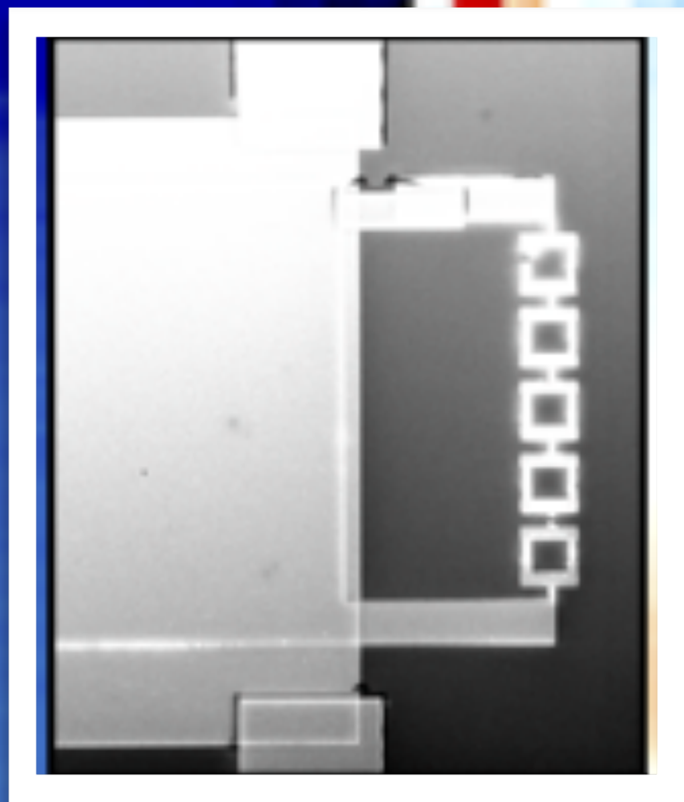
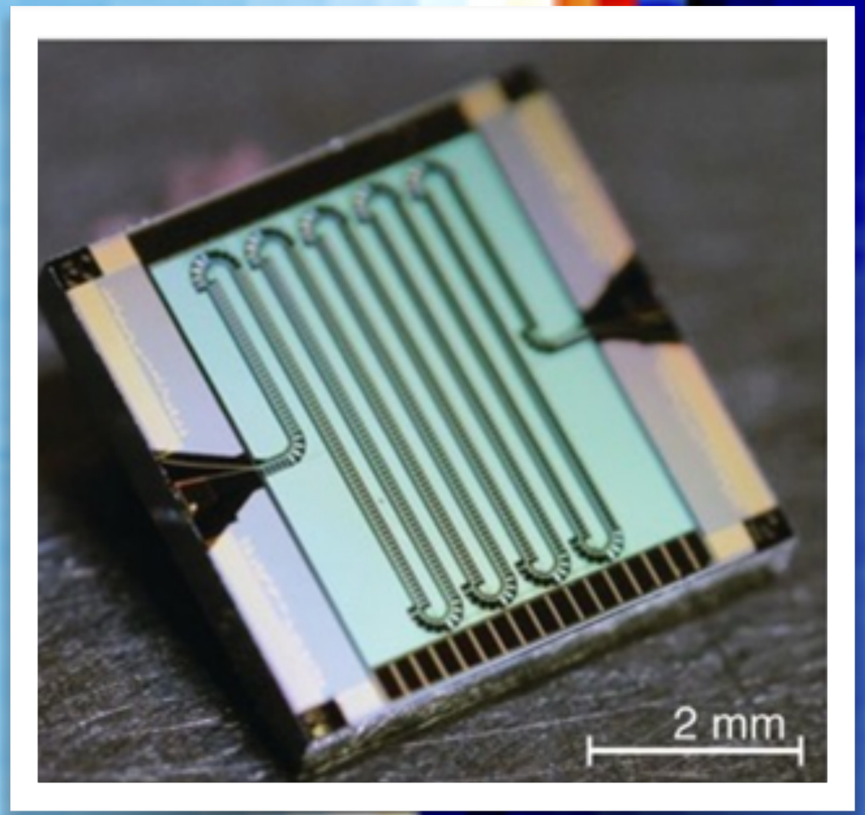
ADMX experiment

Realization of "invisible" axion dark matter search with quantum amplifiers





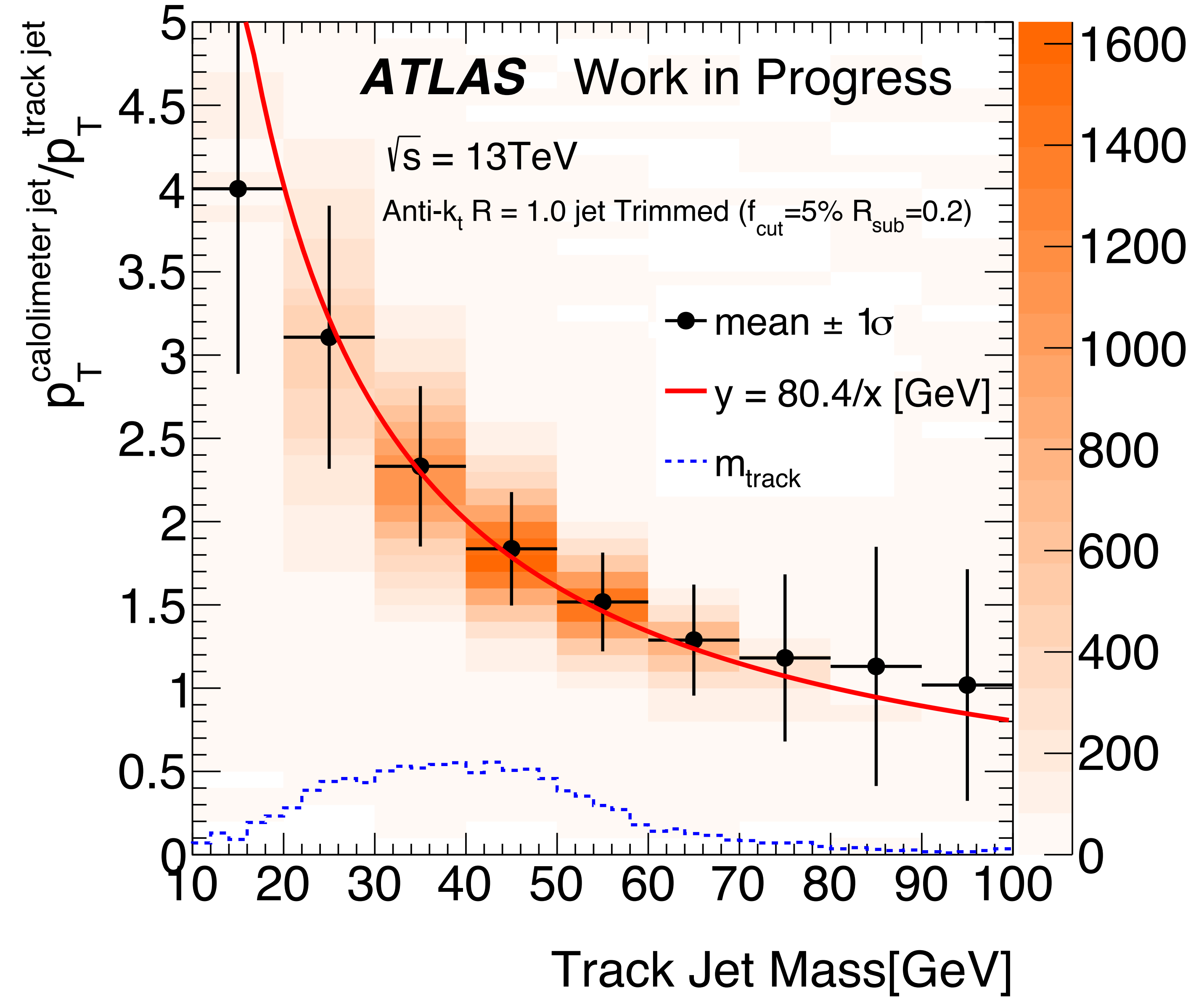
Tatsumi Nitta
University of Washington
(JSPS Overseas Research Fellow)
@University of Tokyo, ICEPP Seminar
December 21, 2021

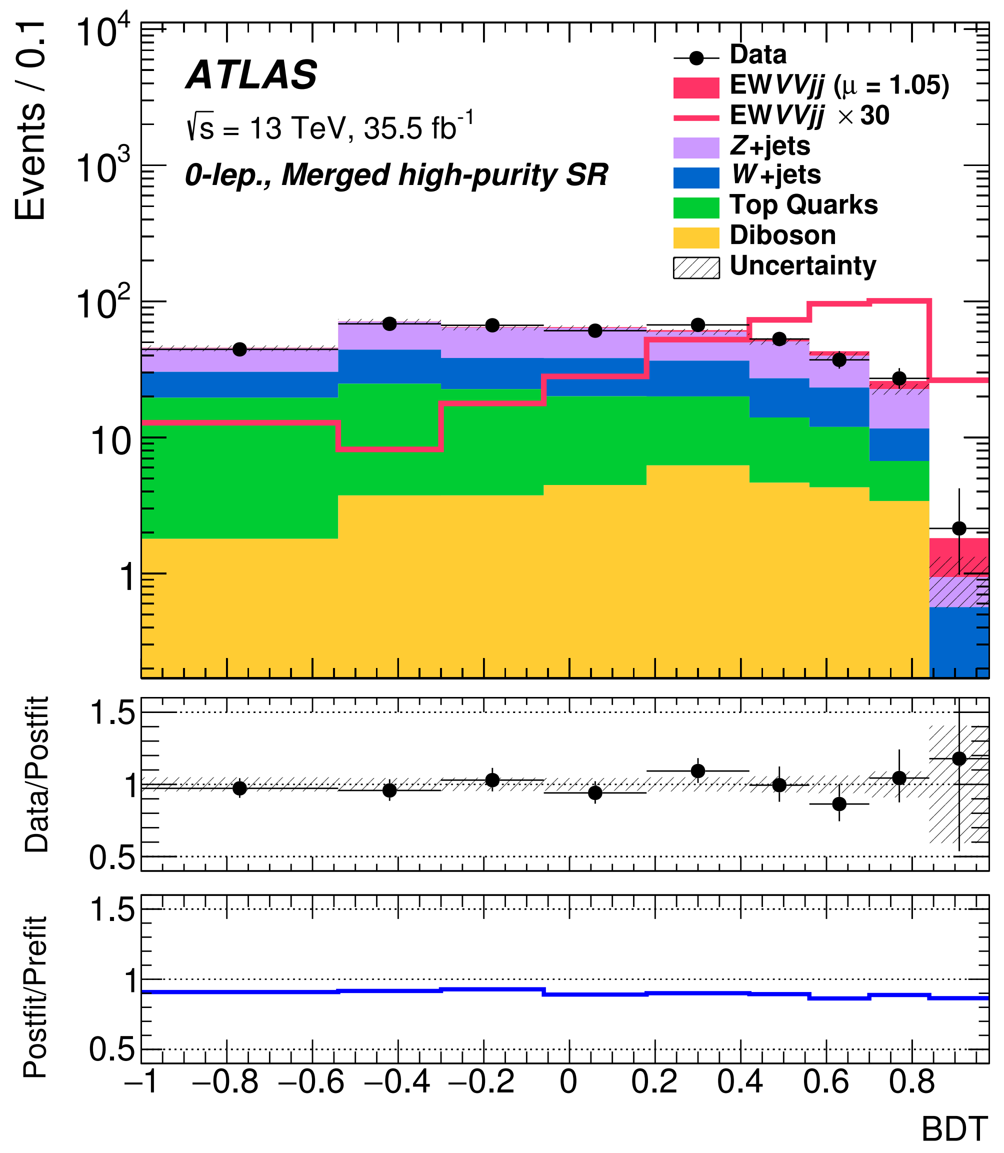
Self Introduction

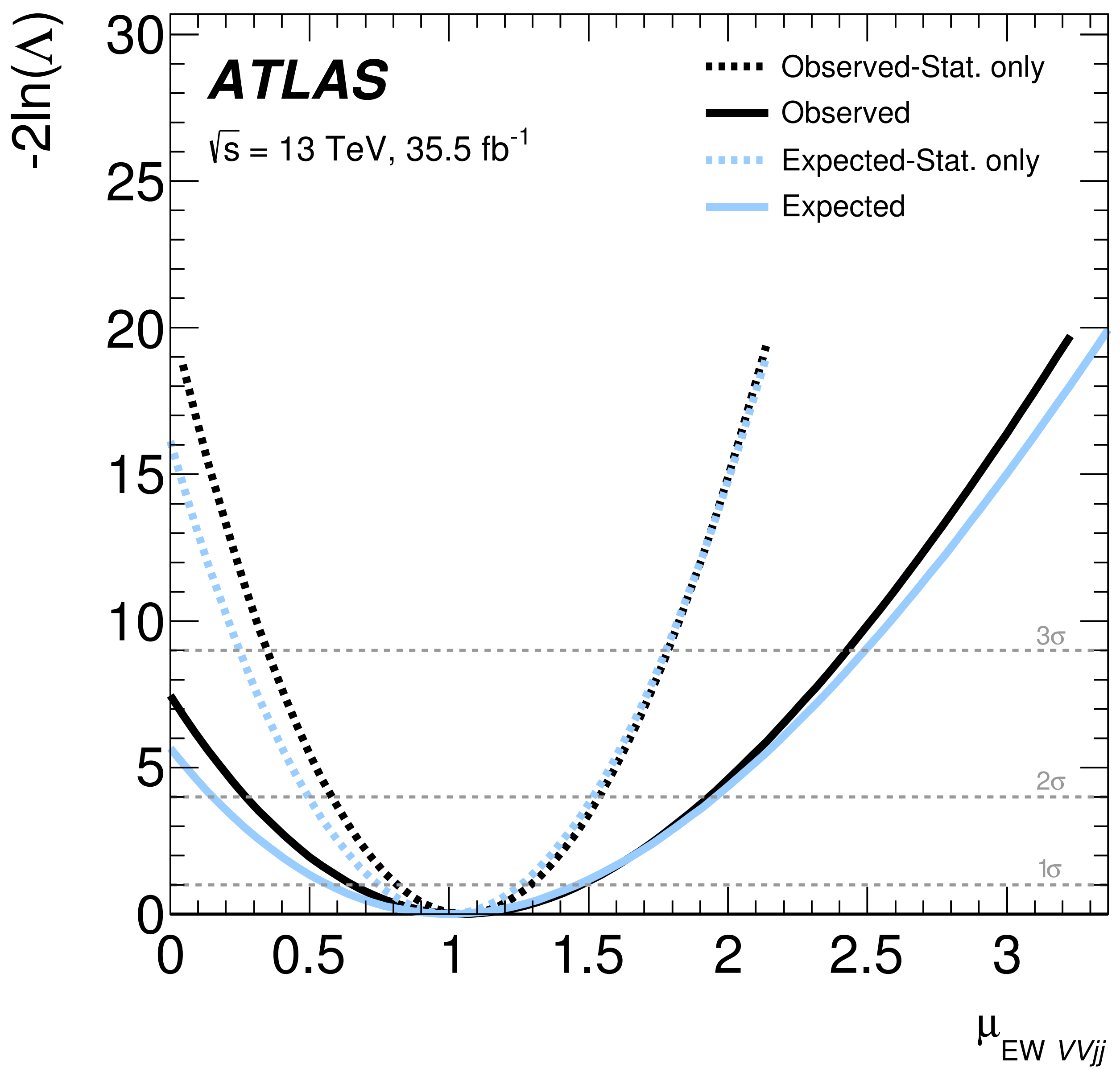
Tatsumi Nitta (新田 龍海)

2015-20 Waseda University, B.S., M.S., Ph.D., Advisor: Kohei Yorita

ATLAS experiment: W/Z/t Jets, Vector Boson Scattering, etc



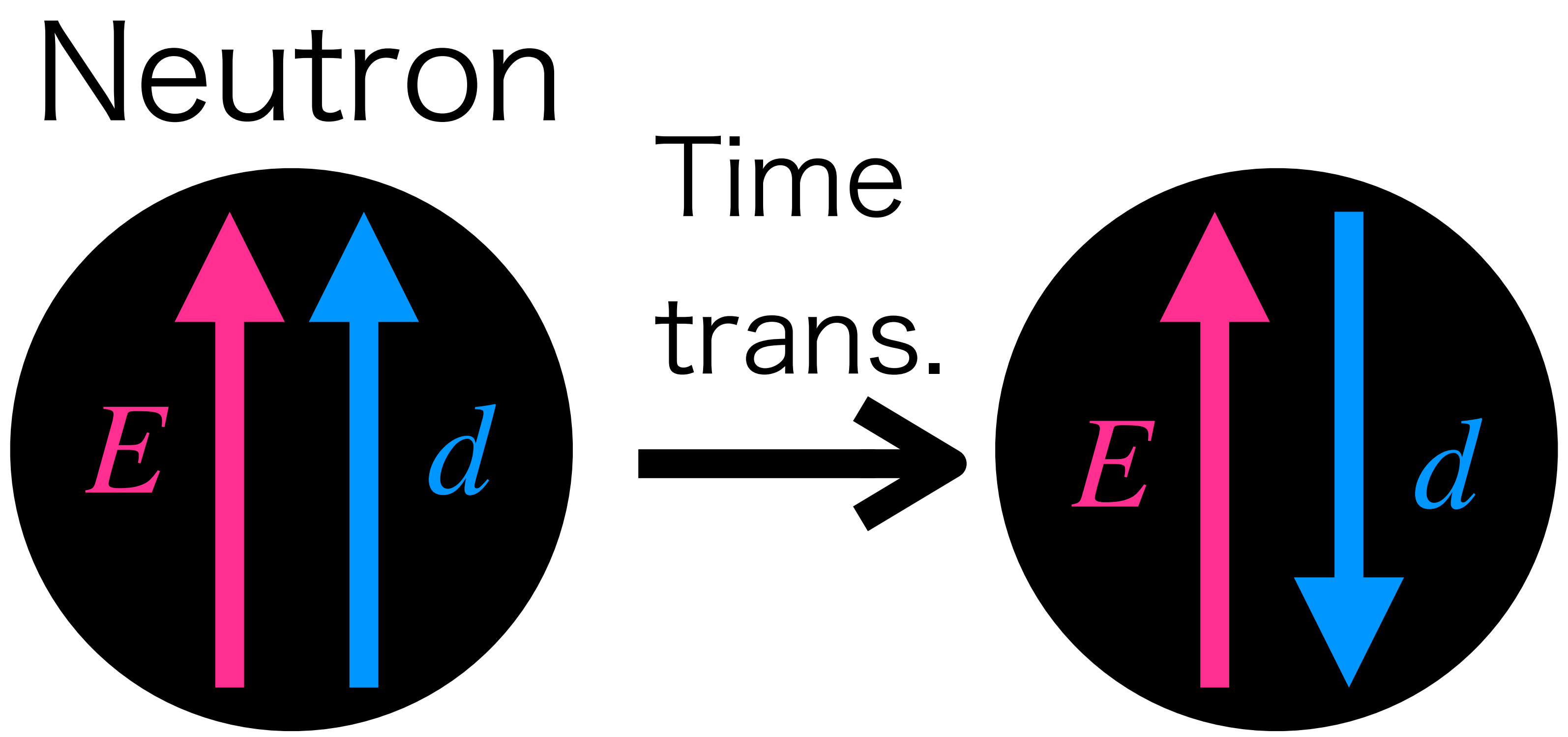




2020-: University of Washington (海外学振), PI: Gray Rybka,

ADMX: Commissioning, Operation, Analysis

Strong CP Problem & PQ solution



$$\mathscr{H} = -\mathbf{d}\cdot\mathbf{E}$$

Non zero $\mathbf{d}$ → T (CP) violation

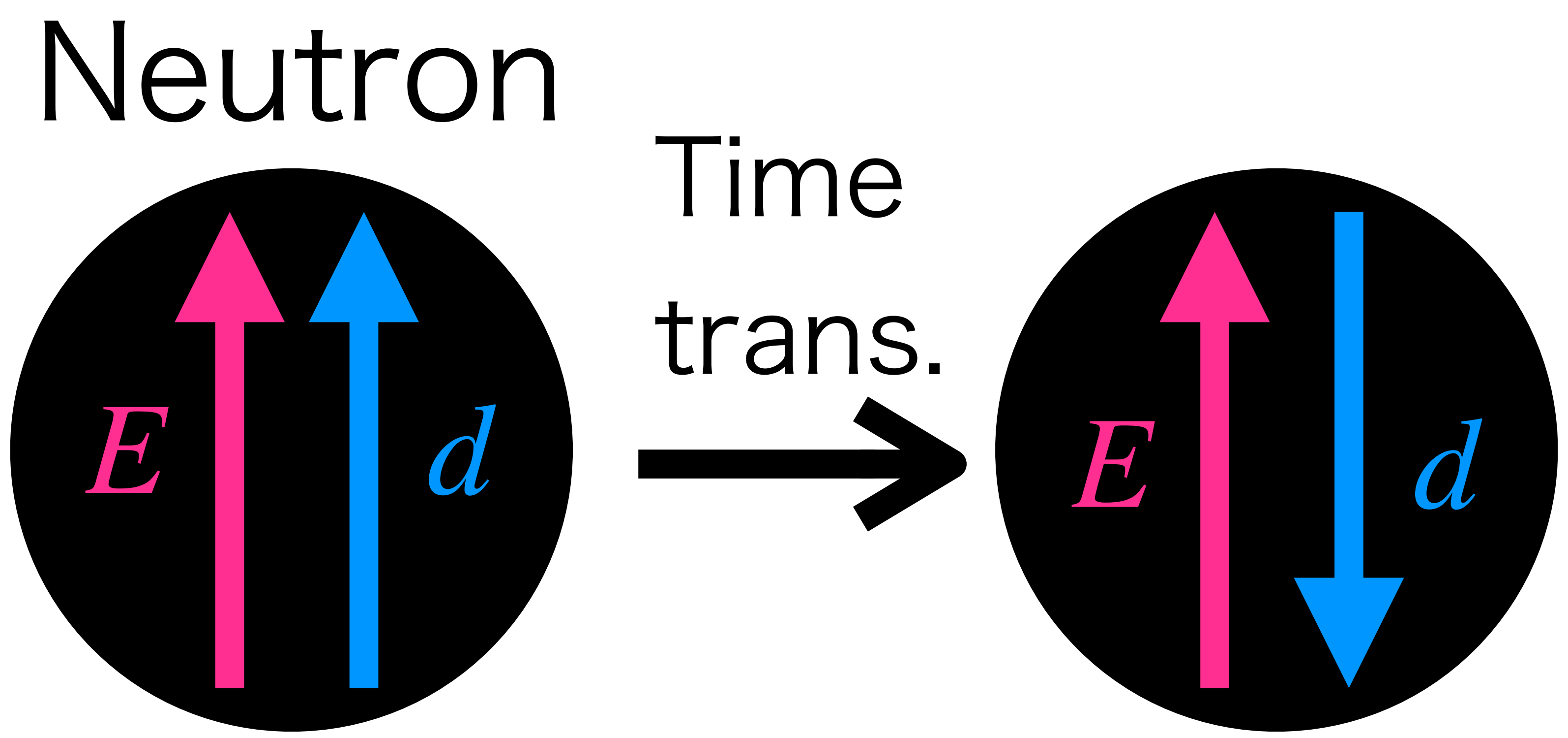
$$|\mathbf{d}| \sim \bar{\theta}\cdot 3.6\times 10^{-16}\ e\cdot \mathrm{cm}$$

$$\bar{\theta} = \theta + \det(\mathrm{M}),\ \det(\mathrm{M}) \neq 0$$

Recent limits: $< 1.8\times 10^{-26}\ \mathrm{e}\cdot\mathrm{cm}$

$\rightarrow \bar{\theta} < 10^{-10}$: **BSM must exist**

Strong CP Problem & PQ solution



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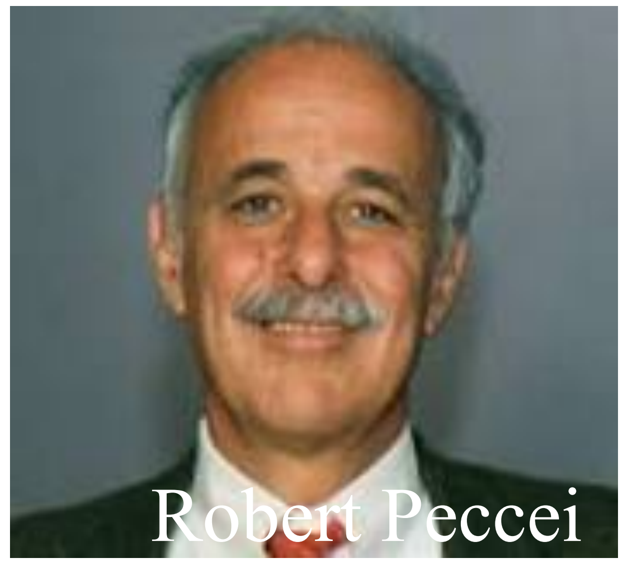
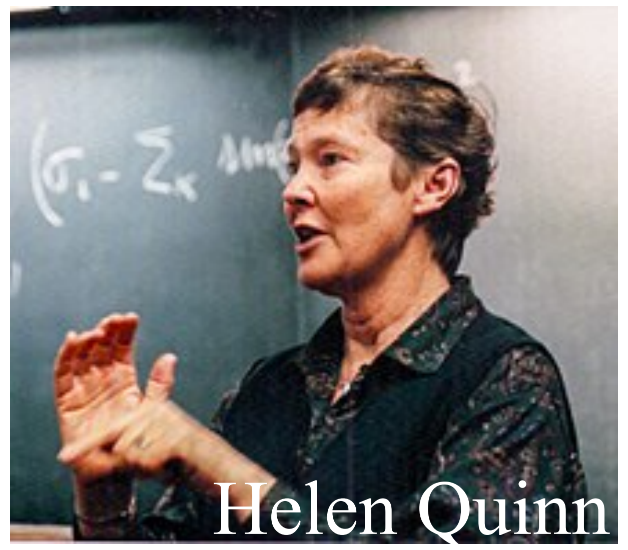
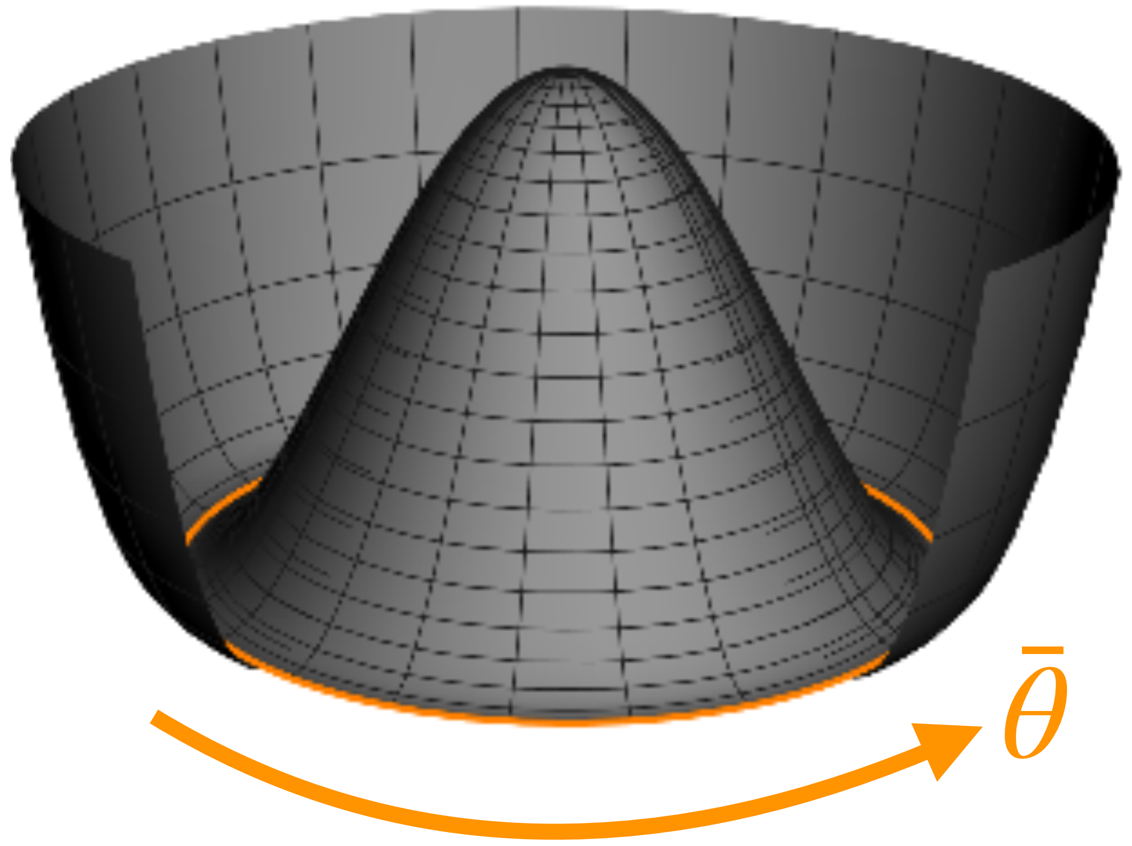




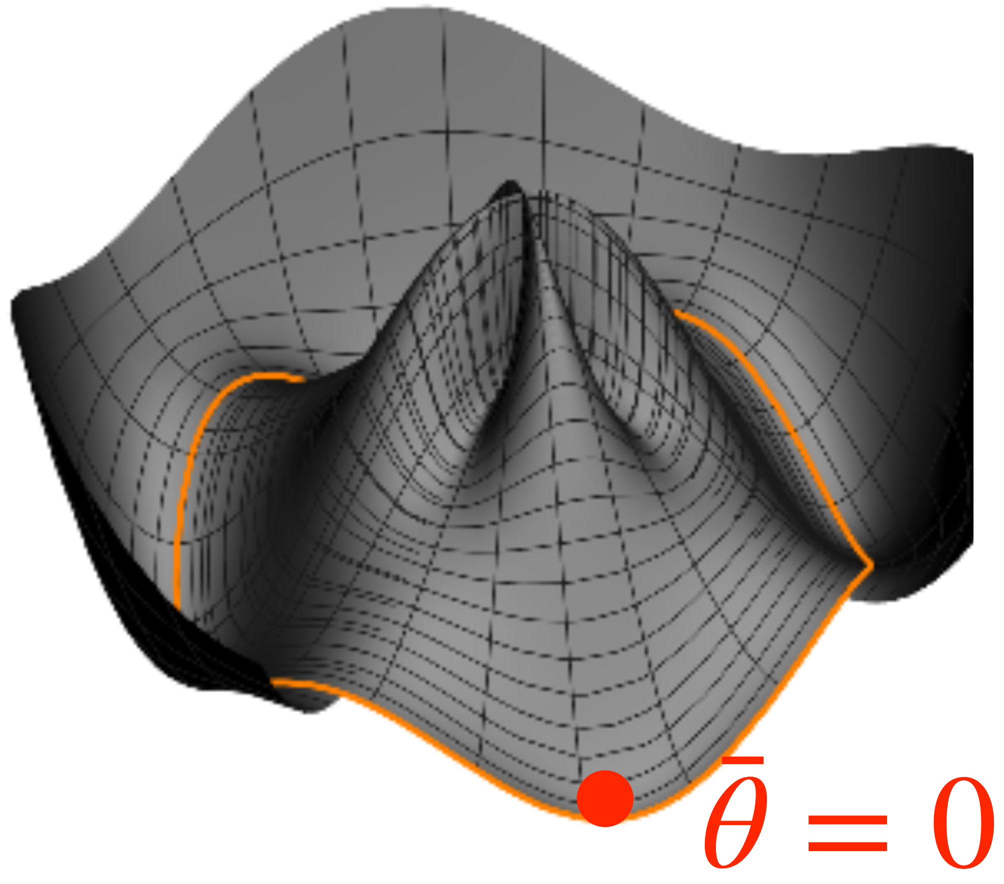
added $U_A(1)$ in SM

$\bar{\theta} \propto a(t,x)$

PQ symmetry breaking

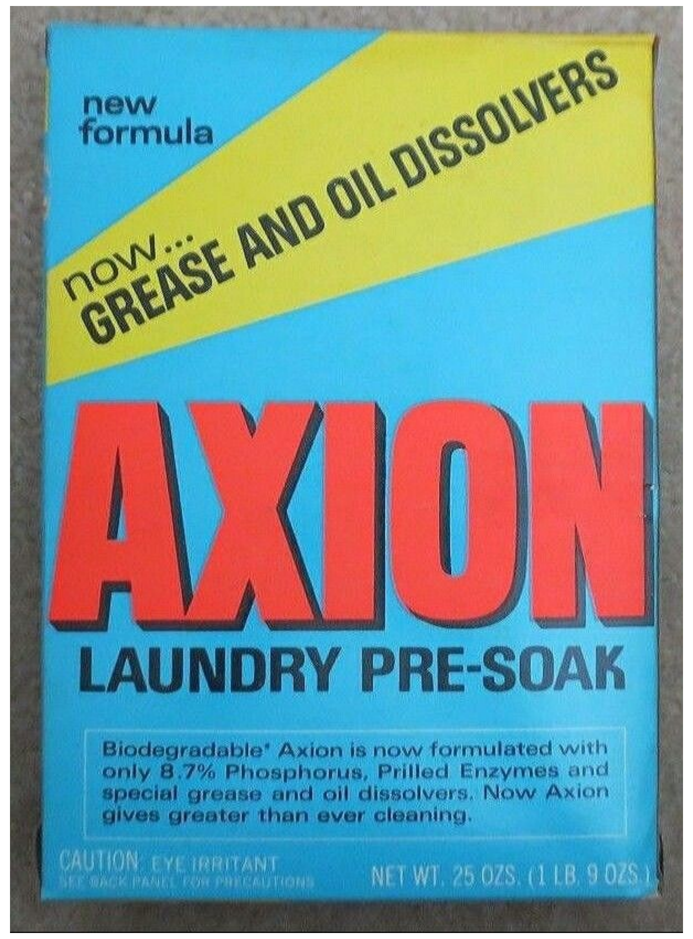


QCD cross over



Existence of PQ symmetry solves the Strong CP problem

“invisible” Axion Dark Matter

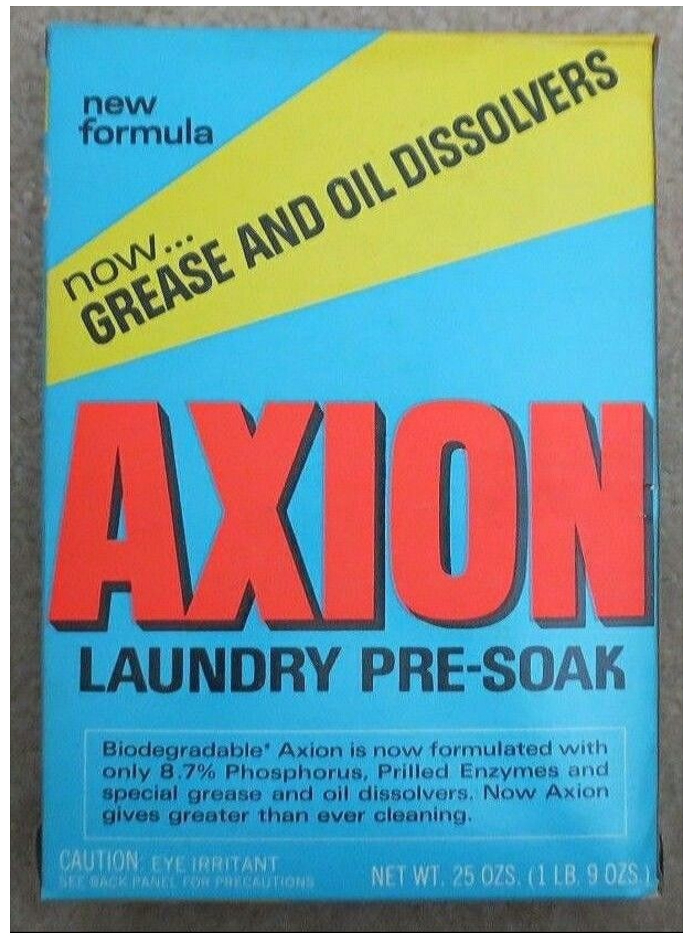


COLGATE-PALMOLIVE

PQ symmetry breaking→ **NG-boson, Axion** Weinberg, Wilczek `78

Mass of Axion: $$m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6\ \mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

"invisible" Axion Dark Matter



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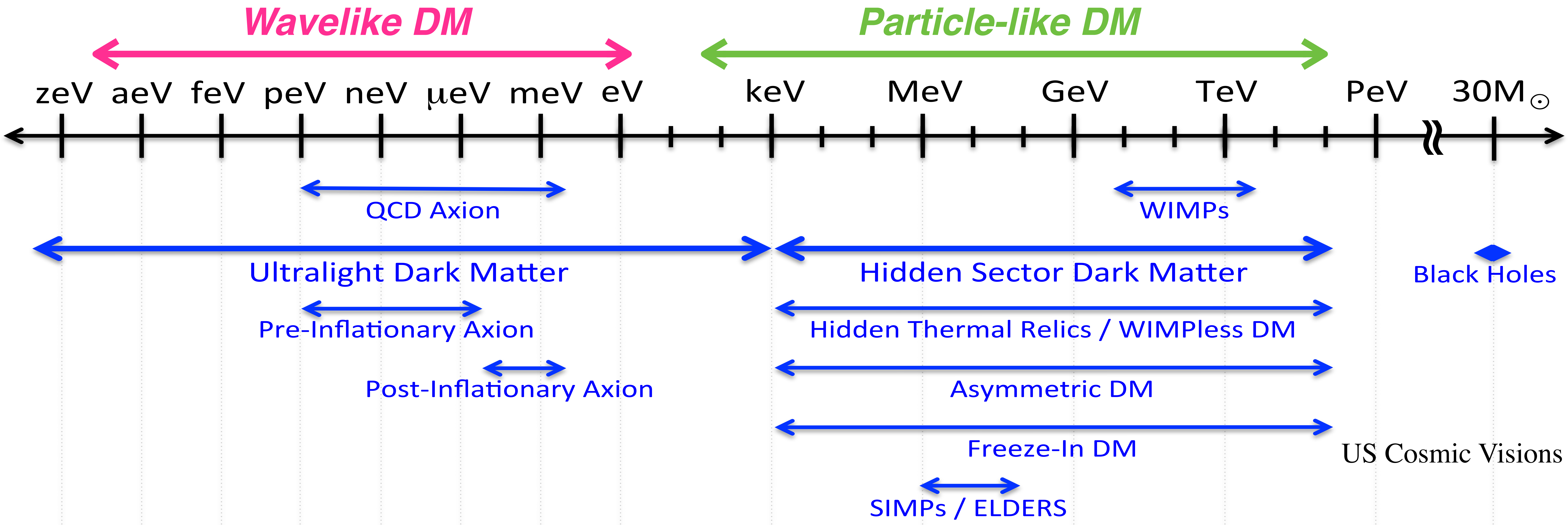


US Cosmic Visions (2017)

Wavelike Dark Matter

$m_a = \mathcal{O}(1)\ \mu\mathrm{eV/c^2},\ \rho_a \sim 0.45\ \mathrm{GeV/cc}, \quad \lambda_{de\ Broglie} = \mathcal{O}(100)\ \mathrm{m} \gg \bar{d}_{\mathrm{DM}}$ **(mean DM distance)**

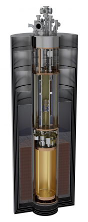
Wavelike Dark Matter

$m_a = \mathcal{O}(1)\ \mu\mathrm{eV/c^2},\ \rho_a \sim 0.45\ \mathrm{GeV/cc}, \quad \lambda_{de\ Broglie} = \mathcal{O}(100)\ \mathrm{m} \gg \bar{d}_{\mathrm{DM}}$ **(mean DM distance)**

$O(100\ \mathrm{m})$

$v_a \sim 10^{-3}c$

$t_c \sim 1\ \mathrm{ms}$

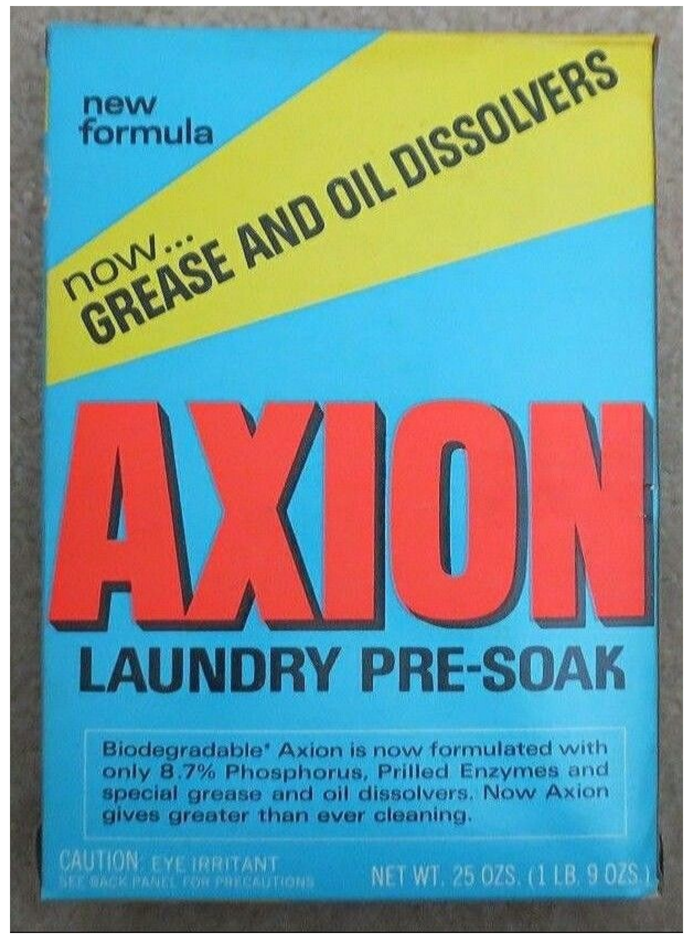


$t_c \gg t_{\mathrm{obs}},\ P \propto t$

$t_c \ll t_{\mathrm{obs}},\ P \propto \sqrt{t}$ **(ADMX case)**

Axion DM is like a bunch of gigantic slow laser pulses

“invisible” Axion Dark Matter



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Benchmark Models

KSVZ: Heavy quark carries PQ-charge

DFSZ: a Higgs doublet carries PQ-charge

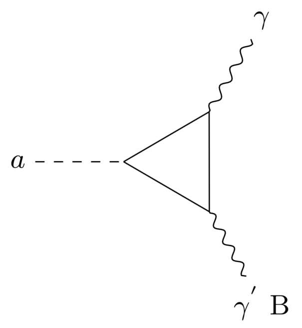
Coupling is so small
→ “invisible” Axion

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the “Invisible” Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Couplings & Experiments



$g_{a\gamma\gamma}$

Cavity: **ADMX**, HAYSTAC, CAPP

Dish Antenna: MADMAX, Orpheus

BRASS

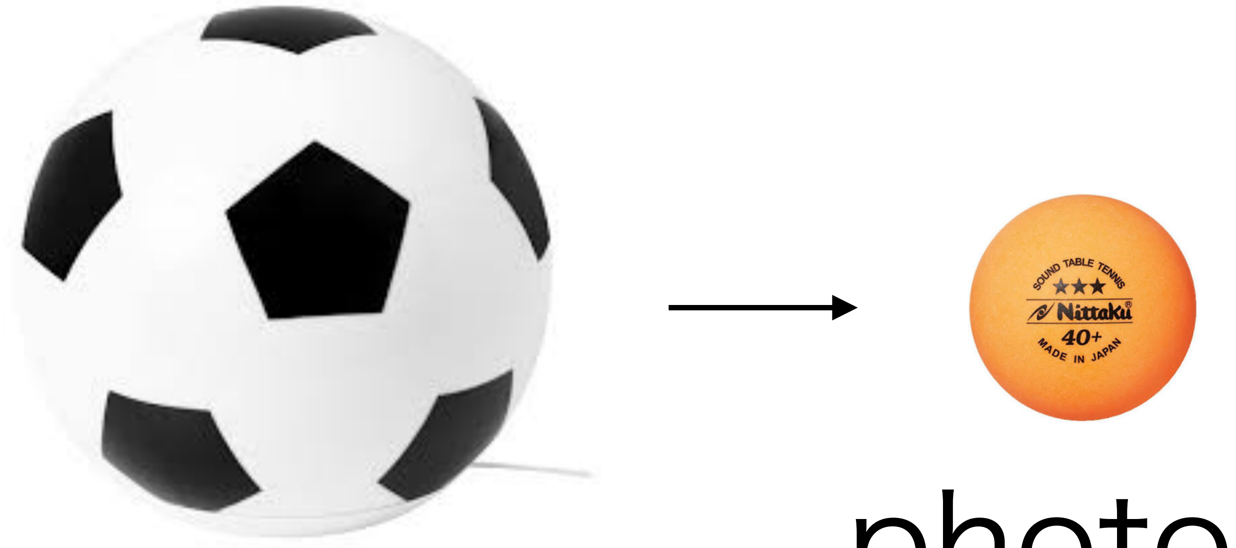
Plasma: Alpha

Lumped Element: ABRA, DM-radio, SHAFT

Helioscope: CAST

Laser: Alps, DANCE etc…

Momentum/Energy conservations



axion

photon

Boundary Condition :

Cavity, dish

Dispersion relation

(Massive photon): Plasma

g_{aff} WIMP searches (LUX, XENON1T), CASPEr-wind

g_{agg} CASPEr-electric

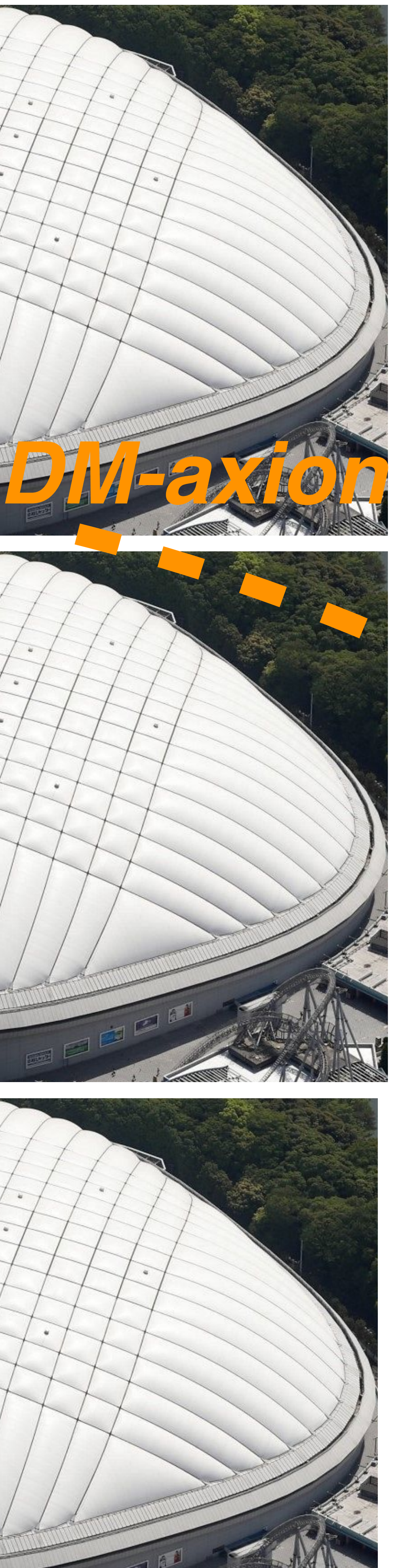
$g_{gravity}$ Axion Super radiance

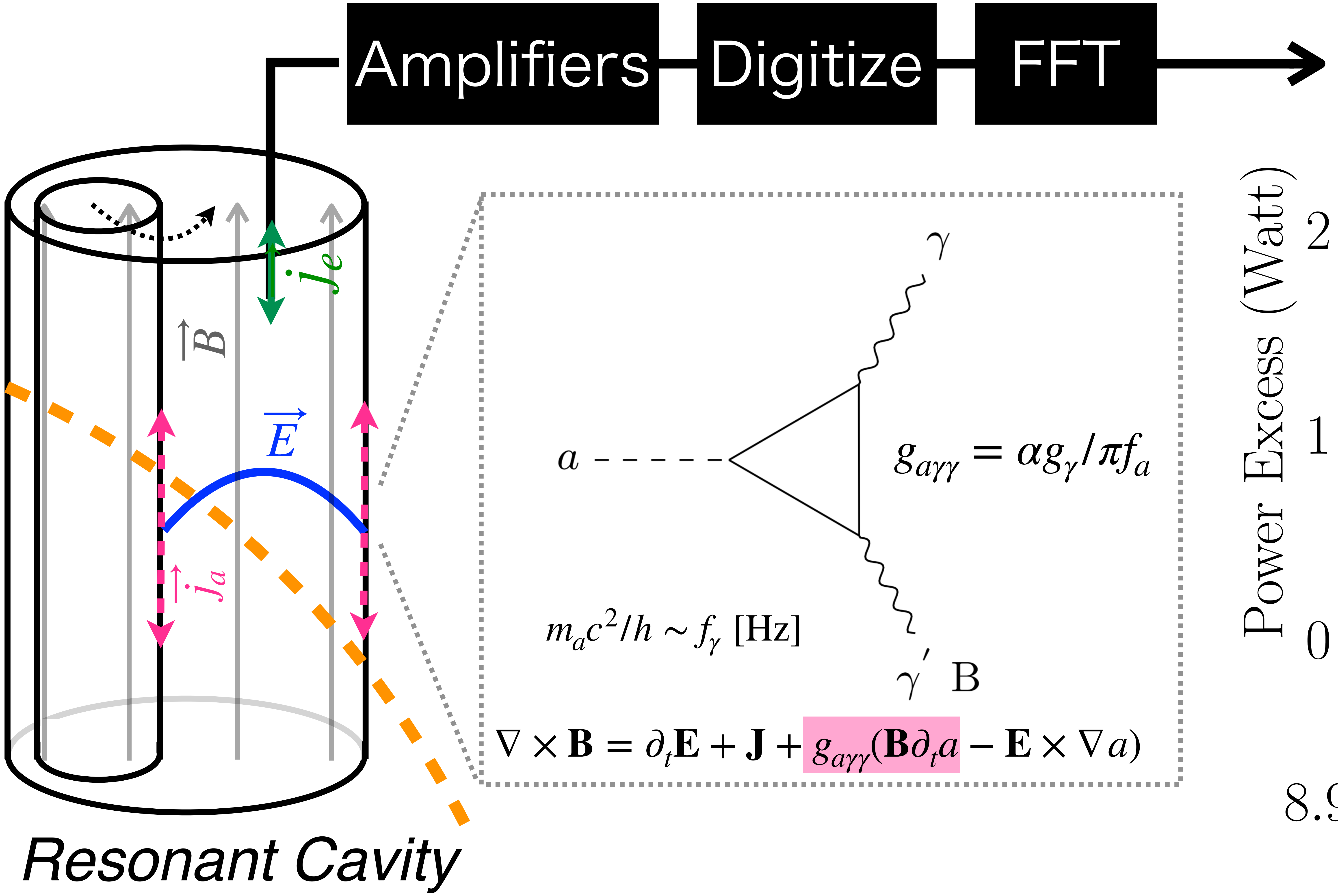
Indirect searches

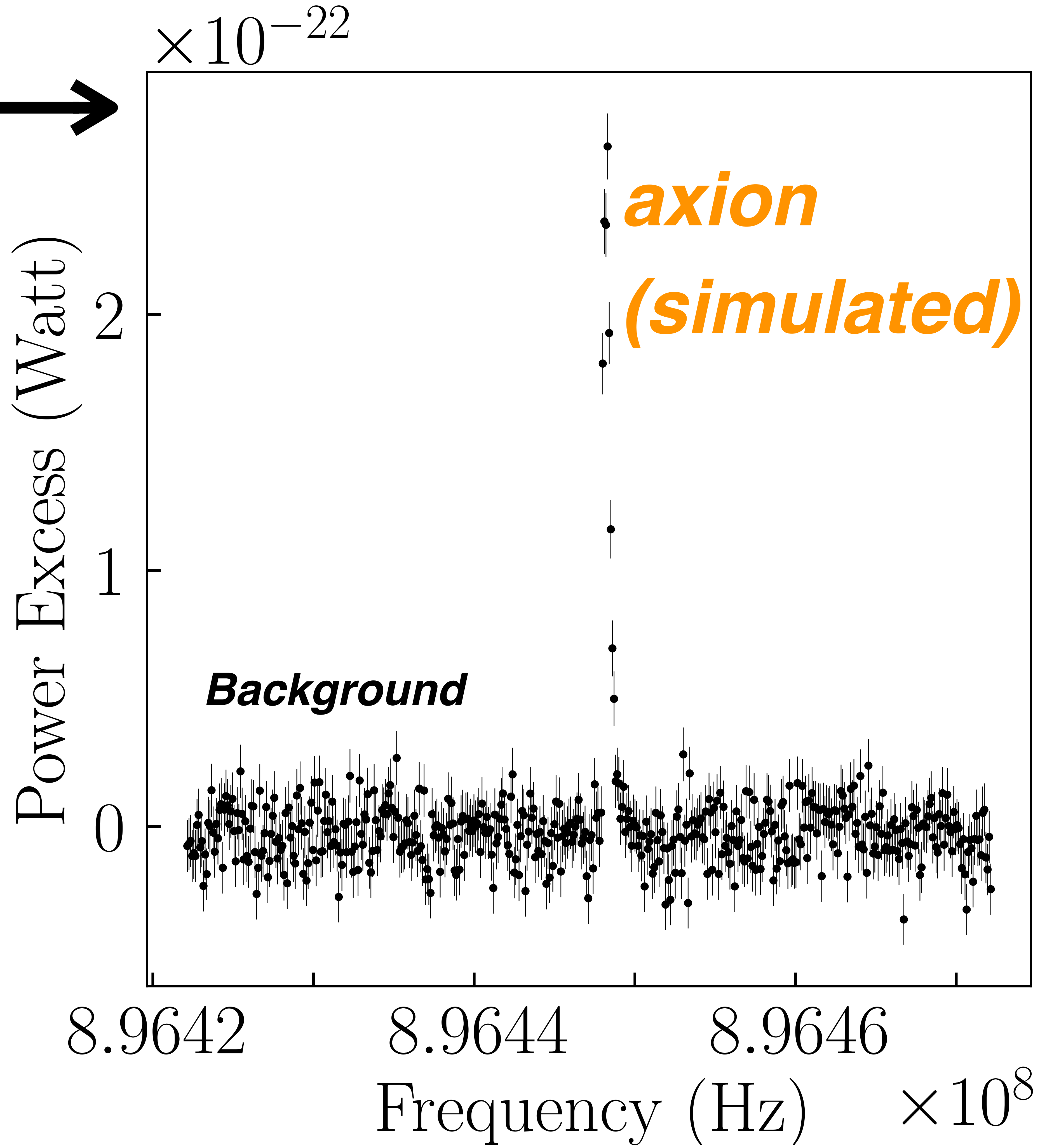
- stelar cooling
- supernova
- neutron star etc…

Resonant Cavity Haloscope

Only successful "invisible" axion dark matter detection technique so far







Sensitivity, Scan Speed

$$C = \frac{\left|\int dV \mathbf{B}(\mathbf{x}) \cdot \mathbf{E}(\mathbf{x})\right|^2}{VB^2 \int dV \epsilon_{\mathbf{r}} |\mathbf{E}(\mathbf{x})|^2}$$

Signal

Physics determines

Experiment determines

$$P_{\text{axion}} \sim 7.9 \times 10^{-23}\ \text{W} \left(\frac{\beta}{1+\beta}\right) \left(\frac{k_\gamma}{0.36}\right)^2 \left(\frac{f}{1\ \text{GHz}}\right) \left(\frac{\rho}{0.45\ \text{GeV/cc}}\right) \left(\frac{B}{7.6\ \text{T}}\right)^2 \left(\frac{V}{136\ \ell}\right) \left(\frac{Q_L}{80\ 000}\right) \left(\frac{C}{0.4}\right)$$

Background

$$T_{\text{sys}} = T_{\text{phys.}} + T_{\text{amp1}} + T_{\text{amp2}}/G_{\text{amp1}} + \cdots$$

Sensitivity: $\text{SNR} = \dfrac{P_{\text{axion}}}{k_b T_{\text{sys}}} \sqrt{\dfrac{t}{b}}$

Scan speed

$$\frac{df}{dt} \sim 543 \frac{\text{MHz}}{\text{yr}} \left(\frac{\beta}{1+\beta}\right)^2 \left(\frac{k_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \text{GHz}}\right)^2 \left(\frac{\rho}{0.45\ \text{GeV/cc}}\right)^2 \left(\frac{3.5}{\text{target SNR}}\right)^2 \left(\frac{B}{7.6\ \text{T}}\right)^4 \left(\frac{V}{136\ \ell}\right)^2 \left(\frac{Q_L}{30\ 000}\right) \left(\frac{C}{0.4}\right)^2 \left(\frac{0.2}{T\text{sys}}\right)^2$$

Axion & QIS (Quantum Information Sience)

ADMX (2002)

The Astrophysical Journal, 571:L27–L30, 2002 May 20

EXPERIMENTAL CONSTRAINTS ON THE AXION DARK MATTER HALO DENSITY

S. J. Asztalos, E. Daw, H. Peng, L. J Rosenberg, and D. B. Yu
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
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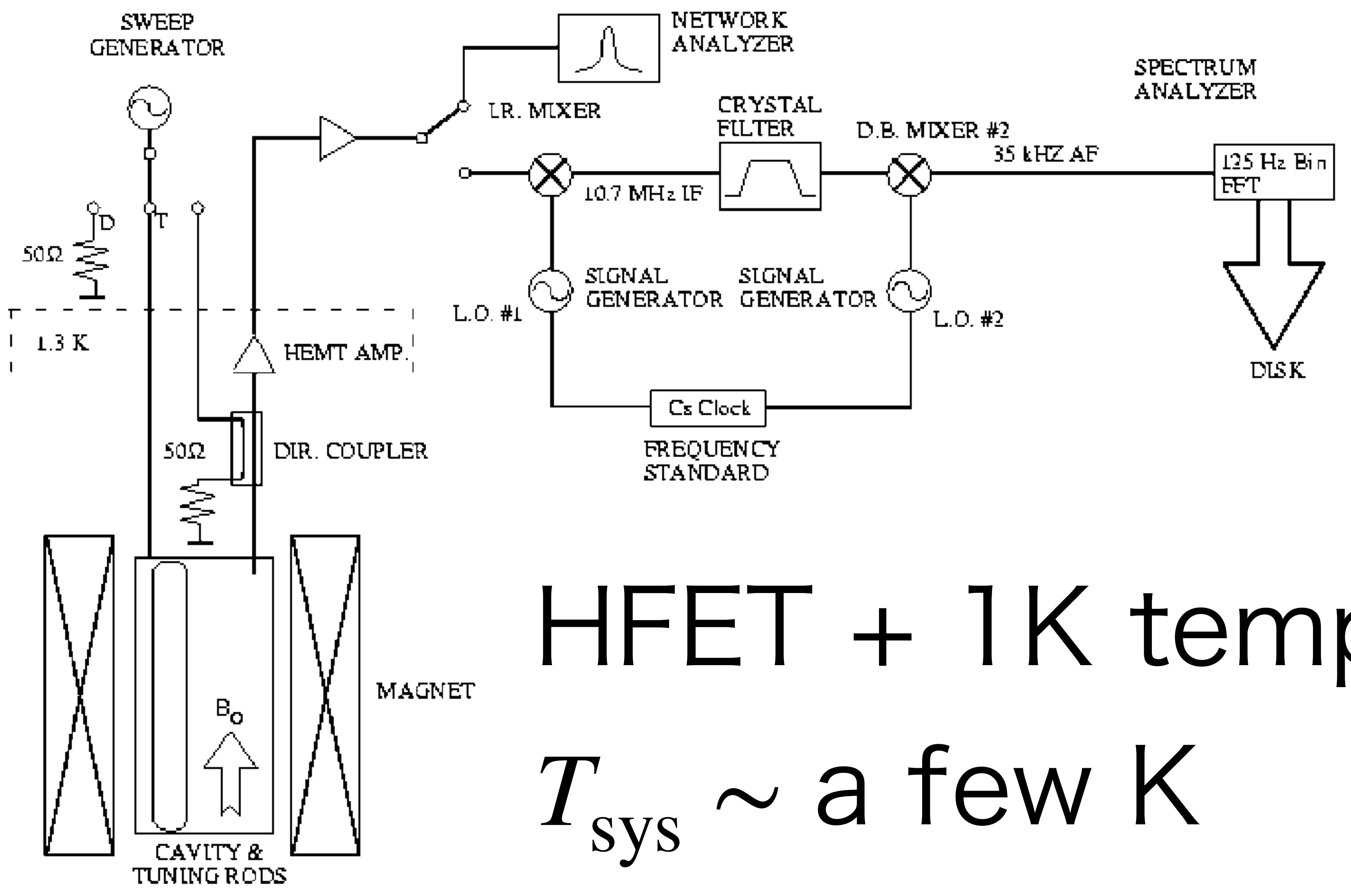
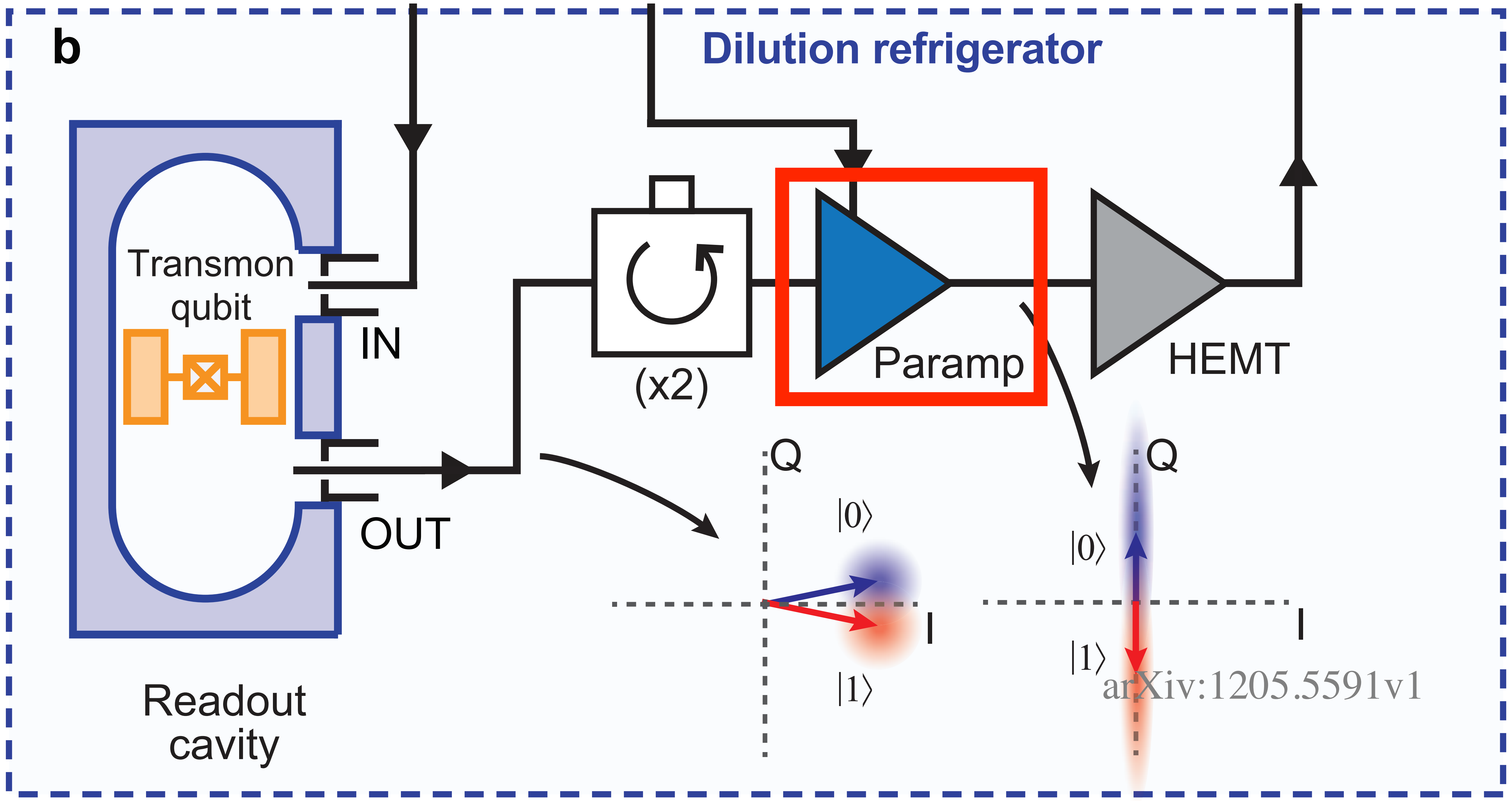
Received 2002 February 11; accepted 2002 April 10; published 2002 May 2



HFET + 1K temp

T_{sys} ~ a few K

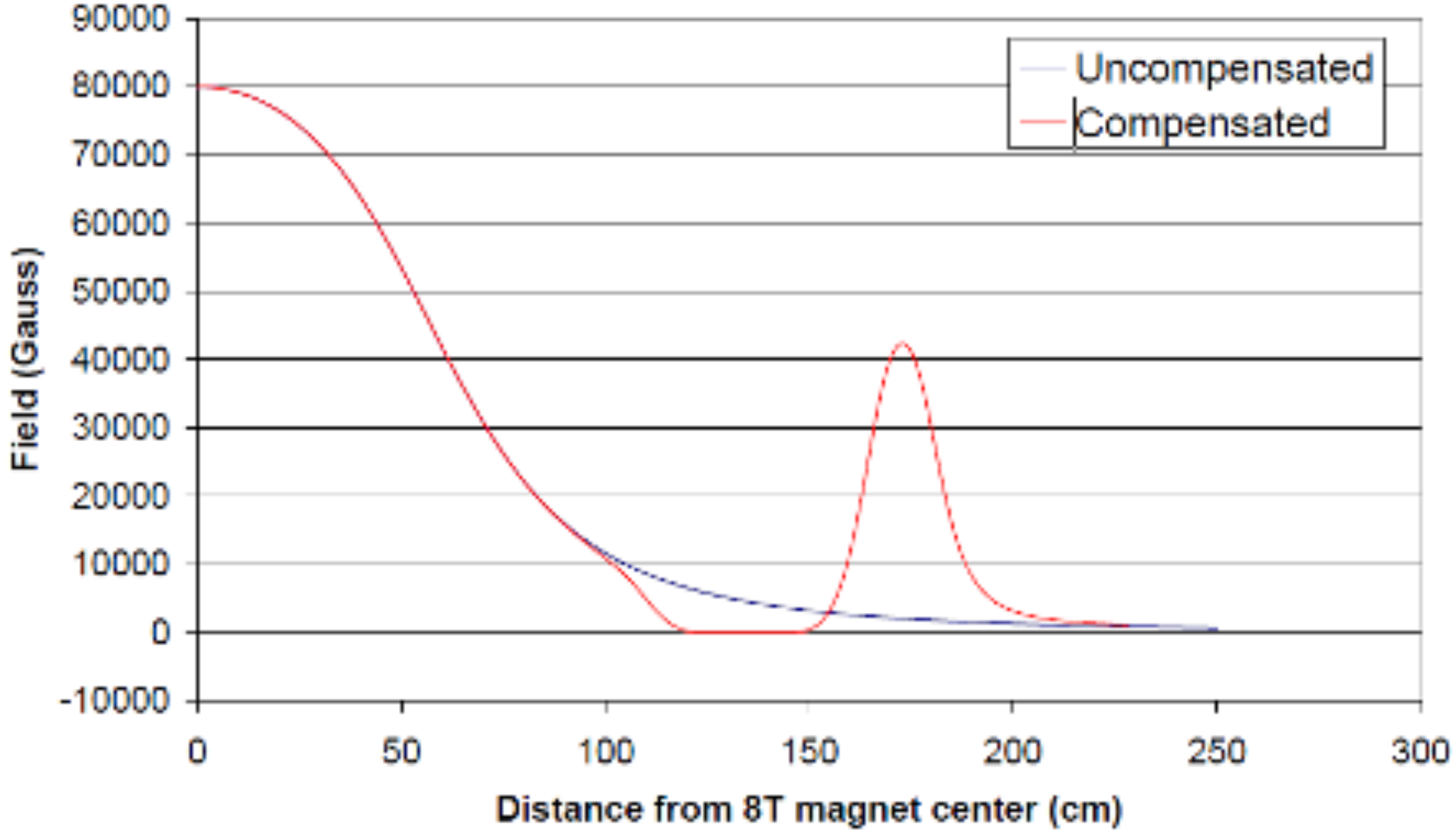
Quantum amplifier is ubiquitous tool for superconducting qubit



Axion & QIS

B-field:

- Essential for axion search: design 8 T
- Enemy of Josephson junction: require <0.01 T



Bucking coil + μ-metal shield creates a sub Gauss region next to the 8 T region.

Bucking coil

Main magnet

Axion & QIS

ADMX (2002) → Quantum Amp. → ADMX (2018)

The Astrophysical Journal, 571:L27–L30, 2002 May 20

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Received 2002 February 11; accepted 2002 April 10; published 2002 May 2

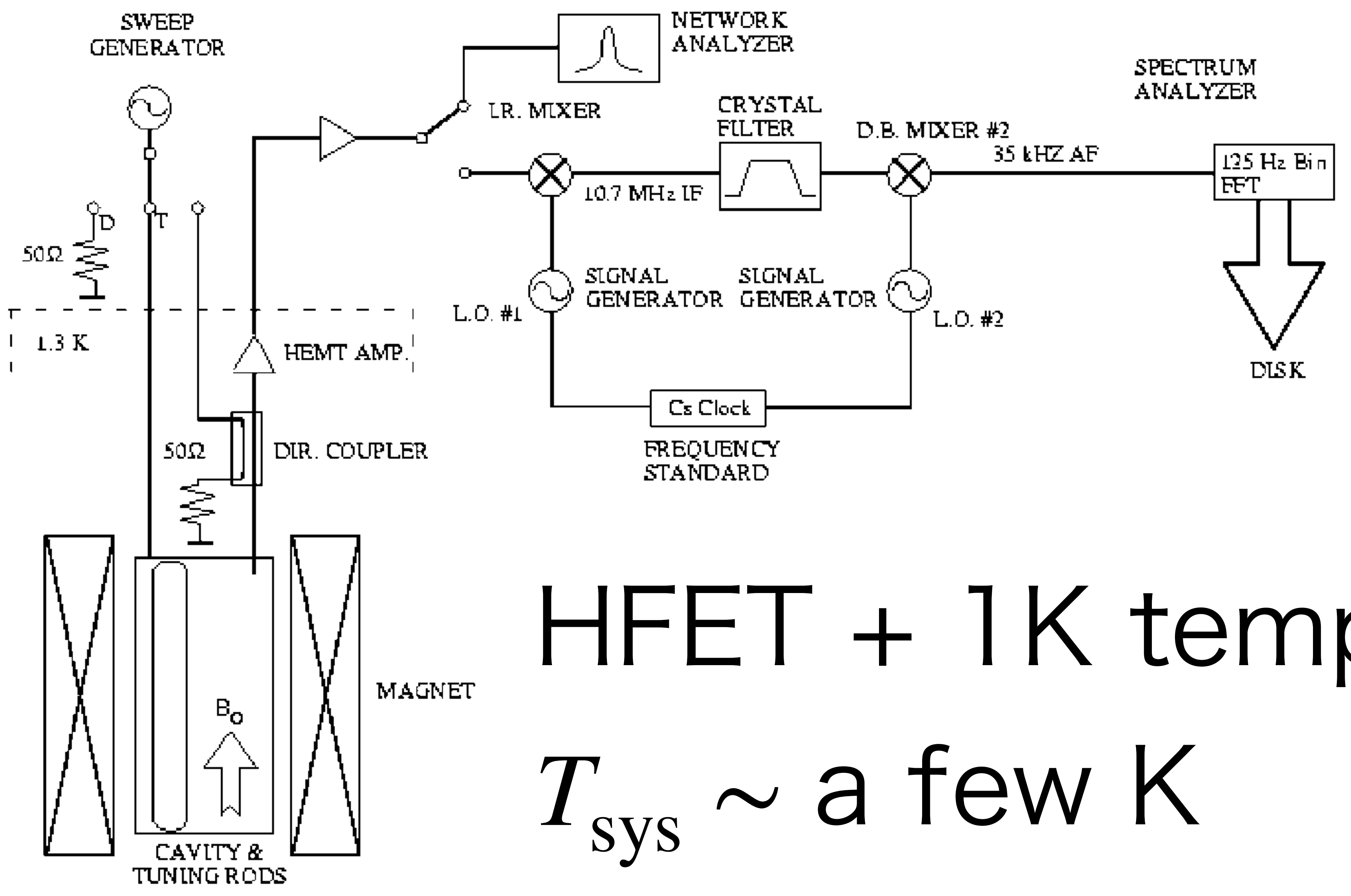
PHYSICAL REVIEW LETTERS **120,** 151301 (2018)

Editors' Suggestion | Featured in Physics

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

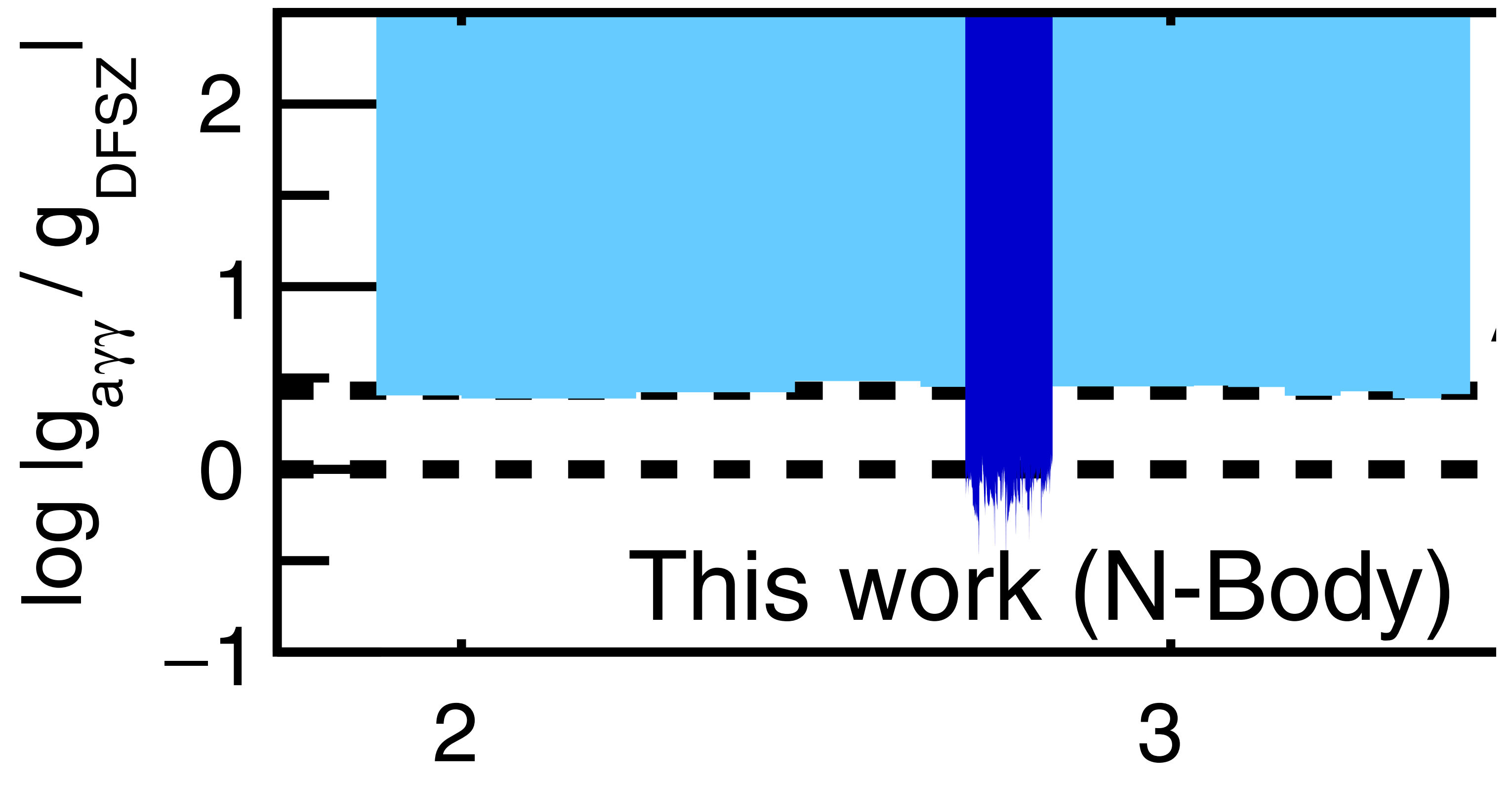
N. Du,[1] N. Force,[1] R. Khatiwada,[1] E. Lentz,[1] R. Ottens,[1] L. J Rosenberg,[1] G. Rybka,[1,*] G. Carosi,[2] N. Woollett,[2] D. Bowring,[3] A. S. Chou,[3] A. Sonnenschein,[3] W. Wester,[3] C. Boutan,[4] N. S. Oblath,[4] R. Bradley,[5] E. J. Daw,[6] A. V. Dixit,[7] J. Clarke,[8] S. R. O'Kelley,[8] N. Crisosto,[9] J. R. Gleason,[9] S. Jois,[9] P. Sikivie,[9] I. Stern,[9] N. S. Sullivan,[9] D. B Tanner,[9]

(ADMX Collaboration) and G. C. Hilton[10]



HFET + 1K temp

$T_{\rm sys} \sim$ a few K



Quantum Amp

+ 100 mK temp

$T_{\rm sys} \sim$ **a few 100 mK**

$\frac{df}{dt} \propto 1/T_{\rm sys}^2$ -> 100x FOM

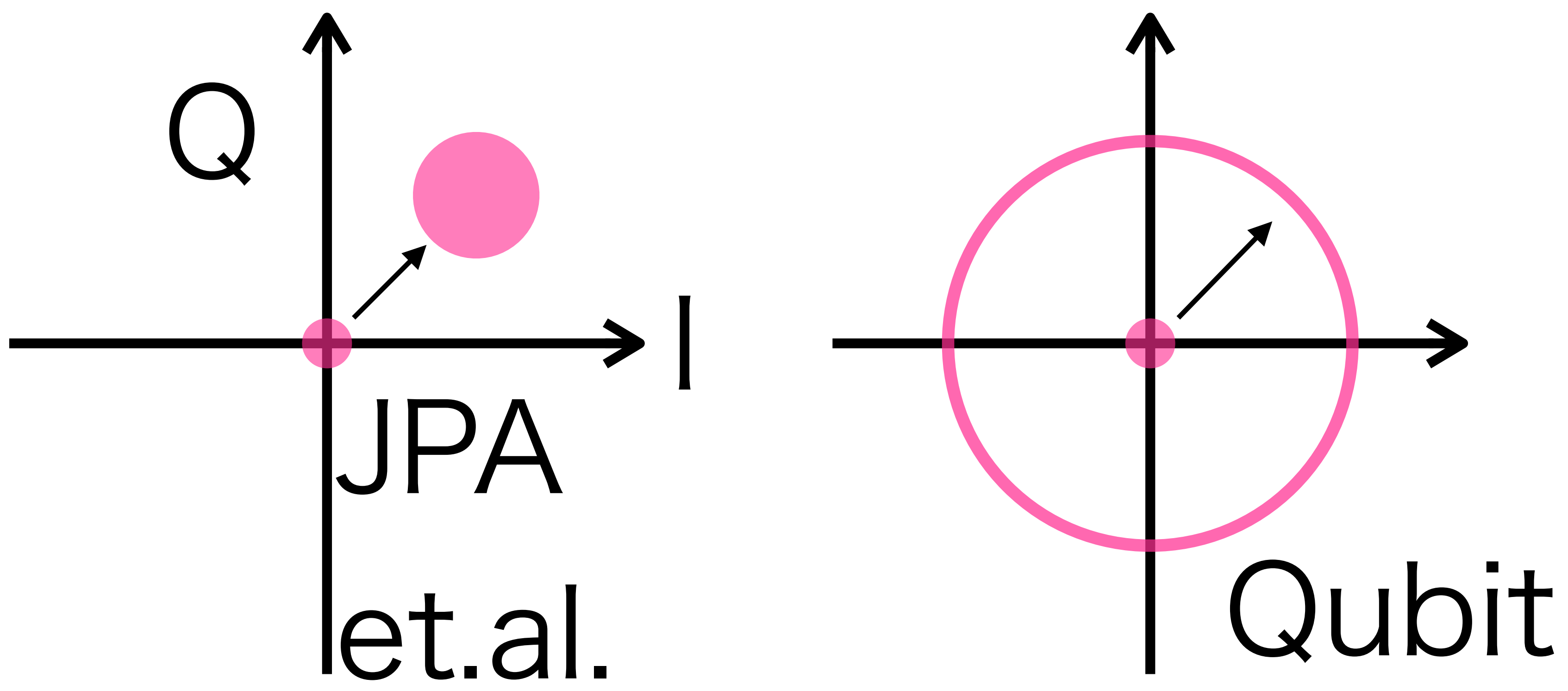
Enabling "invisible" axion search

Axion & QIS

Current axion search will hit standard quantum limit

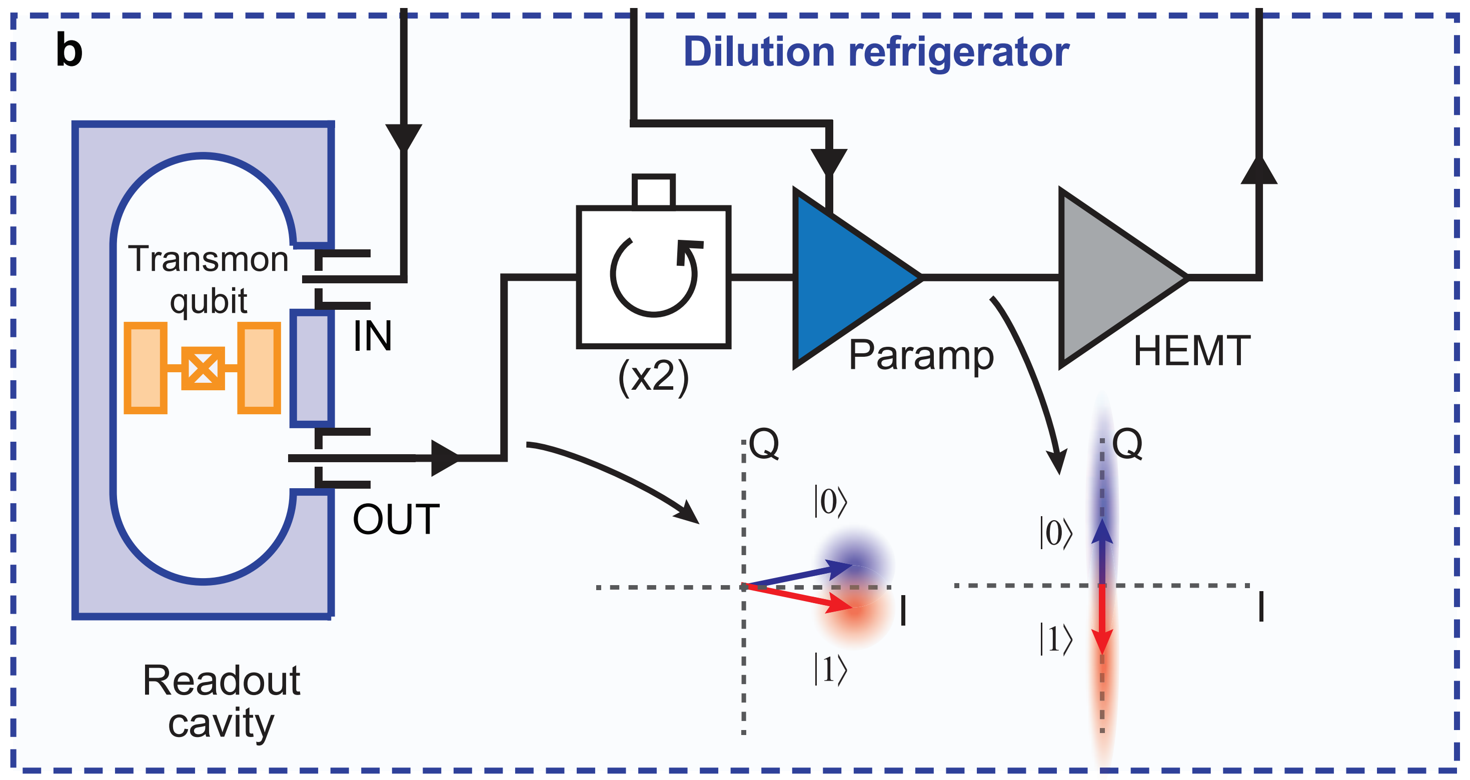
$\Delta n \Delta \phi \geq \frac{1}{2}$: ~30 mK@1GHz, ~300 mK@10GHz

Qubit subverts the limit (ignore phase)

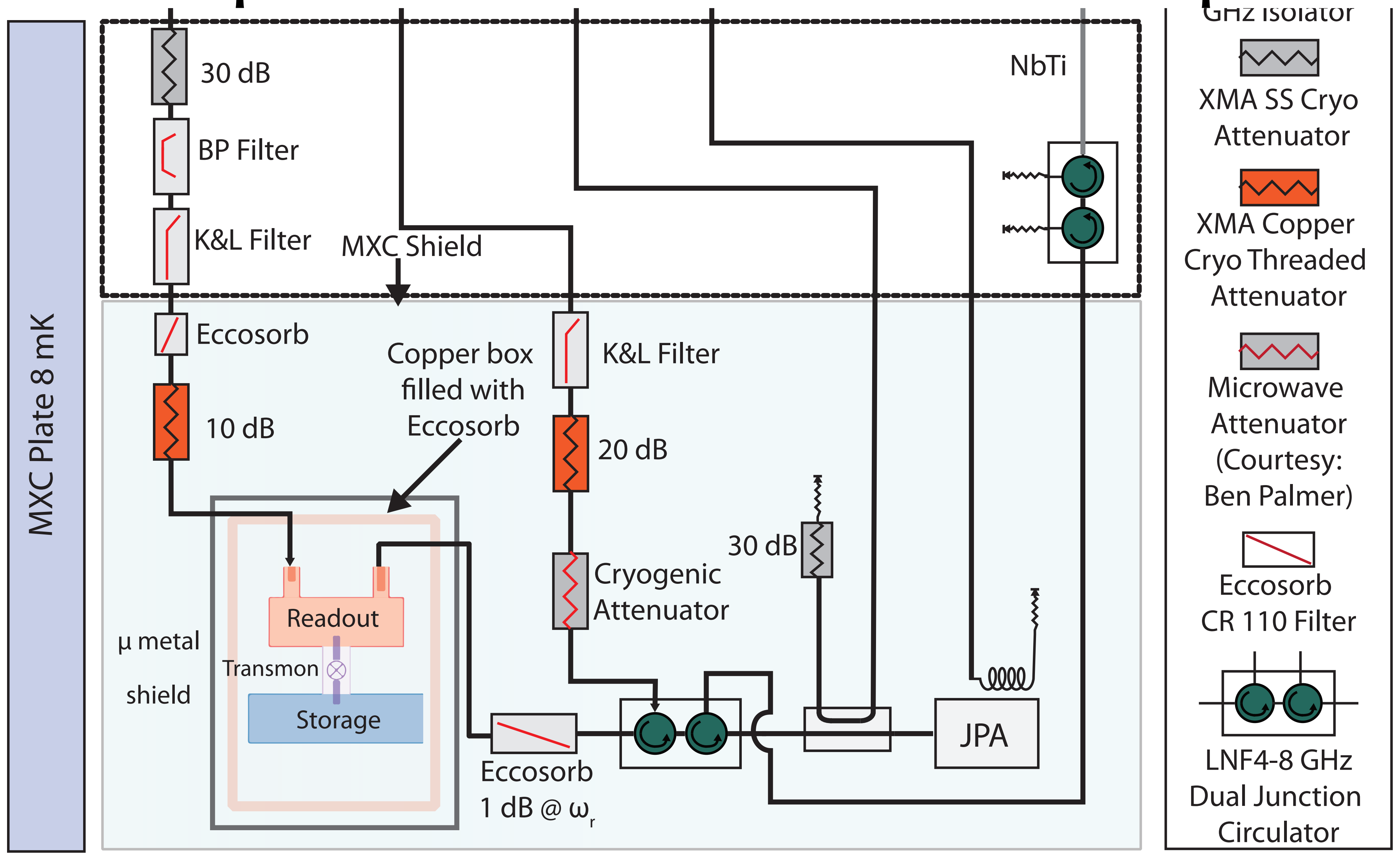


achieved 1000x scan speed than current ADMX

qubit



dark photon search with qubit



Akash et.al., Phys. Rev. Lett. **126**, 141302

Next innovation in axion search could come from QIS again

ADMX experiment

@University of Washington, Seattle, United States, ~50 collaborators from

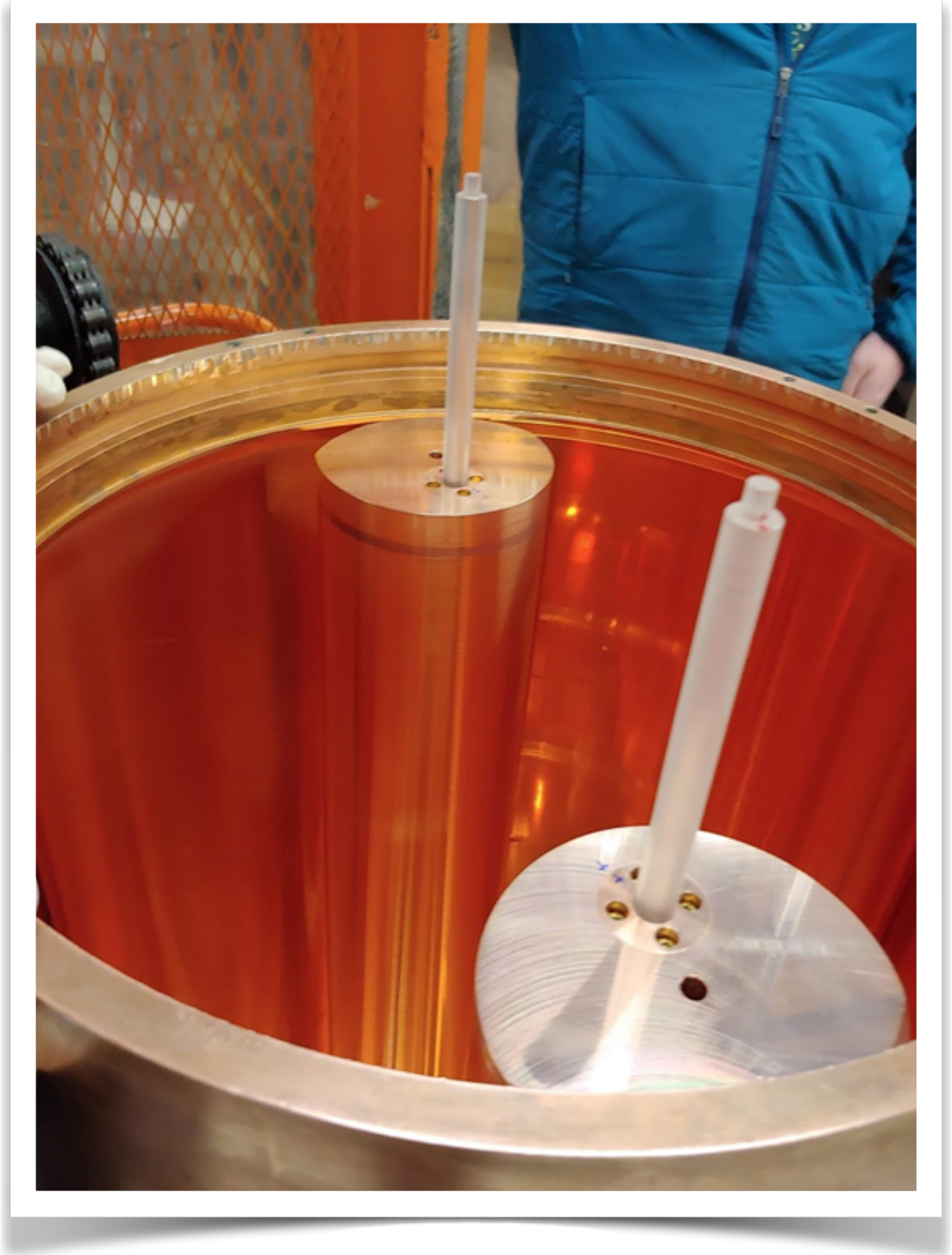
UW, FNAL, LLNL, LBNL, PNNL, LANL, Florida, UWA, Wash U, Sheffield, Chicago, IIT, Berkeley

ADMX experiment

Cavity

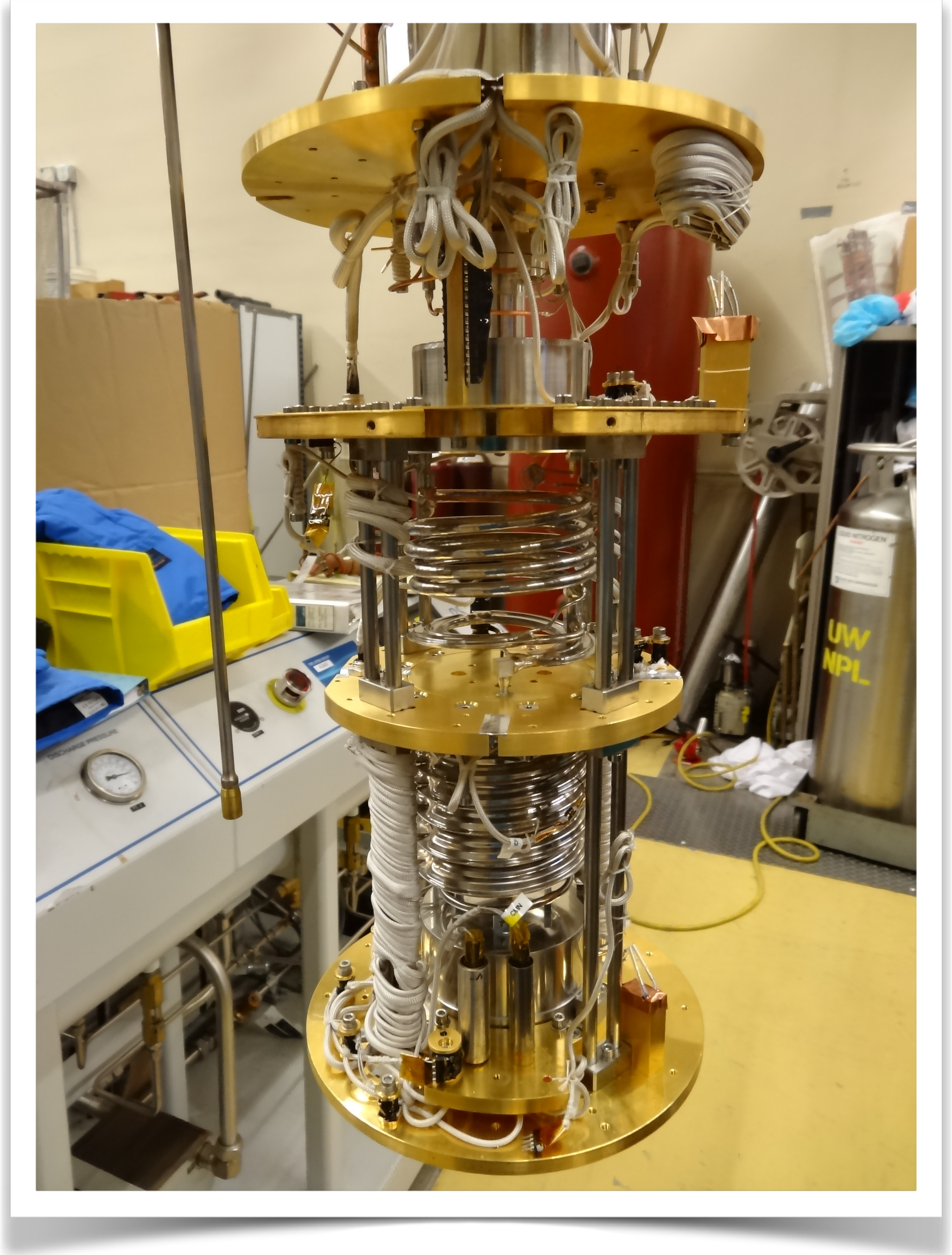
- Copper plated
- Sapphire axles

Q_{unload}~160k, 136 L



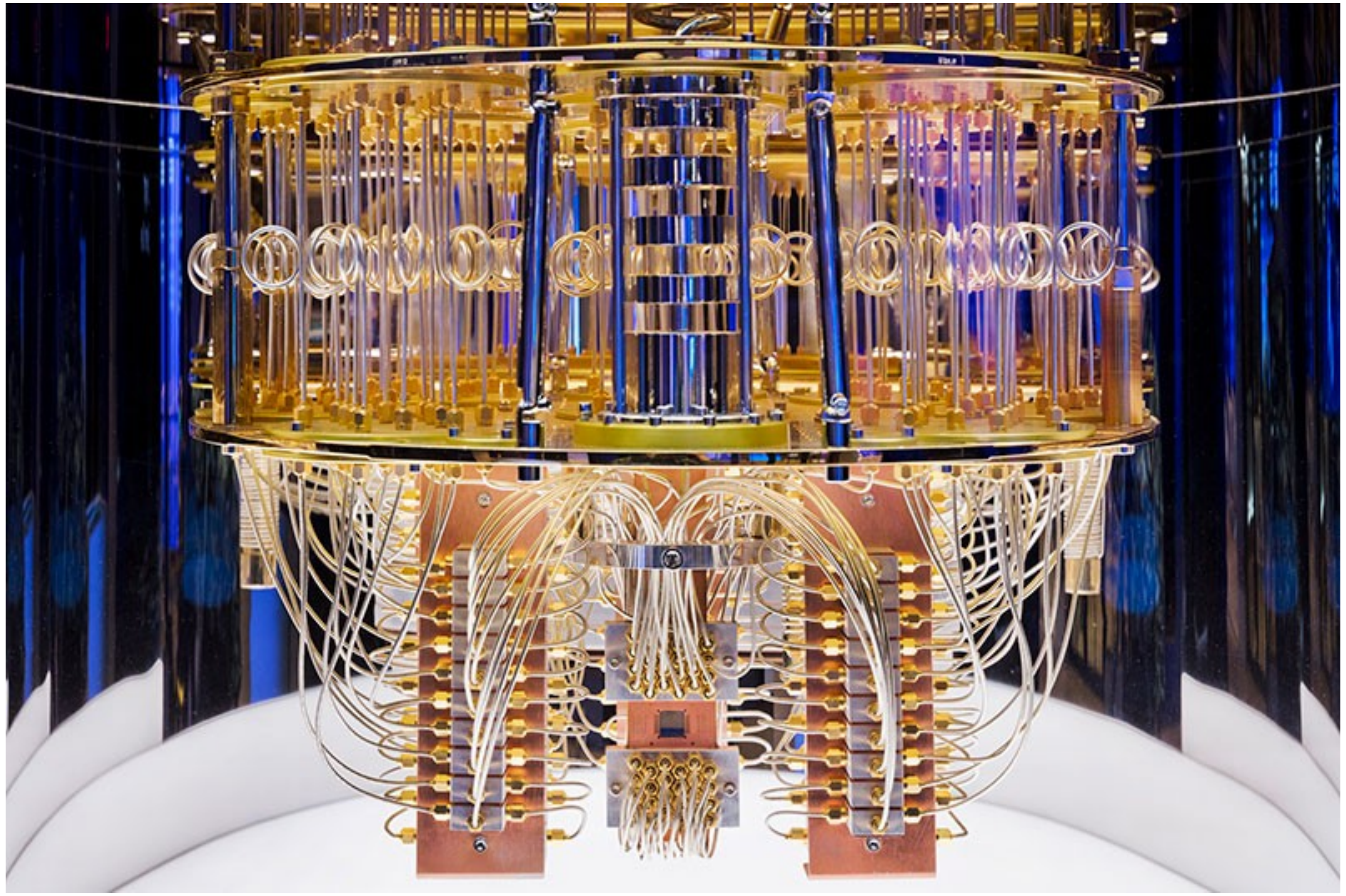
Dilution Refrigerator

- Janis JDR-800
- 800 μW@100 mK
- 8 mK w/o any load



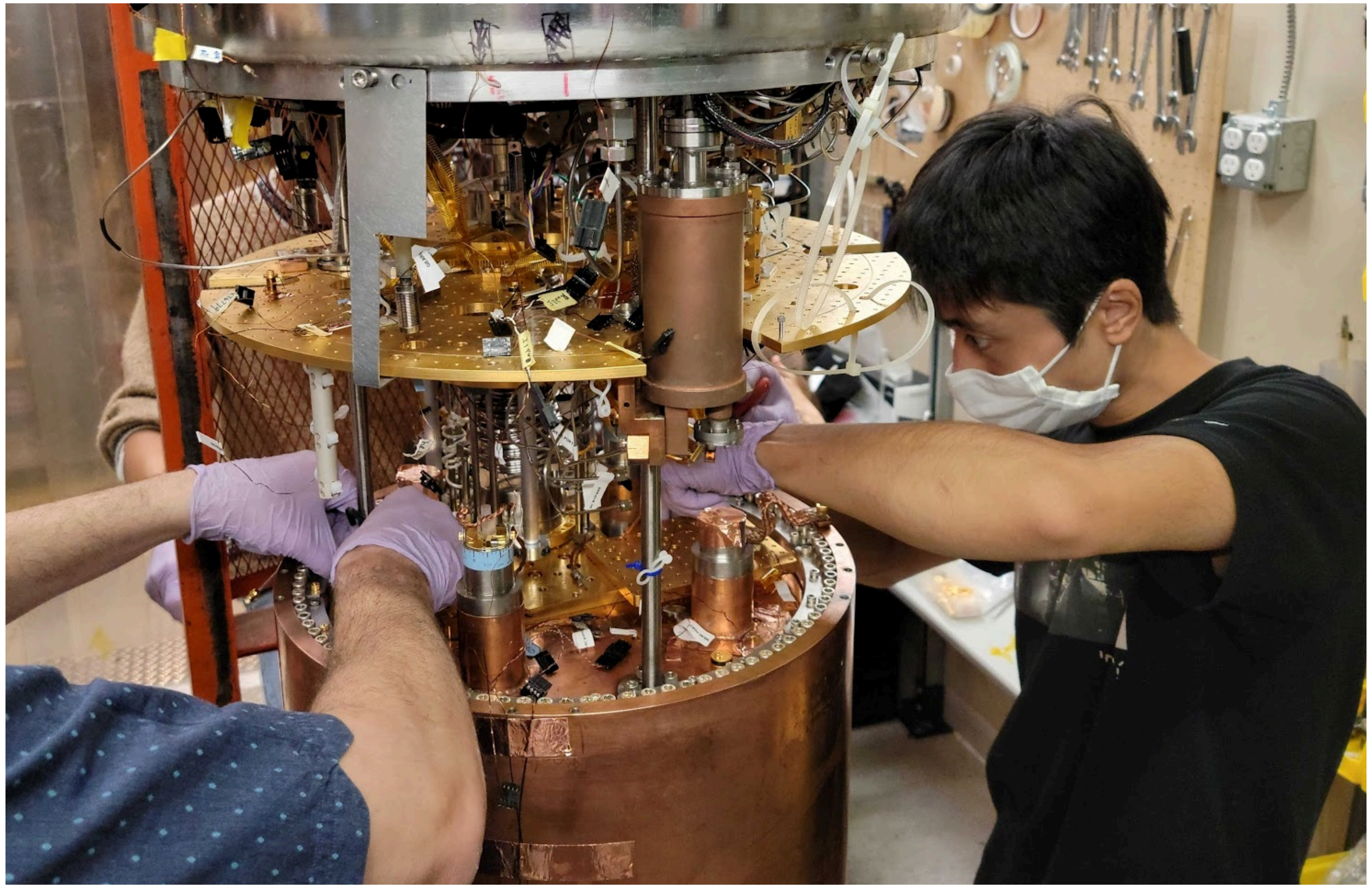
Inside the ADMX

An ideal



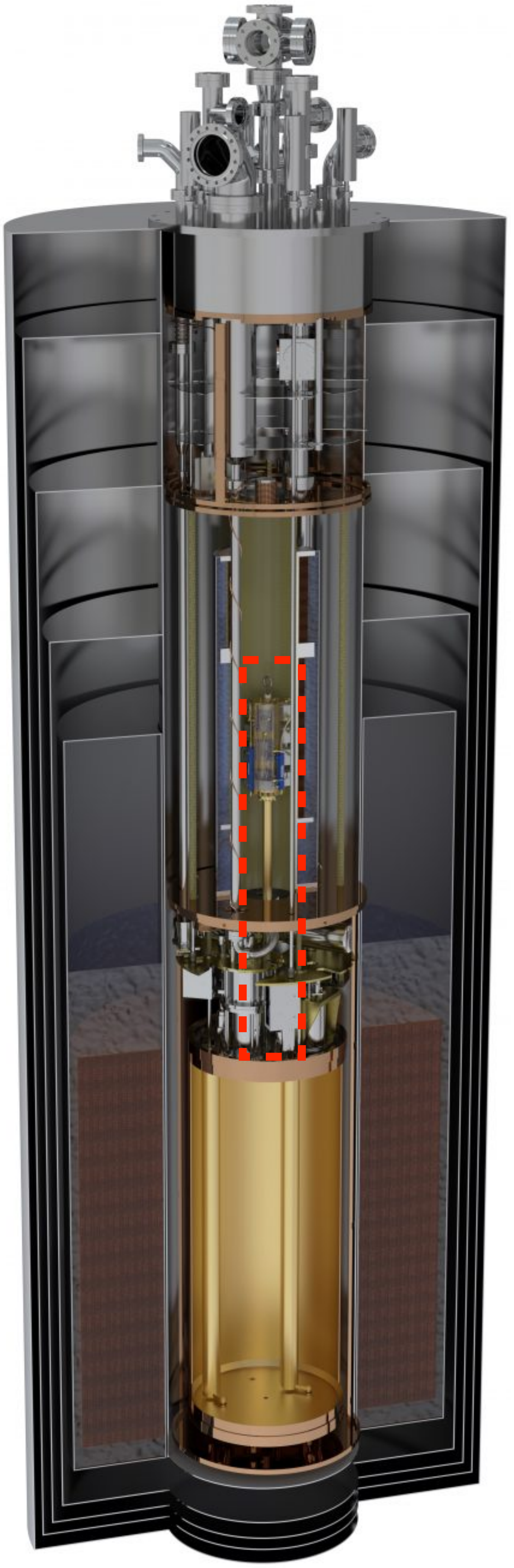
IBM Q System One

Reality

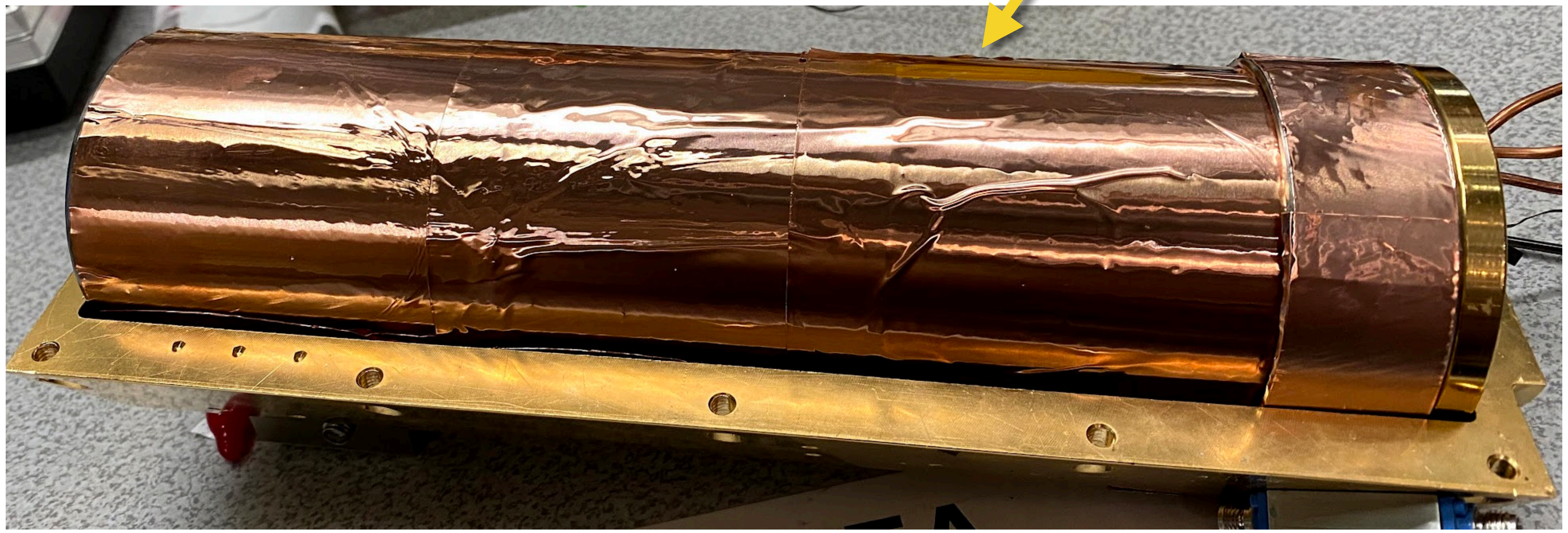


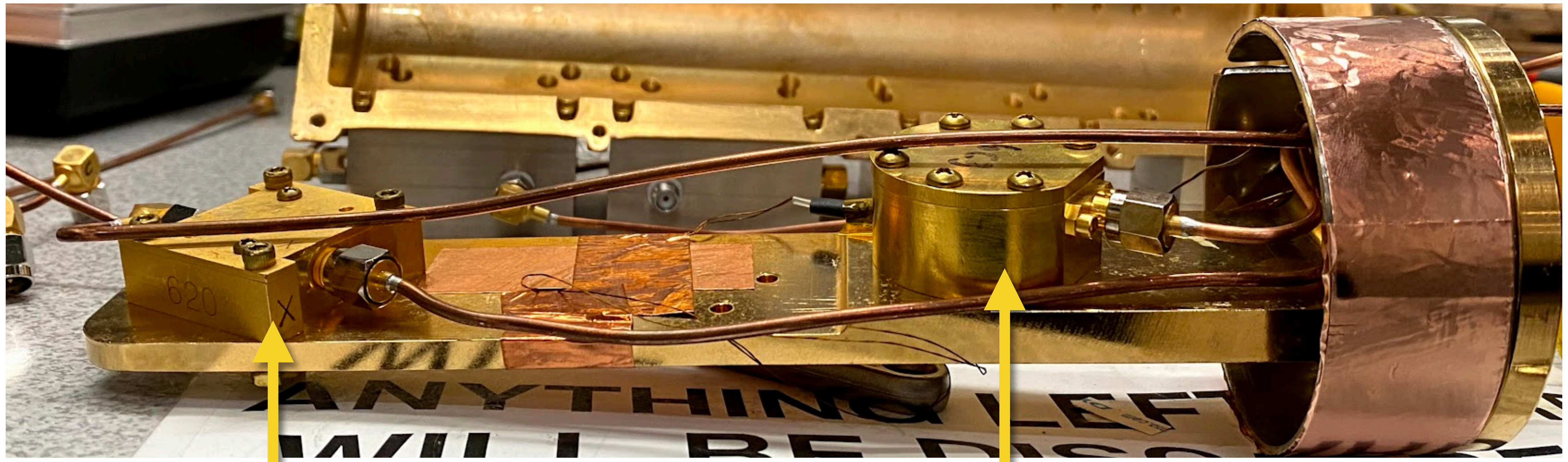
ADMX-Gen2 Run1C

Inside the ADMX



μ-metal shield

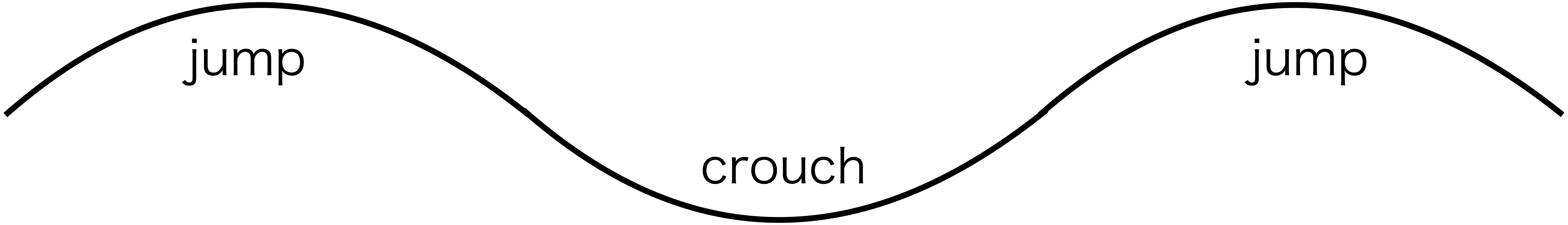




TWPA

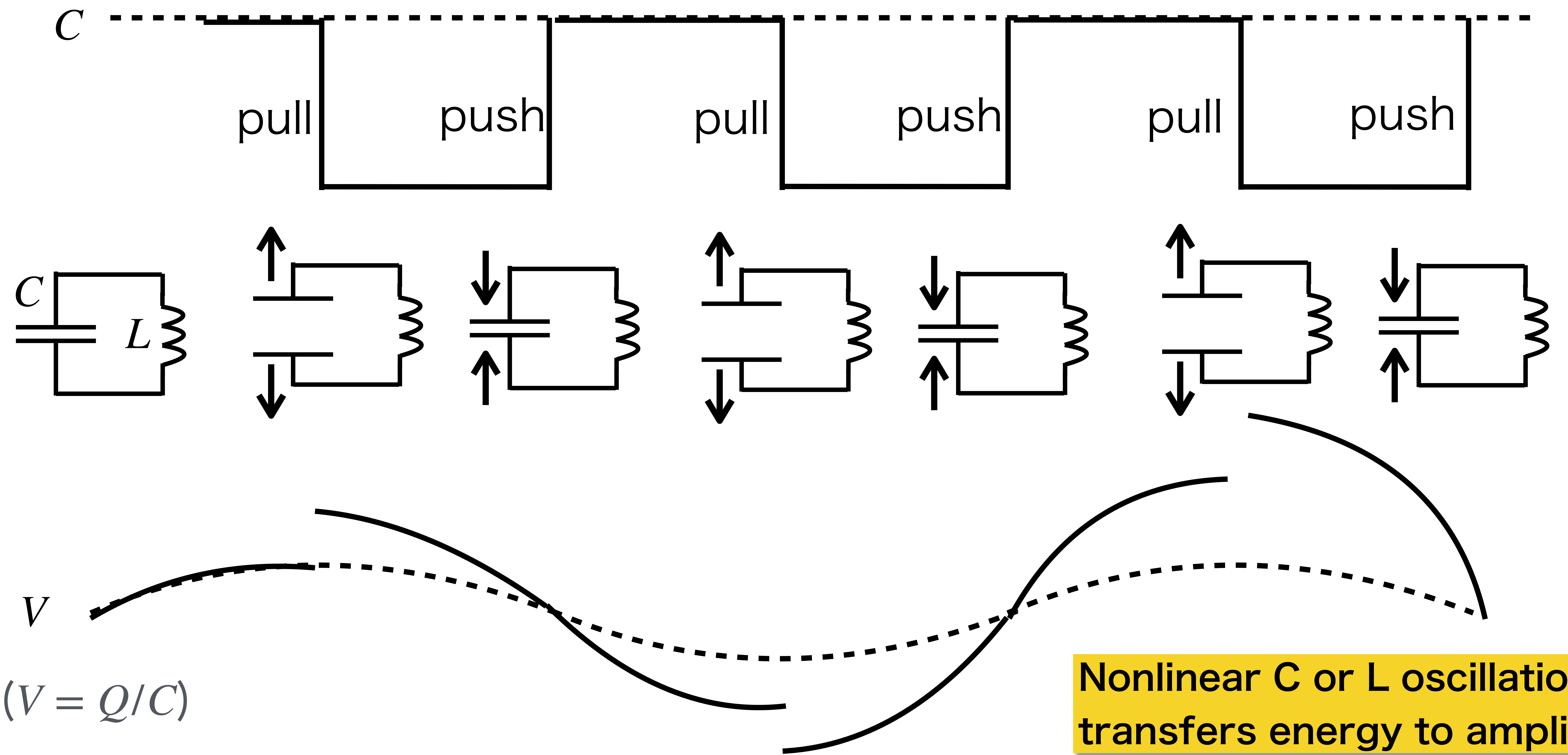
JPA

Parametric Amplifier



https://www.nytimes.com/interactive/2014/02/18/sports/olympics/mens-ski-halfpipe.html

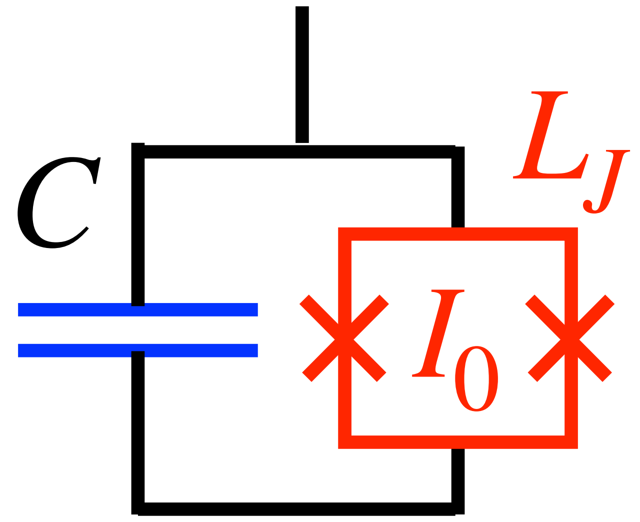
Parametric Amplifier

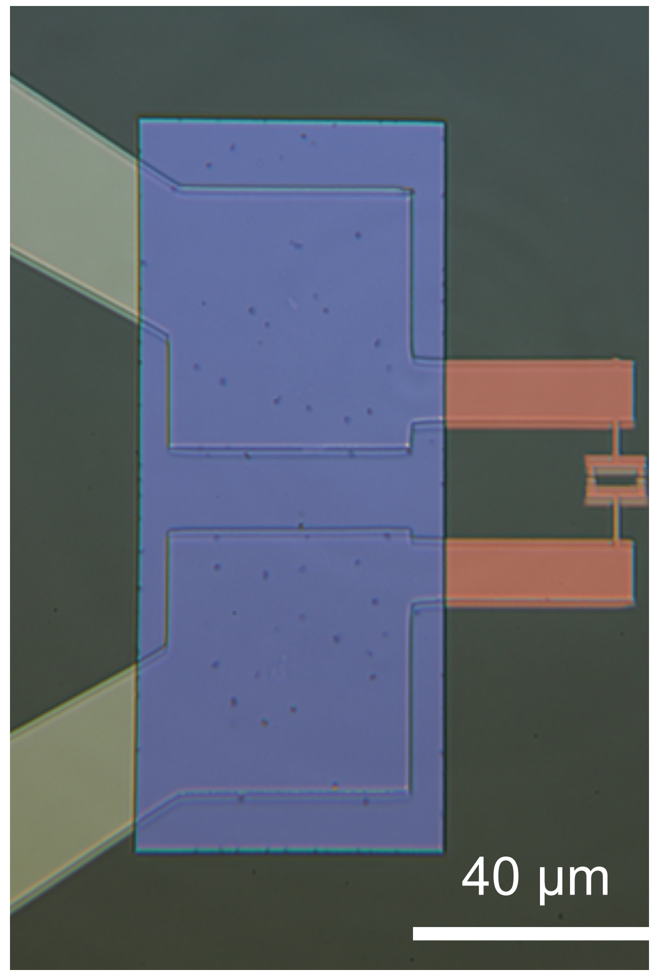


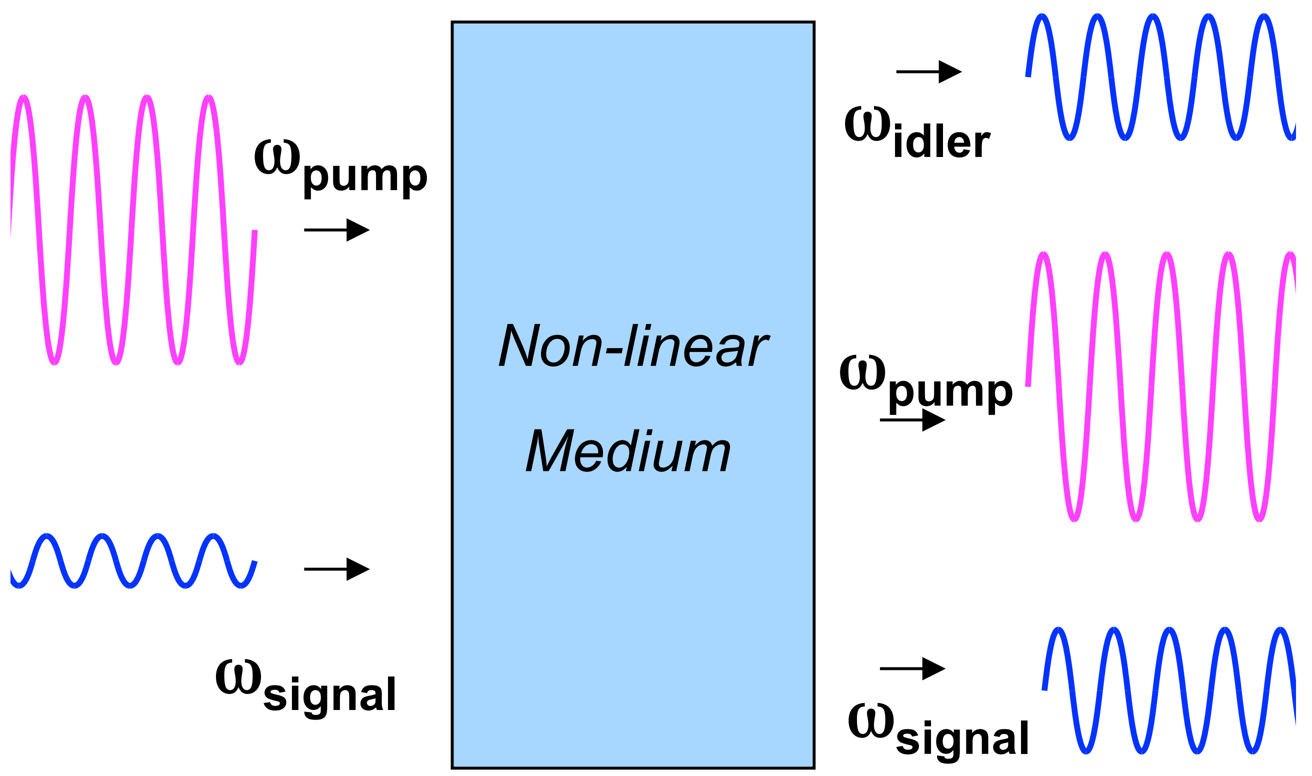
Nonlinear C or L oscillation transfers energy to amplitude

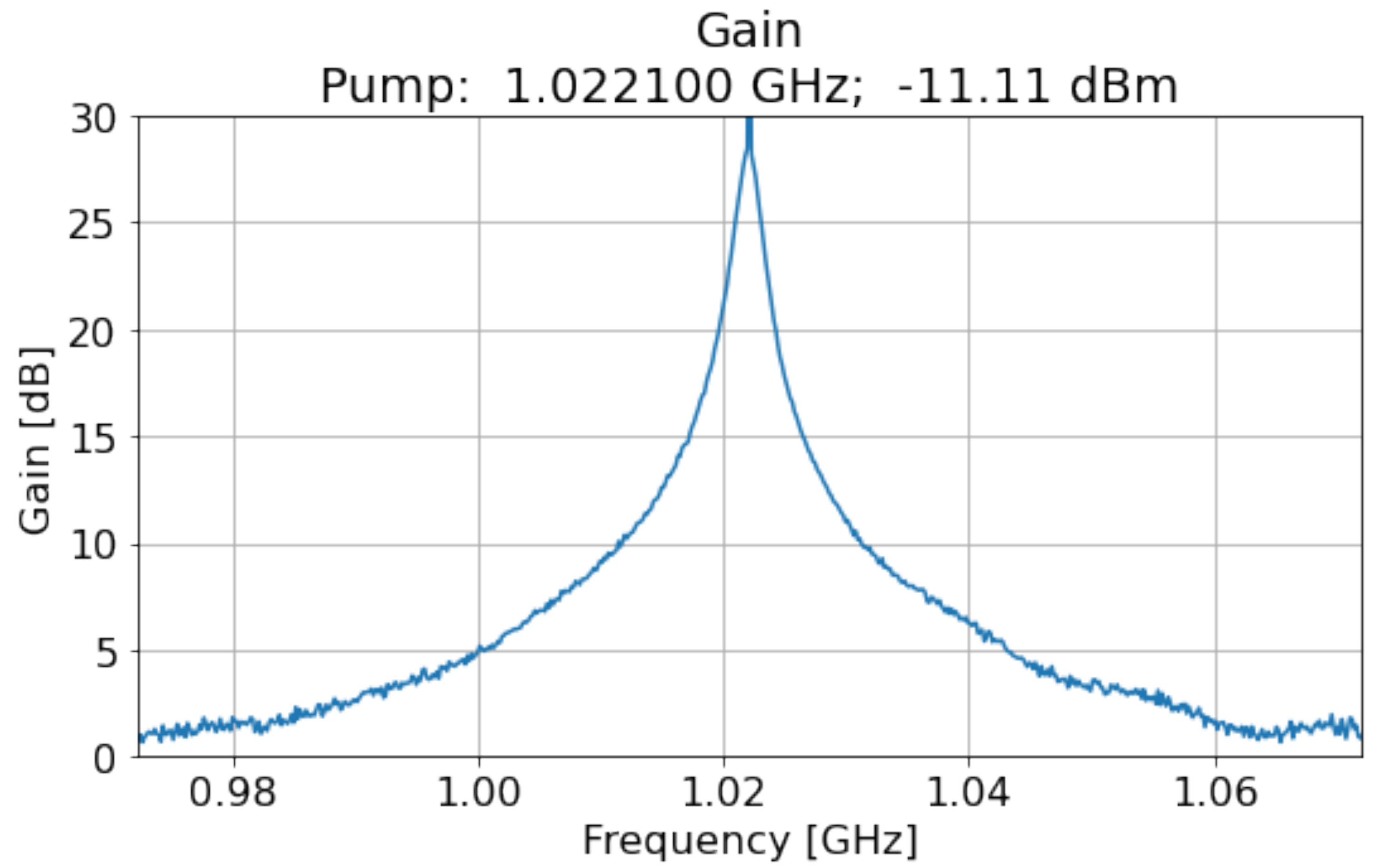
Josephson Parametric Amplifier

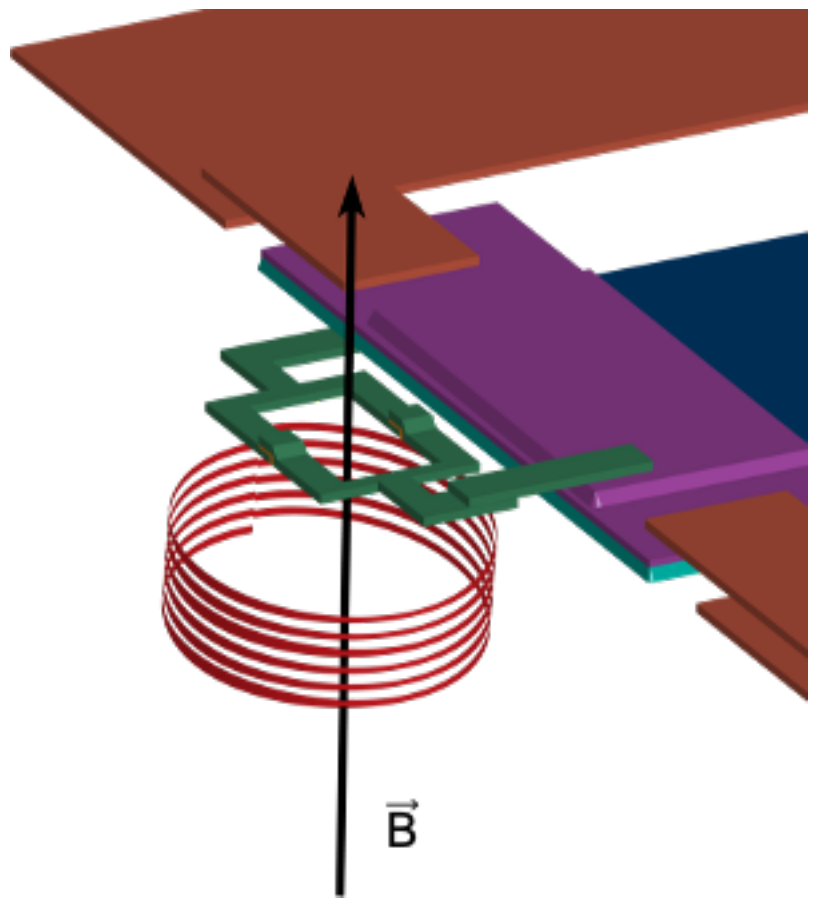
Josephson Junction is
Nonlinear Inductor

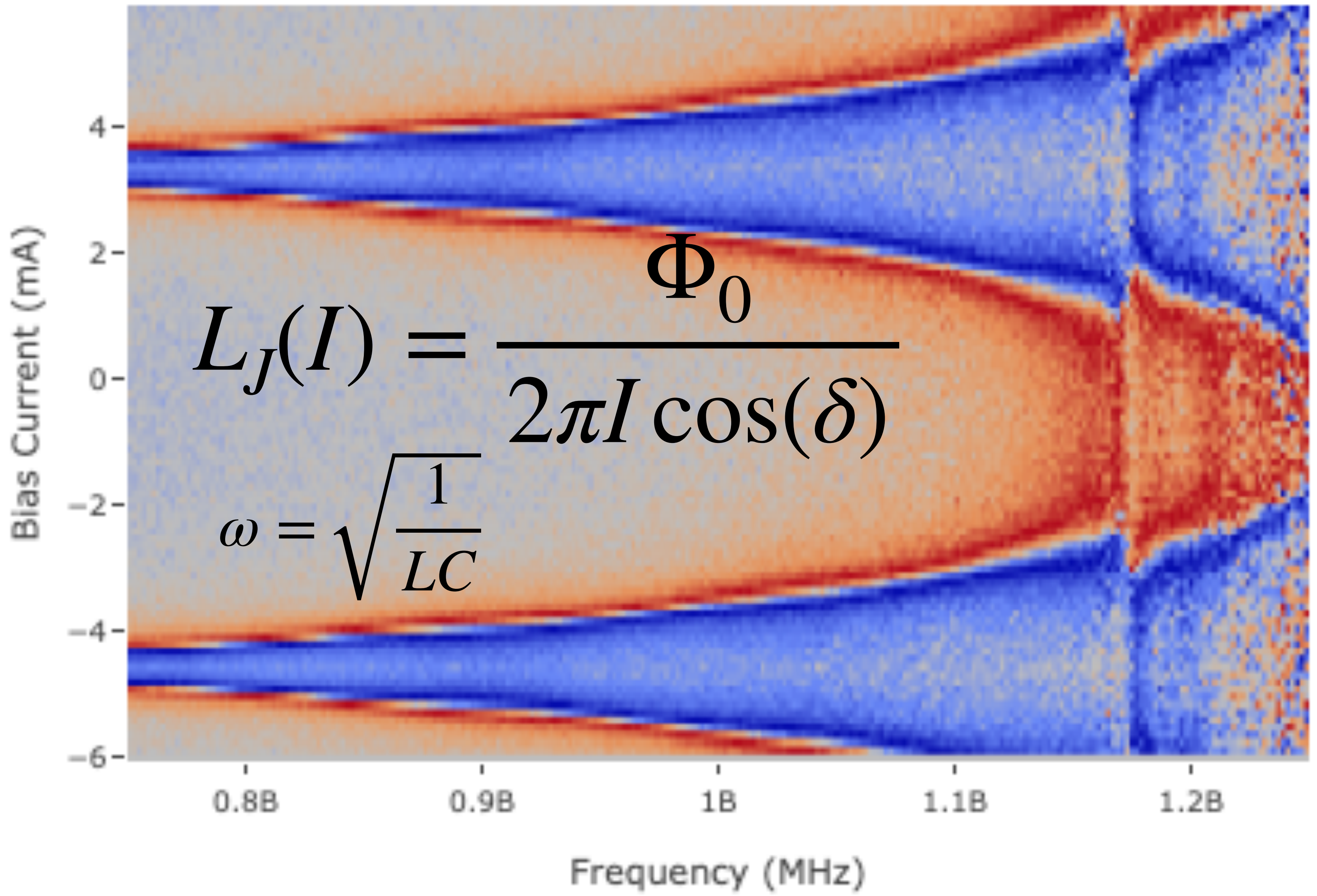












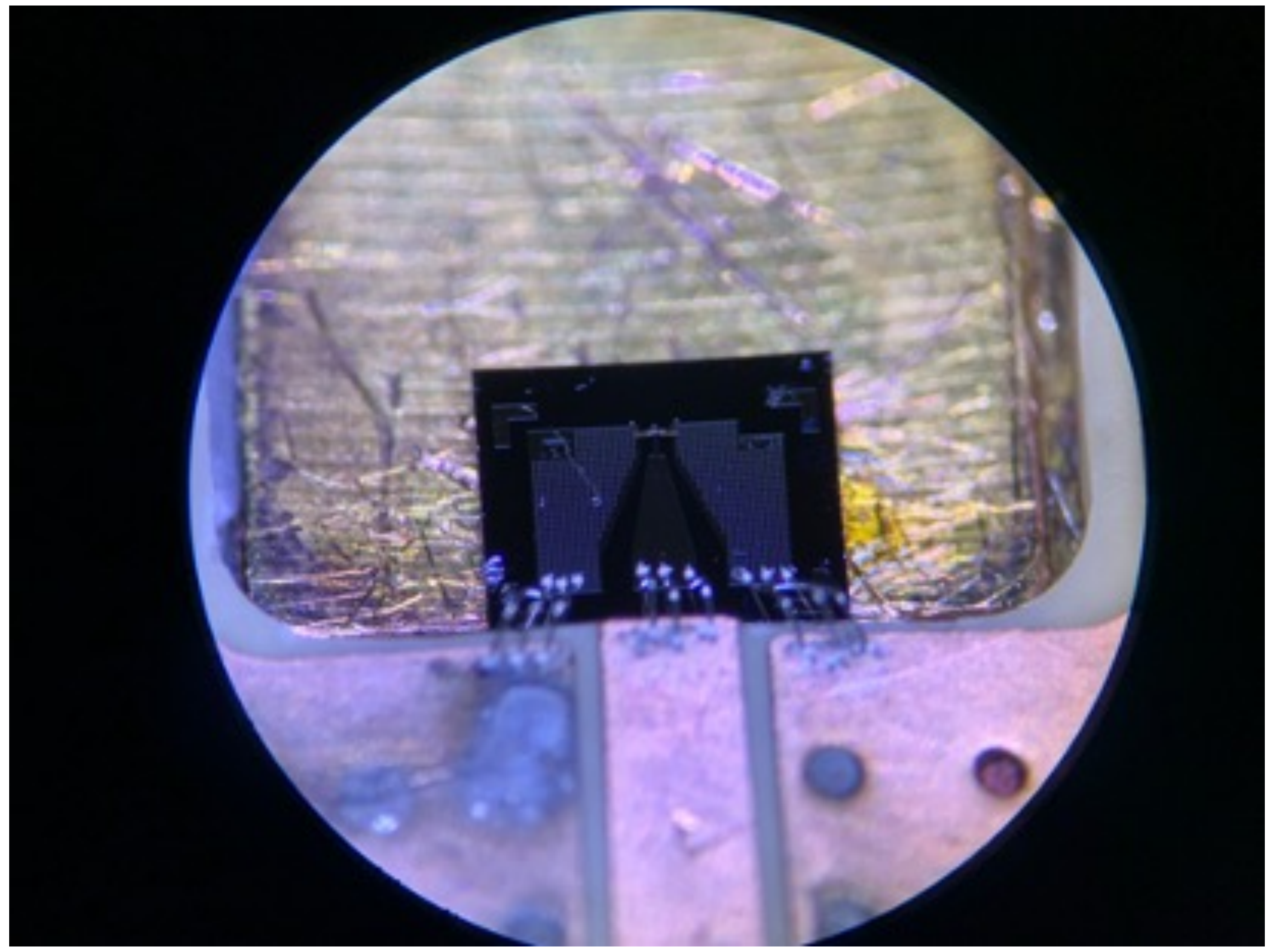
Minimum Noise

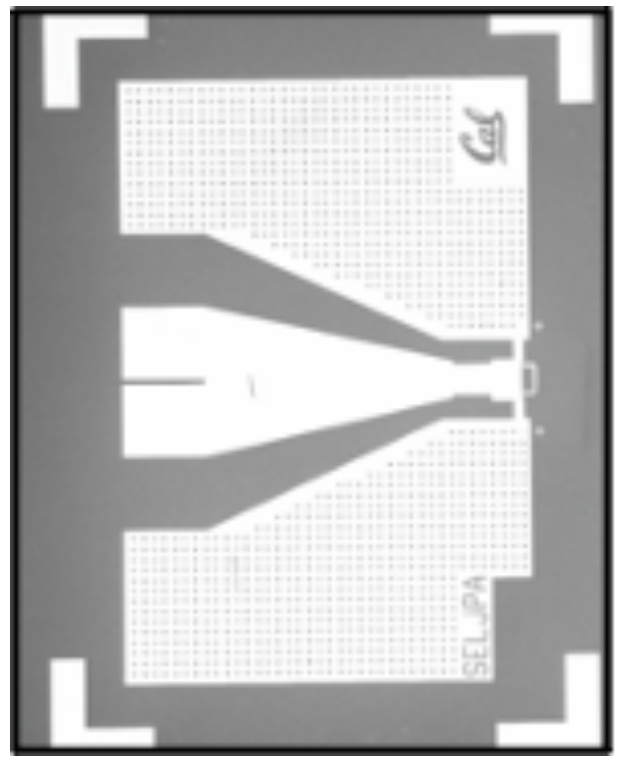
$$T_{\text{idler}} \sim T_{\text{hottest part}} \sim 100\ \text{mK} > \underset{\text{(SQL)}}{\frac{fbh}{2}}$$

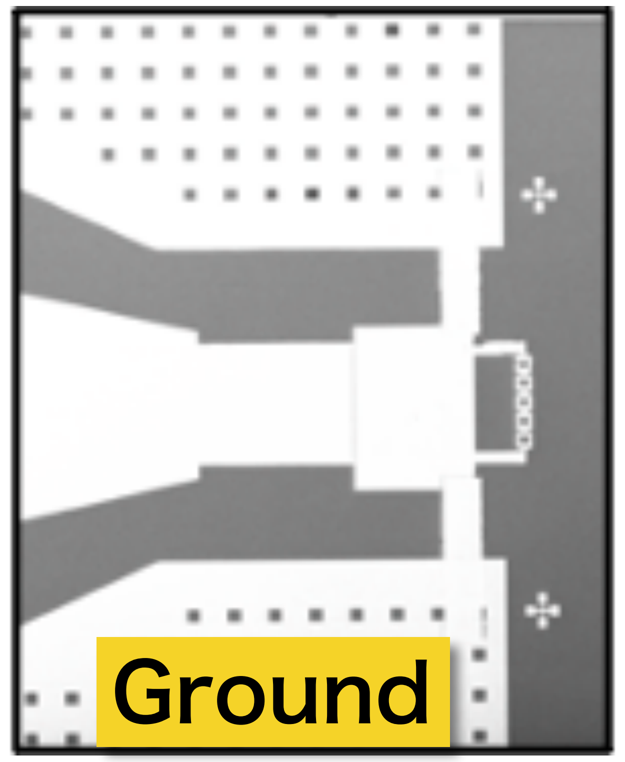
This is way smaller than HFET (~1K)

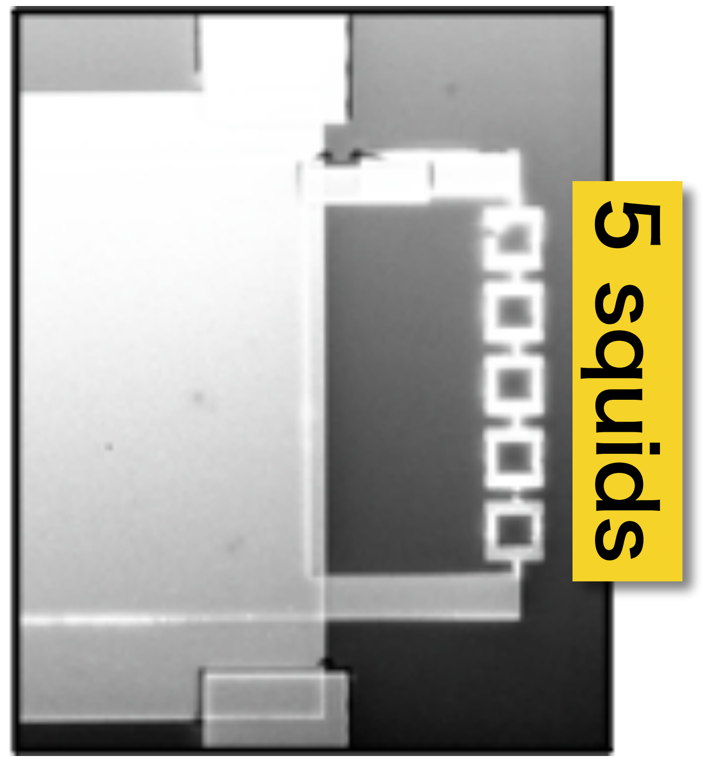
JPA for ADMX

Fabricated at UC Berkeley, Siddiqi group

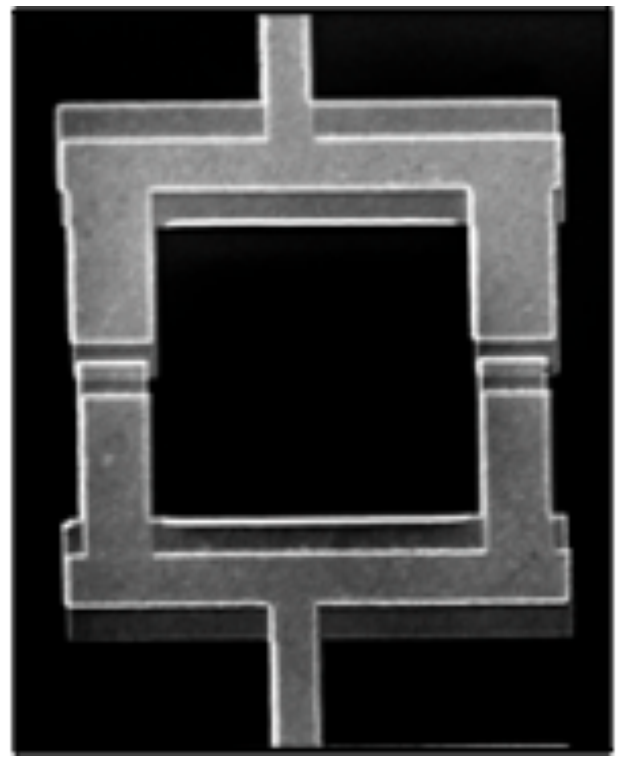




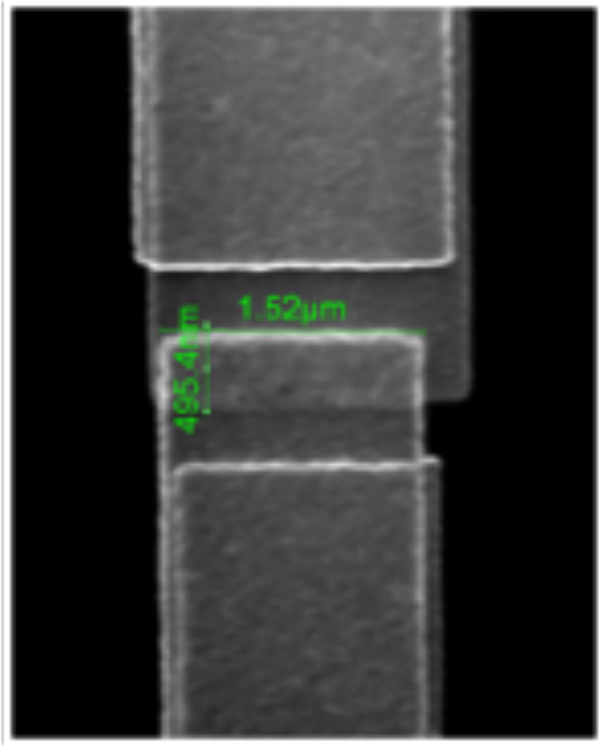




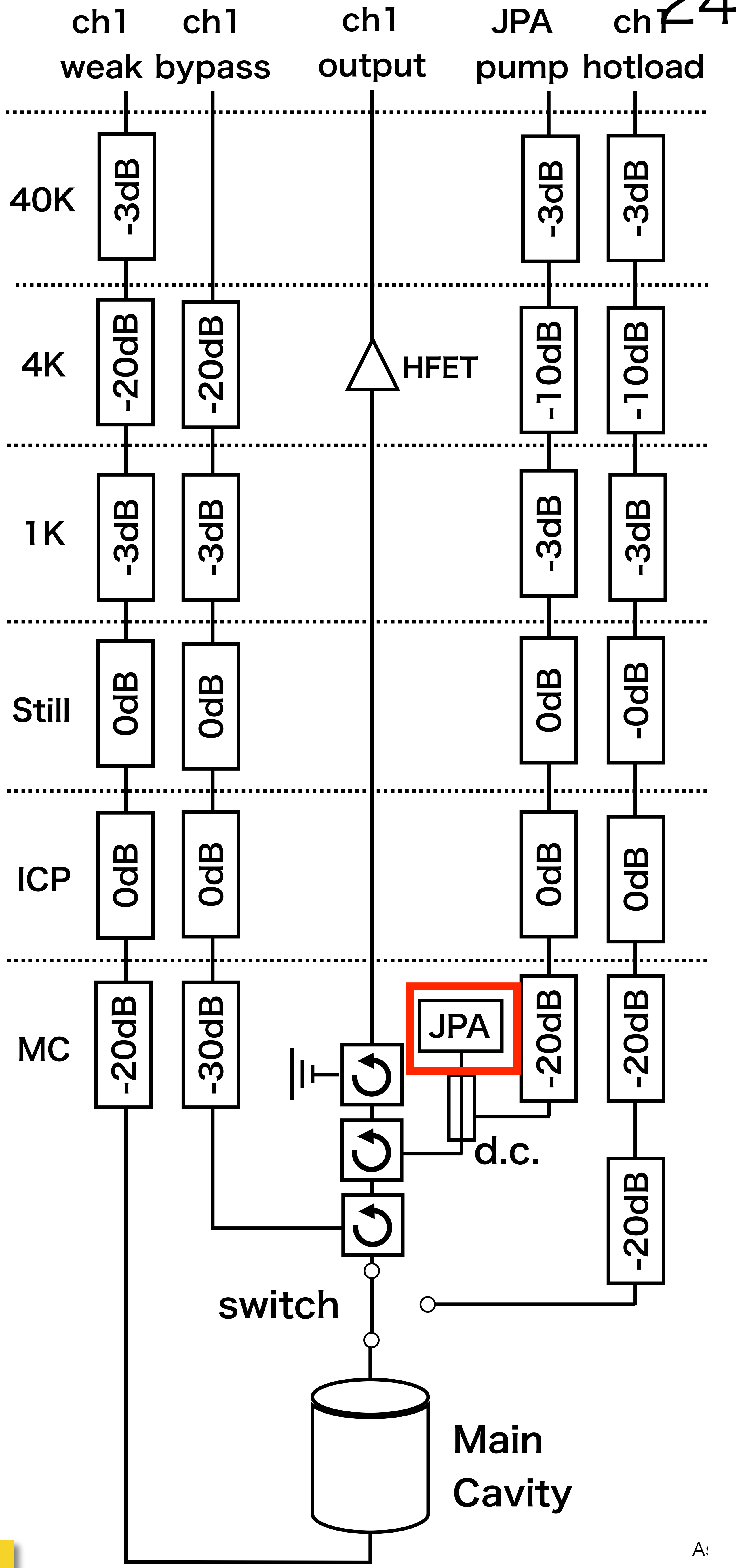
Capacitance



DC SQUID



Josephson Junction



Recent results

2018:

First DFSZ limit 2.7-2.8 μeV

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

Editors' Suggestion   Featured in Physics

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

N. Du,[1] N. Force,[1] R. Khatiwada,[1] E. Lentz,[1] R. Ottens,[1] L. J Rosenberg,[1] G. Rybka,[1,*] G. Carosi,[2] N. Woollett,[2] D. Bowring,[3] A. S. Chou,[3] A. Sonnenschein,[3] W. Wester,[3] C. Boutan,[4] N. S. Oblath,[4] R. Bradley,[5] E. J. Daw,[6] A. V. Dixit,[7] J. Clarke,[8] S. R. O'Kelley,[8] N. Crisosto,[9] J. R. Gleason,[9] S. Jois,[9] P. Sikivie,[9] I. Stern,[9] N. S. Sullivan,[9] D. B Tanner,[9]

(ADMX Collaboration) and G. C. Hilton[10]

2020:

Extend to 2.8-3.3 μeV

PHYSICAL REVIEW LETTERS **124,** 101303 (2020)

Editors' Suggestion

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

T. Braine,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1,*] S. Kimes,[1] L. J. Rosenberg,[1] G. Rybka,[1] J. Yang,[1] D. Bowring,[2] A. S. Chou,[2] R. Khatiwada,[2] A. Sonnenschein,[2] W. Wester,[2] G. Carosi,[3] N. Woollett,[3] L. D. Duffy,[4] R. Bradley,[5] C. Boutan,[6] M. Jones,[6] B. H. LaRoque,[6] N. S. Oblath,[6] M. S. Taubman,[6] J. Clarke,[7] A. Dove,[7] A. Eddins,[7] S. R. O'Kelley,[7] S. Nawaz,[7] I. Siddiqi,[7] N. Stevenson,[7] A. Agrawal,[8] A. V. Dixit,[8] J. R. Gleason,[9] S. Jois,[9] P. Sikivie,[9] J. A. Solomon,[9] N. S. Sullivan,[9] D. B. Tanner,[9] E. Lentz,[10] E. J. Daw,[11] J. H. Buckley,[12] P. M. Harrington,[12] E. A. Henriksen,[12] and K. W. Murch[12]

(ADMX Collaboration)

2021:

https://arxiv.org/pdf/2110.06096.pdf

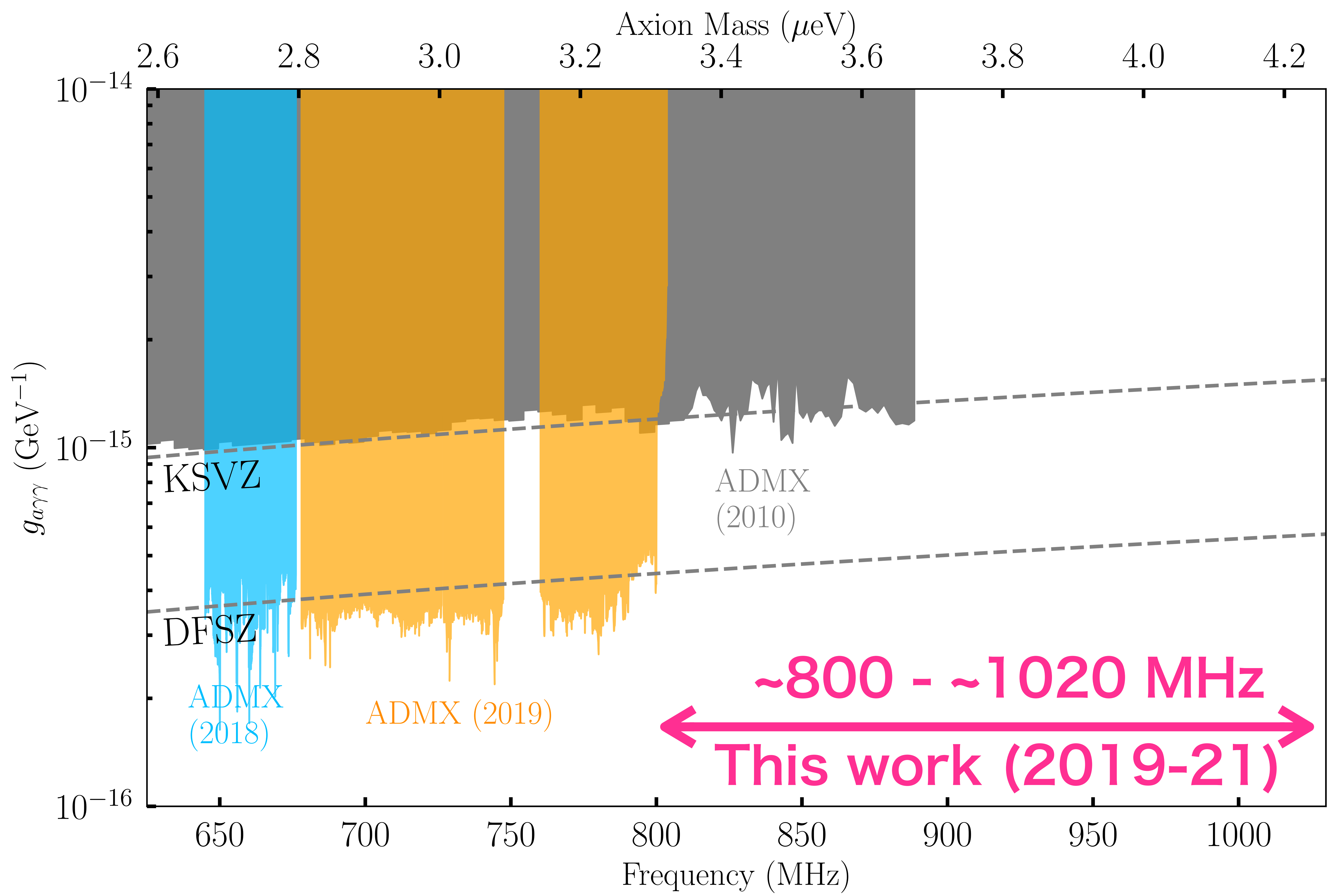
This talk (Accepted by PRL)

Search for "Invisible" Axion Dark Matter in the 3.3–4.2 μeV Mass Range

C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1,*] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A. T. Hipp,[5] S. Jois,[5] P. Sikivie,[5] N. S. Sullivan,[5] D. B. Tanner,[5] E. Lentz,[6] R. Khatiwada,[7,4] G. Carosi,[8] N. Robertson,[8] N. Woollett,[8] L. D. Duffy,[9] C. Boutan,[10] M. Jones,[10] B. H. LaRoque,[10] N. S. Oblath,[10] M. S. Taubman,[10] E. J. Daw,[11] M. G. Perry,[11] J. H. Buckley,[12] C. Gaikwad,[12] J. Hoffman,[12] K. W. Murch,[12] M. Goryachev,[13] B. T. McAllister,[13] A. Quiskamp,[13] C. Thomson,[13] and M. E. Tobar[13]

(ADMX Collaboration)

Data-taking Summary



Period:

October 2019 - May 2021

Frequency range:

~800 - ~1020 MHz

→ **The widest coverage** (for DFSZ)

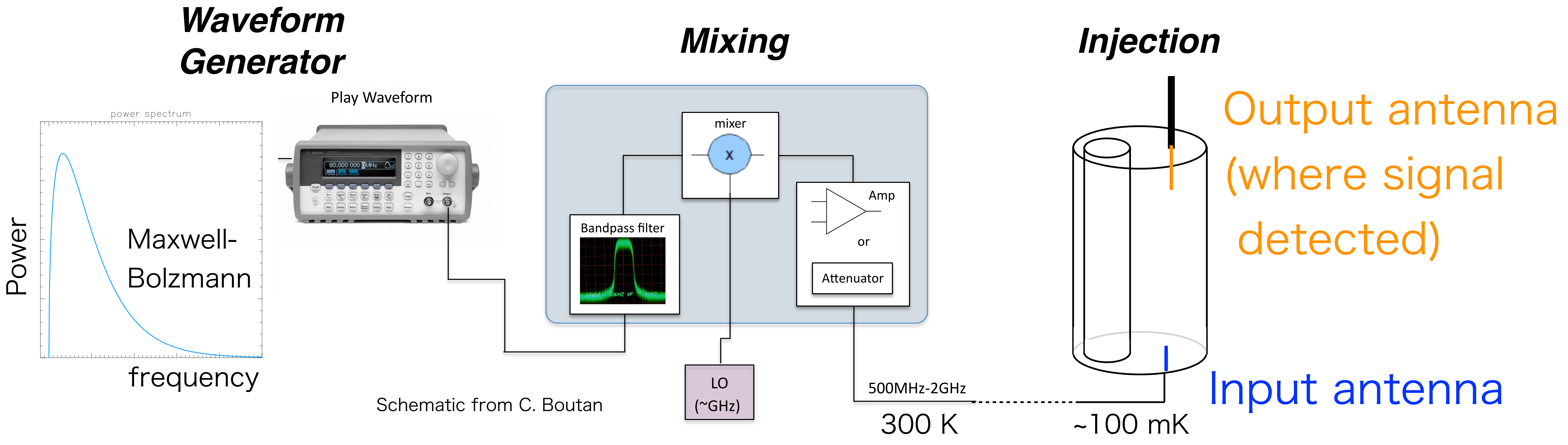
Noise Temperature:

Measured with SNRI and y-factor measurements

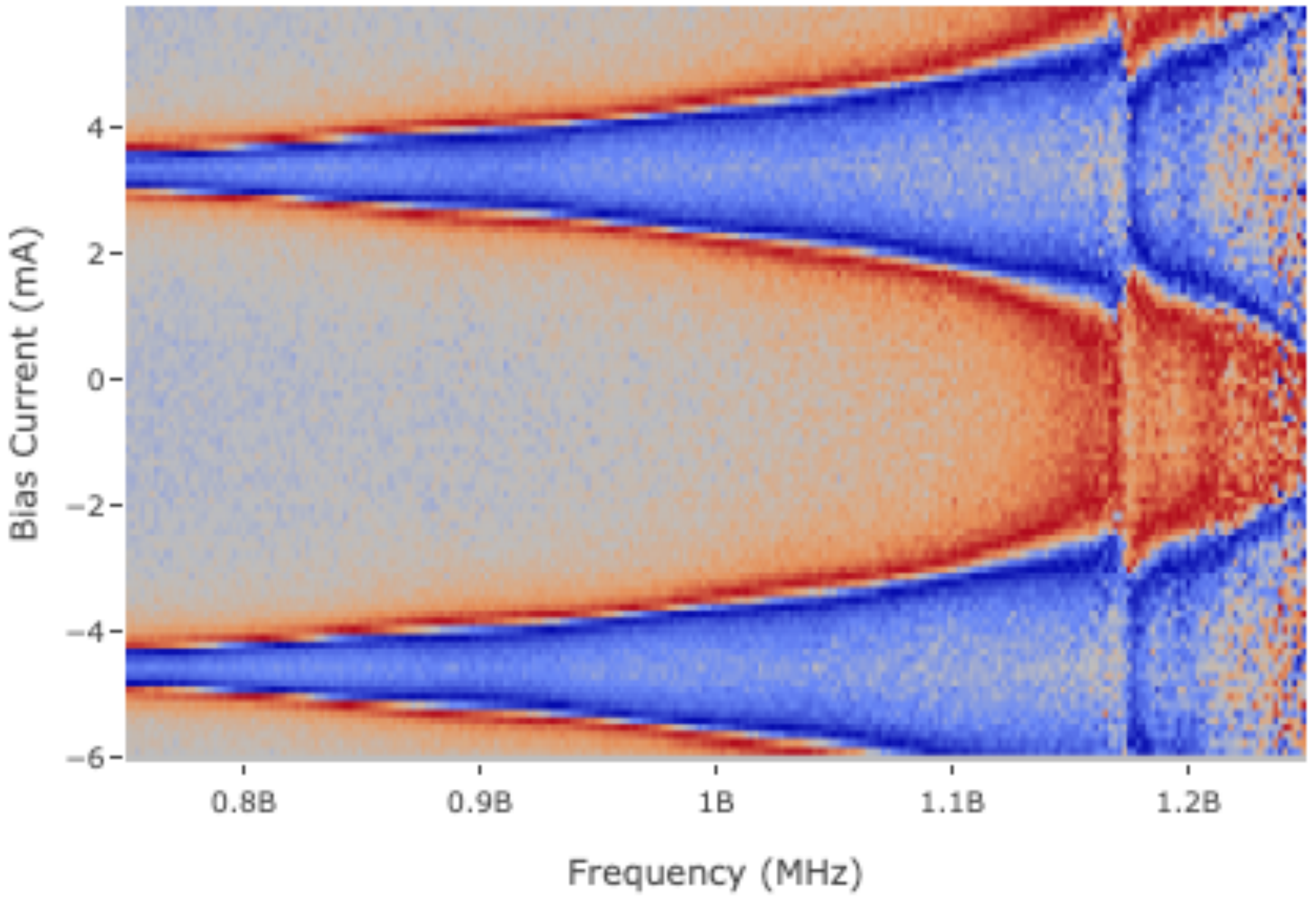
→ **~600 mK (expected: ~300 mK)**

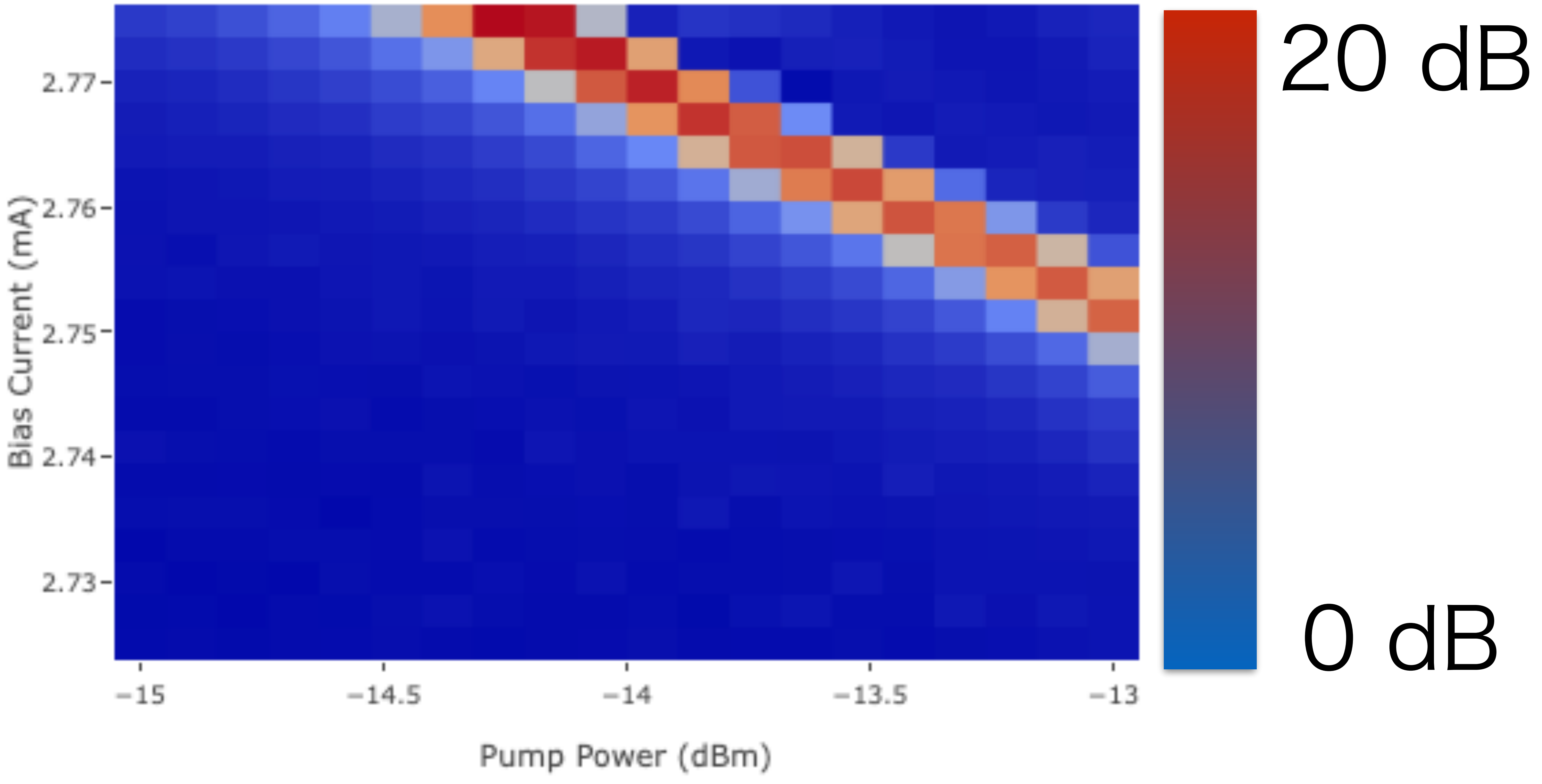
Synthetic Axion Generator (SAG)

Artificial signal injection system to test RF system and analyzers



JPA Operation



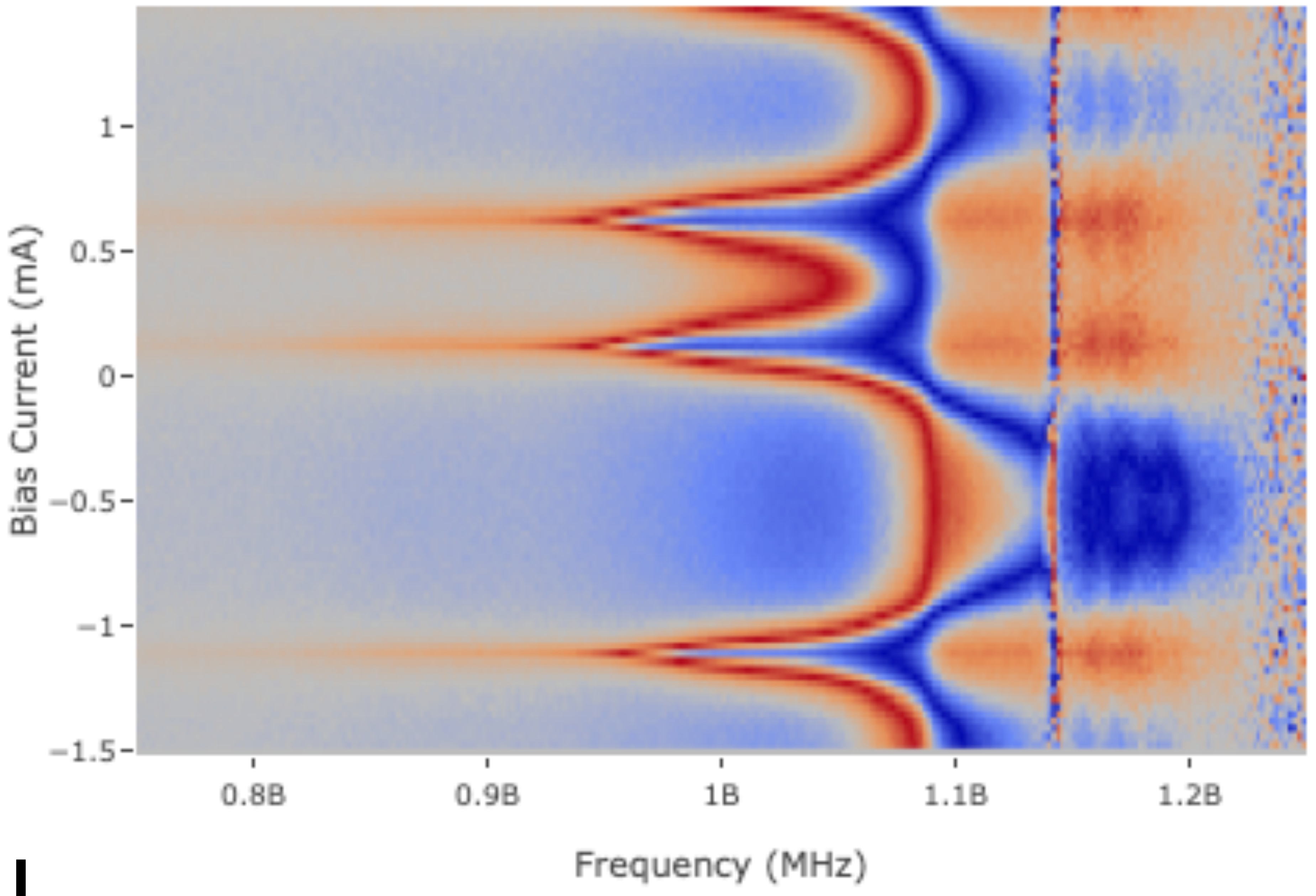


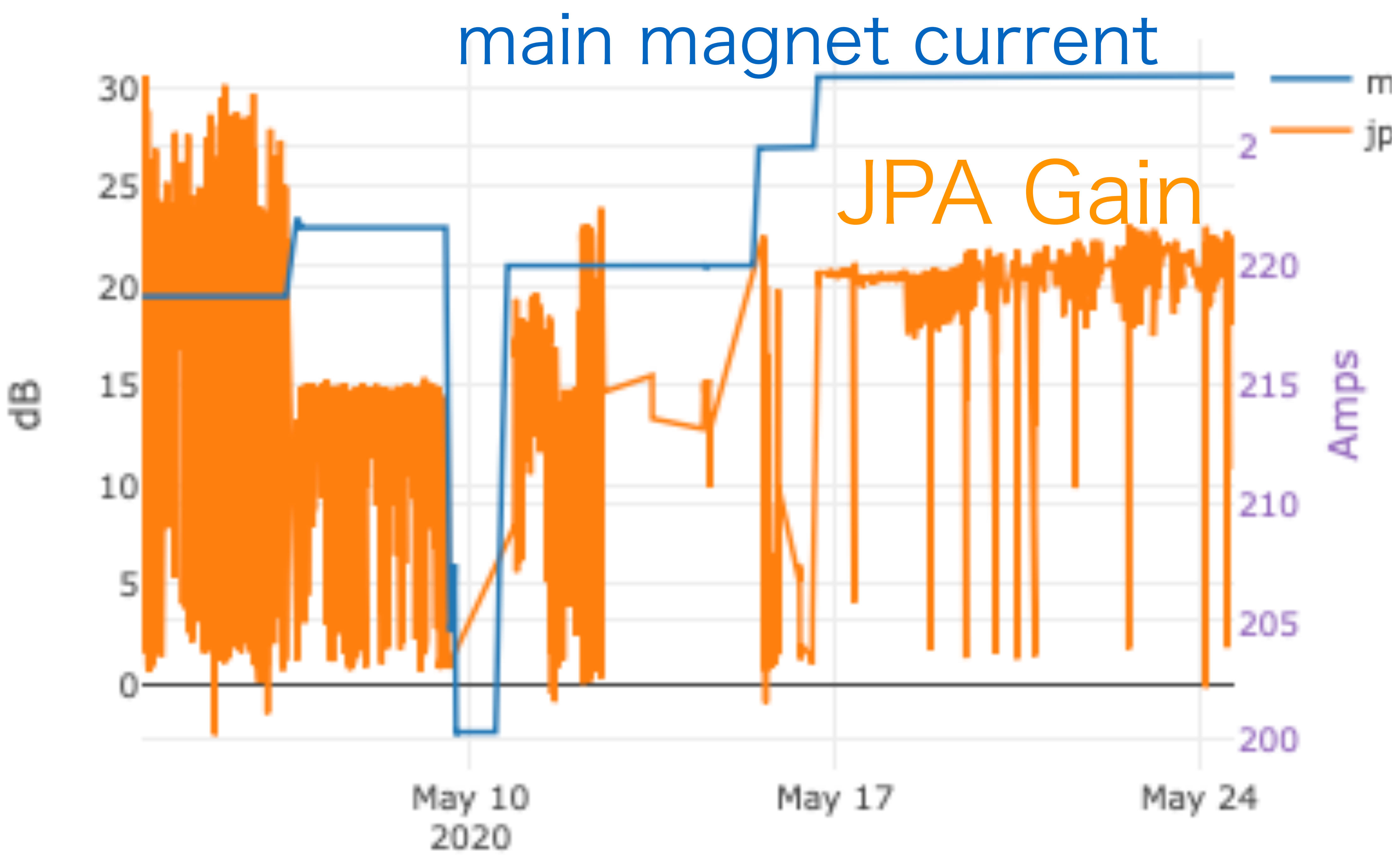
Repeating:

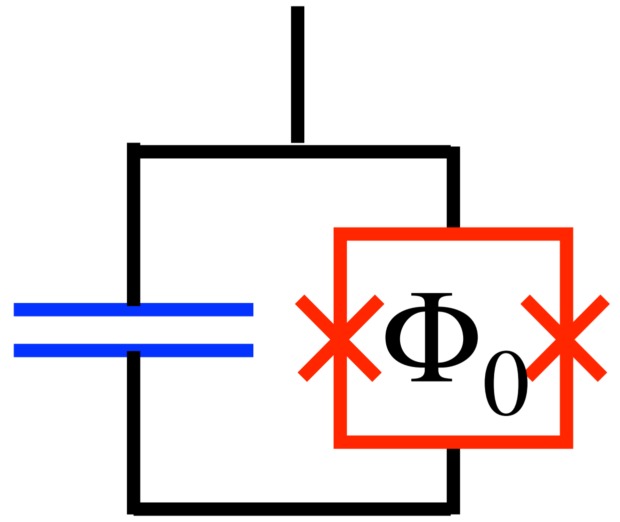
Frequency moving → Fine tuning bias current & pump power

Malfunction & Solution

Trapped flux quanta







Has to go above critical temperature of Al

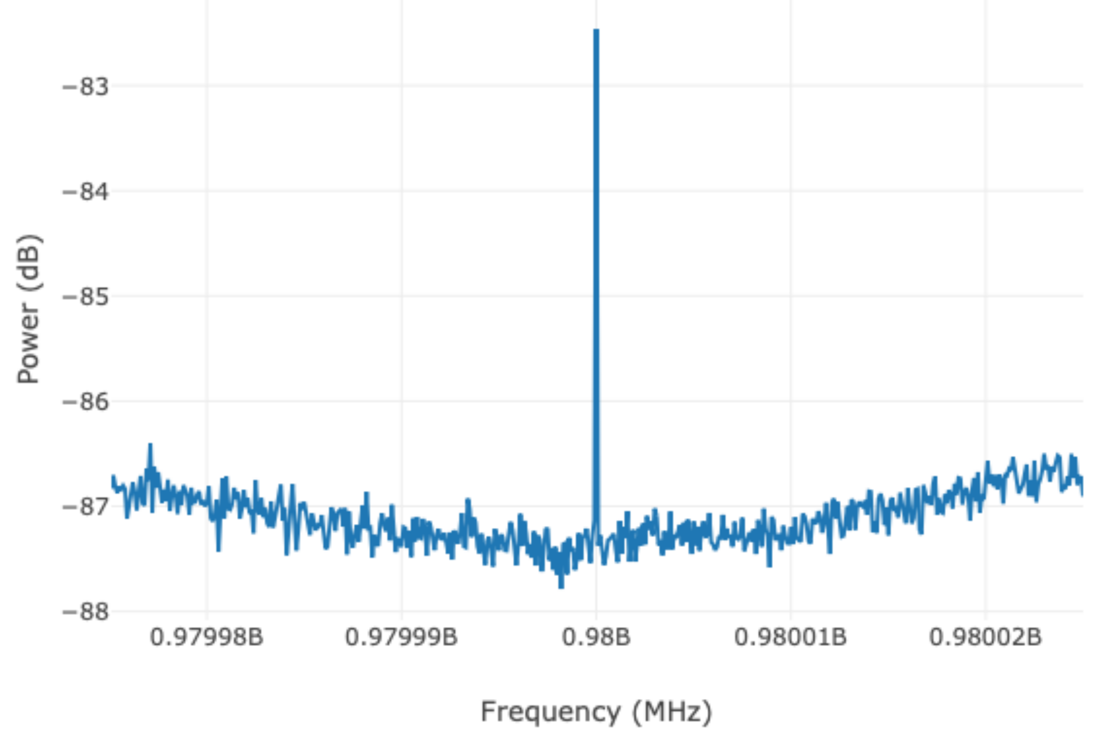
SQUID is the most sensitive magnetic field sensor

→ Have to modify magnet current to get highest performance

Observed Excesses

Found 15 excesses in 800-1020 MHz

Frequency [MHz]	Persistence	At Same Frequency	Not in Air	Enhanced on Resonance
839.669	✓	×	✓	×
840.268	✓	✓	✓	×
860.000	✓	✓	×	×
891.070	✓	✓	✓	×
896.448	✓	✓	✓	✓
974.989	×	✓	✓	×
974.999	×	✓	✓	×
960.000	✓	✓	×	×
980.000	✓	✓	×	×
990.000	✓	✓	×	×
990.031	×	✓	✓	×
1000.000	✓	✓	×	×
1000.013	×	✓	✓	×
1010.000	✓	✓	×	×
1020.000	✓	✓	×	×



14 excesses were identified as non-axion-like excesses right away.

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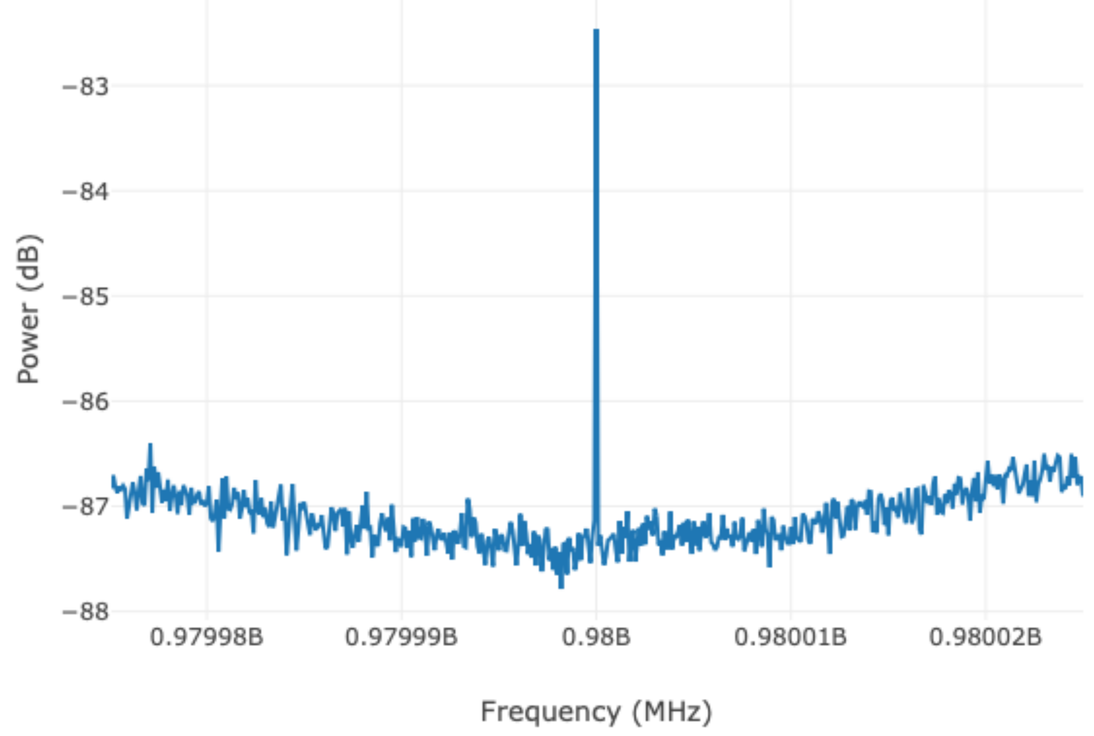
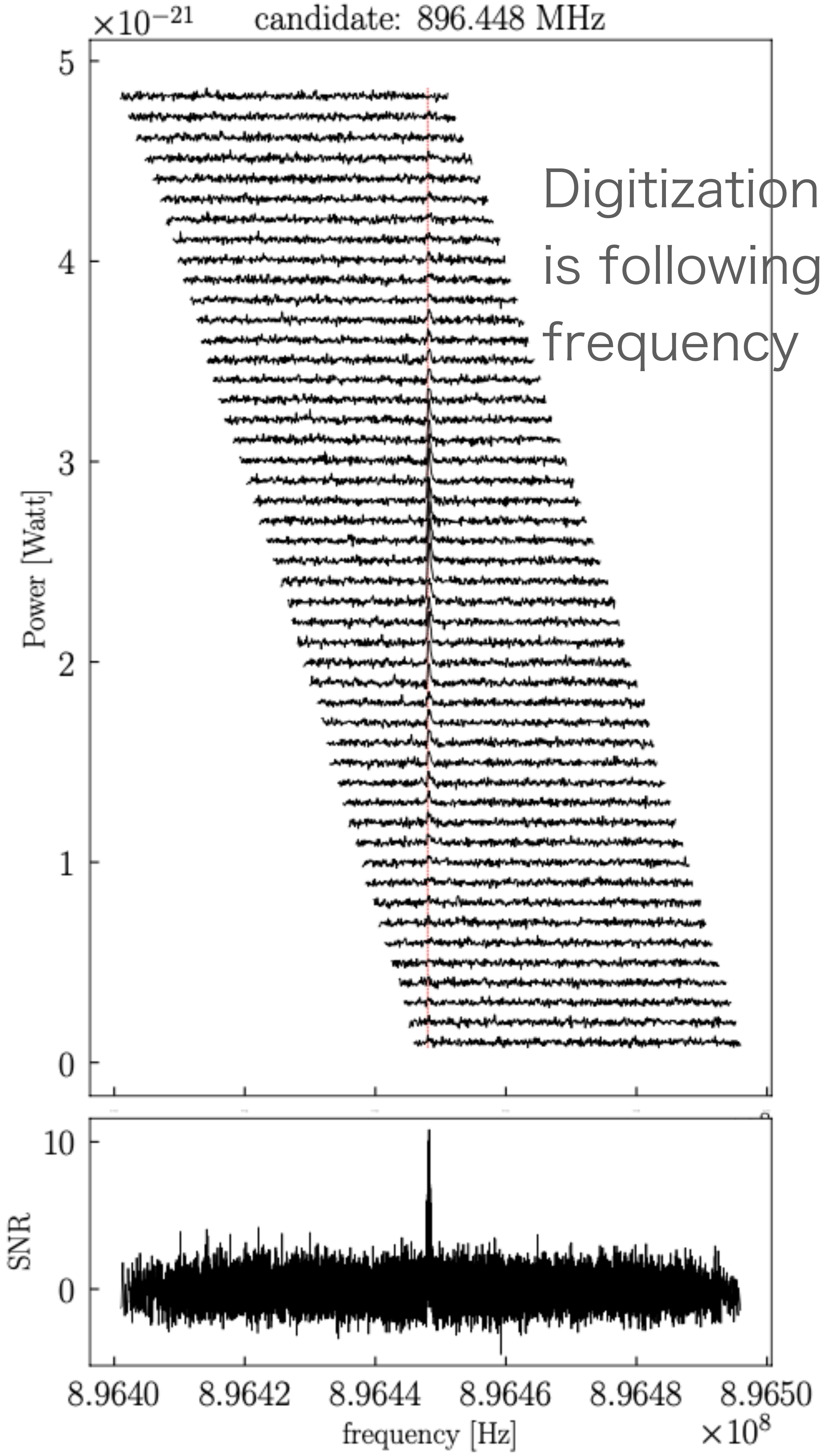
960.000	[illegible]	[illegible]	[illegible]	×
980.000	[illegible]	[illegible]	[illegible]	×
990.000	[illegible]	[illegible]	[illegible]	×
990.031	×	✓	✓	×
1000.000	✓	✓	×	×
1000.013	×	✓	✓	×
1010.000	✓	✓	×	×
1020.000	✓	✓	×	×

896.448 MHz is really axion-like!



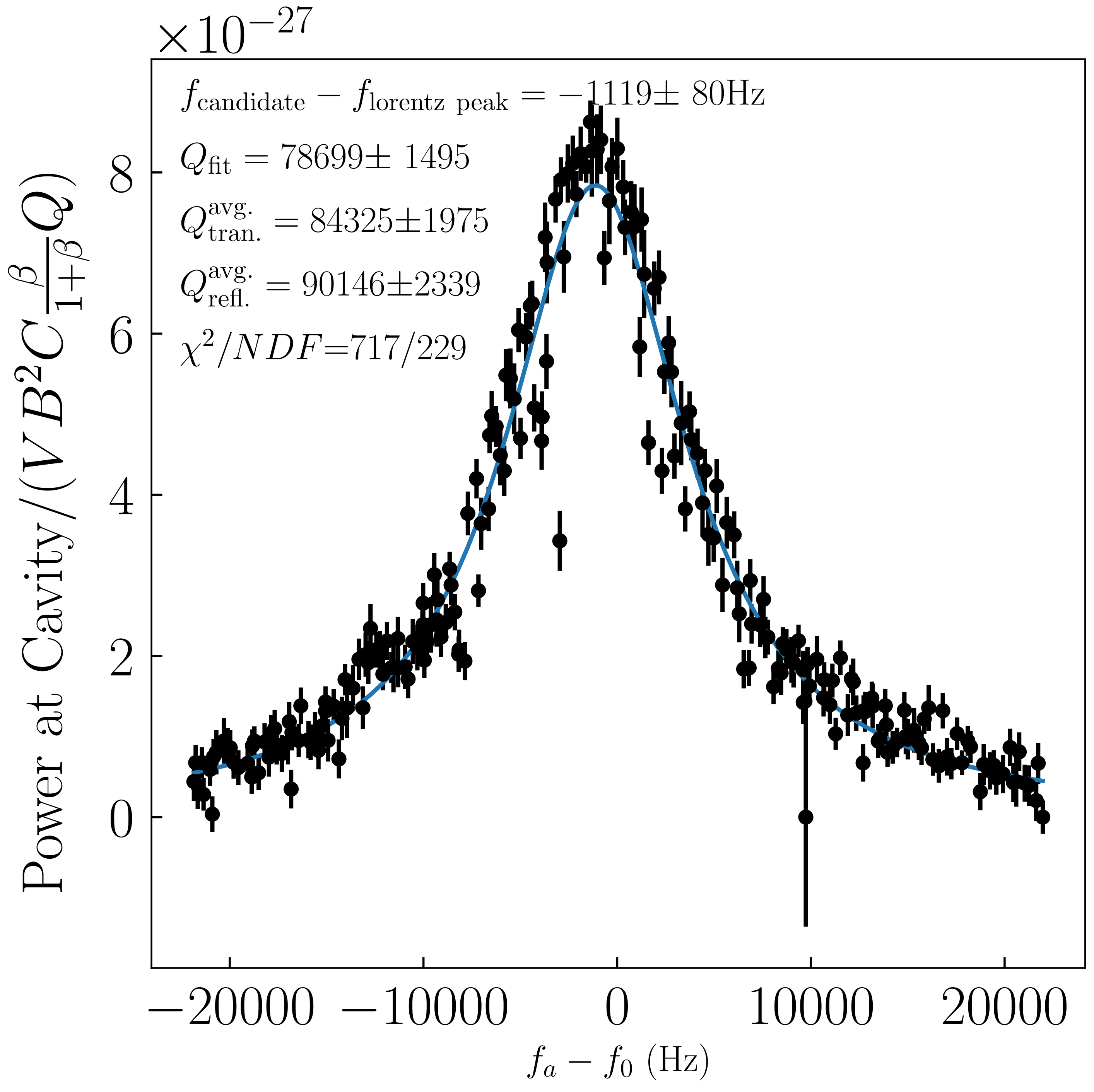
14 excesses were identified as non-axion-like excesses right away.

Stringent Axion Tests



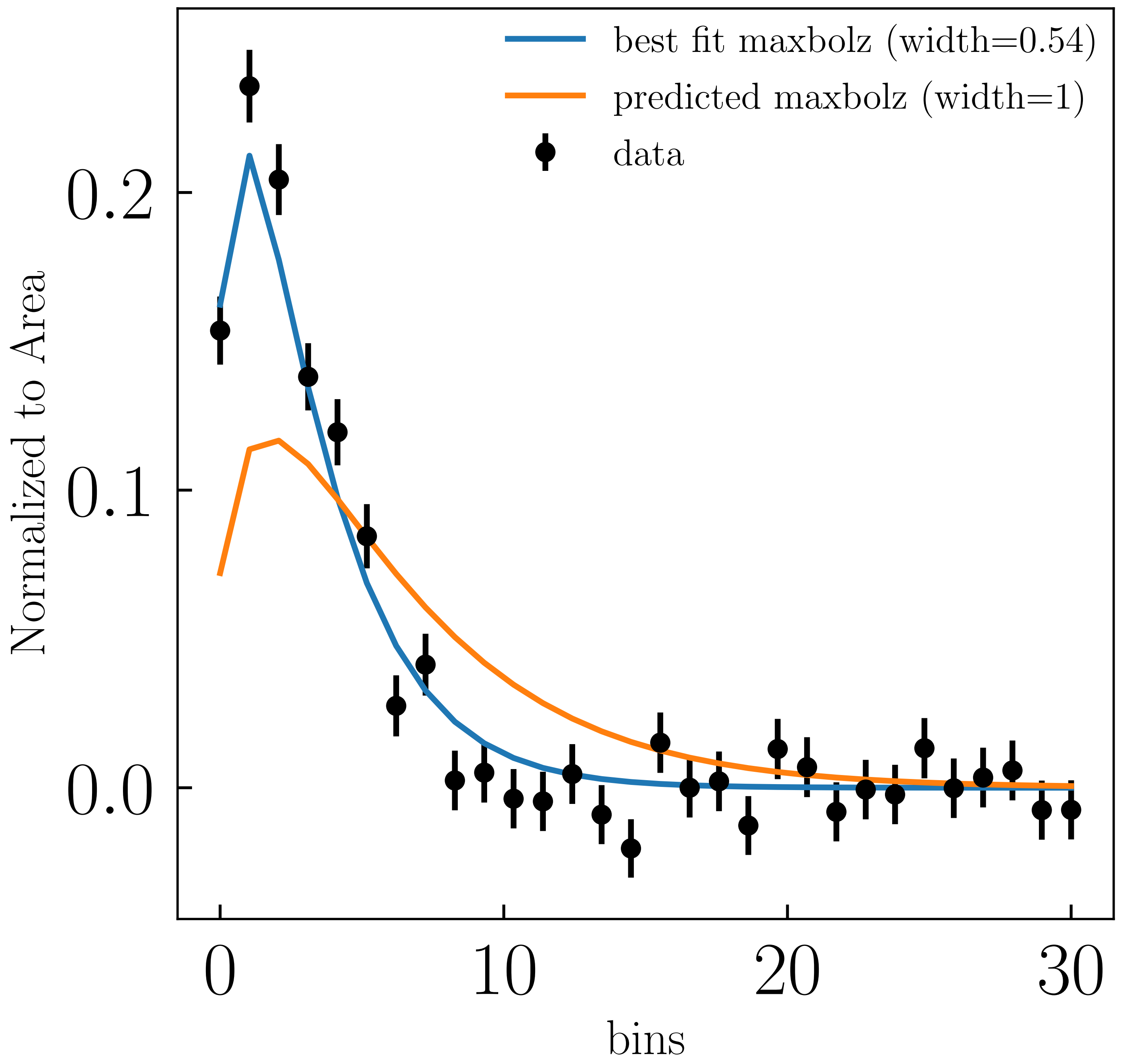
Digitization window
is following resonant
frequency

←Test1: Persistance



Test2: Cavity Enhancement

Axion is enhanced by cavity
Lorentzian shape.

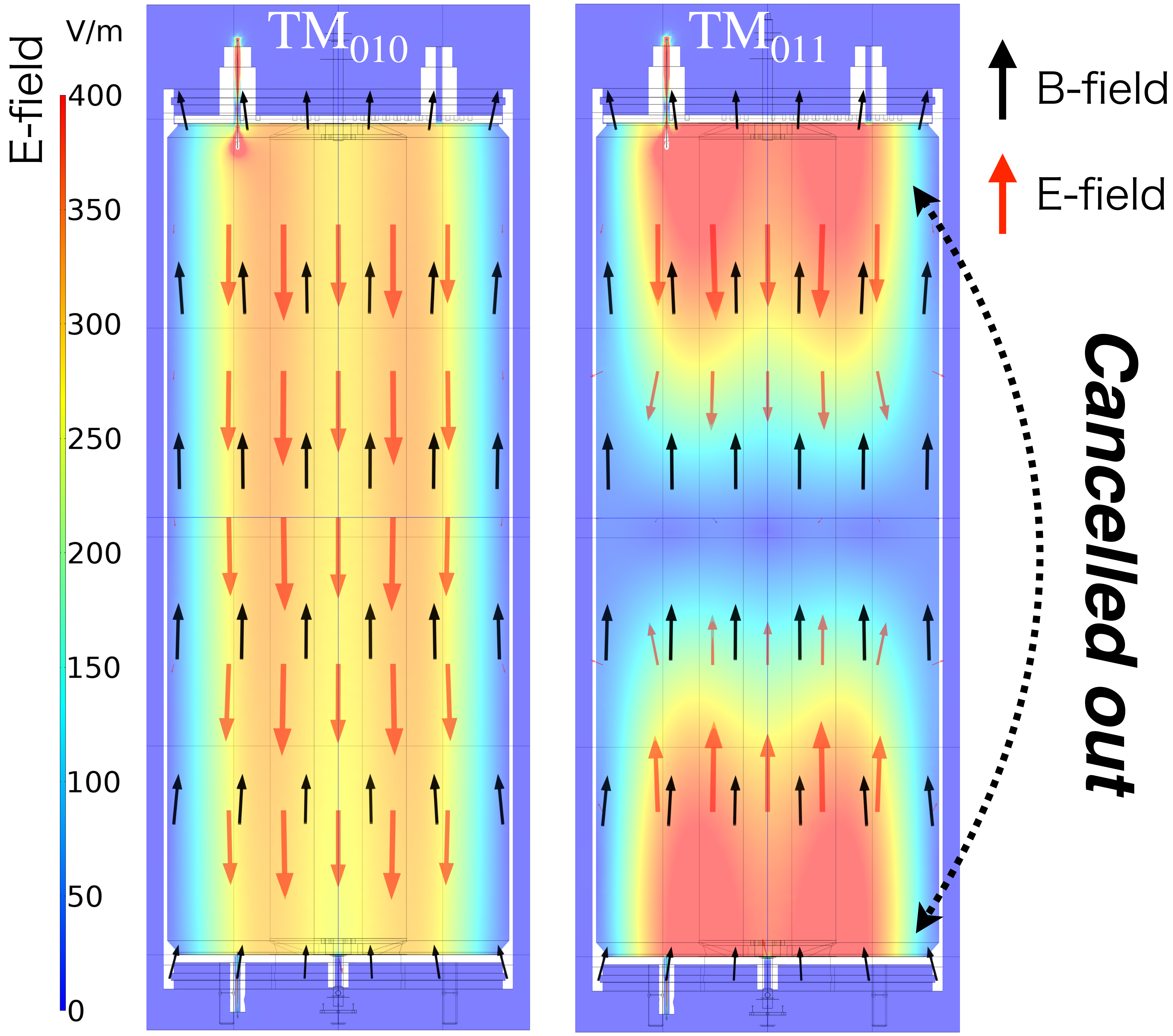


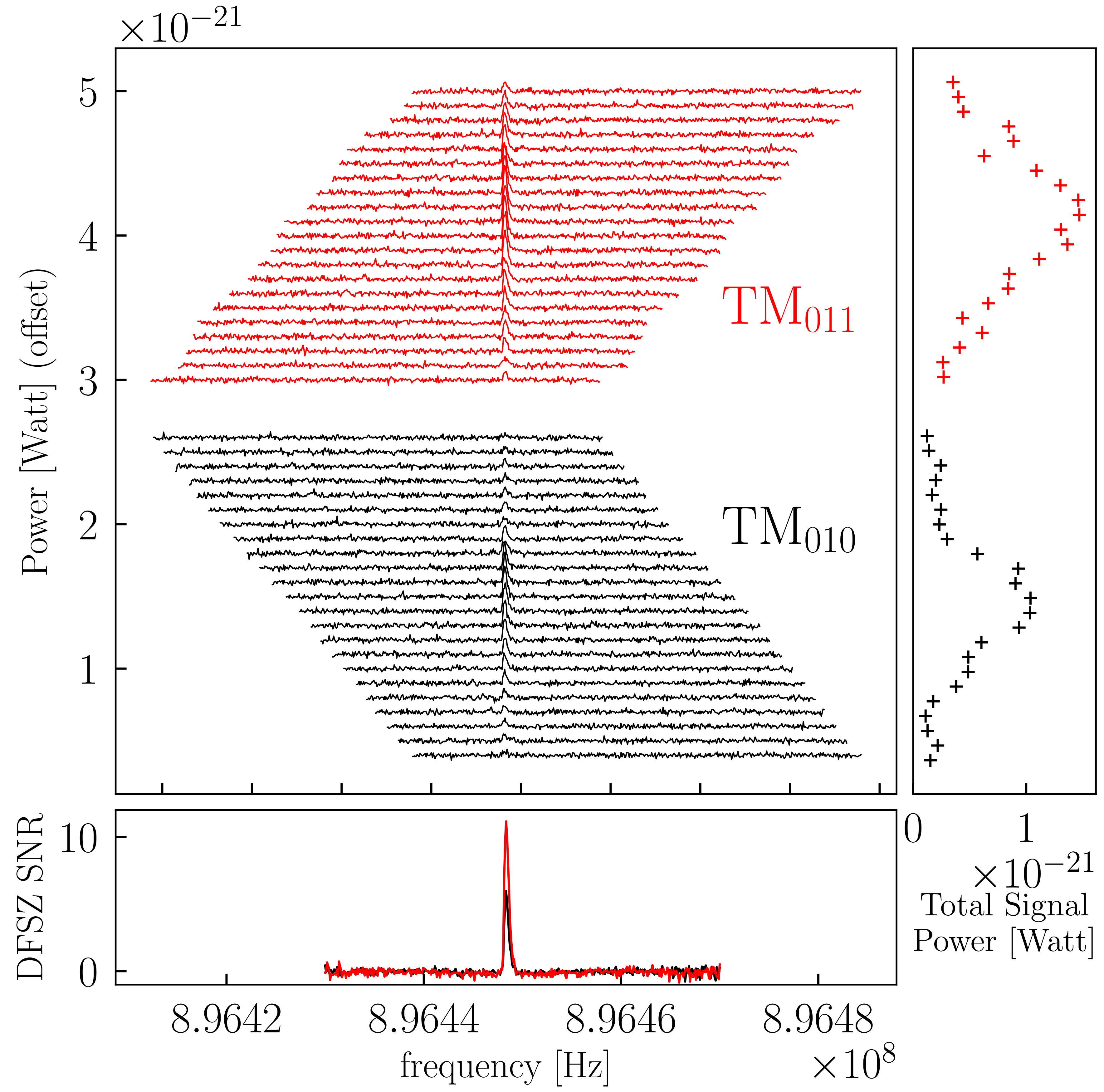
Test3: Signal Shape

Axion is expected to be
maxwell-boltzman distribution

Stringent Axion Tests

Test4: Disappearance in TM011





It turns out to be blinded synthetic signal (not axion).

→ We verify our procedure to detect axions

Results

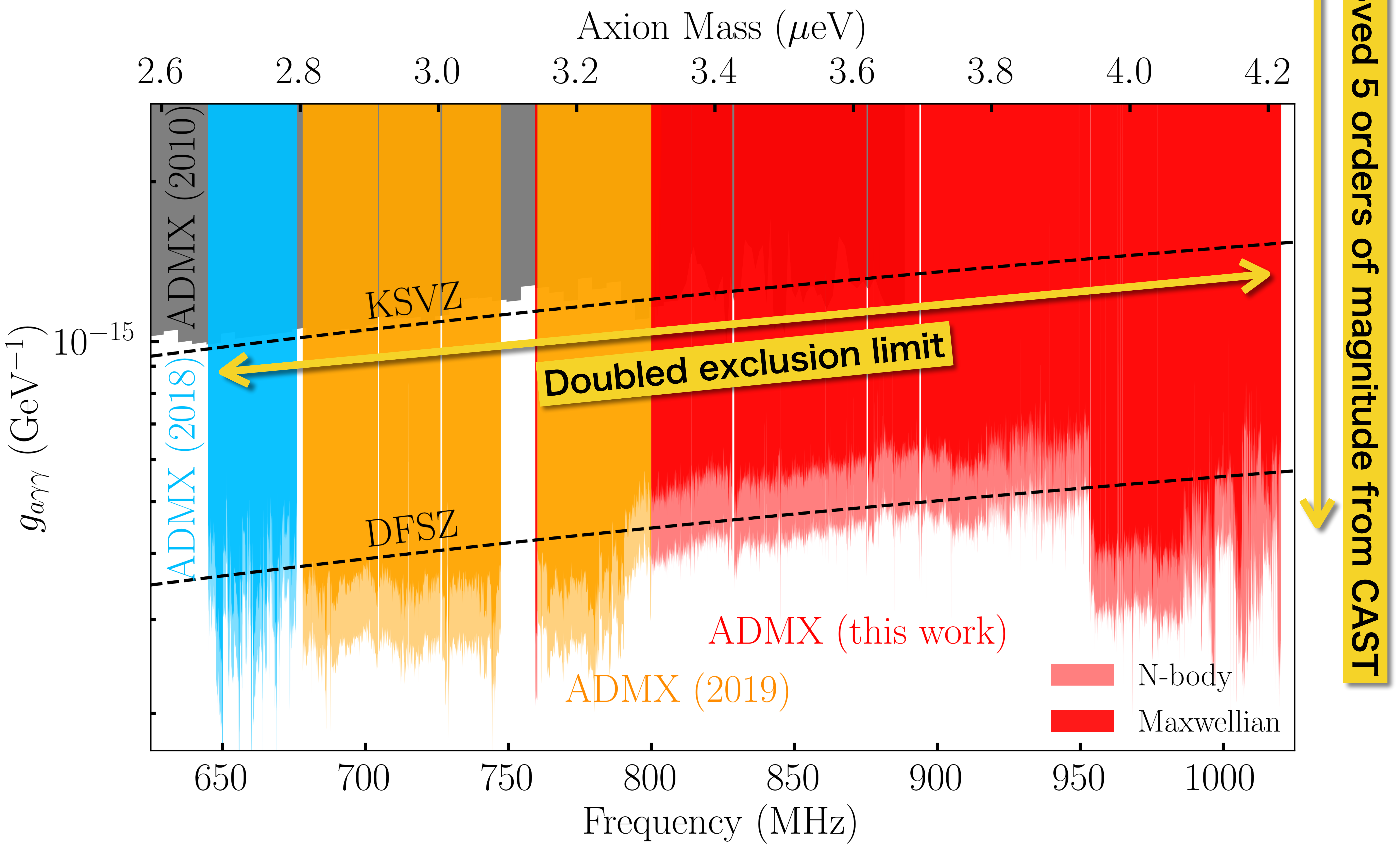
Ruled out:

KSVZ axions

800 – 1020 MHz

DFSZ axions

~ 970 MHz

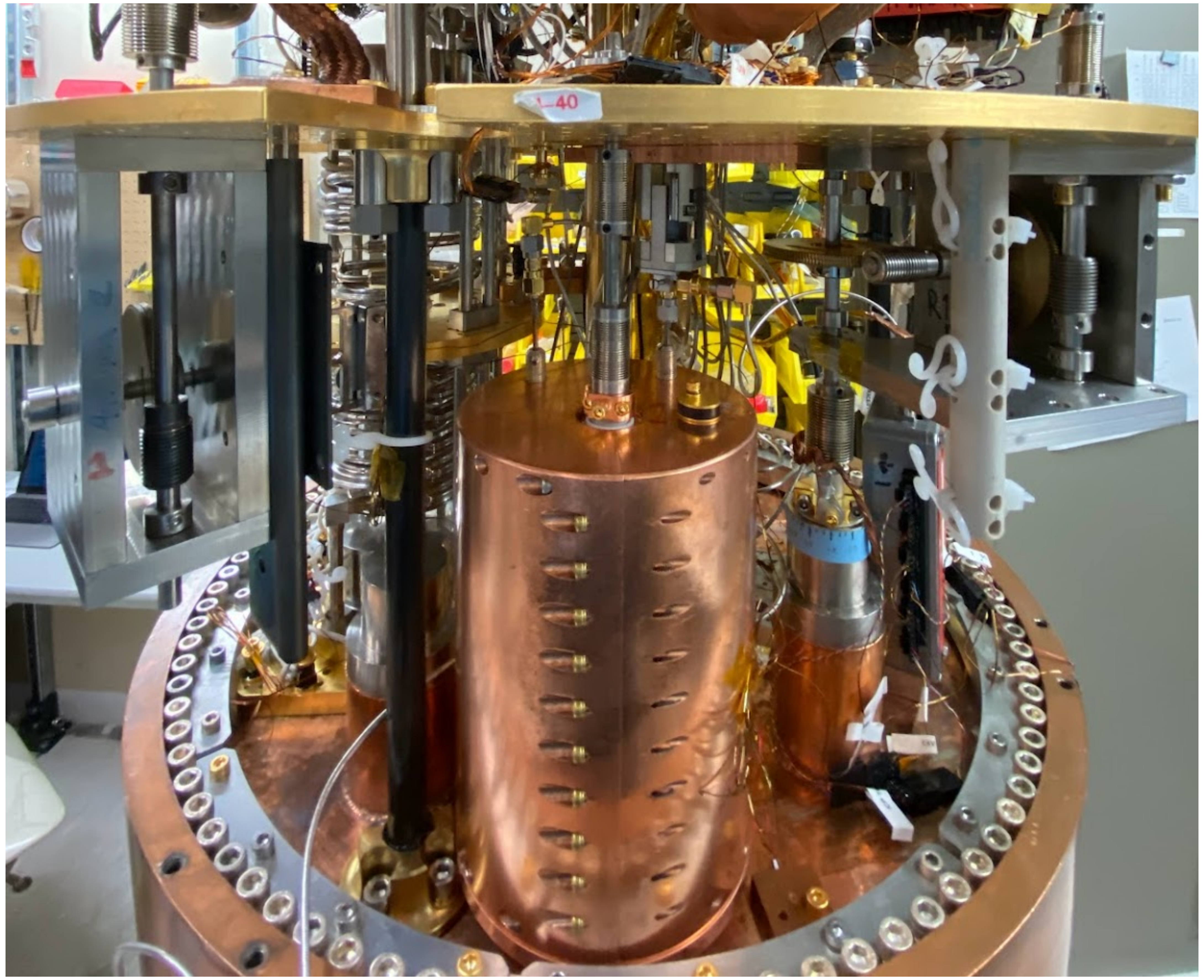


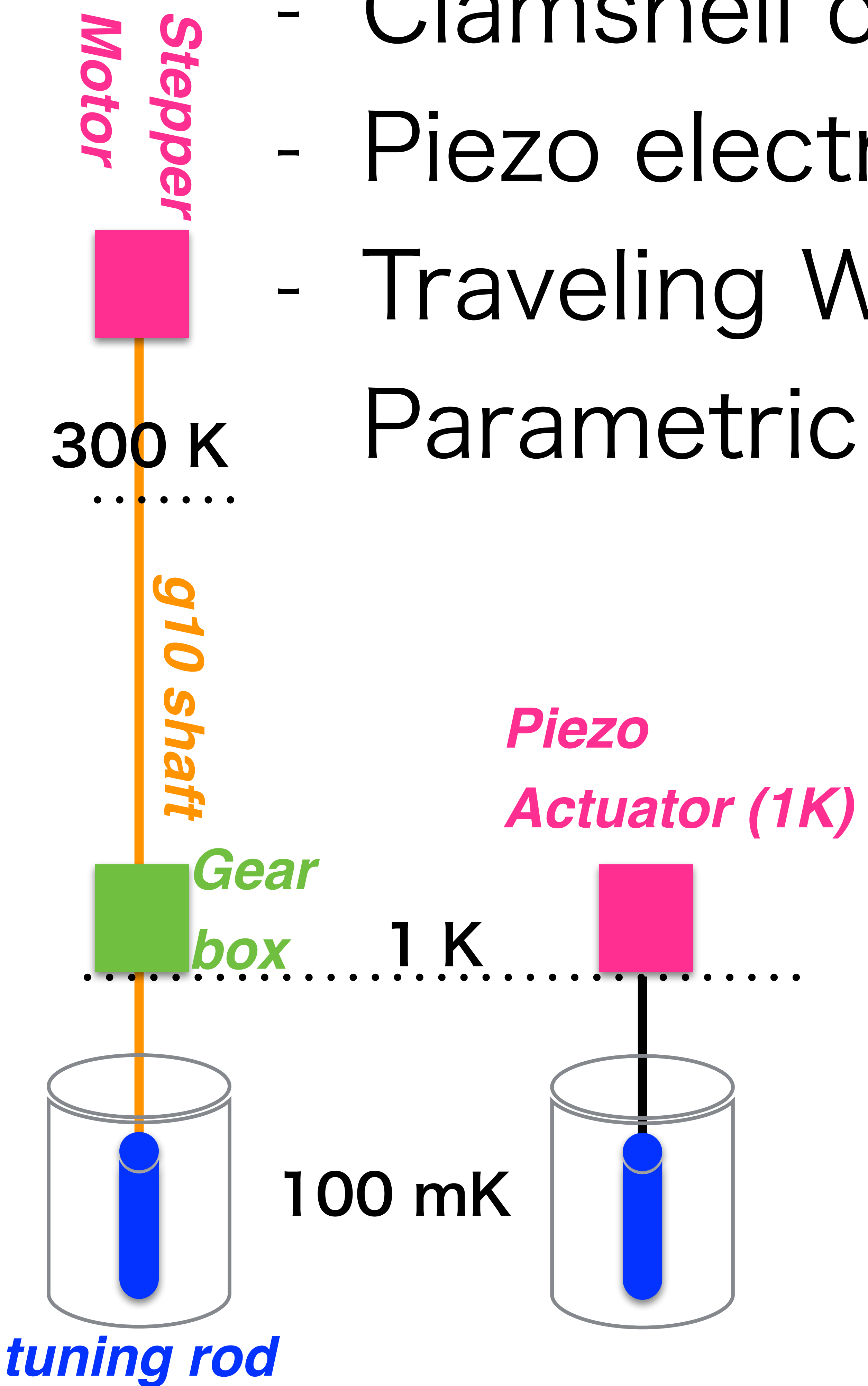
N-body: 0.6 GeV/cc

Maxwellian: 0.45 GeV/cc

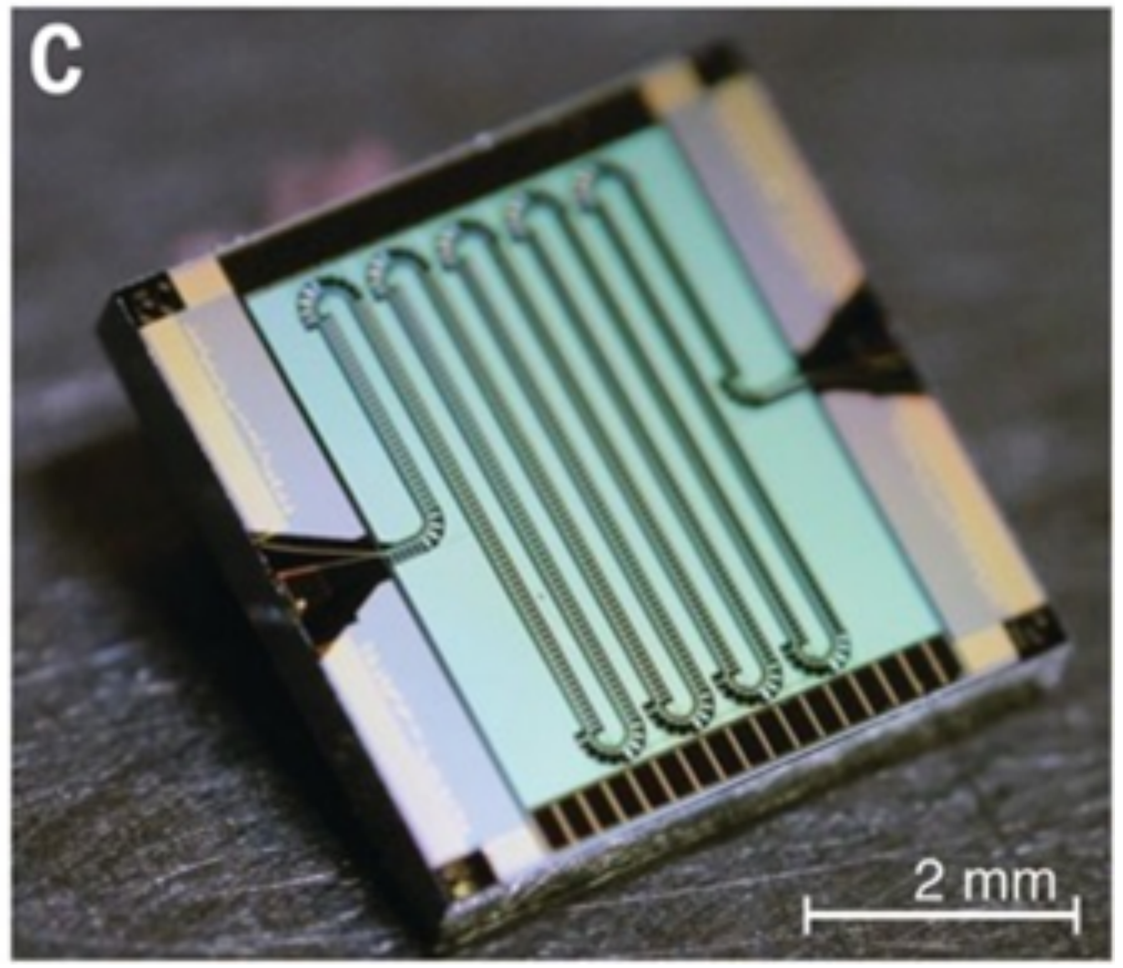
ADMX Sidecar

- Pathfinder experiment on top of the ADMX main cavity
- 4-7 GHz tuning range
- Clamshell cavity
- Piezo electronic tuning
- Traveling Wave Josephson Parametric Amplifier (TWPA)

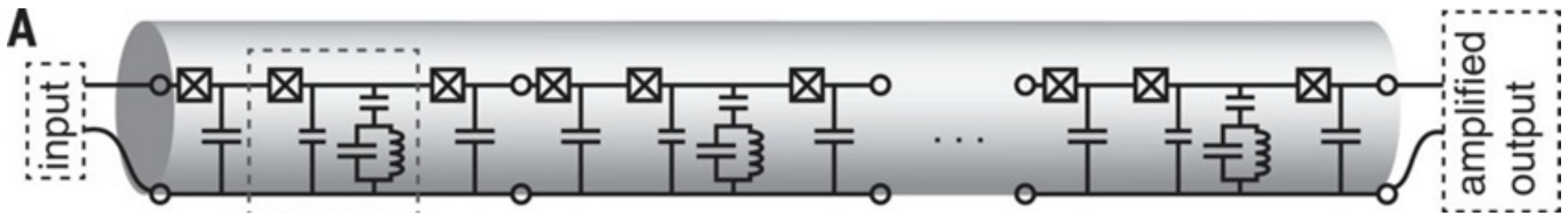


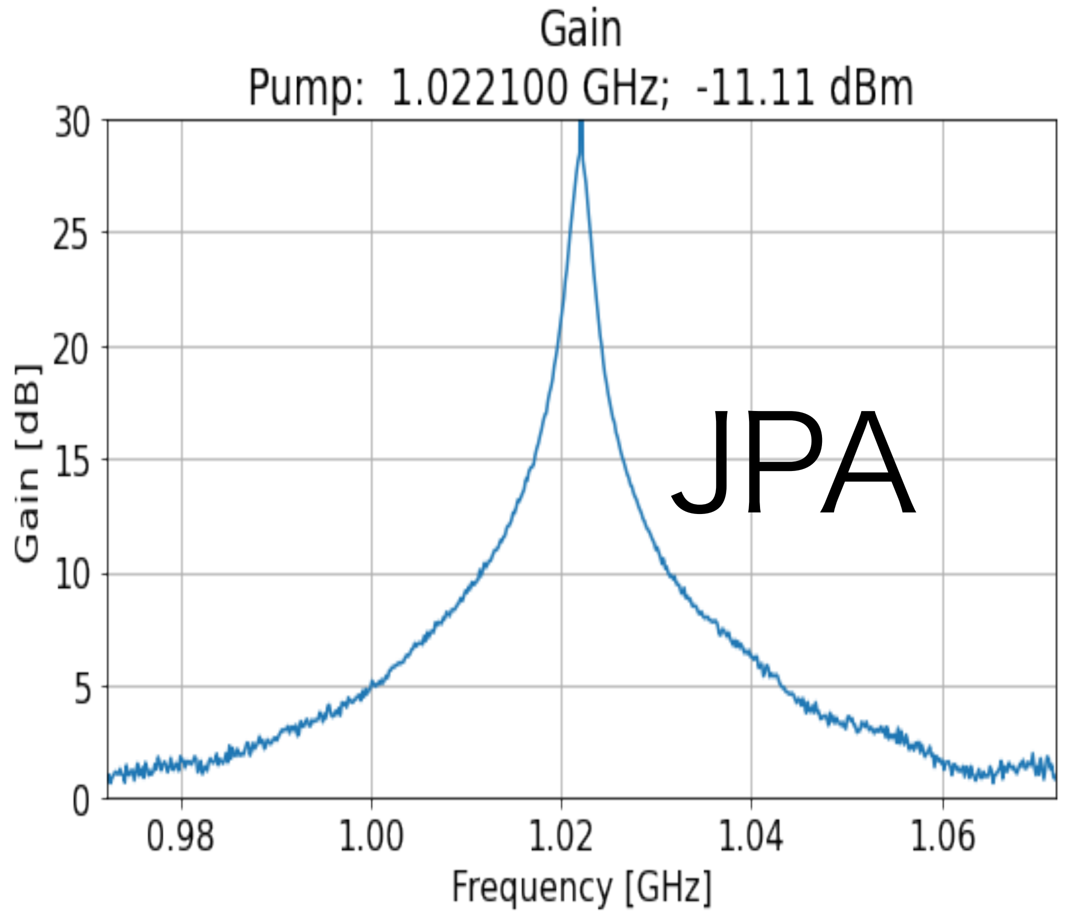


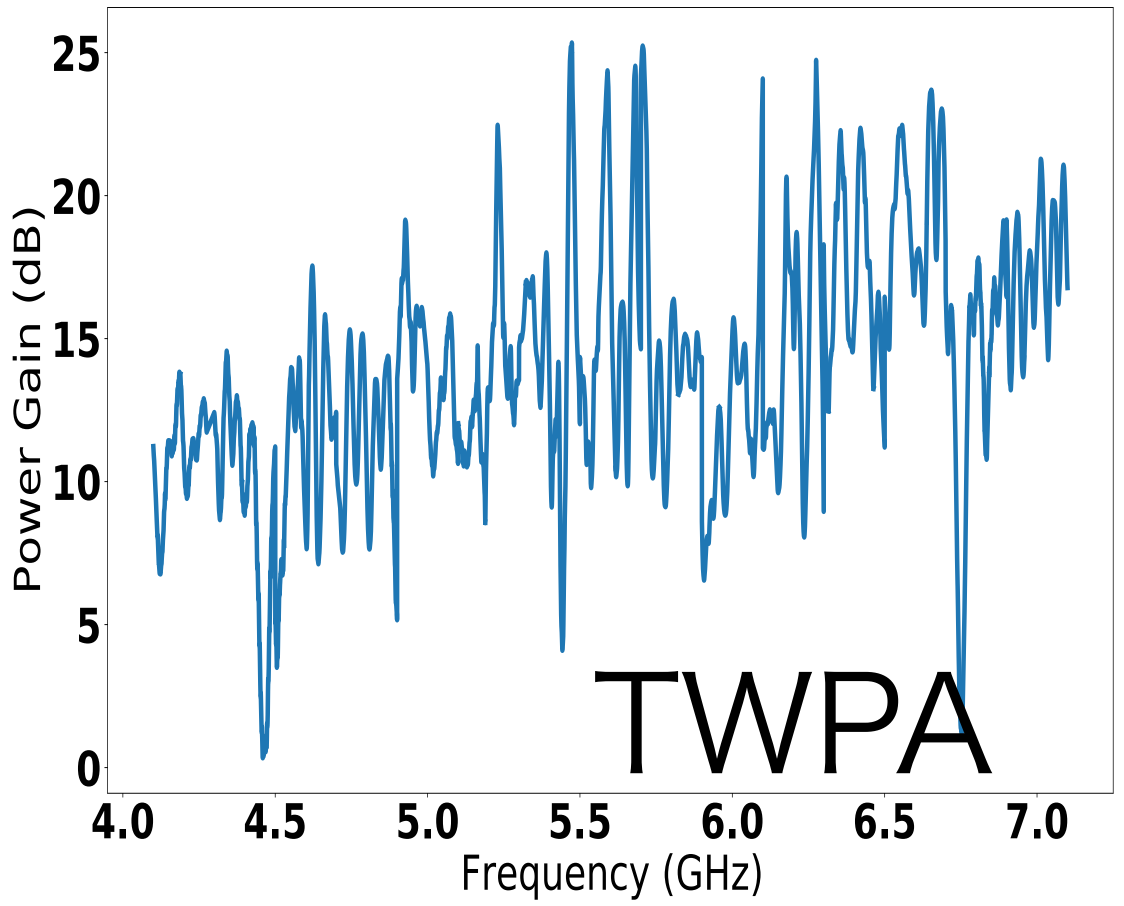
TWPA



Traveling Wave Parametric Amplifier







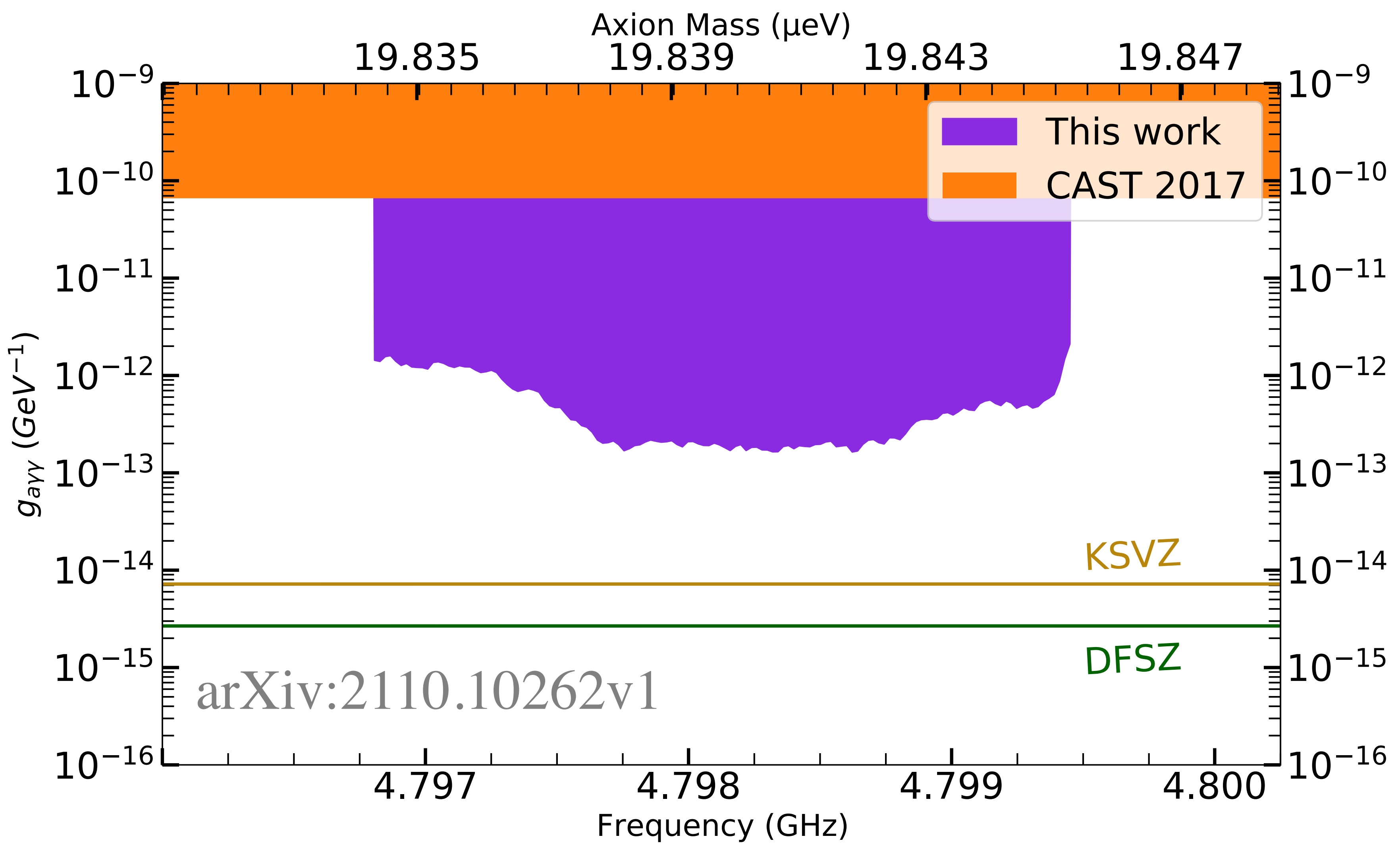
O(100) Josephson junctions in series

Pros:

- Broadband gain (several GHz)
- A bit more B-field tolerance than JPA

Cons:

- Decent gain: TWPA ~15 dB, JPA ~ 30 dB



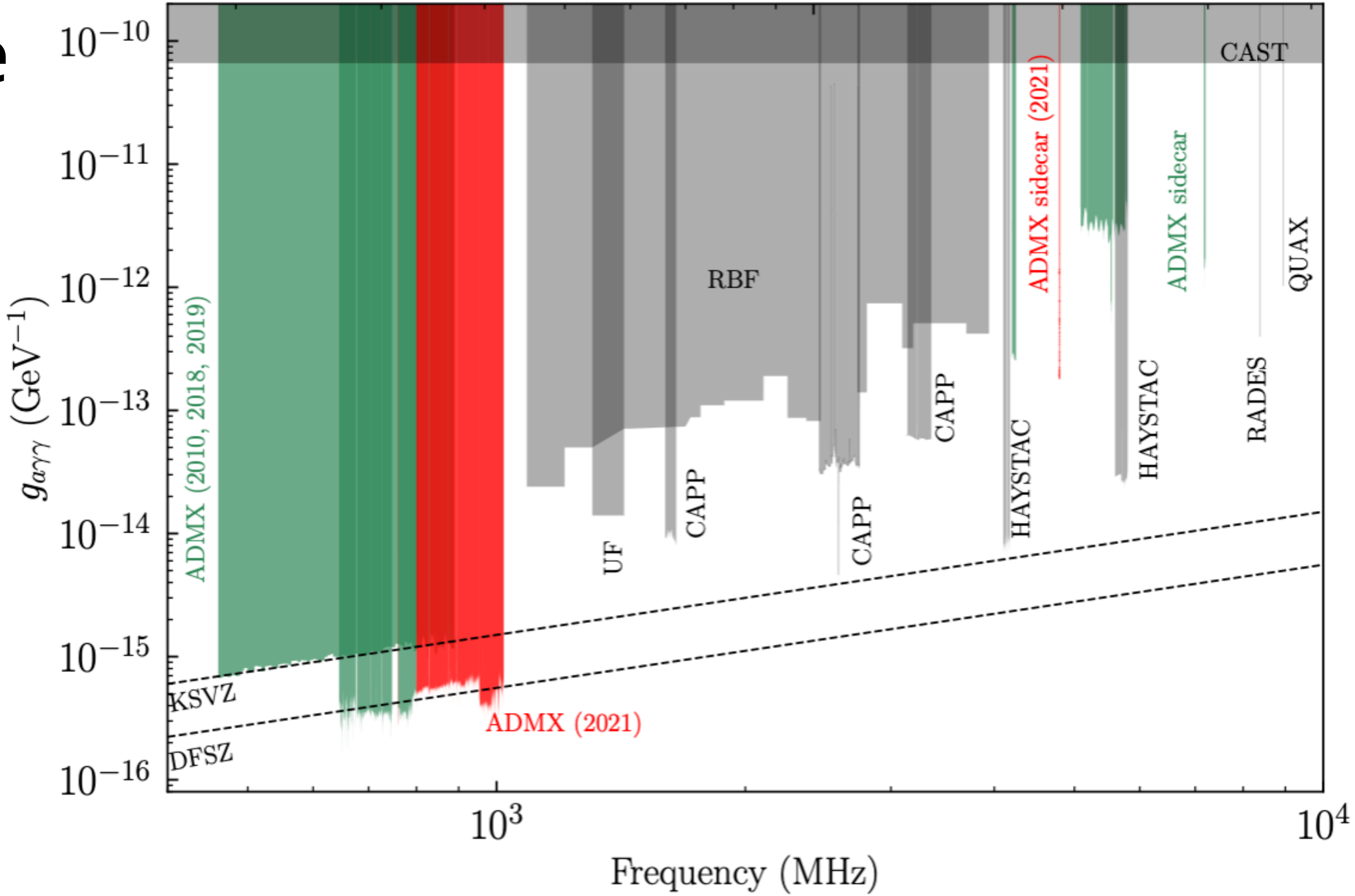
First application for axion search

Dark Matter Axion Search Using a Josephson Traveling Wave Parametric Amplifier

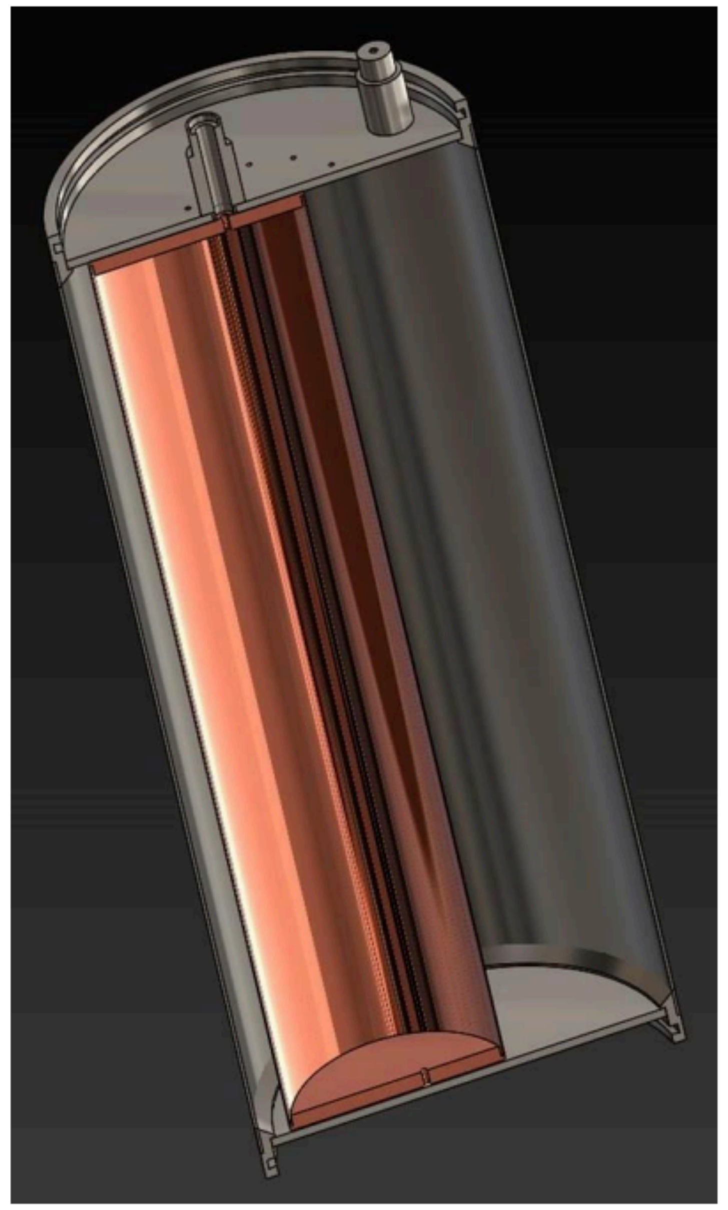
C.Bartram,[1,*] T. Braine,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A. T. Hipp,[5] S. Jois,[5] P. Sikivie,[5] N. S. Sullivan,[5] D. B. Tanner,[5] E. Lentz,[6] R. Khatiwada,[7,4] G. Carosi,[8] C. Cisneros,[8] N. Robertson,[8] N. Woollett,[8] L. D. Duffy,[9] C. Boutan,[10] M. Jones,[10] B. H. LaRoque,[10] N. S. Oblath,[10] M. S. Taubman,[10] E. J. Daw,[11] M. G. Perry,[11] J. H. Buckley,[12] C. Gaikwad,[12] J. Hoffman,[12] K. Murch,[12] M. Goryachev,[13] B. T. McAllister,[13] A. Quiskamp,[13] C. Thomson,[13] and M. E. Tobar[13]
(ADMX Collaboration)

arXiv:2110.10262v1

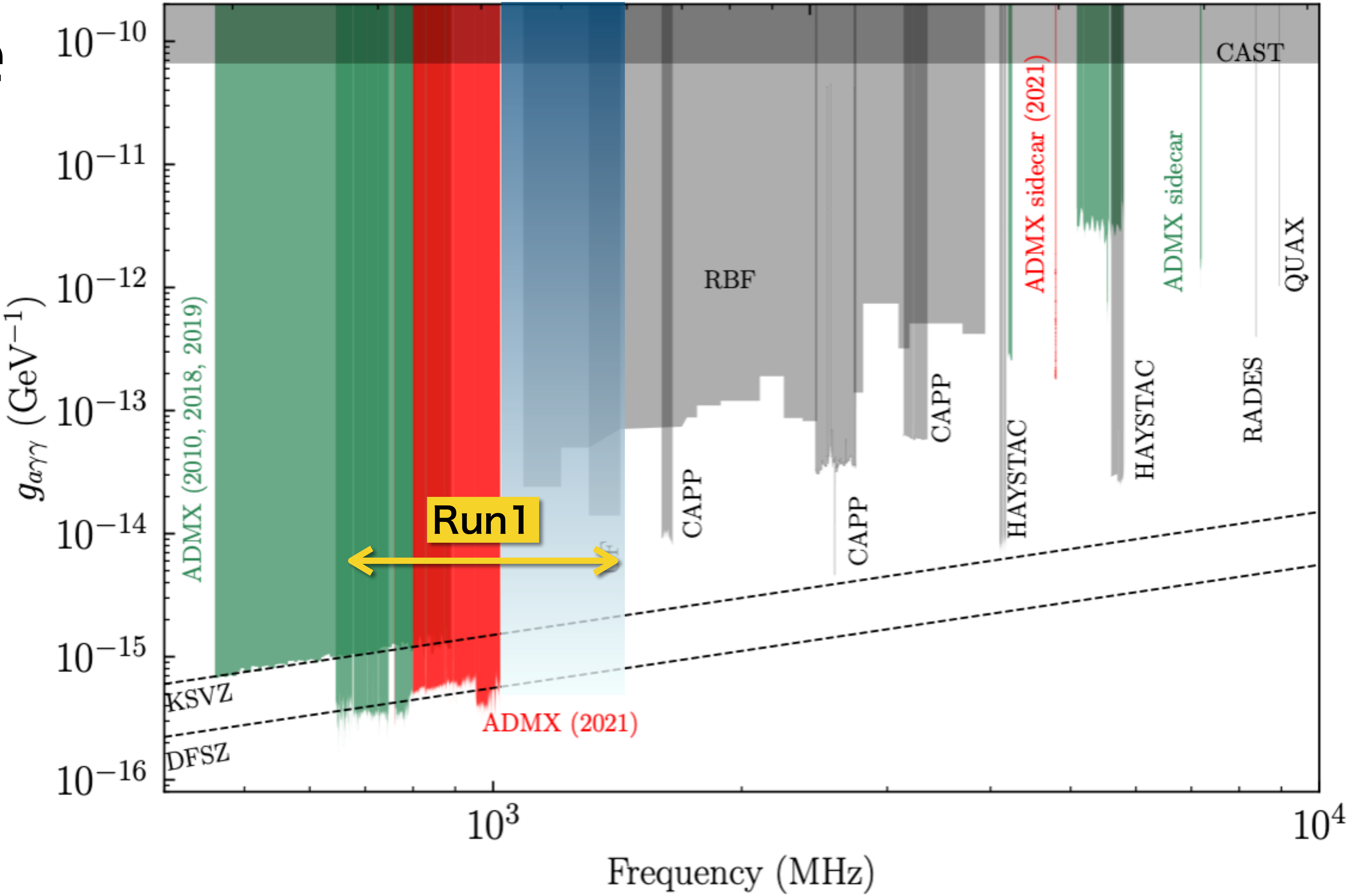
Future Plans



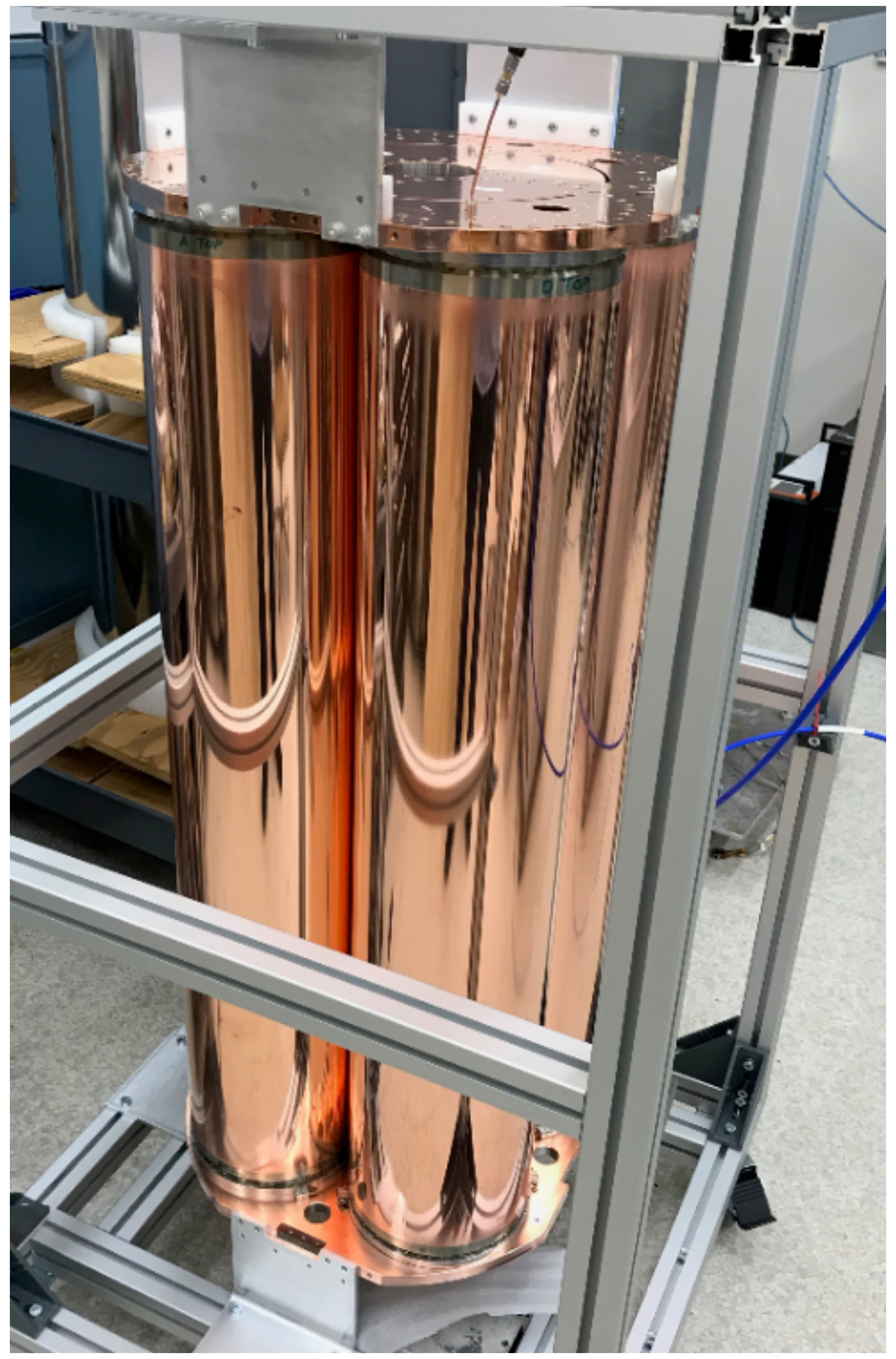
Future Plans



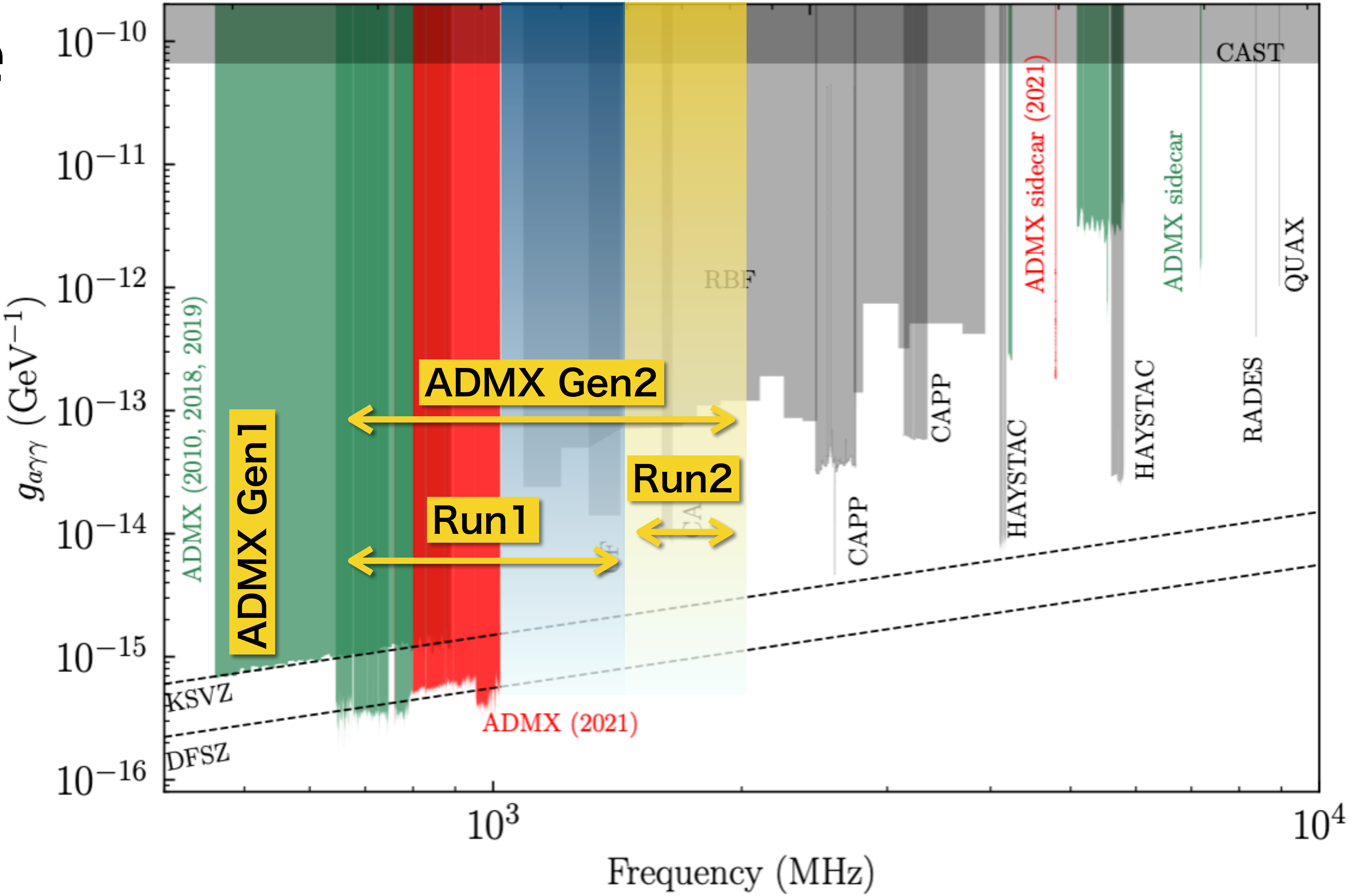
Bigger tuning rod



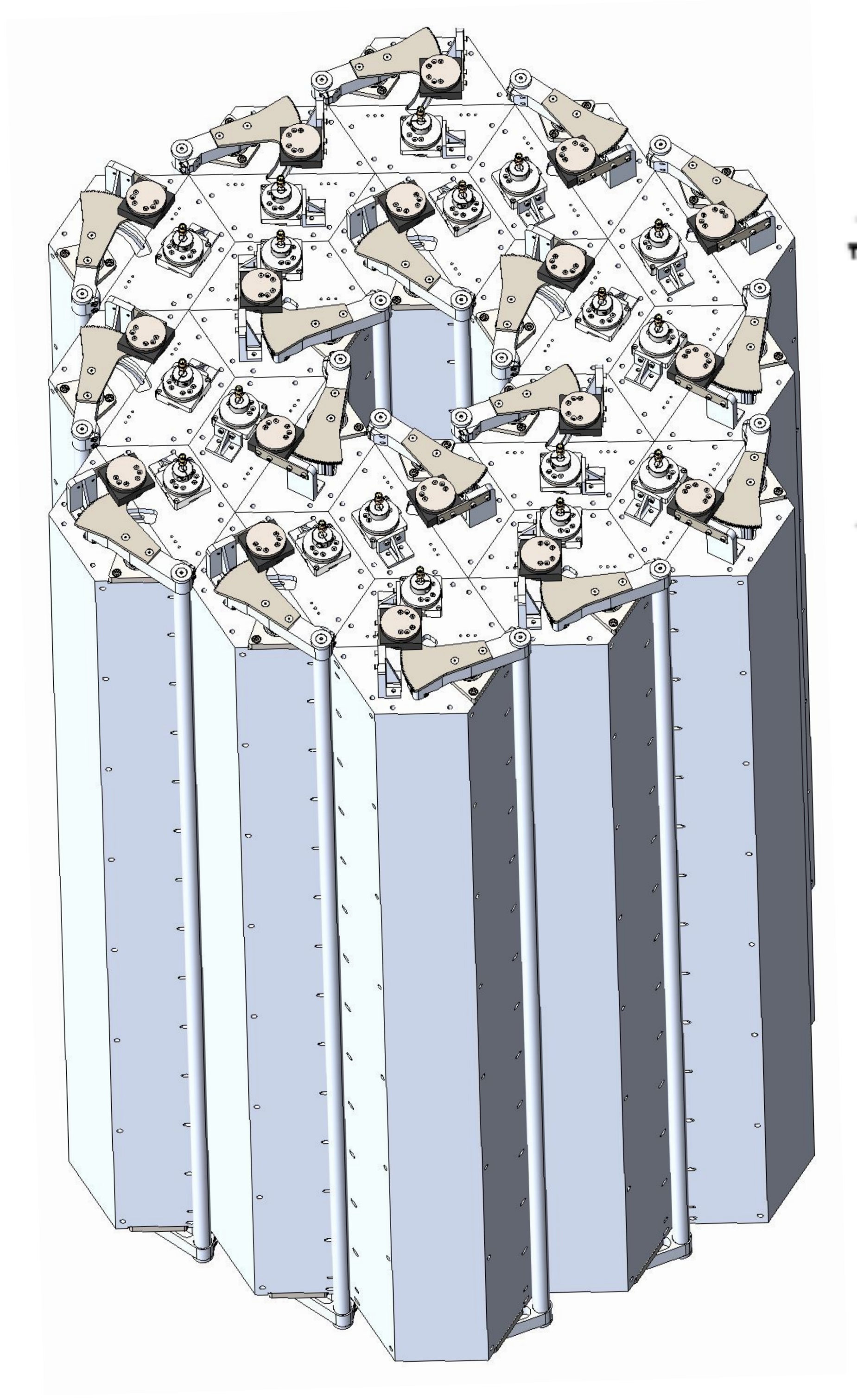
Future Plans



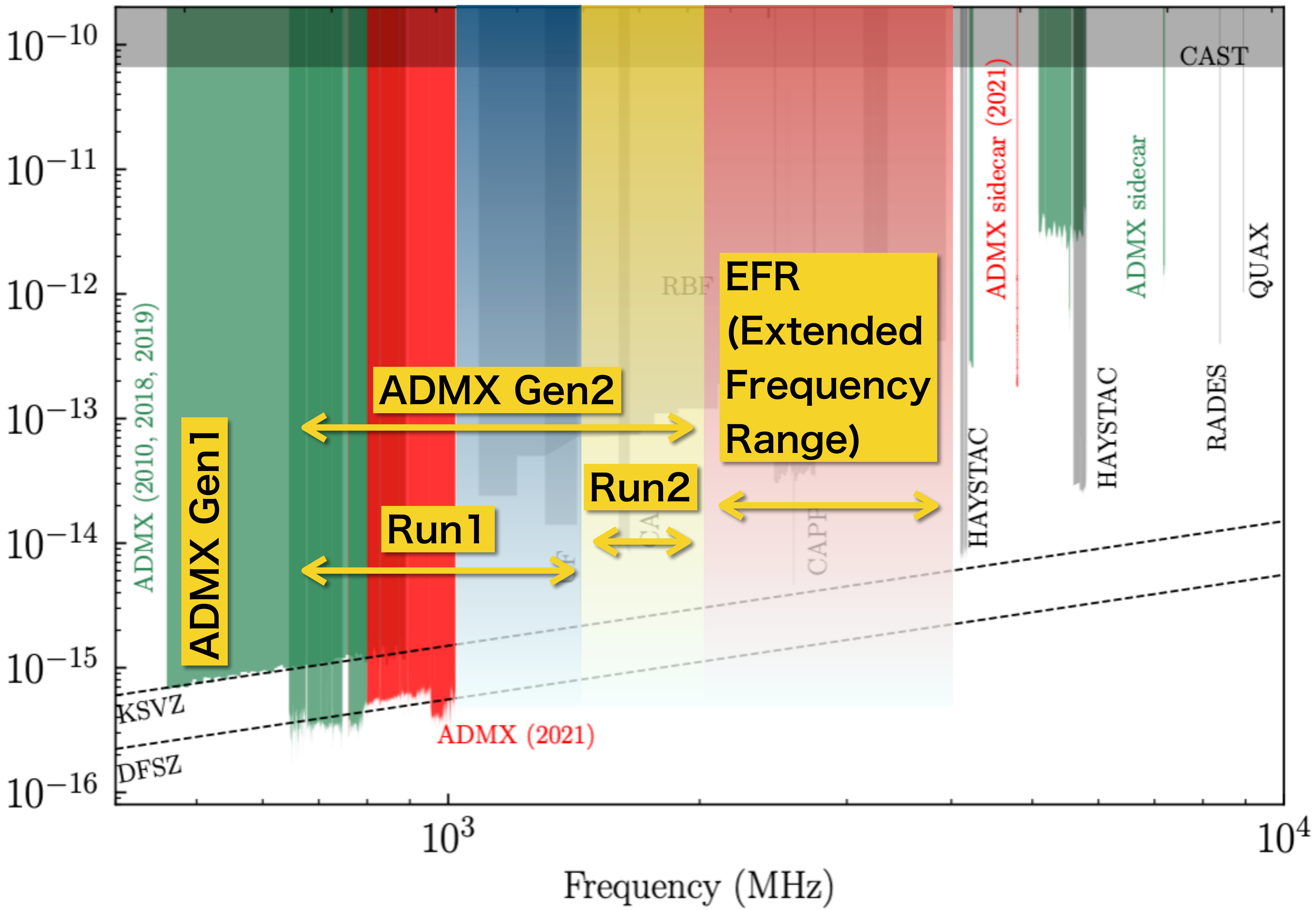
4-cavity array



Future Plans

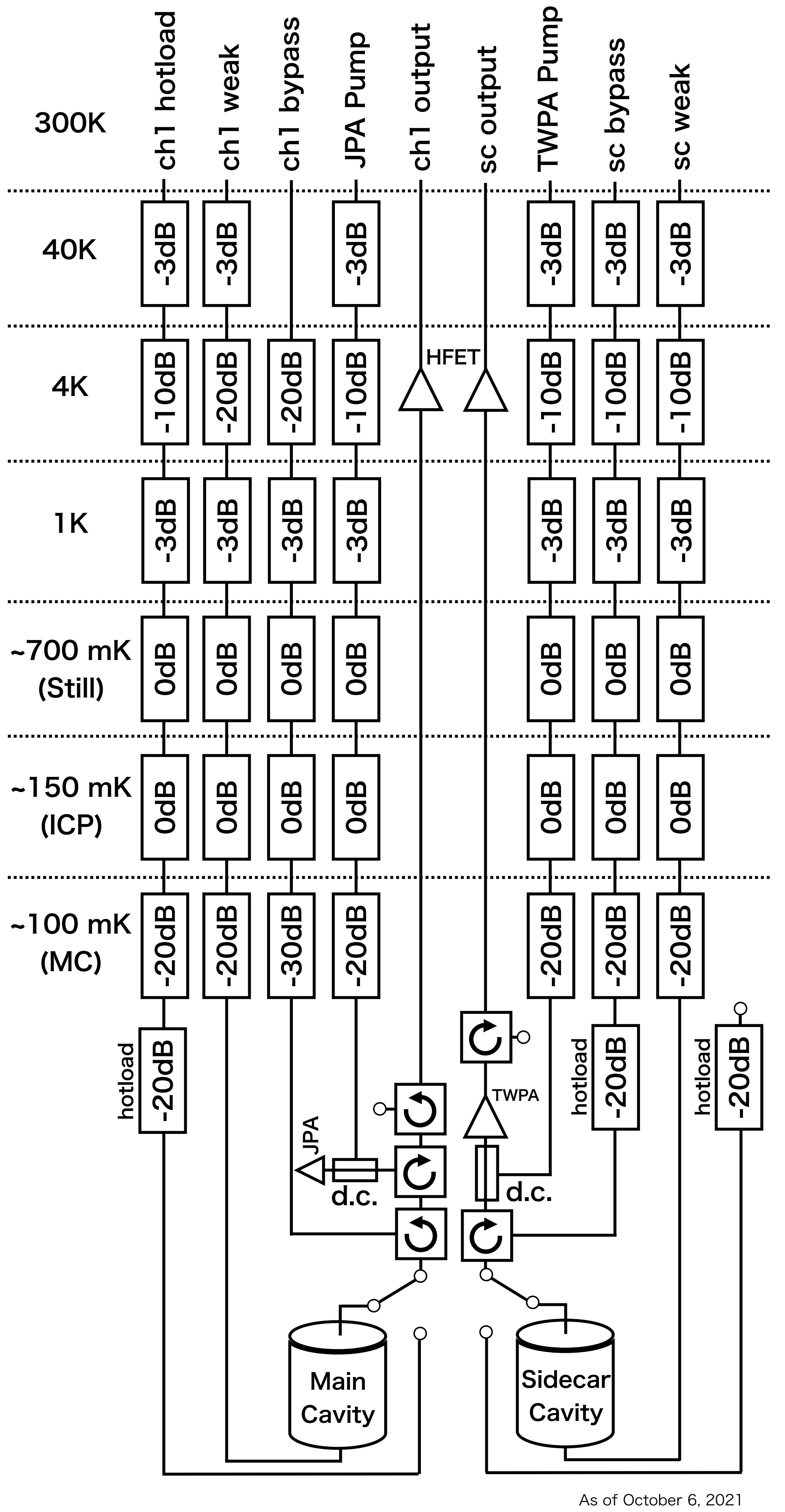


18-cavity array

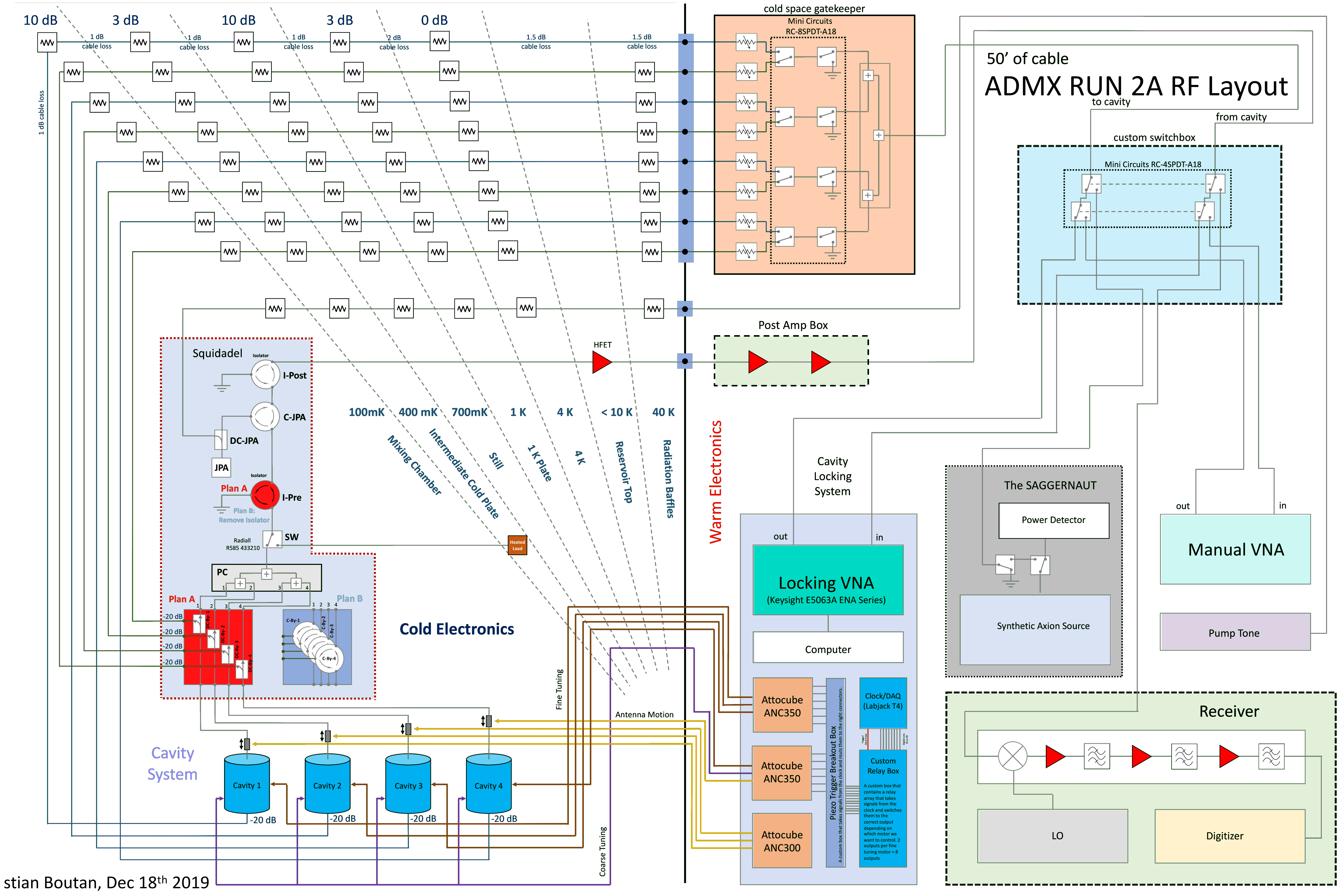


4-Cavity System

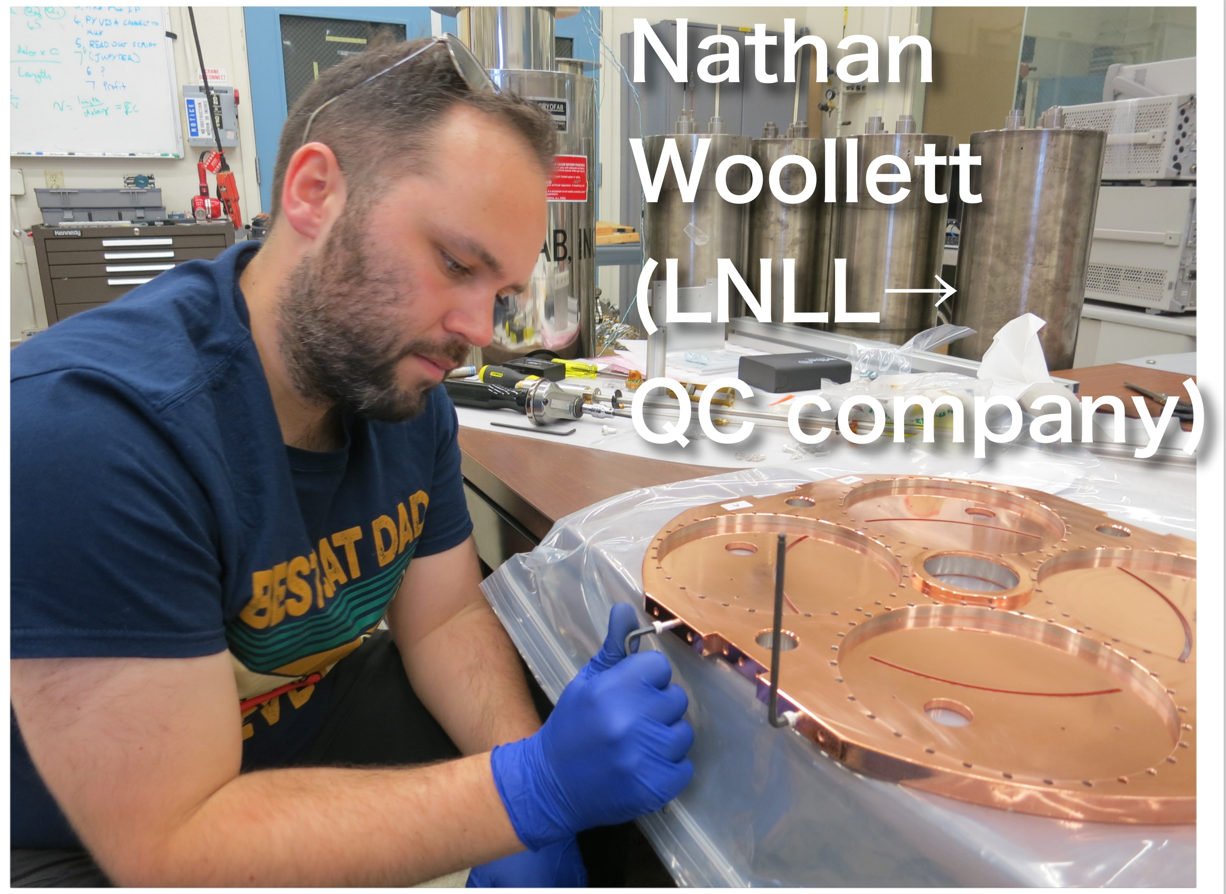
Current ADMX

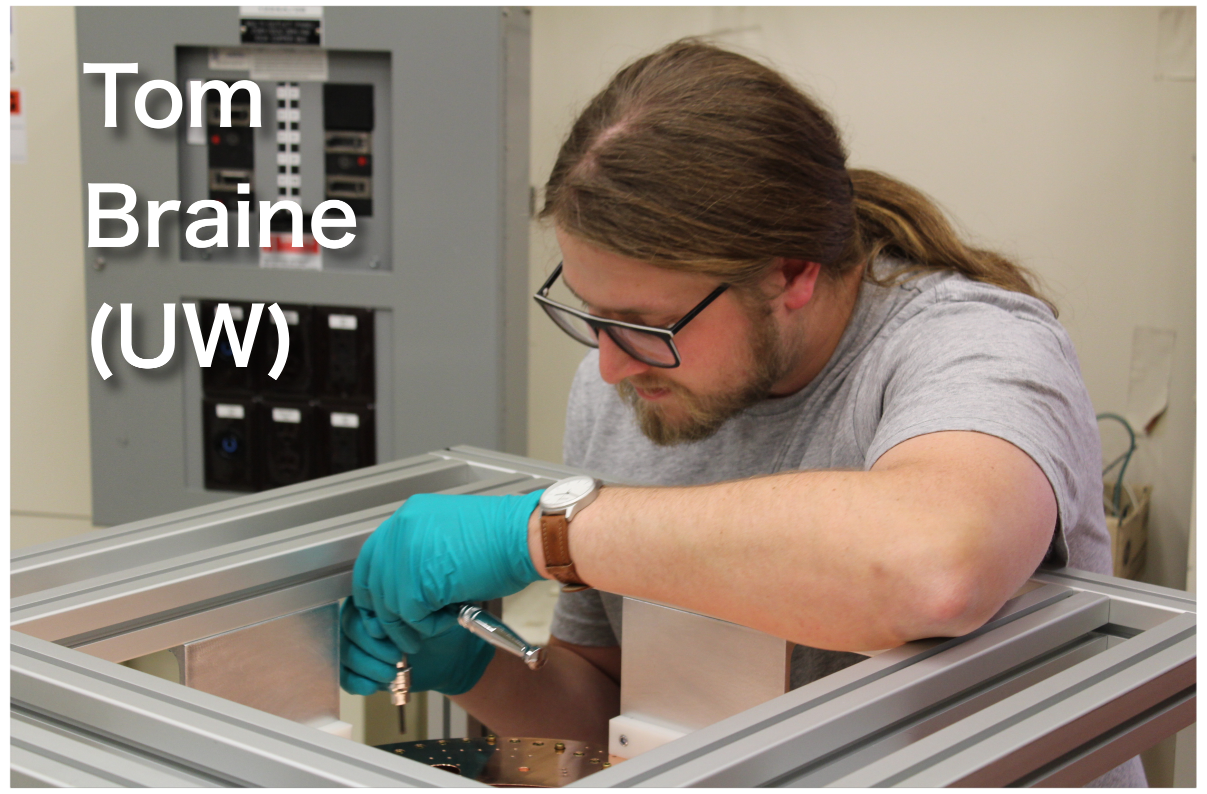


4-Cavity System

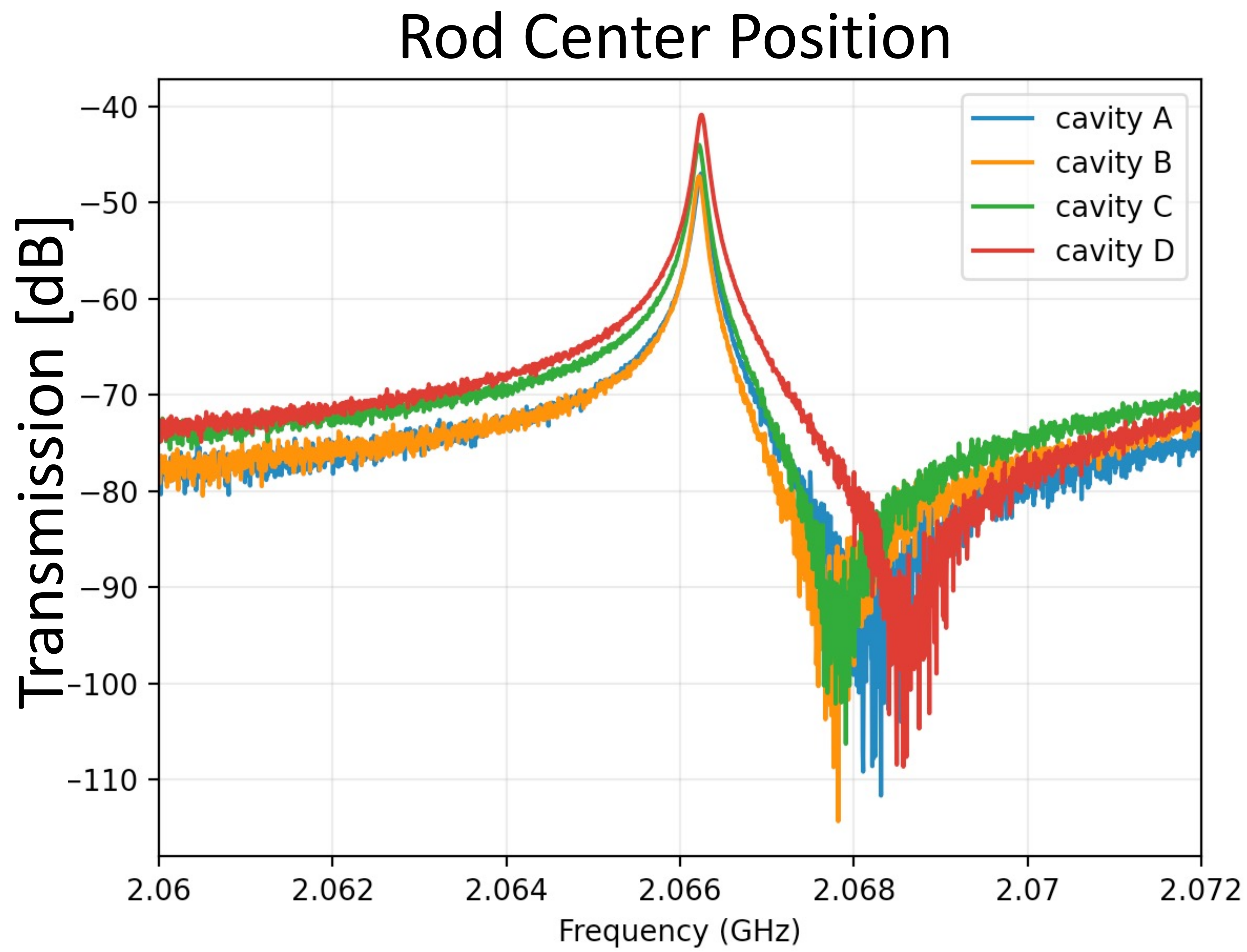


4-Cavity Array





Fabricated LLNL & Tested at FNAL now



Spread ~ 50kHz

$Q_A \sim (16.7 \pm 0.5)$k

$Q_B \sim (18.7 \pm 0.5)$k

$Q_C \sim (16.8 \pm 0.5)$k

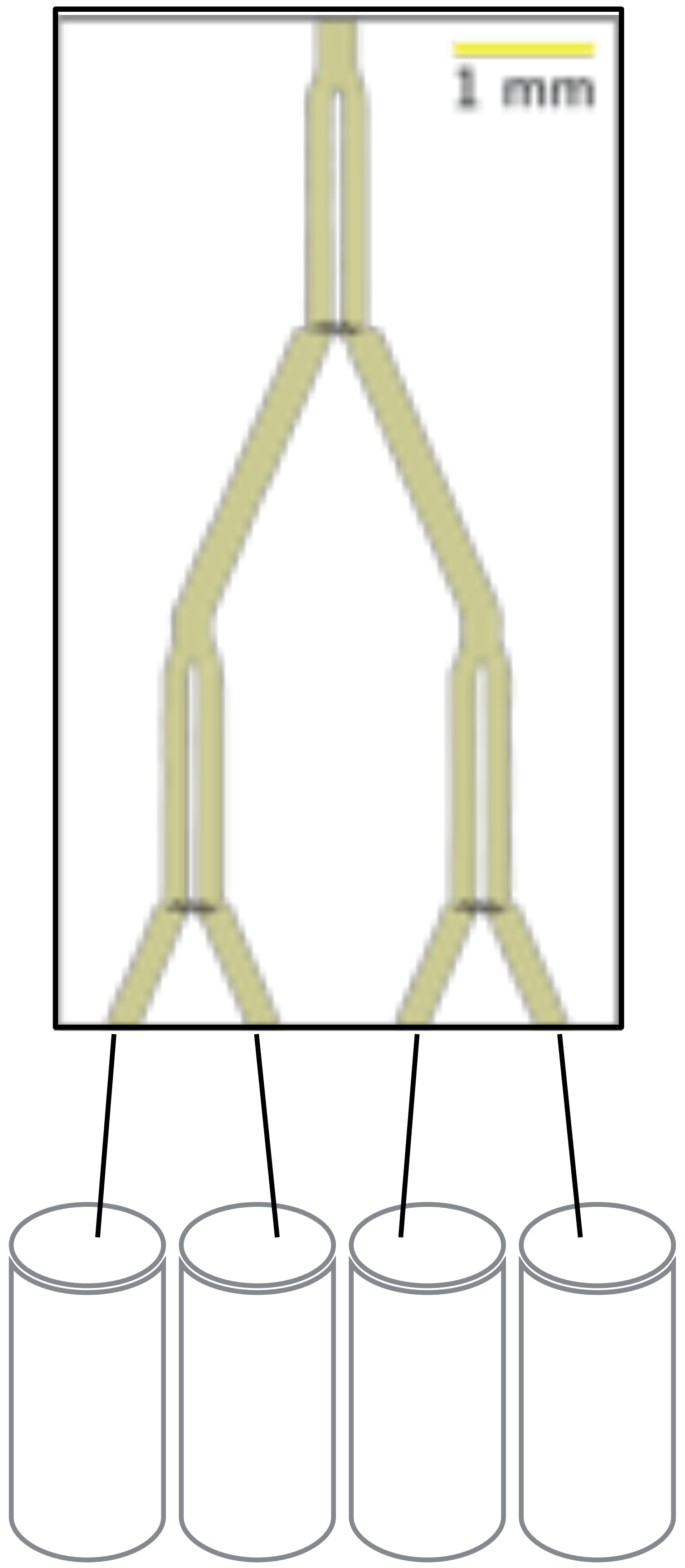
$Q_D \sim (17.5 \pm 0.5)$k

@room temp

Promising initial results

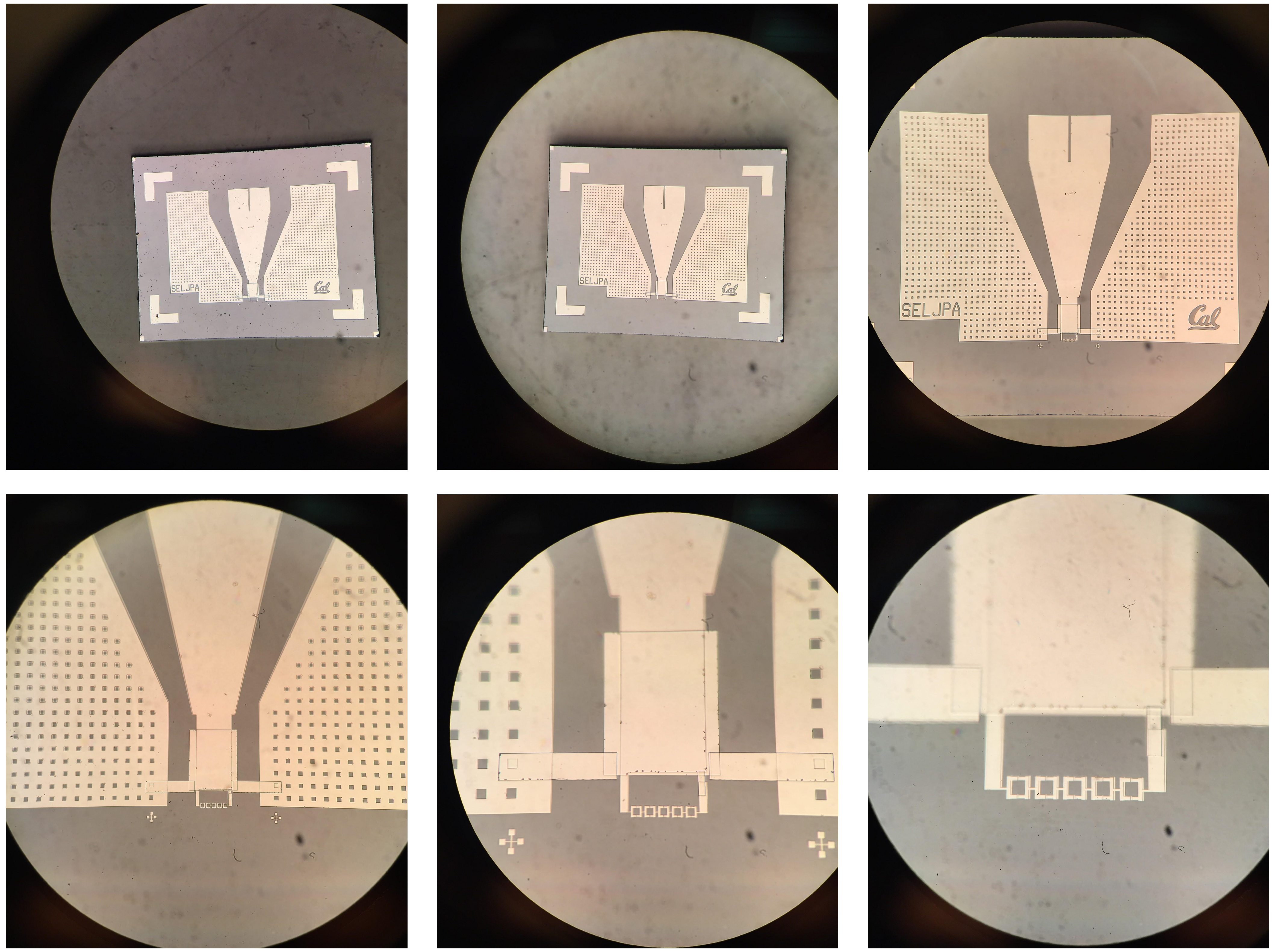
4-Cavity Electronics

Fabricated and tested at Wash U



First test indicates 0.5 dB insertion loss

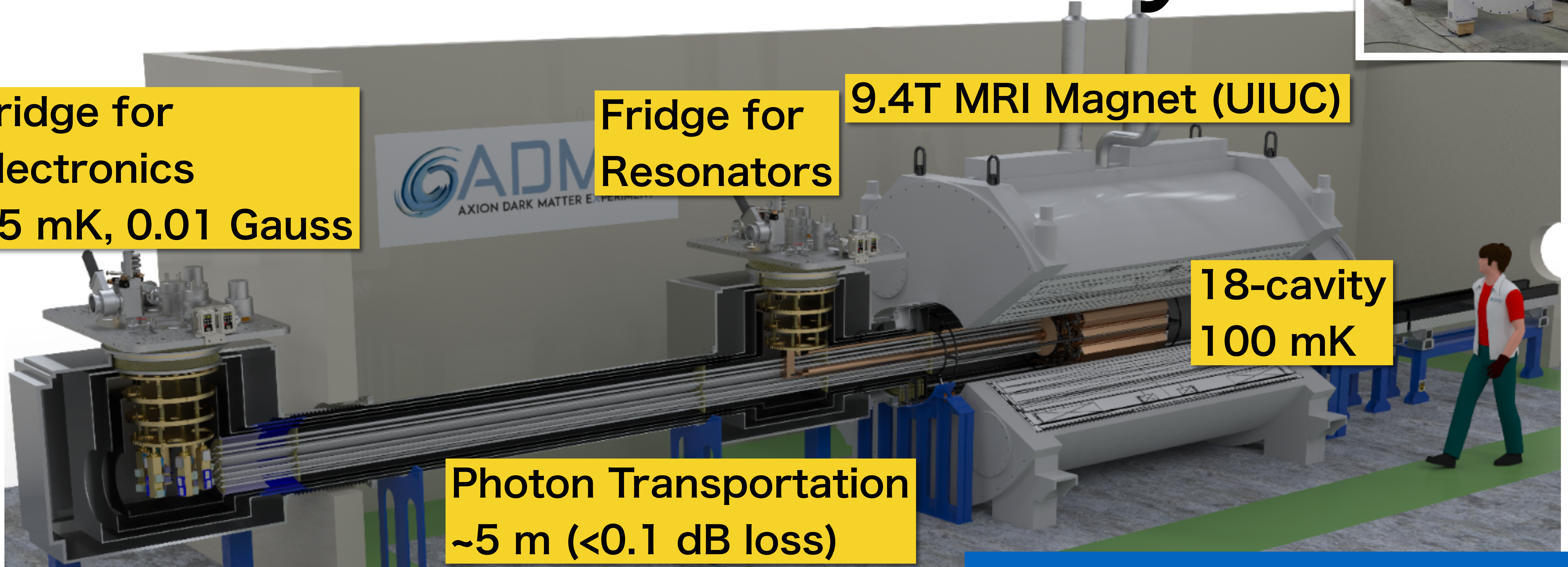
Fabricated at Berkeley and tested at Wash U

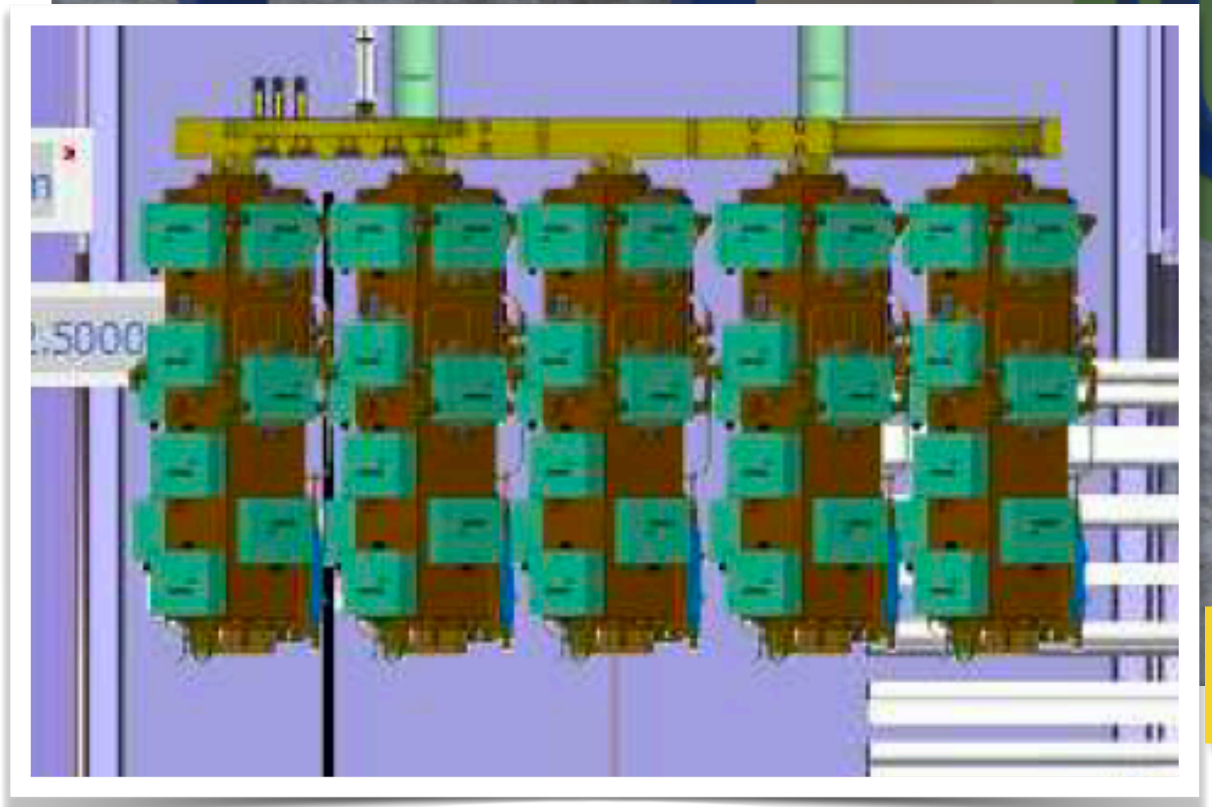


Continue to use JPA

Promising performance

ADMX EFR (18-Cavity)





	ADMX Run1	ADMX EFR
Volume (L)	117	258
B-filed (T)	7.6	9.4
System Noise (K)	350	425
Scan Speed FOM	1	4.8

Summary

Quantum amplifiers make "invisible" axion visible. (if it exists)

Ruled out one of the "invisible" axion model in $m_a = 3.2 - 4.1\ \mu\mathrm{eV}$

ADMX is aiming to search axions up to 4 GHz.

QIS technology potentially makes another innovation in the axion search in the near future.

This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009800, No. DESC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DEFG02-96ER40956, No. DEAC52-07NA27344, No. DEC03-76SF00098, and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE- AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices. UWA participation is funded by the ARC Centre of Excellence for Engineered Quantum Systems, CE170100009, Dark Matter Particle Physics, CE200100008, and Forrest Research Foundation. Speaker of this talk is supported by JSPS Overseas Research Fellowships No. 202060305. LLNL Release No. LLNL-JRNL-826807.