Physics 290
468 Birge
February 14, 2018

Advances in the Microwave Cavity Search for Dark Matter Axions

It's the Axion. Embrace it.

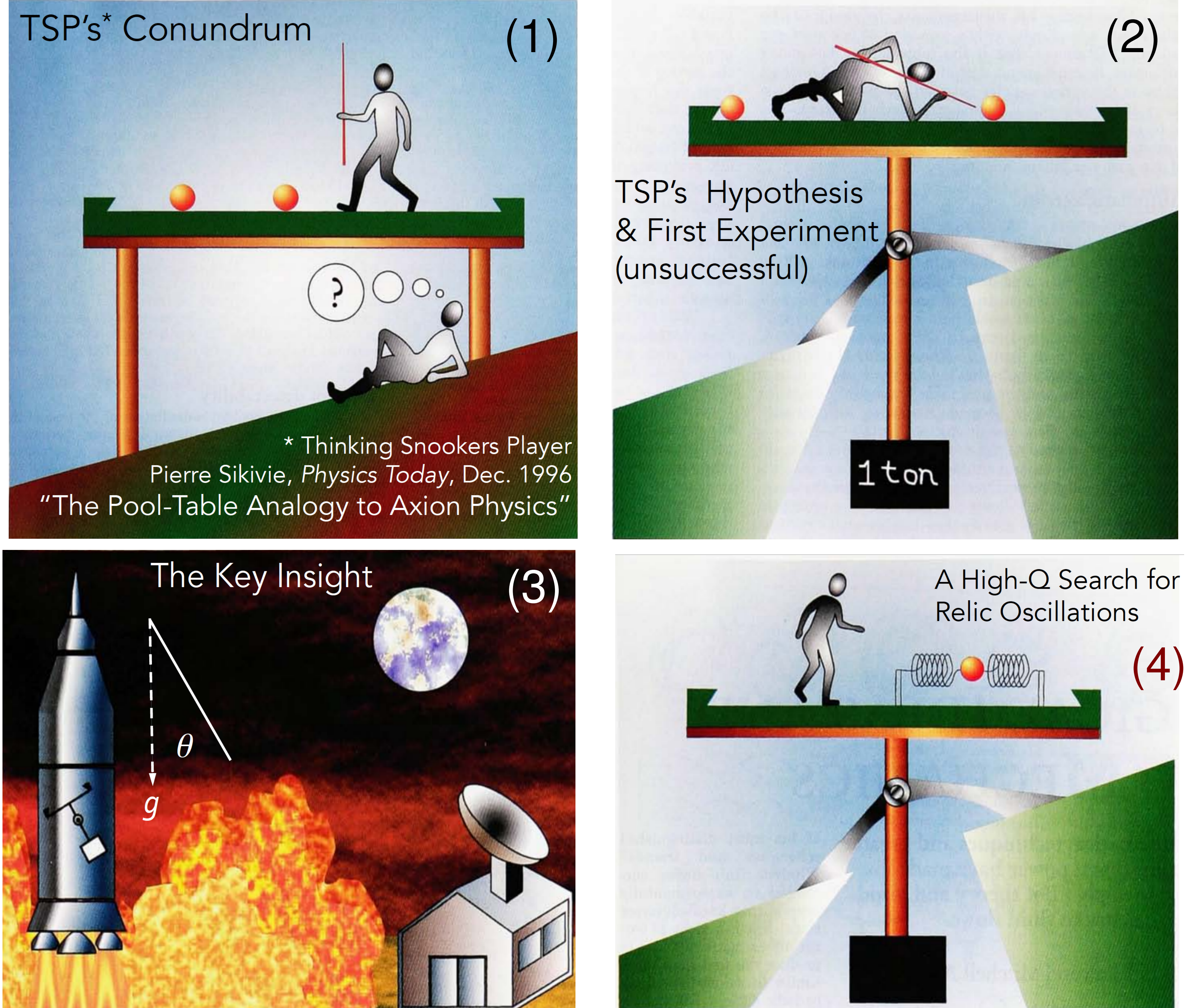
Karl van Bibbe
UC Berkeley

Outline

- Some preliminaries on the particle physics & cosmology of the axion
- The microwave cavity search for axionic dark matter
- Where we are today – ADMX & HAYSTAC
- Towards improved sensitivity, higher & lower masses
- When will the axion be found, and what then?

See P.W. Graham, I.J. Irastorza, S.K. Lamoreaux, A. Lindner, K. A. van Bibber, Annual Reviews of Nuclear and Particle Science 65 (2015) 485

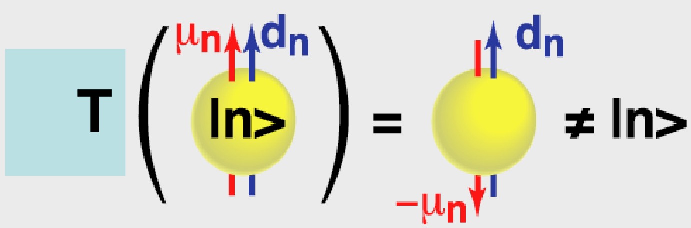
The Axion, Particle Physics & Cosmology


TSP's* Conundrum
(1)
* Thinking Snookers Player
Pierre Sikivie, *Physics Today*, Dec. 1996
"The Pool-Table Analogy to Axion Physics"
(2)
TSP's Hypothesis
& First Experiment
(unsuccessful)
1 ton
The Key Insight
(3)
θ
g
A High-Q Search for
Relic Oscillations
(4)

The Axion

The Strong-CP Problem

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



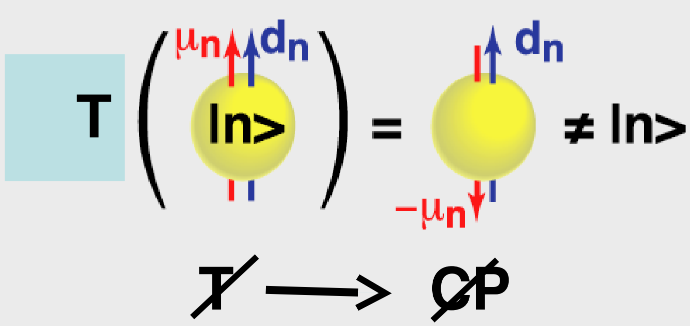
$\not{T} \longrightarrow \not{CP}$

- Why?

The Axion

The Strong-CP Problem

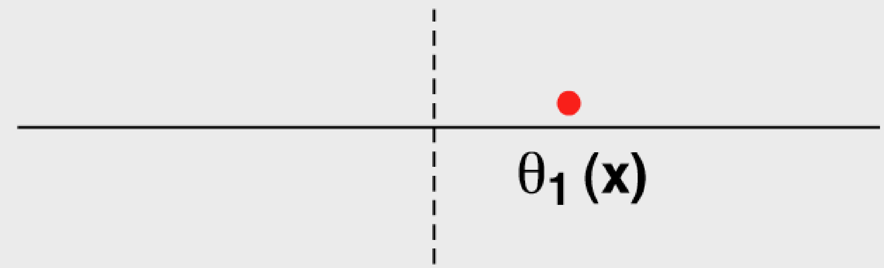
- $\mathcal{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



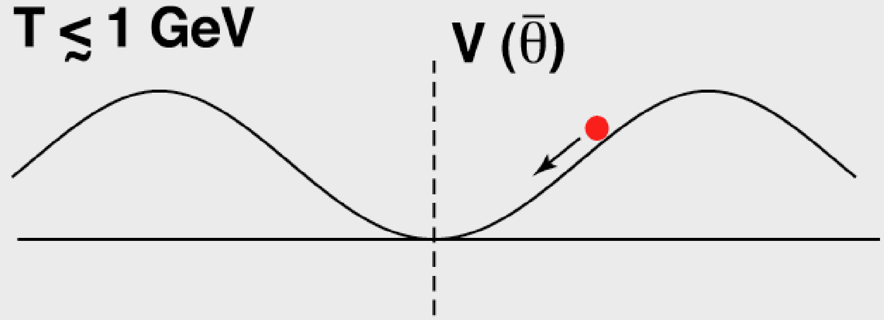
- Why?

Peccei-Quinn / Weinberg-Wilczek

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

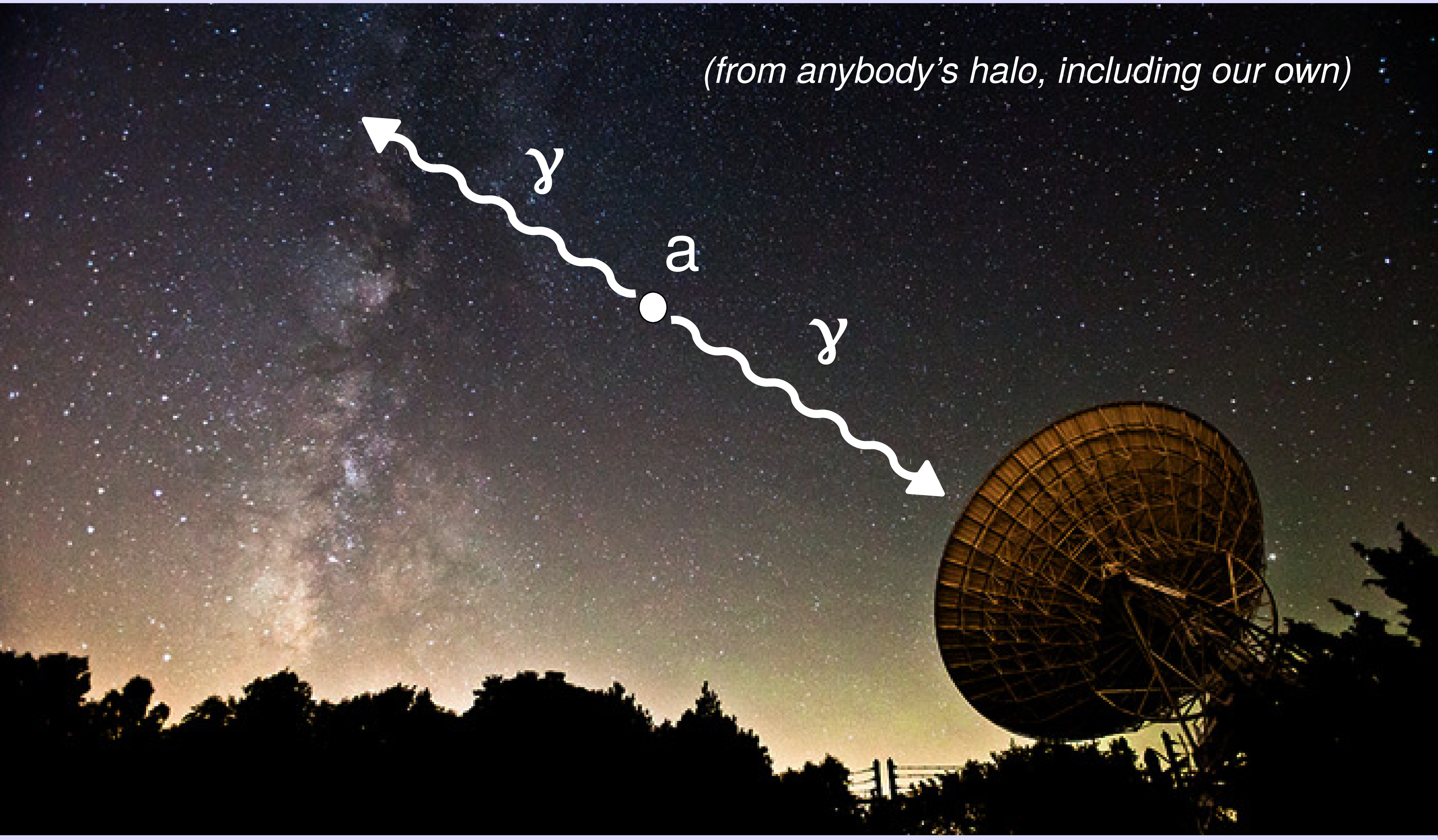


- $T \lesssim 1$ GeV



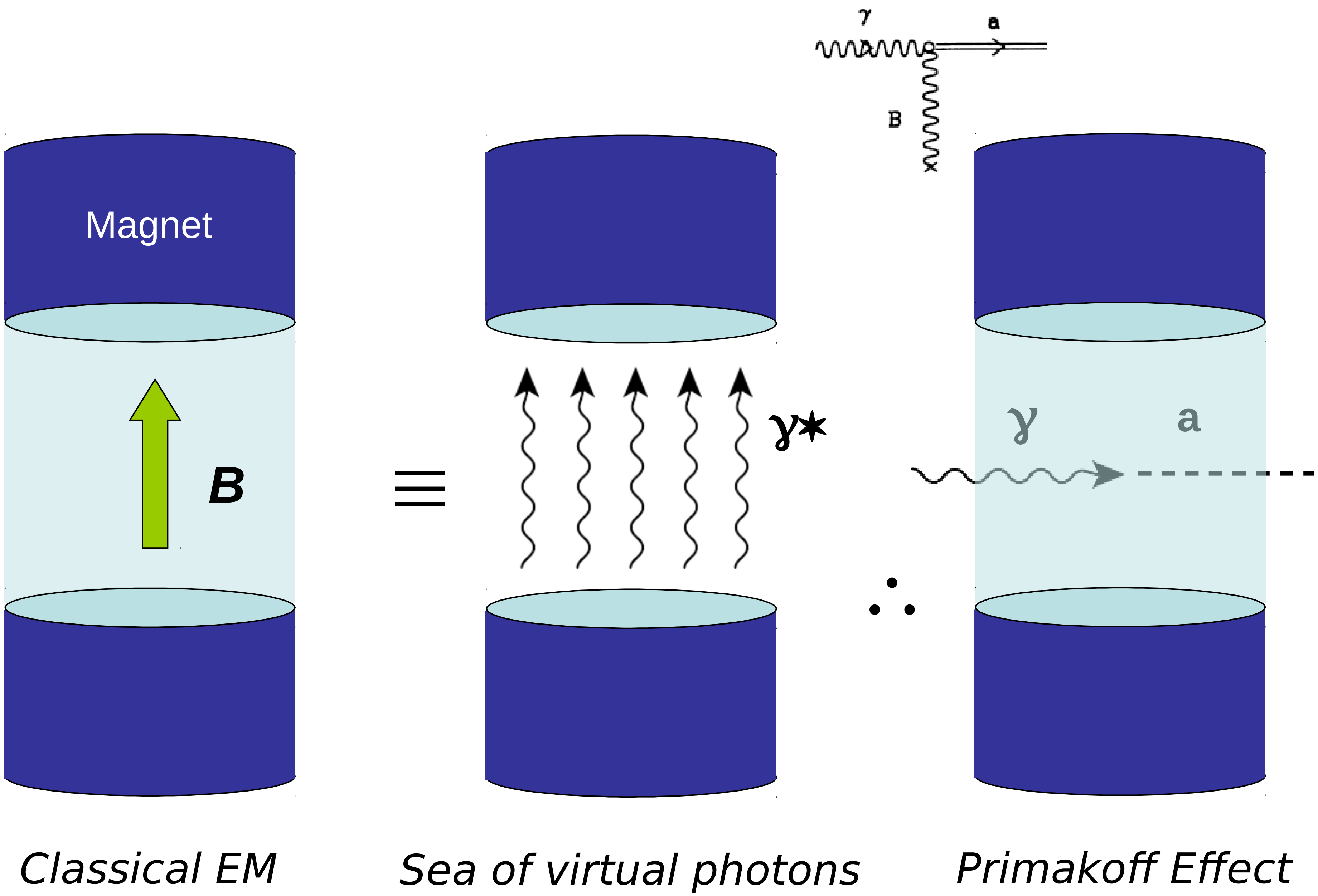
  - $\bar{\theta}$ dynamically → 0
  - Remnant oscillation = Axion

Why not just look for an unidentified radio line at which E_{γ}

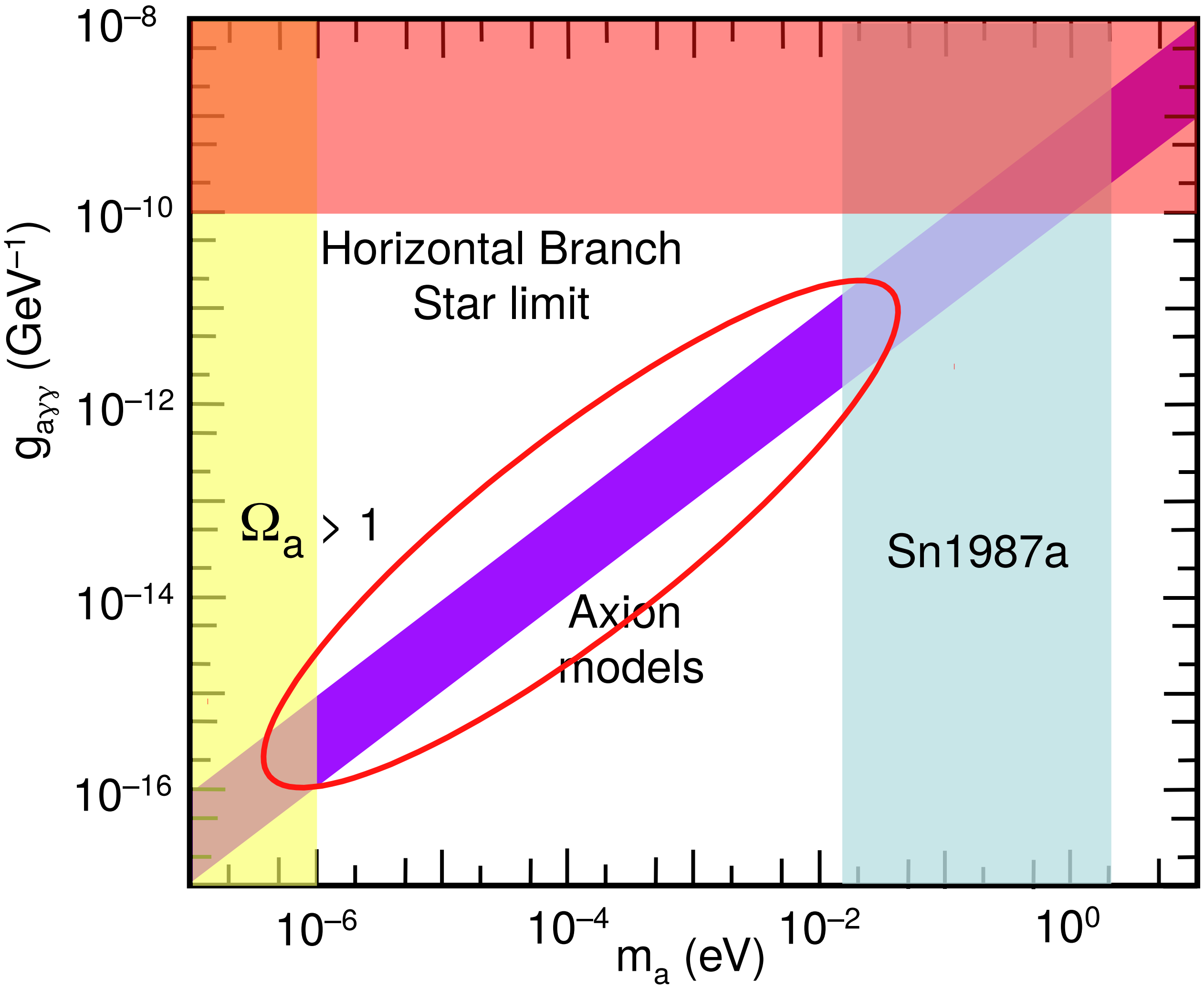


Problematically, the lifetime $\tau \sim 10^{60}$ sec for $m_a \sim \mu eV$

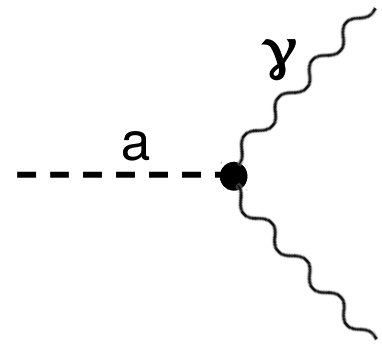
The Primakoff Effect P. Sikivie, Phys. Rev. Lett. 51 (1983) 1415



Axion phenomenology & the canonical limits



Light cousin of π^0: $J^{\pi} = 0^-$



m_a , $g_{aii} \propto f_a^{-1}$ ∴ $g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6} \rightarrow m_a > 1\ \mu$eV

Sn1987a ν pulse precludes NN→NNa for $m_a \sim 10^{-(3-0)}$ eV

Horizontal Branch Stars preclude $g_{a\gamma\gamma} > 10^{-10}$ GeV^{-1}

G.G. Raffelt *"Stars as Laboratories for Fundamental Physics"* U. Chicago Press (1996)

Good news – Parameter space is bounded

Bad news – All couplings are *extraordinarily* weak

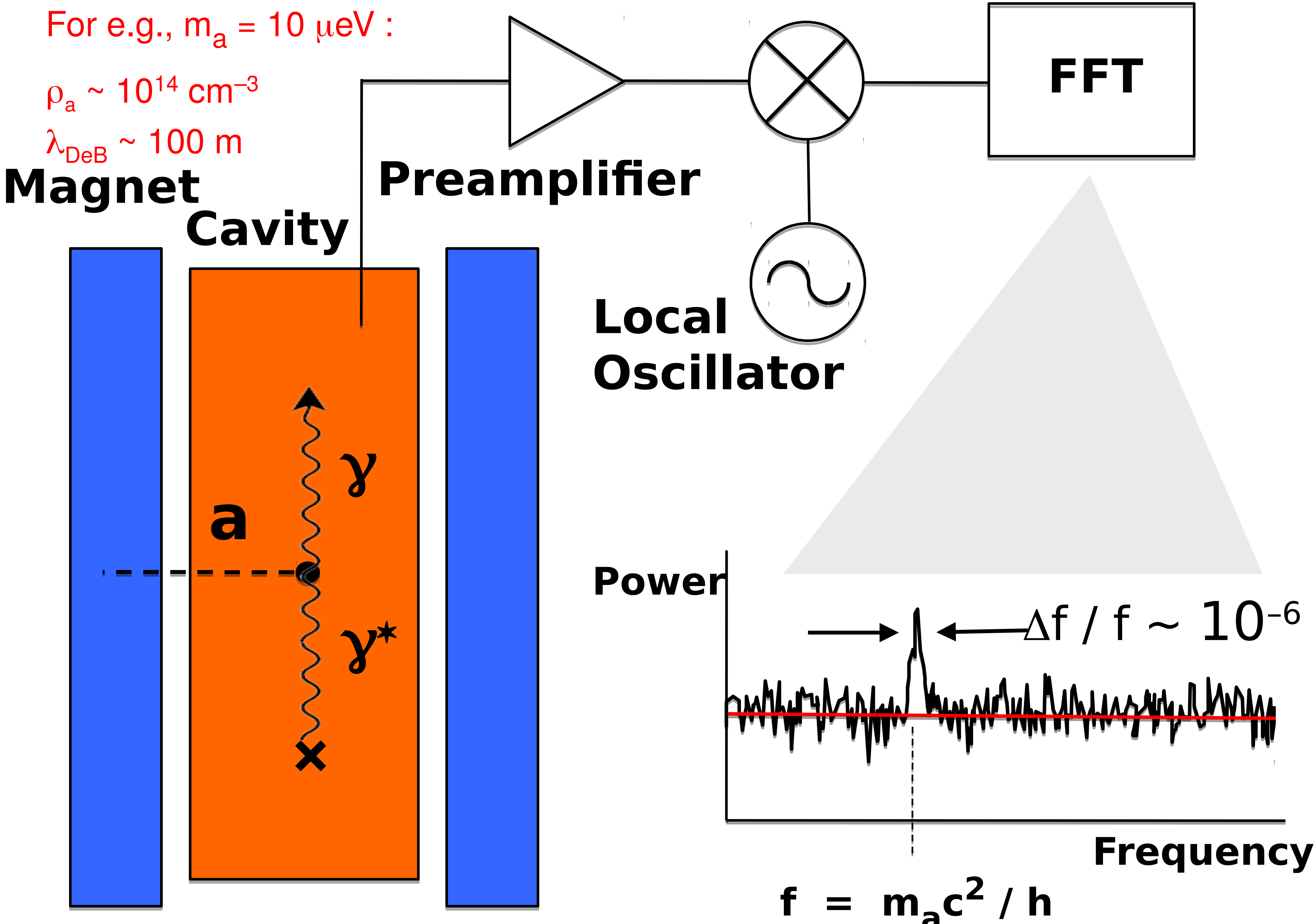
Microwave cavity searches for DM axions

The microwave cavity axion search - Your car radio on steroids

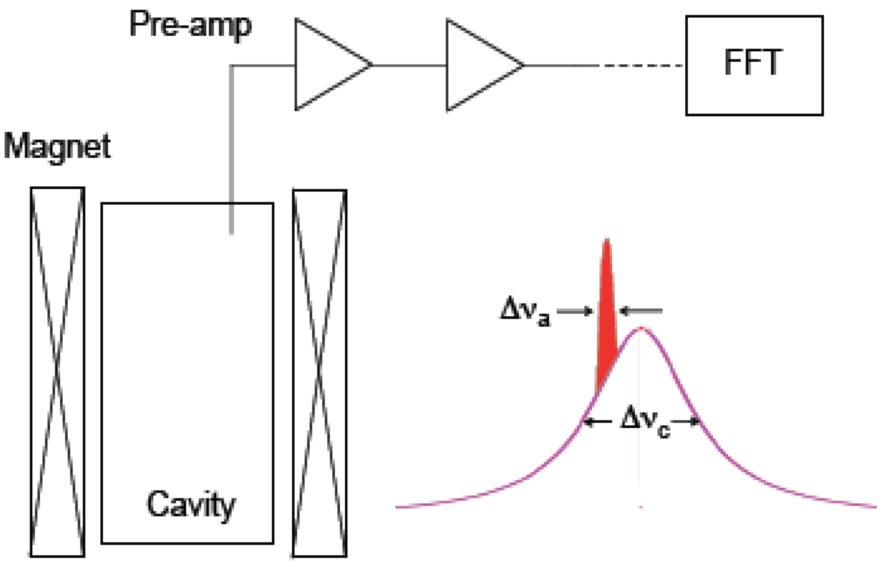
For e.g., m_a = 10 μeV :

$\rho_a \sim 10^{14}\ cm^{-3}$

$\lambda_{DeB} \sim 100$ m



Signal to Noise & detectability



Cavity Bandwidth: $\Delta\nu_c / \nu_c = Q^{-1} \sim 10^{-4}$

Axion Bandwidth: $\Delta\nu_a / \nu_a \sim \beta^2 \sim 10^{-6}$

Conversion Power: $P \sim g_{a\gamma\gamma}^2 (\rho_a / m_a) B^2 Q_c V C_{nm\ell} \sim 10^{-23}$ watt

Signal to Noise Ratio: $$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

System Noise Temperature: $$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2}\right) + kT_A$$

Note $T_S \approx T + T_A$, for $T >> h\nu$

Linear amplifiers are subject to the Standard Quantum

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

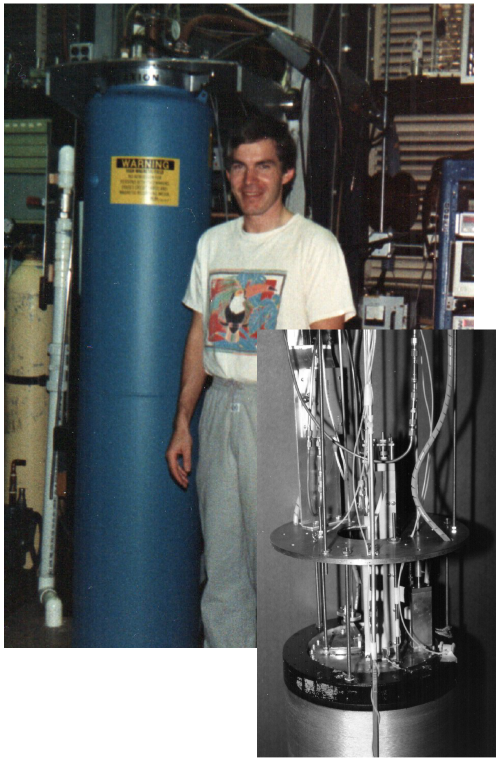
ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

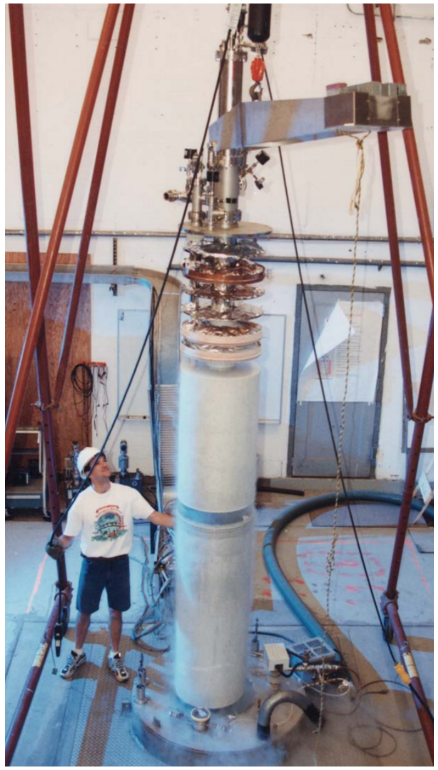
The SQL can be evaded by

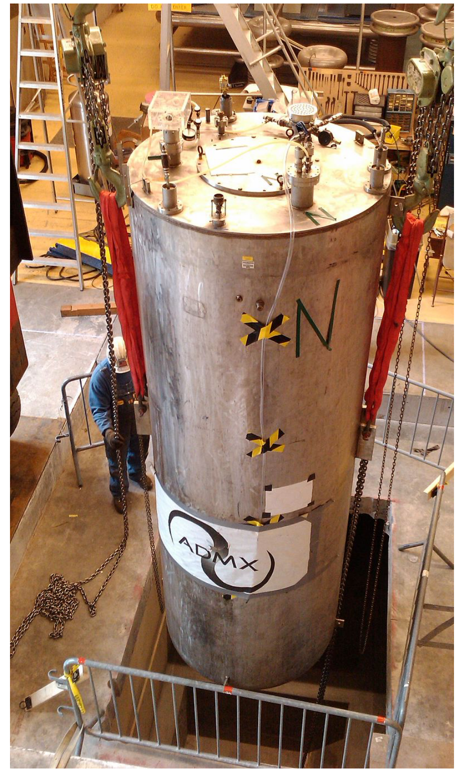
- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)

Thirty Years in One Slide

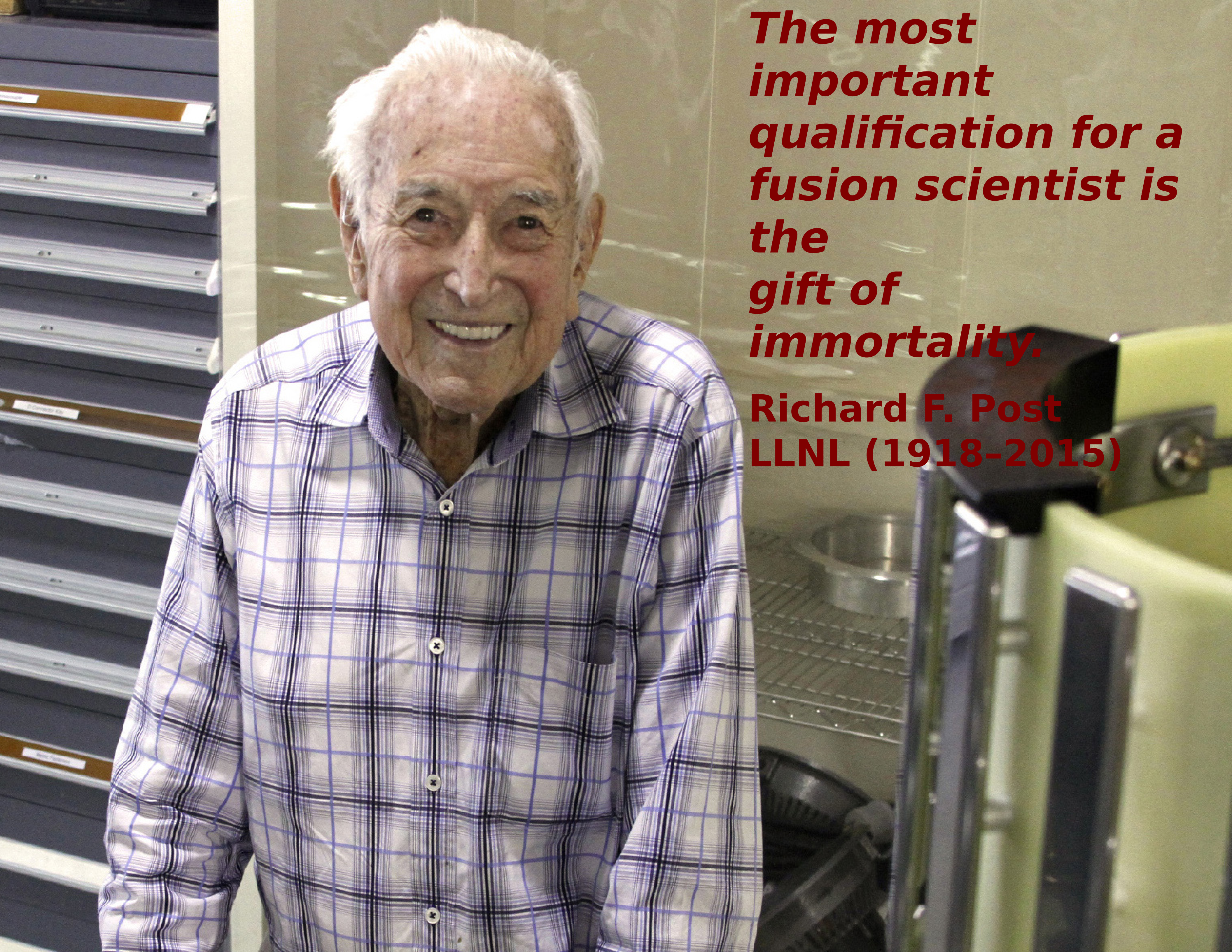
Published Haloscopes







UF / RBF	ADMX @ LLNL	ADMX @ UW	HAYSTAC
1985 – 1990	1995 – 2010	2016 – present	2015 – present
HEMT	HEMT, SQUID	SQUID + dil. fridge	JPA + dil. fridge
f ~ 2.5 GHz	~ 0.5 GHz	~ 0.5 GHz	~ 6 GHz
V ~ 5 L	~ 200 L	~ 150 L	~ 1.5 L
T_{SYS} ~ 5-20 K	~ 3 K	~ 500 mK	~ 600 mK
T_{SYS}/T_{Q} ~100-	~ 50 – 100	~ 10	~ 2


The most
important
qualification for a
fusion scientist is
the
gift of
immortality.
Richard F. Post
LLNL (1918–2015)

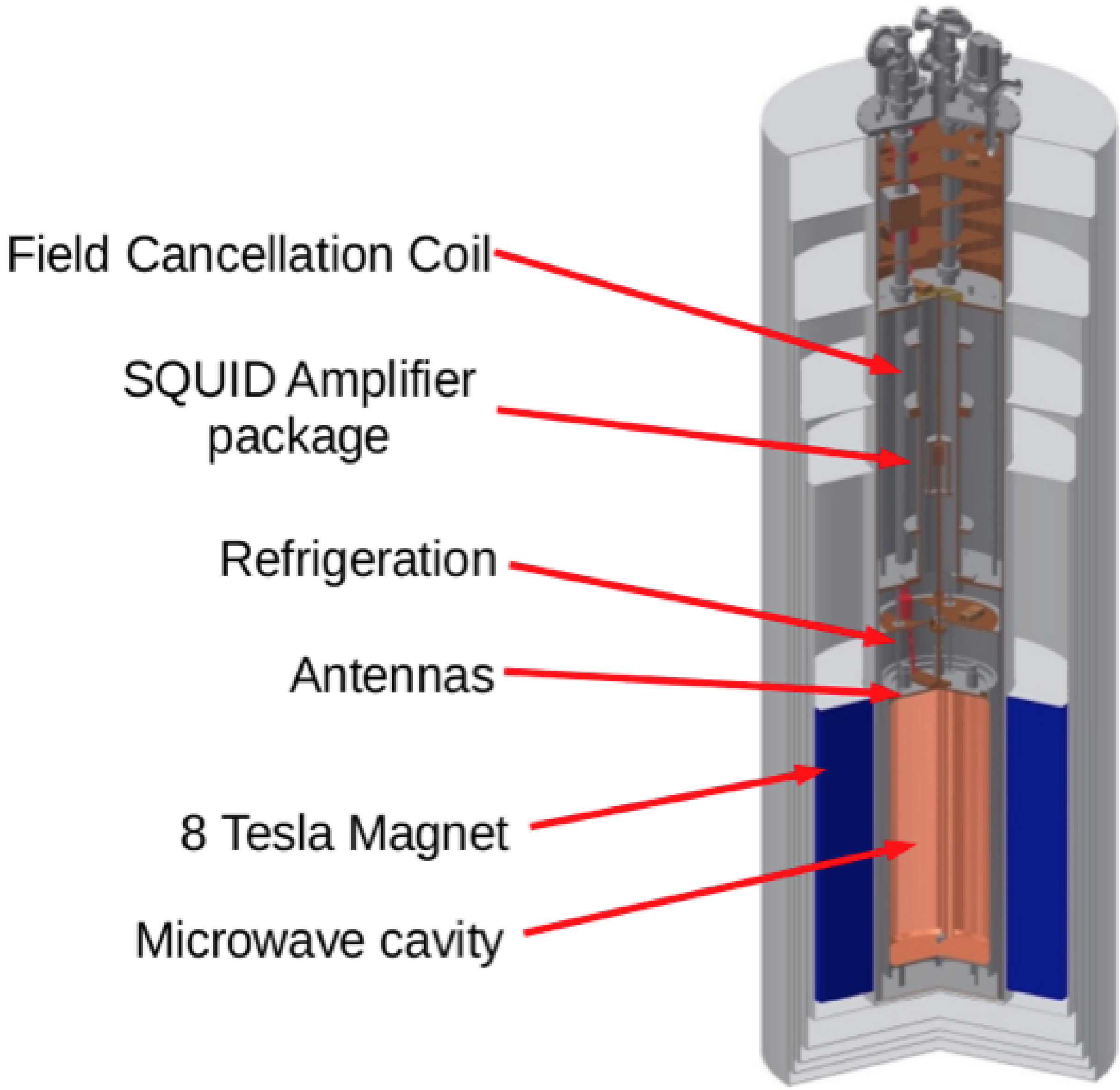

Ditto, Dark
Matter !

ADMX

&

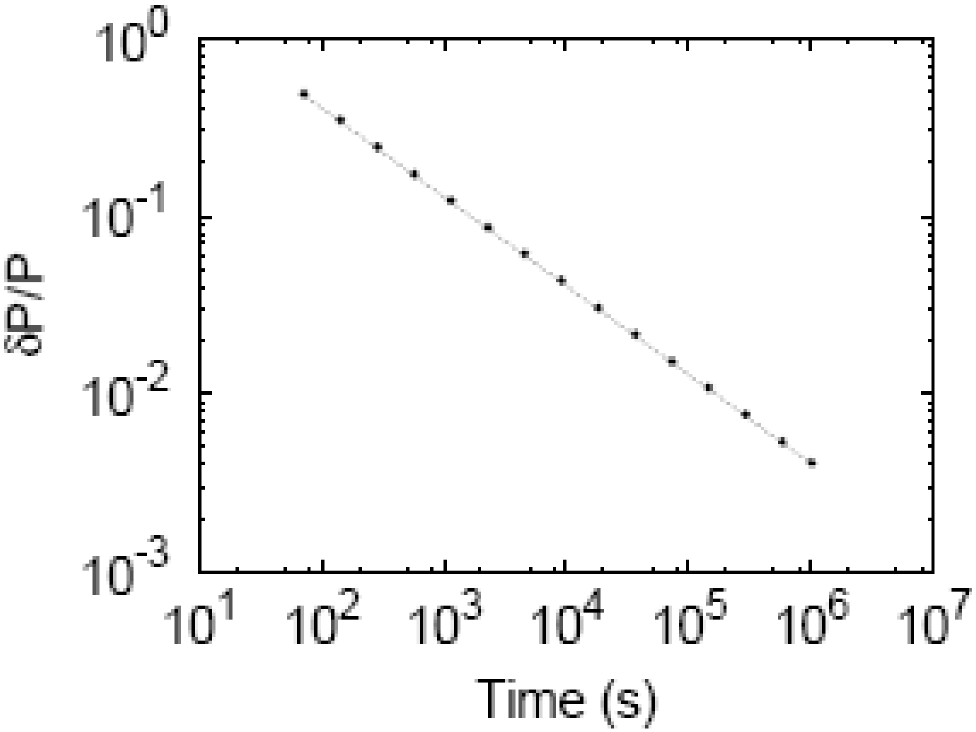
HAYSTAC

Axion Dark Matter eXperiment (ADMX)



UW, UF, LLNL, UCB, NRAO, Sheffield, FNAL, LANL, PNNL, ...

Even at T_{SYS} ~ 3K ADMX was the world's quietest radio receiver



Dicke Radiometer equation:

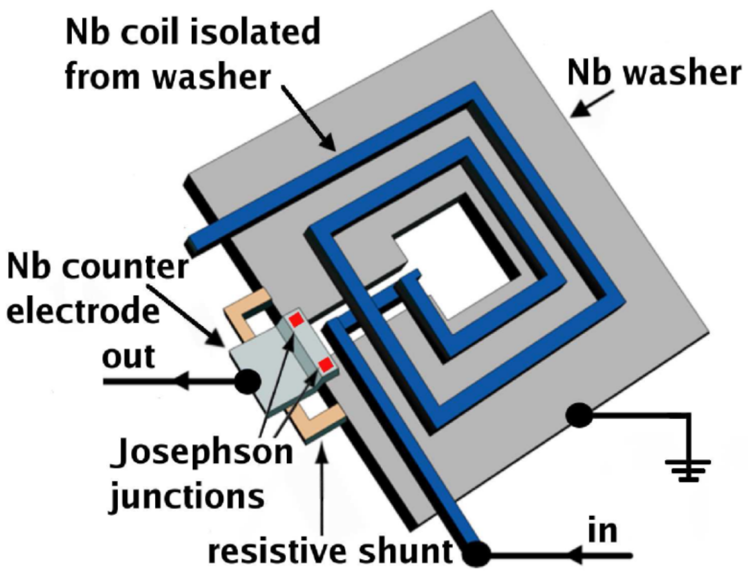
$$\frac{s}{n} = \frac{P_s}{kT_n}\sqrt{\frac{t}{\Delta\nu}}$$

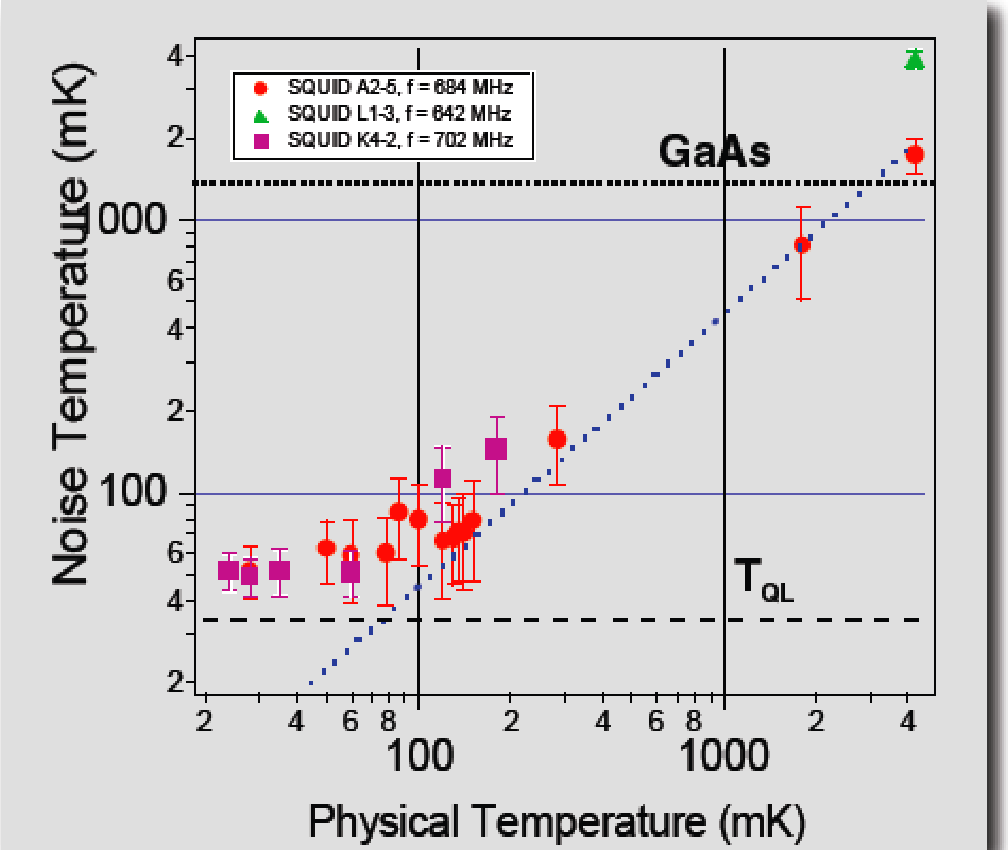
Systematics-limited for signals of 10 W – 10 of DFSZ axion power.

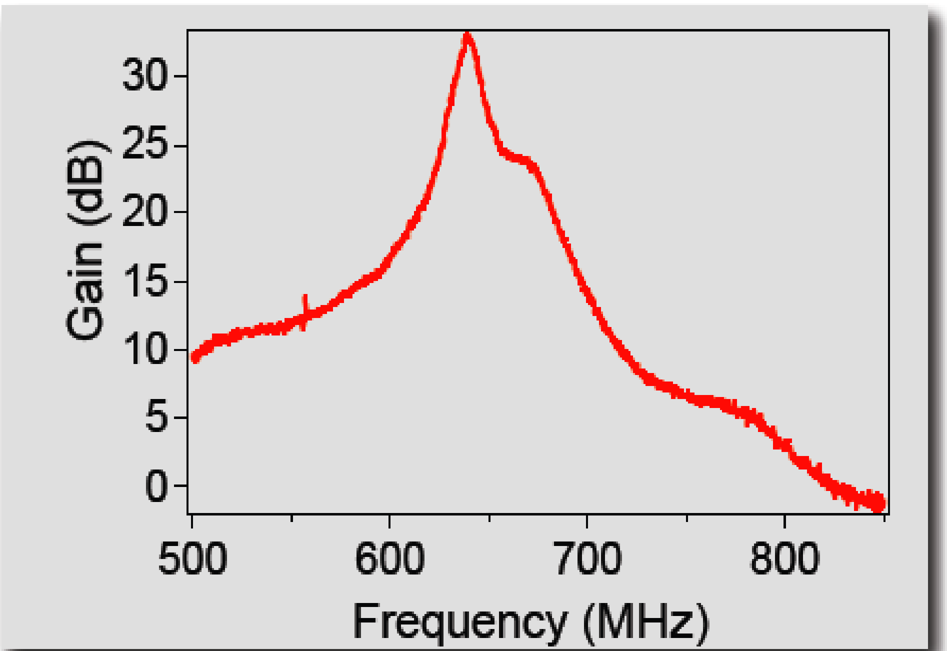
Last signal received from Pioneer 10 (6 billion miles away) ~ 10^{-21} W

The Breakthrough Technology: Microstrip SQUID amplifiers

John Clarke *et al.* 1998

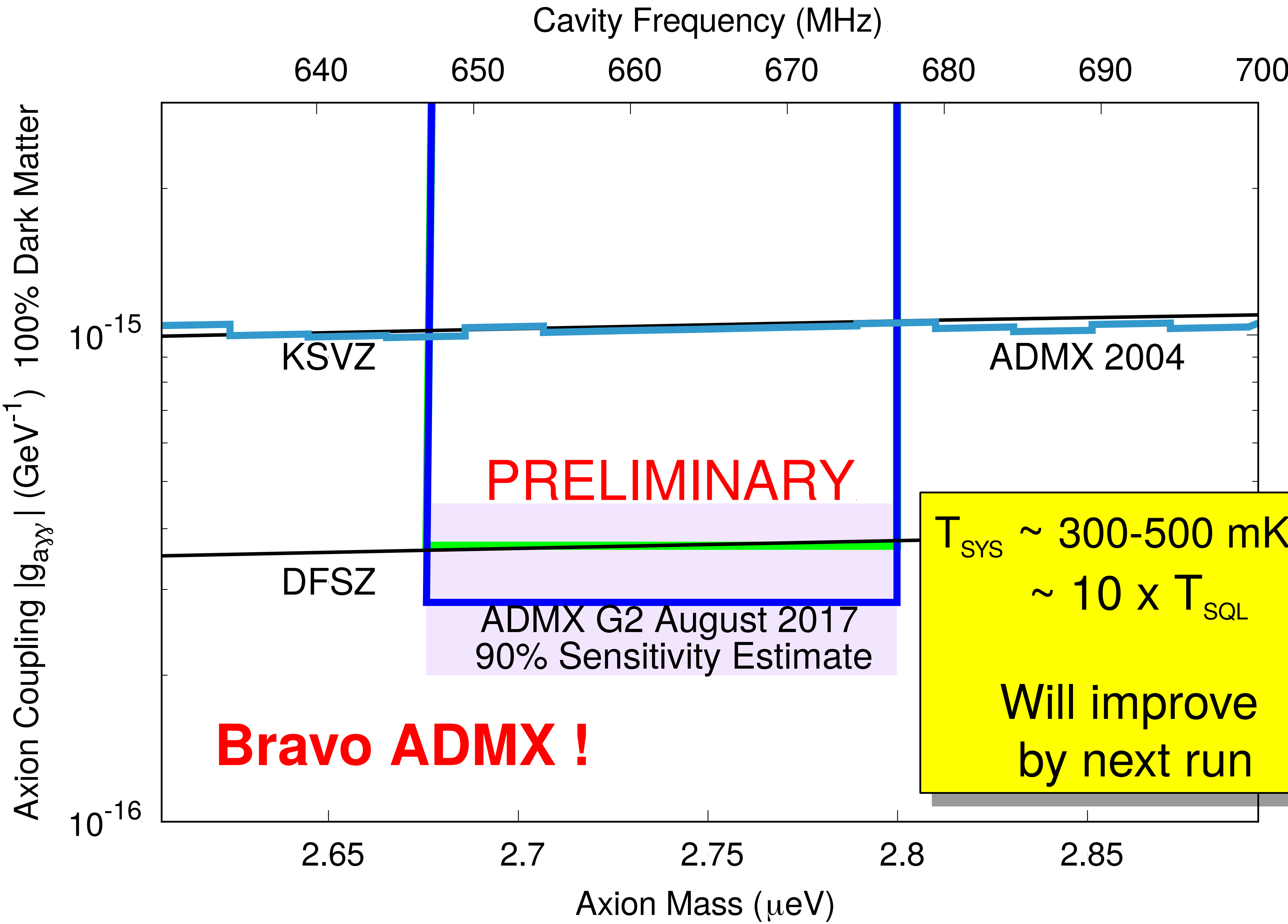






High frequency SQUID amplifiers have become a cornerstone of QI/QC

ADMX Gen.2 preliminary result – DFSZ reached

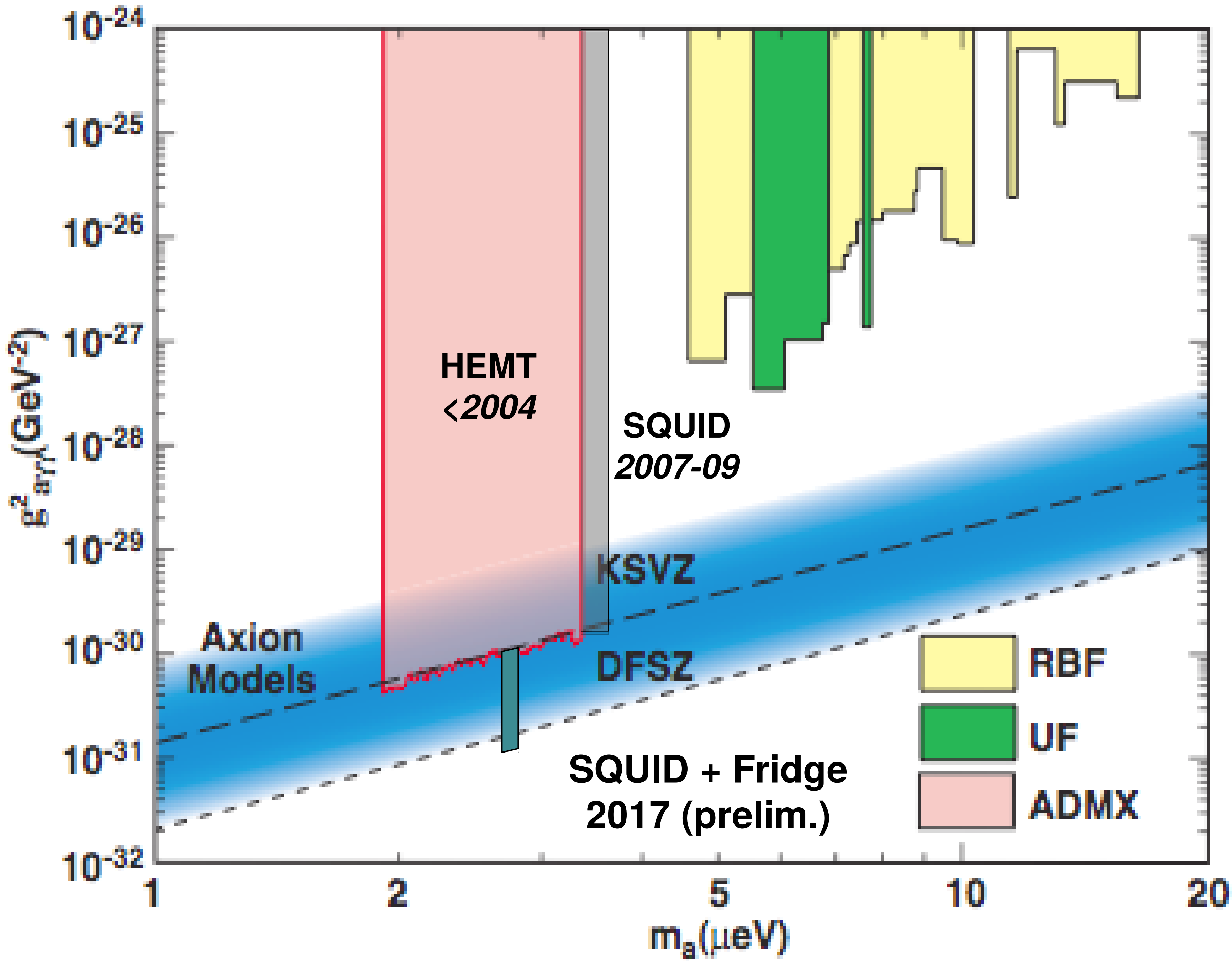


T_{SYS} ~ 300-500 mK

~ 10 x T_{SQL}

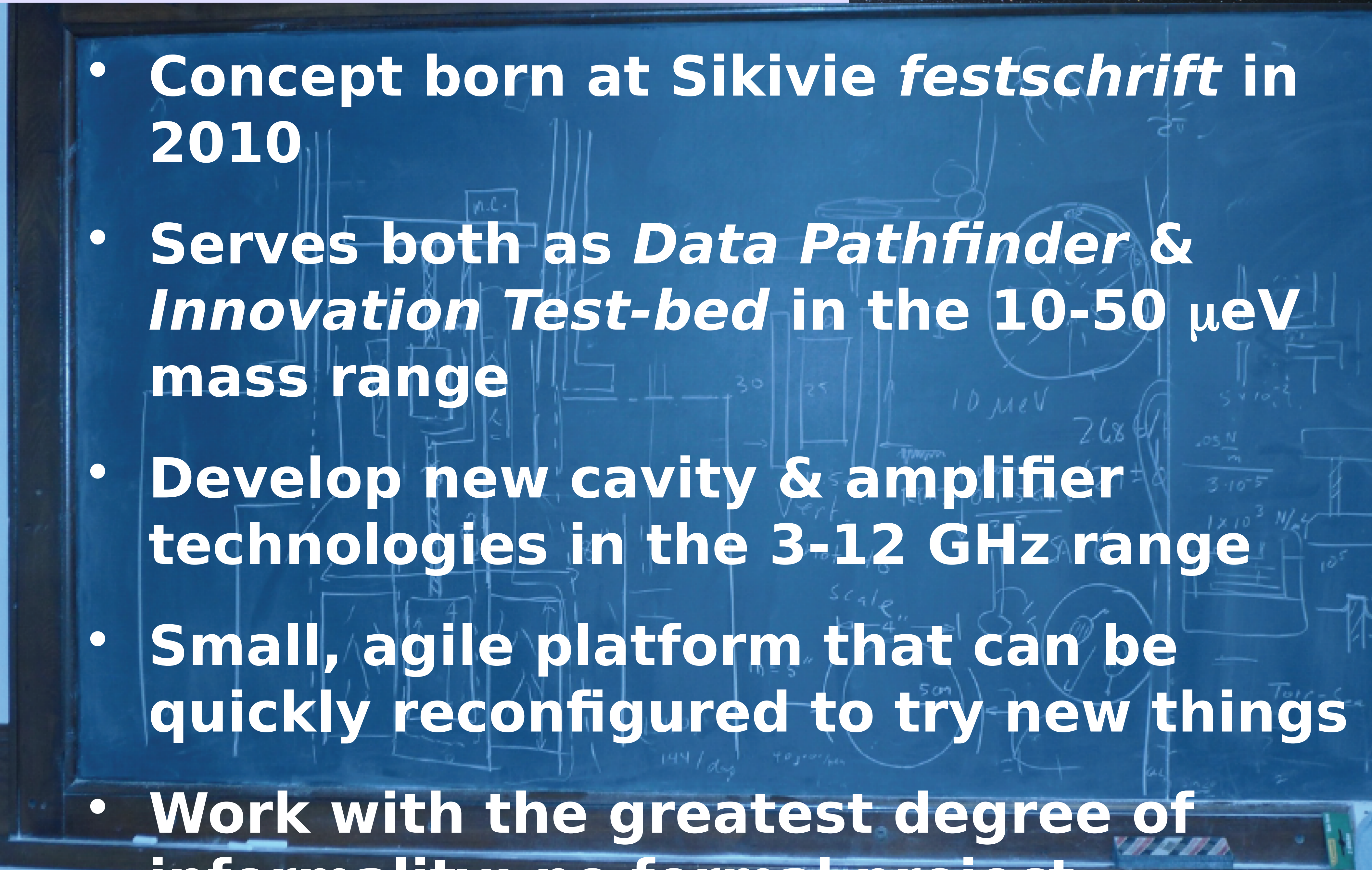
Will improve by next run

The situation 30 years later – We need to pick up the pace!



Motivation & philosophy

HAYSTAC



- **Concept born at Sikivie *festschrift* in 2010**
- **Serves both as *Data Pathfinder* & *Innovation Test-bed* in the 10-50 μeV mass range**
- **Develop new cavity & amplifier technologies in the 3-12 GHz range**
- **Small, agile platform that can be quickly reconfigured to try new things**
- **Work with the greatest degree of**

BTW, the drawing on Steve Lamoreaux’s blackboard *was* our TDR !

The team

Yale University

Steve Lamoreaux, Yulia Gurevich, Ling Zhong, Ben Brubaker, Sid Cahn

UC Berkeley

Karl van Bibber, Maria Simanovskaia, Samantha Lewis, Jaben Root, Saad Al Kenany, Kelly Backes, Nicholas Rapidis, Isabella Urdinaran, Tim Shokair

CU Boulder/JILA

Konrad W. Lehnert, Daniel Palken, William F. Kindel, Maxime Malnou, M.A. Anil

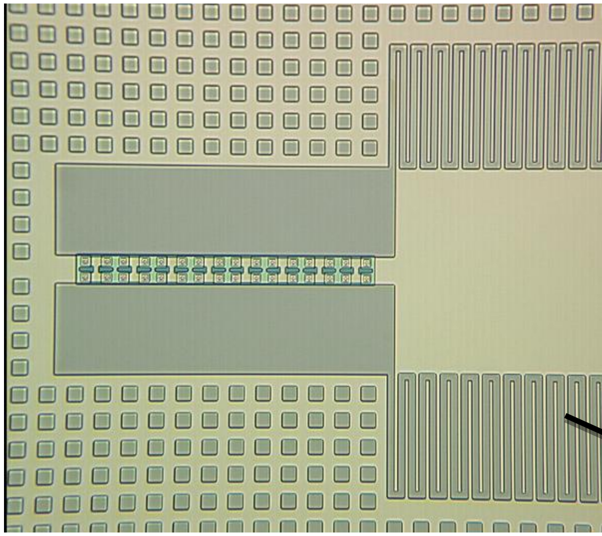
Lawrence Livermore National Lab

Gianpaolo Carosi

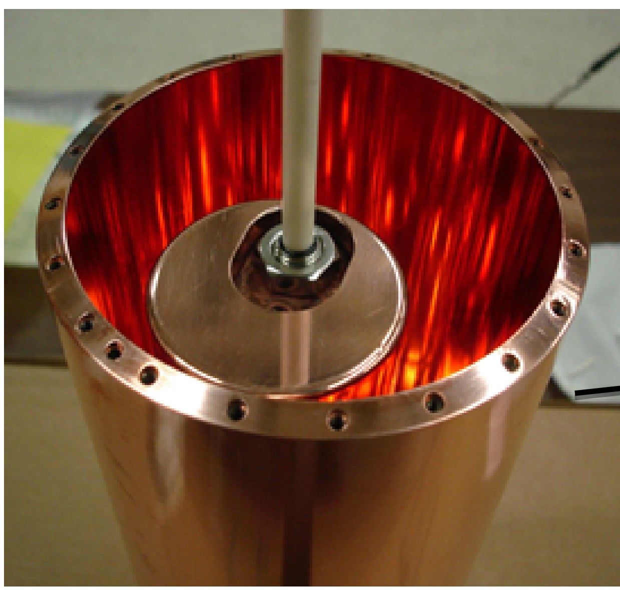
Integration at Yale

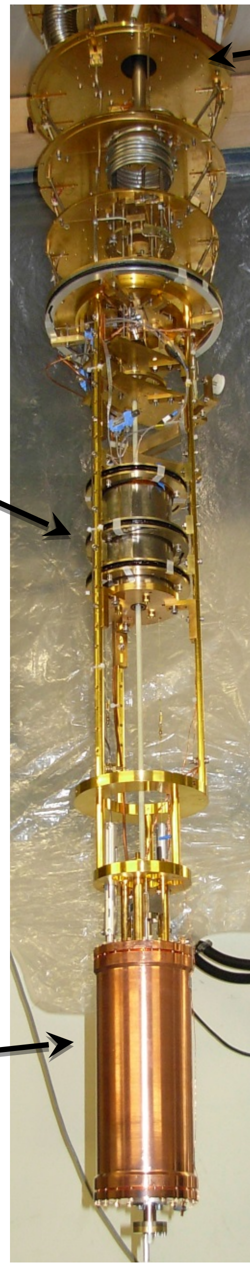
HAYSTAC

Josephson Parametric Amplifier

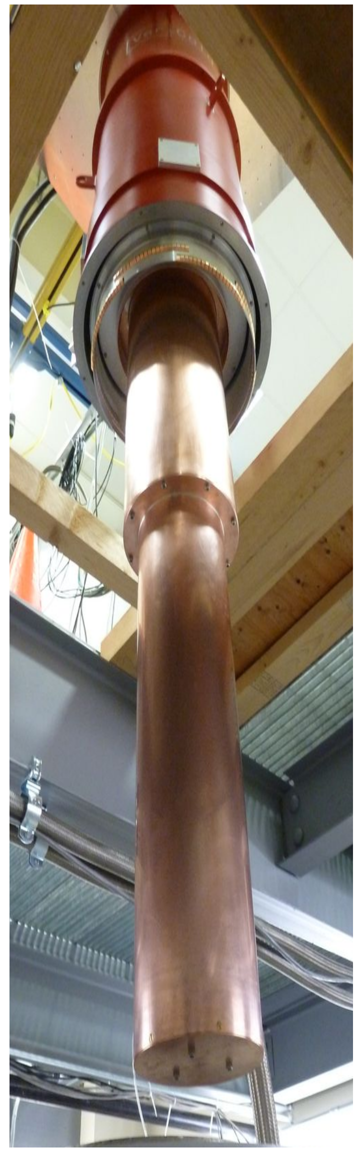


Microwave Cavity (copper)





$^3He/^4He$ Dilution Refrigerator



9.4 Tesla, 10 Liter Magnet

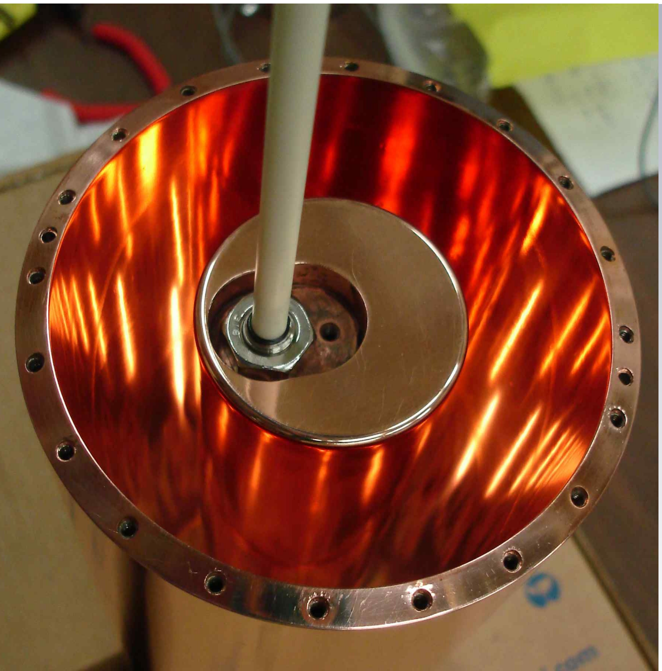
Microwave cavity (Berkeley/LLN

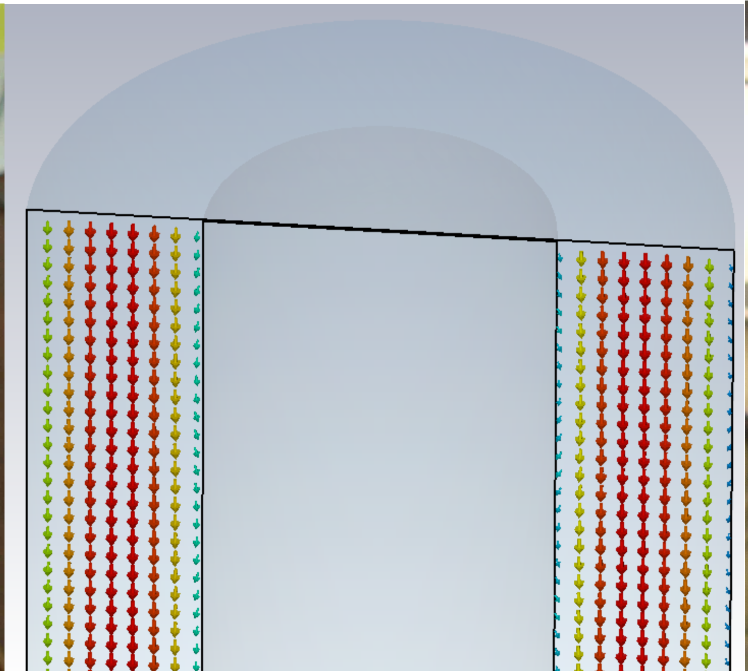
Cu body with off-axis tuning rod

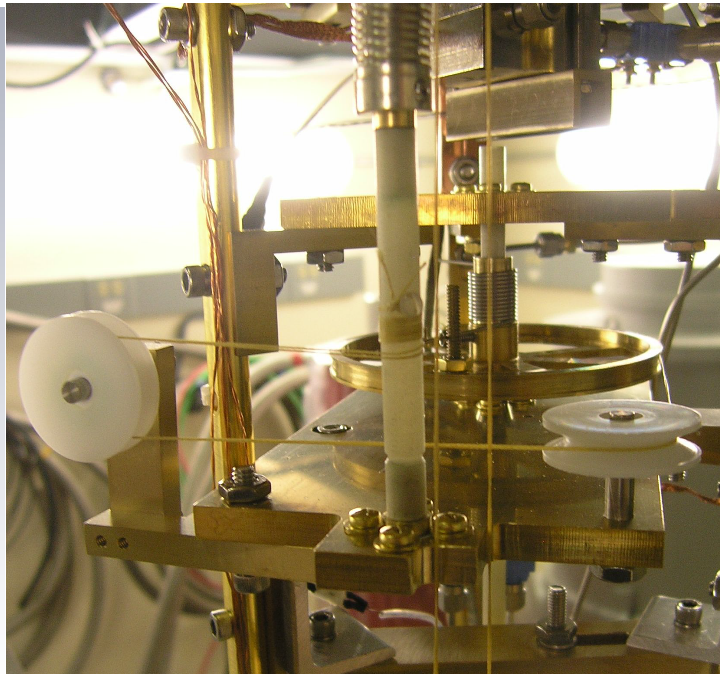
Tunable over 3.6 – 5.8 GHz

Q_c ~ 20,000

Stepping motors and Kevlar lines used for motion



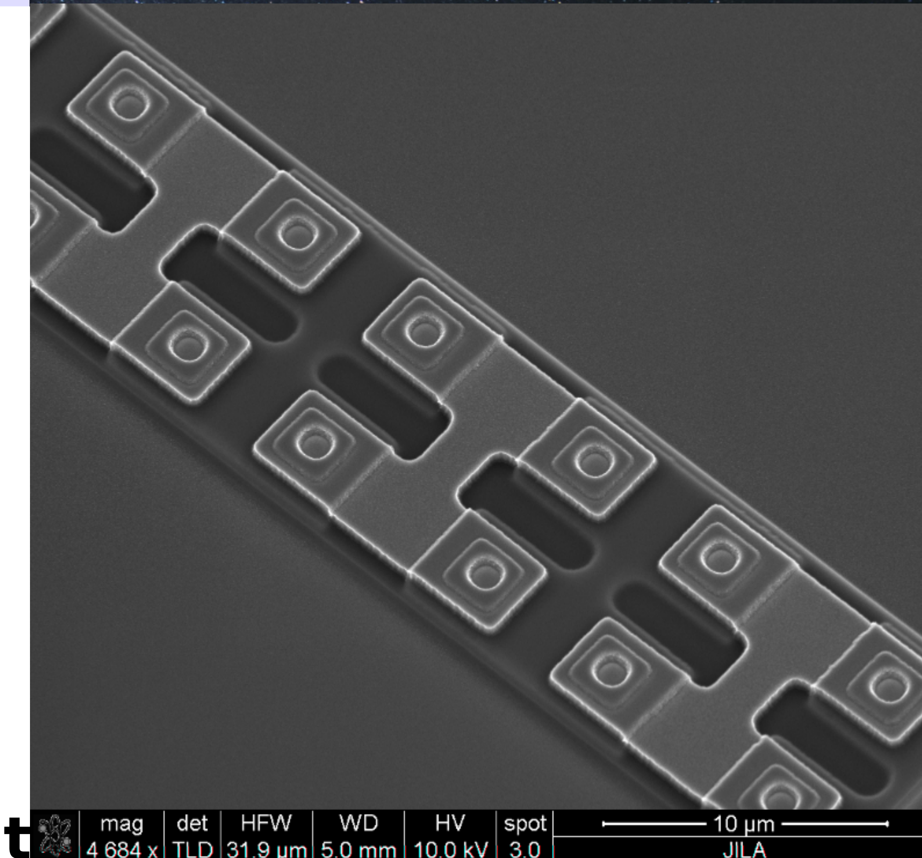


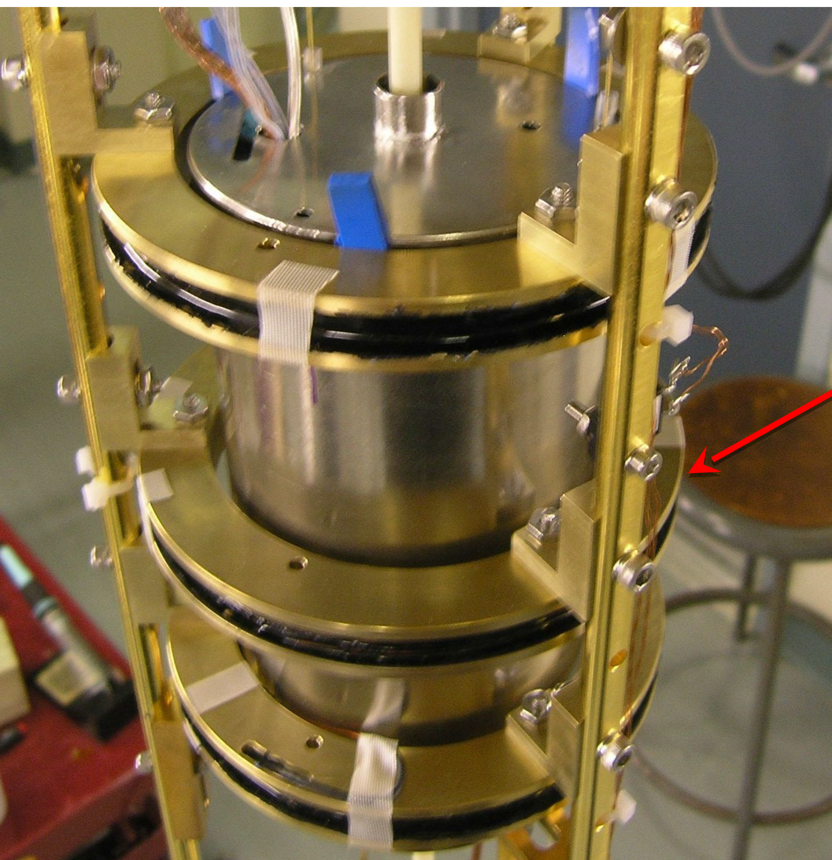


JPA (Colorado/JILA)

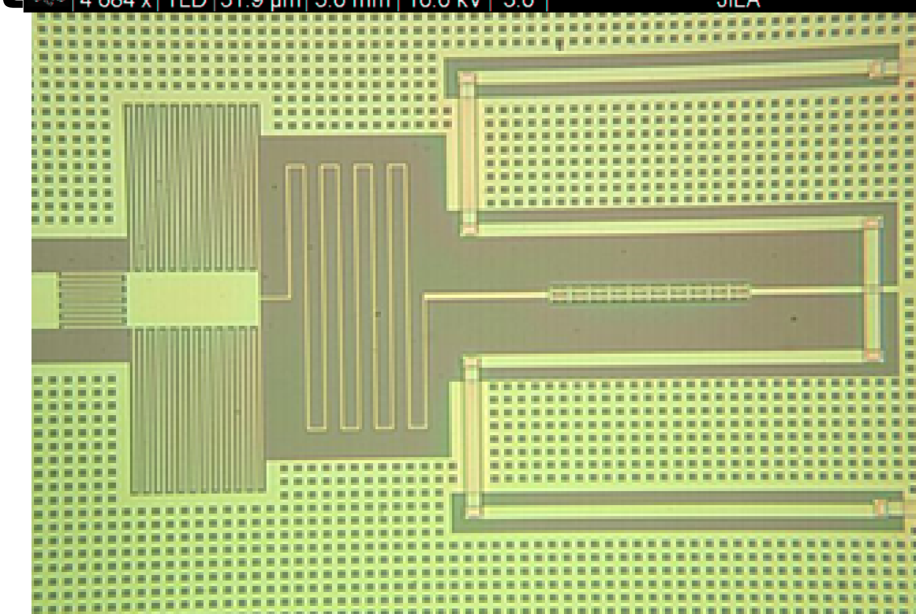
HAYSTAC

- **Josephson Parametric Amplifier composed of SQUIDs**
- **Tunable from 4.4-6.5 GHz with 20 dB of gain**

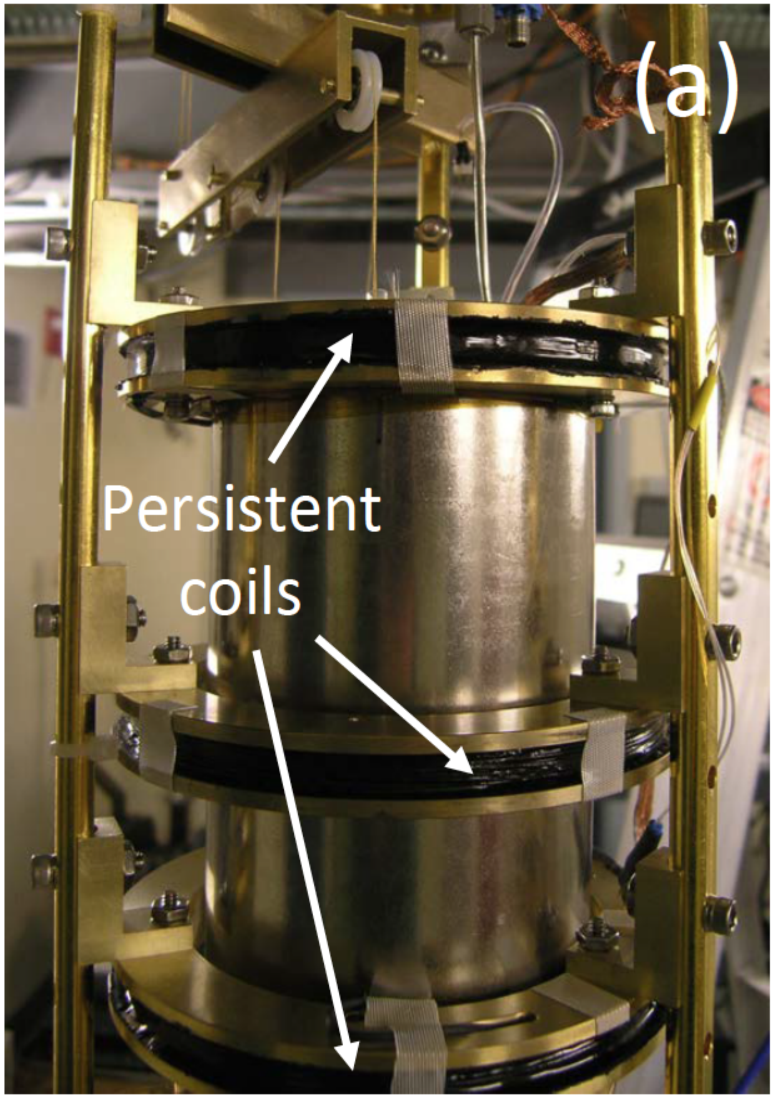


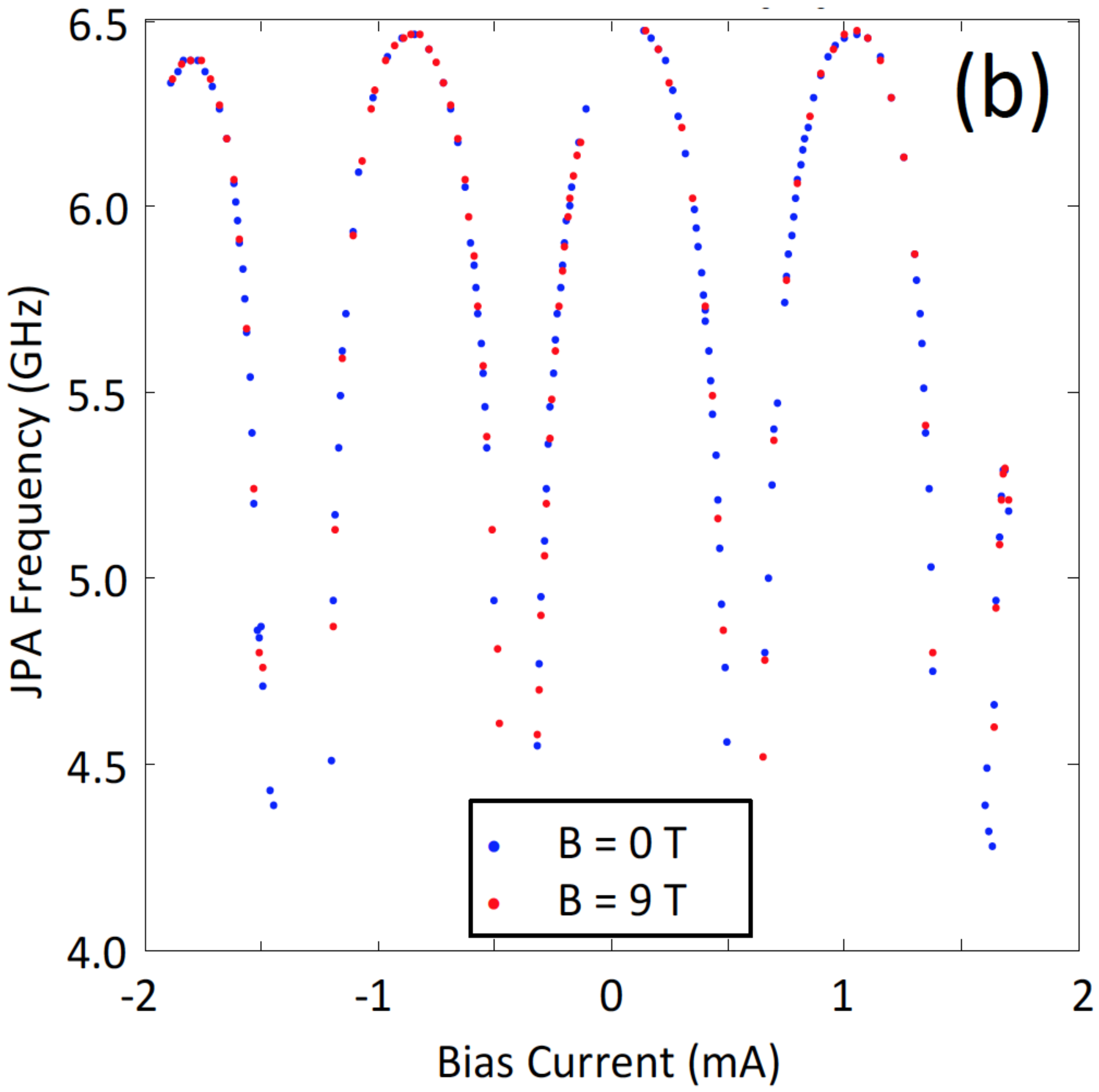


Persistent coils for cancellati on of fringe fields



One of the myriad of challenges: Magnetic shielding of the JPA





“It takes a licking & keeps on ti

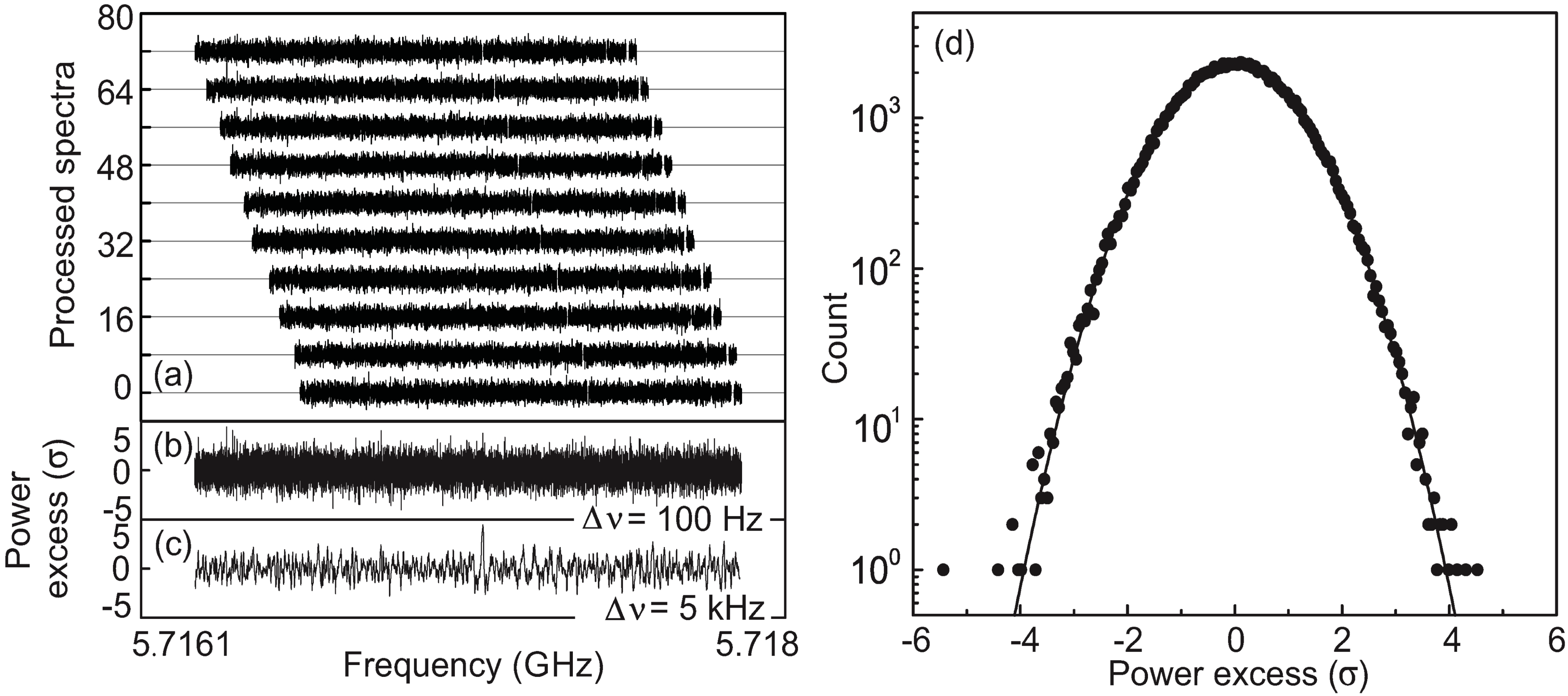
(Timex watch commercial, 1950’s)

- Experienced a magnet quench in early March 2016
- Surprisingly little damage
- Repairs completed, experiment back in operation by

Experiment rebuilt with much less mass of copper

What the data looks like

HAYSTAC

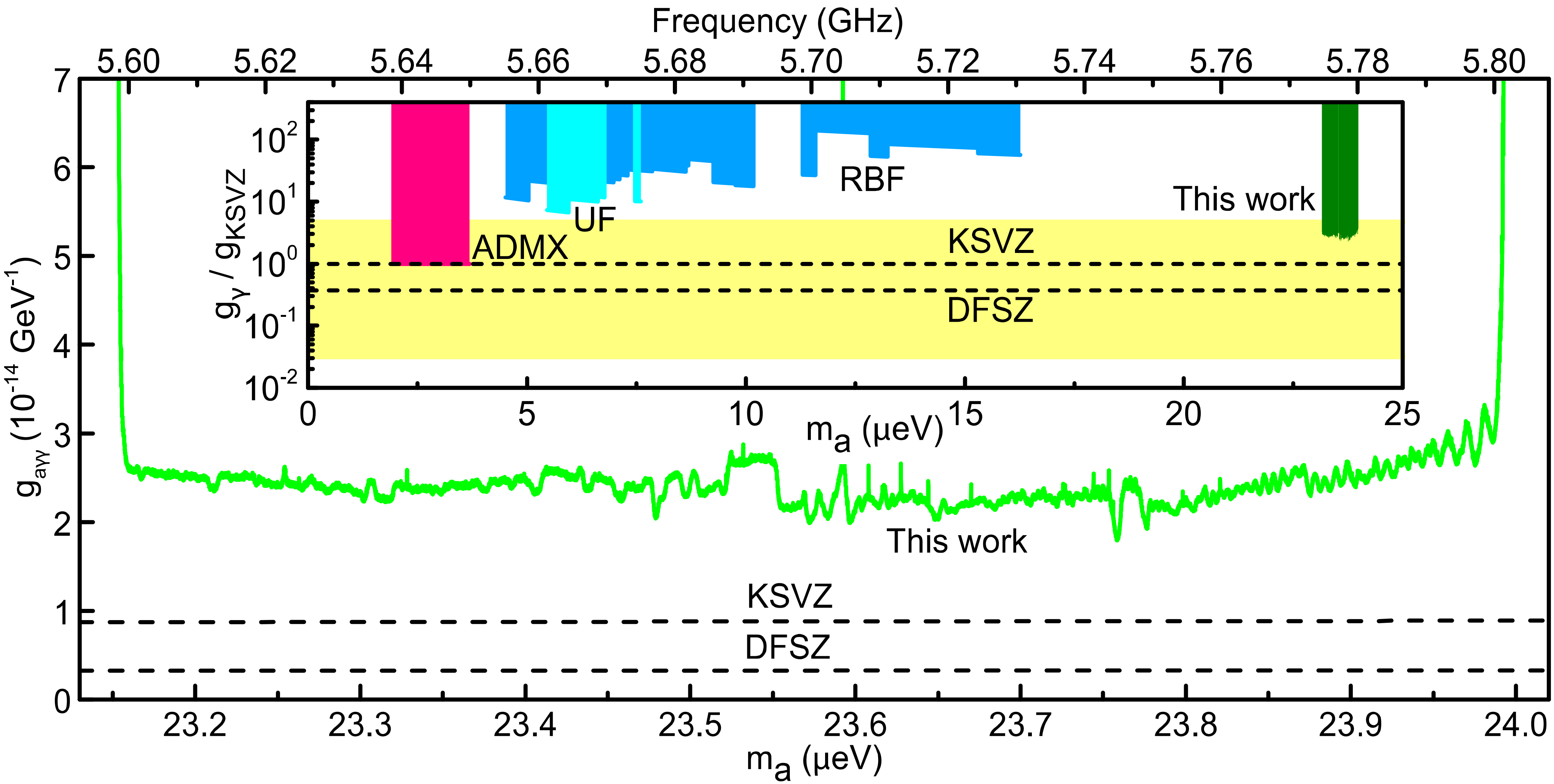


$T_{SYS} \sim 3 \times T_{SQL}$ for first run; 'hot rod' implicated, thermal link improved

$T_{SYS} \sim 2 \times T_{SQL}$ for second run in 2017

Results from 2016-17 runs

B. Brubaker et al., Phys. Rev. Lett. 118 (2017) 06



PRL Editor's Suggestion & APS Highlight

See also S. Al Kenany et al., Nucl. Instr. Meth. Res. Sec. A 854 (2017) 11

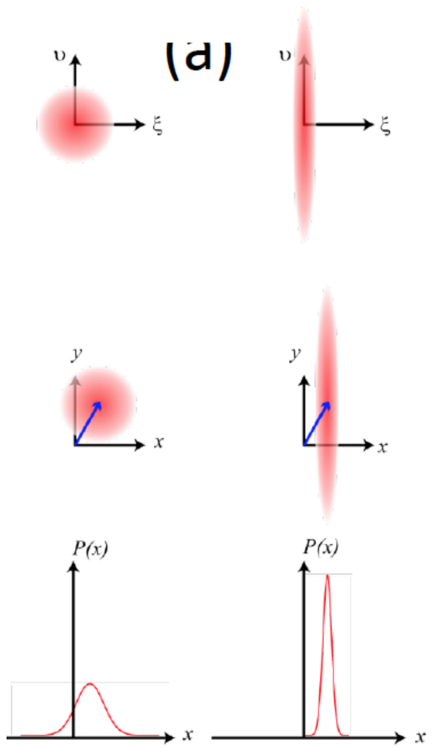
Innovations: Deeper, Higher, Lower

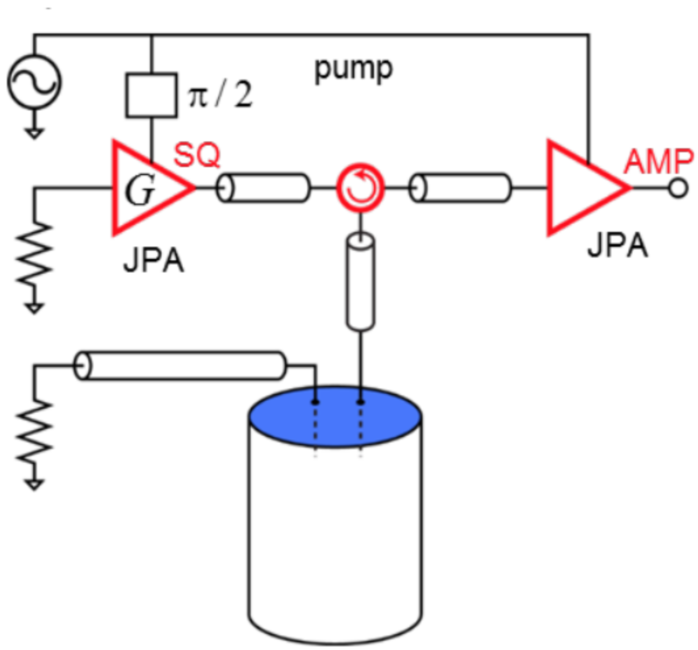
Squeezed-vacuum state receiv HAYSTAC

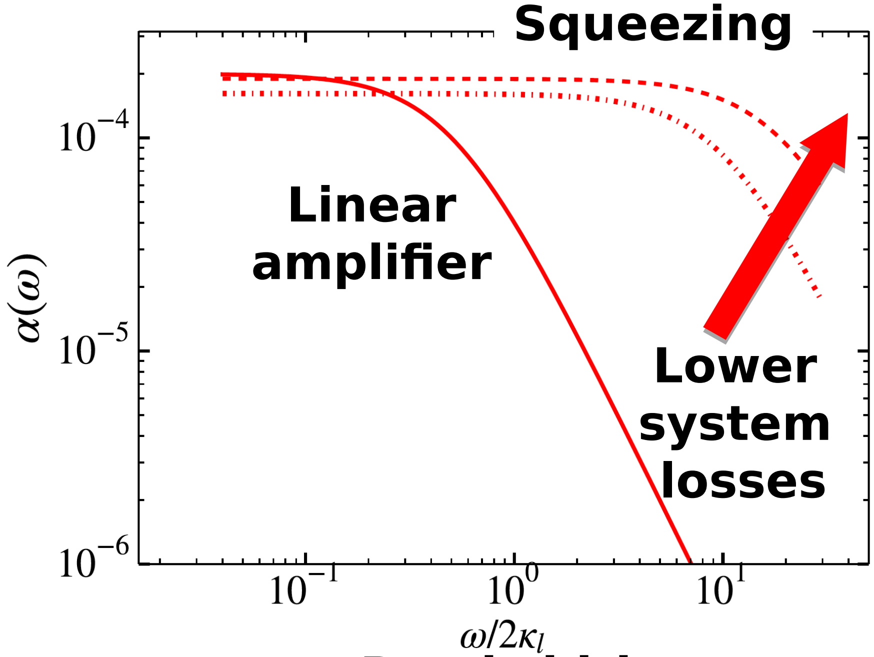
"Accelerating dark-matter axion searches with quantum information technology"
(S. Girvin, K. Lehnert & students), arXiv:1607.02529v1

Evading the Standard Quantum Lim

$$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT}-1}+\frac{1}{2}\right)+kT_A$$



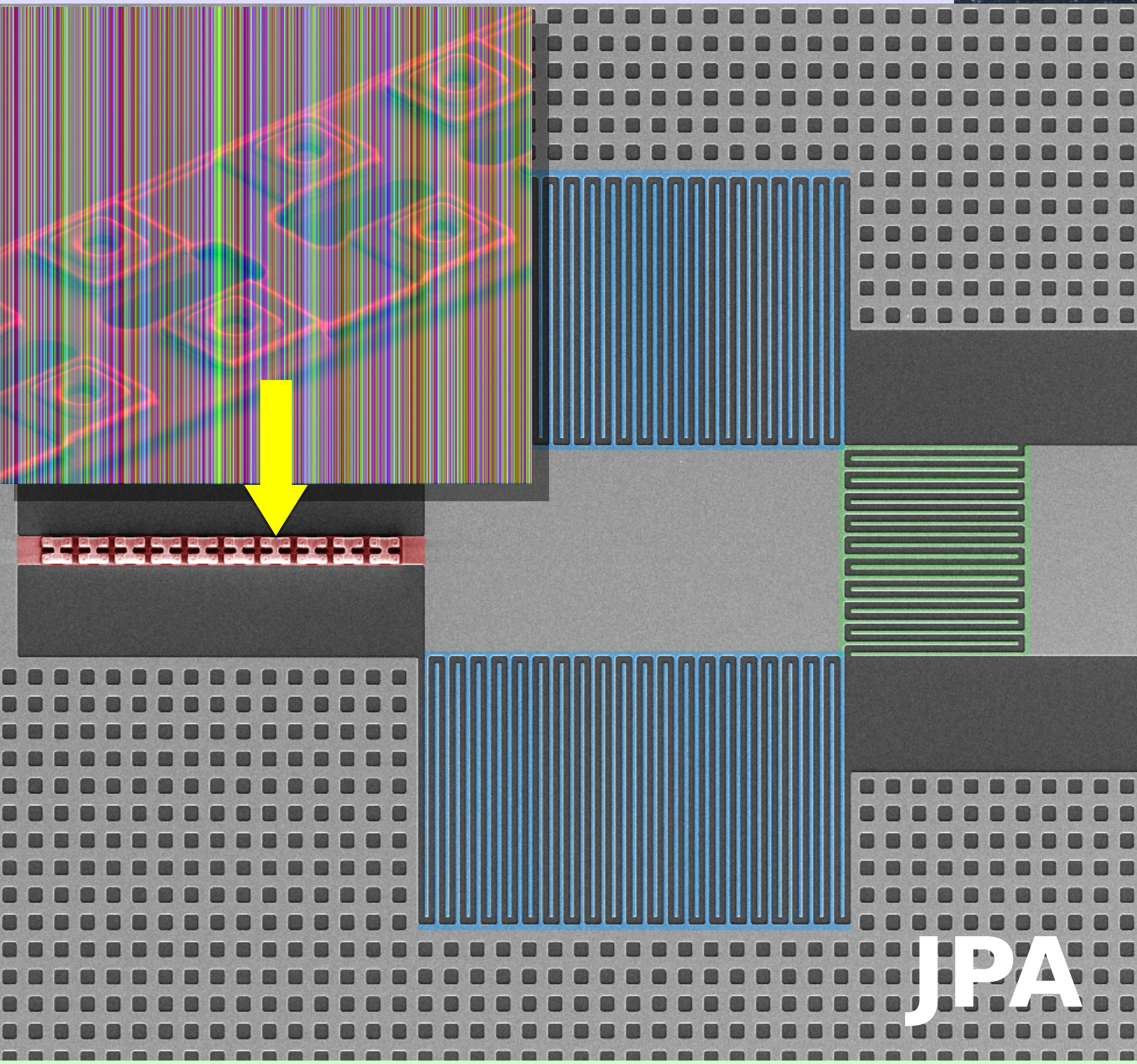


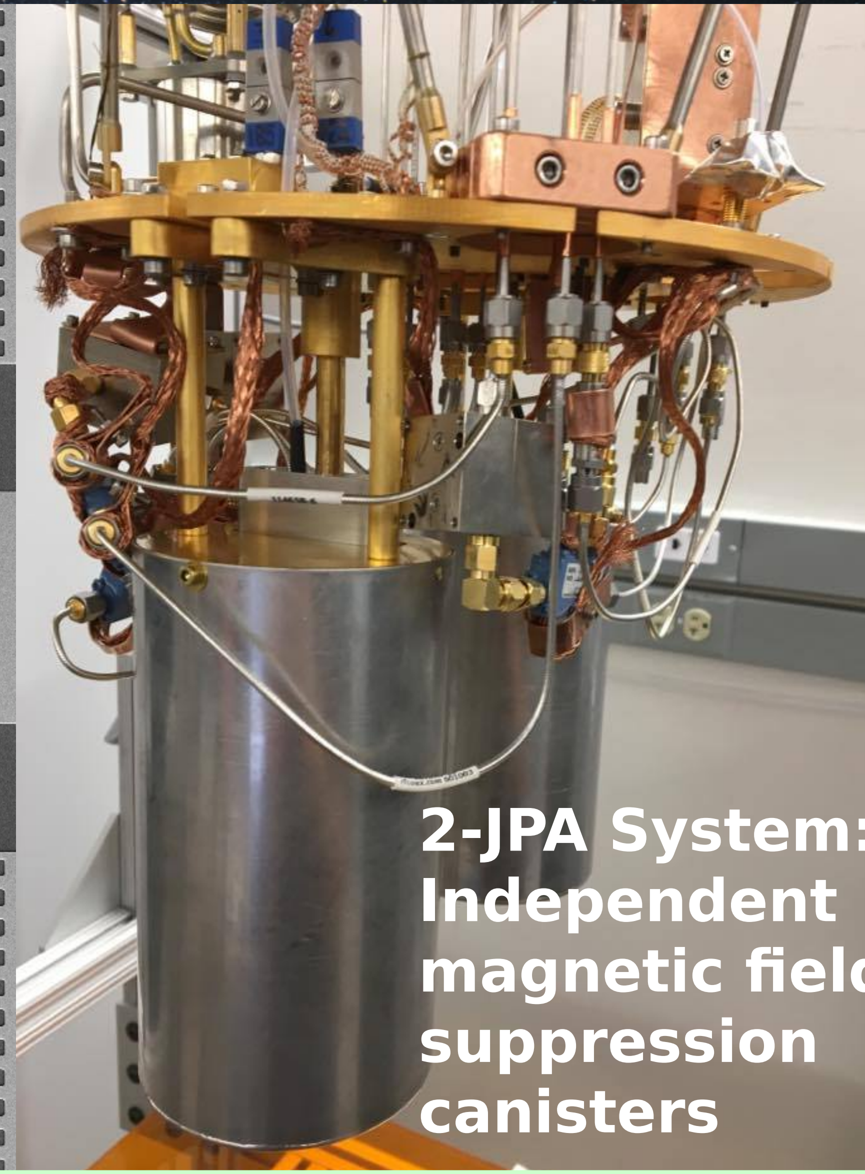


As one reduces losses in the system, the sensitivity optimizes for overc
the cavity, thus broadening the bandwidth & increasing the scan ra

Squeezed-state receiver being prepared at JILA

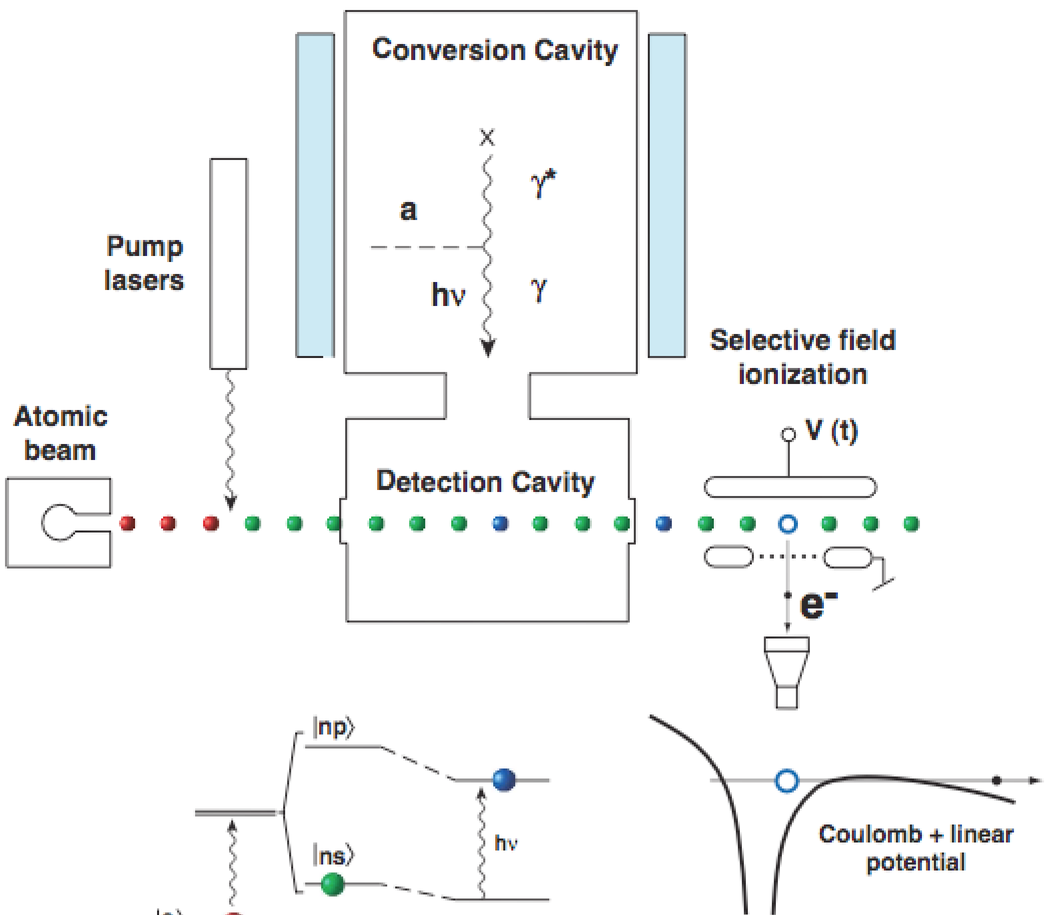
HAYSTAC

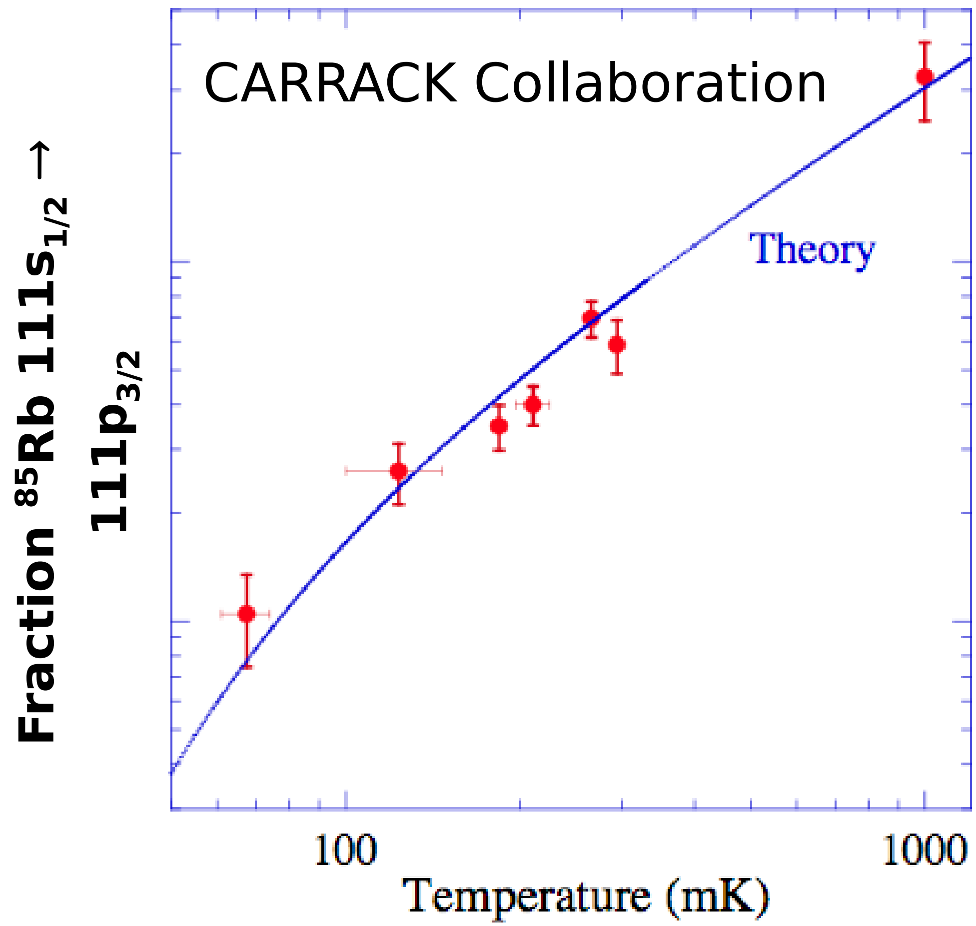




Lehnert group has built squeezed-state receivers; achieved $T_{SYS} \sim$ ¼ T_{S}
[F. Mallet *et al.*, PRL 106 (2011) 220502]. Integration in HAYSTAC this y

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



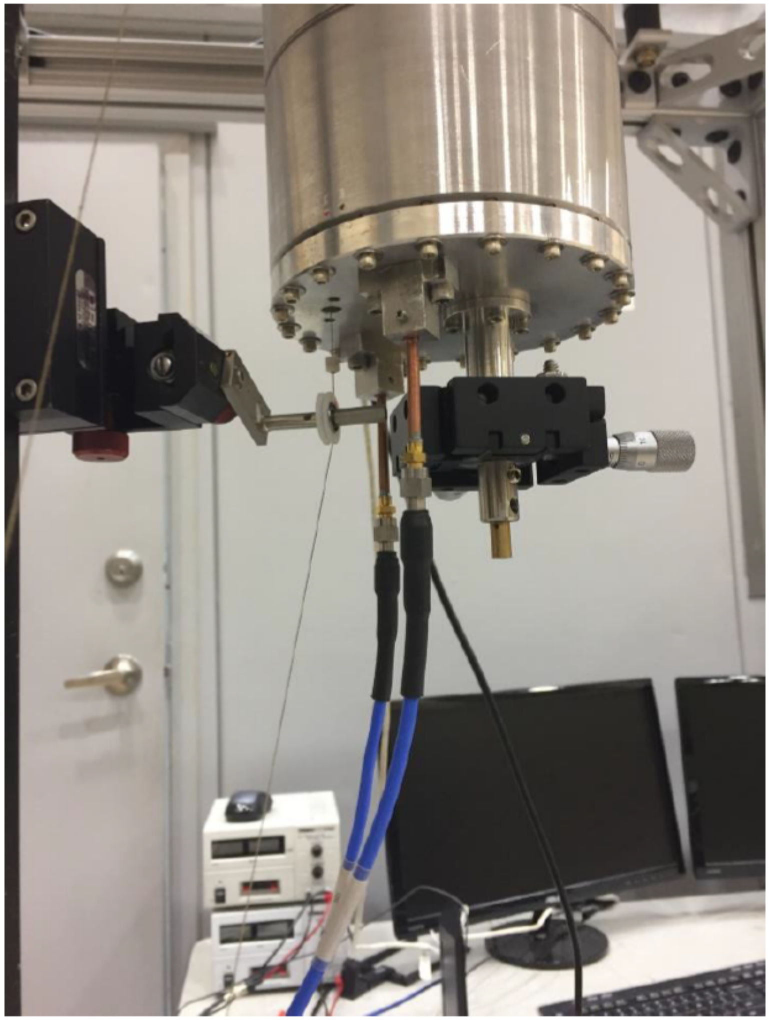


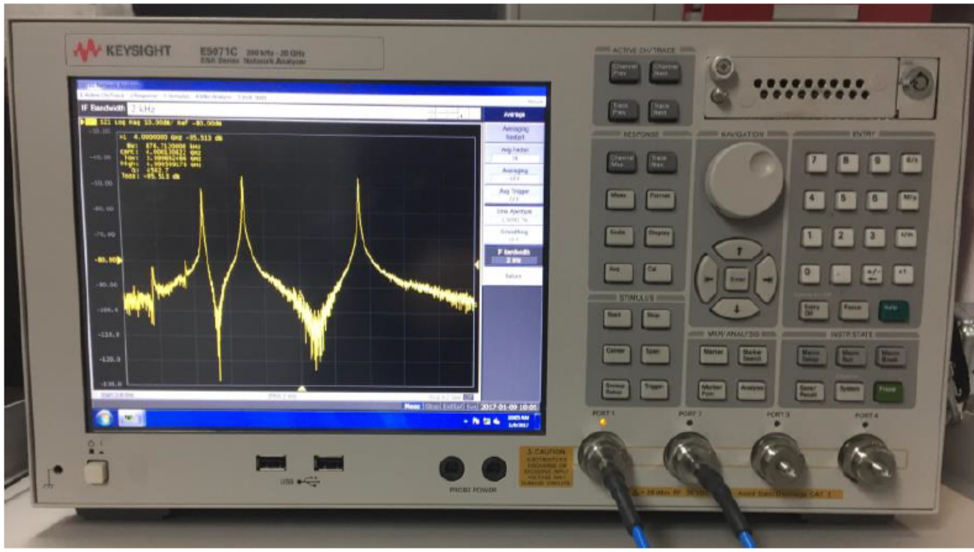
M. Tada et al., Phys. Lett. A (2002)

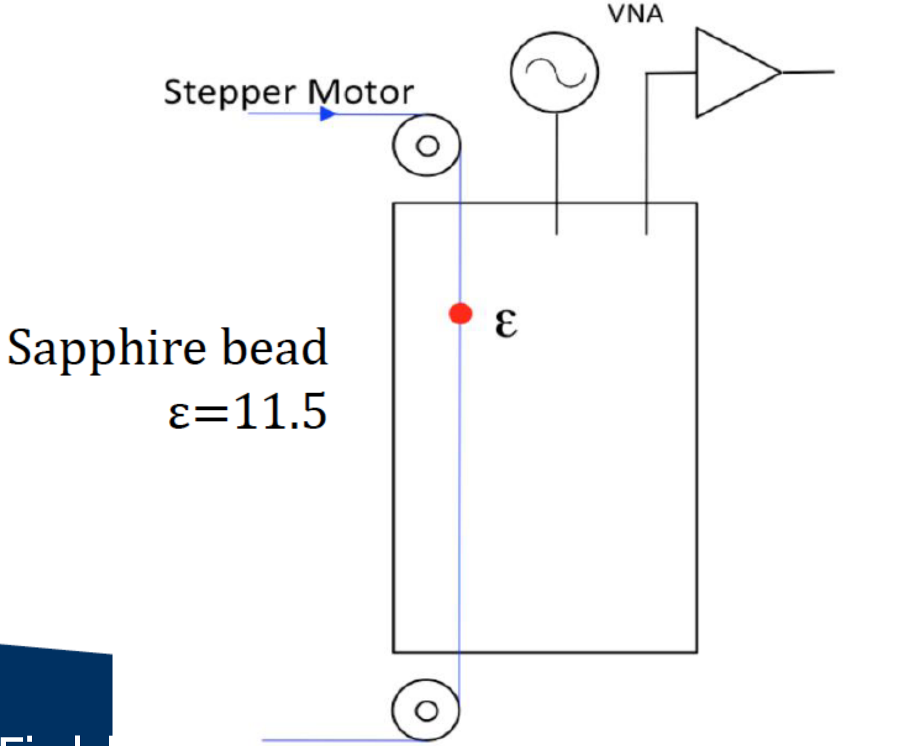
The blackbody spectrum has been measured at 2527 MHz
a factor of ~2 below the standard quantum limit (~120mK)

Cavity R&D at Berkeley HAYSTAC

High vibration isolation designed by Al Kenany



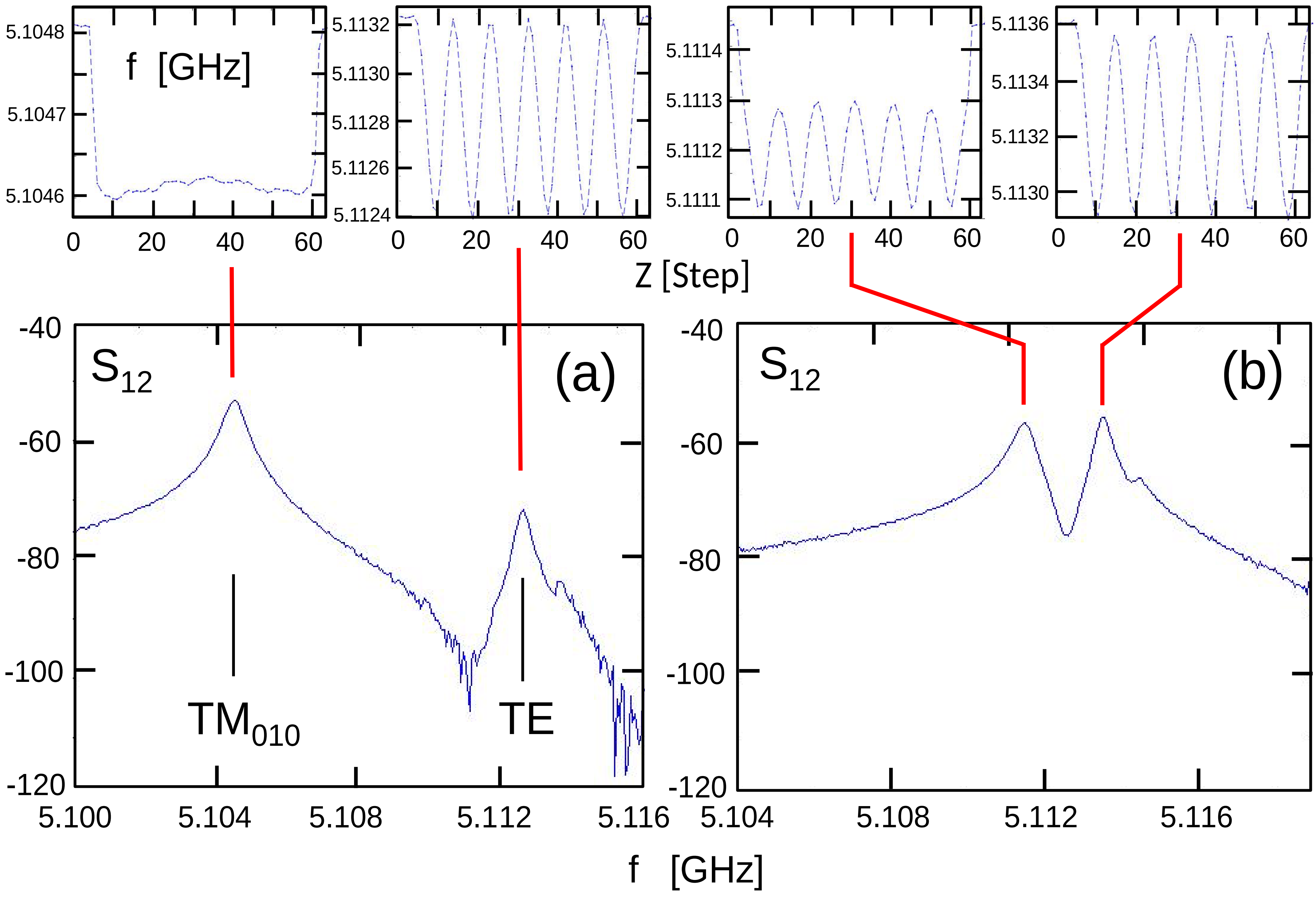




Berkeley UNIVERSITY OF CALIFORNIA

Bead Perturbation Technique for Electric Field Profiling

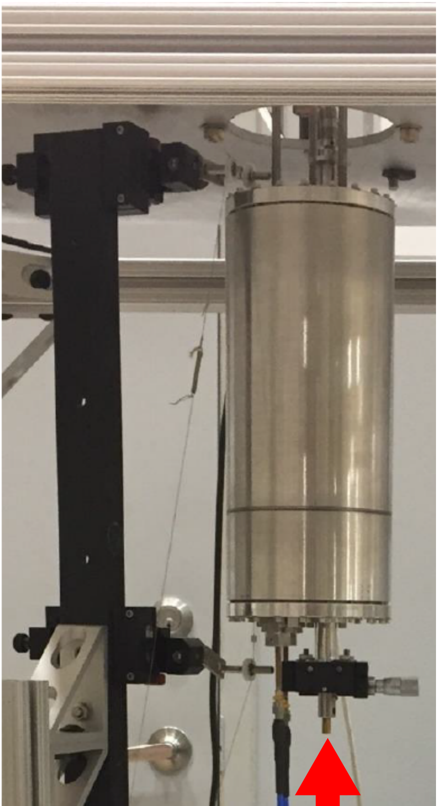
Example: Two-level mixing of TM_{010} and TE modes

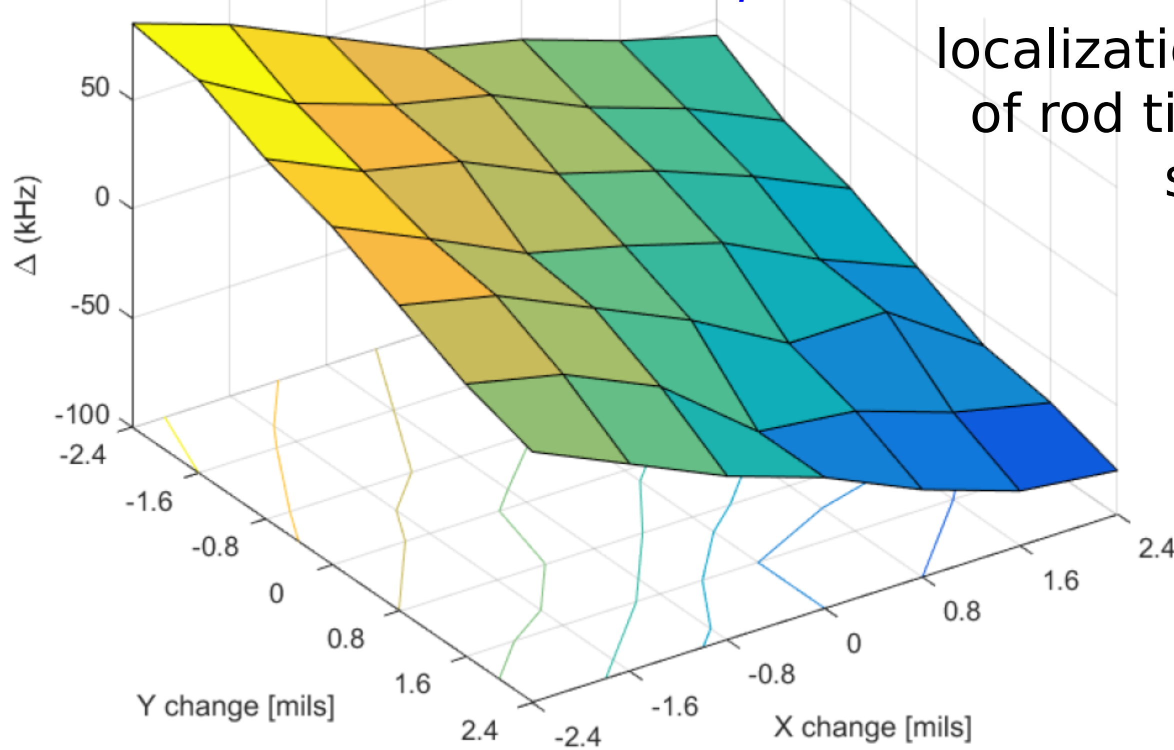


Combining Precision Metrology, Simulations & Field Mapping in Study of Tuning Rod Misalignme

HAYSTAC

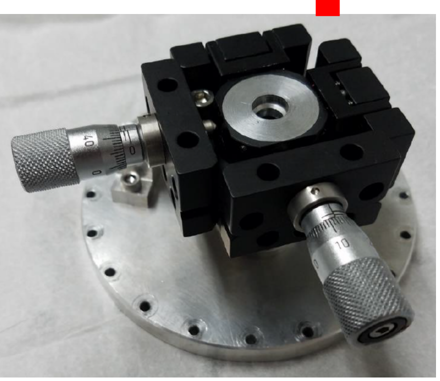
Samantha Lewis & Nicholas Rapidis



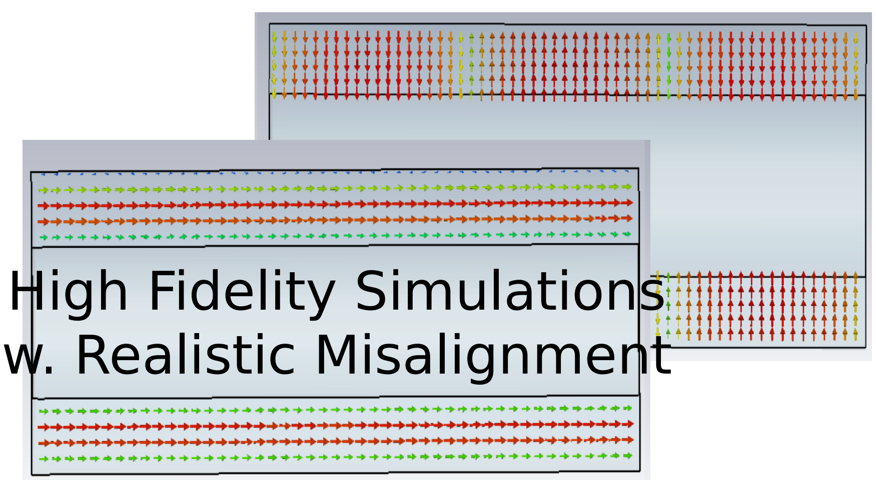


Measured field localization as a function of rod tilt in (x,y); each step is 1.5 mrad

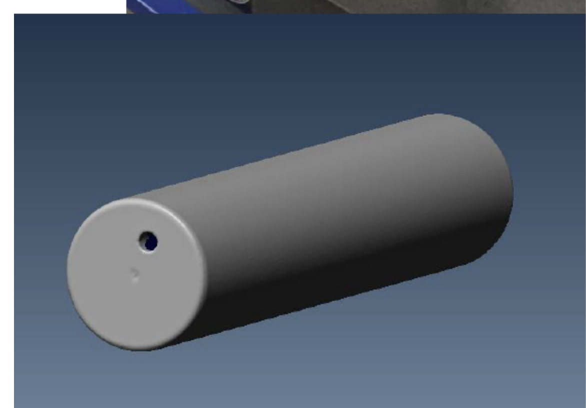
Laser Metrology



Field Mapping

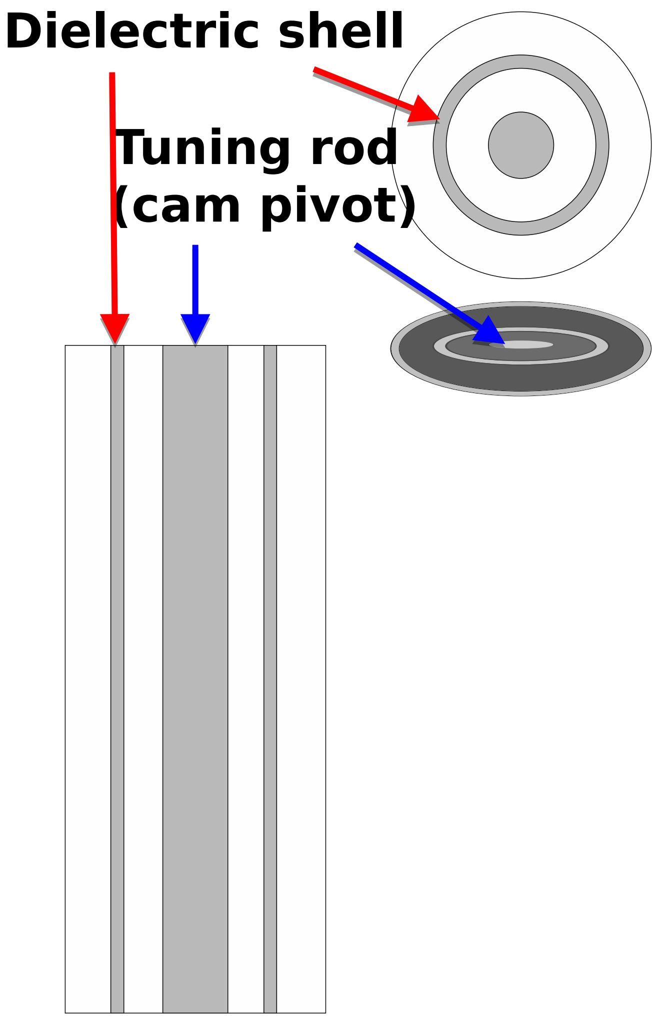


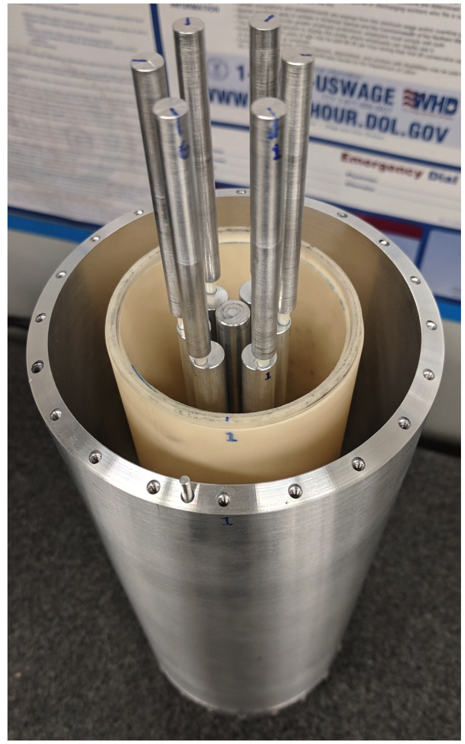
High Fidelity Simulations w. Realistic Misalignment

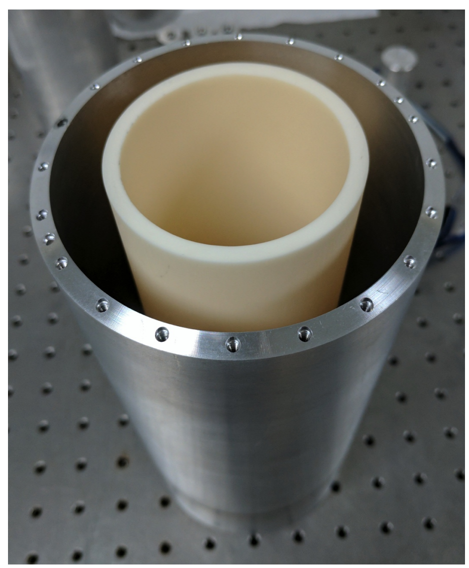


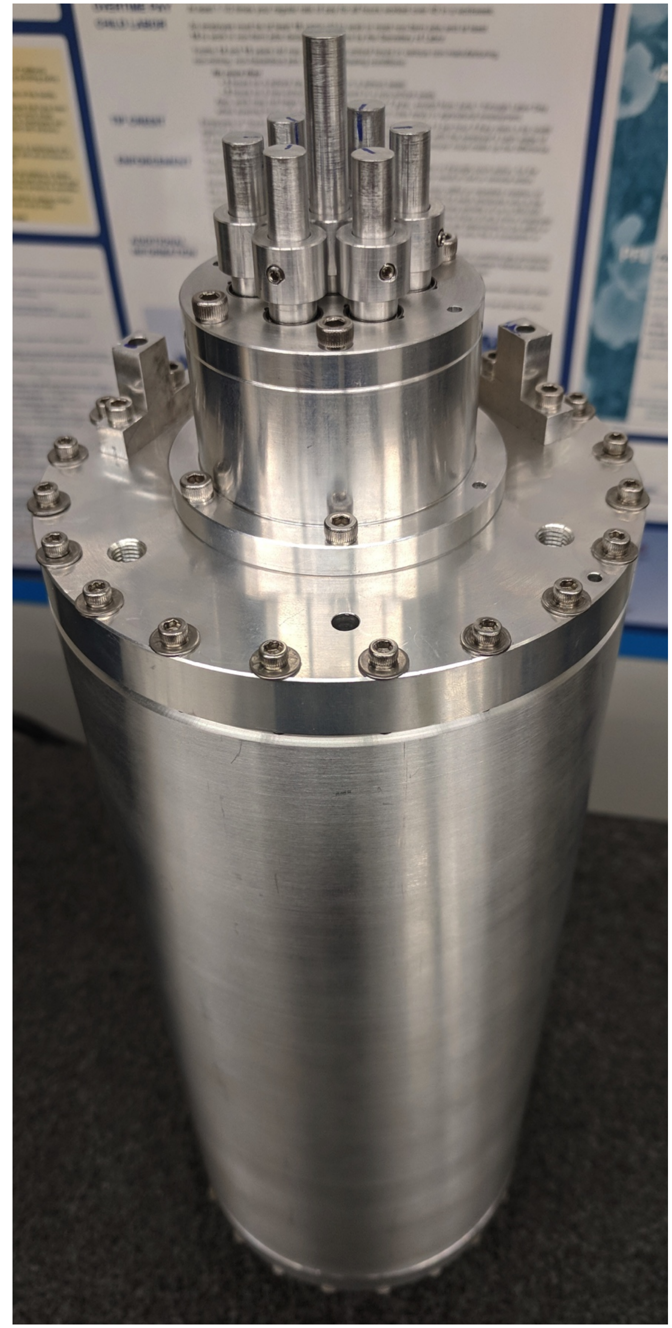
A TM$_{030}$ cavity based on a Dielectric Bragg Resonato

HAYSTAC





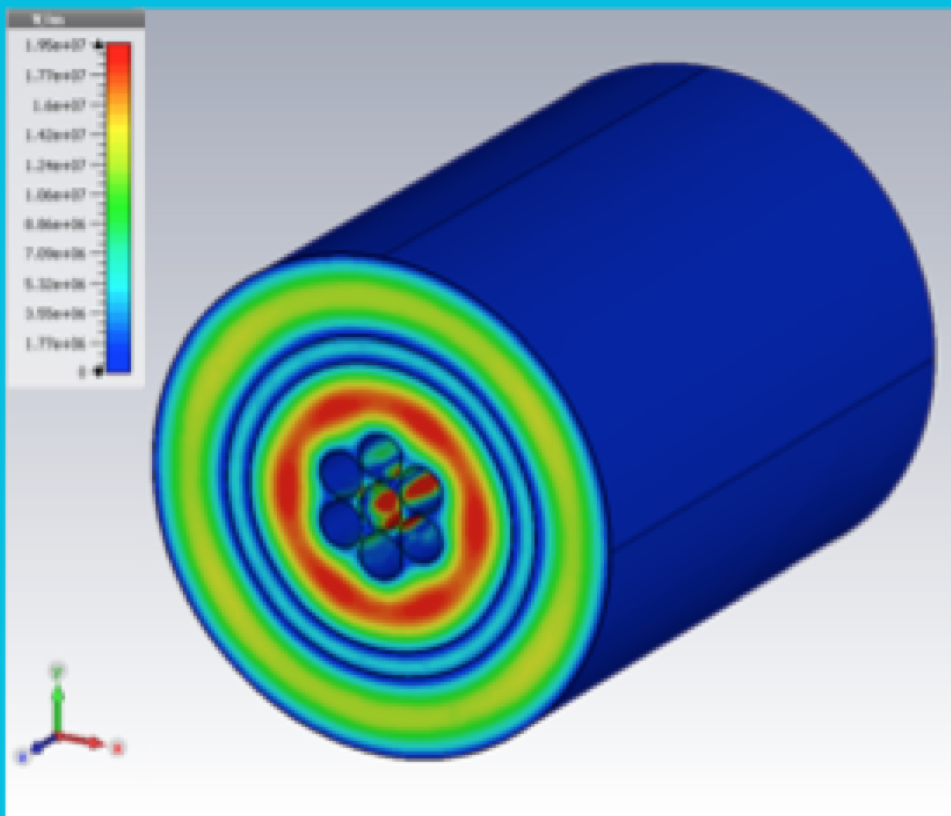


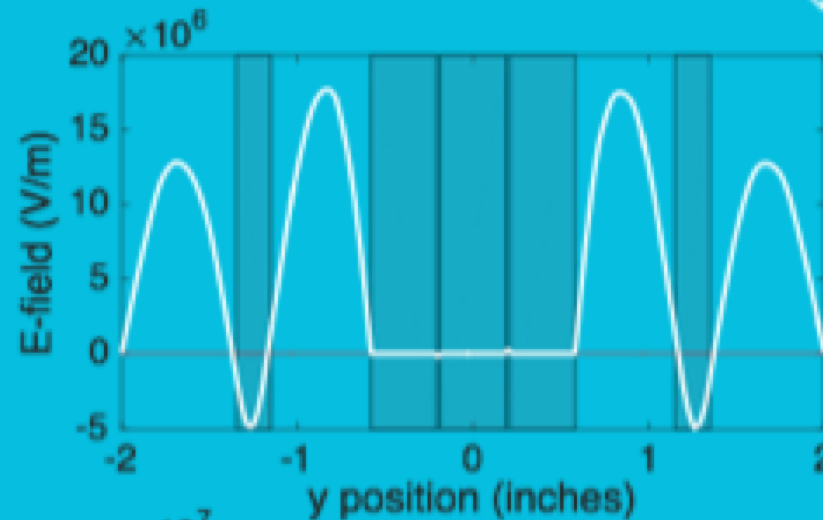


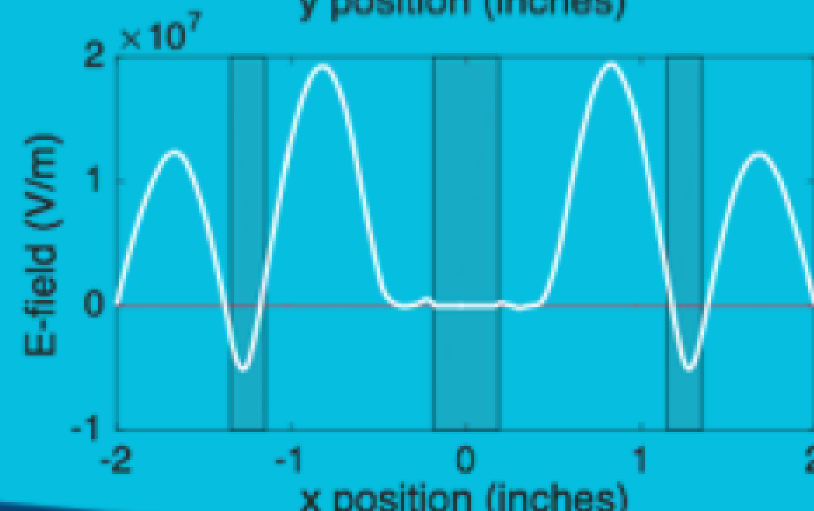
Inspired by DBR of Tabor & Flory (IEEE, 1995), but in fact steals a leaf out of the book of Rybka et al!

Maria Simanovskaia

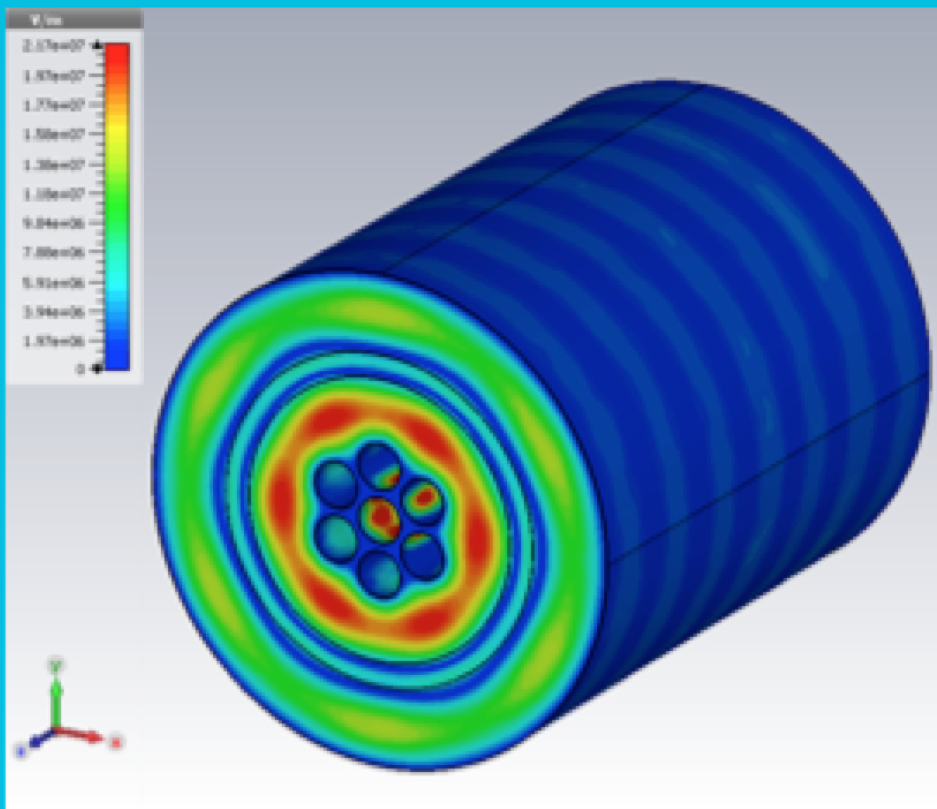
0.375” OD x 7 rods			
Offset	Frequency	Form factor	Q factor
0.3950”	9.36 GHz	0.58	20163

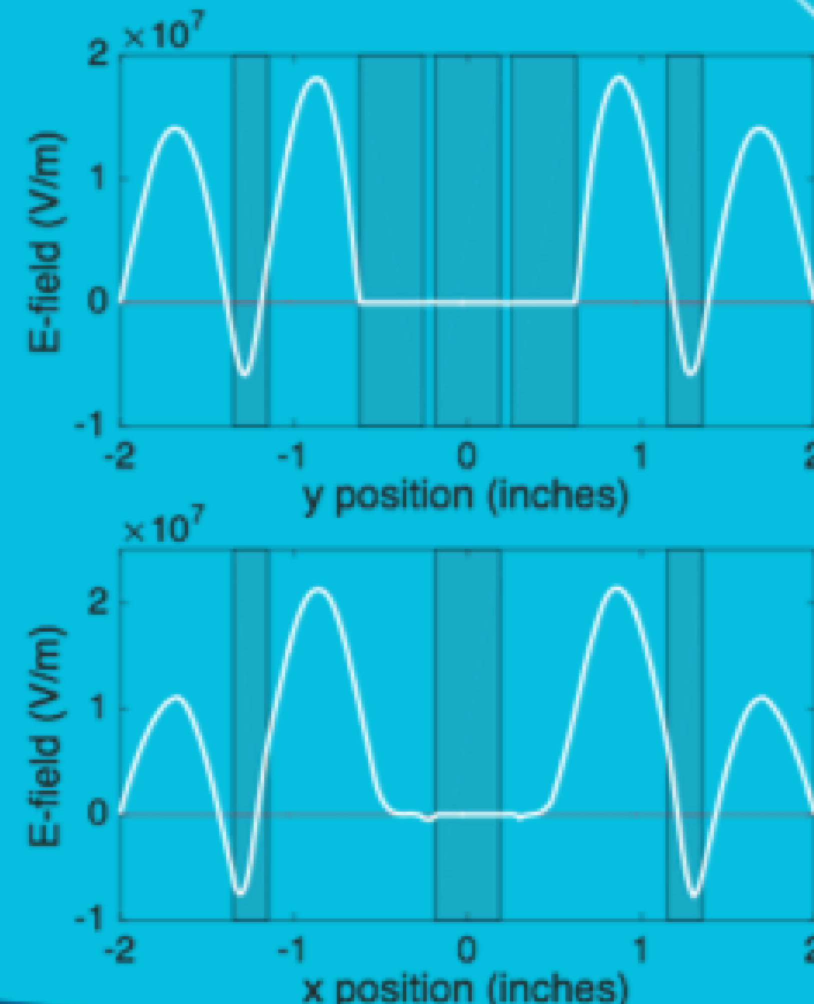




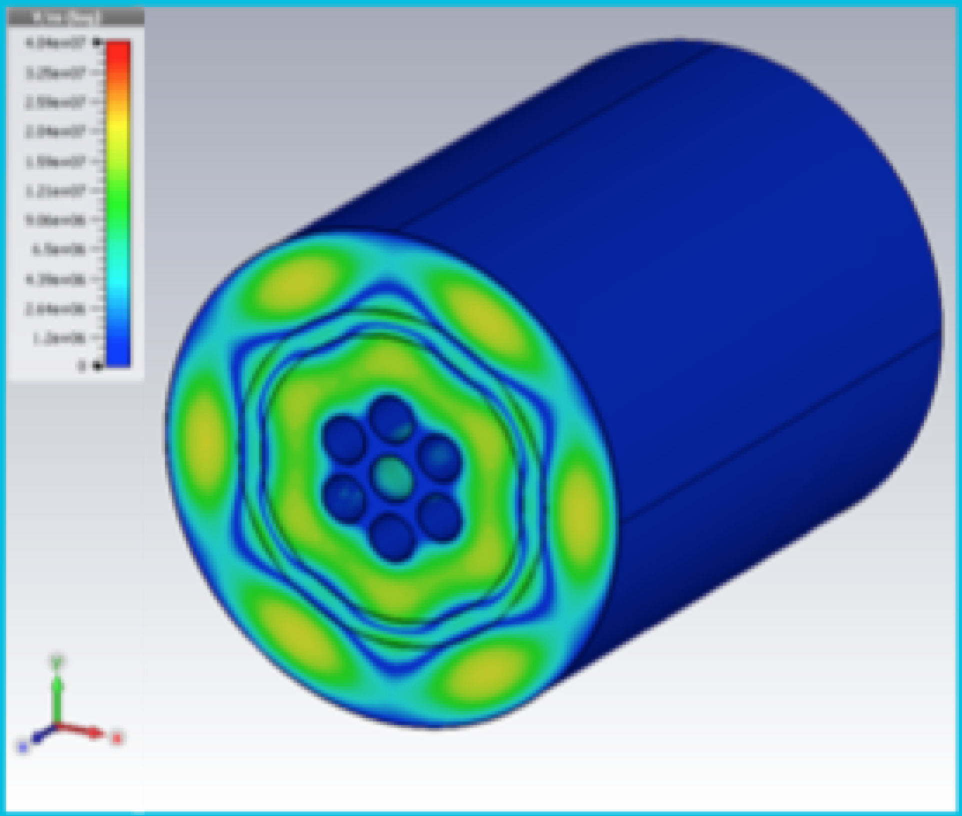


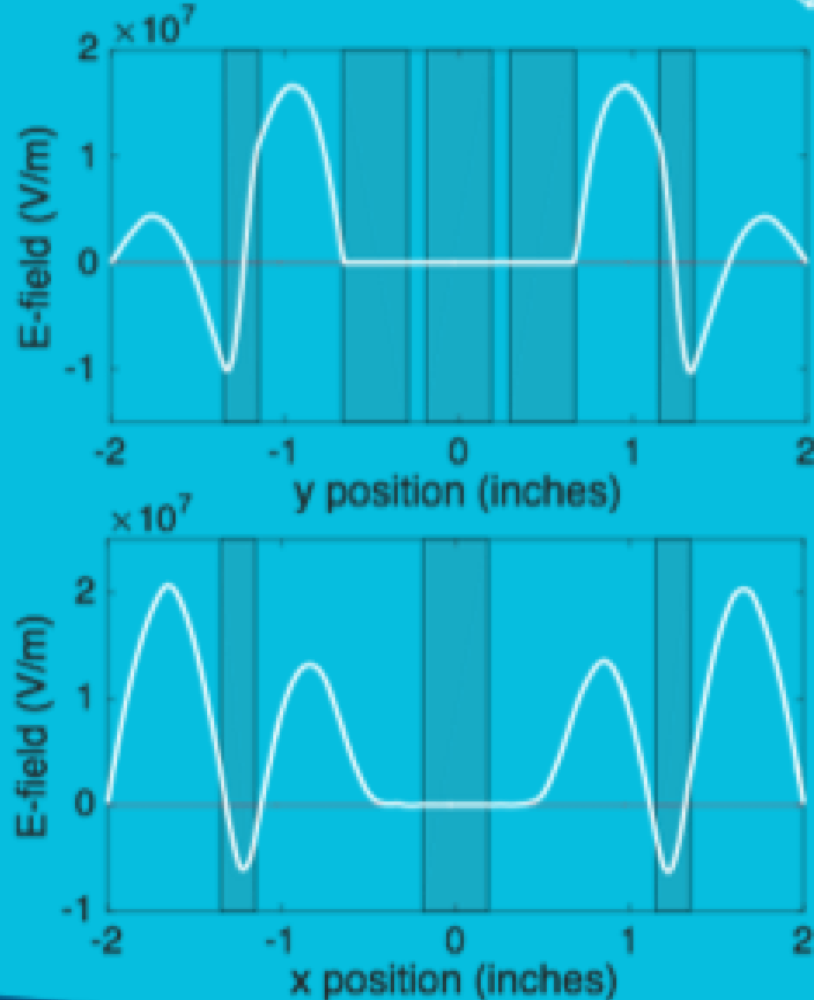
0.375” OD x 7 rods			
Offset	Frequency	Form factor	Q factor
0.4375”	9.59 GHz	0.55	22521





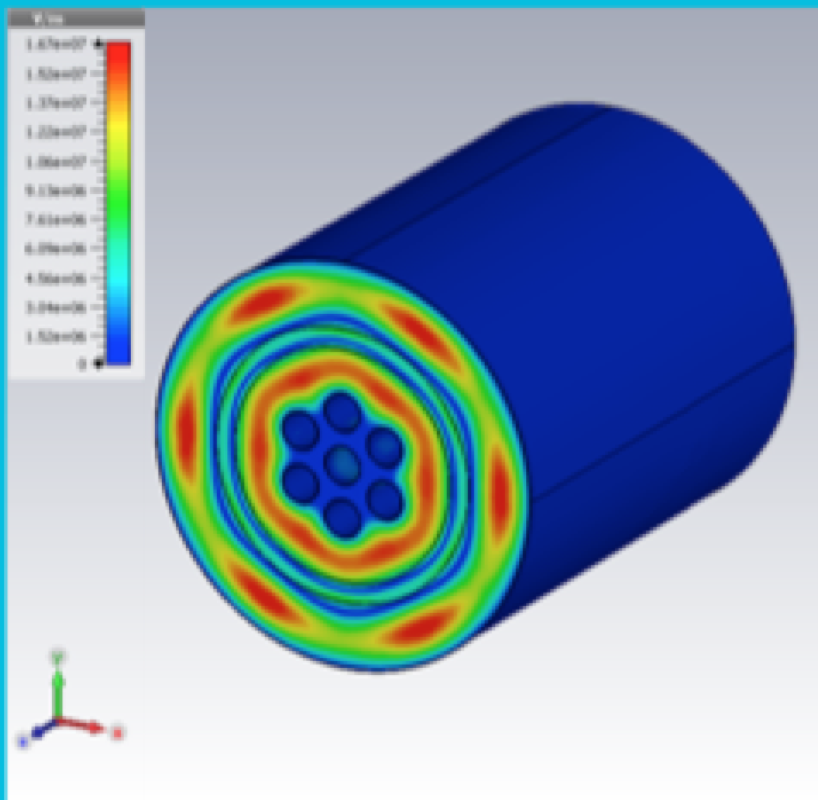
0.375” OD x 7 rods			
Offset	Frequency	Form factor	Q factor
0.4800”	9.82 GHz	0.47	29550

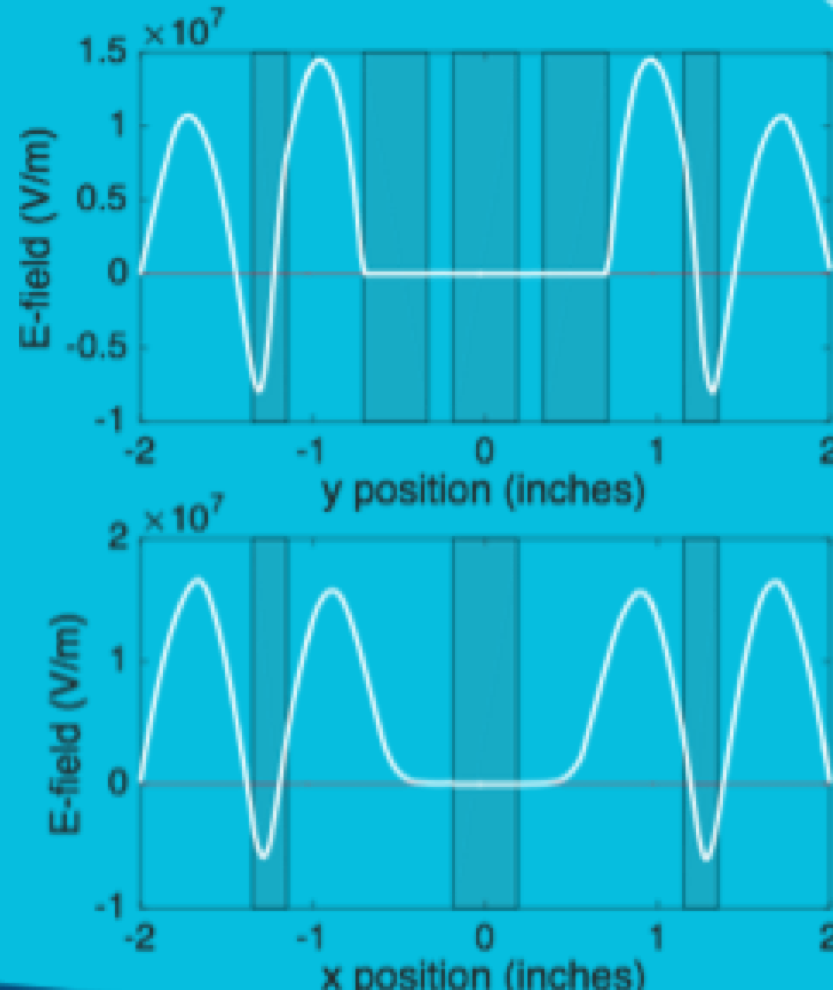




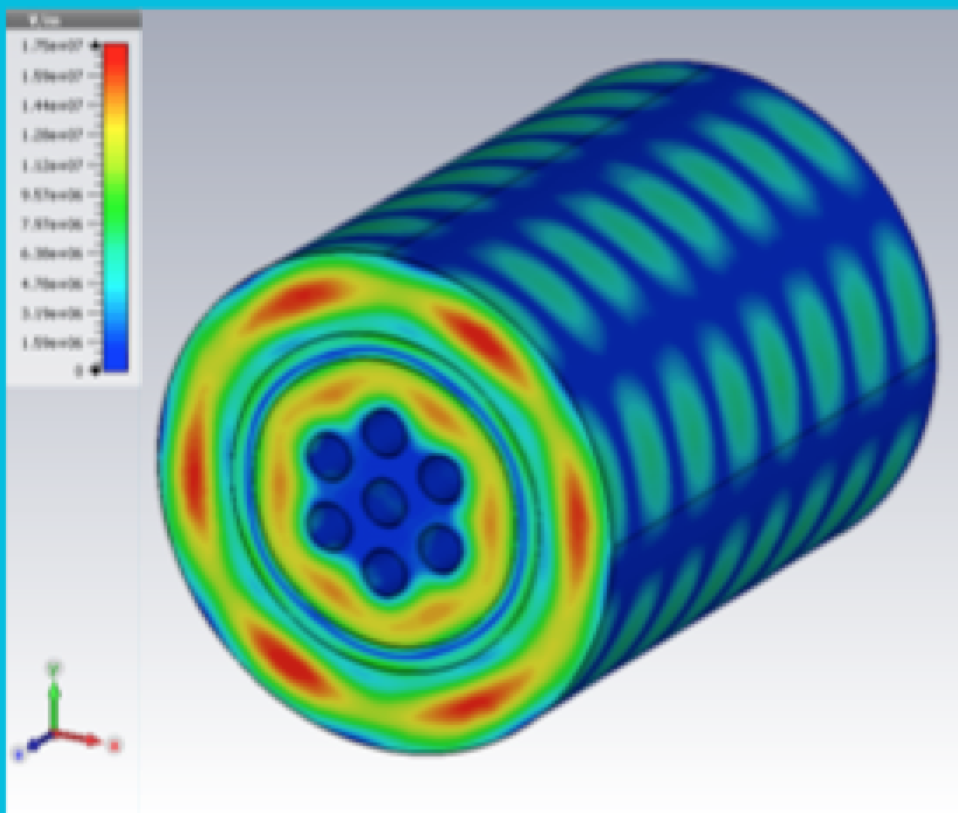
Berkeley
UNIVERSITY OF CALIFORNIA

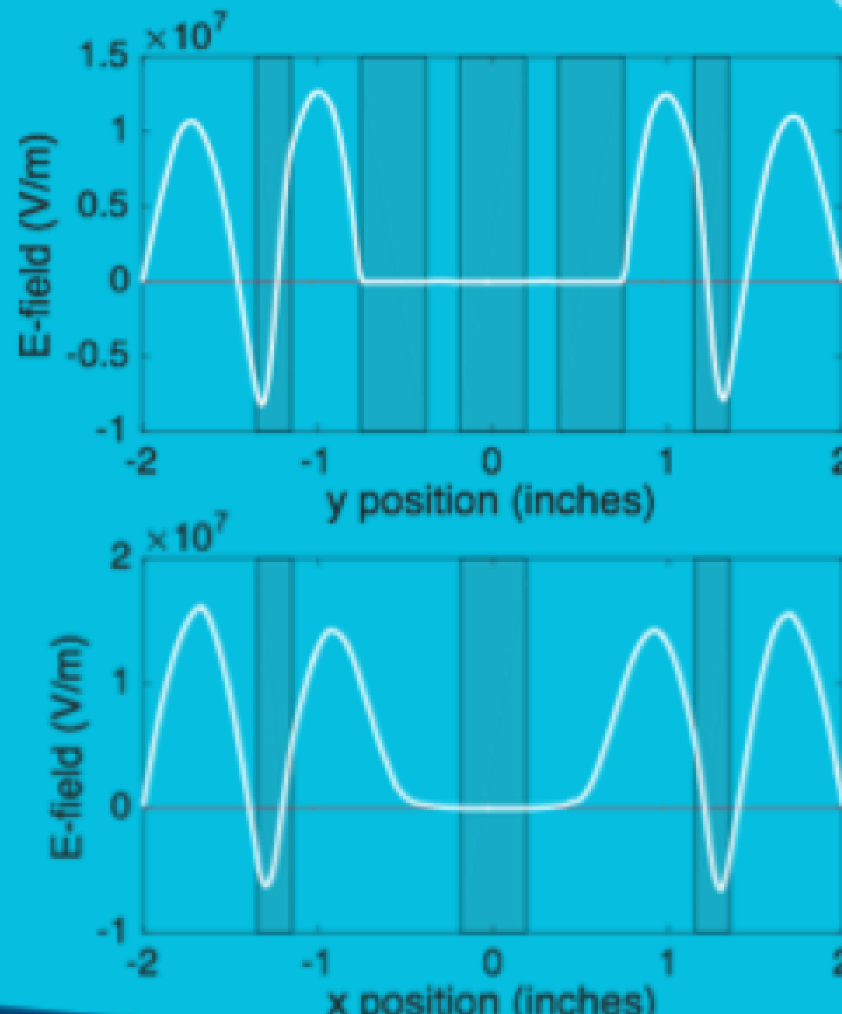
0.375” OD x 7 rods			
Offset	Frequency	Form factor	Q factor
0.5225”	9.99 GHz	0.53	26691



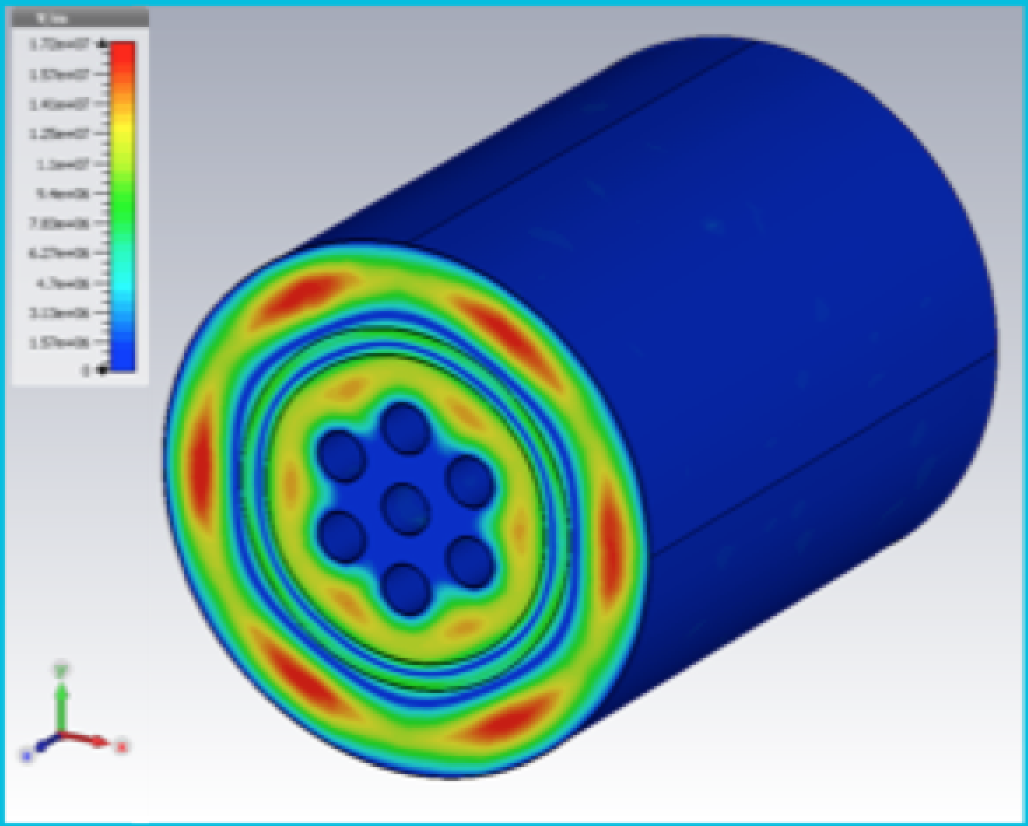


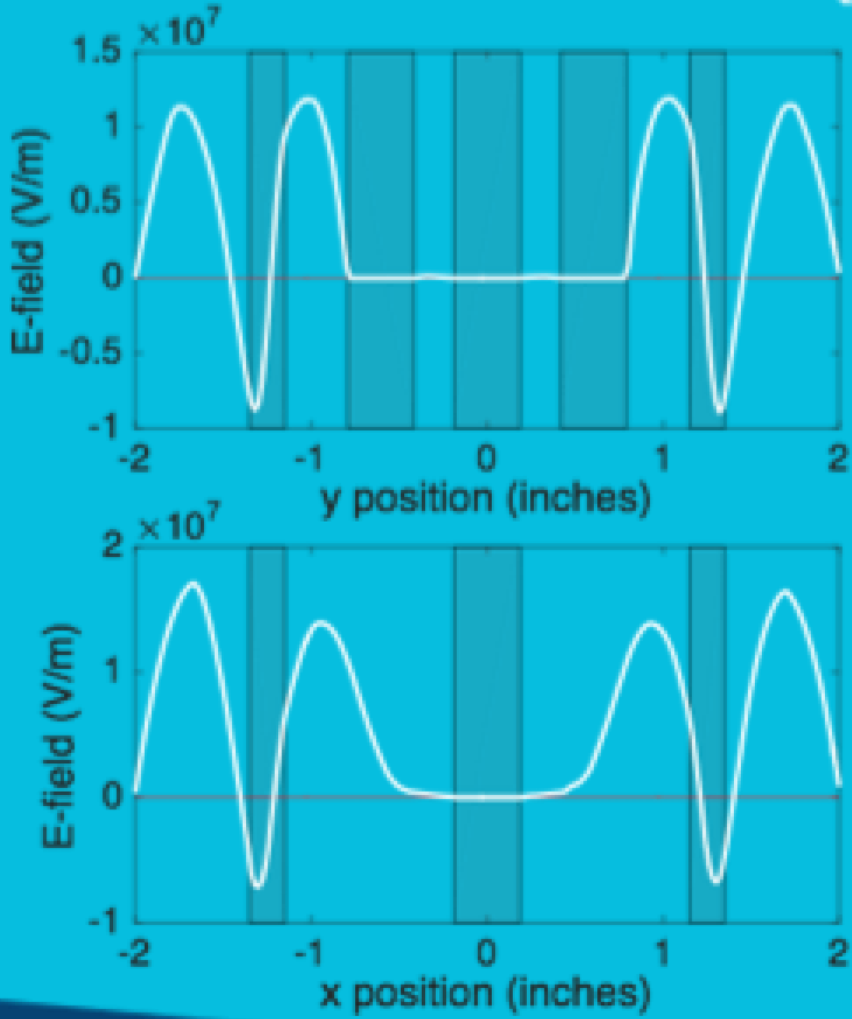
0.375” OD x 7 rods			
Offset	Frequency	Form factor	Q factor
0.5650”	10.15 GHz	0.46	29082





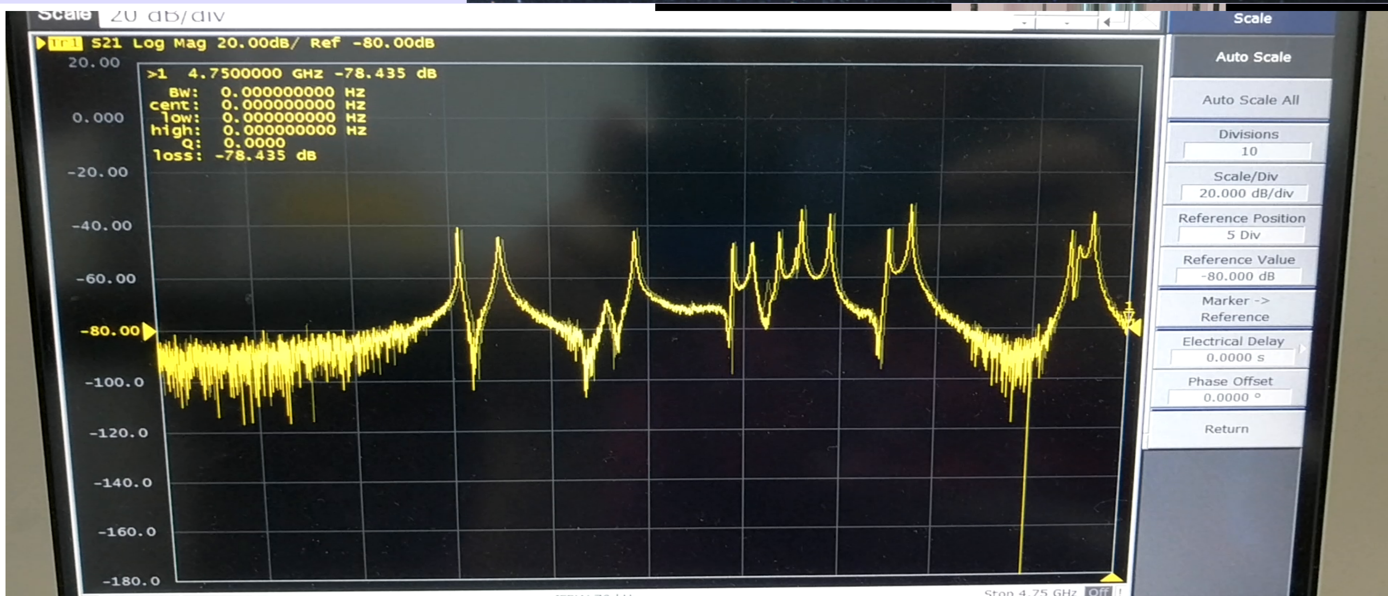
0.375" OD x 7 rods			
Offset	Frequency	Form factor	Q factor
0.6050"	10.27 GHz	0.50	27215

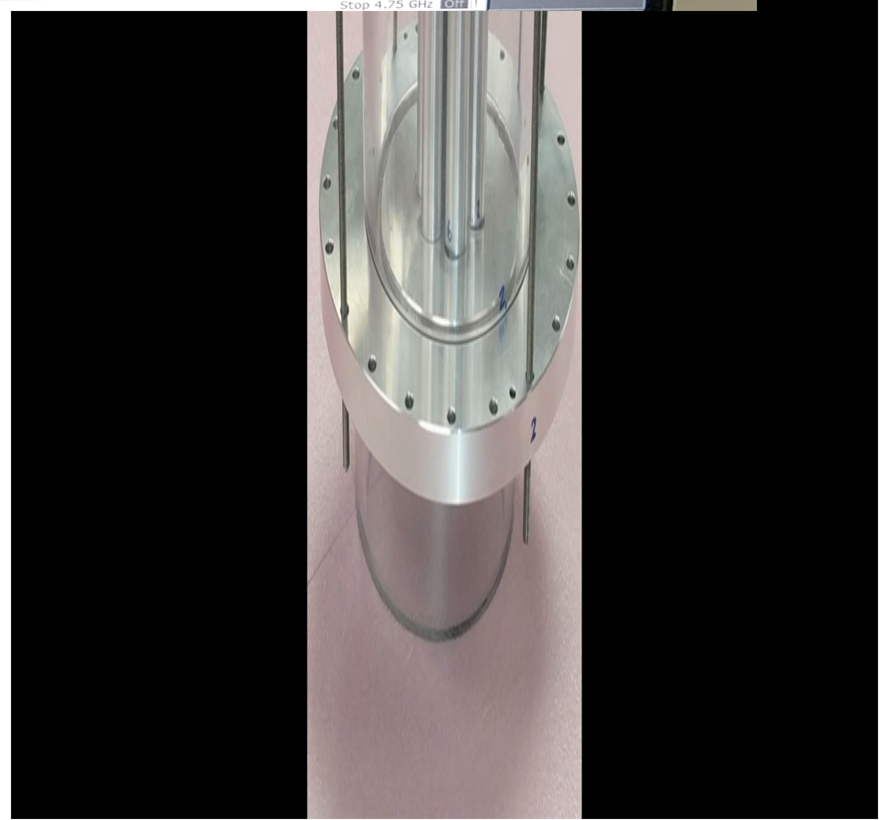




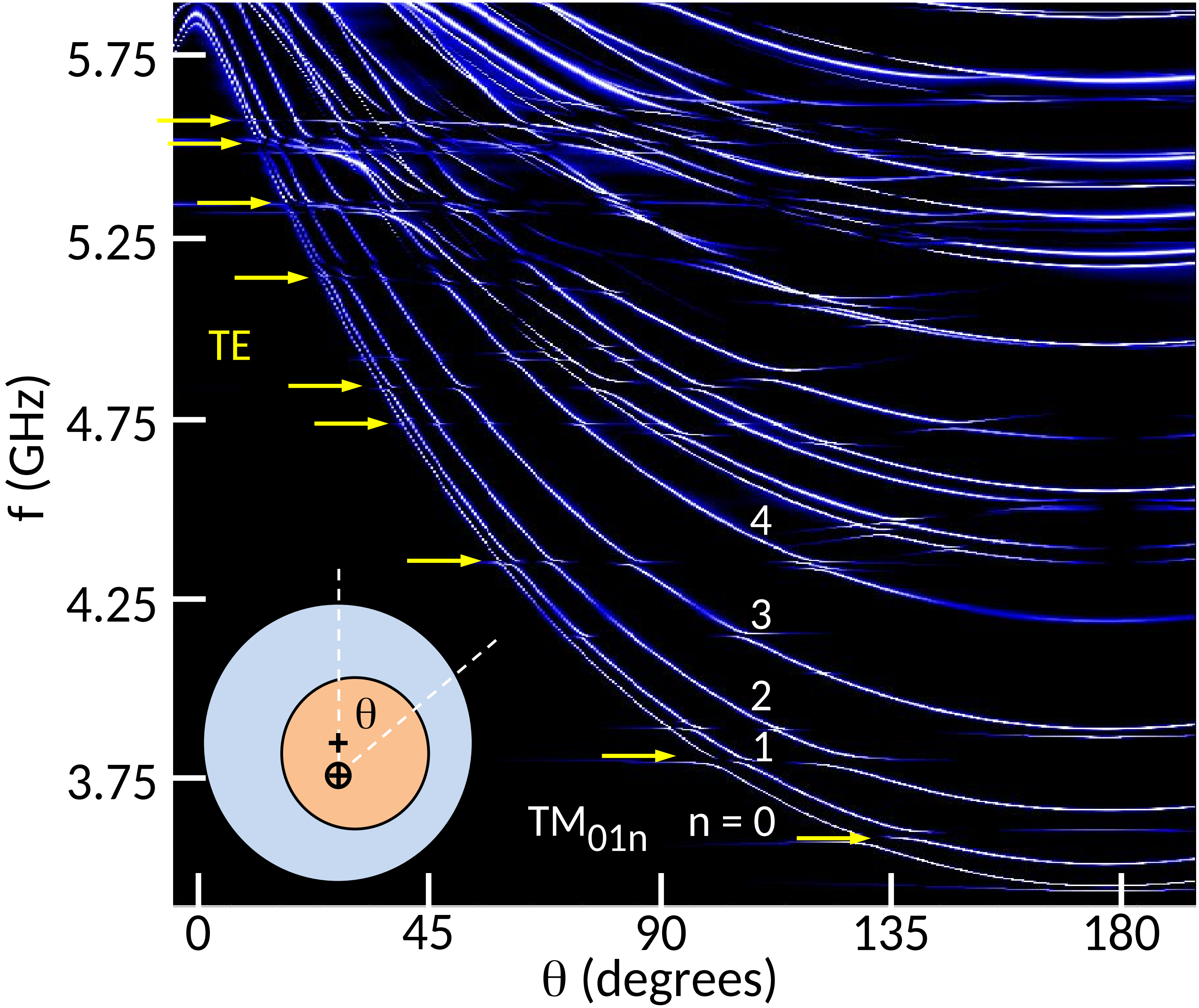
Berkeley
UNIVERSITY OF CALIFORNIA

Mechanical motion



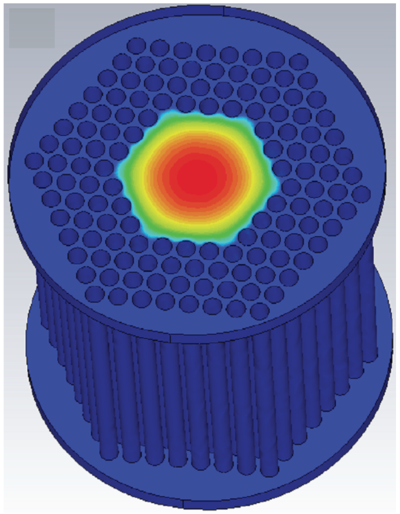


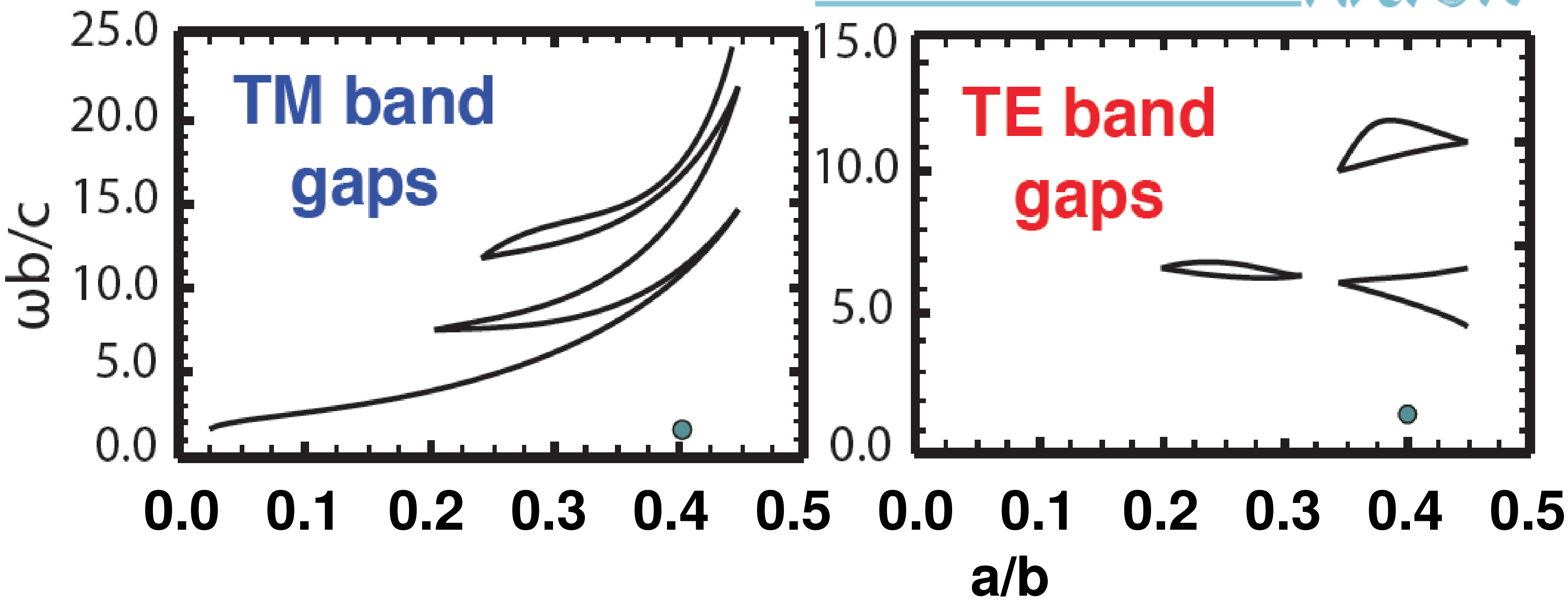
Bane of the search – thicket of TE-TM_{010} mode crossings

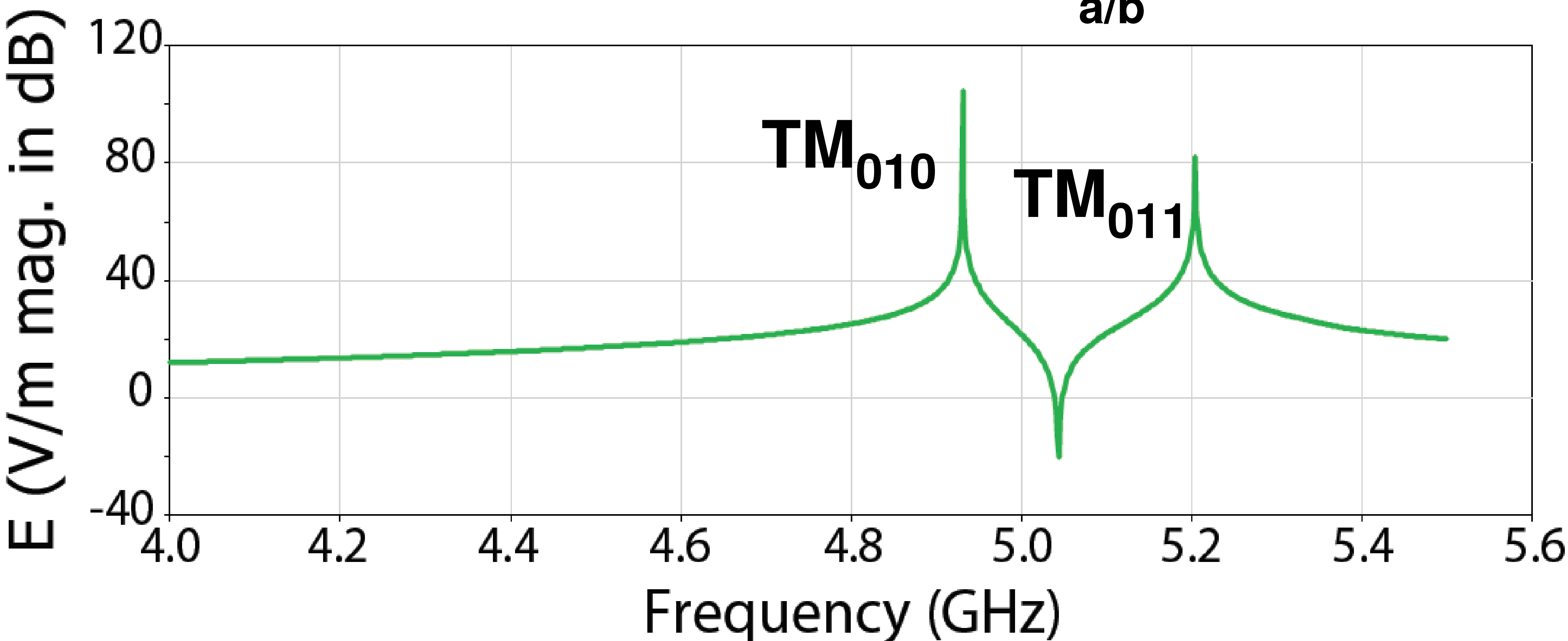


Cutting down the TE forest: Photonic Band Gap resonator

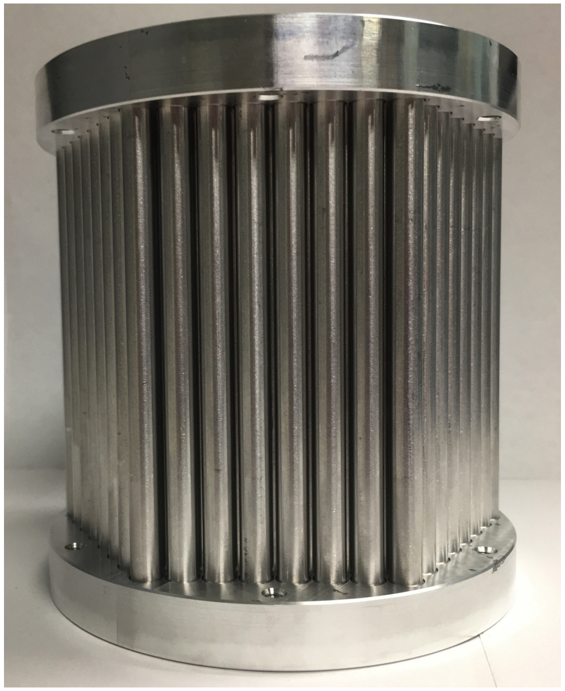
HAYSTAC

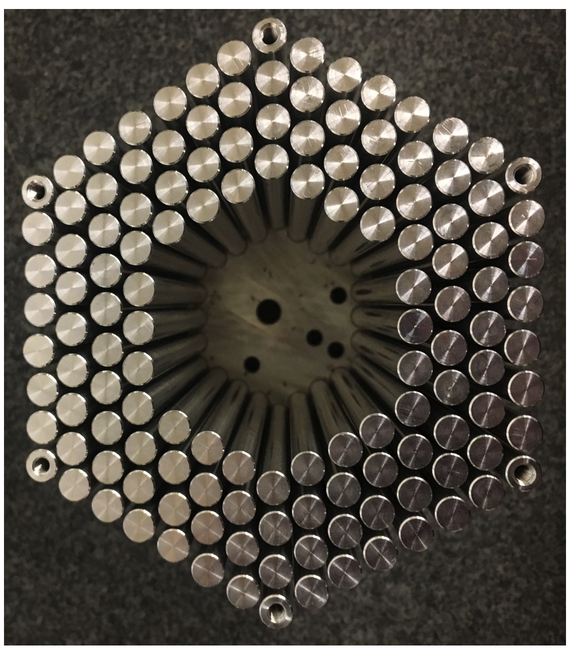


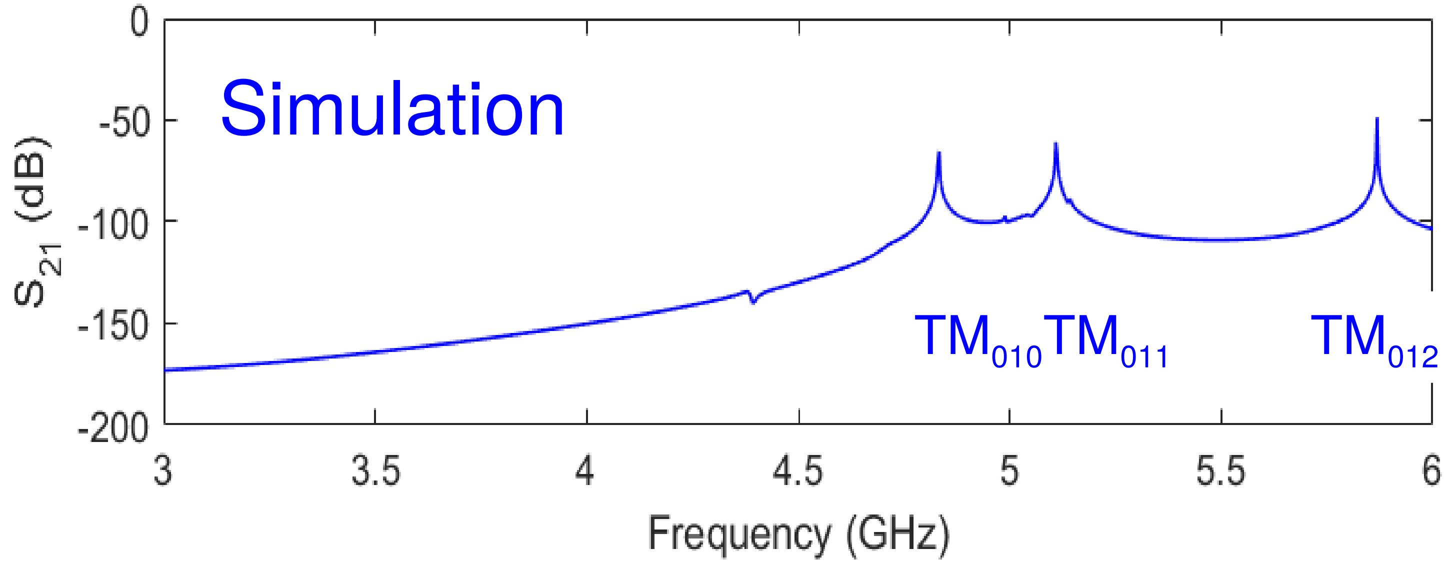


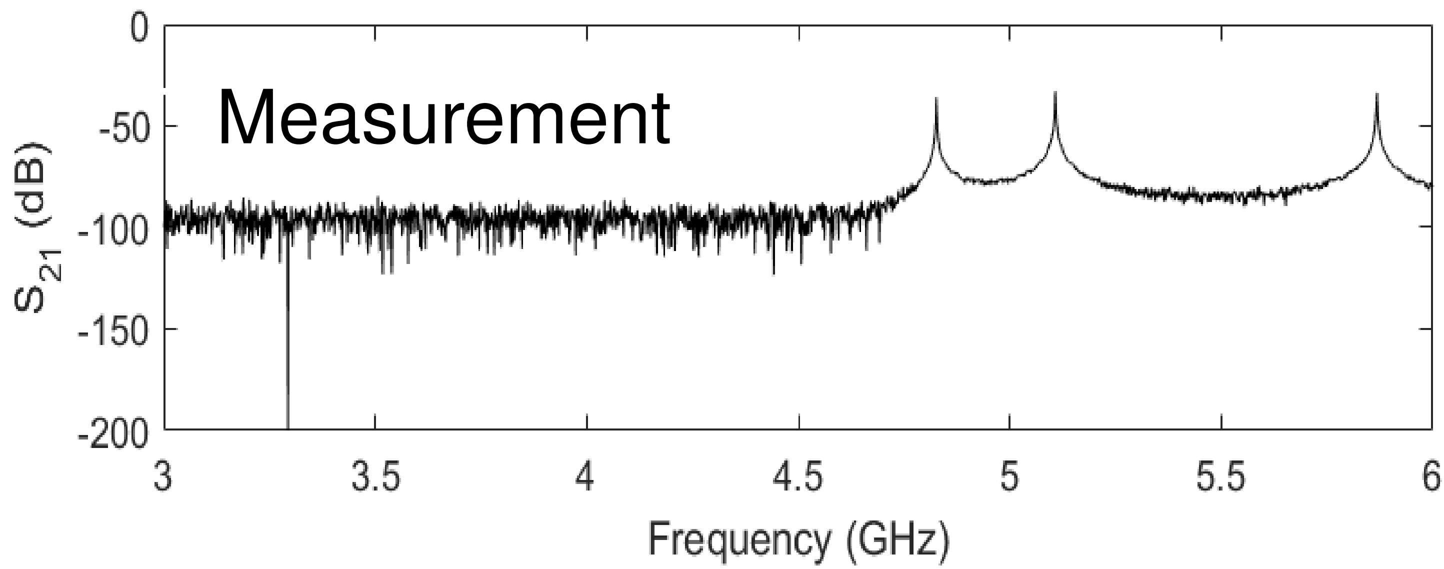


PBG Fixed-Frequency Prototyp



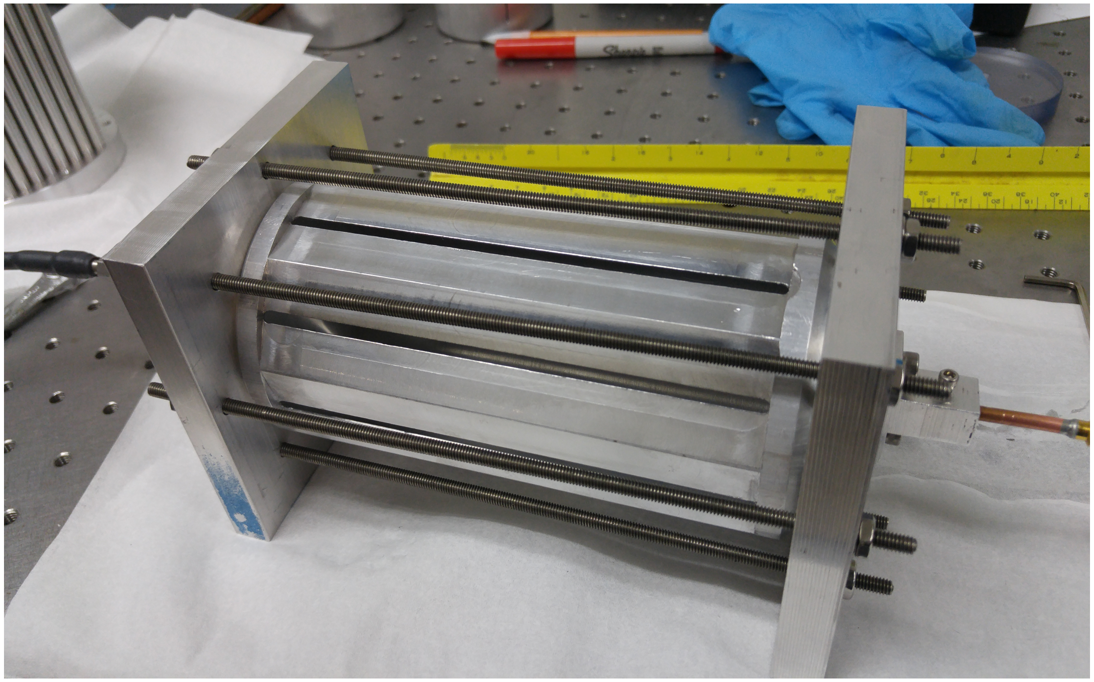


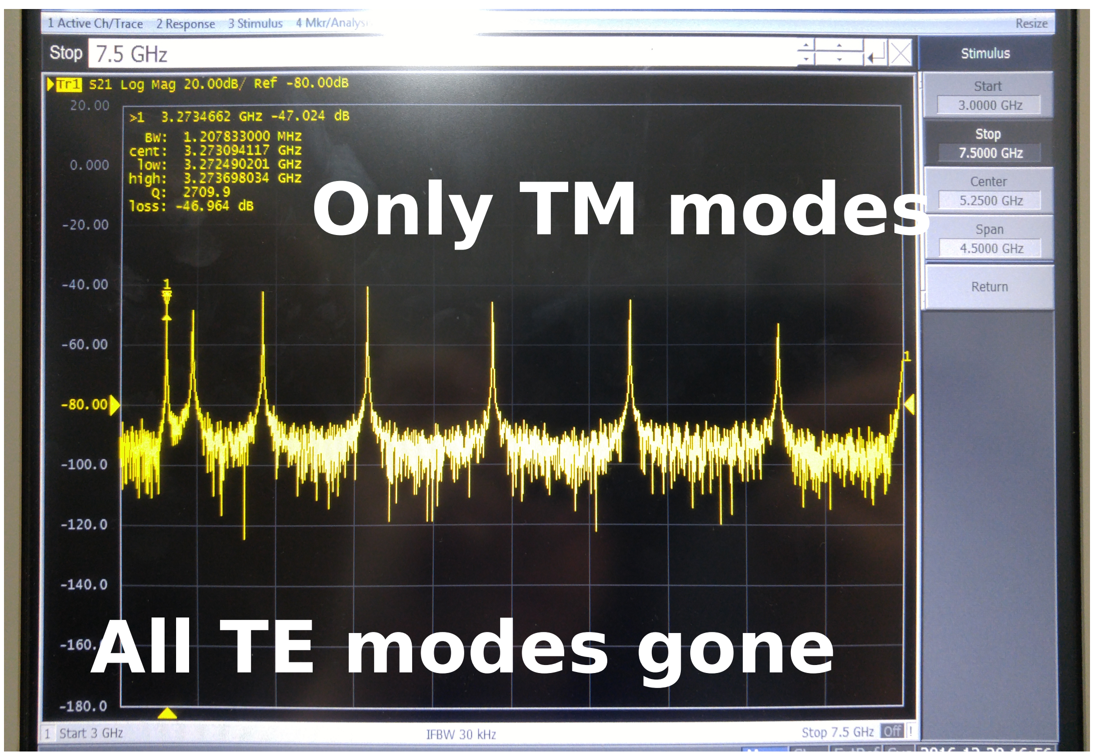




No TE modes in evidence; tunable PBG similarly shows good behavior, but more studies being done

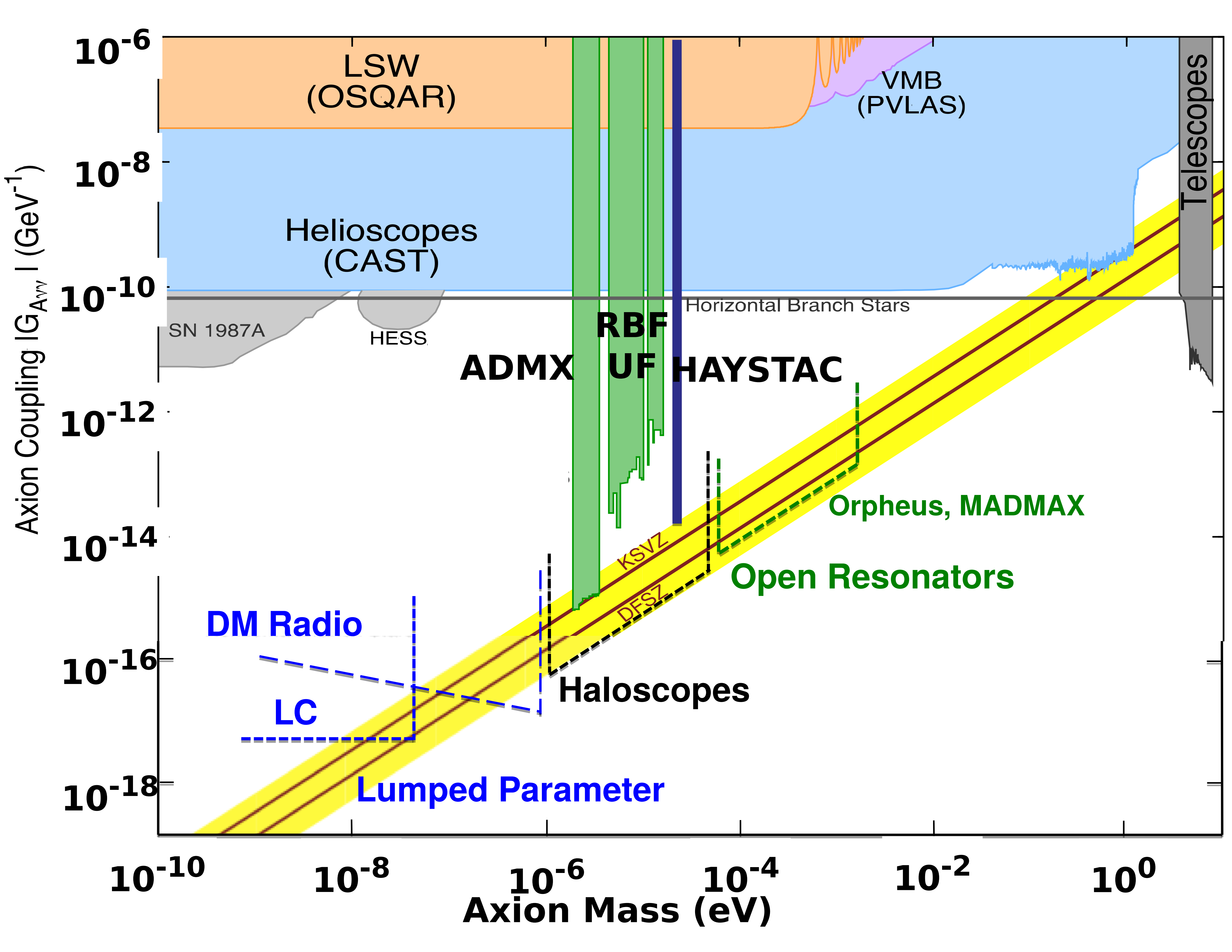
Slotted cavities – even simpler





- An undergraduate project
- Simple idea: TM surface currents in barrel are *axial*, TE are *circumferential*
- Cut longitudinal slots in the barrel to frustrate TE modes
- Simulation optimizes the width & depth of slots
- TE modes completely

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



LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes
(CAST)
Horizontal Branch Stars
SN 1987A
HESS
RBF
UF
ADMX
HAYSTAC
Orpheus, MADMAX
KSVZ
DFSZ
Open Resonators
DM Radio
Haloscopes
LC
Lumped Parameter
Axion Coupling |G$_{A\gamma\gamma}$| (GeV^{-1})
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
Axion Mass (eV)

Final observations

- Progress over the past thirty years has been solid.
- The axion search is the one experiment where sensitivity is *not* the problem, but mass coverage – both in extent and in speed – continues to be. We have not turned the corner yet.
- The goal posts have moved; we have much more ground to cover than we thought a decade ago: at least neV to meV.
- The state of R&D is excellent; there is now a critical mass community to tackle the problems, and the agencies are to be thanked for their increased support.
- Particularly noteworthy are the parallel initiatives by

And profound gratitude to our sponsors

The National Science Foundation

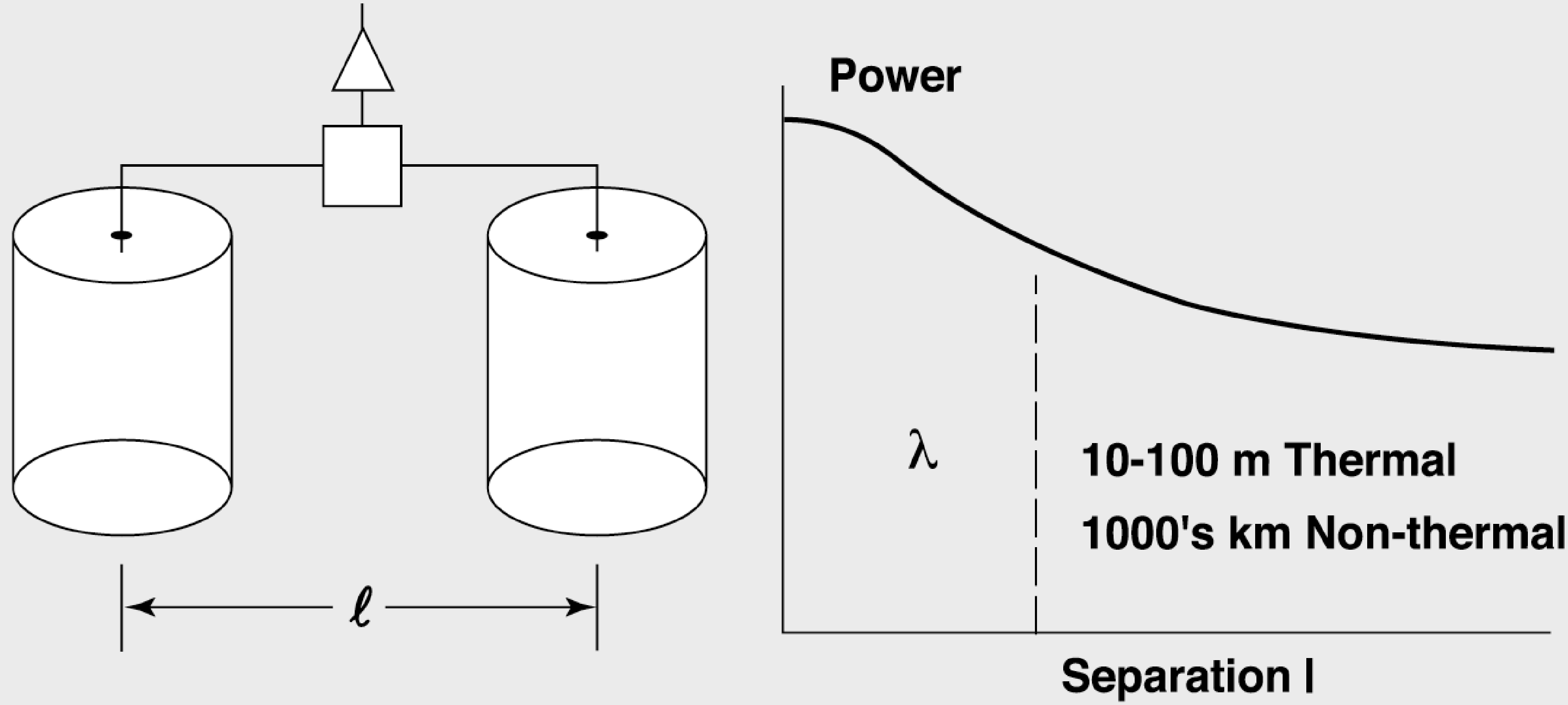
The US Department of Energy

The Heising-Simons Foundation

When shall the axion be found?

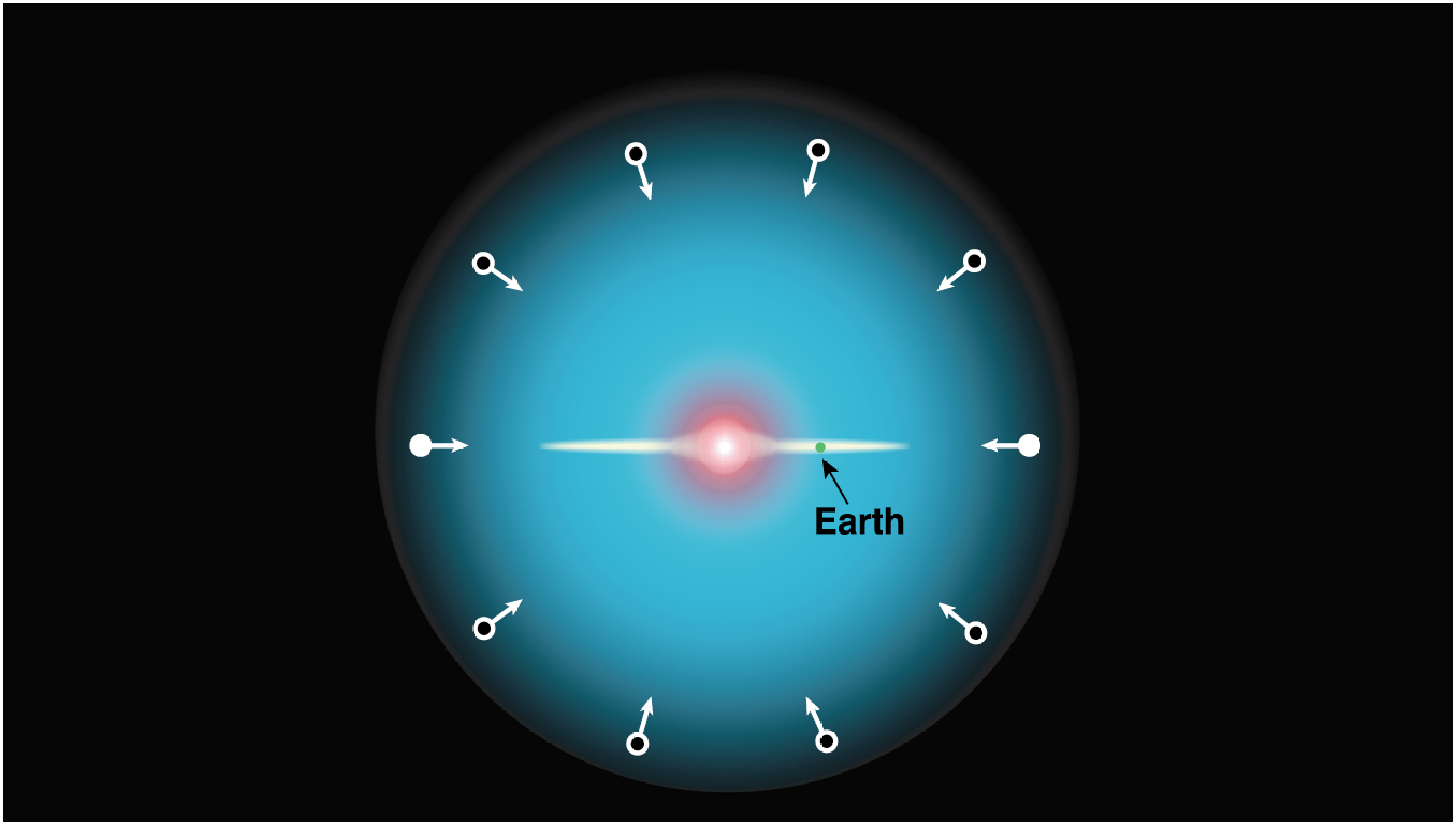
And then what?

The Study of Unique Quantum System



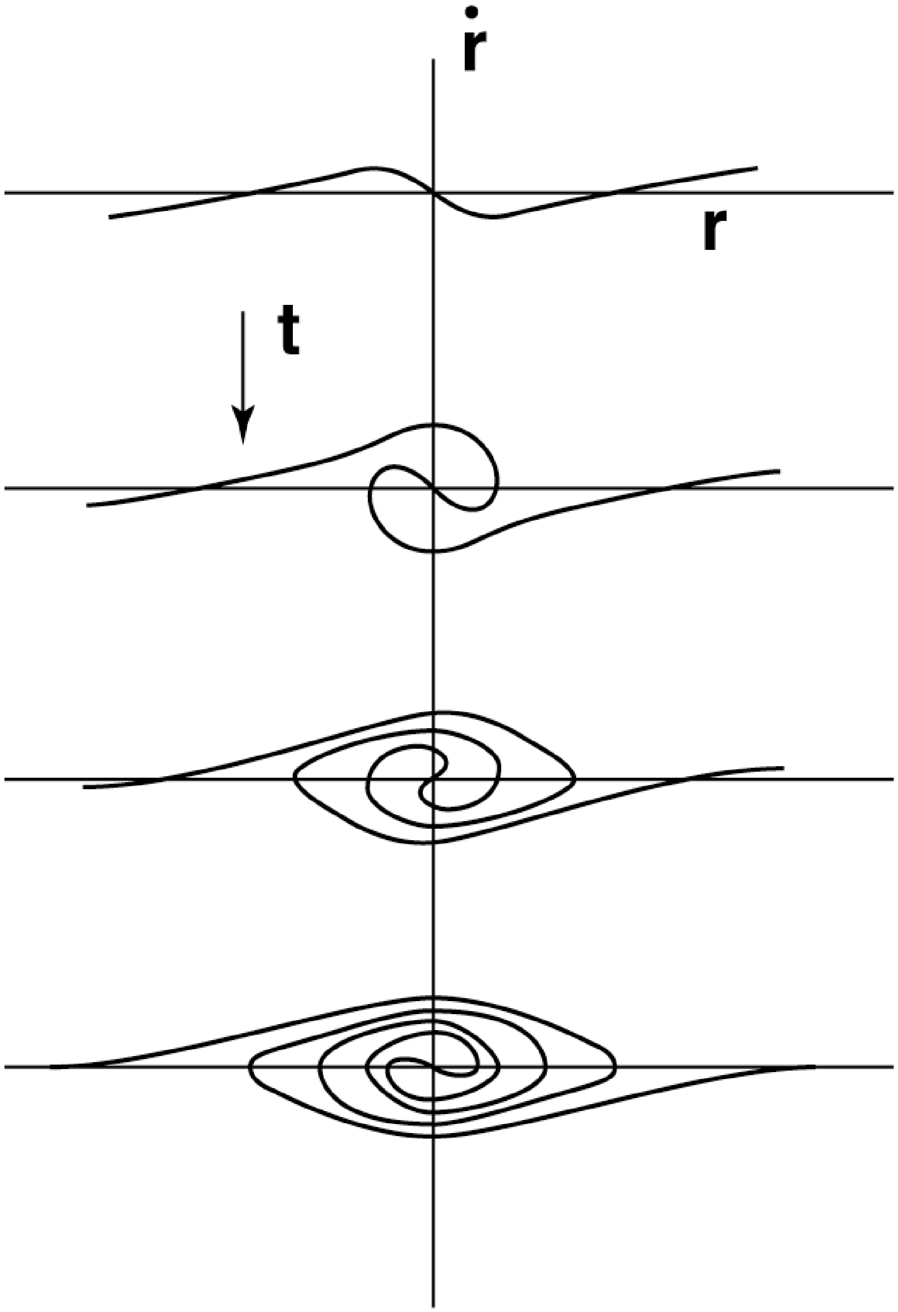
And should the axion posses fine-structure, it would constitute a “movie” of the formation of our Milky Way galaxy

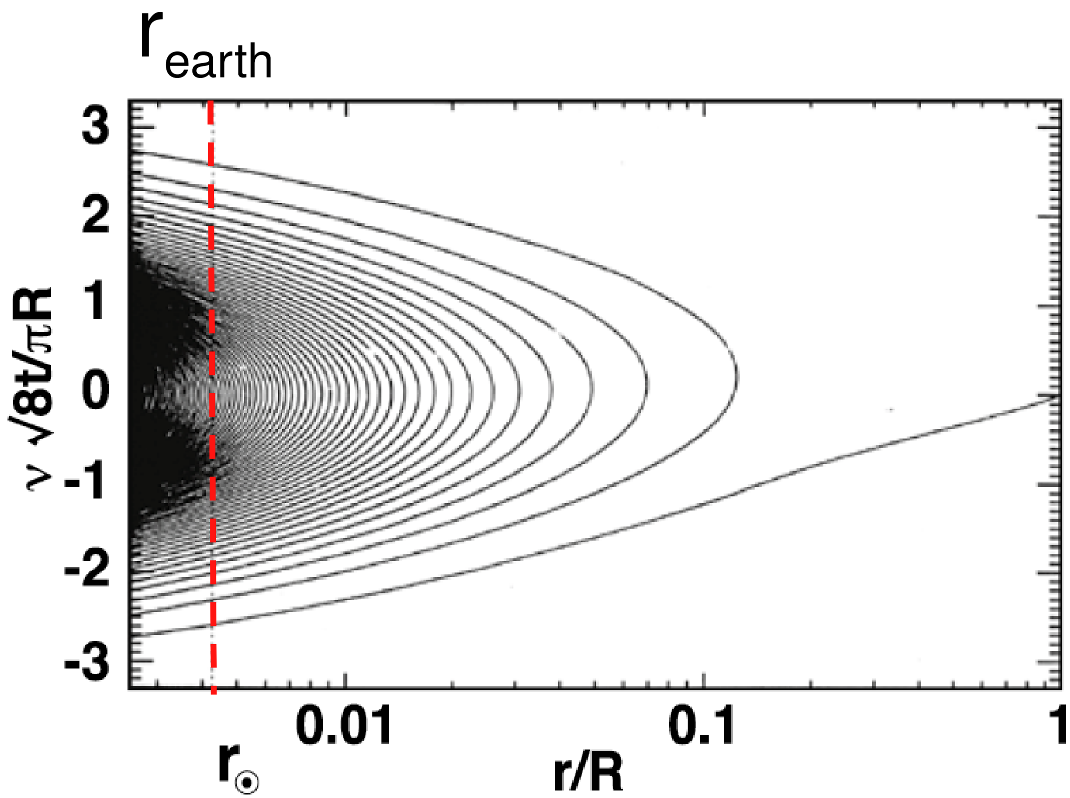
Modulation of fine structure may enable precision geolocation without GPS



Late-infall axions pass through our position with specific velocities

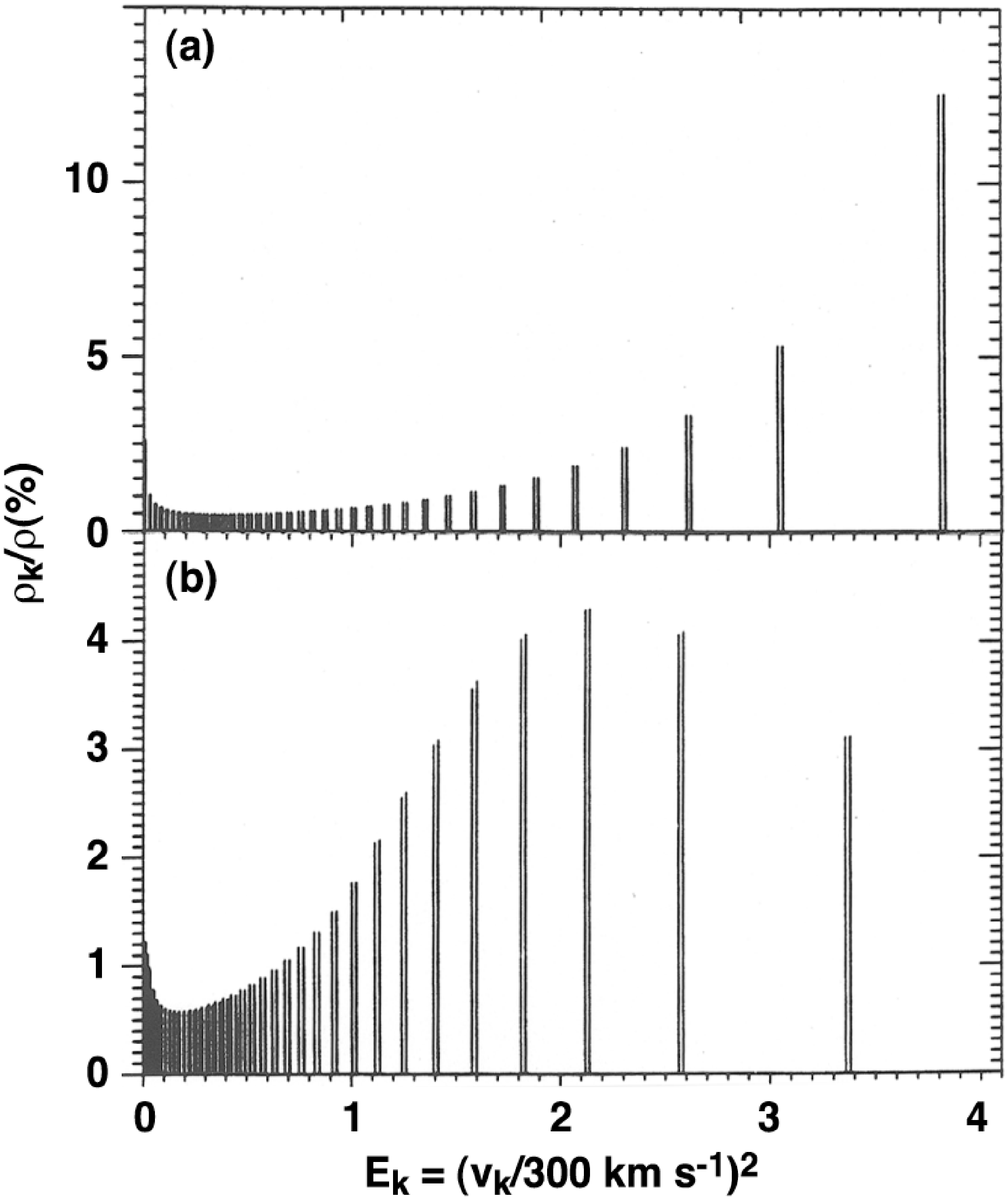
Axionic phase space in a Sikivie infall model





- Model begins with
  - Zero Temperature CDM
  - Hubble expansion
  - Initial density perturbation r = o
- Grows self-consistent potential

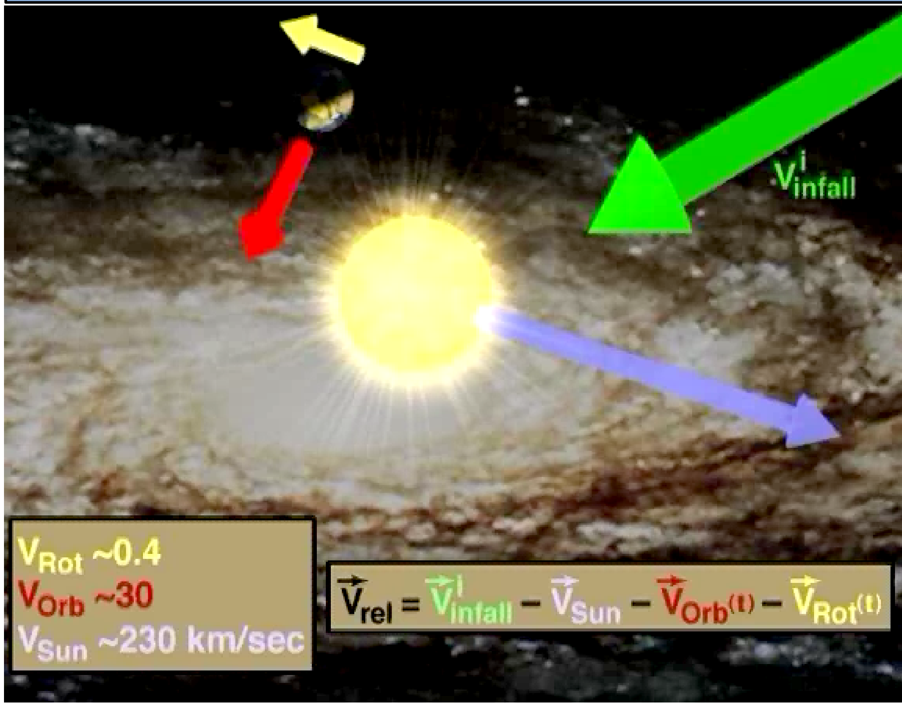
Sikivie infall model (II)



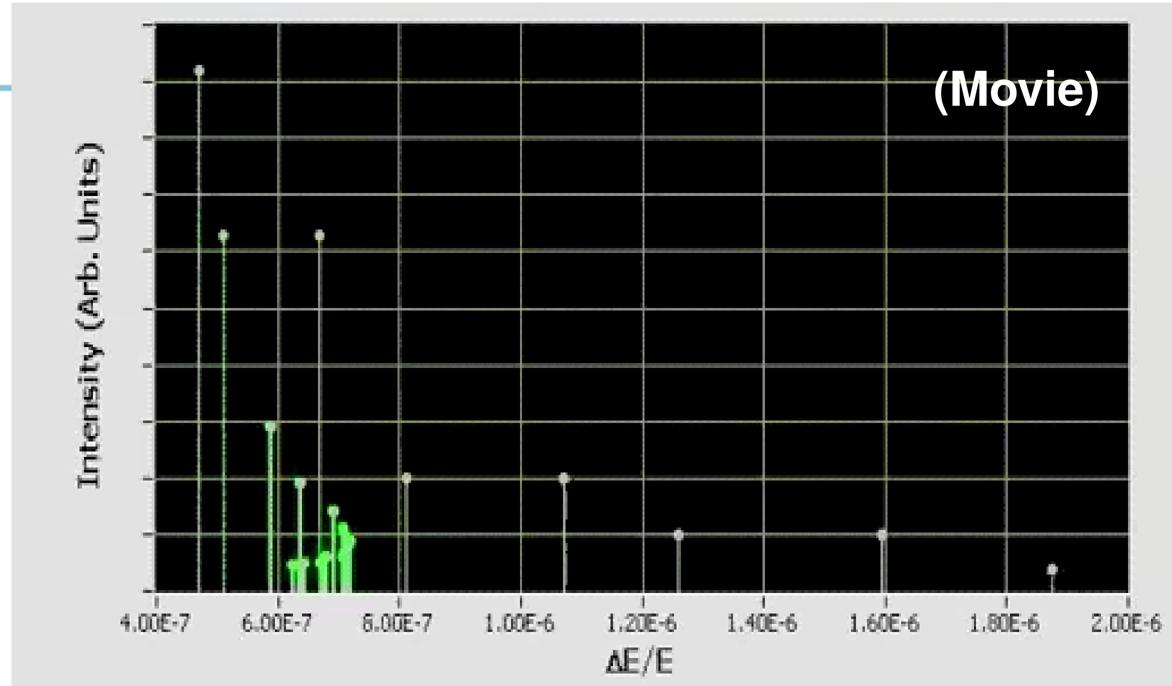
(a) No angular momentum

(b) Finite angular momentum

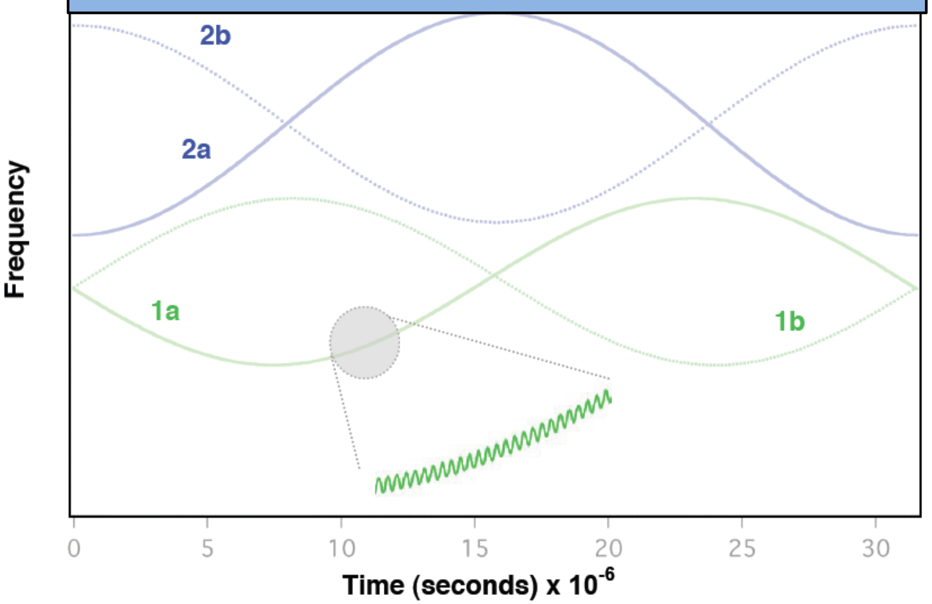
Modulation of one infall line



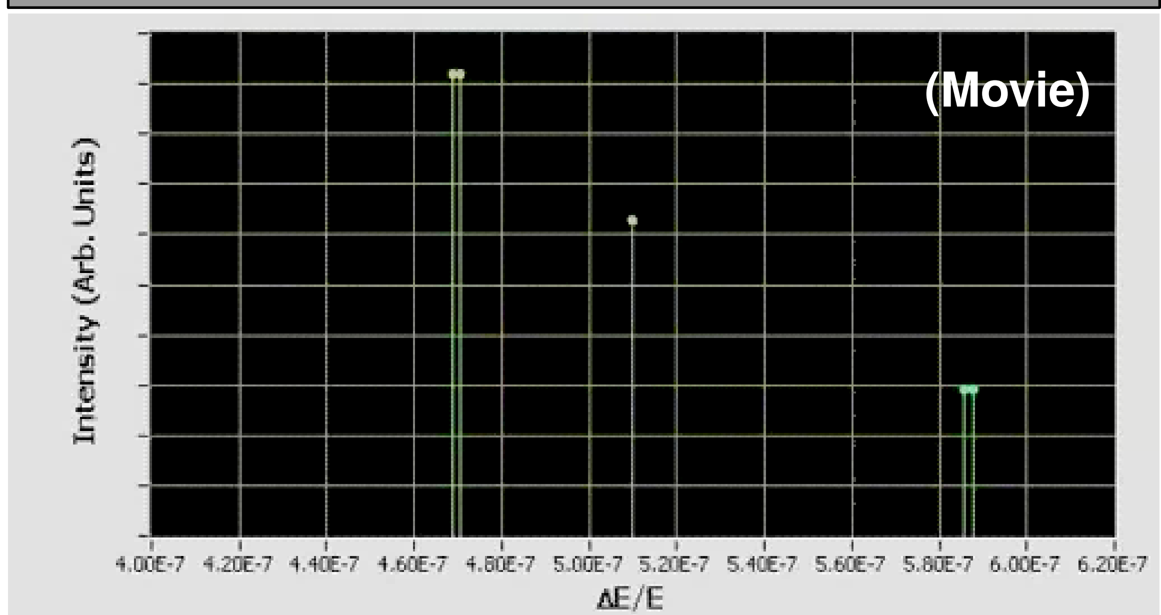
Annual Modulation: Earth's orbit around Sun



Vector DM Flow is uniquely determined



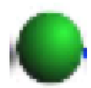
Daily Modulation: Earth's spin on its axis



Backup Slides

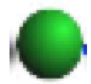
Primakoff effect (1951)

Problem: How to accurately measure the lifetime of the neutral pion, $\tau_{\pi 0}$ which was known to be very short?

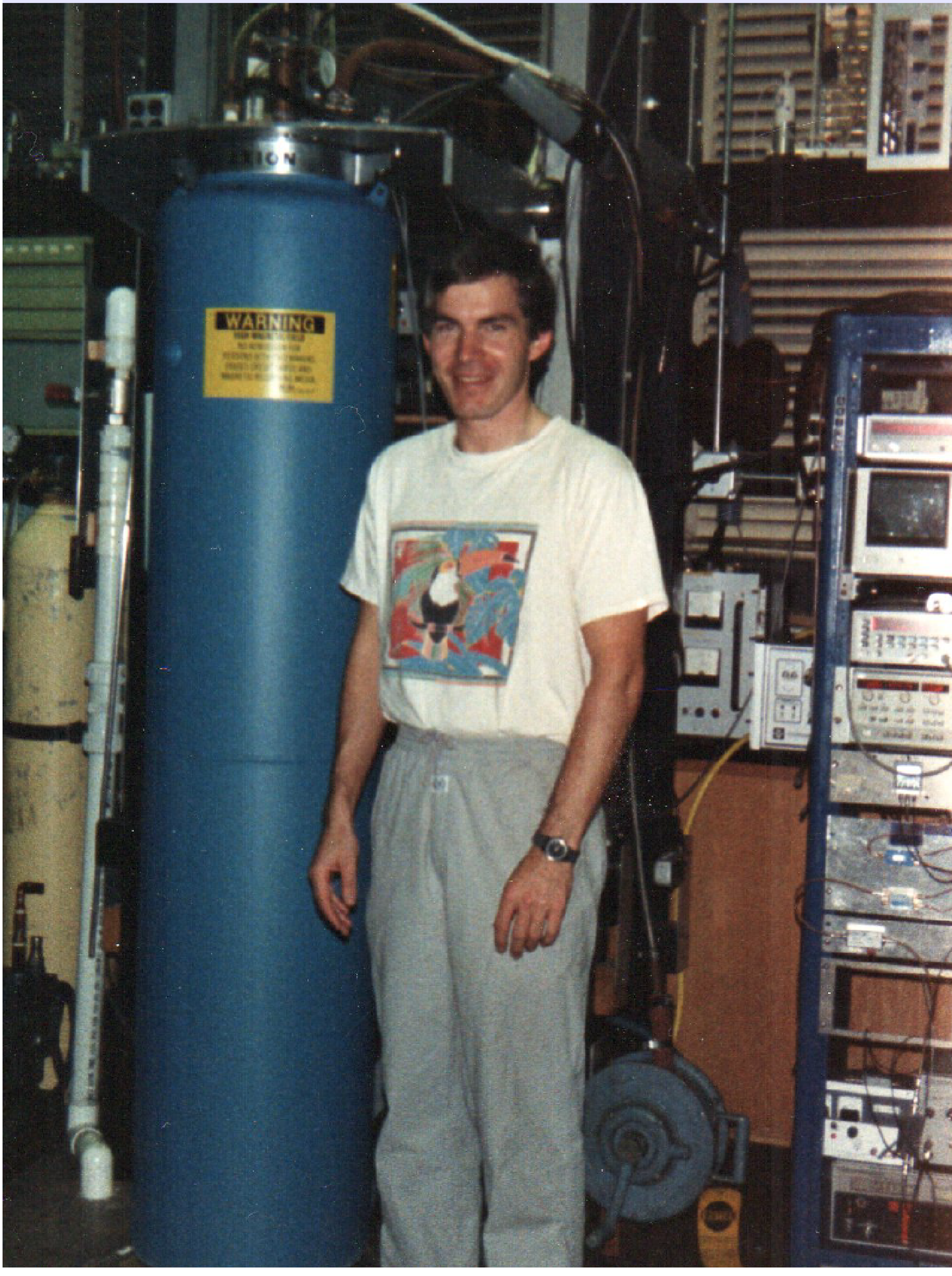


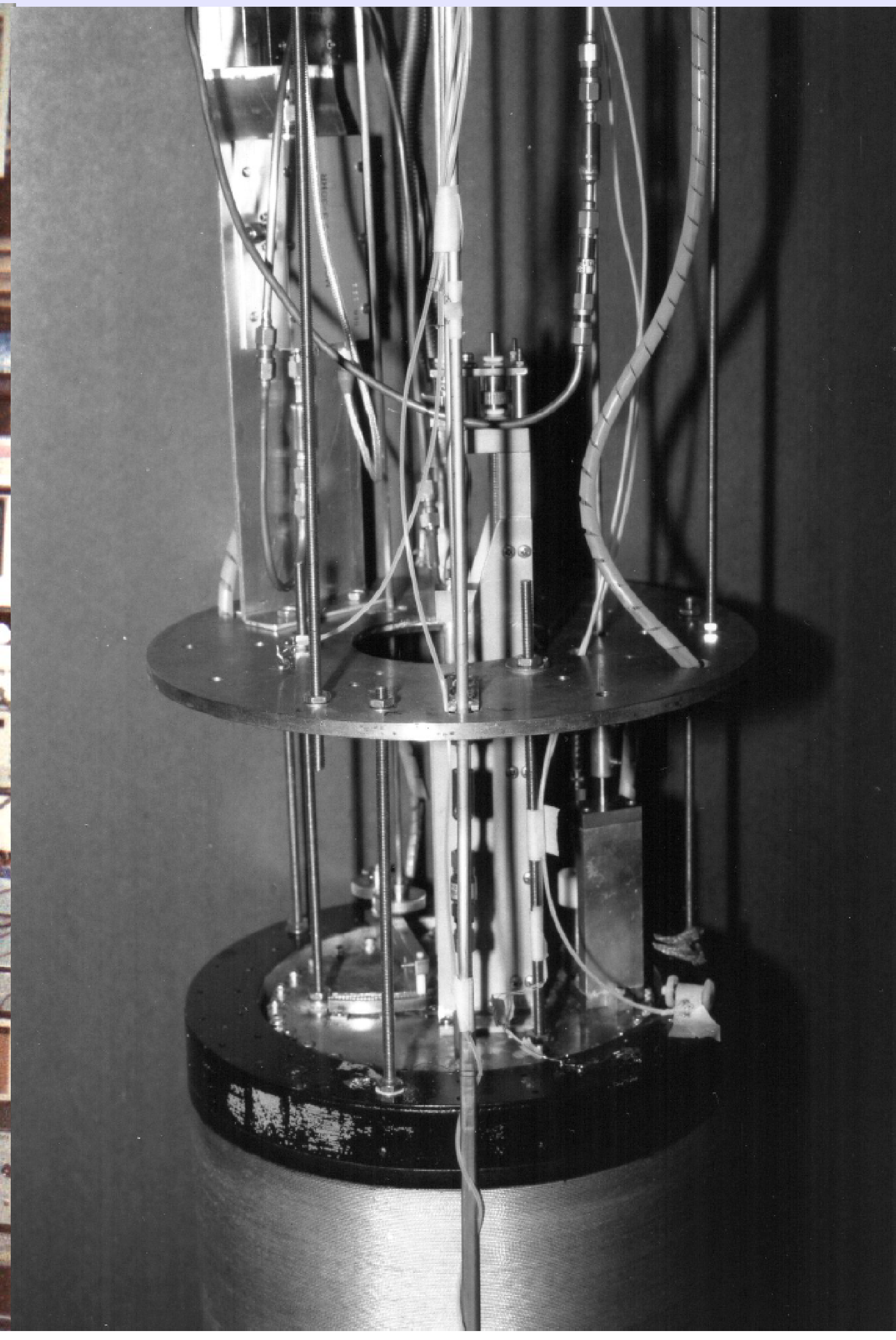
Primakoff – experiment (1965): $\tau \sim 8.7 \times 10^{-17}$ sec

σ □ $g_{\pi\gamma\gamma}$ □ τ

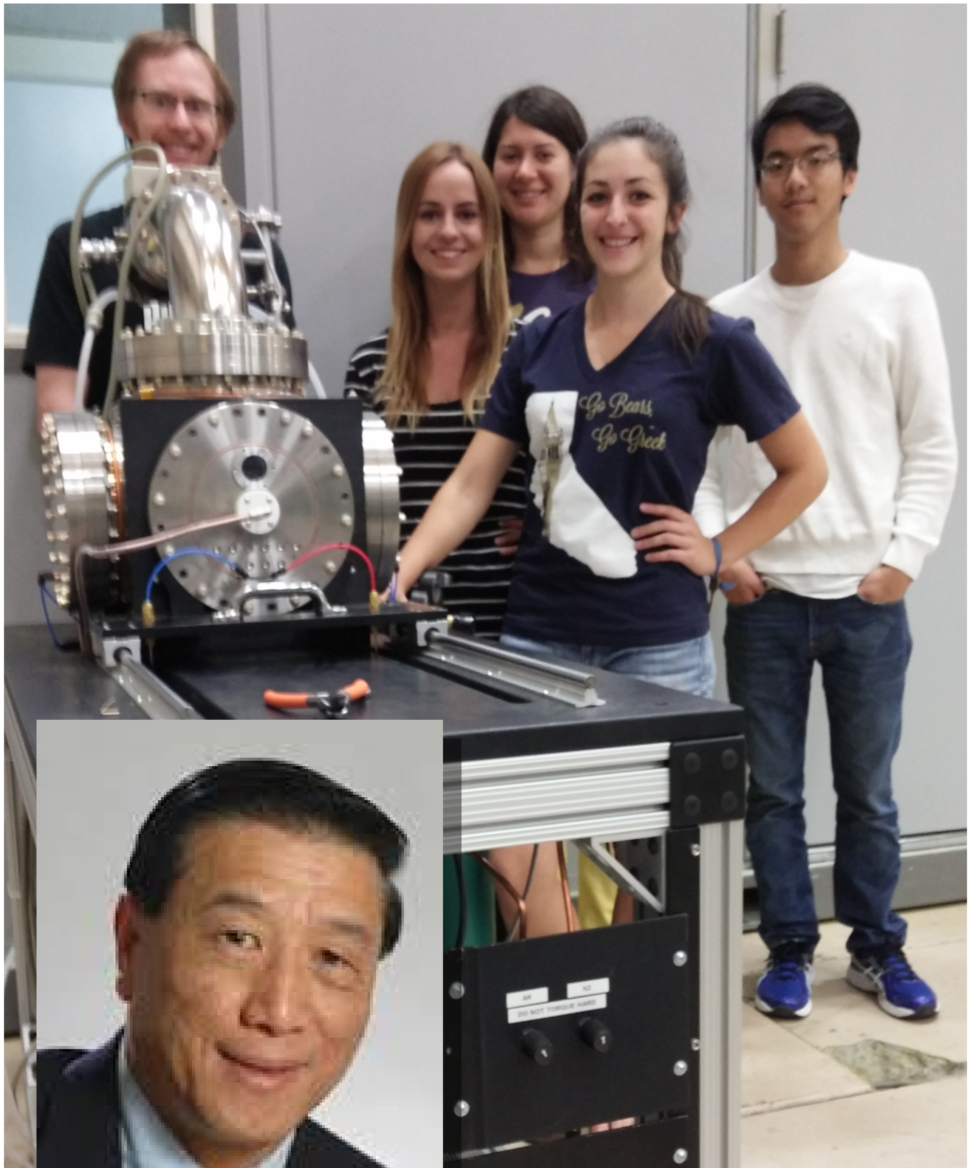


The Florida Experiment – Williamson Hall c. 1989





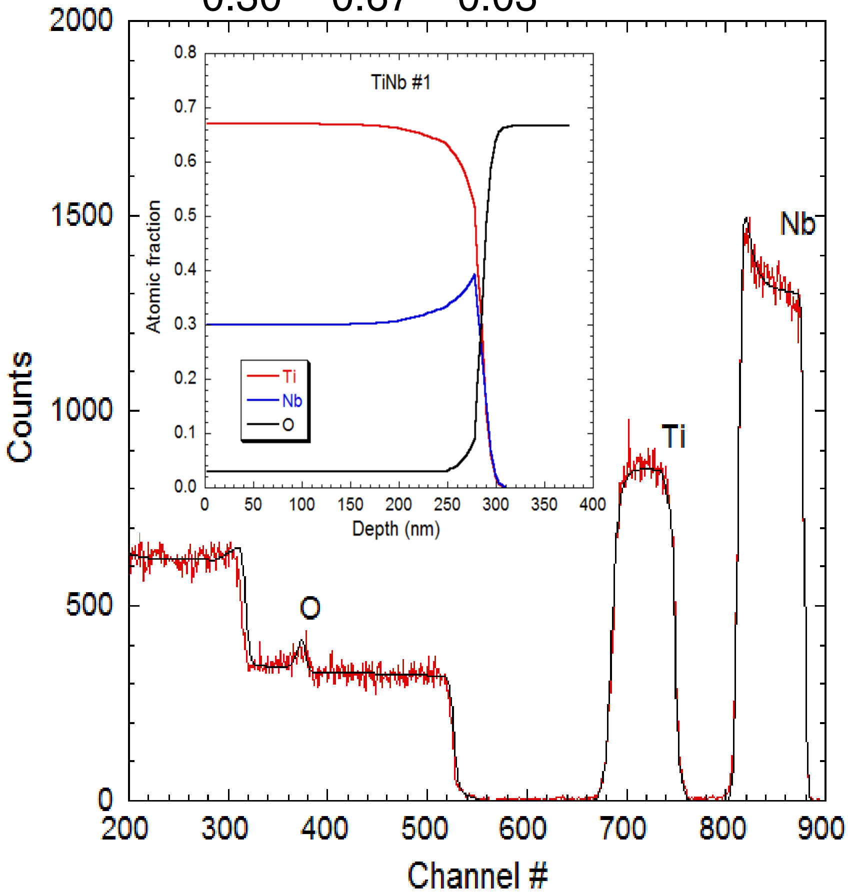
Development of cavities with thin film coatings of Type-II superconductors, e.g. $Nb_xTi_{1-x}N$ by RF plasma deposition

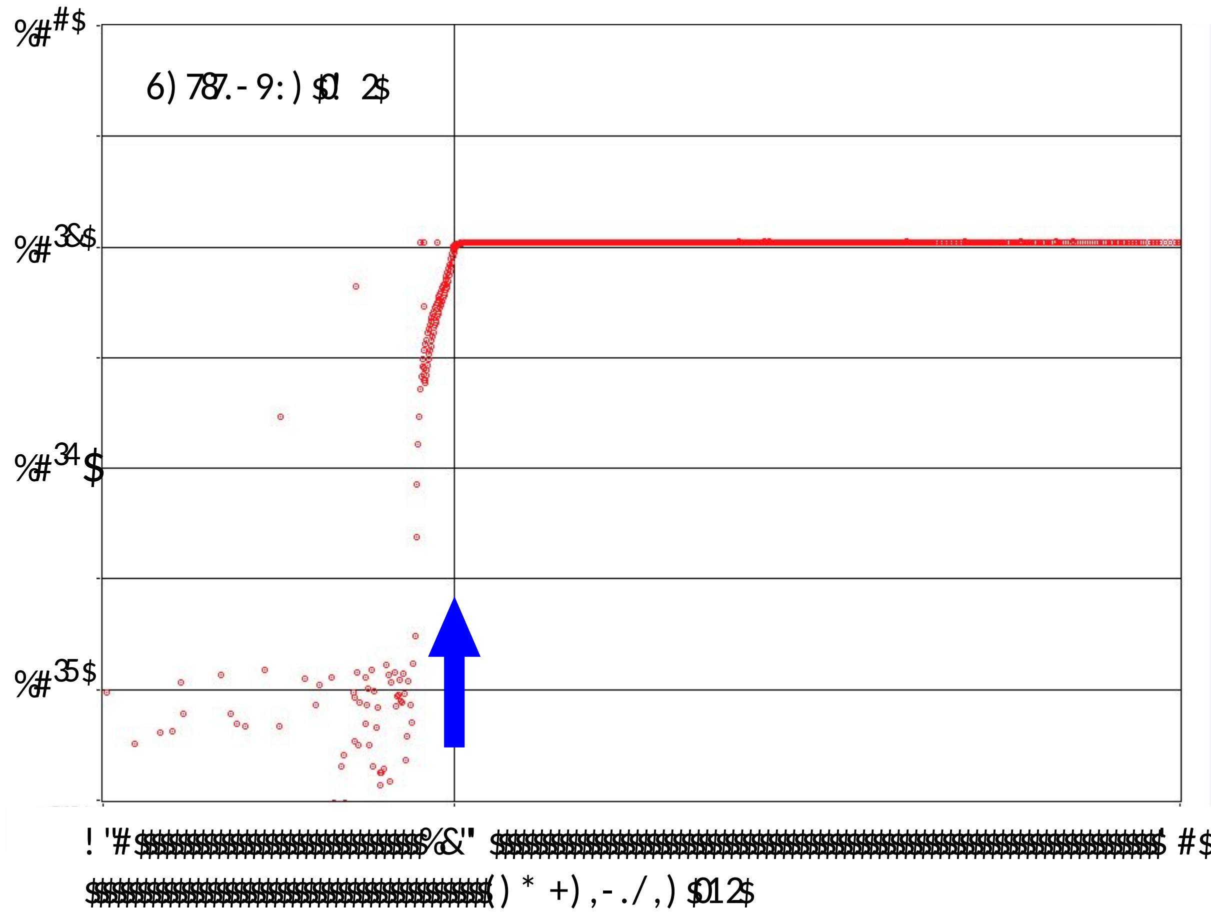


RF plasma deposition technology pioneered by Ka-Ngo Leung

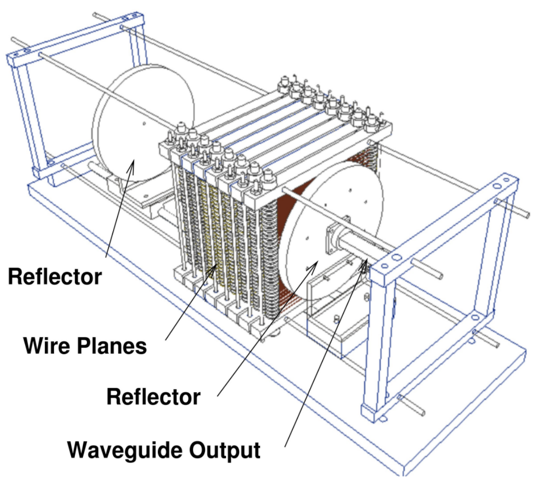
Thin films of the desired stoichiometry, thickness and transition temperature have been successfully made – RF cavity prototype is next

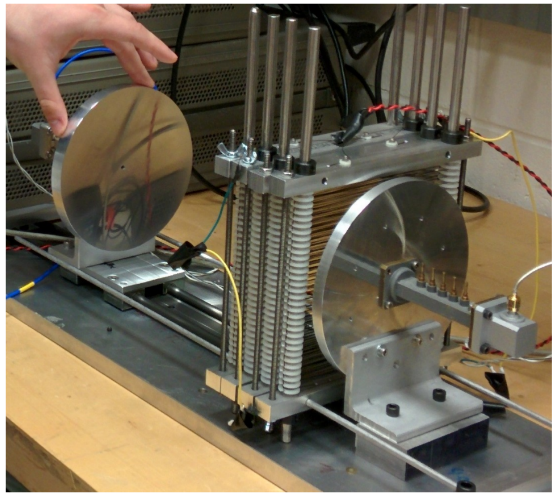
$Nb_{0.30}Ti_{0.67}O_{0.03}$: 280 nm

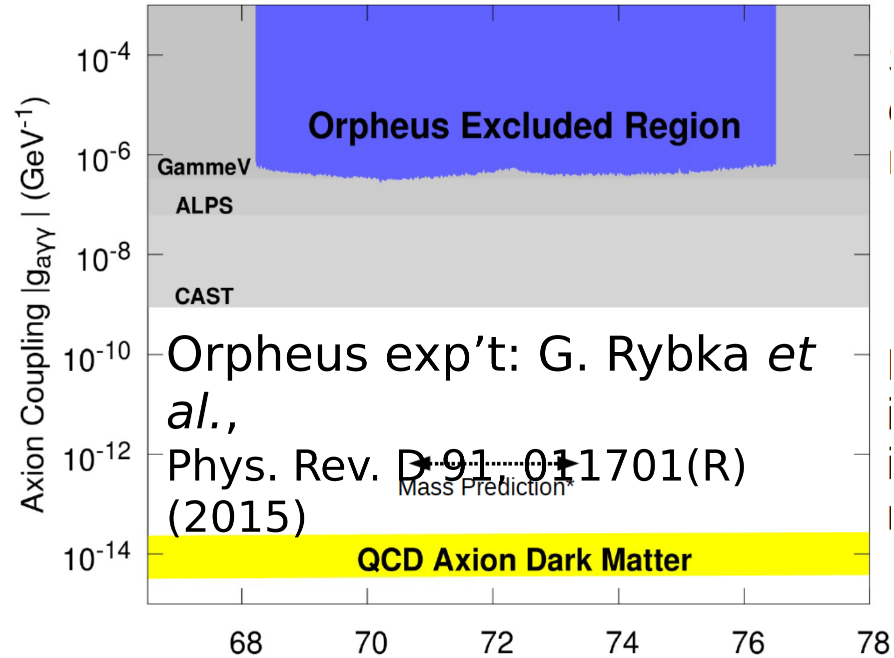




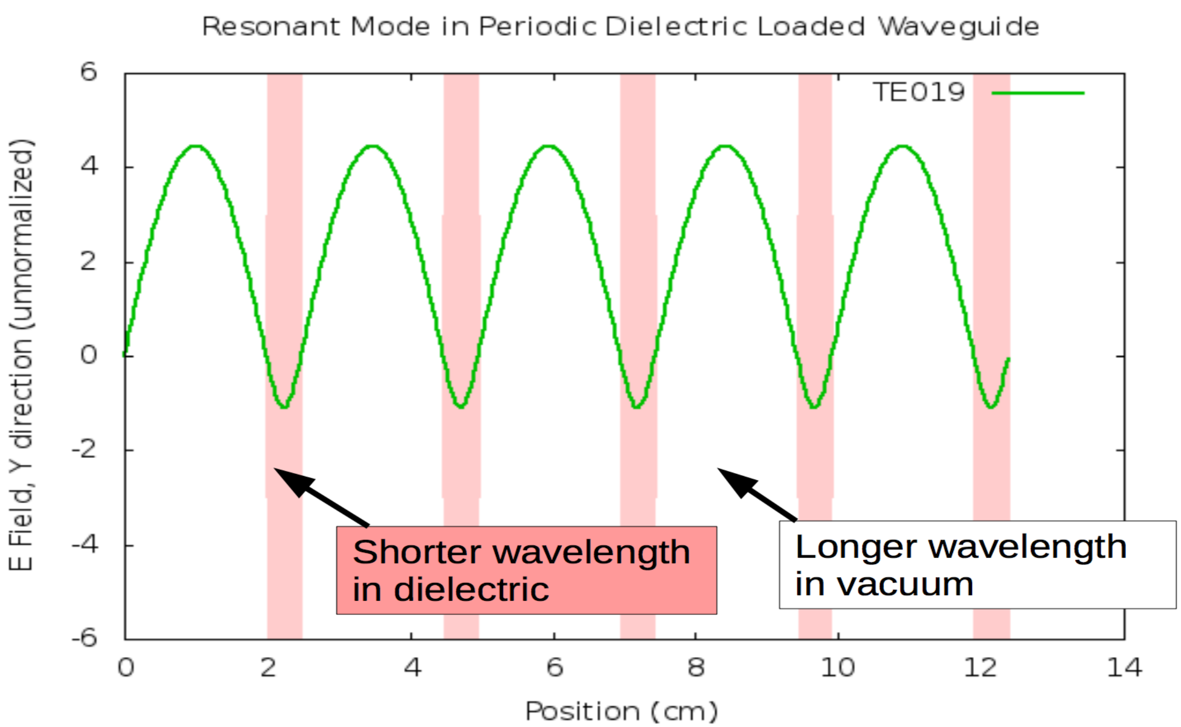
Higher Frequencies – Open Resonators (Orpheus, MADMAX)

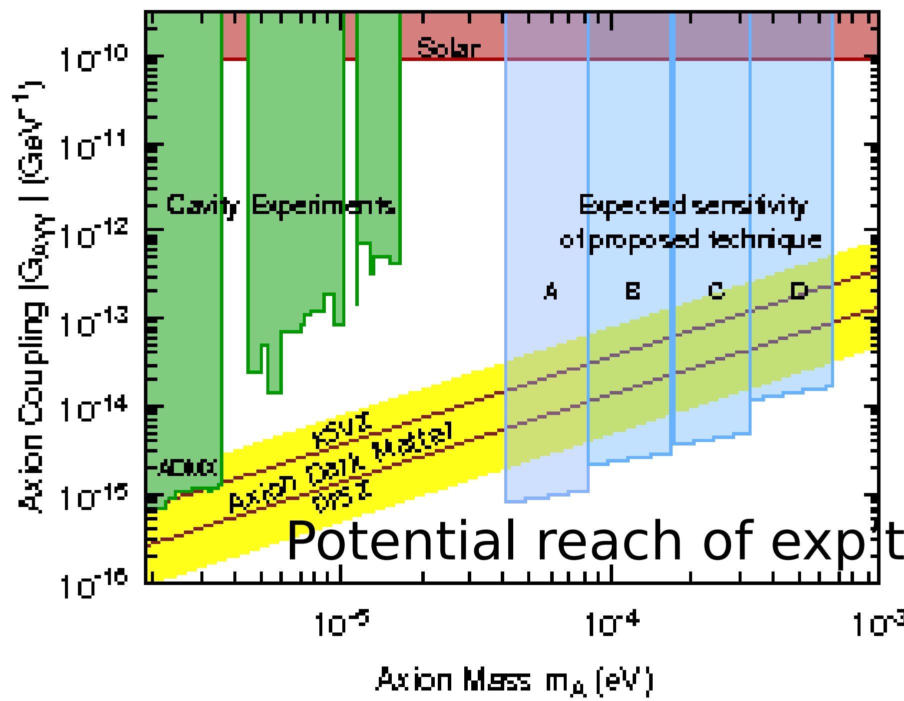






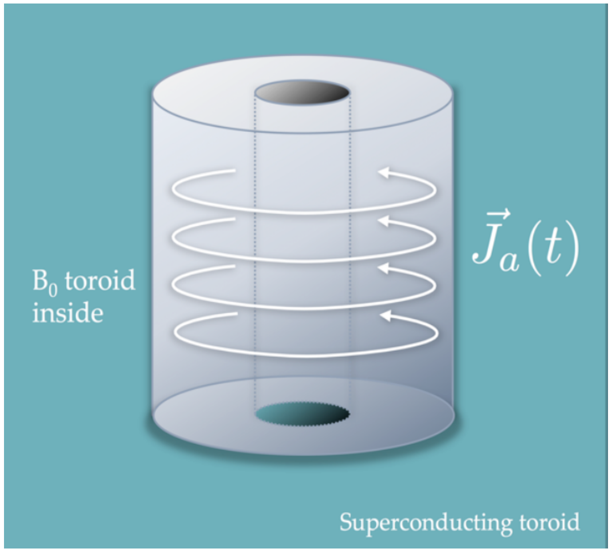
Orpheus exp't: G. Rybka *et al.*,
Phys. Rev. D 91, 011701(R) (2015)

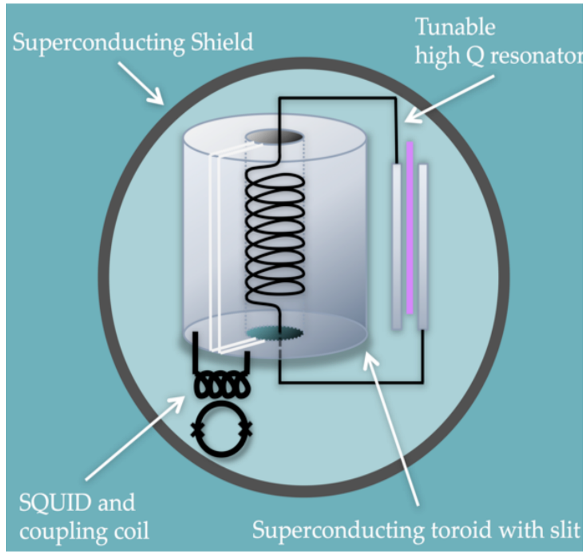




Potential reach of exp't

Lower Frequencies – Lumped Parameter Oscillators



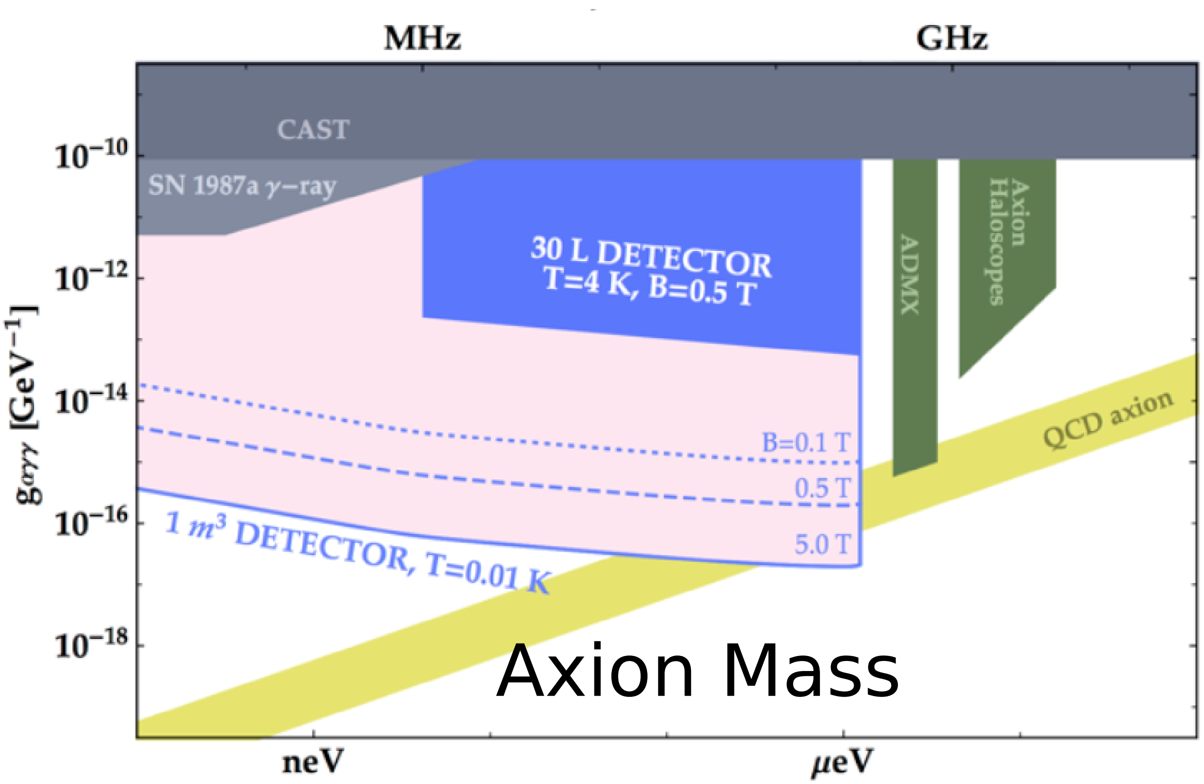


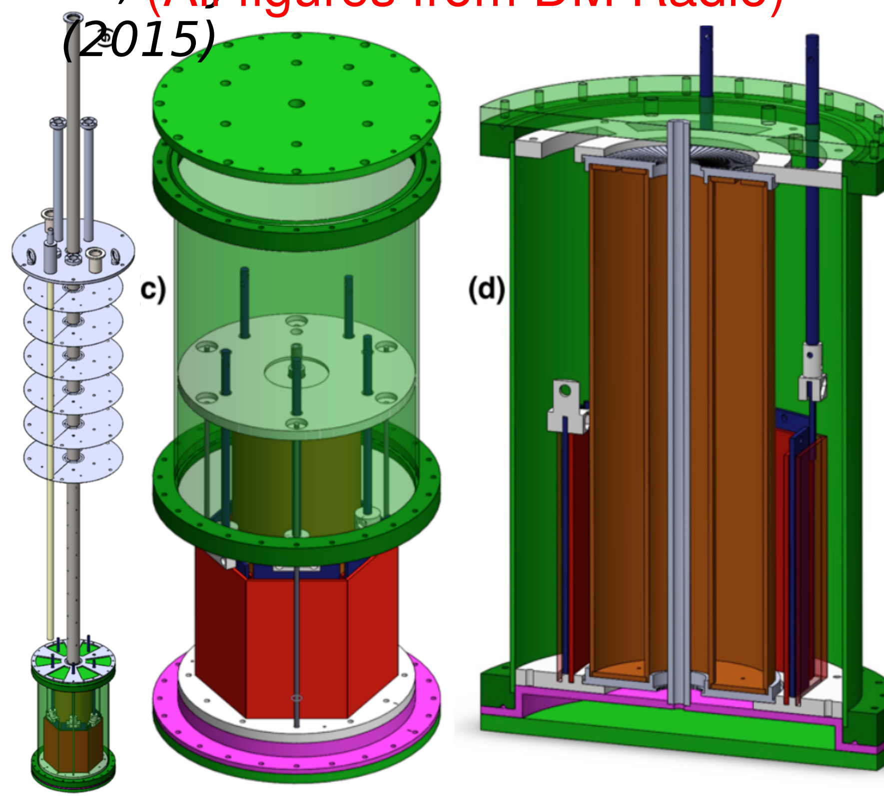
In a nutshell – Break the relationship between cavity diameter & frequency.

LC project *(U. Florida): Sikivie et al., Phys. Rev. Lett. 112, 131301 (2014)*

DM Radio *(SLAC): Chaudhuri et al., Phys. Rev. D 92:075012, (2015)*

(All figures from DM Radio)





Final provocative thought (*"Throw deep, Mr. Presid*