ADMX: Recent results at the DFSZ frontier and future prospects for axion haloscopes

N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L.J Rosenberg, and G. Rybka
University of Washington

G.P. Carosi, N Wollett,
Livermore

A.S. Chou, A. Sonnenschein, and W. Wester
FNAL

C. Boutan and N. Oblath
PNNL

John Clarke, S. O'Kelley, Karl van Bibber
UC Berkeley

Leanne Dufffy
Los Alamos

Richard Bradley
NRAO

Ed Daw
Sheffield

Nicole Crisosto, Jeff Hoskins, J. Gleason,

R. Jois, I. Stern, Jihee Yang,

Pierre Sikivie, Neil Sullivan, D.B.T.
University of Florida

ADMX is the Axion Dark Matter eXperiment

ADMX Collaboration

UF UNIVERSITY of FLORIDA

UNIVERSITY OF WASHINGTON 1861

Lawrence Livermore National Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

NRAO

The University Of Sheffield.

Fermilab

Pacific Northwest NATIONAL LABORATORY

WASHINGTON UNIVERSITY IN ST. LOUIS 1853 *

Los Alamos NATIONAL LABORATORY

<u>Sponsors</u>

<u>ADMX is a DOE Gen 2 project</u>

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

NSF

HEISING - SIMONS FOUNDATION

Primary sponsor

R&D support

ADMX

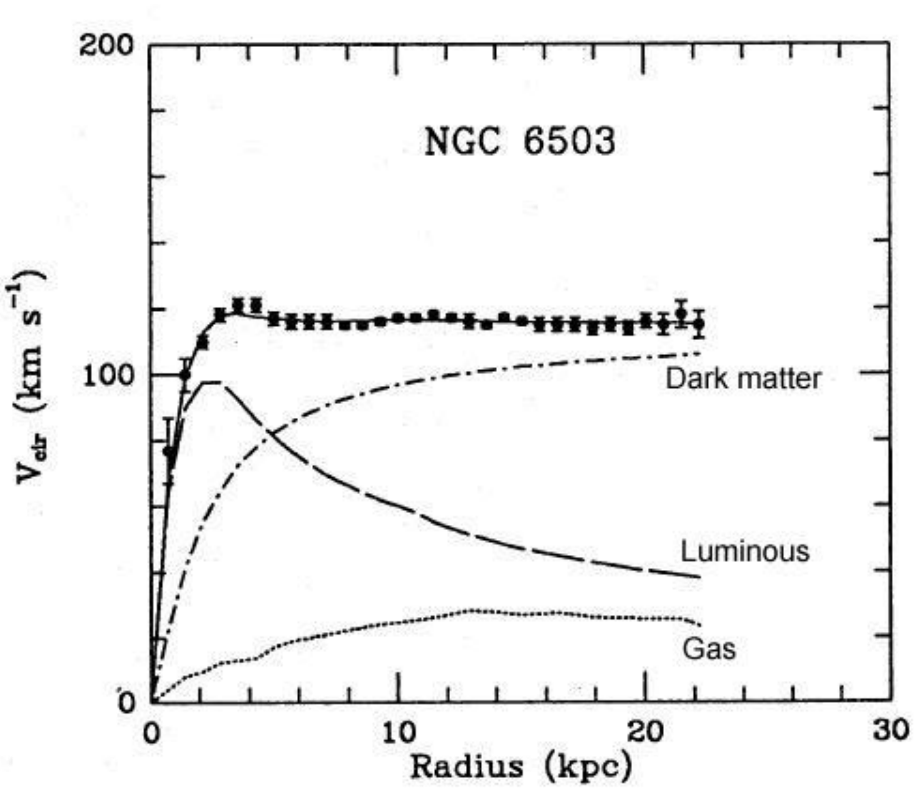
Outline

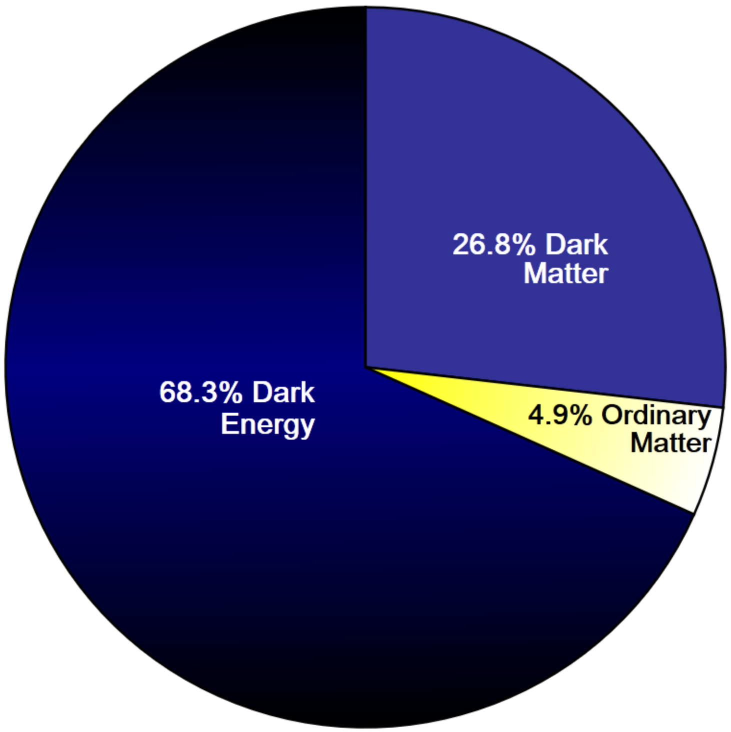
- A minimal introduction
- Some technical details
- ADMX is operating at DFSZ sensitivity
- Technology in hand to detect the axion if the mass is in the 1.2 to 8.3 meV range (mc^2/h = 0.33 to 2 GHz)
- A 32 T HTSC magnet could allow a search up to 25 μeV (6 GHz)
- It is an exciting time for axion researchers!

Evidence for dark matter: now very compelling

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

Faber and Gallagher ARAA 1979





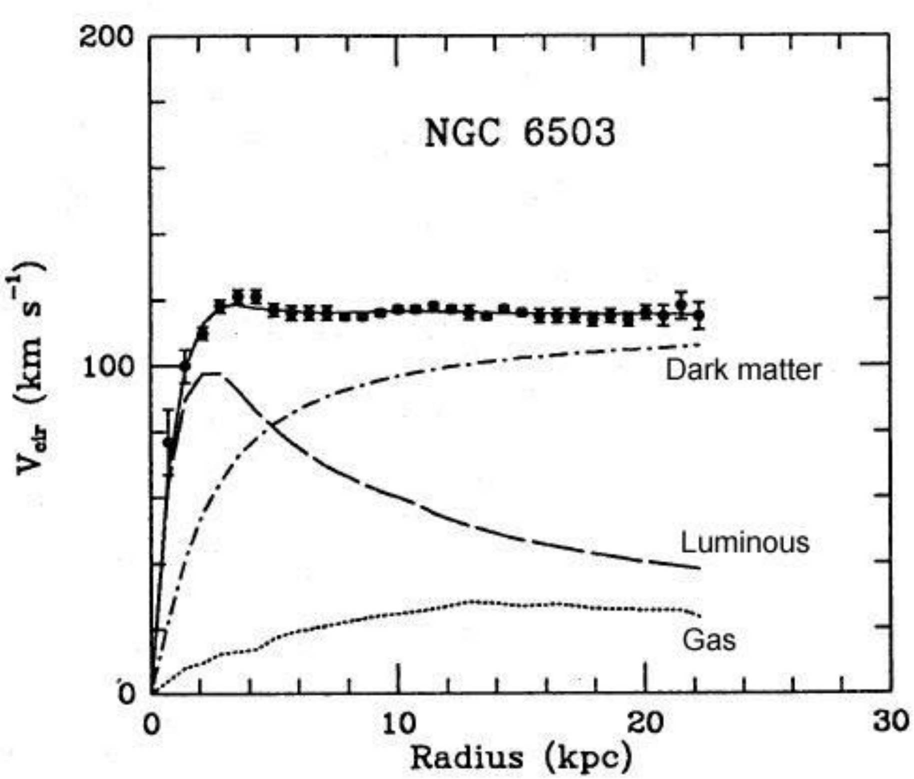
Planck

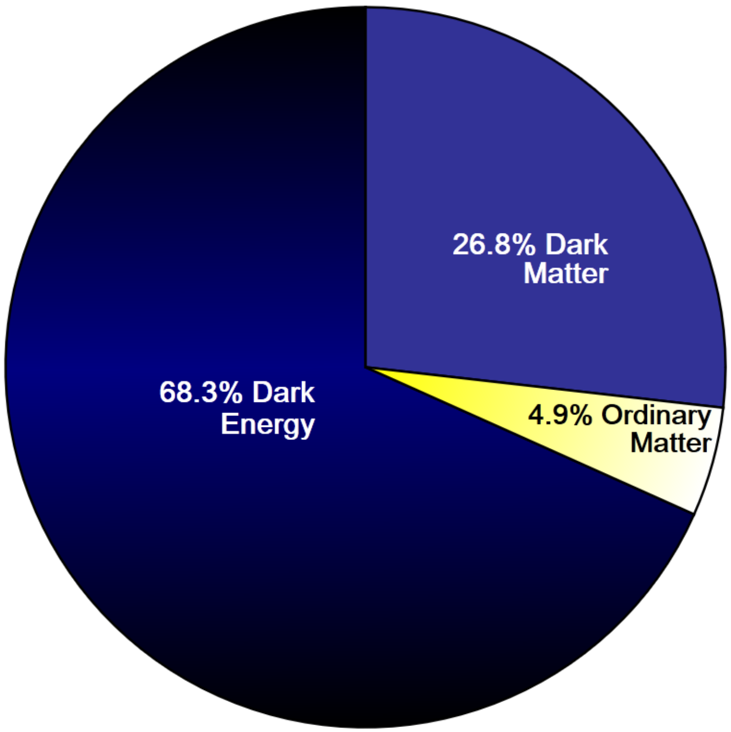
- A cold particle relic from the Big Bang is strongly implied for DM
- Candidates: Neutrinos ? WIMPs ? Axions ?

Evidence for dark matter: now very compelling

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

Faber and Gallagher ARAA 1979



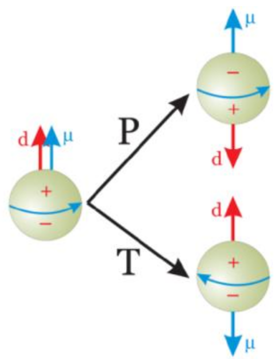


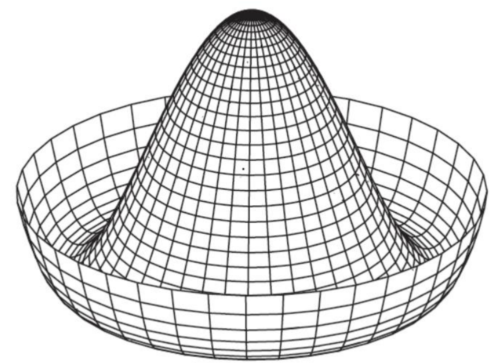
Planck

- A cold particle relic from the Big Bang is strongly implied for DM
- Candidate: Axions

Axions: arose from a solution to the "strong CP problem" in Quantum ChromoDynamics

- 1973: QCD.
  Thought to respect the observed conservation of C, P and CP.
- 1975: QCD theory is hugely CP-violating.
- QCD CP violation should, e.g., give a large neutron electric dipole moment. Not observed. (A discrepancy of 10^{10}.)



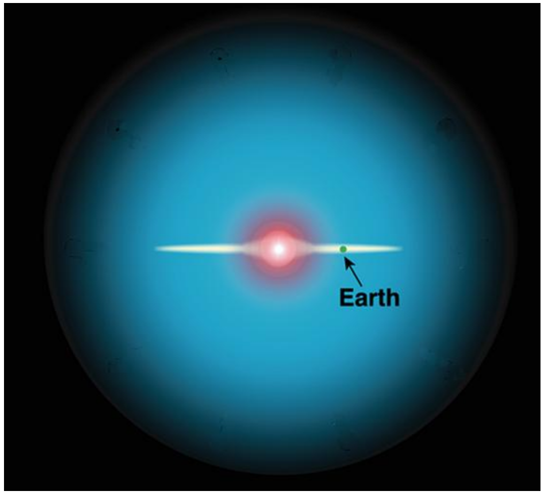


- 1977: Peccei and Quinn postulate a hidden broken symmetry to conserve CP in the strong sector $\Rightarrow$
  1) A new Goldstone boson (the axion);
  2) Remnant axion VEV nulls QCD CP violation.

The axion - 1980 to now

- PQWW axions not observed in various experiments. (Suggesting a very light axion, the “invisible” axion.)
- Like an ultra-light, ultra-weakly interacting π^0
- The axion decays by two-photon emission

  $a \to \gamma\gamma$ (but $\tau \sim 10^{42}$ years >> $\tau_{universe}$)

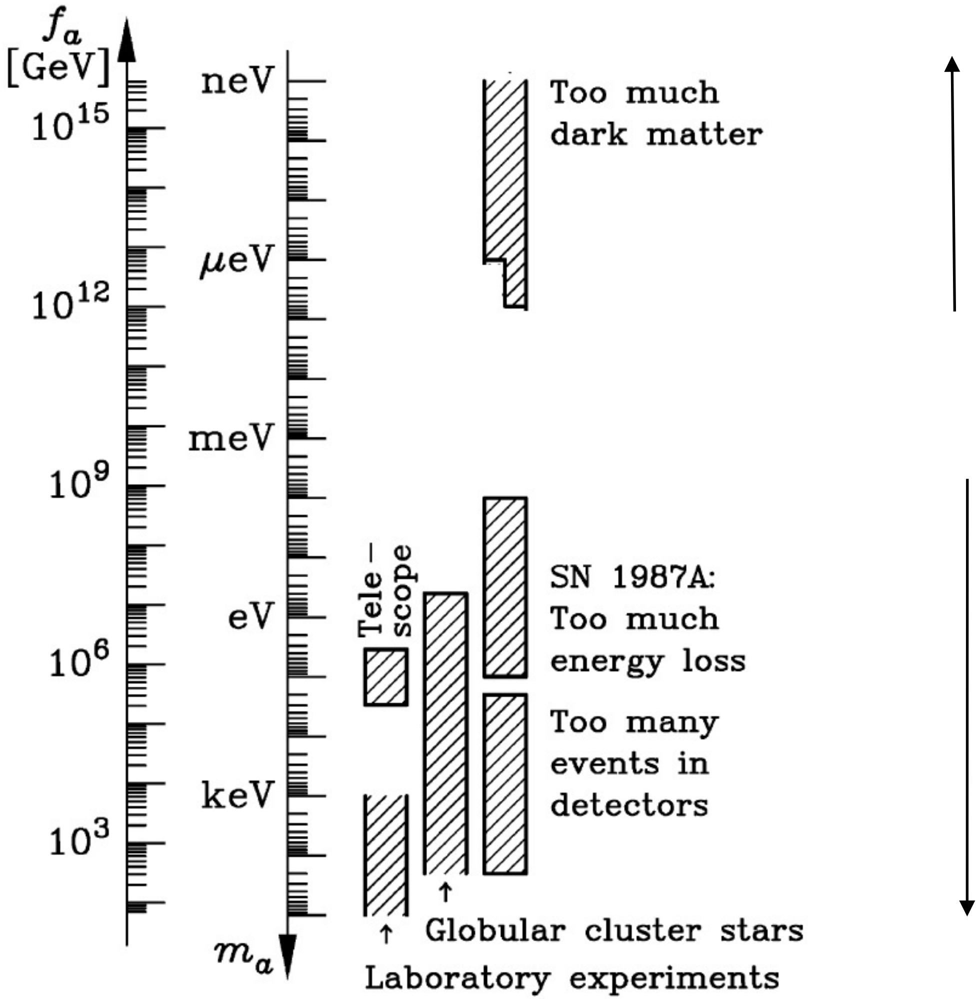


- Light axions very weakly coupled:

  $g_{aii} \propto m_a$

- Galactic halos may consist of axions
- ρ_{halo} = 0.45 GeV/cm^3 ~ 10^{14} /cm^3
- Recent ideas (Bose condensation, caustics) make the case for axions even stronger
- As do experiments: No supersymmetric particle at CERN, negative results from WIMP searches (LUX, CDMS etc.)

Present window for the axion mass



Very light axions forbidden: else too much dark matter

Depends on Ω_{CDM} ~ 27%

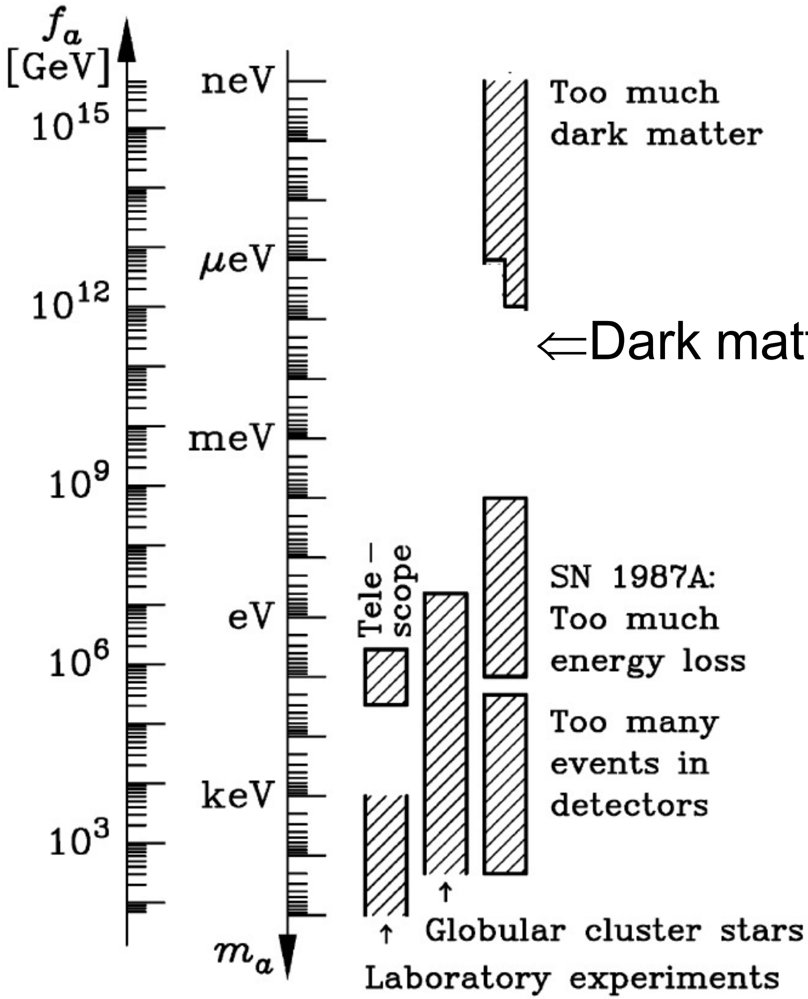
Astrophysical bounds

Beam dump

Heavy axions forbidden: else new pion-like particle

- A very light axion (3-30 μeV) is an ideal dark-matter candidate
- 3 μeV is 0.7 GHz

Present window for the axion mass



Very light axions forbidden: else too much dark matter

Depends on Ω_{CDM} ~ 27%

⇐Dark matter: “invisible axions”

Astrophysical bounds

Beam dump

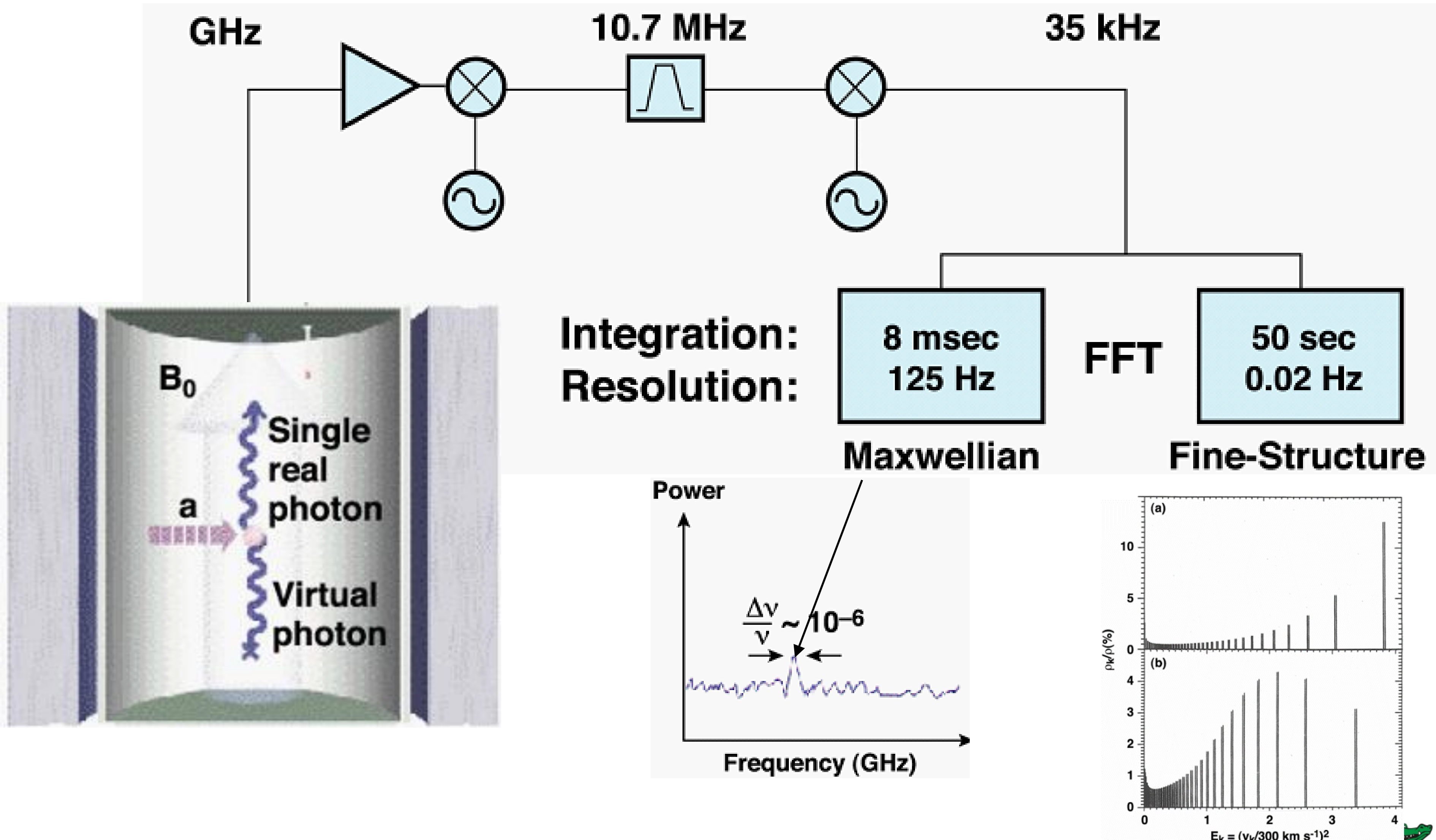
Heavy axions forbidden: else new pion-like particle

- A very light axion (3-30 μeV) is an ideal dark-matter candidate
- 3 μeV is 0.7 GHz

The “invisible” axion

- Light axion thought to be invisible
  - •Very long half life
  - •Does not affect stellar evolution
  - •Or supernovae
  - •Penetrates ordinary matter
- Only gravity…
- Pierre Sikivie made them visible again
  - •Decay is two photon
  - •Put virtual photon in by hand (static B or E field)
  - •Stimulates decay

Axion Haloscope



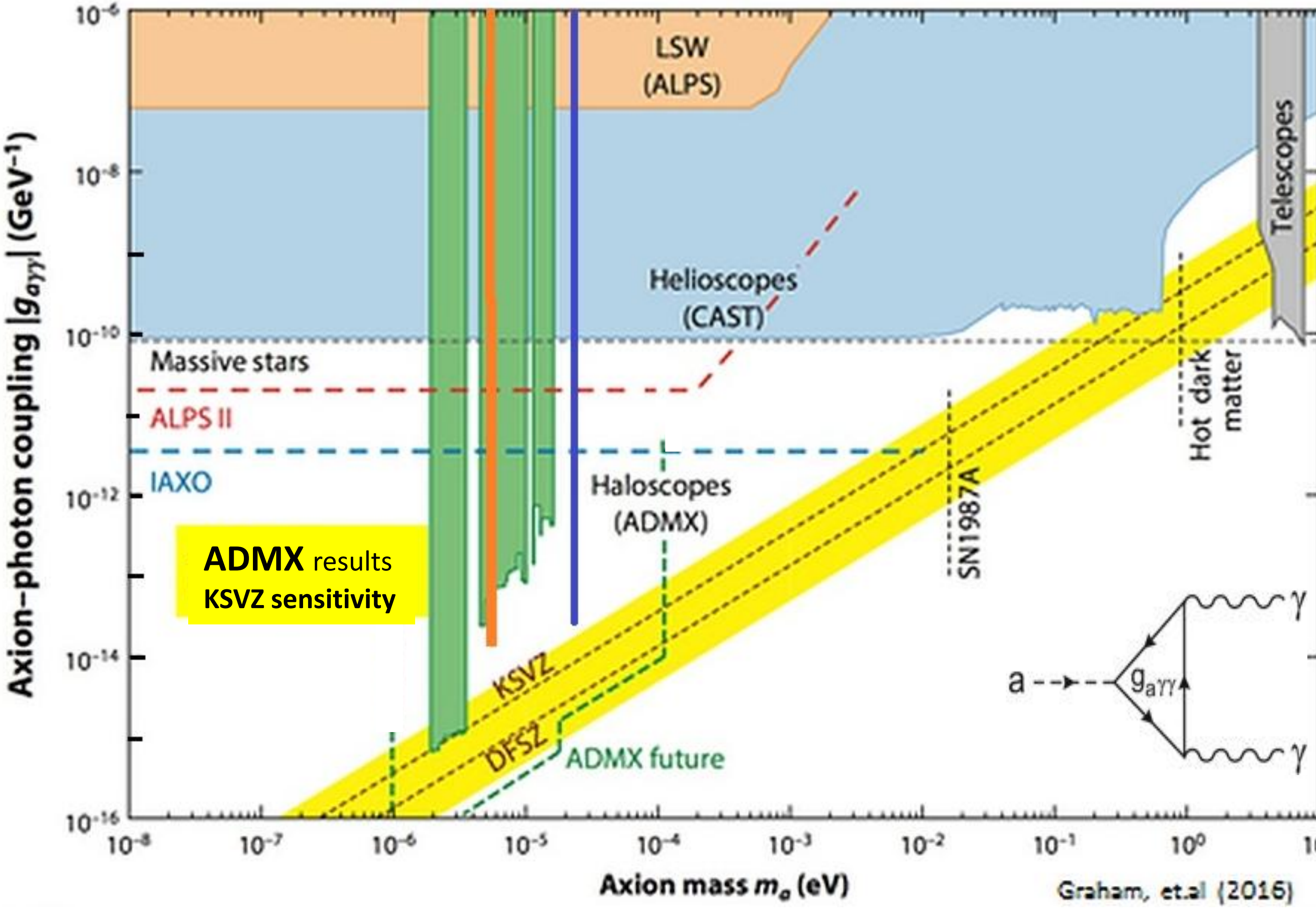
The signals are very weak

- Power from the cavity is

$$P = 130 \text{ yW} \left(\frac{V}{200\ \ell}\right) \left(\frac{B_0}{8 \text{ Tesla}}\right)^2 \left(\frac{C_{nl}}{0.5}\right) \left(\frac{g_\gamma}{0.36}\right)^2 \cdot \left(\frac{\rho_{\text{a}}}{0.5 \text{ yg/cm}^3}\right) \left(\frac{f_{\text{a}}}{1 \text{ GHz}}\right) \left(\frac{Q_{\text{L}}}{100,000}\right)$$

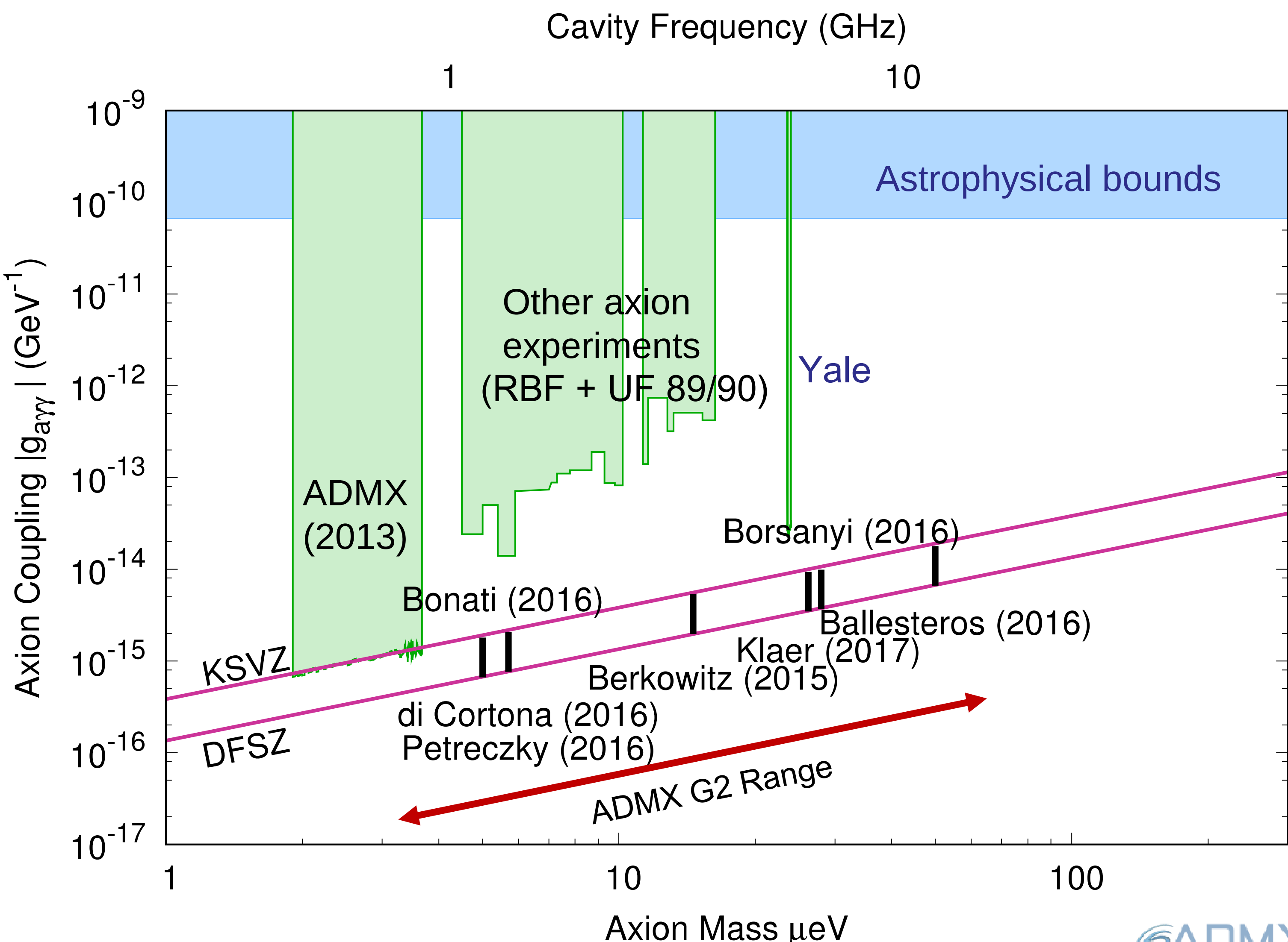
- 1 GHz ⇔ 4 μeV ⇔ 50 mK
- 6×10^{-23} W is about 100 photons/sec
- C_{nl} is a form factor, overlap of $\vec{E} \cdot \vec{B}_0$ in the cavity.
- $g_\gamma \sim$ 0.36 (DFSZ) while $g_\gamma \sim$ 0.97 (KSVZ)
- $Q_{\text{L}} \sim$ 120,000 (GHz/f)$^{2/3}$ (ASE) and $Q_a \sim 10^6$

2013 limits on axion coupling to two photons

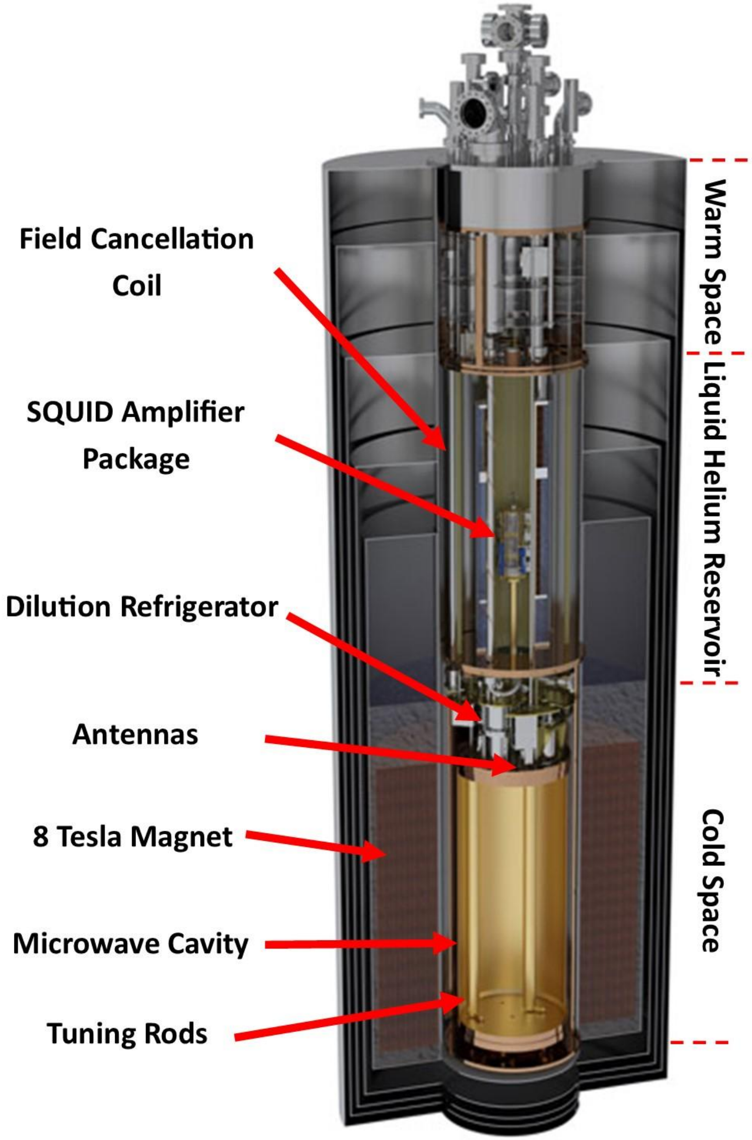


Computational and experimental perspective on DM axions

- Analytic and lattice predictions of the axion mass
- Assume 100% of the dark matter is axions, post-inflationary



ADMX Design



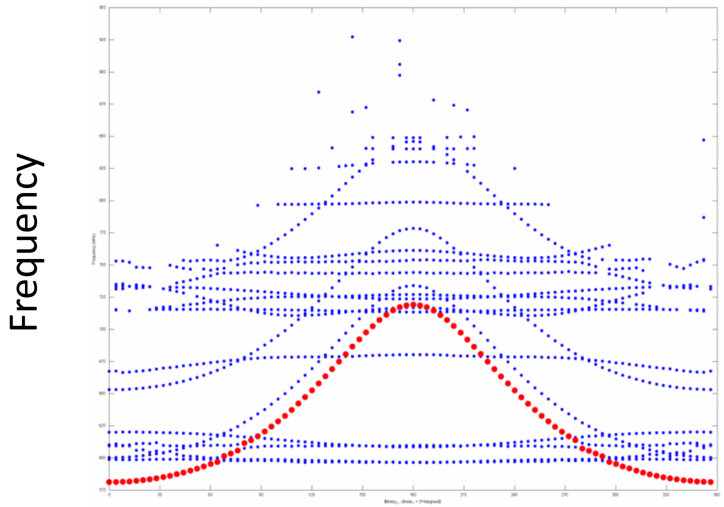
Field Cancellation Coil
SQUID Amplifier Package
Dilution Refrigerator
Antennas
8 Tesla Magnet
Microwave Cavity
Tuning Rods
Warm Space
Liquid Helium Reservoir
Cold Space

Resonator

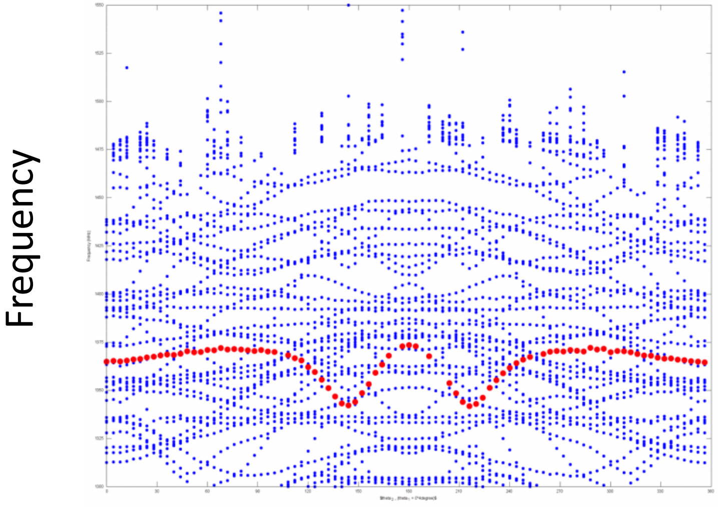
- Copper coated stainless steel cylinder
- 0.5 m diameter x 1 m tall
- Tuned with two tuning rods
- 500 MHz to 1 GHz
- Amplifiers for TM_{010} and TM_{020} modes

Tuning Rods

TM_{010}

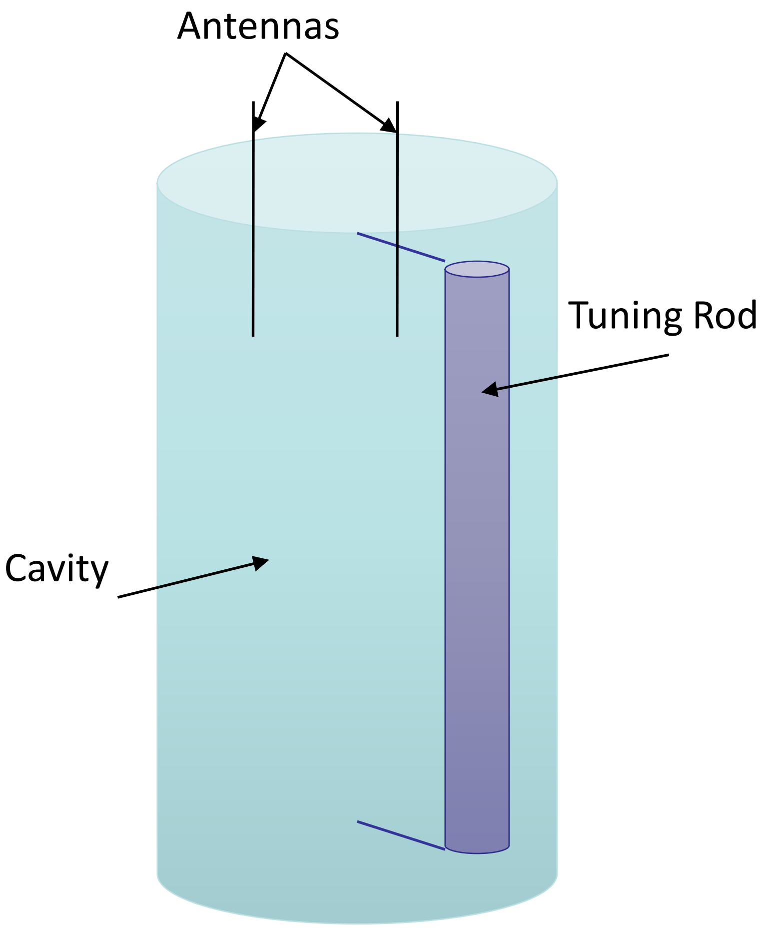


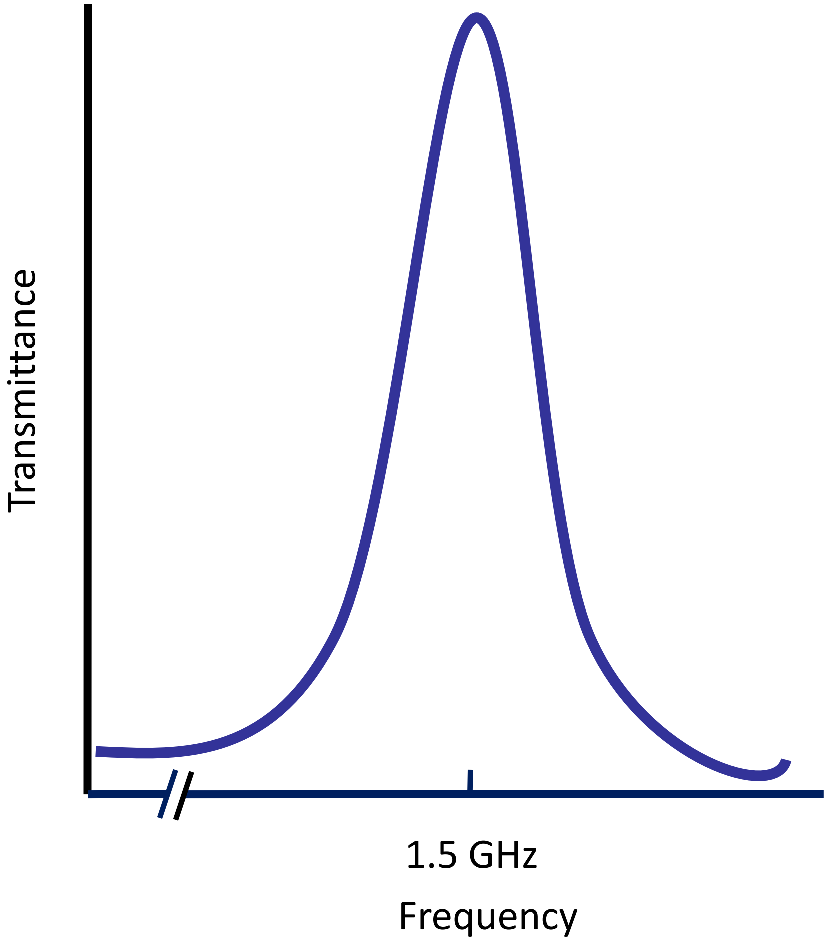
TM_{020}



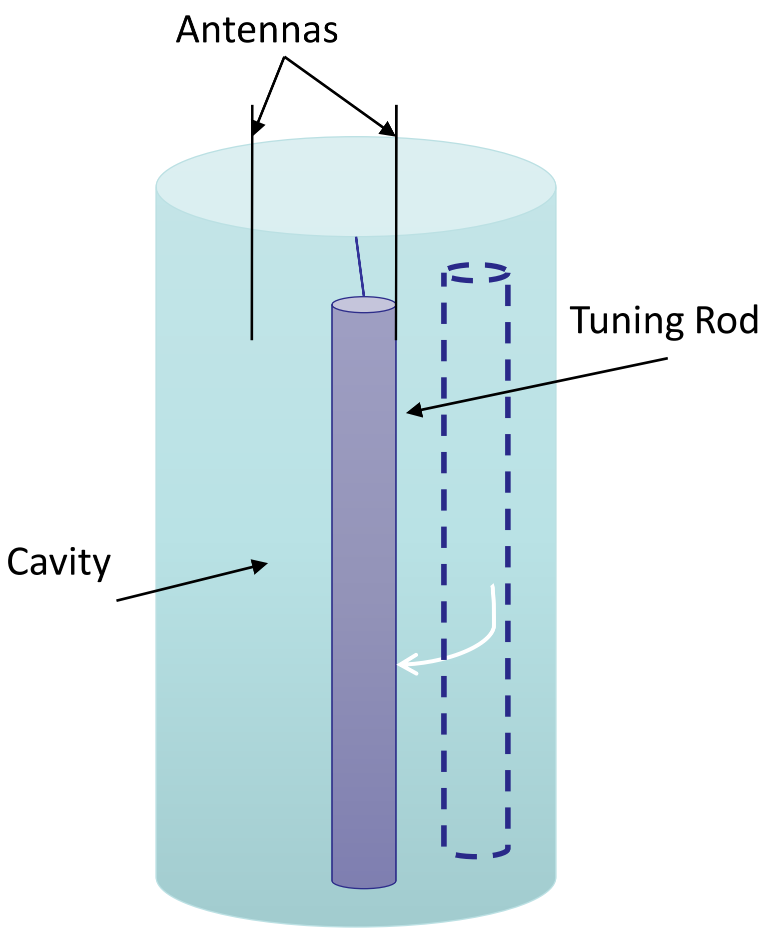
ADMX

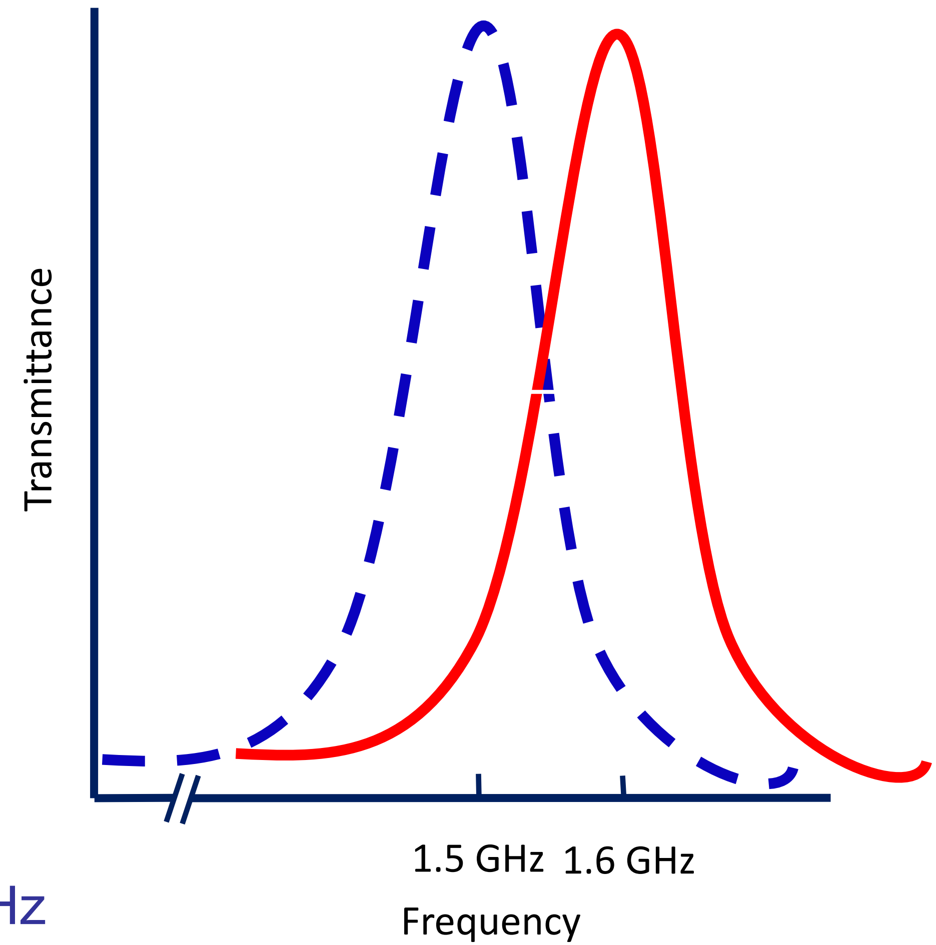
Cavity tuning





Cavity tuning

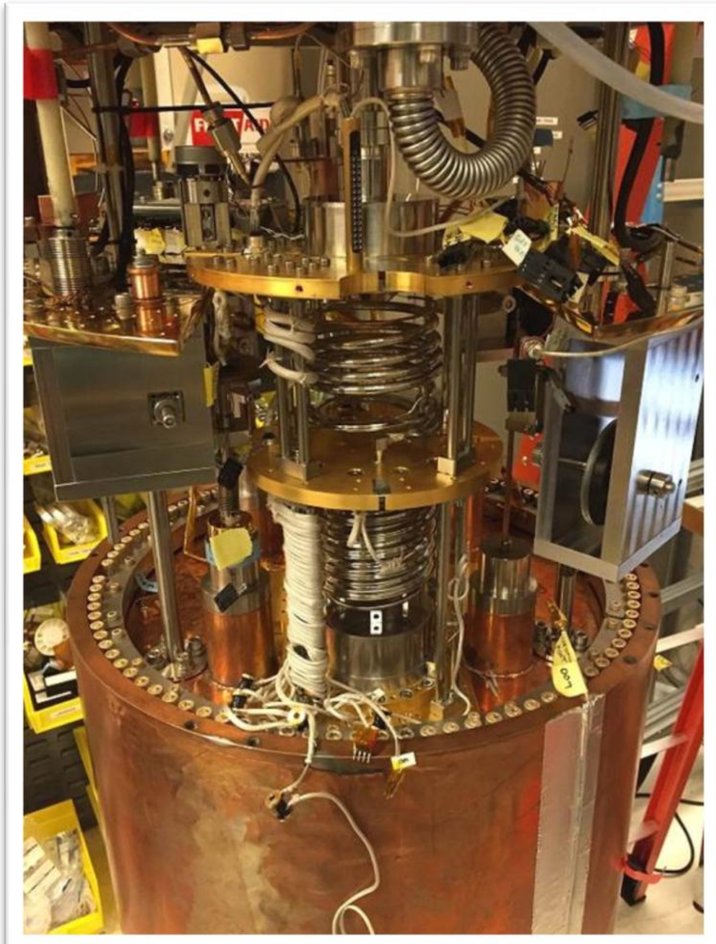




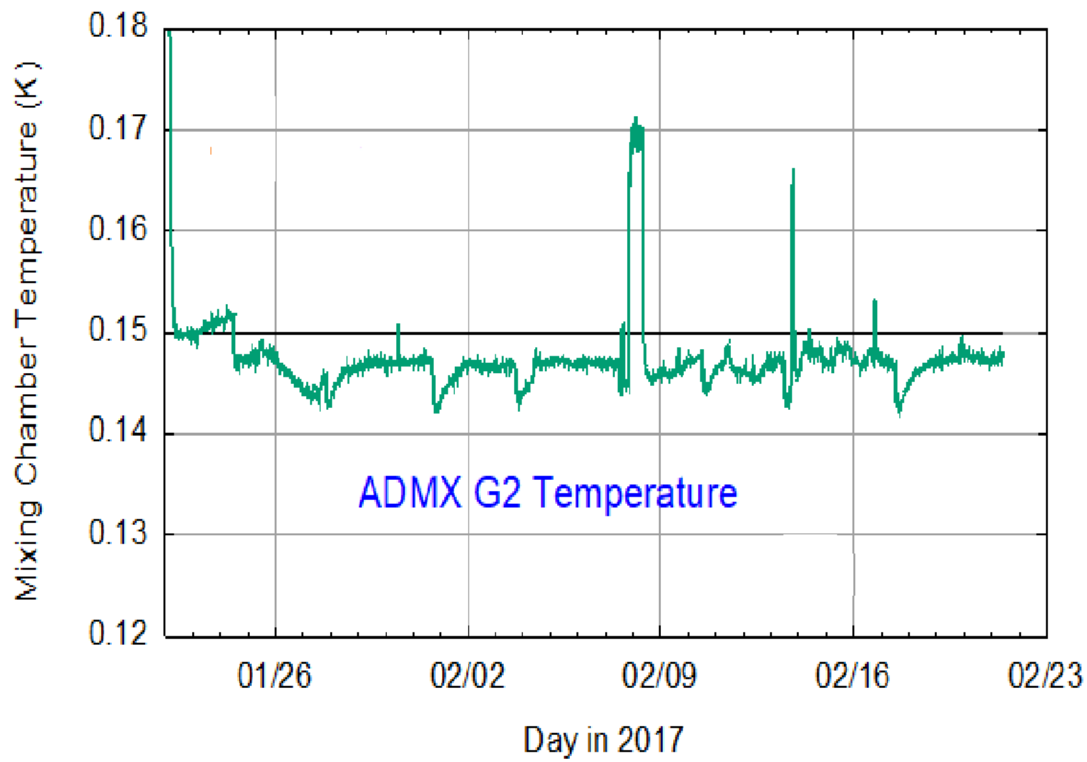
- Steps of about $f_0/10Q$ ~ 2 kHz
- 10^5 steps for 200 MHz
- 4 x 10^6 sec @ 40 sec/scan

Cryogenics

Cavity and electronics cooled with dilution refrigerator

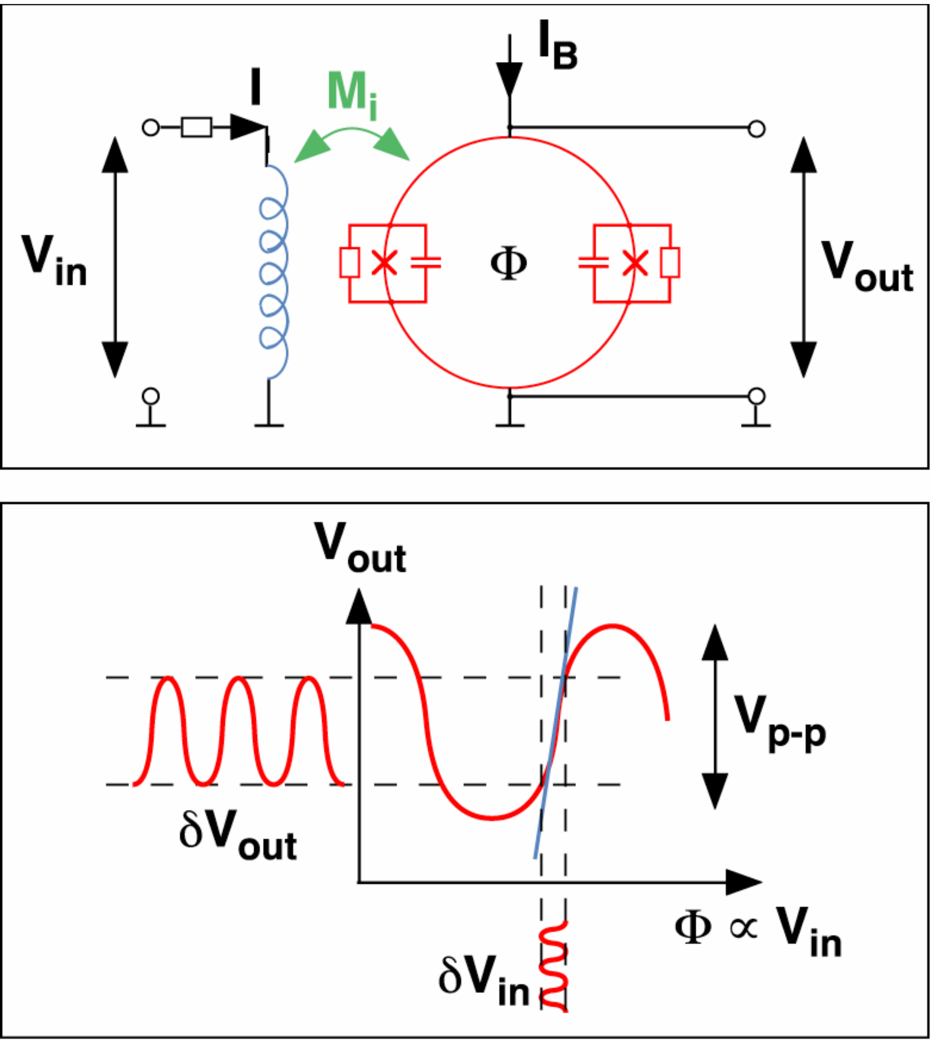


Dilution Refrigerator above ADMX cavity



Run 1 average: 148 mK. Now: 95 mK.

SQUID amplifiers



Quantum limit at 700 MHz is ~ 33 mK

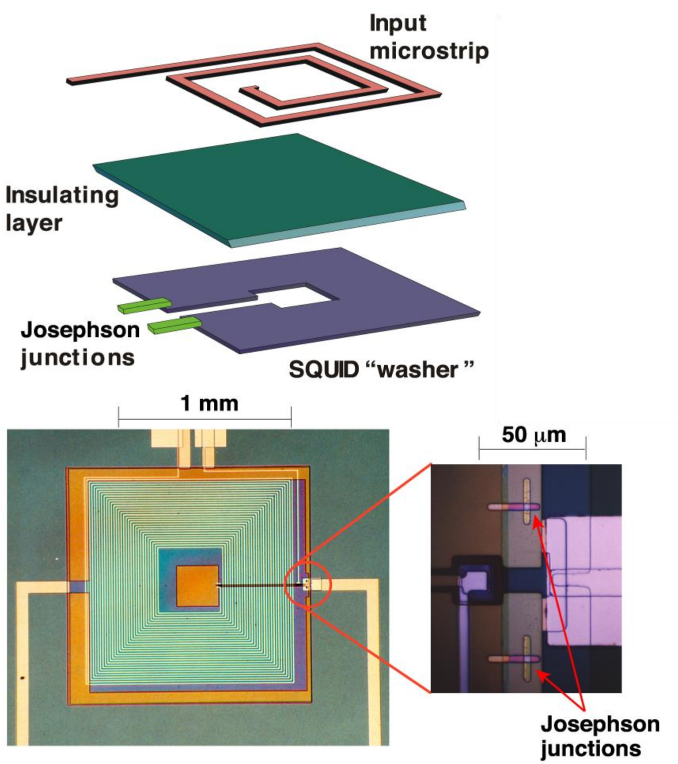
SQUID amplifier -- a flux-to-voltage transducer

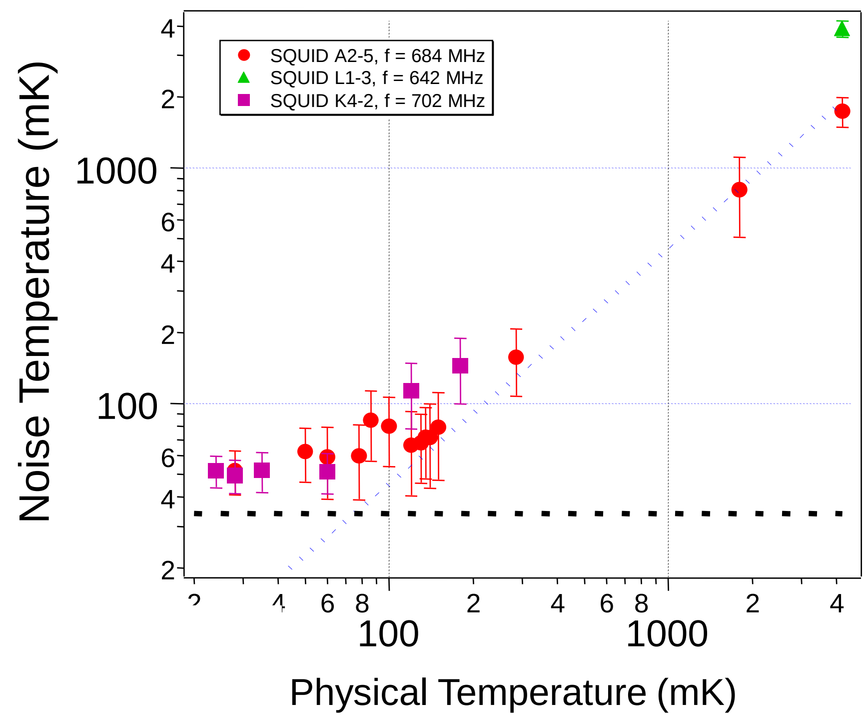
SQUID noise arises from Nyquist noise in shunt resistance - scales linearly with *T*

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

GHz SQUID amplifiers

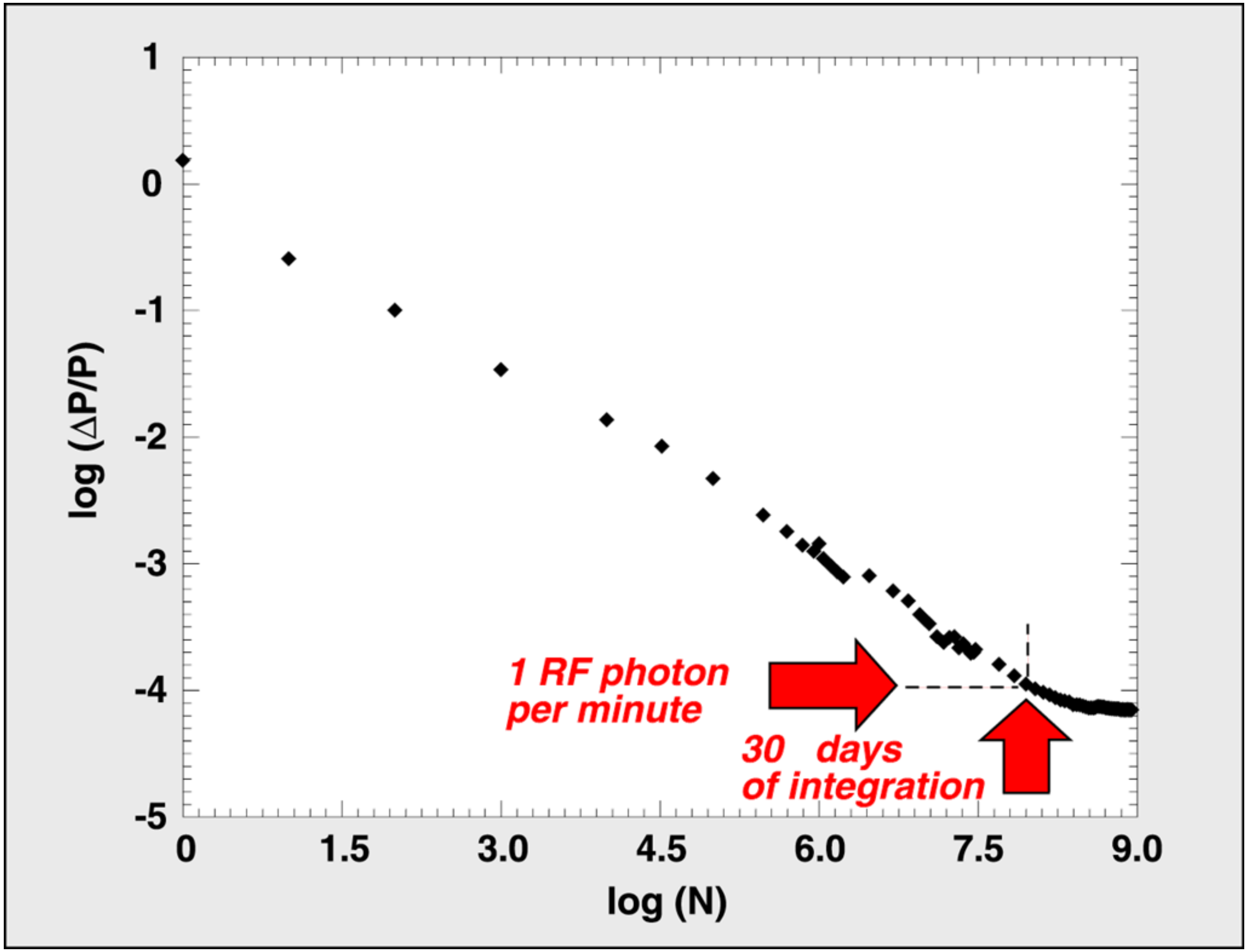
Microstrip SQUID, varactor tuned, 100-1100 MHz (John Clarke, Michal Muck, Darin Kinion, Sean O'Kelly, Berkeley)





- *Our latest SQUIDs are within 15% of the Standard Quantum Limit* ($hf = kT$)
- *Josephson parametric amplifiers too*

The world's quietest receiver



We are systematics-limited for signals of 10^{-26} W — 0.1% of DFSZ axion power!

P02552-ljr-u-018

World's Most Sensitive RF Receiver

- How sensitive?
  - $\sim 10^{-26}$ W ($\frac{1}{100}$ yoctoWatt)
  - $\sim$ 1 photon per minute

World's Most Sensitive RF Receiver

- How sensitive?
  - $\sim 10^{-26}$ W ($\frac{1}{100}$ yoctoWatt)
  - $\sim$ 1 photon per minute
- A cellphone with equivalent capabilities

ADMX

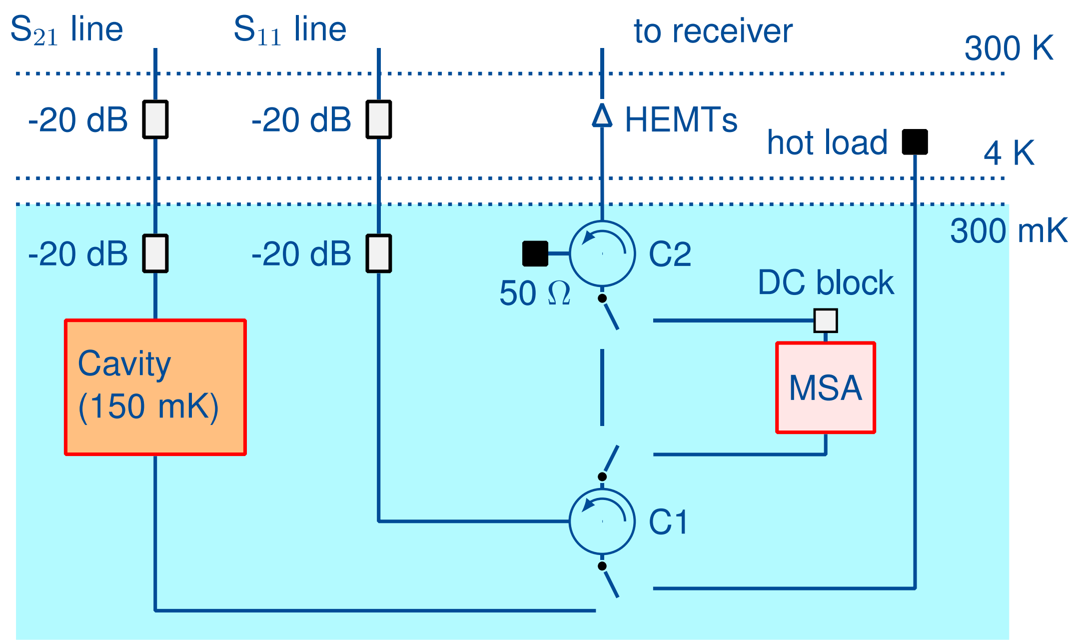
World's Most Sensitive RF Receiver

- How sensitive?
  - ~ 10^{-26} W ($\frac{1}{100}$ yoctoWatt)
  - ~ 1 photon per minute
- A cellphone with equivalent capabilities
  - 4 bars on Mars!!!

Low temperature data acquisition system

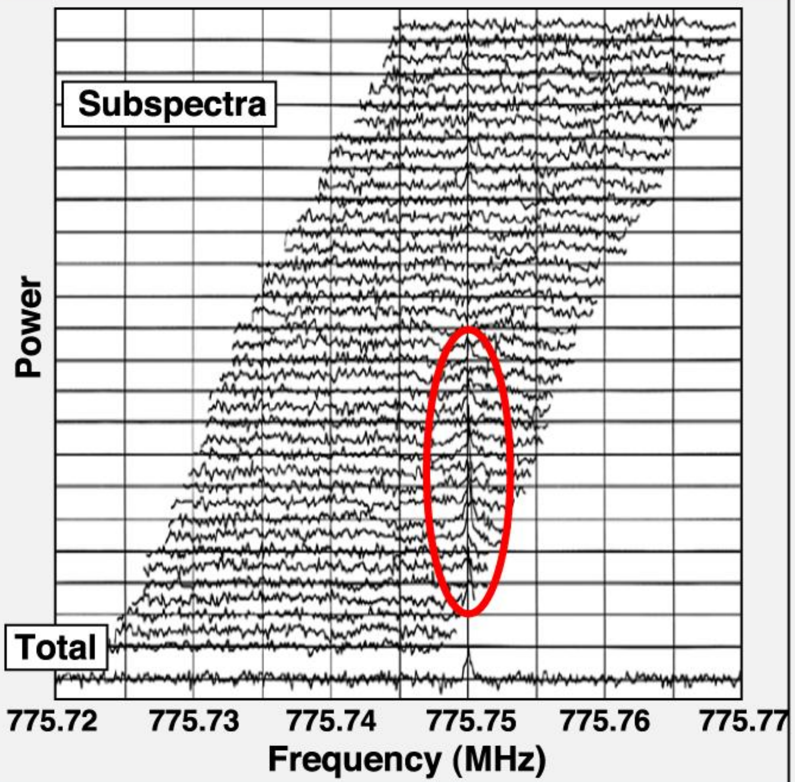
- Noise figure characterization:
  - Injection of swept power & fake axions
  - Reflection ➔ antenna coupling
  - Hot/cold load: for T_N
  - SQUID at $T_{physical} \sim 300$ mK
  - Cavity at $T_{physical} \sim 150$ mK
  - Total system noise ~ 0.5 K*

    *includes attenuation + post-amplifier contributions.



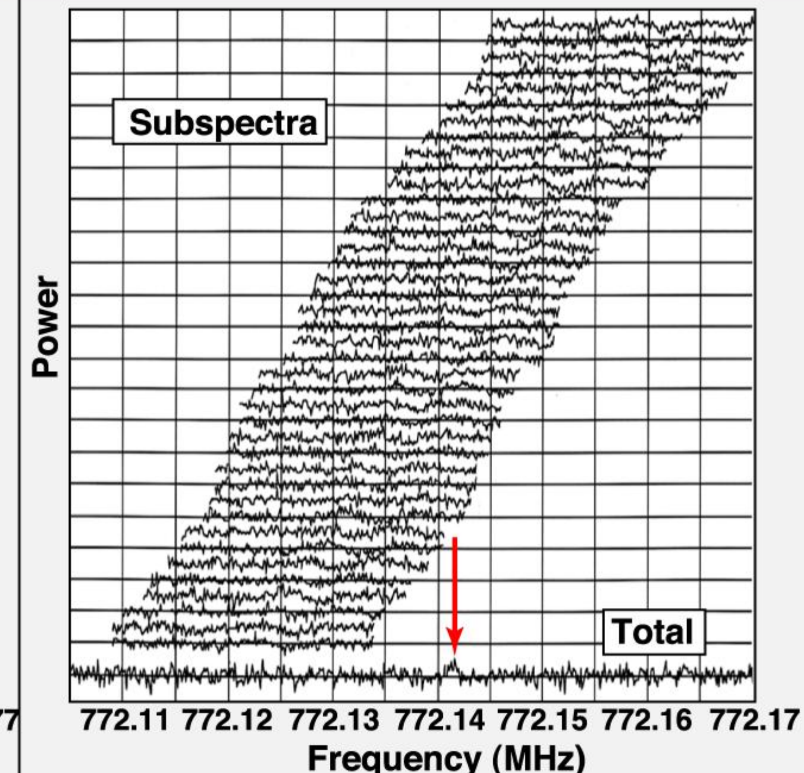
Sample data and candidates

Environmental



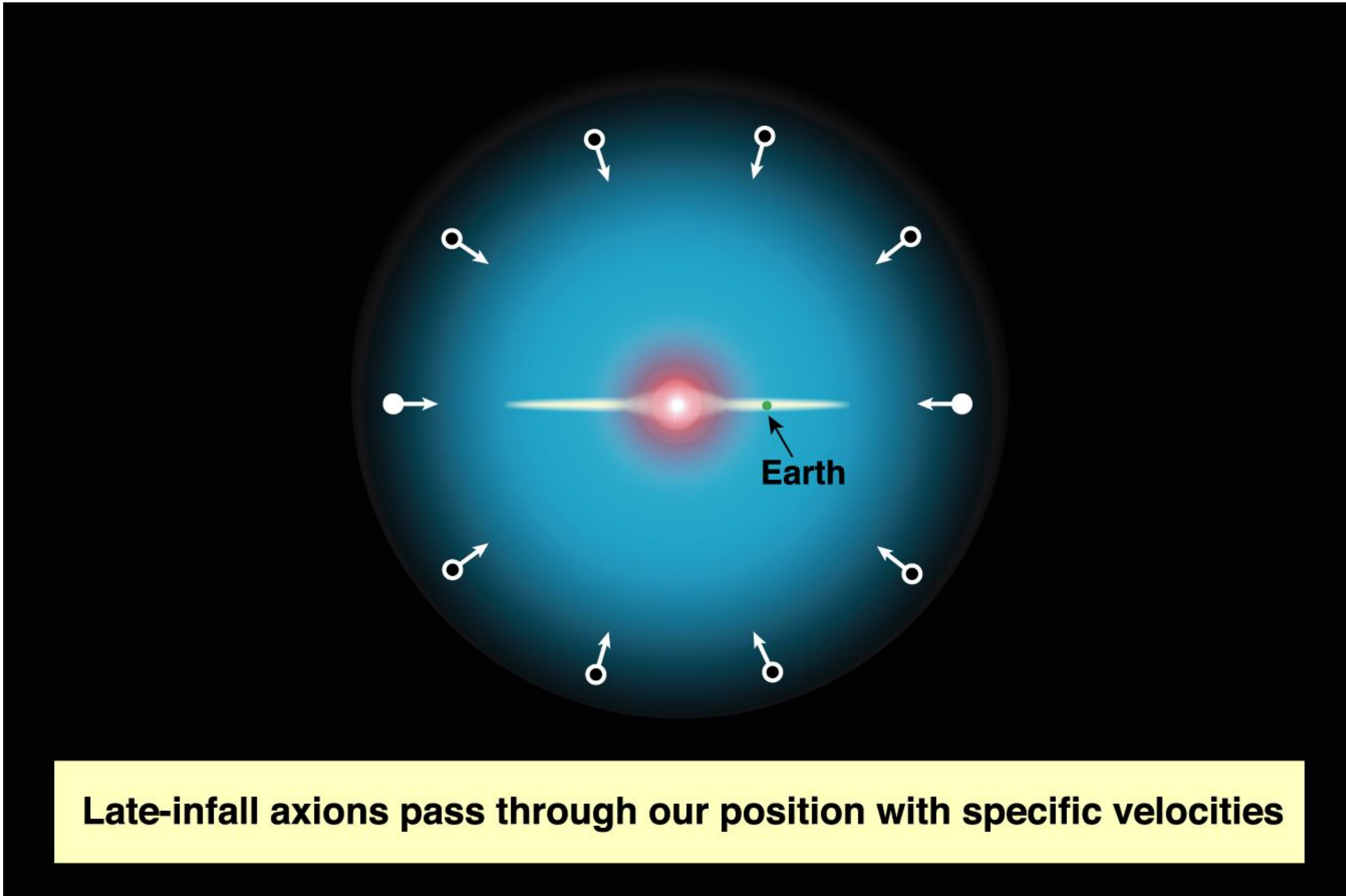
Signal maximizes off-resonance: Radio peak

Statistical

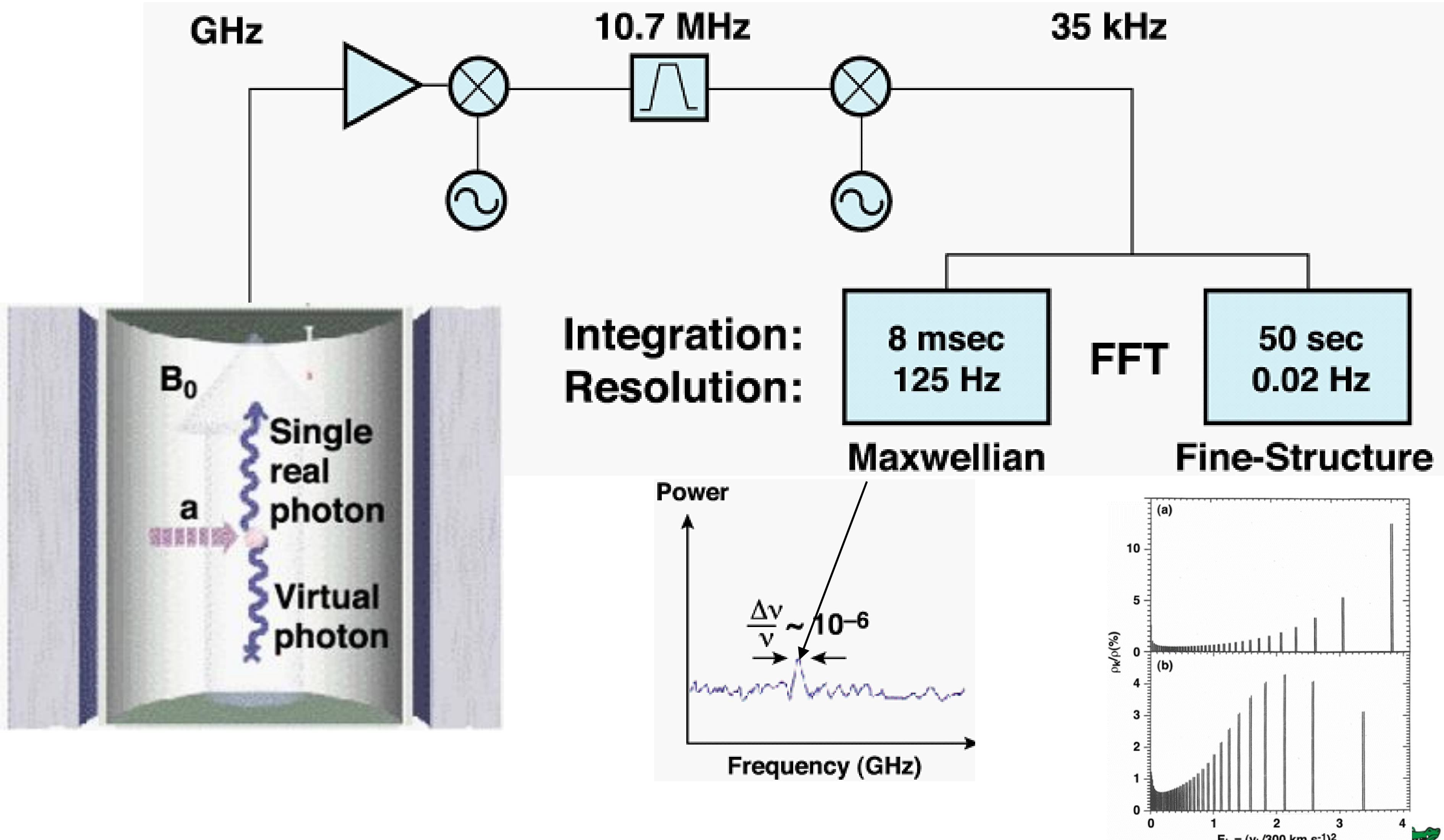


Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

Could there be sharp features in the axion spectrum?

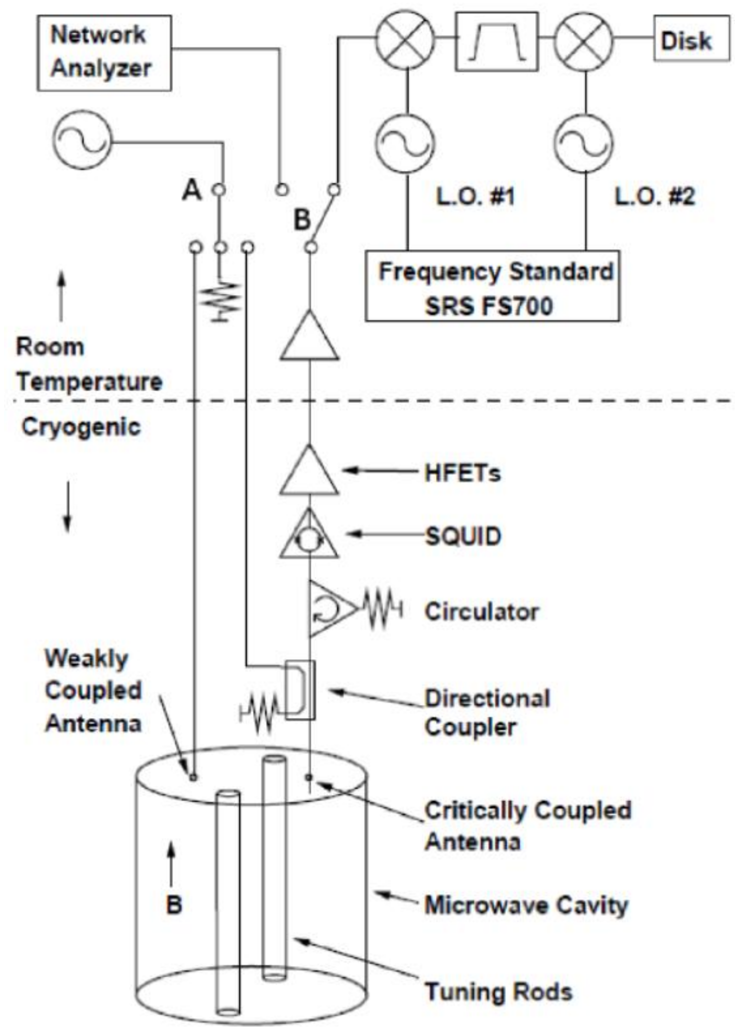


Cavity axion detector has high resolution channel

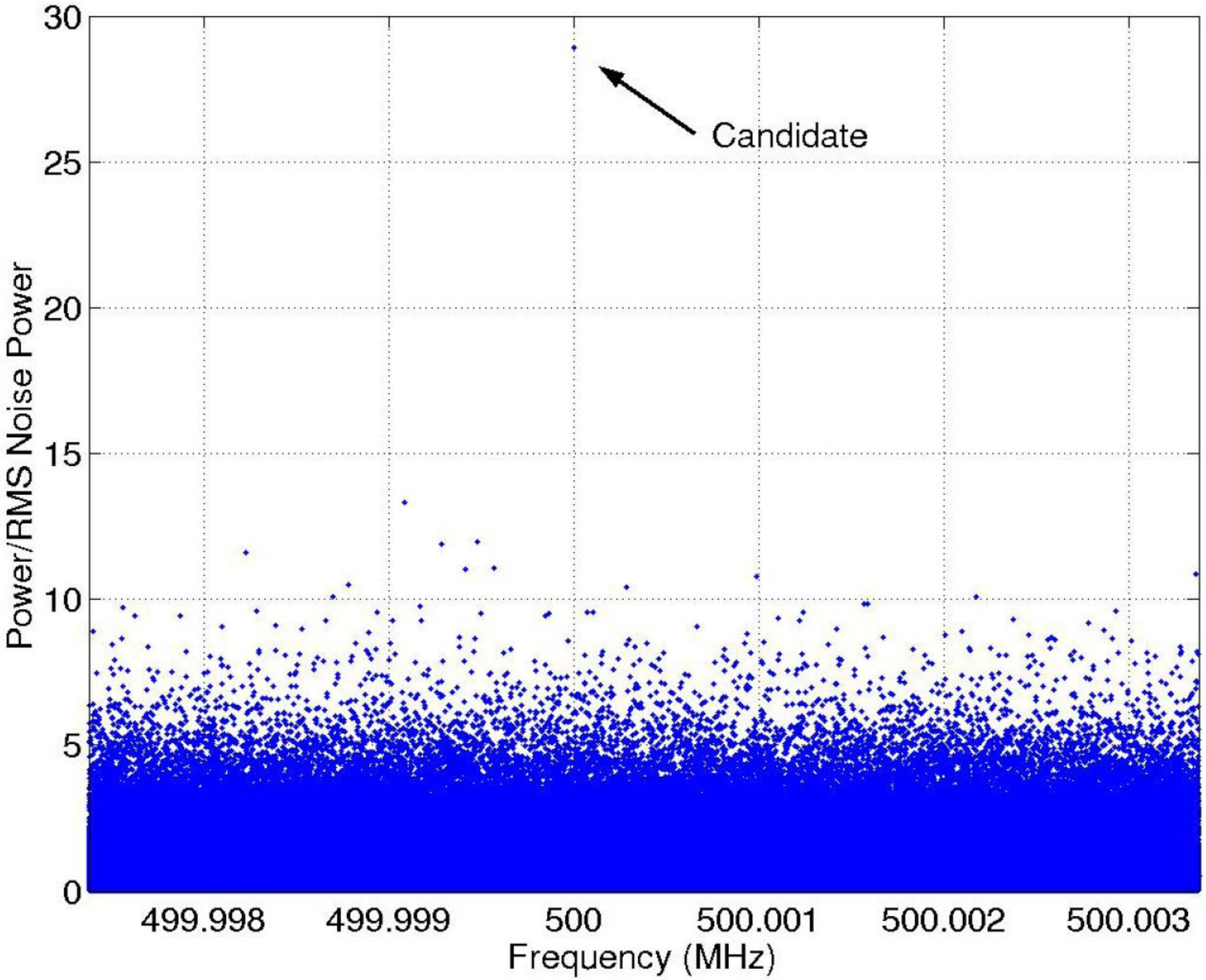


High-resolution search offers additional discovery opportunity

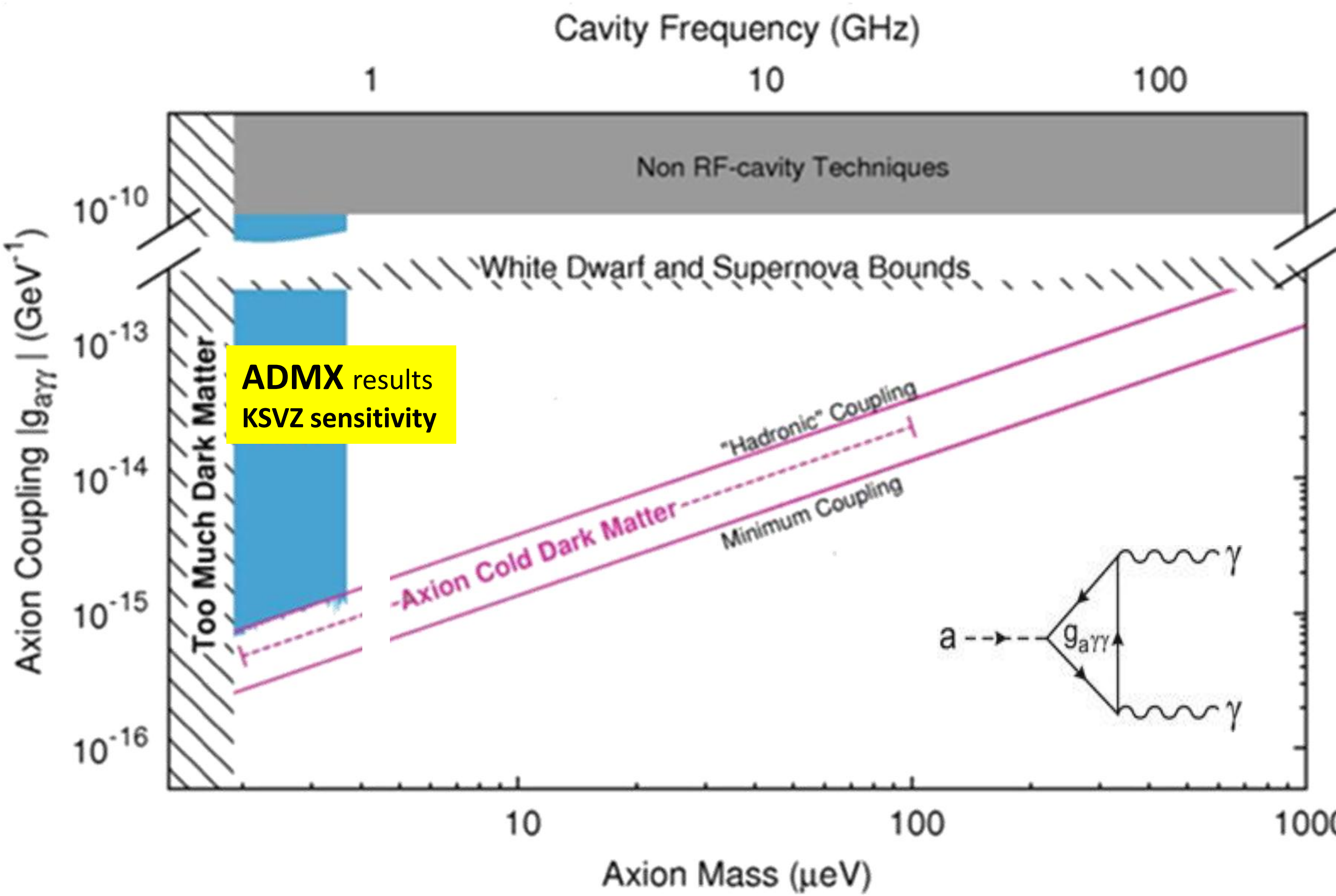
- Measure cavity output for ~100 sec.
- Signal bandwidth
  ~ 50 kHz
- 10 million points
- FFT, search for power in one or two bins.
- Phase noise in local oscillators is an issue
- Search must allow for a Doppler shift of ~ 80 Hz in 6 months
- But: signal always there!



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



ADMX limits up to 2017



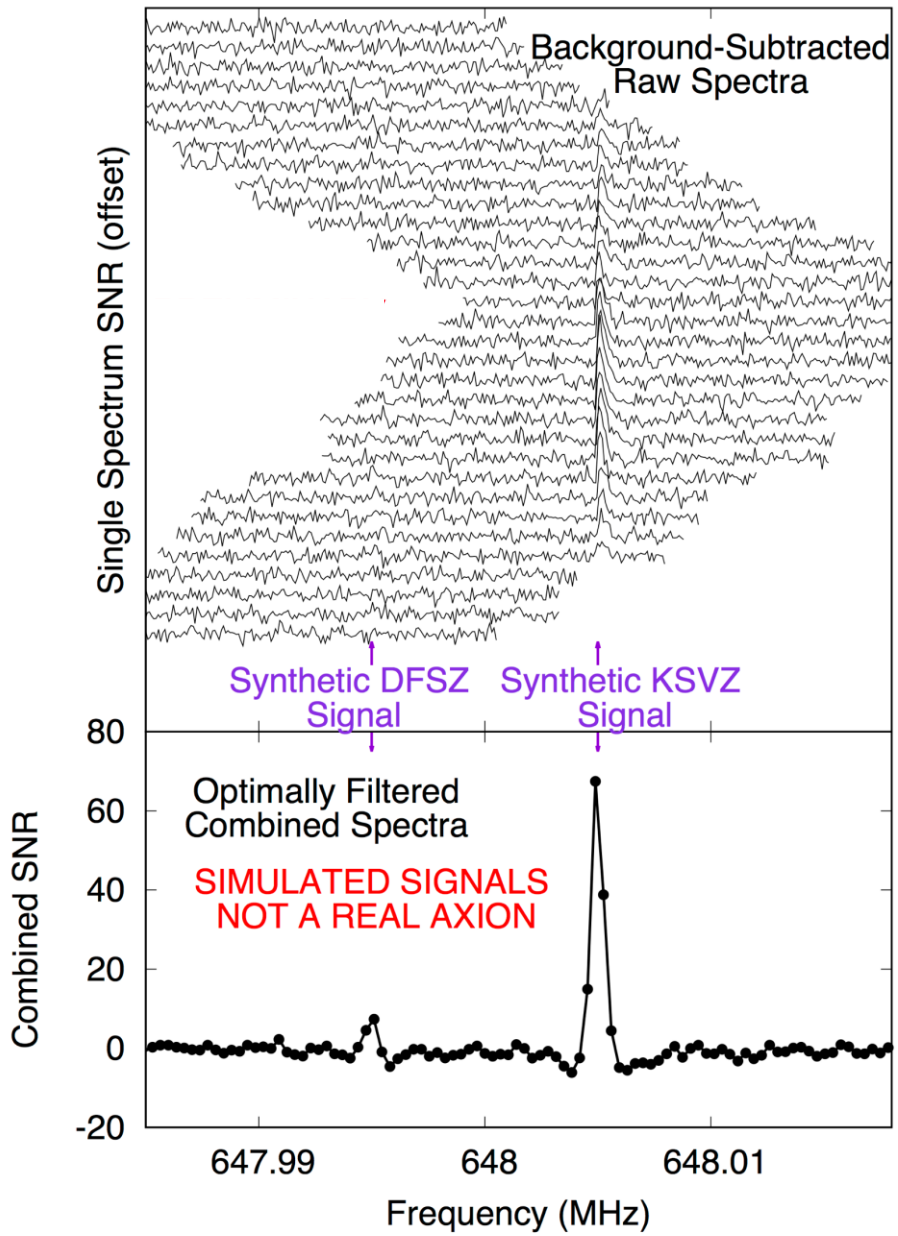
First search at DFSZ sensitivity

- January–May 2017
- 150 mK physical *T*
- 160 mK excess noise from squid amplifier
- DFSZ sensitivity in 100 sec integration

- Du et al, PRL

Analysis of Simulated Signals Injected into Real Data

- Synthetic signals are software-injected to evaluate analysis.
- KSVZ and DFSZ axion shown here.
- Conclusion: DFSZ axion signals should be observed if present
- Note: There is a black ops team who do blind injections (hardware not software) from time to time.



Requirements for a detection

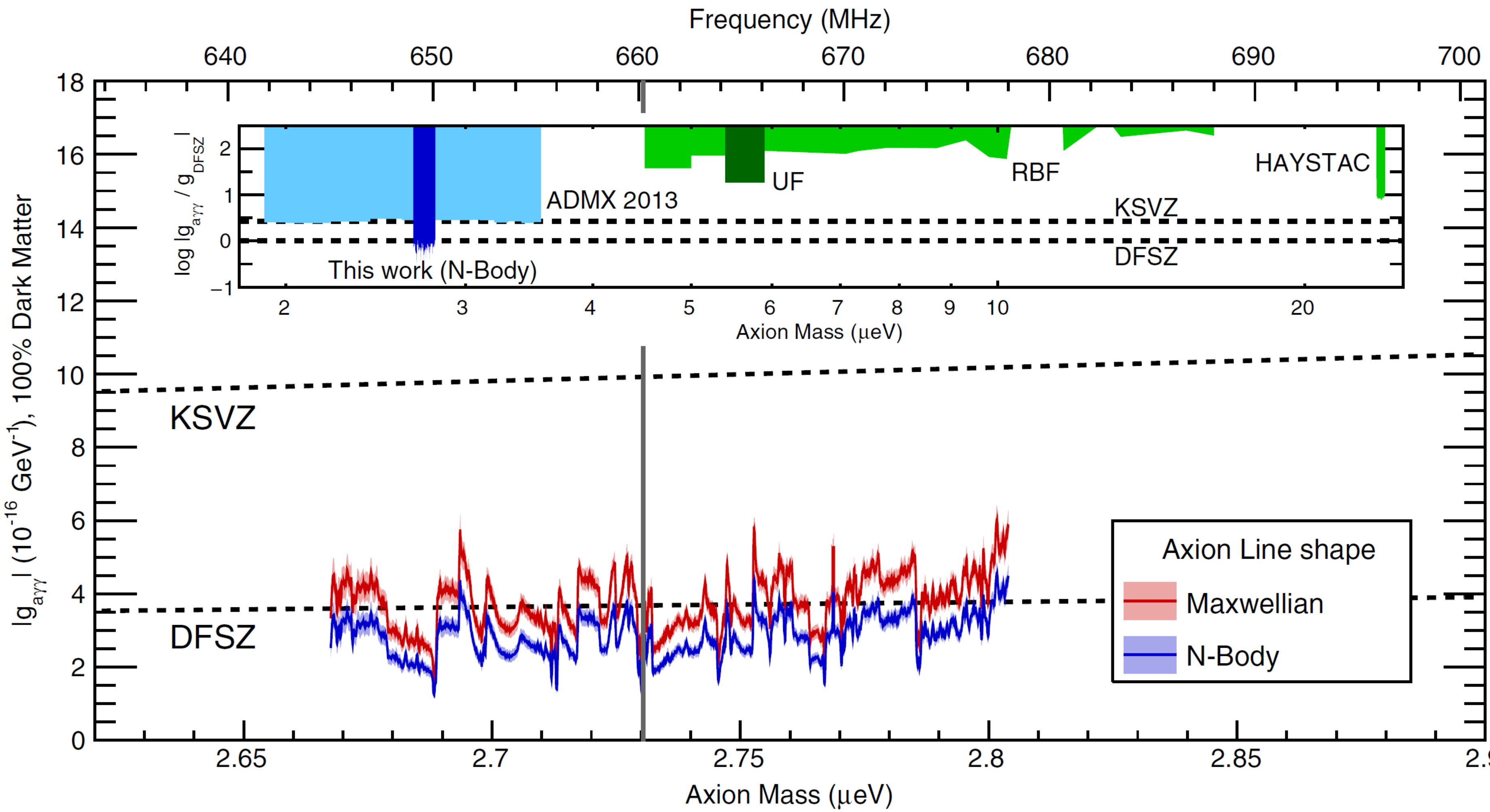
We have a lot of knobs …

- The signal is always there
  - If we spend not 100 sec but 100 days at f_{ax}, the S/N increases from 5 to 1500

  ➔ measure halo kinetic energy spectrum with 700 ppm precision
- Signal strength follows the Lorentzian lineshape of the cavity
- The signal is suppressed for modes not called TM_{010}
- The signal scales with B^2
  - We can turn the signal down by reducing the field
- The signal has a tiny daily (3.8 Hz) and annual (230 Hz) frequency modulation due to motion of the earth relative to the axion frame.

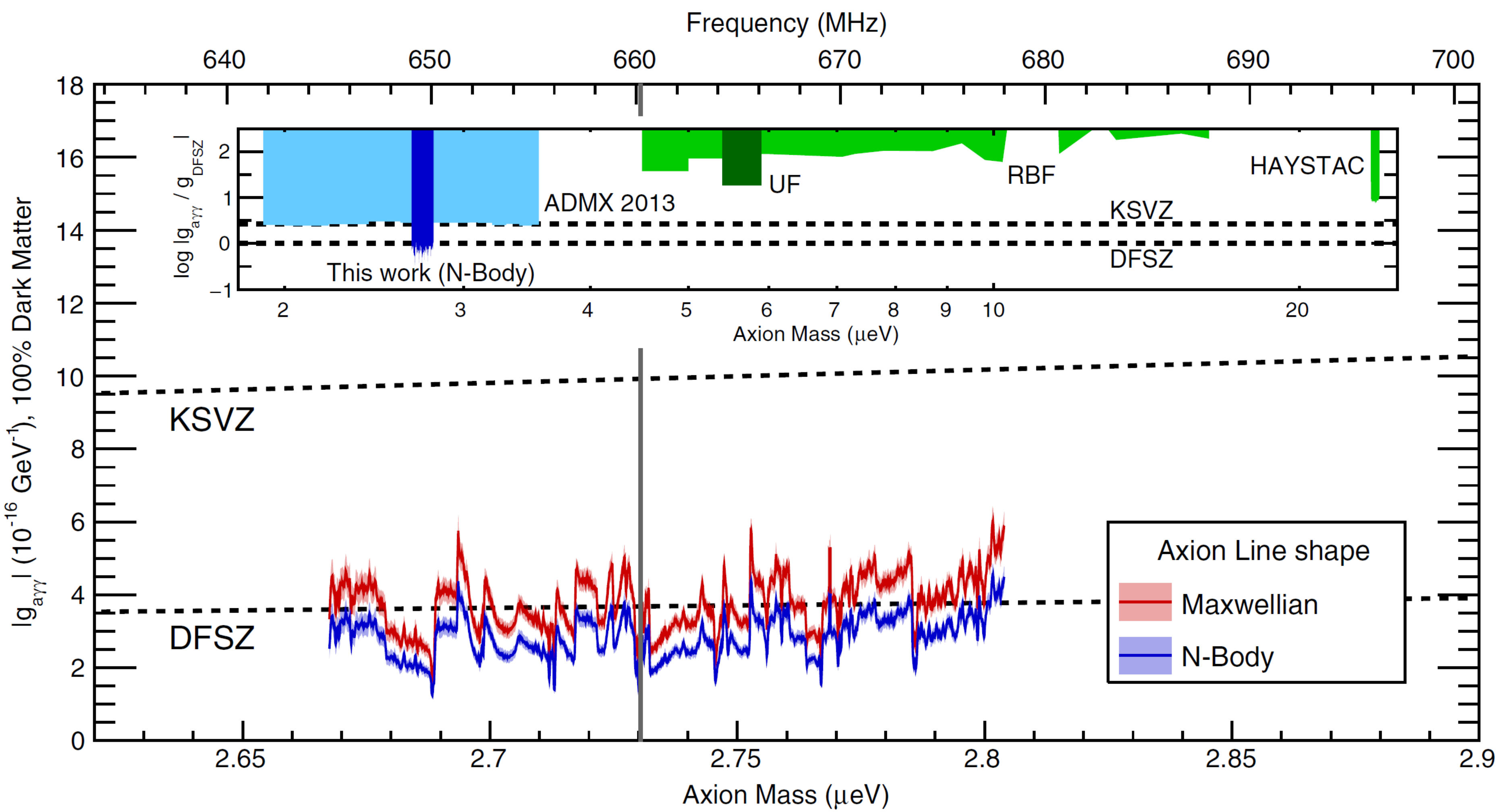
- So far, nothing has passed these tests
- So, we set a limit

ADMX 2017 exclusion limits



N. Du *et al.* (ADMX Collaboration), "Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment," Phys. Rev. Lett. **120**, 151301 (2018).

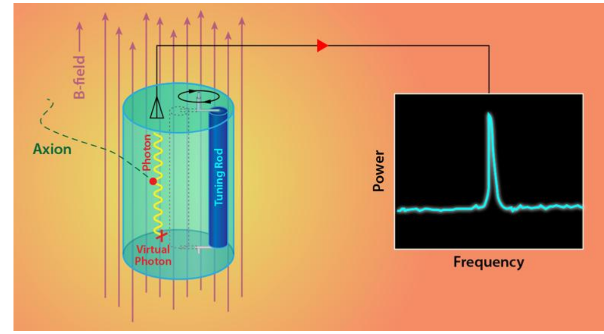
ADMX 2017 exclusion limits



- Did not find an axion
- But we could have.
- First measurement at the DFSZ frontier
- A discovery could occur at any time

Press Coverage (Gray Rybka's notes)

"Homing in on Axions?" – Physics Viewpoint



"If Tiny Dark Matter Particle Exists, This Experiment Is Now Ready to Find It" - Gizmodo

"The search for mysterious dark matter underdogs steps up" – Science News

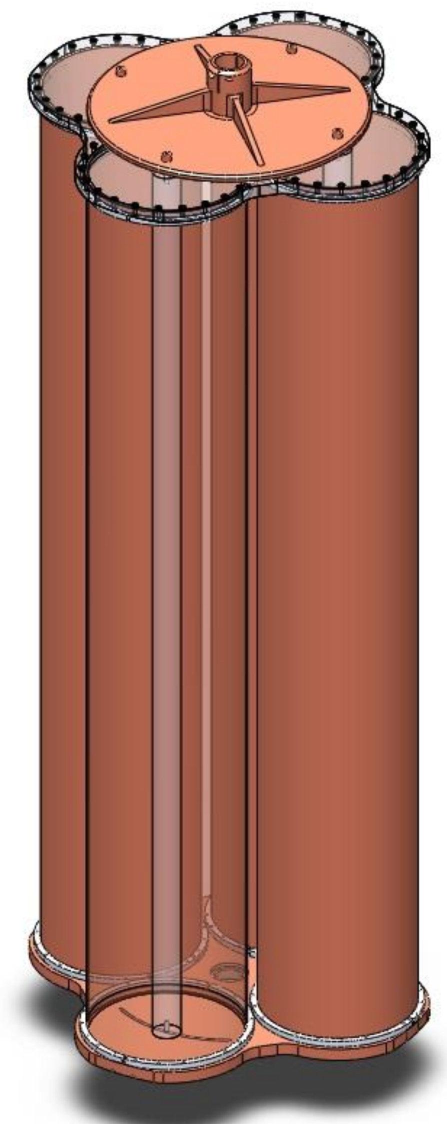
"ADMX brings new excitement to dark matter search" – Symmetry Magazine

Plus we were trending on Reddit!

The future

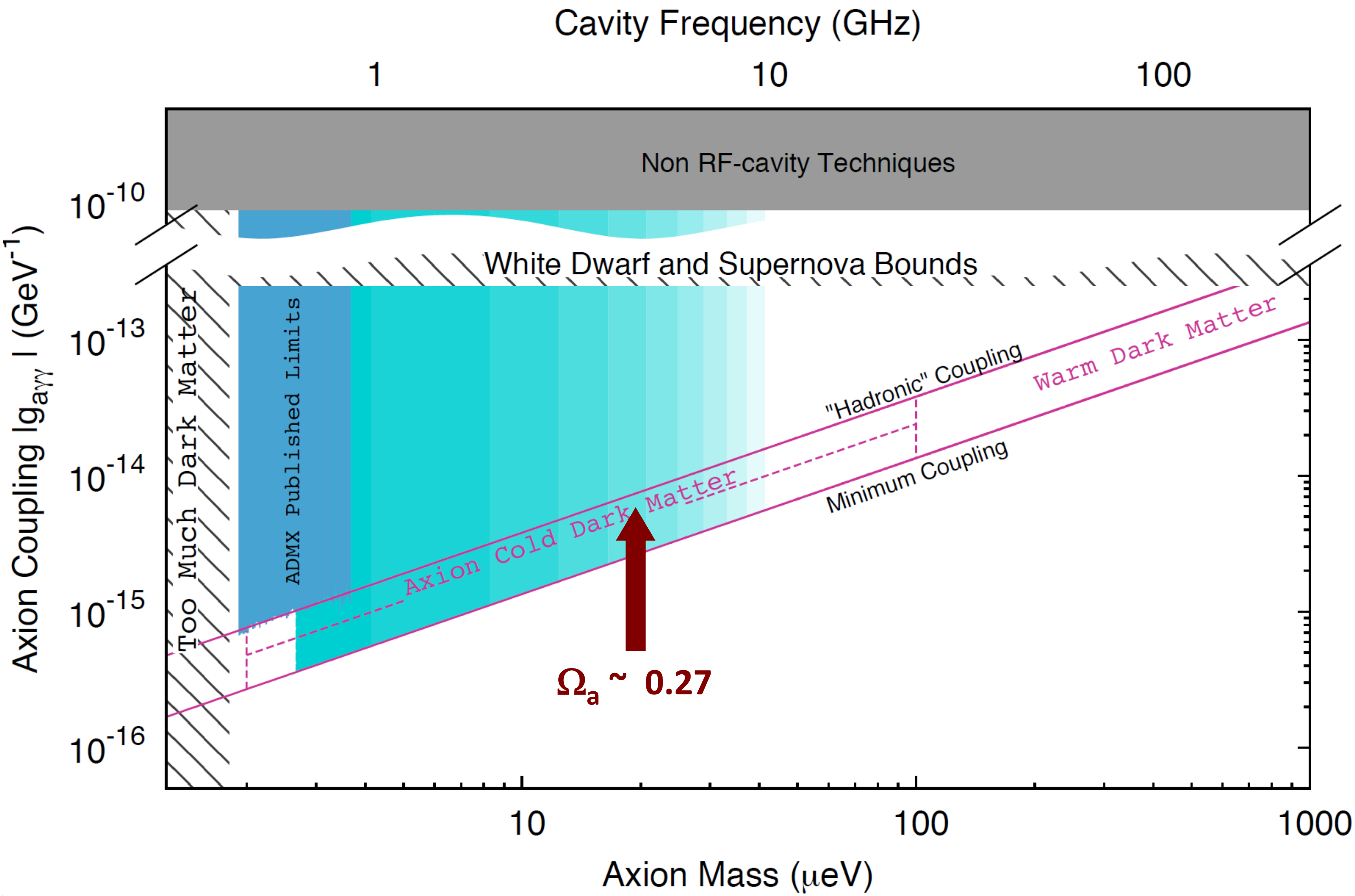
- Currently cold
- Reached 90 mK at mixing chamber; but only 200 mK at SQUID
- Scaning at DFSZ over 0.66 to 1 GHz (2.7 to 4.1 μeV)
- 2019–2020: 4 cavity array; 1–2 GHz; 4.1–8.3 μeV

- Then what?



ADMX goal: to 10 GHz

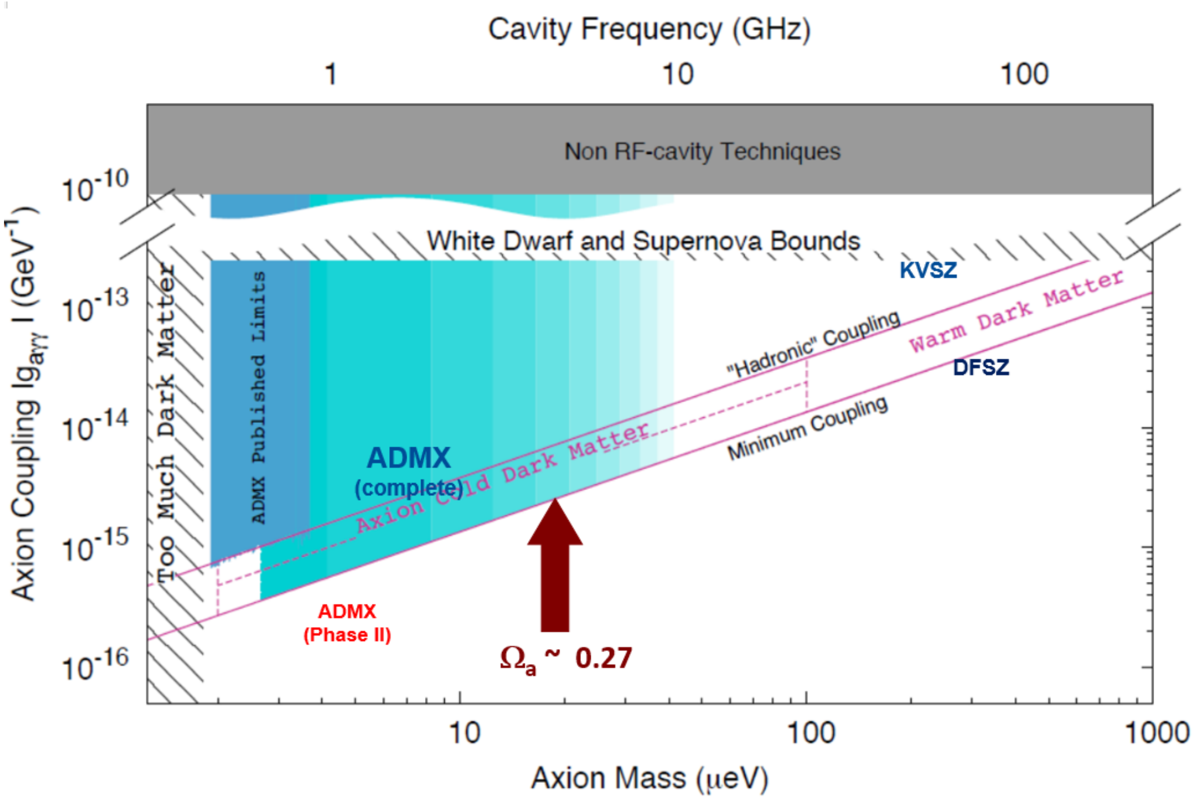
Misalignment gives ~ 4−5 GHz if Ω_a ~ 0.27



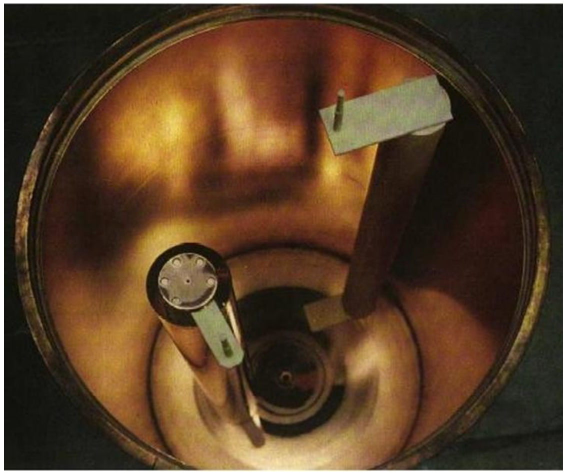
ADMX should procure a new magnet

Higher field ➔ Smaller volume ➔ Search higher frequencies, at and above ~ 4—5 GHz

B^2V is the factor to maintain!



$$\frac{r}{1\ \mathrm{cm}} = \frac{11.5\ \mathrm{GHz}}{f}$$



ADMX

Why? The signals are very weak

- Power from the cavity goes as $B^2 V$

$$P = 130 \text{ yW} \left(\frac{V}{200\ \ell}\right)\left(\frac{B_0}{8 \text{ Tesla}}\right)^2\left(\frac{C_{nl}}{0.5}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5 \text{ yg}/\text{cm}^3}\right)\left(\frac{f_\mathrm{a}}{1 \text{ GHz}}\right)\left(\frac{Q_\mathrm{L}}{100,000}\right)$$

- 1 GHz ⇔ 4 μeV ⇔ 50 mK
- 25 yW is about 40 photons/sec
- Axion signal (from kinetic energy spread) ~ kHz in width
- C_{nl} is a form factor, overlap of $\vec{E} \cdot \vec{B}_0$ in the cavity ~ 0.5
- $g_\gamma \sim$ 0.36 (DFSZ) while $g_\gamma \sim$ 0.97 (KSVZ)
- $Q_\mathrm{L} \sim$ 120,000 (GHz/f)$^{2/3}$ (ASE) so bandwidth is 10 kHz

Search rate set by radiometer equation

$$\frac{s}{n} = \frac{P}{kT_n}\sqrt{\frac{t}{\Delta f}}$$

- Search rate is set by desired SNR, emitted power^2, cavity Q, and system noise temperature^{-2}

$$\frac{df}{dt} = 90\ \mathrm{GHz/yr}\left(\frac{5}{s/n}\right)\left(\frac{V}{200\ \ell}\right)^2\left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^4\left(\frac{C_{nl}}{0.5}\right)^2\left(\frac{g_\gamma}{0.36}\right)^4 \cdot \left(\frac{\rho_\mathrm{a}}{0.5\cdot 10^{-24}\ \mathrm{g/cm^3}}\right)^2\left(\frac{f_\mathrm{a}}{1\ \mathrm{GHz}}\right)^2\left(\frac{Q_\mathrm{L}}{100,000}\right)\left(\frac{100\ \mathrm{mK}}{T_n}\right)^2$$

- SQUID amplifiers have excess noise about half their physical temperature
- When $hf \sim kT$, shot noise appears
- System noise temperature $\sim T + T/2 + hf/k$

Strawman: Single cavity

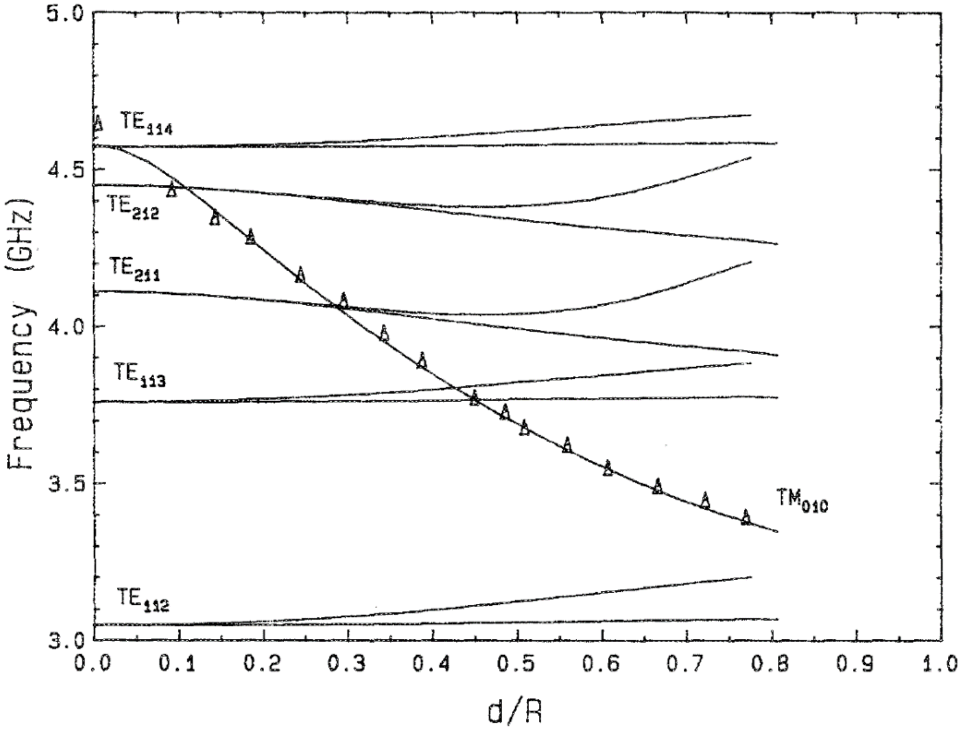
- Single cylinder, 8 T field; change size to resonate at search frequency

$$P = 130 \text{ yW} \left(\frac{1 \text{ GHz}}{f}\right)^{2.67}$$

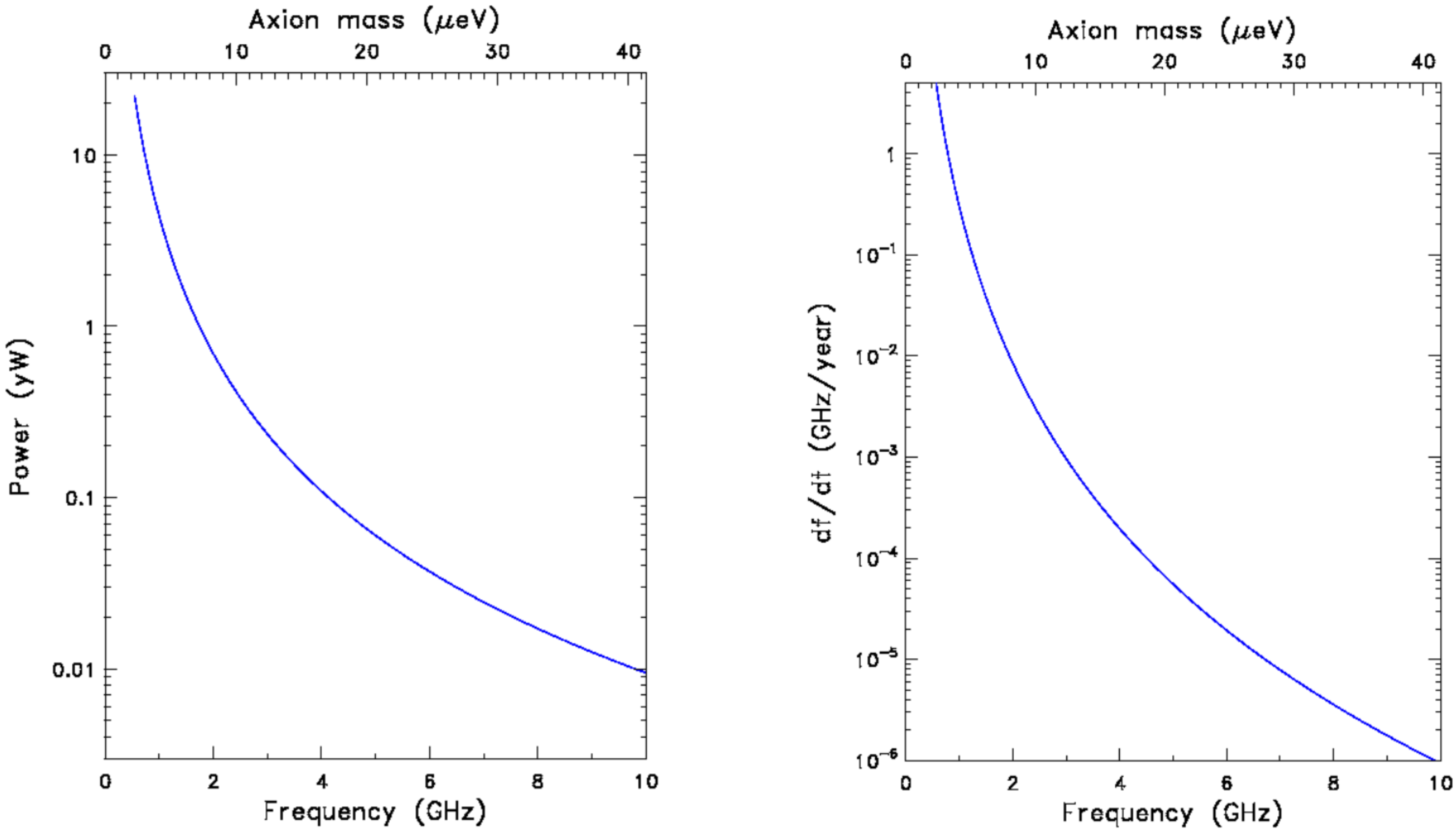
- Volume decreases as f^{-3}, the Q decreases as $f^{-2/3}$ while the mass increases as f

- Length as well as diameter changes because the cavity cannot get too long
  - The longer the cavity, the more TE/TEM modes there are
  - Typically:

$$L \sim 4.4r$$



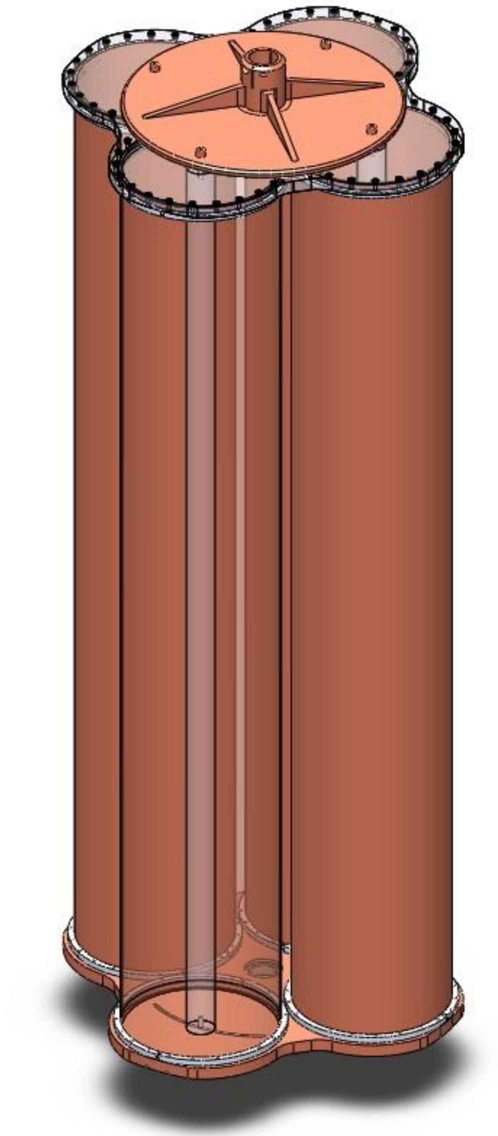
Strawman 2: Single cavity



- Power and scan rate decrease as frequency goes up ☹
- Just the opposite of what we want.

Strong magnet is essential

- Use multiple cavities, tuned together and added in phase. (Maybe up to 16)
- Complexity reduced at a given frequency if volume of high-field space is decreased
- Lower volume means weaker signal, so need to compensate with higher field
- $B_0^2 V$ is the factor to maintain
- So a stronger magnet is needed!



Requirements

- The design must be sensitive to the most weakly coupled axions and be able to detect axions with mass up to ~40 μeV
  - Cavity resonance: up to ~10 GHz ⇔ 40 μeV
- Measurement times and scan rates similar to current ADMX
- Magnet must be almost a turnkey system.
  - Go to max field and stay there for 3 months
  - Reliable. A quench damages SQUID amplifier; destroys circulators; deforms cavity
- Magnet requirements strongly connected to cavity, RF system, and cryogenics
- Integrated dilution fridge: 800 μW at 100 mK
- Integrated “bucking coil” to provide zero-field region for SQUID

So now I can see how useful various magnet designs are

$$P = 130\ \mathrm{yW} \left(\frac{V}{200\ \ell}\right)\left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2\left(\frac{C_{nl}}{0.5}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5\ \mathrm{yg/cm^3}}\right)\left(\frac{f_\mathrm{a}}{1\ \mathrm{GHz}}\right)\left(\frac{Q_\mathrm{L}}{100,000}\right)$$

$$\frac{df}{dt} = 90\ \mathrm{GHz/yr}\left(\frac{5}{s/n}\right)\left(\frac{V}{200\ \ell}\right)^2\left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^4\left(\frac{C_{nl}}{0.5}\right)^2\left(\frac{g_\gamma}{0.36}\right)^4 \cdot \left(\frac{\rho_\mathrm{a}}{0.5\cdot 10^{-24}\ \mathrm{g/cm^3}}\right)^2\left(\frac{f_\mathrm{a}}{1\ \mathrm{GHz}}\right)^2\left(\frac{Q_\mathrm{L}}{100,000}\right)\left(\frac{100\ \mathrm{mK}}{T_n}\right)^2$$

ADMX

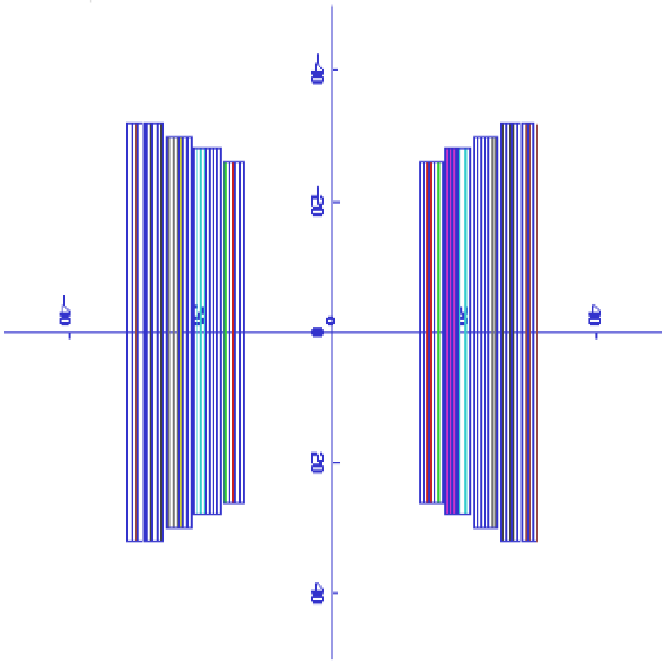
Diam	TM_{010}	B	Cavities	Total V	Tnoise	P	Time for an octive
cm	freq	T		liters	K	yW	months
ADMX magnet							
42	0.55	7.4	1	138	0.17	107	2
16	1.44	7.4	4	80	0.20	96	6

"NMR" magnet, including latest Bruker

Diam	TM010	B	Cavities	Total V	Tnoise	P	Time for an octive
cm	freq	T		liters	K	yW	months
ADMX magnet							
42	0.55	7.4	1	138	0.17	107	2
16	1.44	7.4	4	80	0.20	96	6
NMR magnet							
5.4	4.26	18	1	1.0	0.17	11	541
5.4	4.26	28	1	1.0	0.17	26	92

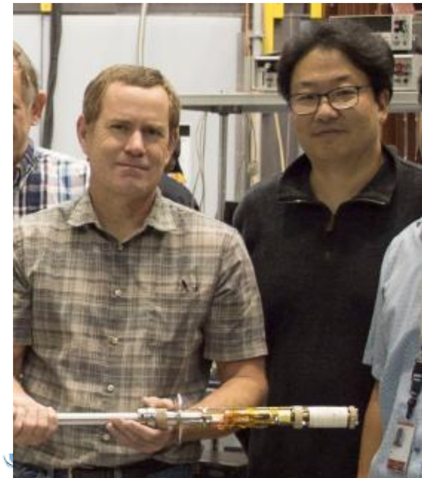
Large diameter NbTi/Nb_3Sn outsert for 32 T at NHMFL

Diam	TM010	B	Cavities	Total V	Tnoise	P	Time for an octive
cm	freq	T		liters	K	yW	months
ADMX magnet							
42	0.55	7.4	1	138	0.17	107	2
16	1.44	7.4	4	80	0.20	96	6
NMR magnet							
5.4	4.26	18	1	1.0	0.17	11	541
5.4	4.26	28	1	1.0	0.17	26	92
Outsert for NHMFL HTSC magnet (Oxford)							
25	0.92	15	1	16	0.16	52	9
9.3	2.47	15	4	9	0.22	49	32



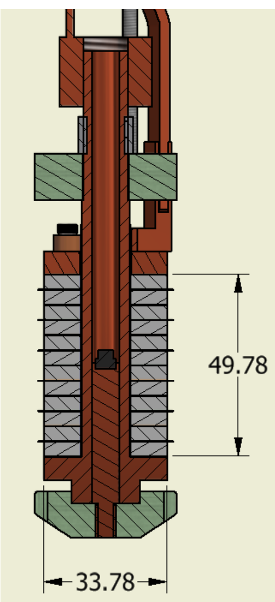
32 T, 6 inch diameter NI ReBCO design from NHMFL

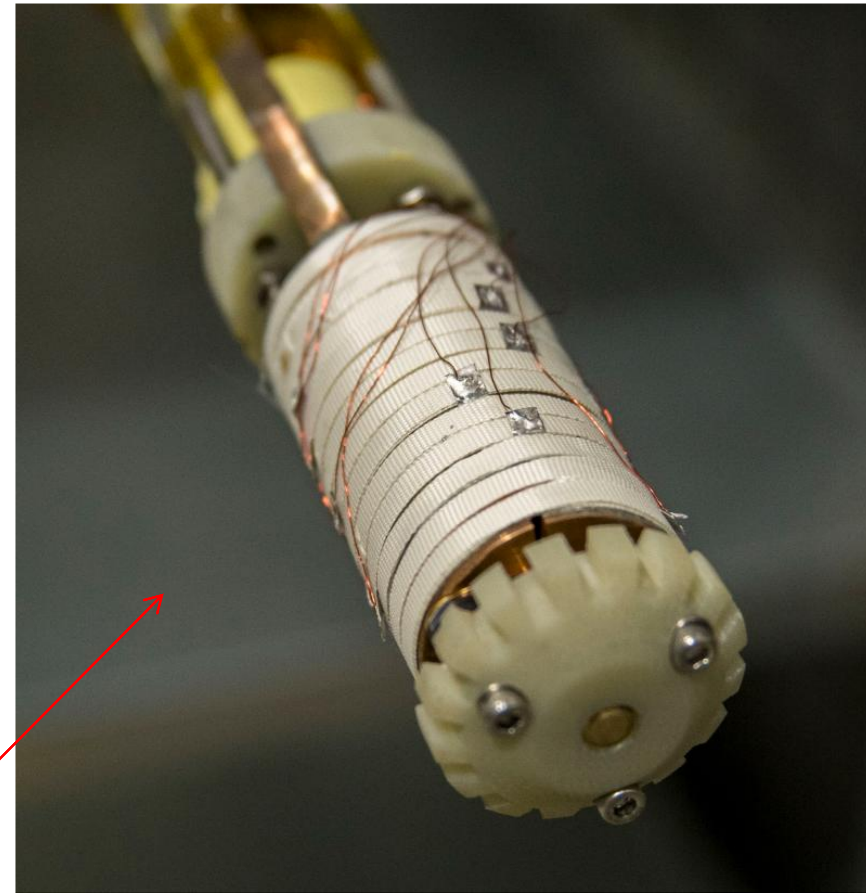
Diam cm	TM_{010} freq	B T	Cavities	Total V liters	Tnoise K	P yW	Time for an octive months
ADMX magnet							
42	0.55	7.4	1	138	0.17	107	2
16	1.44	7.4	4	80	0.20	96	6
NMR magnet							
5.4	4.26	18	1	1.0	0.17	11	541
5.4	4.26	28	1	1.0	0.17	26	92
Outsert for NHMFL HTSC magnet (Oxford)							
25	0.92	15	1	16	0.16	52	9
9.3	2.47	15	4	9	0.22	49	32
32 T NI ReBCO (Maglab)							
15	1.51	32	1	6.6	0.17	133	2
5.7	4.05	32	4	4	0.25	116	10



NHMFL No-Insulation Magnet Technology

- HTSC test magnet
  - Total central field = 42.5 T
    - No-insulation coil = 11.5 T
    - Resistive magnet = 31.0 T
  - Reached 1151 A/mm^2
  - HTS tape thickness = 42 μm (5 μm Cu on each side)

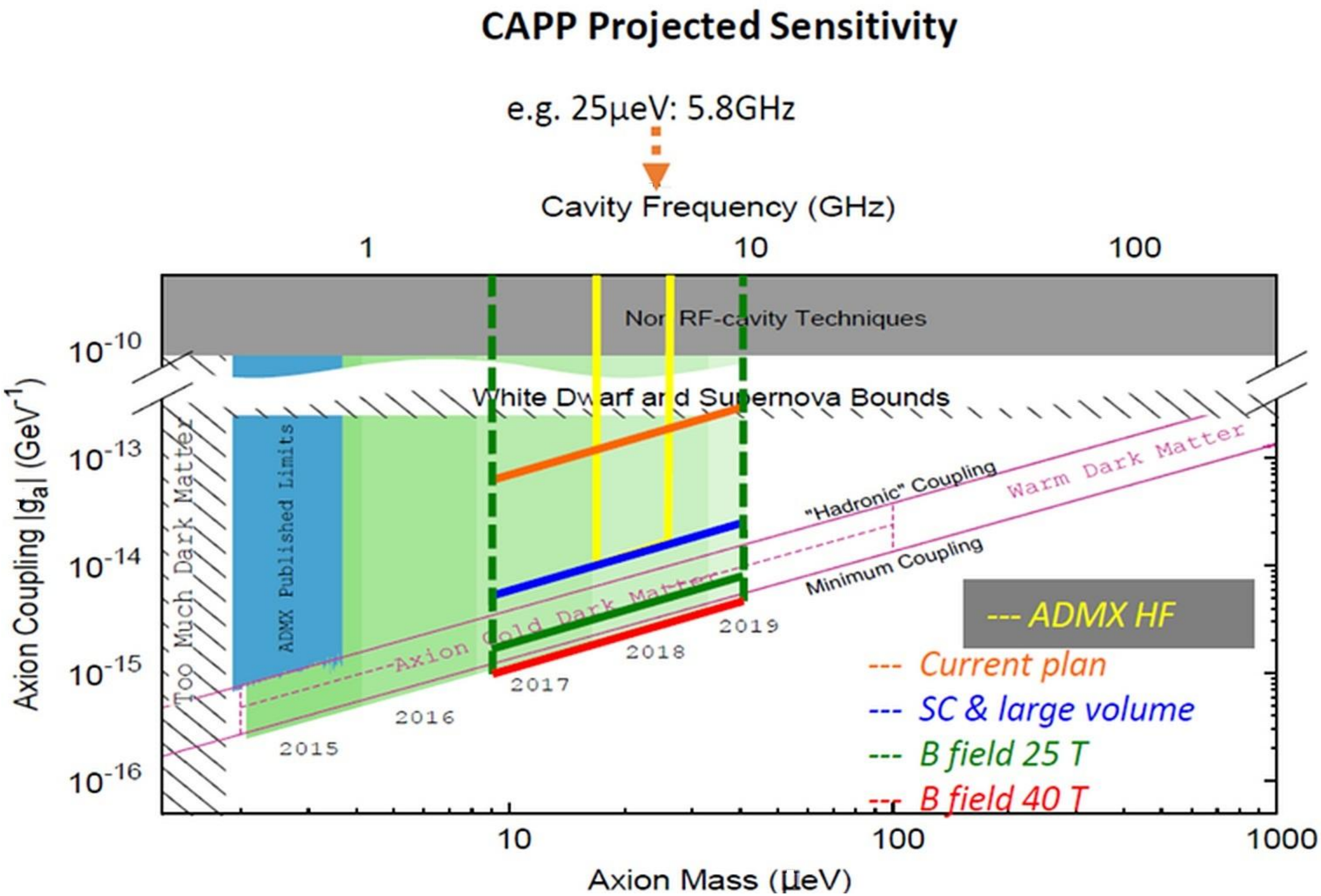




Seungyong Hahn and Ian Dixon

We are not alone in having these thoughts

Eleni Petrakou, CAPP



Conclusions

- ADMX is operating at DFSZ sensitivity

- Technology in hand to detect the axion if the mass is in the 1.2 to 8.3 meV range (mc^2/h = 0.33 to 2 GHz)

- A 32 T HTSC magnet could allow a search up to 40 μeV (10 GHz)

Conclusions

- ADMX is operating at DFSZ sensitivity
- Technology in hand to detect the axion if the mass is in the 1.2 to 8.3 meV range (mc^2/h = 0.33 to 2 GHz)
- A 32 T HTSC magnet could allow a search up to 40 μeV (10 GHz)

He who controls magnetism will control the universe

- It is an exciting time for axion researchers!

THE END