Recent Results from the Axion Dark Matter Experiment (ADMX)

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CIPANP 2018

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Peccei-Quinn solution to the Strong-CP problem

Roberto Peccei

Helen Quinn

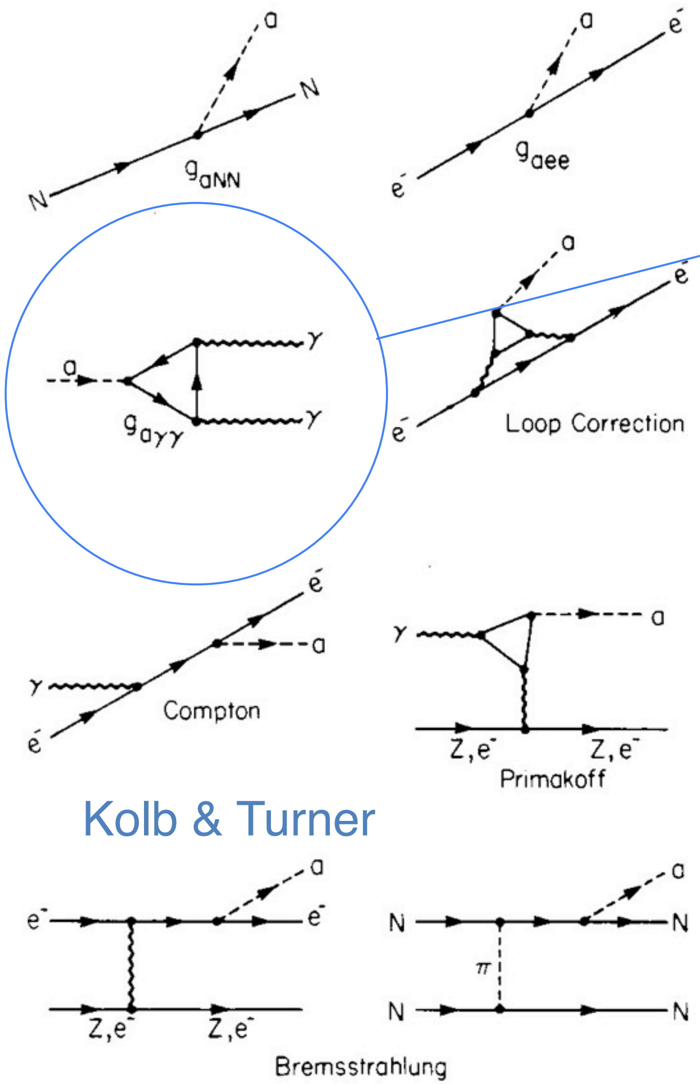
Steven Wienberg

Frank Wilczek

- Peccei & Quinn: Postulate new U(1) symmetry that would be spontaneously broken.
- Weinberg & Wilczek: A new Goldstone boson (the axion)
- Remnant axion VEV nulls QCD CP violation.
- Only free parameter: Symmetry breaking scale (f_a).
- "Invisble Axion": f_a >> Weak Scale
- Two general classes of models
  - **KSVZ** [Kim (1979), Shifman, Vainshtein, Sakharov (1980)]: "QCD axion" or "hadronic axion"
  - **DFSZ** [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

"clean up" the Strong-CP problem

Axion couplings



Kolb & Turner

General classes of couplings

Axion – Nucleon
Axion – Electron
Axion – Photon

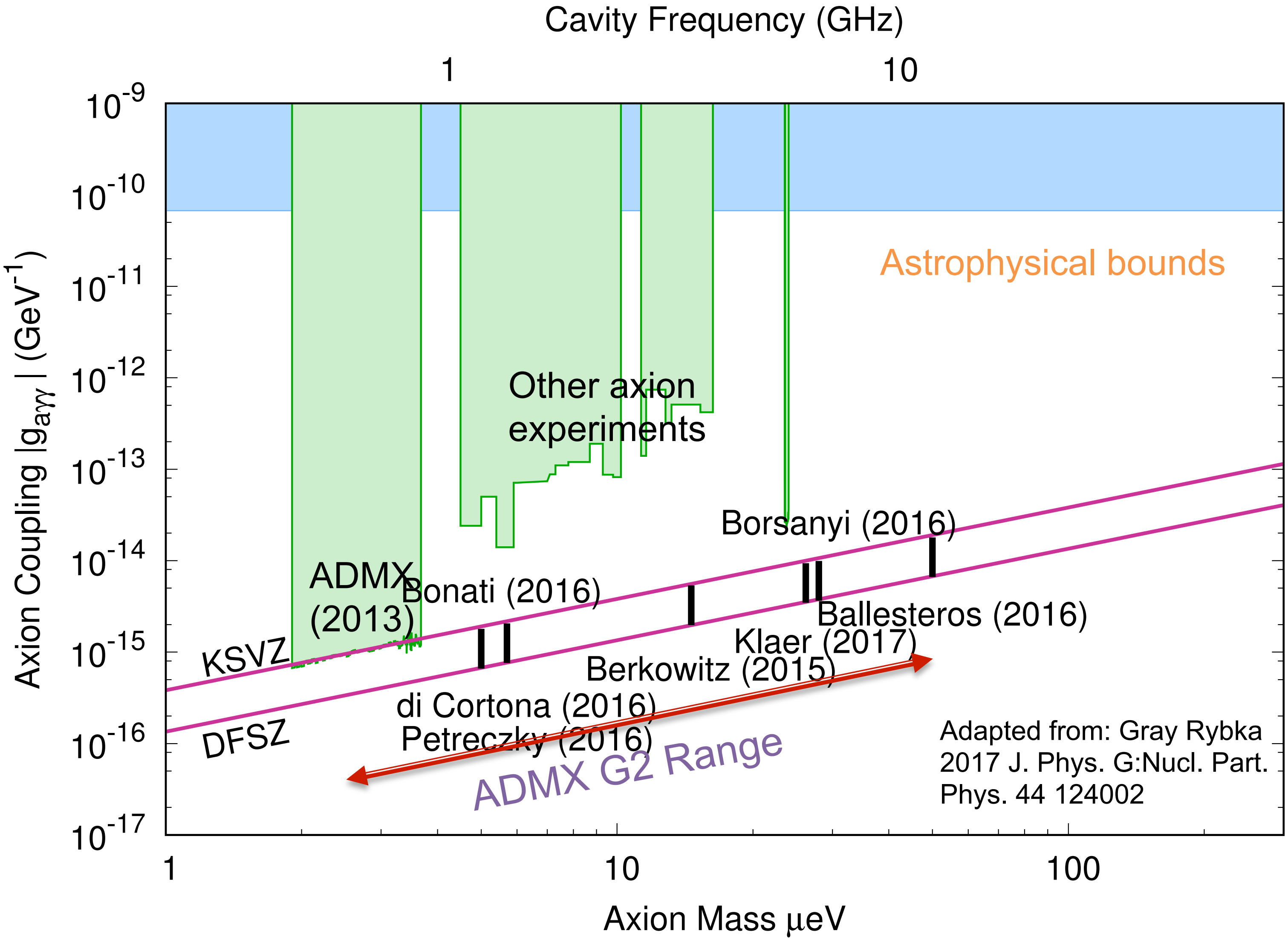
$g_{a\gamma\gamma}$ is a process with small model uncertainty
Coupling used for haloscopes

Rate depends on "unification group" (the particles in the loops), ratio of u/d quark masses. The U(1) charges at the axion vertex cancel with little model dependence

$$g_{a\gamma\gamma} \sim \frac{\alpha}{f_{PQ}}\left(\frac{E}{N} - 1.95\right)$$

Experimental Perspective on DM Axions

Analytic and Lattice QCD predictions of the axion mass, given it makes 100% Dark matter



ADMX: Collaboration

University of Washington

University of Florida

Lawrence Livermore National Laboratory

Berkeley University of California

NRAO

The University Of Sheffield.

Fermilab

Pacific Northwest National Laboratory

Washington University in St. Louis

Los Alamos National Laboratory

Sponsors

ADMX now DOE Gen 2 project

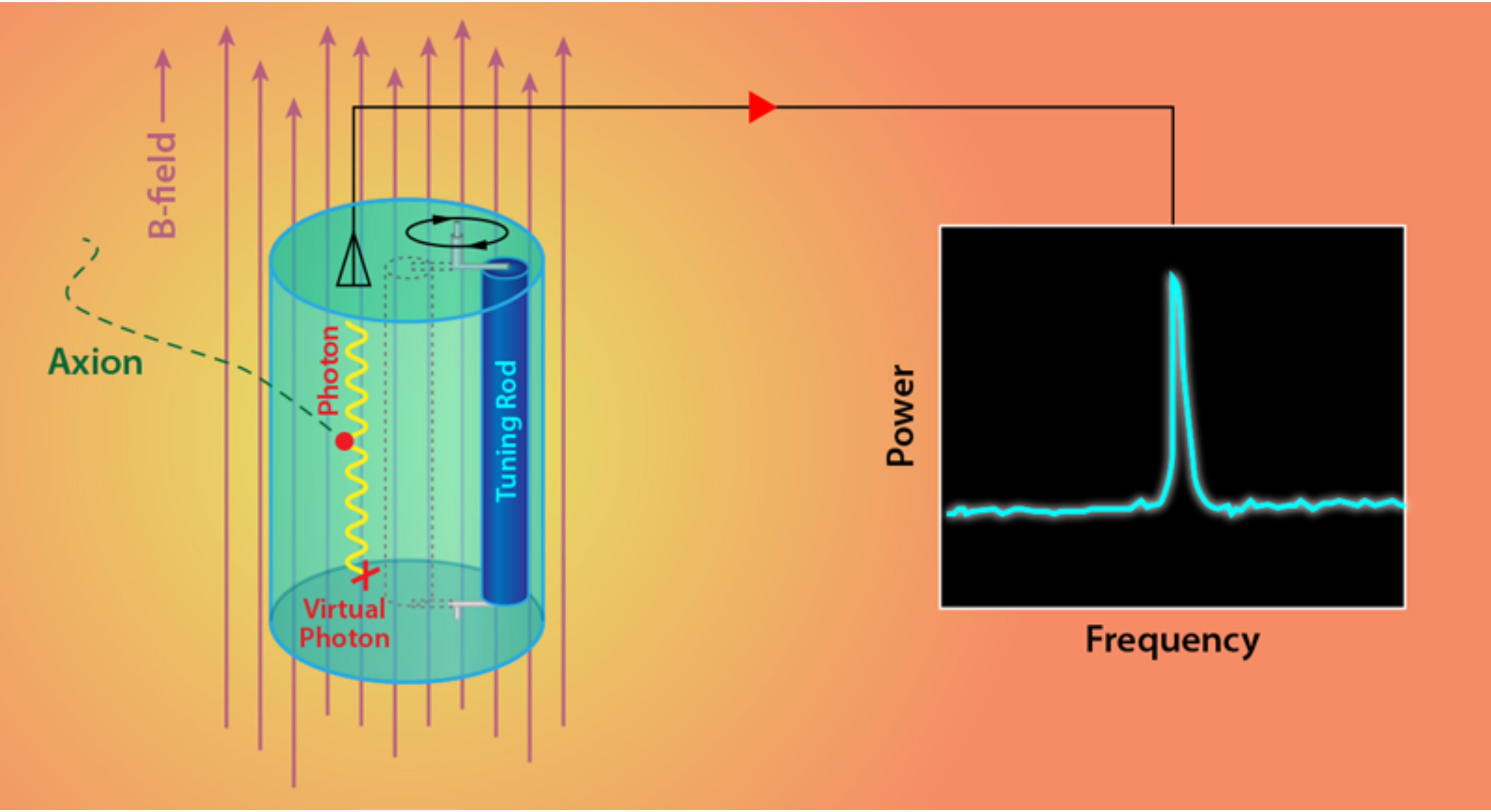
Department of Energy, United States of America · NSF

Primary sponsor

Heising - Simons Foundation

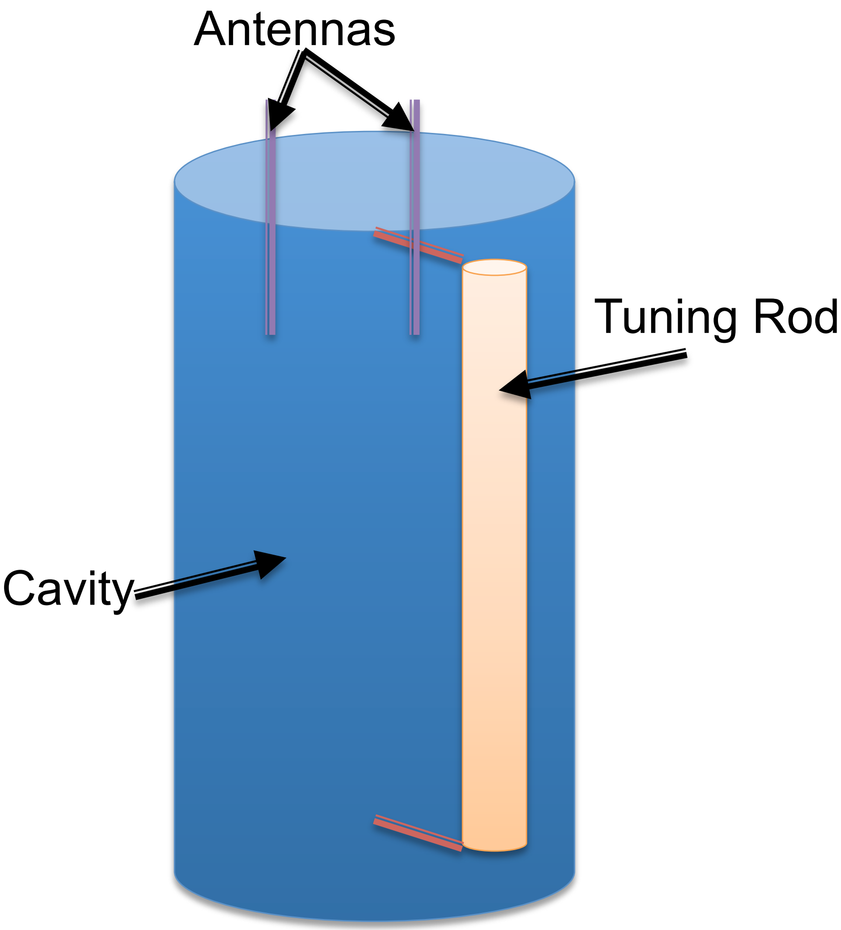
R&D support

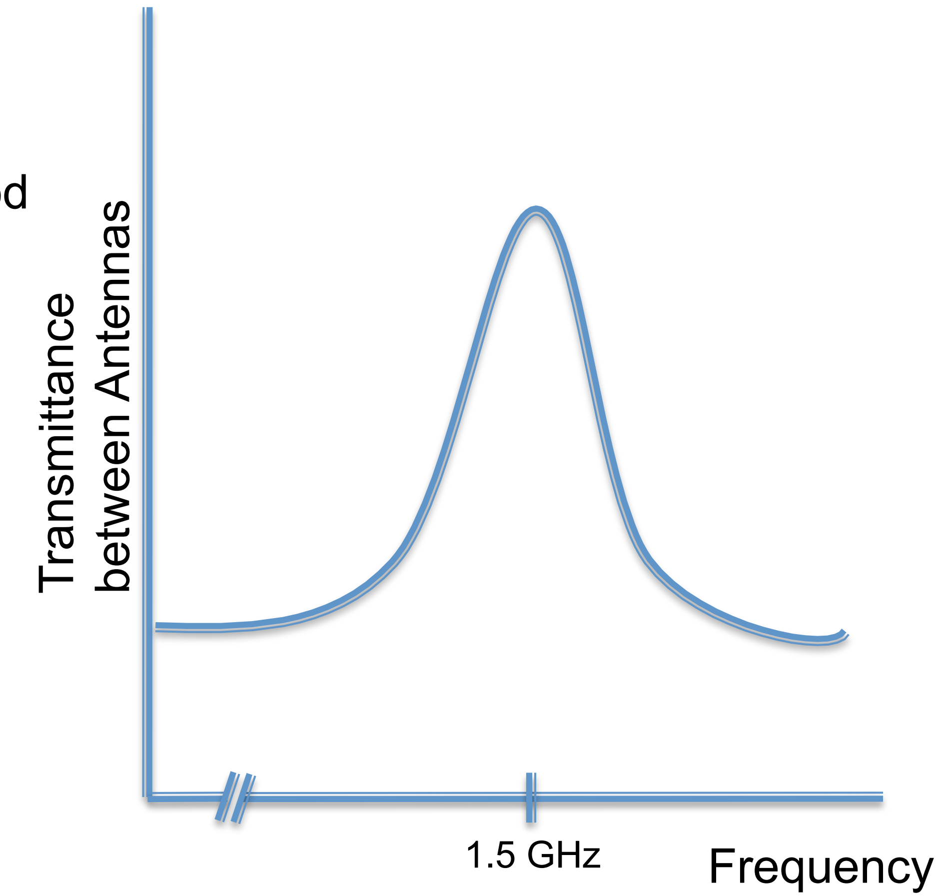
The ADMX experimental layout



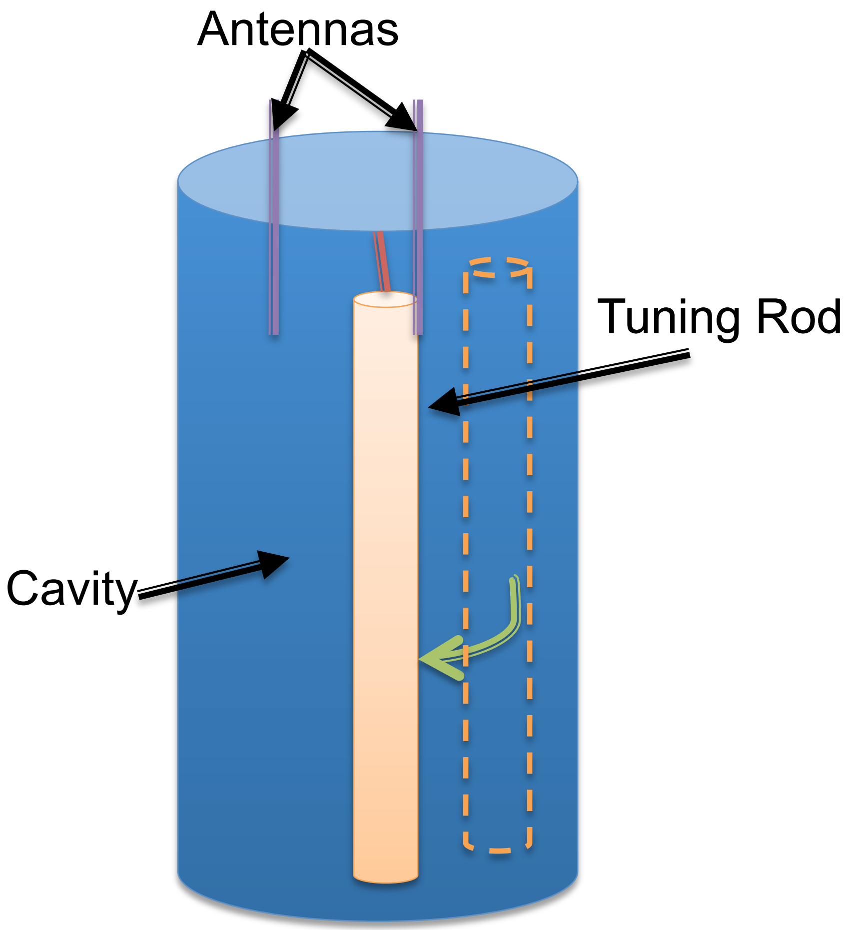
*Frank T. Avignone III **"Viewpoint: Homing in on Axions?"** April 9th 2018 APS article
Image credit: C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker

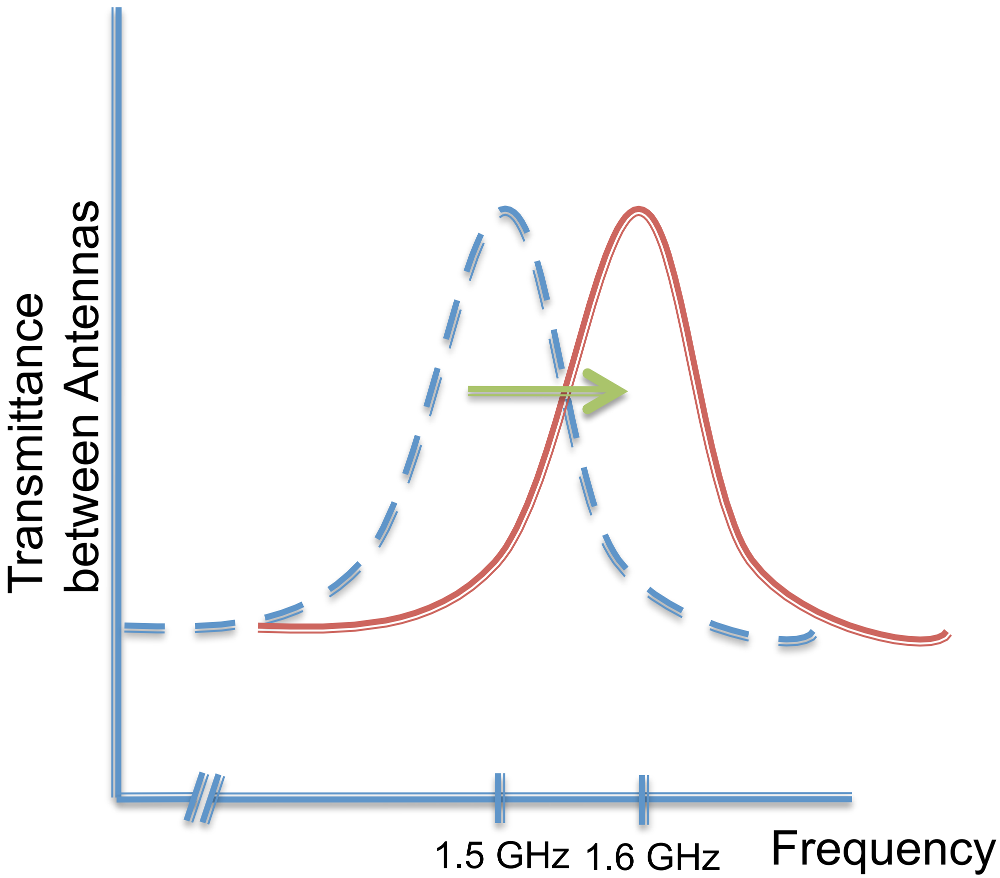
Microwave Cavity needs tunable resonance



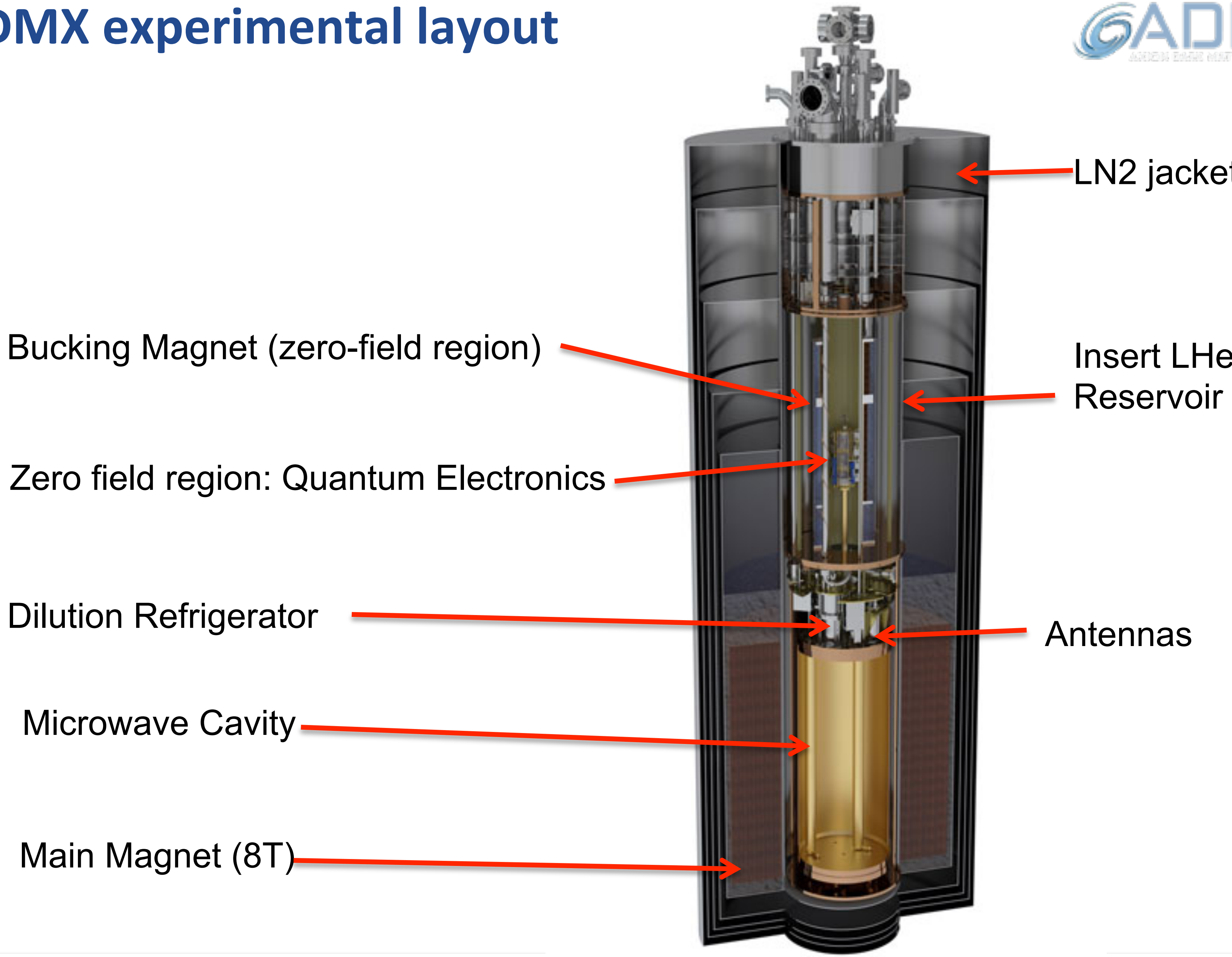


Microwave Cavity needs tunable resonance





ADMX experimental layout



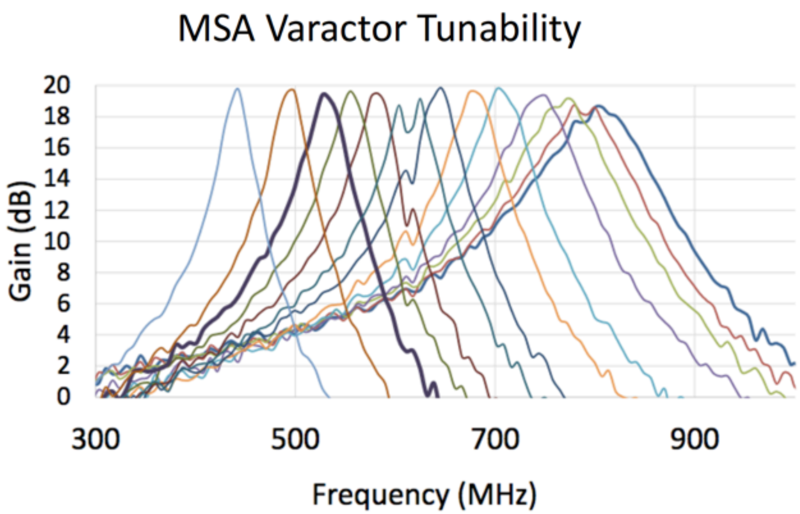
Scan Rate from Dicke Radiometer equation

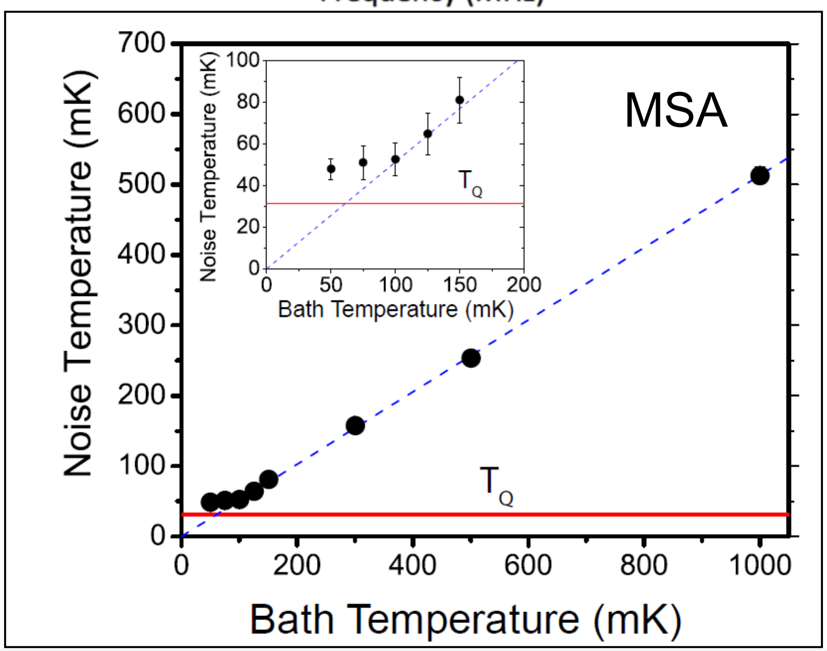
- Rate determined from SNR

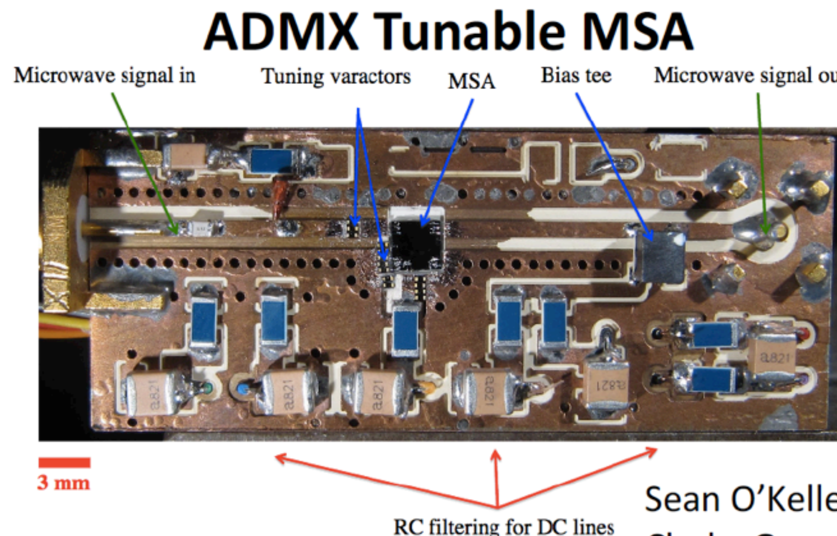
$$\frac{df}{dt} \approx 750\ MHz/year \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{5}{SNR}\right)^2 \left(\frac{f}{1\ GHz}\right)^2 \cdot$$
$$\left(\frac{B_0}{8\ T}\right)^4 \left(\frac{V}{100l}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

- *SNR* is the Signal-to-Noise for detection (usually set to 5),
- *f* is the frequency being searched (where 1 GHz ~ m_a = 4.1 ueV)
- T_{sys} is the total system temperature ($T_{sys} = T_{cavity} + T_{amps}$)
- To scan at this sensitivity would take > 100 years with original ADMX

Quantum-limited amplifiers







Sean O'Kelley, Clarke Group, UC Berkeley

< 1 GHz

Yanjie Qiu, Siddiqi Group, UC Berkeley

> 1 GHz

Receiver Chain: MSA

Injection of swept power & fake axions

Reflection to look at antenna coupling

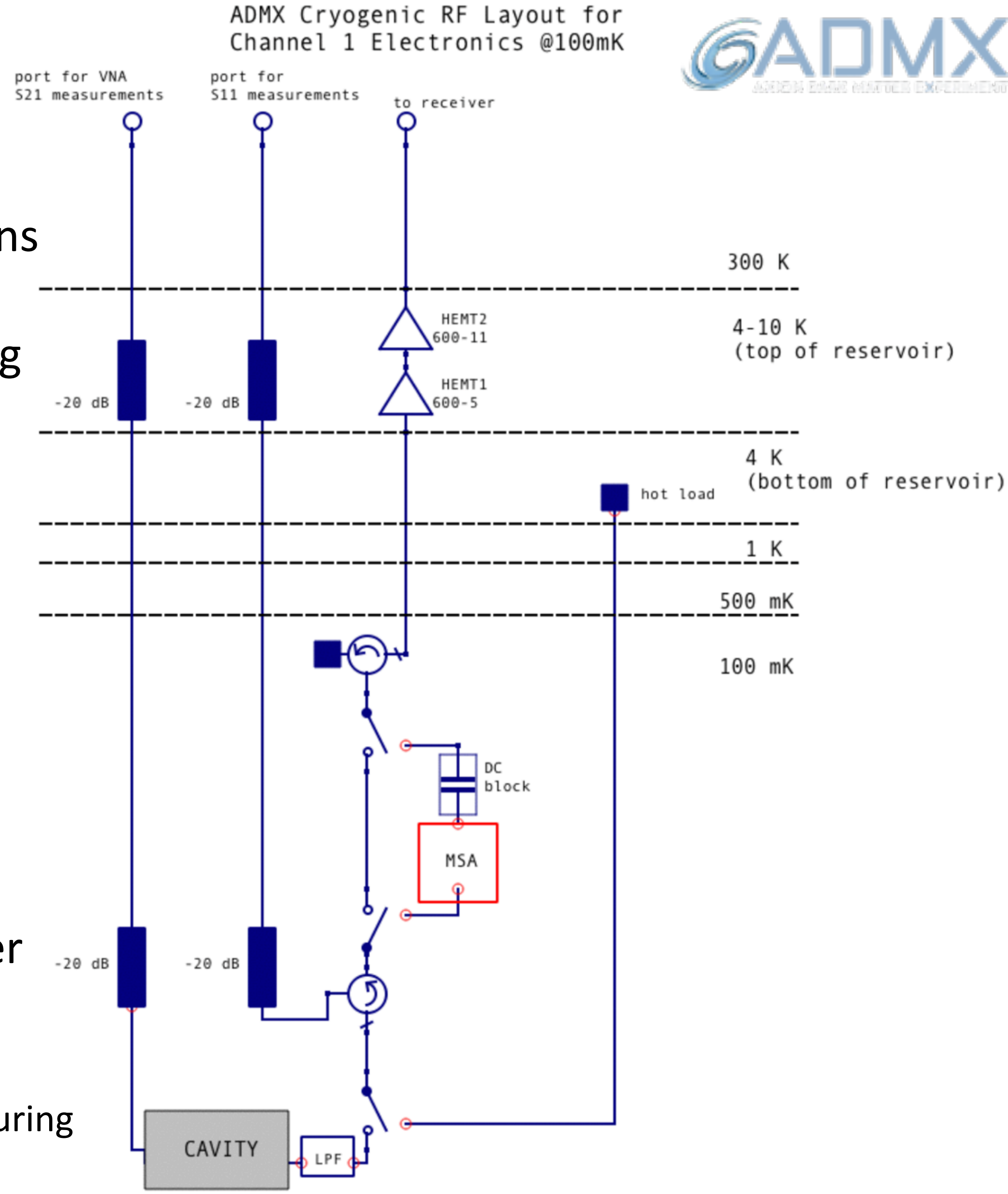
Hot / Cold load:
Measure system noise temperature⁺

SQUID at $T_{physical}$ ~ 300 mK
Cavity at $T_{physical}$ ~ 150 mK

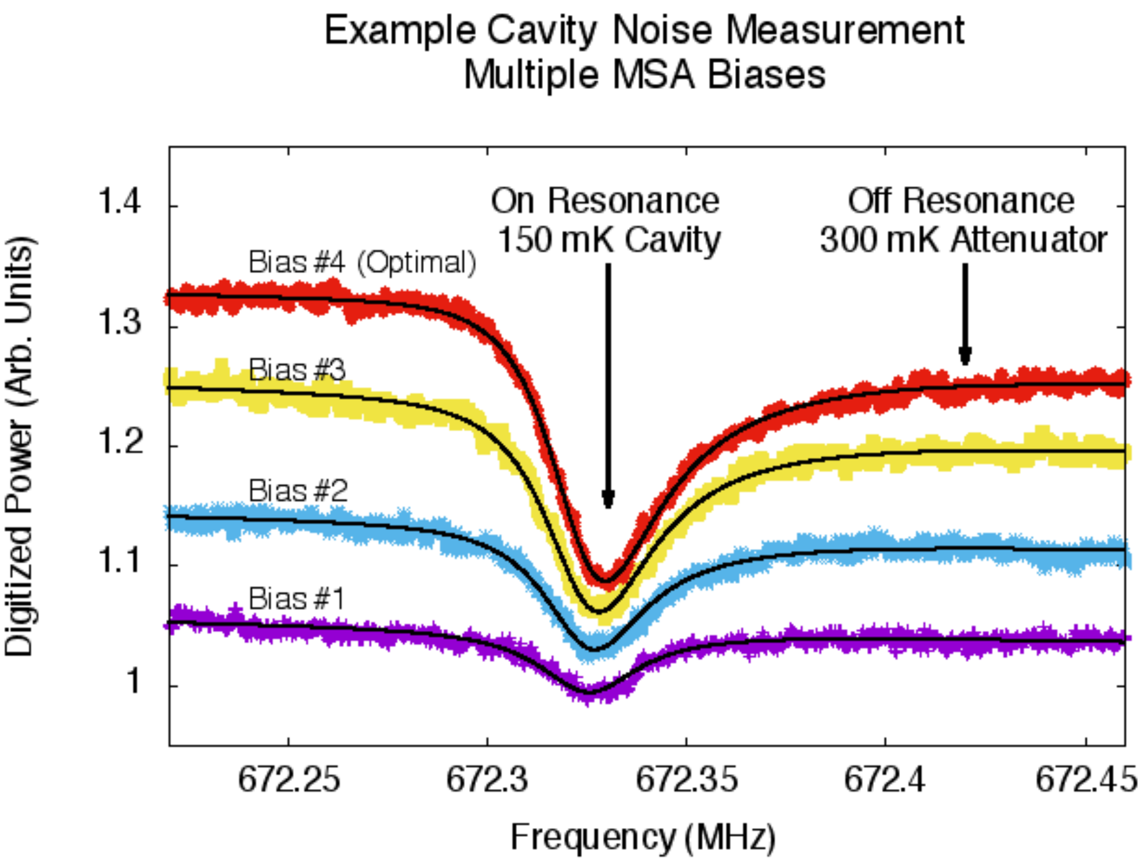
Total system noise ~ 0.5 K*

*includes attenuation + post-amplifier contributions.

⁺The Hot/Cold load system wasn't operated during the recent data run due to an internal RF disconnect. Fixed for the current operations



ADMX G2 low noise temperature



System noise temperature calibrated from difference in power between 150 mK cavity and 300 mK attenuator.

A later system noise at optimal MSA gain is around 300 mK, early noise (shown) around 500 mK.

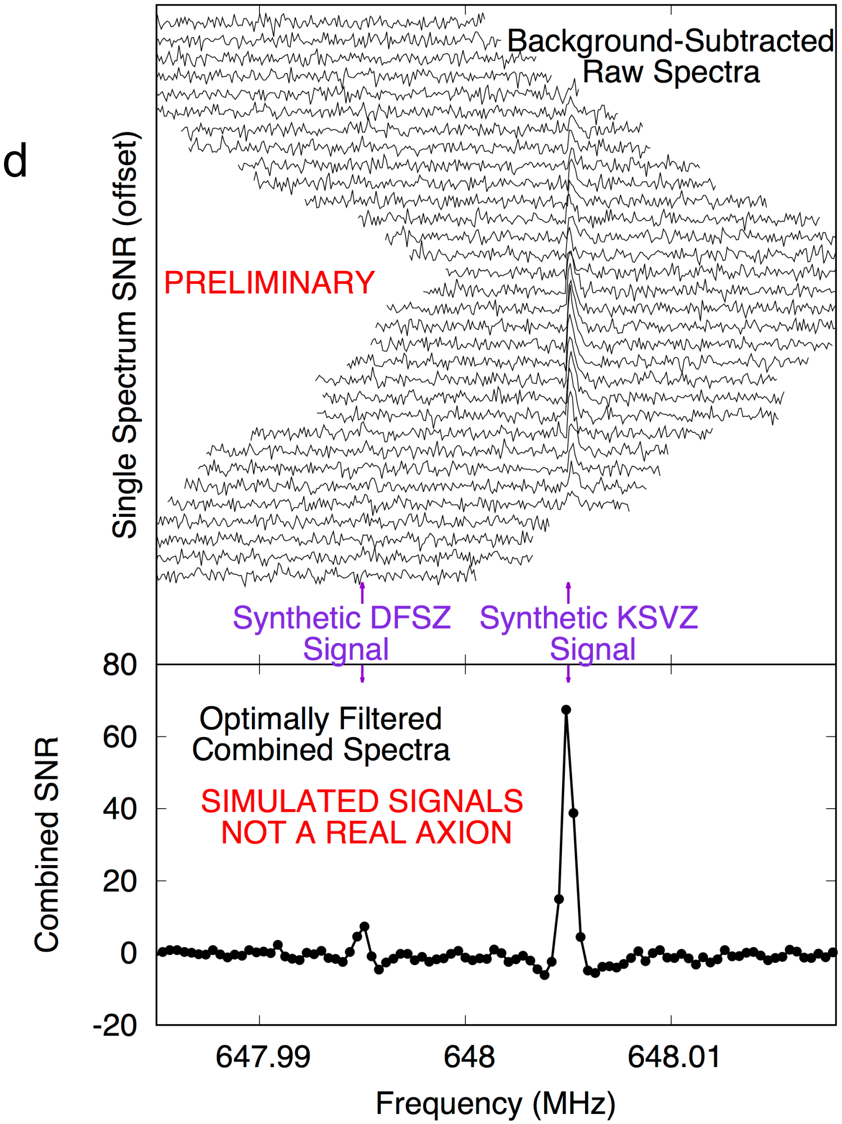
Cold RF model (black line) reproduces receiver response.

ADMX operations

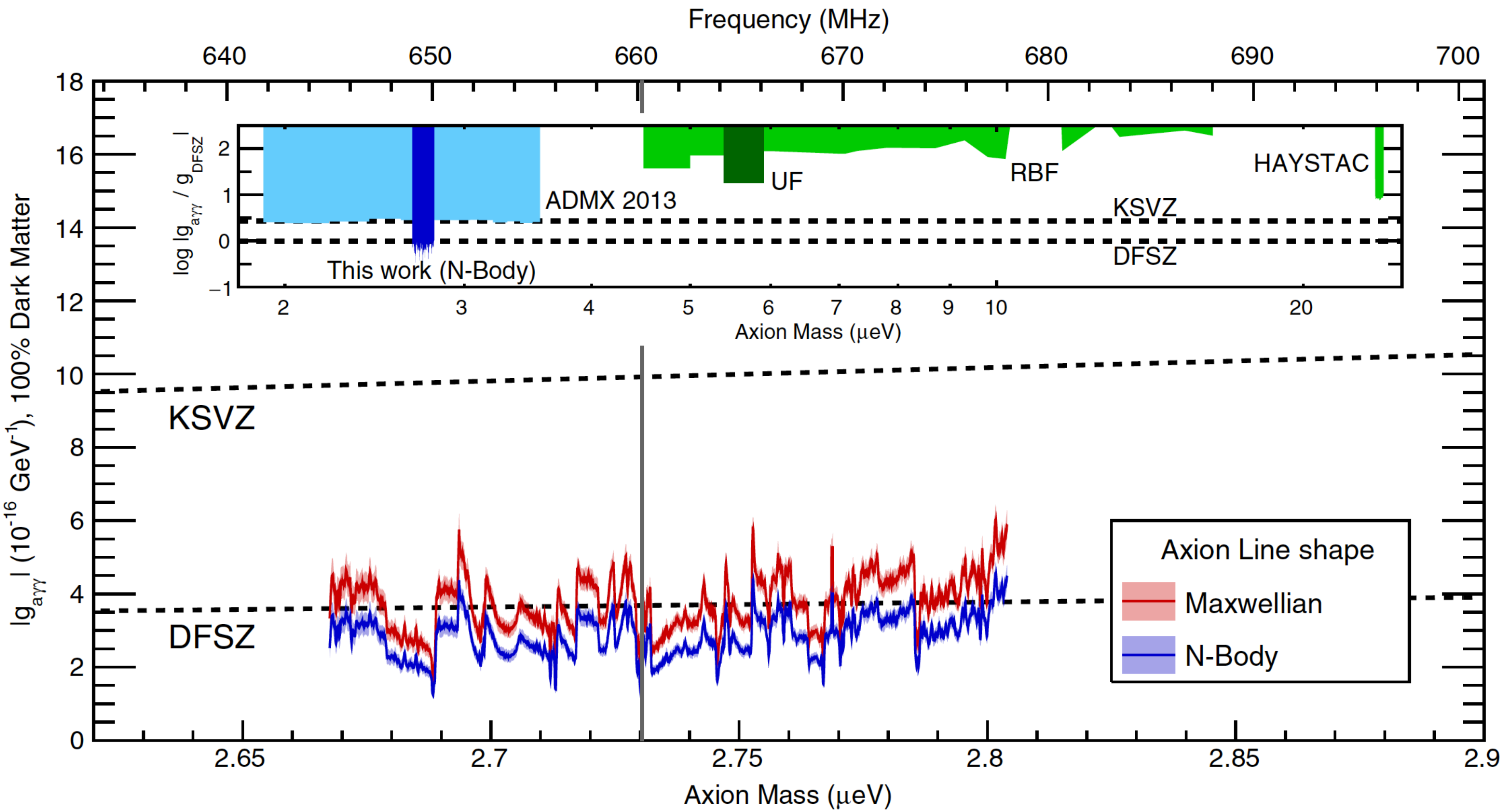
1. Cavity frequency scanned until a desired signal-to-noise level is reached.
2. Regions with power above trigger threshold are flagged as potential candidates
   a. Statistical anomalies, external RF leakage, synthetic injected axions, or AXIONS
3. Rescan candidates; do they persist.
4. If they persist they are transferred to the detection committee
   a. Several immediate checks…
   b. Switch to resonant mode that doesn't couple to axions (TEM mode).
   c. Turn B-Field down (power as B^2).

Further Offline Analysis

- Vary the bin size from time-series data.
- High Res analysis for ultra-sharp lines.



First data at DFSZ sensitivity!



Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment

PHYSICAL REVIEW LETTERS **120,** 151301 (2018)

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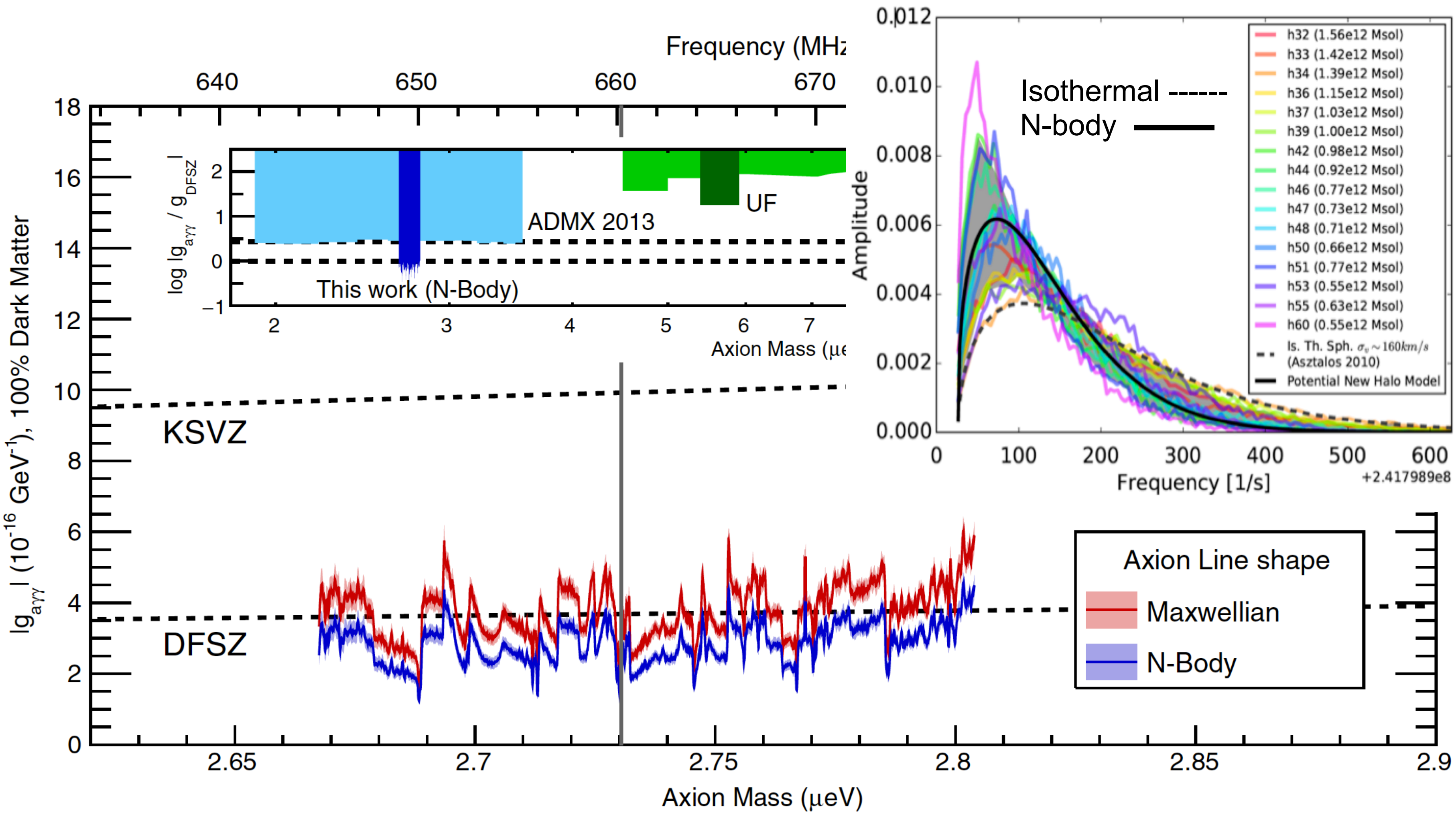

Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment

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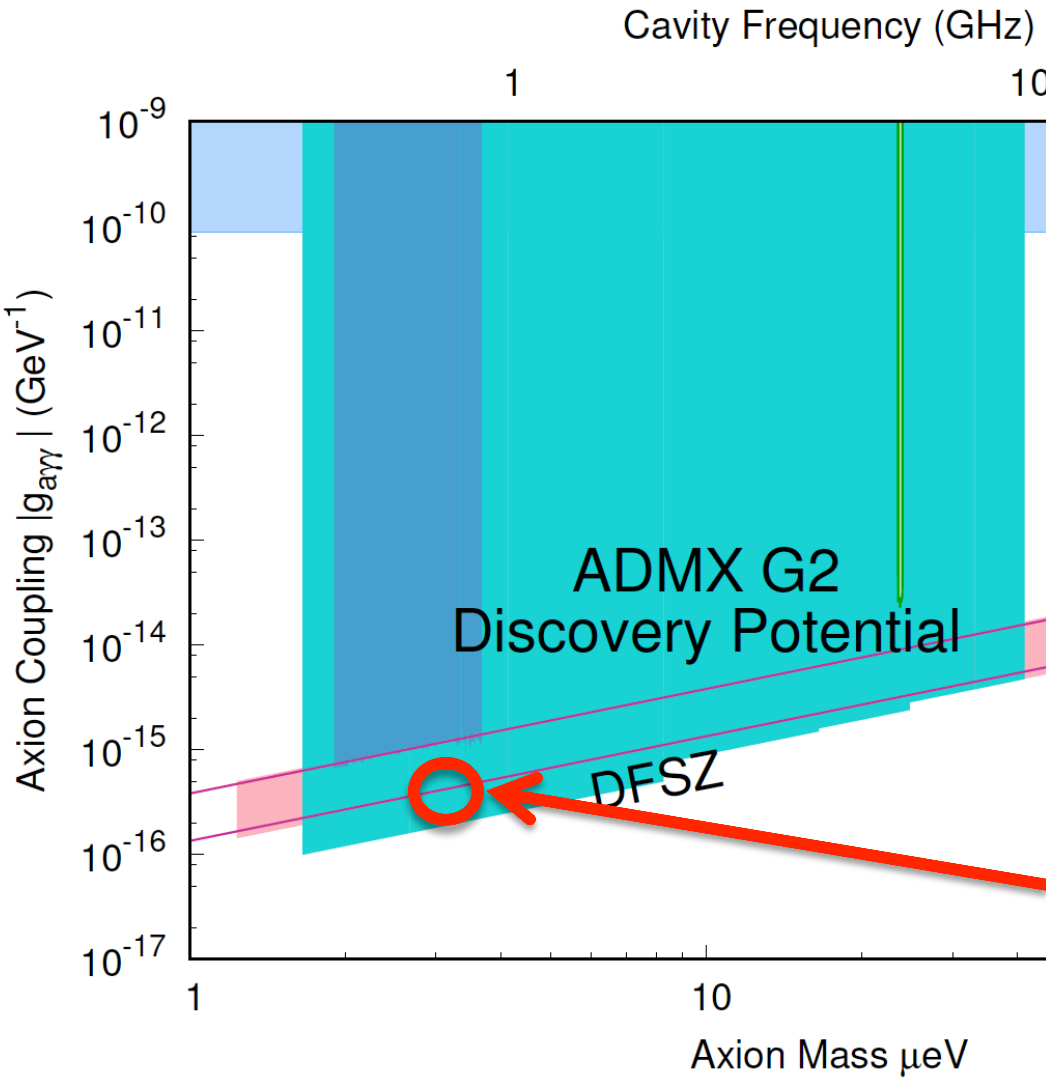
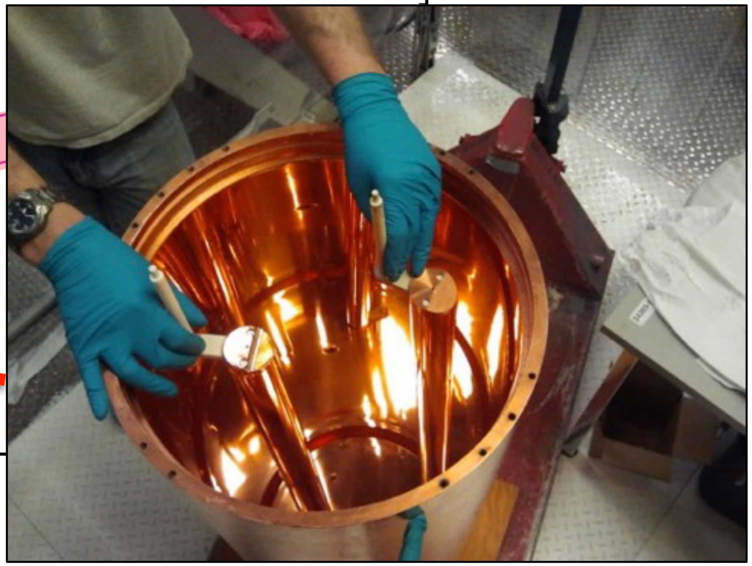
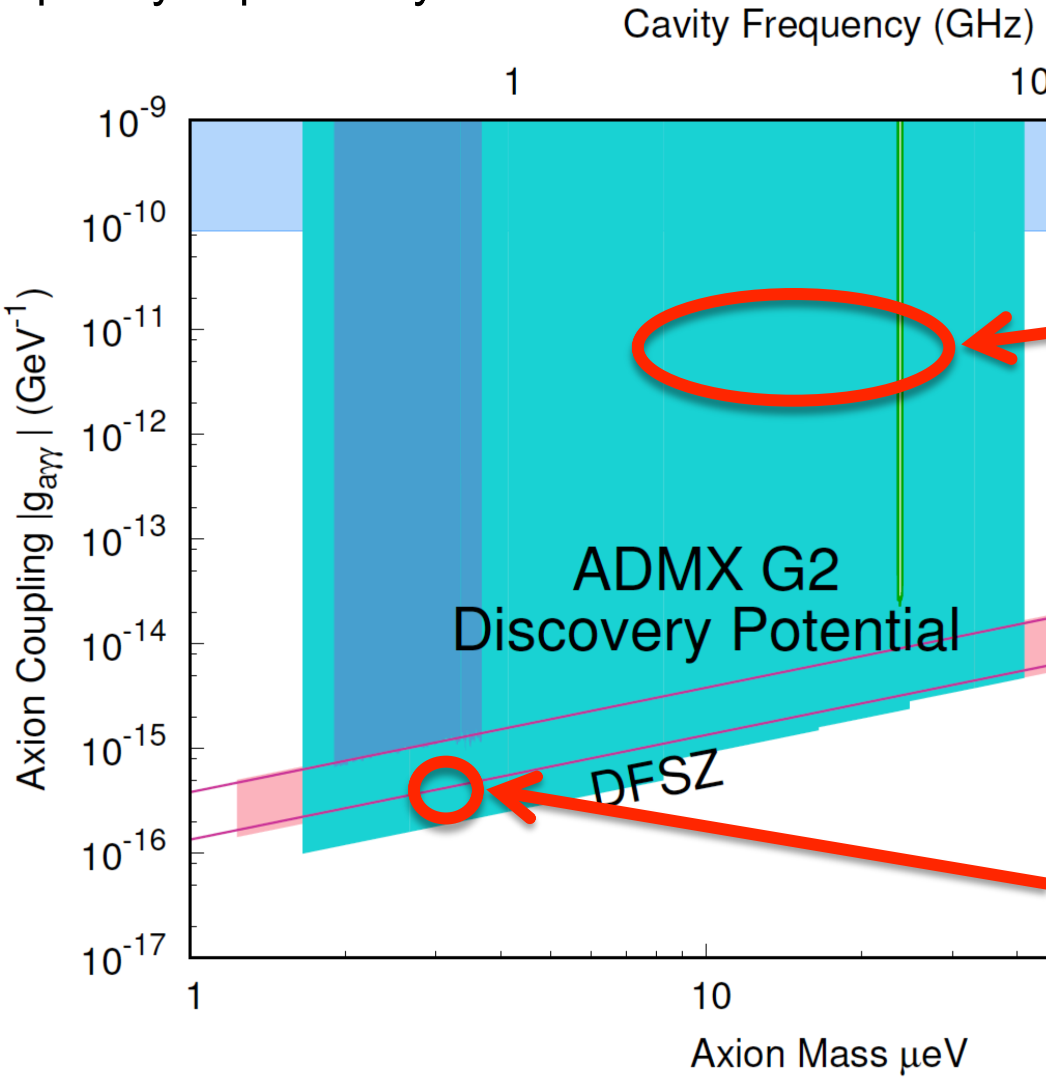
ADMX Main Cavity: Initial run 0.65-0.88 GHz



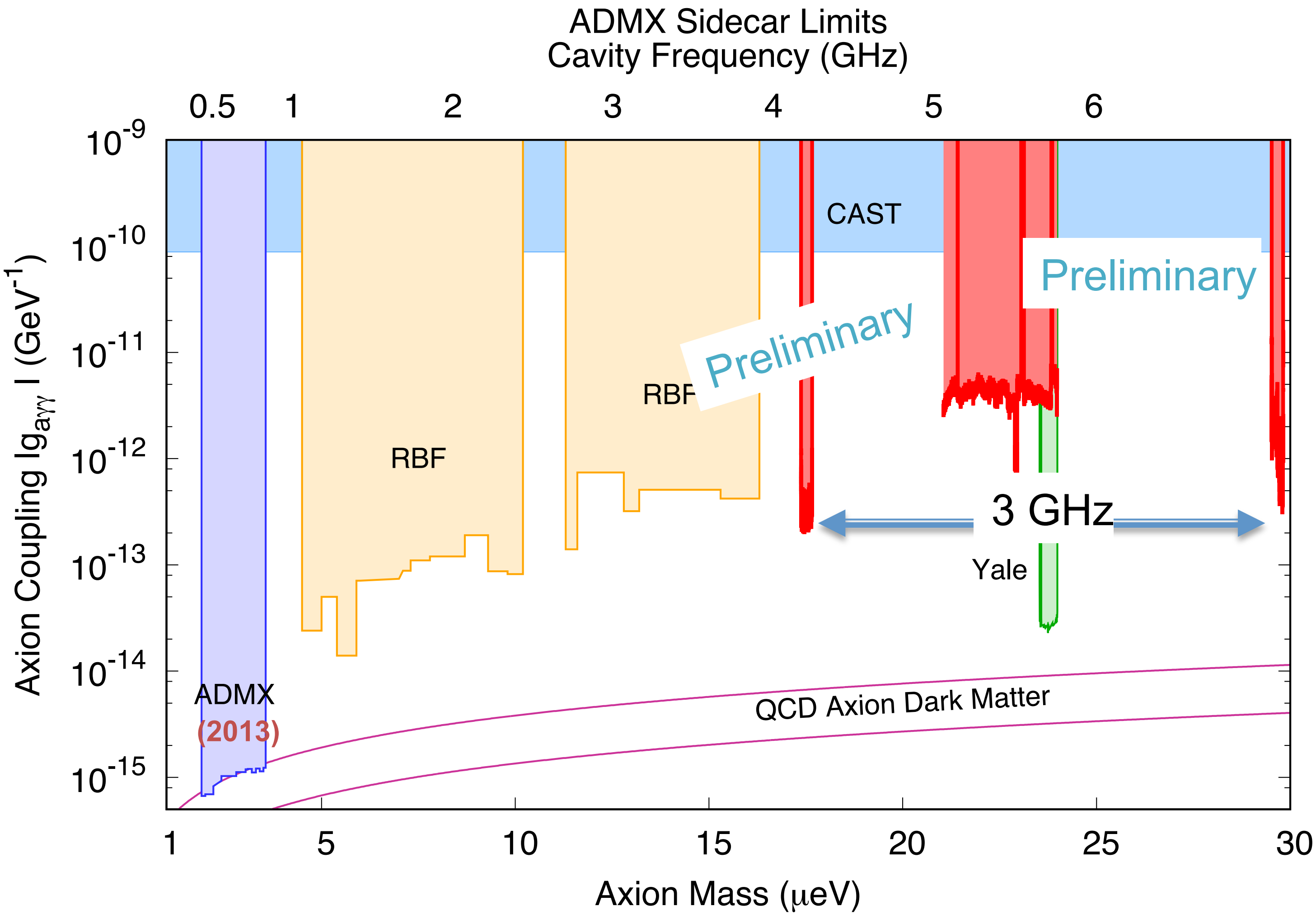


ADMX Sidecar Cavity
4-6 GHz TM_{010} & 6-7 GHz TM_{020}

Completely separate system installed above main cavity



Preliminary ADMX Sidecar Sensitivity Estimate (data from 2016-2017)



ADMX Gen 2 – Run 1B

- **Main ADMX cavity is currently scanning up from 680→890 MHz**

- Using two separate channels operated in series ("SQUIDADEL")

Ch 1: JPA (680 – 800 MHz)

Ch 2: MSA (800 – 890 MHz)

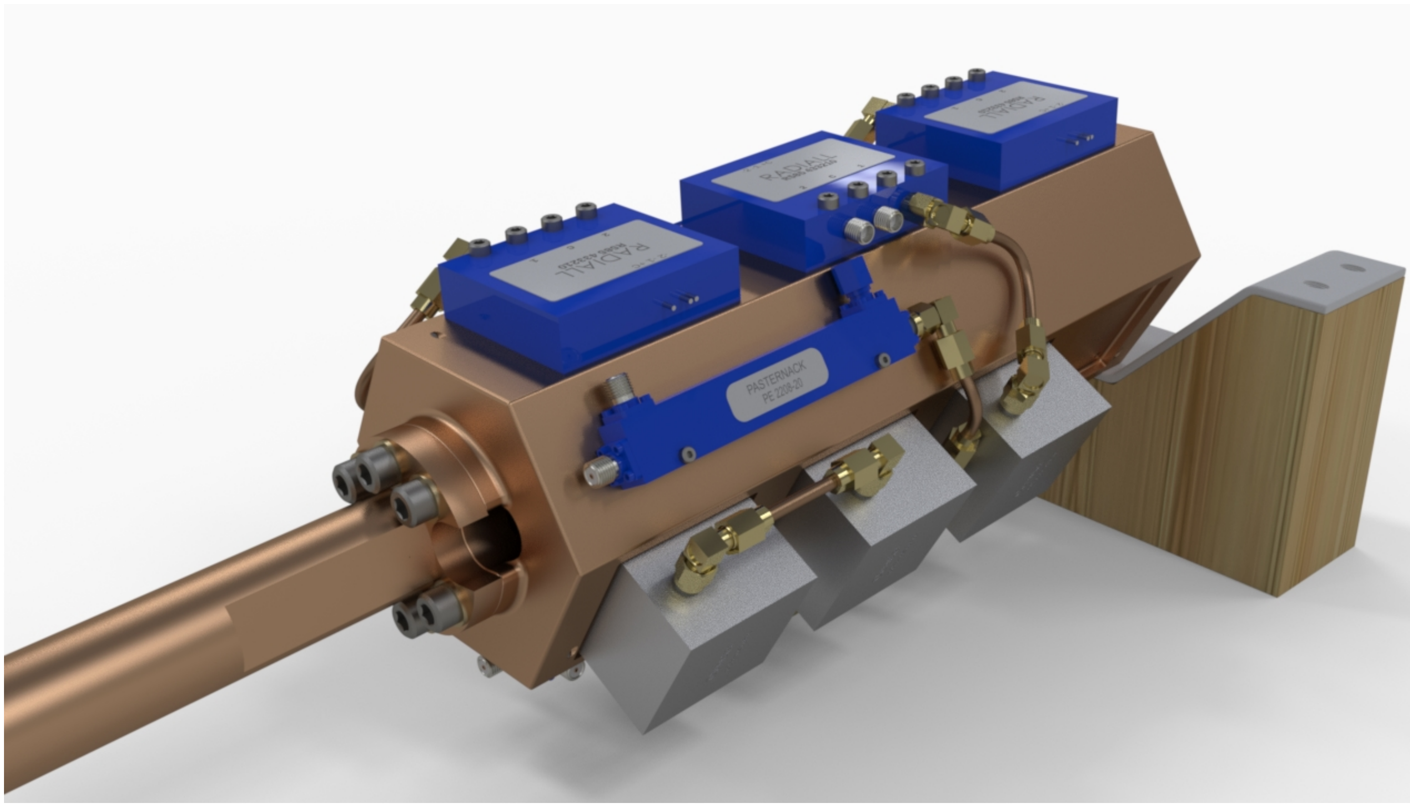
Faster frequency coverage due to:

- **Higher magnetic field (now operating at 7.6 T)**
- **Lower temperatures (dilution refrigerator < 100 mk)**
- **Less time required for engineering studies**

SQUIDADEL for run 1C (800 MHz and up)

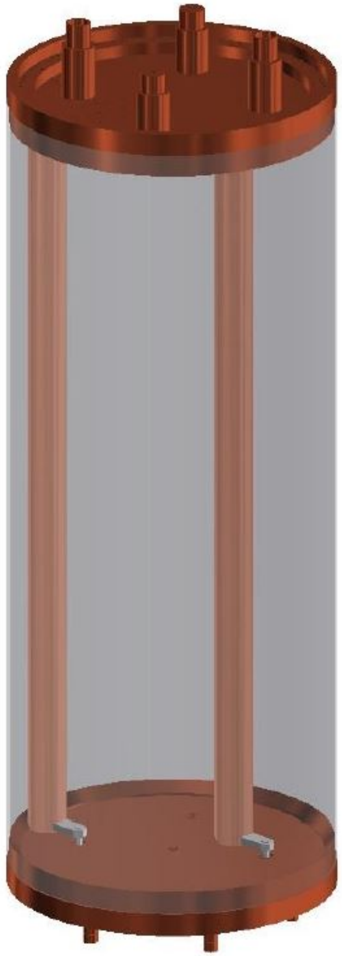
<u>Will contain 3 quantum amplifiers</u>

- 2 JPAs with complimentary frequency bands for the main cavity
- 1 broadband Traveling Wave Parametric Amp on the Sidecar

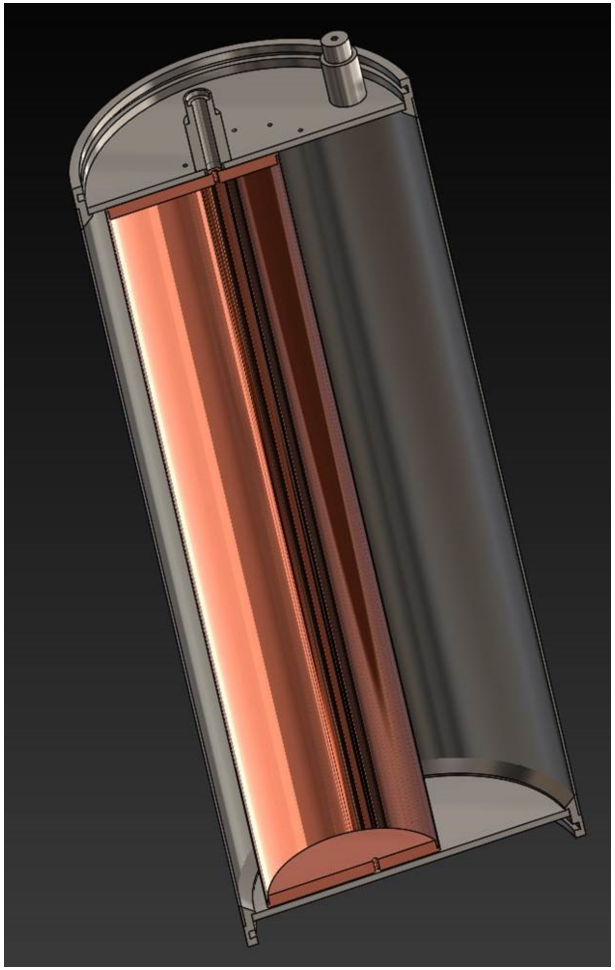


Anticipate installing this fall after run 1b frequency range explored

ADMX Gen 2: 0.65 – 2 GHz: 3 classes of cavities



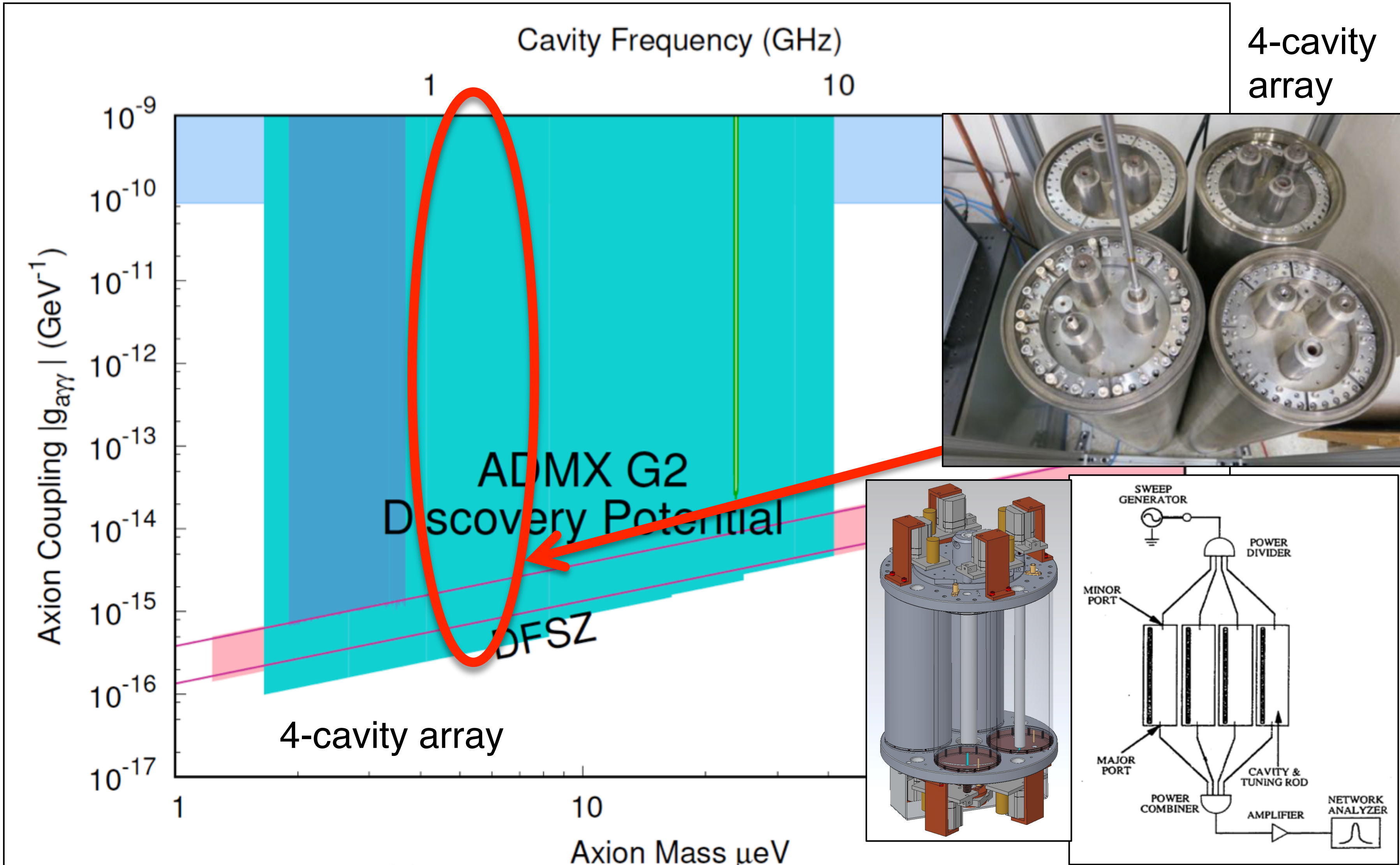
Cavity from run 1a & 1b
Two 2” diameter tuning rods
580 – 890 MHz



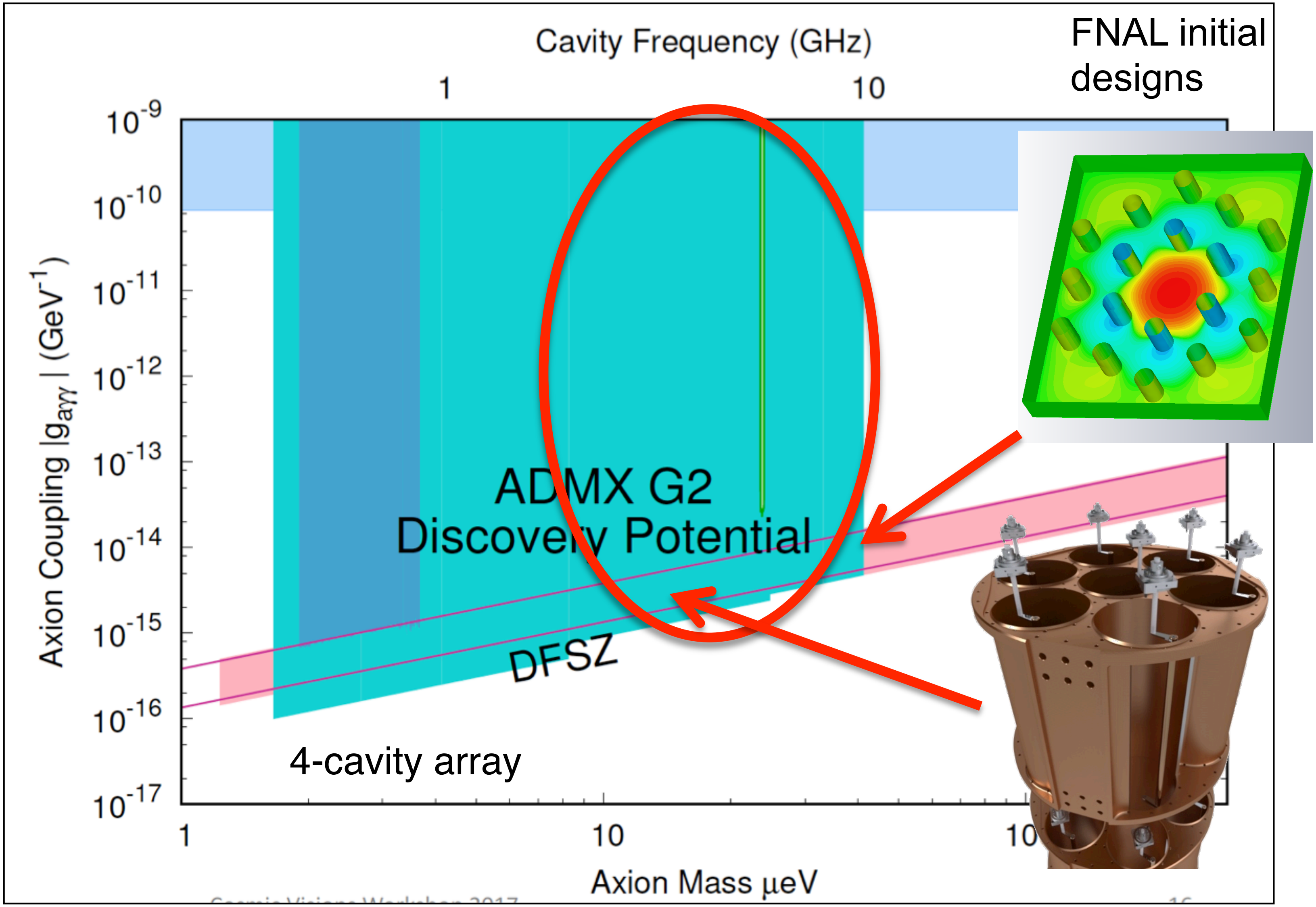
Cavity from run 1c & 1d
One 9” diameter tuning rods
880 – 1500 MHz

Cavity from run 2a
One 9” diameter tuning rods
880 – 1500 MHz

ADMX Science Prospects (1-2 GHz)



ADMX Science Prospects (2+ GHz)



Linear amps subject to the Standard Quantum Limit

$$T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h\nu$$

ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

The SQL can be evaded by:

- Squeezed-vacuum state receiver (e.g., LIGO)
  - HAYSTAC planning to implement (see Karl van Bibber's talk)
  - Single-photon detectors (e.g. qubits, bolometers)
  - ADMX investigating at FNAL & LLNL

- S.K. Lamoreaux et al. (PhysRevD.88.035020)

Farther-out G2 ADMX program:
Studying a transition on the way to 40 μeV/c2 with new magnet

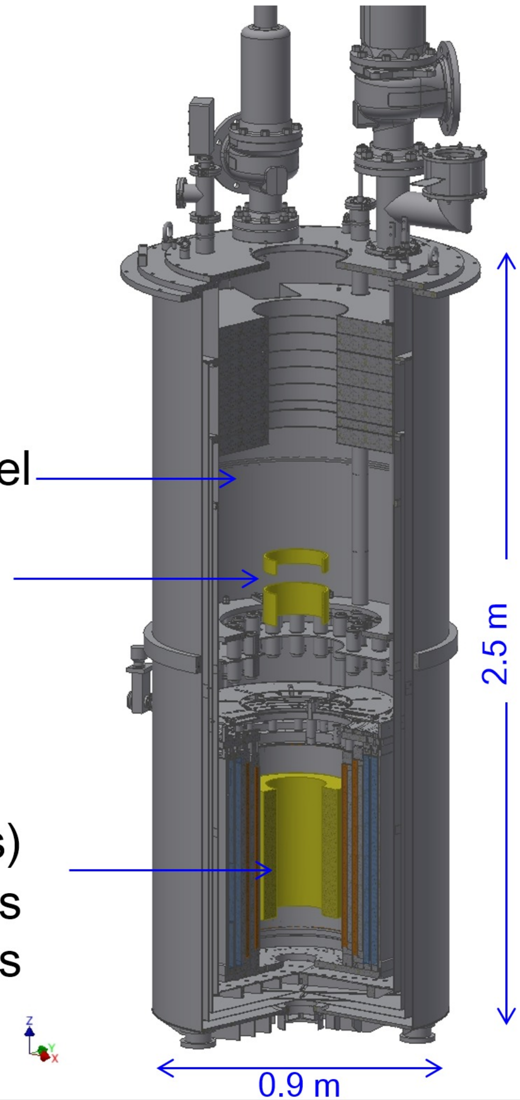
The axion signal power goes as **V^2B^4**.

High-field (32 tesla), smaller diameter.
DFSZ sensitivity at high mass with
many fewer parallel cavities, so much lower risk.

Design study in progress (UF and FSU Magnet Lab)
funded by Heising-Simons Foundation.

Lower cavity cost and risk, but magnet
procurement cost \$5-10M.

In the tradeoffs of complexity, risk and cost, this
may be very attractive. Under study.



Summary

Axions: solve the Strong-CP problem and are a compelling DM candidate

Haloscopes such as ADMX have sensitivity to DM axions:

ADMX Gen 2: **First experiment to reach sensitivity to DFSZ axions!**

Anticipate continuous data taking up to 10 GHz

ADMX uses near-quantum limited amplifiers based on Josephson Junctions

- **Microstrip SQUID Amplifiers (MSA): Prof. John Clarke's group**
- **Josephson Parametric Amplifiers (JPA): Prof. Irfan Siddiqi's group**

Cavity systems in development to cover full frequency range.

Can speed up search with new magnet and by going beyond standard quantum limit

- **squeezing, single photon counting**

Discovery can come at any time!

Supported by DOE Grants DOE grant DE-SC00098000, DOE grant DE-SC0011665, DE-AC52-07NA27344, DE-AC03-76SF00098, the Heising-Simons Foundation, and the Lawrence Livermore National Laboratory, Fermilab and Pacific Northwest National Laboratory LDRD programs. SQUID development was supported by DOE grant DE-AC02-05CH11231.

Questions?

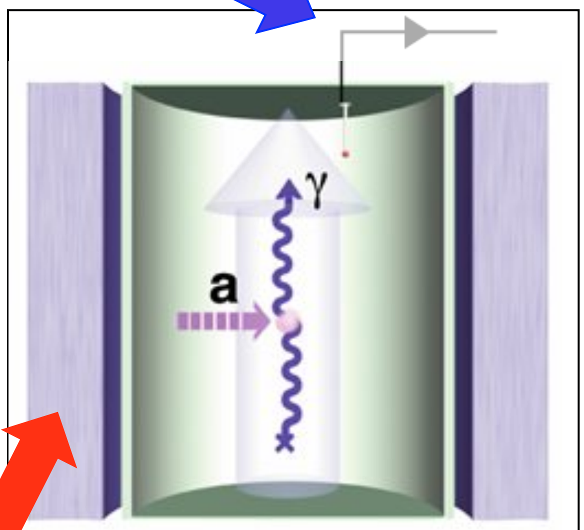
BACKUP SLIDES

The Radiometer equation dictates strategy

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

Integration time limited to ~ 100 sec

** Dicke, 1946*



System noise temp.

$$T_S = T_{phys} + T_N$$

T_{Quant} ~ 48 mK @ 1 GHz

Gen2: Dilution Fridge + Quantum-limited amps

$$P_{sig} \sim (B^2 V\, Q_{cav} C_{010})(g^2 m_a r_a)$$

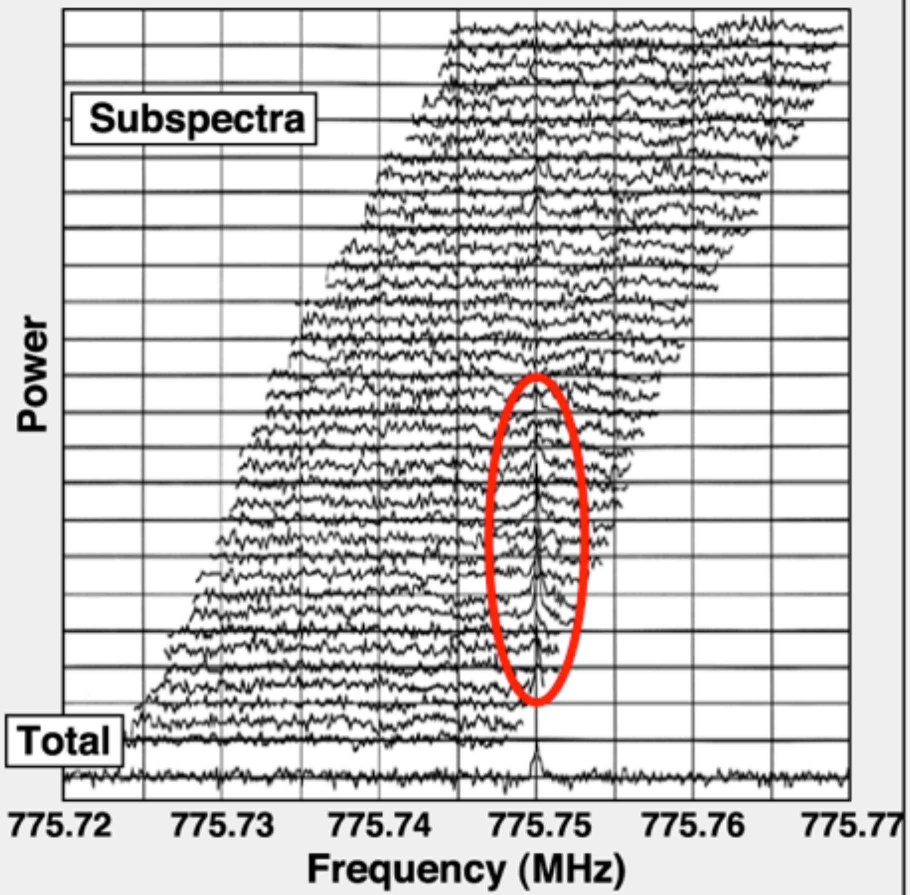
~ 10^{-23} Watts for ADMX

Magnet size, strength B^2V ~ \$

Sample data and candidates

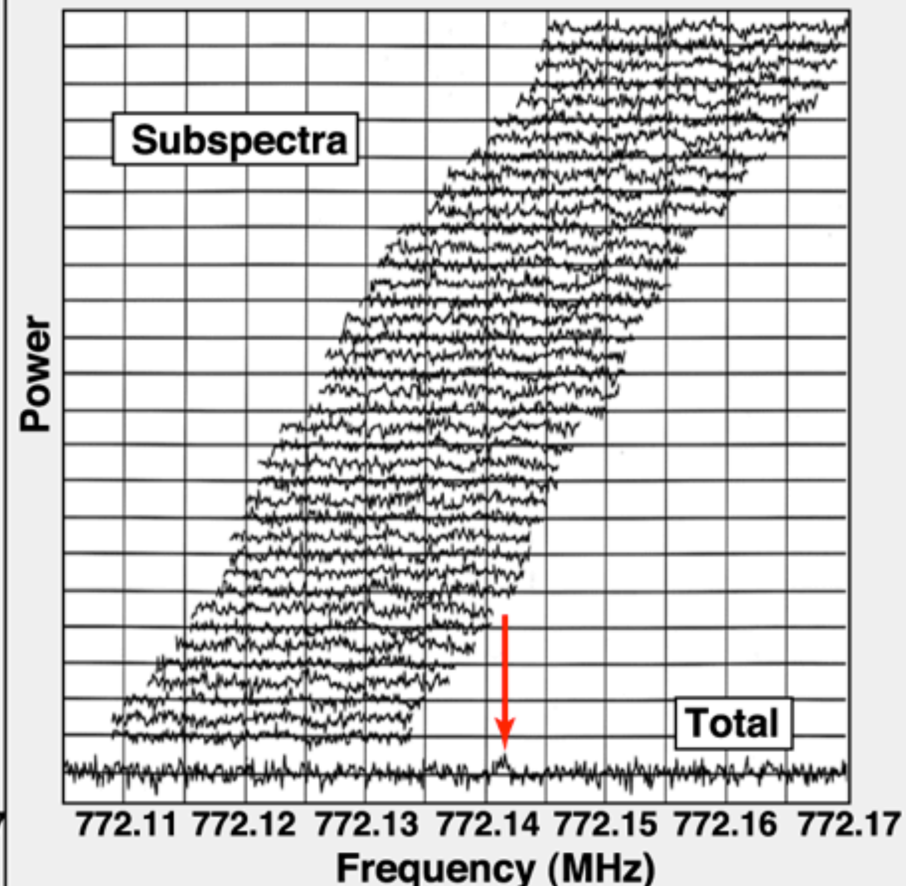
ADMX

Environmental



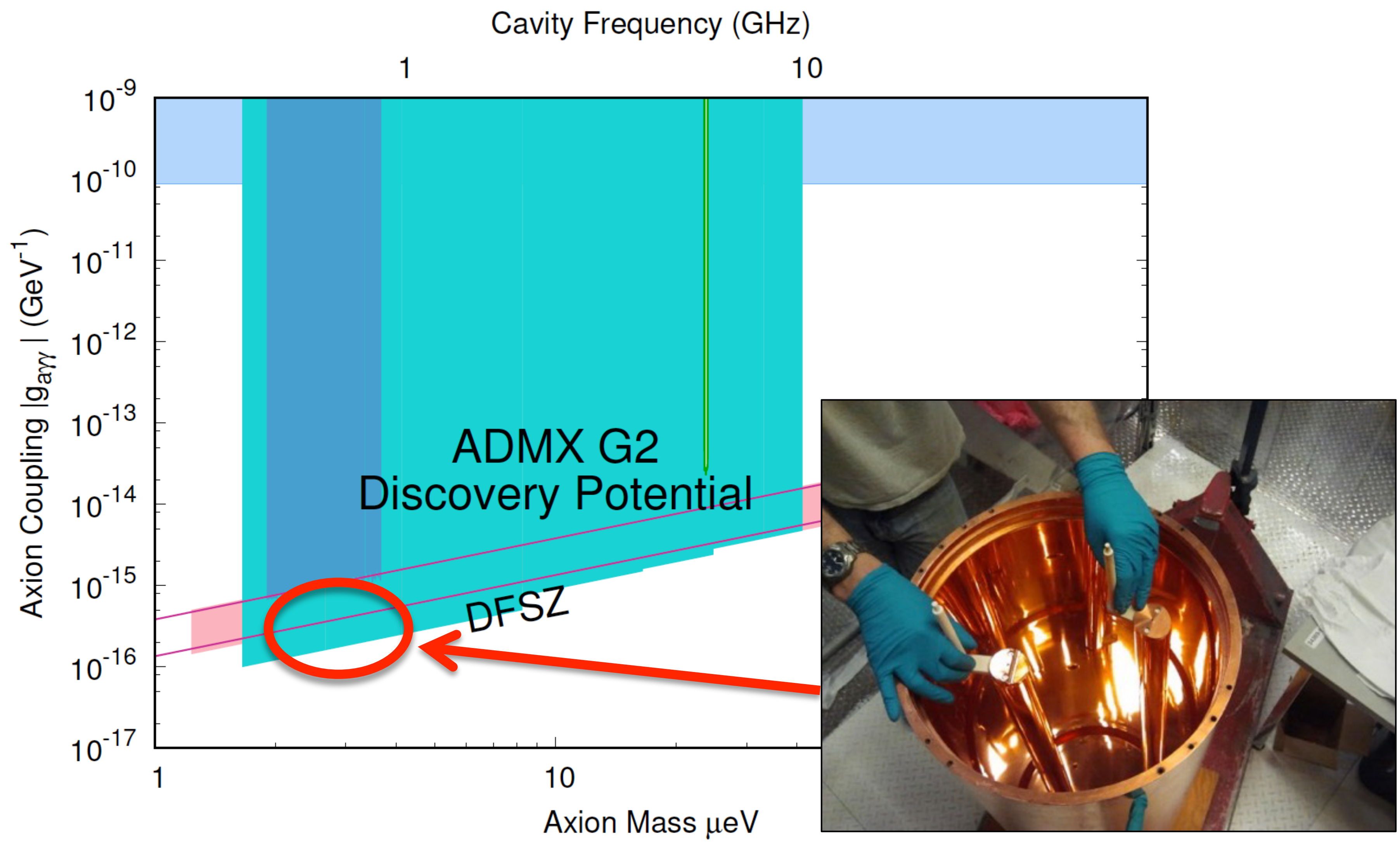
Signal maximizes off-resonance: Radio peak

Statistical



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

ADMX Main Cavity: Near term 0.65-1 GHz



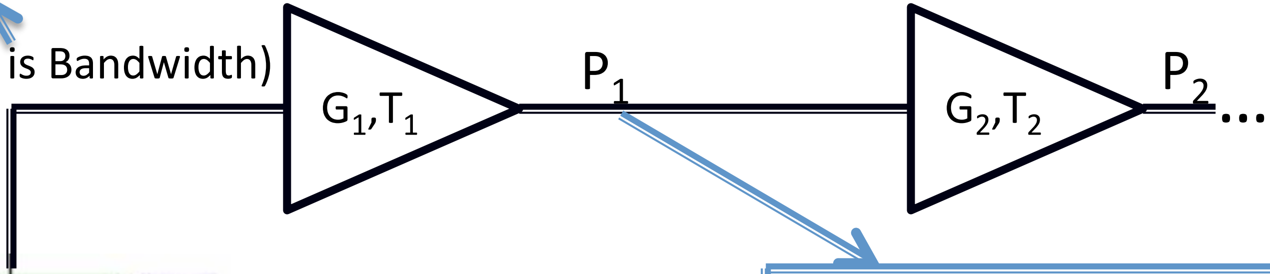
Why is noise temp of first amp crucial?

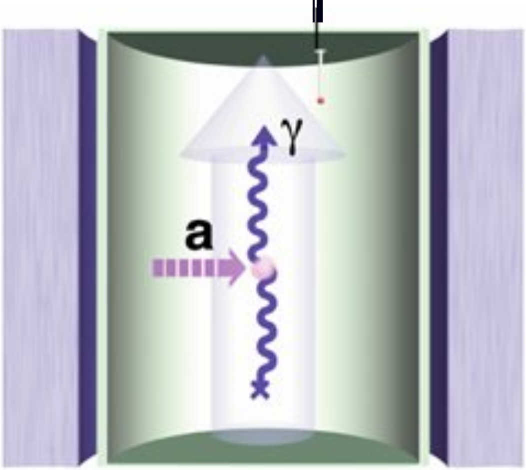
Noise from cavity

$$P_{nc} = Bk_BT_c$$

(B here is Bandwidth)

$$P_1 = G_1Bk_BT_c + P_{N,A_1} = G_1Bk_B(T_c + T_{A_1})$$





$$P_2 = G_2P_1 + P_{N,A_2} = G_2(G_1Bk_B(T_c + T_{A_1})) + G_2Bk_BT_{A_2}$$

Each amps <u>relative</u> contributions to total noise scale by previous amps gain

$$T_A = T_{A_1} + \frac{T_{A_2}}{G_1}$$

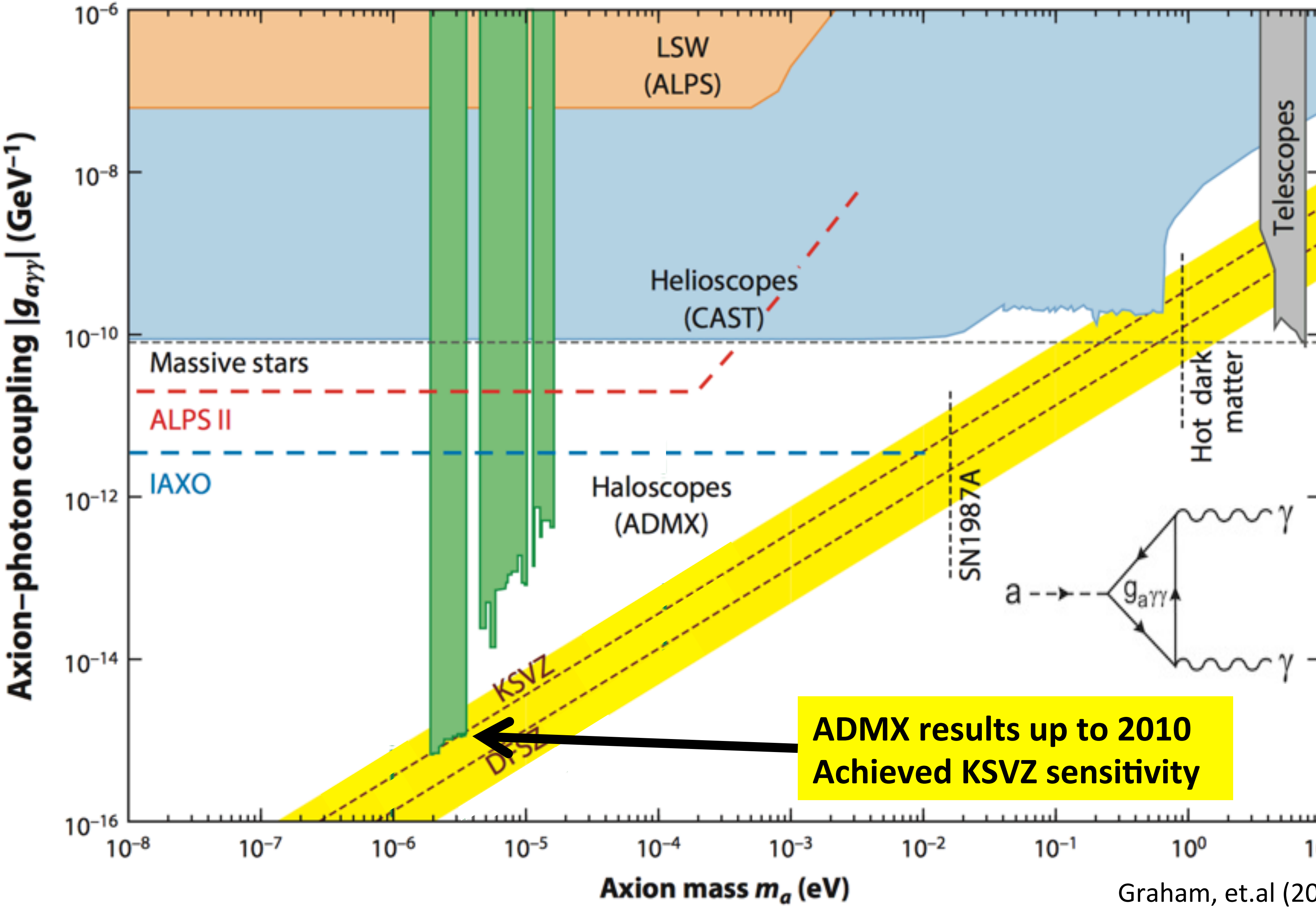
Say T_1 ~ 0.1 K and G_1 ~ 20 dB (or x100)
T_2 ~ 4 K (decent HFET)

Added noise contribution of 2nd amp = 4 K/100 = 0.04 K

Power from axions in cavity

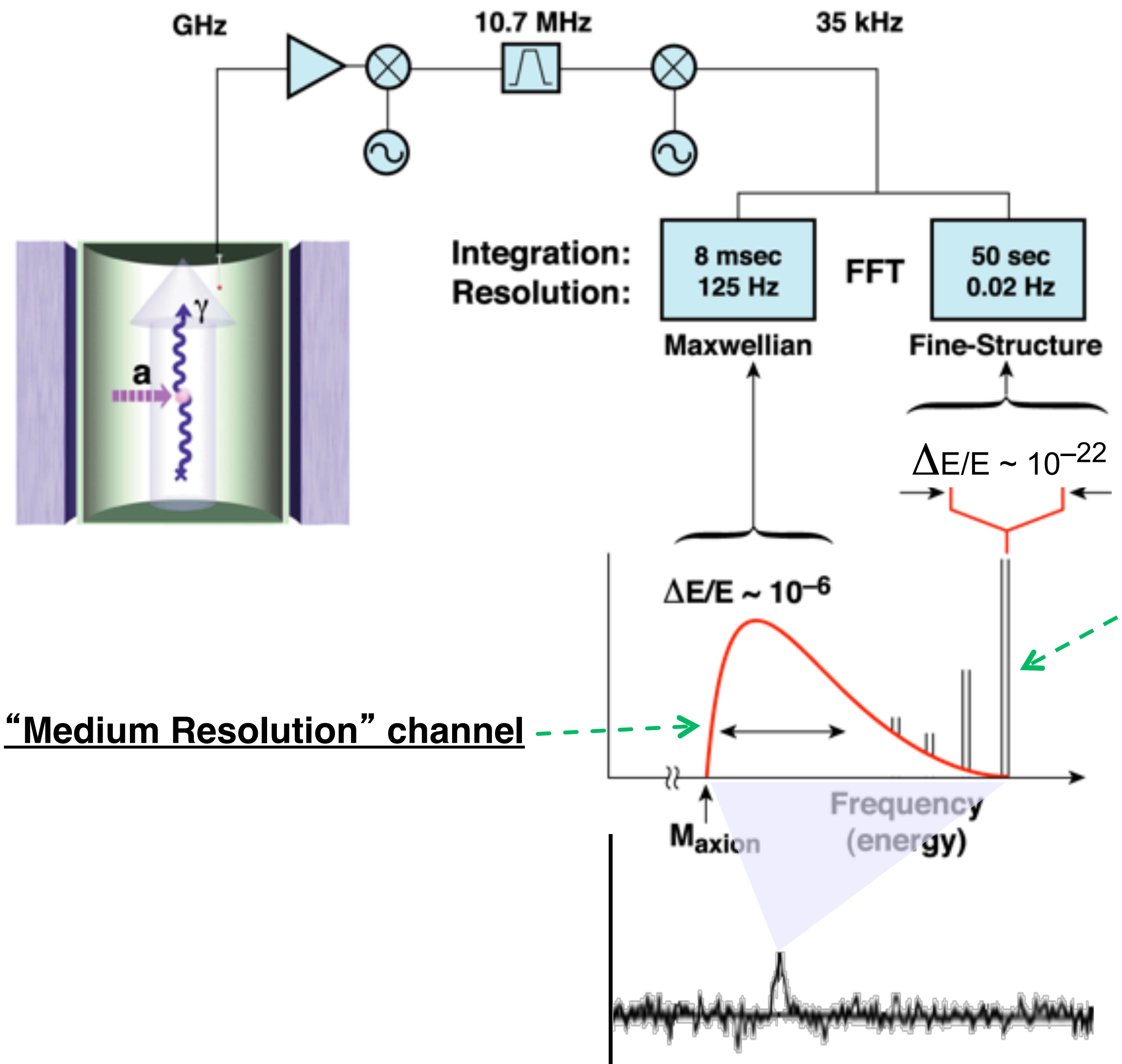
$$P_{a\to\gamma} = \eta g_{a\gamma\gamma}^2\left[\frac{\rho_a}{m_a}\right]B_0^2VCQ_c$$ *~ 10^{-24} W (or ~1.5 photons per second @ 1GHz)*

Axion parameter space



Graham, et.al (2016)

The ADMX experimental layout



Local Milky Way density:

ρ_{halo} ~ *450 MeV/cm³*

Thus for m_a ~ 10 μeV:

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

<u>“High Resolution” channel</u>

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

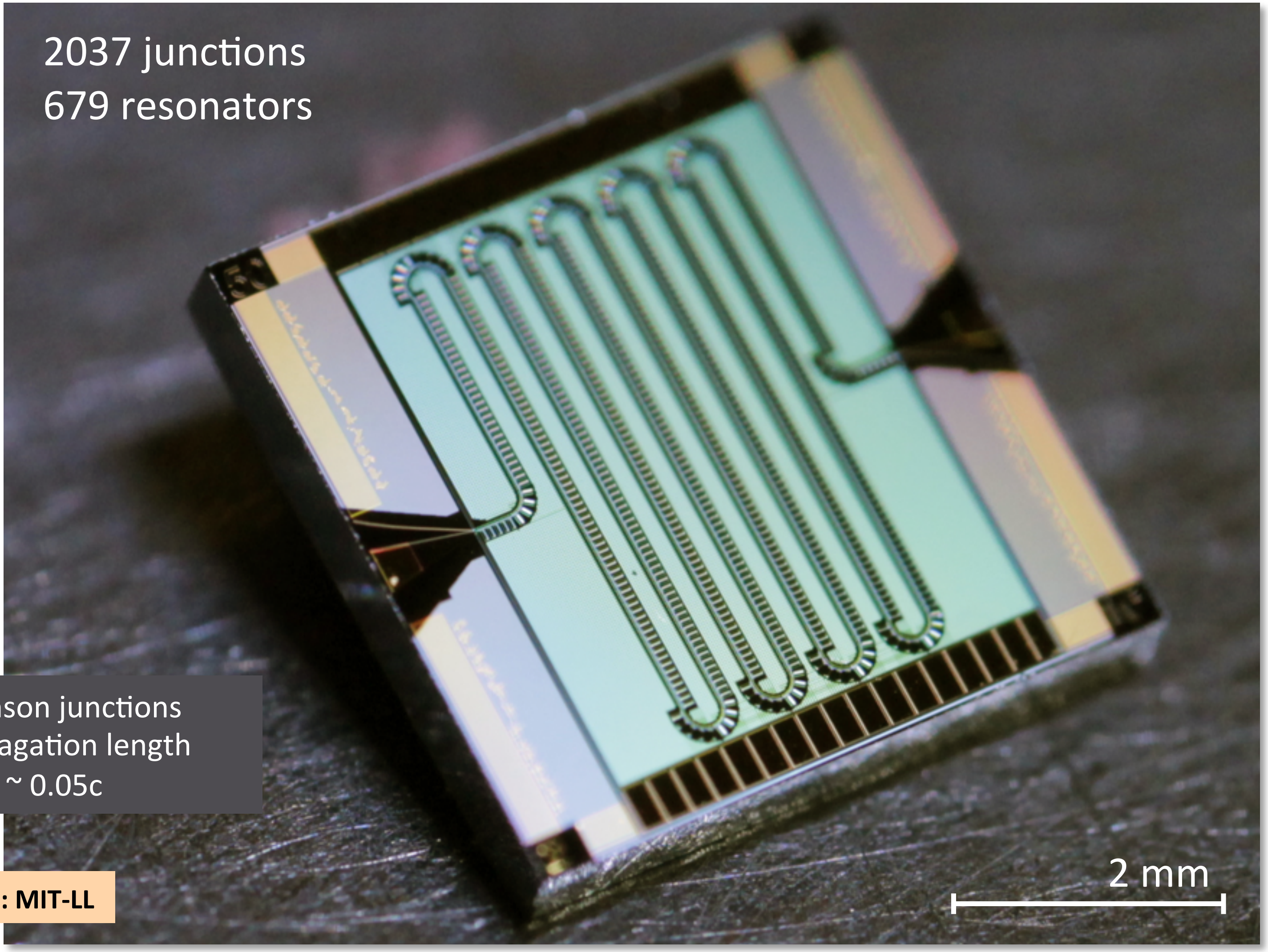
$\lambda_{De\ Broglie} \sim 100\ m$

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

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

Traveling Wave Parametric Amplifier (TWPA)

Broadband quantum limited amplifier



2037 Josephson junctions
3.3 cm propagation length
Slow light: v ~ 0.05c

FABRICATION: MIT-LL

Traveling Wave Parametric Amplifier (TWPA)

Broadband quantum limited amplifier

Recent gain measurements made of TWPA's fabricated by Lincoln Lab

Receiving TWPA from Lincoln Lab to test potential suitability in ADMX