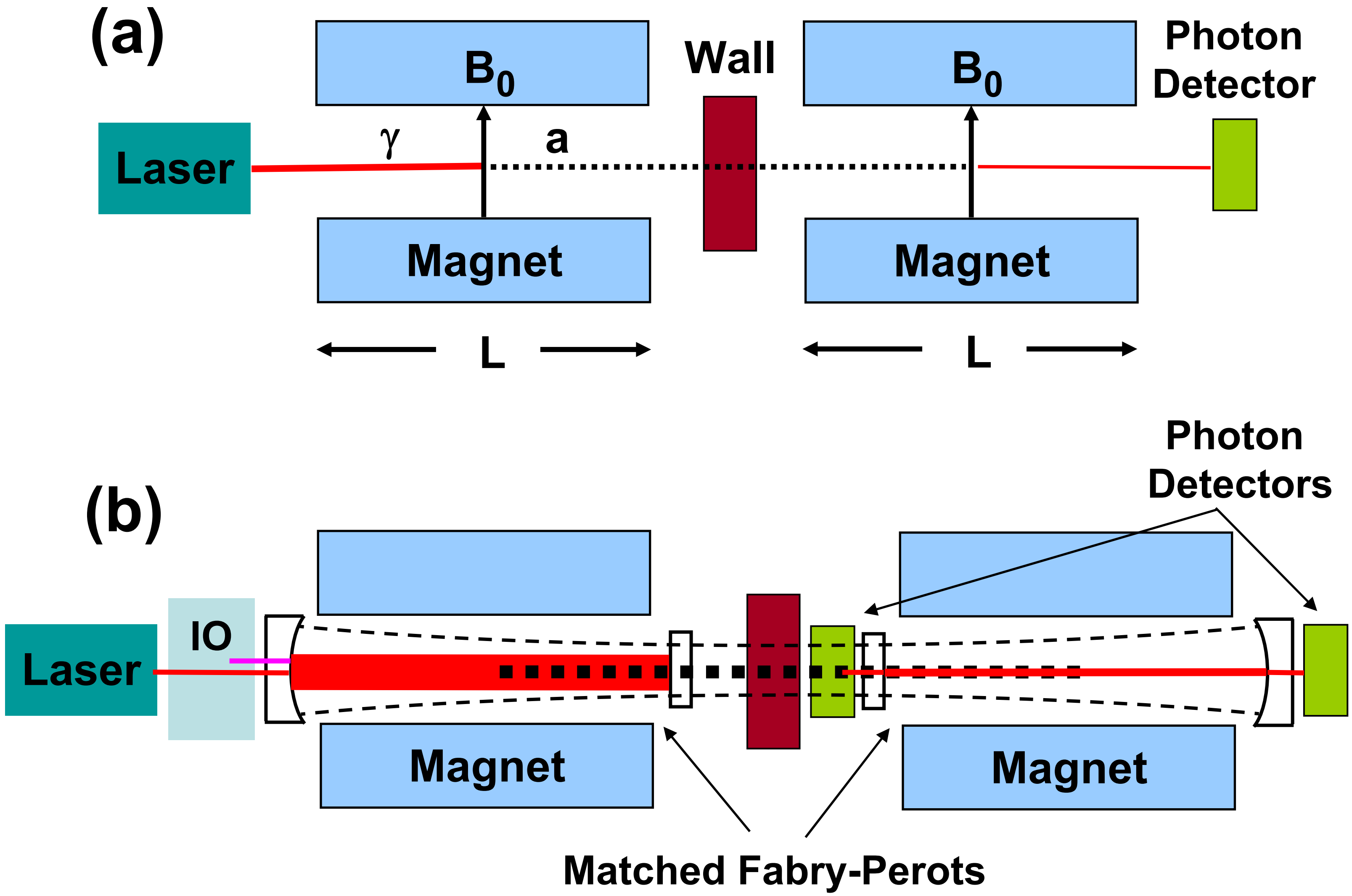
Photon regeneration enhanced by cavities



P. Sikivie et al., *PRL, in press.*

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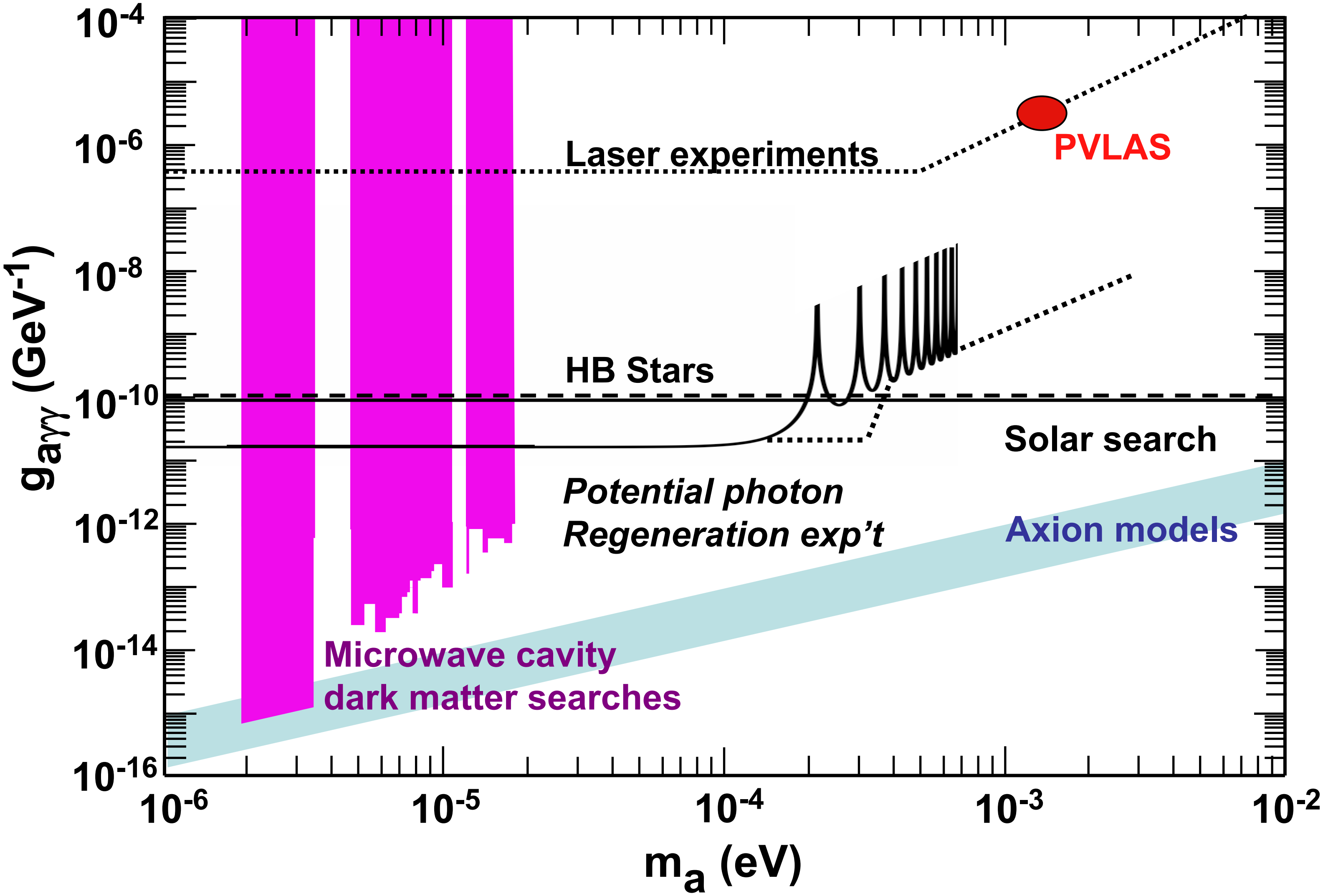
Excluded $g_{a\gamma\gamma}$ vs. m_a



Summary and conclusions

- Peccei-Quinn symmetry remains a promising solution to the strong CP Problem; hence axions are an attractive dark-matter candidate.
- The parameter space where the axion lives is bounded.
- ADMX has scanned a factor of 2 in mass at a sensitivity within the band of model couplings.
- Current experiments are sensitive to realistic axion couplings and masses; they could see an axion at any time.
- Upgrades to ADMX will be sensitive to very feeble axion couplings and will either detect or rule-out Peccei-Quinn axions with m_a in a decade centered around 10^{-5} eV.
- Lab experiments could also observe axions.
- This is an exciting time for axion searchers!

THE END