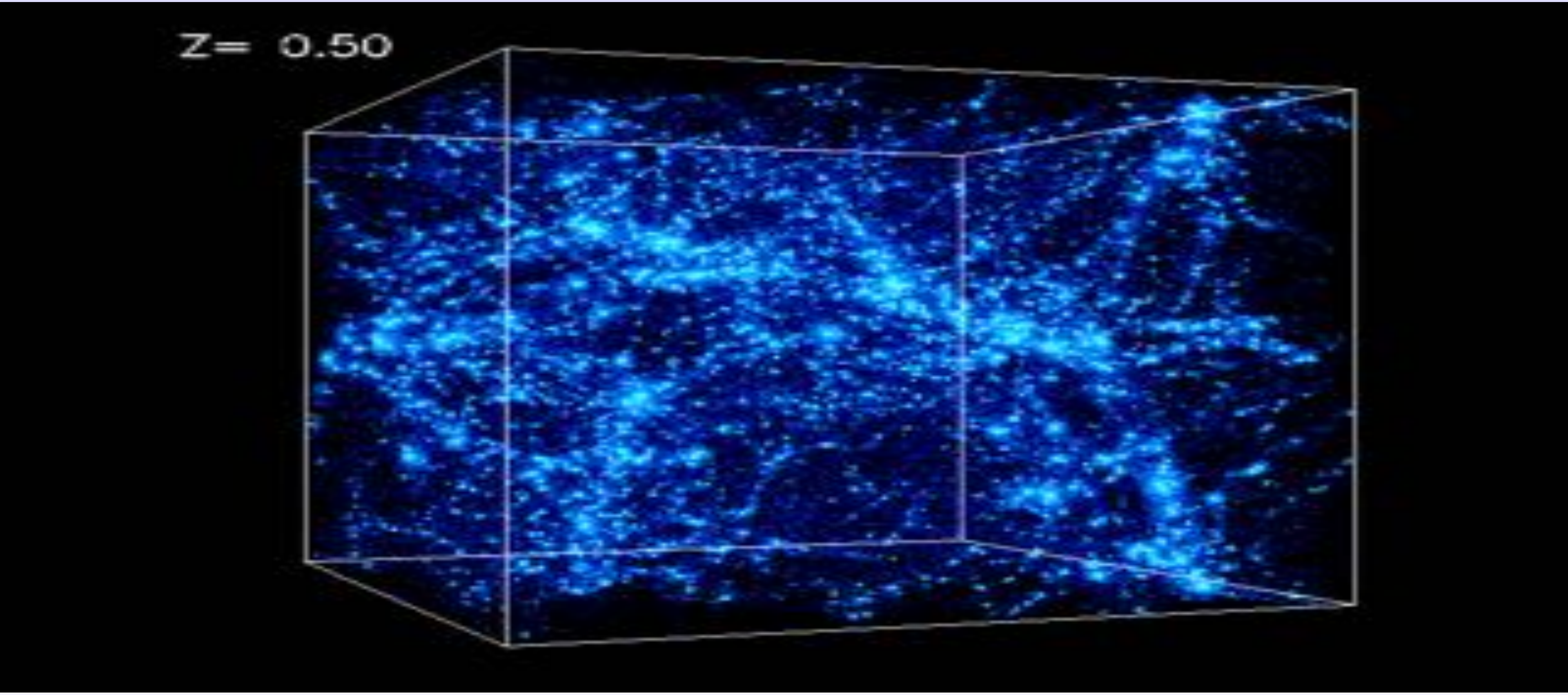
The Extreme Axion Experiment (X3)



S. Al Kenany, University of California, Berkeley

Kyoto University, Division of Physics and Astronomy, July 26, 2016

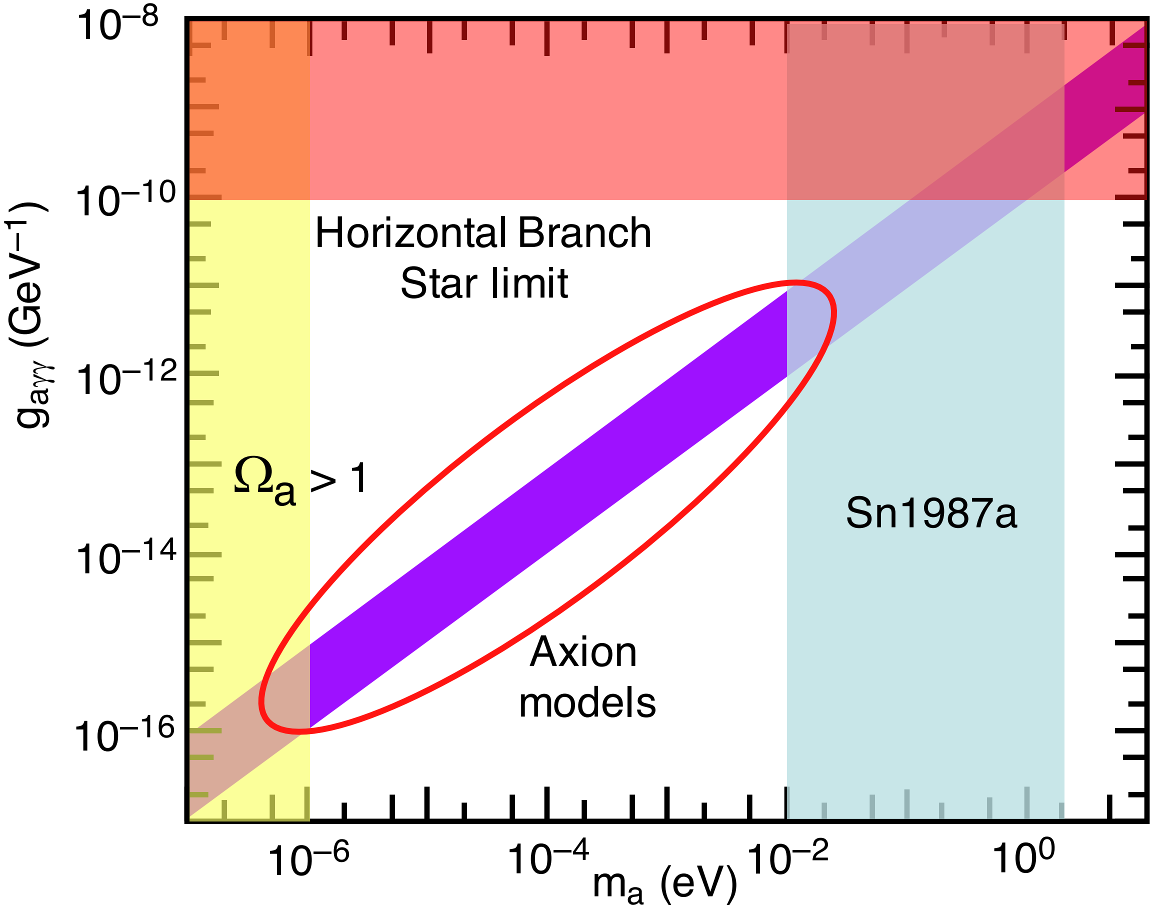
Outline

- (Very) brief basics on the axion
- The microwave cavity search for axionic dark matter
- How to improve its mass reach, speed and sensitivity
- What next?

The Axion

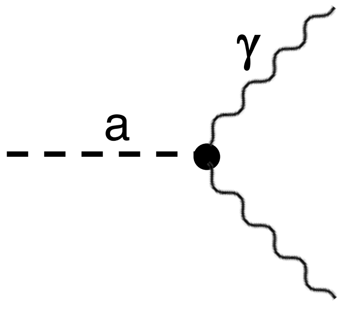
- Strong CP (charge parity) problem – standard model predicts:
- significant amount of CP violation in strong interactions
- (compared to experiment)
- neutron dipole moment nine orders of magnitude larger than
- the current experimental limit
- Peccei and Quinn proposed the axion as a solution to this strong
- CP problem

Axion basics *(arm-chair science – what you learn for free)*



Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

Light cousin of π^0: $J^\pi = 0^-$



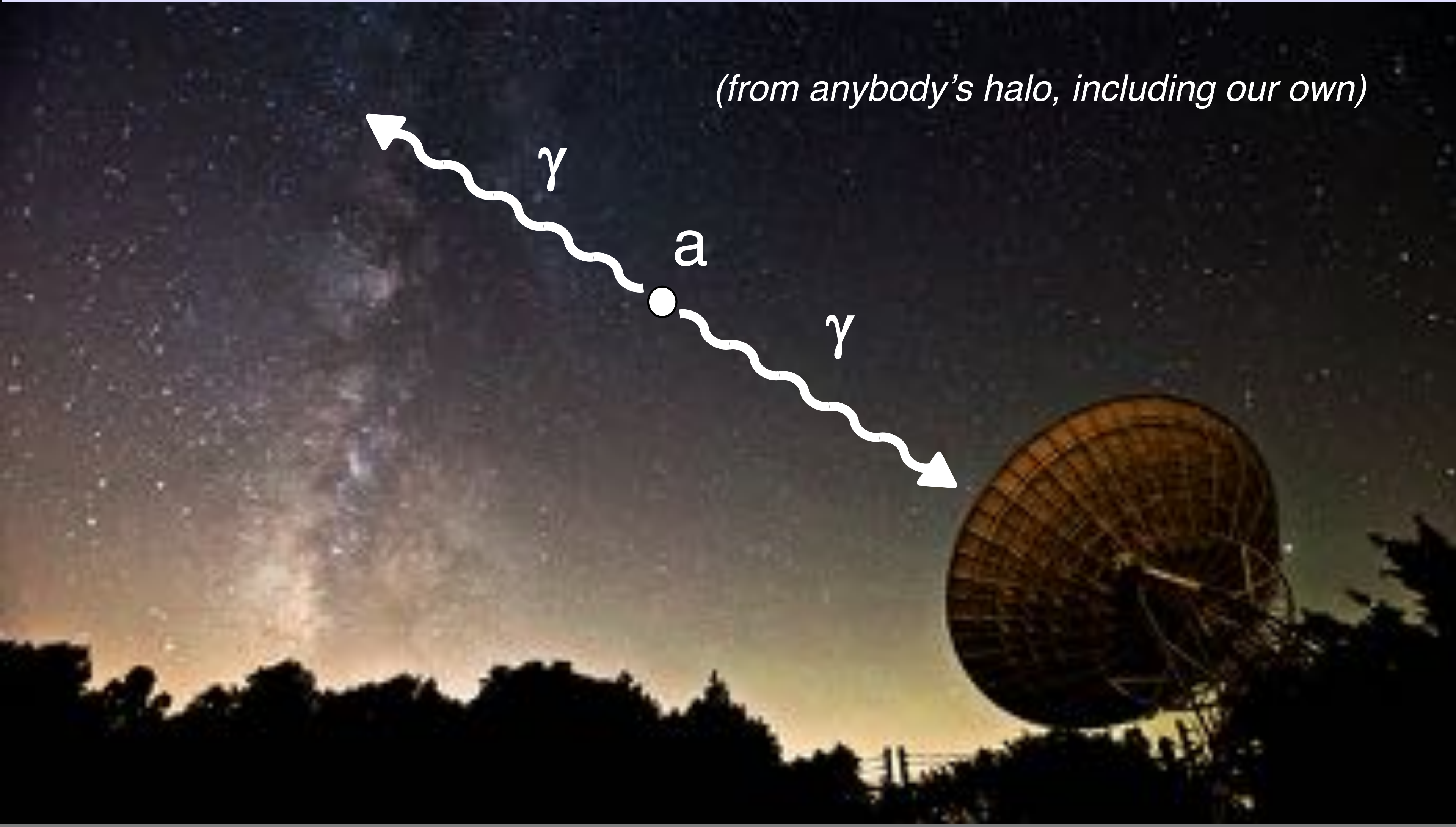
Couplings $\propto$ Axion mass

Total density $\propto$ (mass)$^{-7/6}$

Axion production quenches neutrino pulse from SN1987a if mass too big (~ meV)

Ordinary stellar burning rules out axions if coupling too big

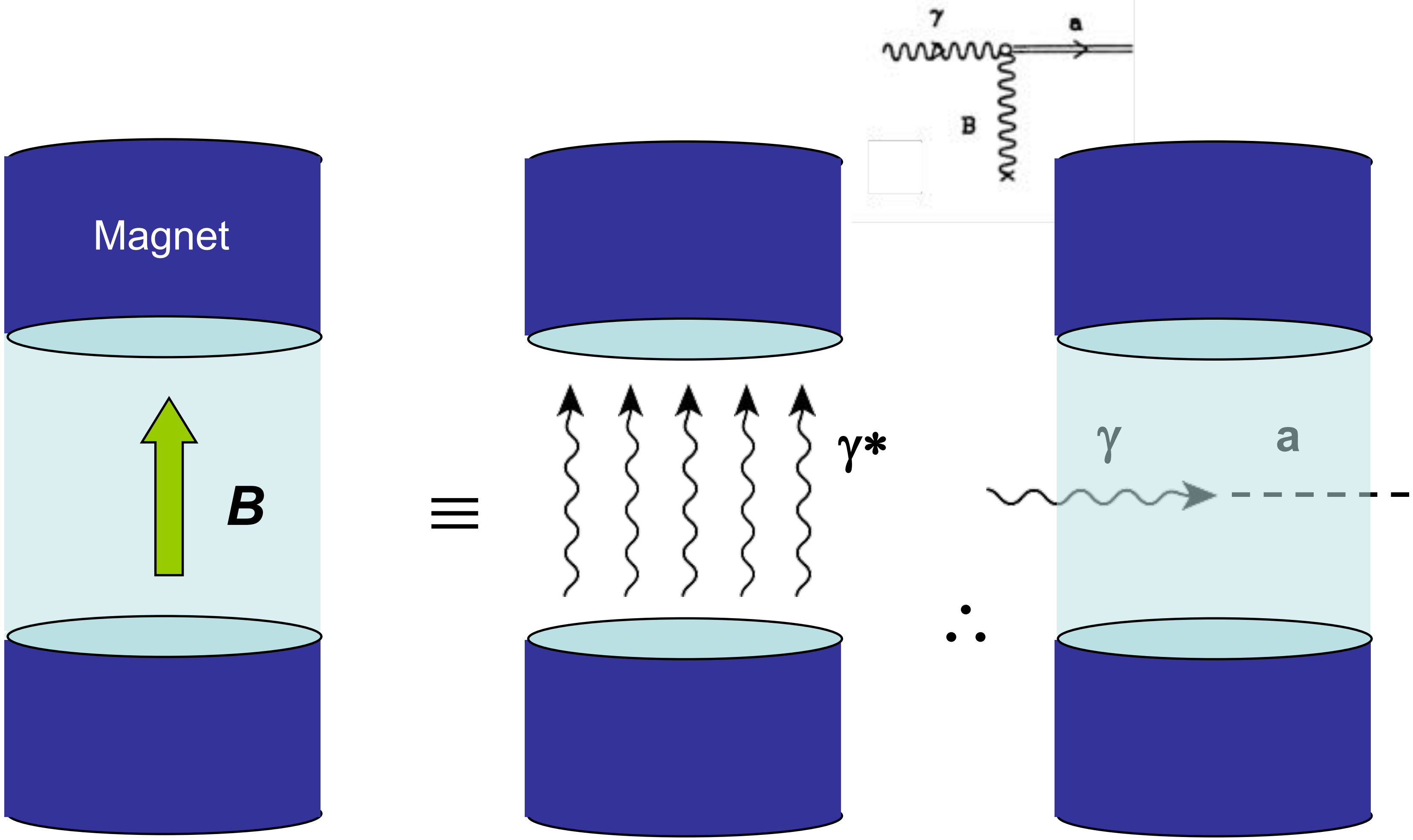
Why is this hard? Why not just look for an unidentified radio line at which $E_\gamma = m_a / 2$?



(from anybody's halo, including our own)

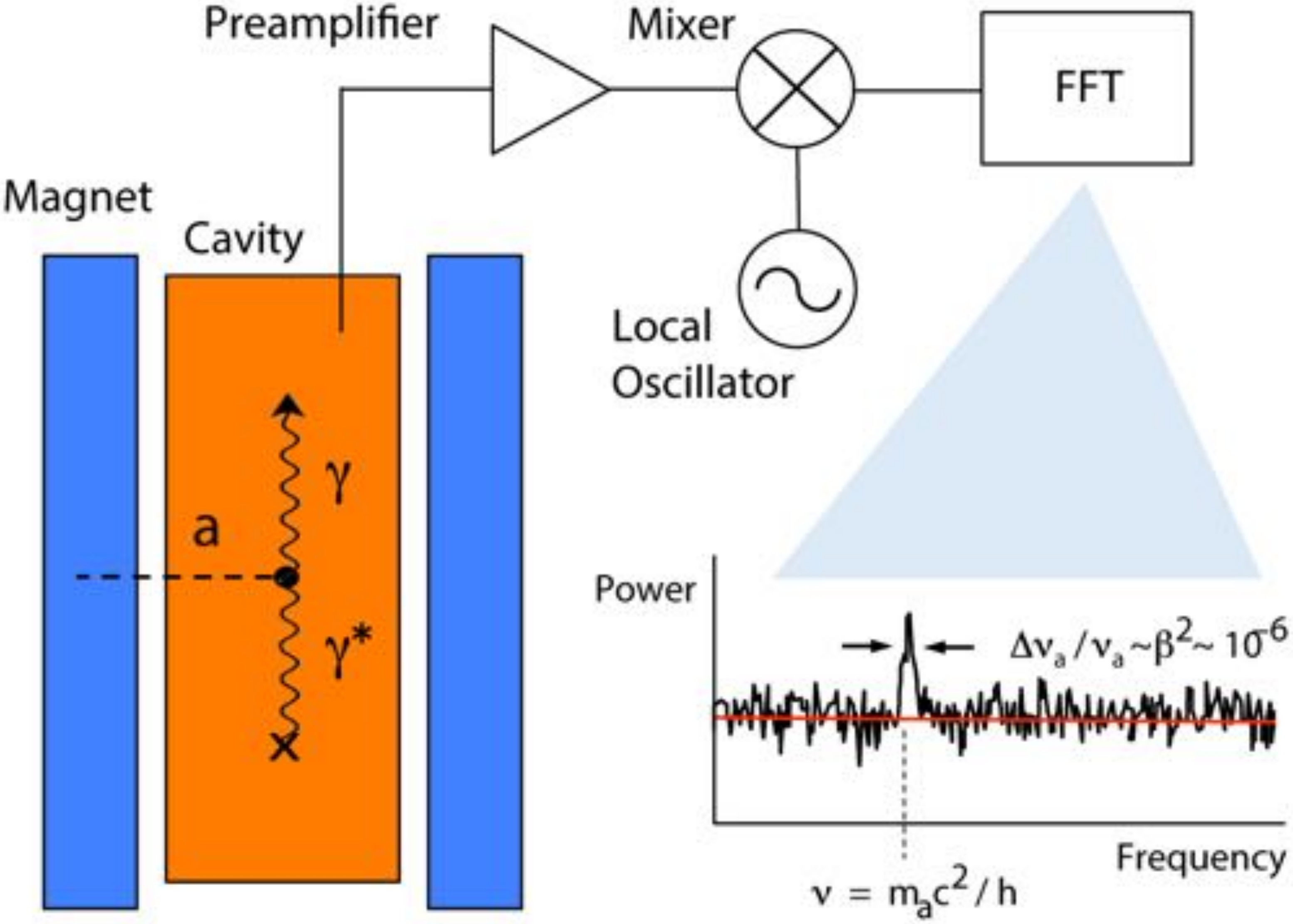
The difficulty is that the spontaneous decay lifetime $\sim 10^{60}$ sec for $m_a \sim$ μeV

The Primakoff Effect

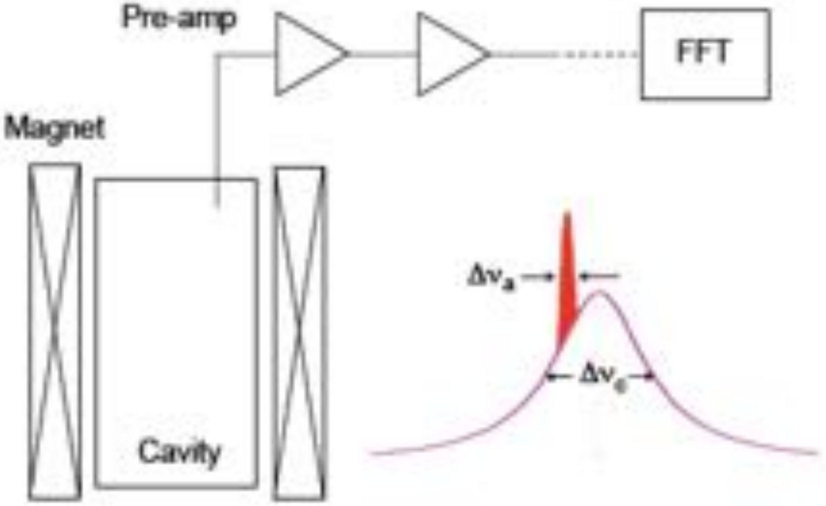


Classical EM field *Sea of virtual photons* *Primakoff Effect*

The microwave cavity axion search – Your car radio on steroids



Axion conversion power and signal detection – details



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

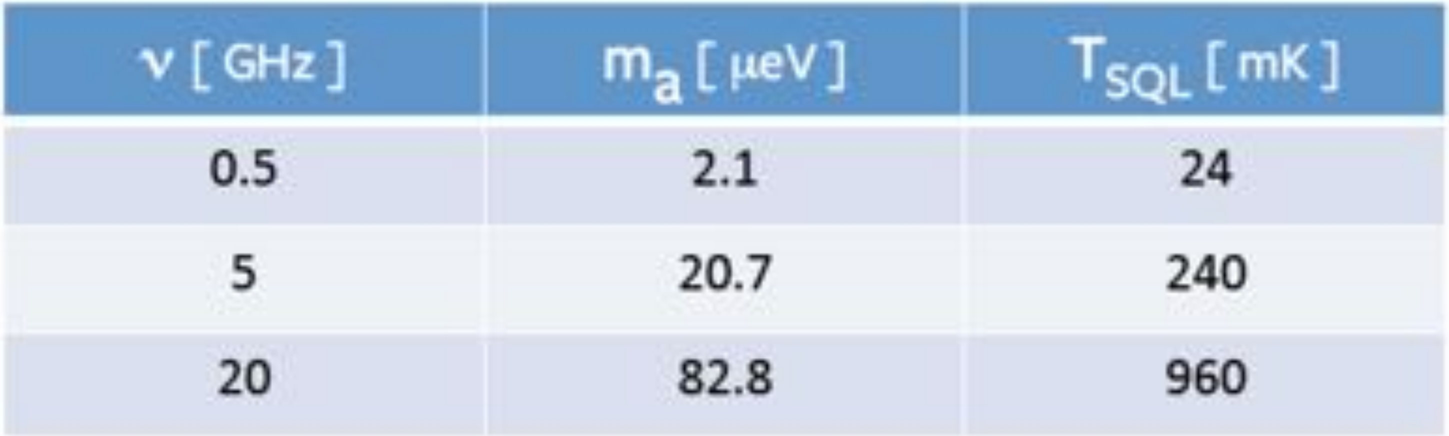
Signal to Noise Ratio: $$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

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 Limit

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

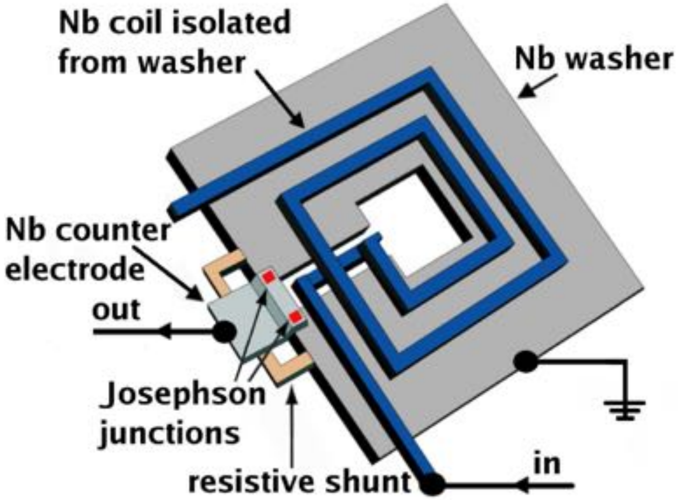


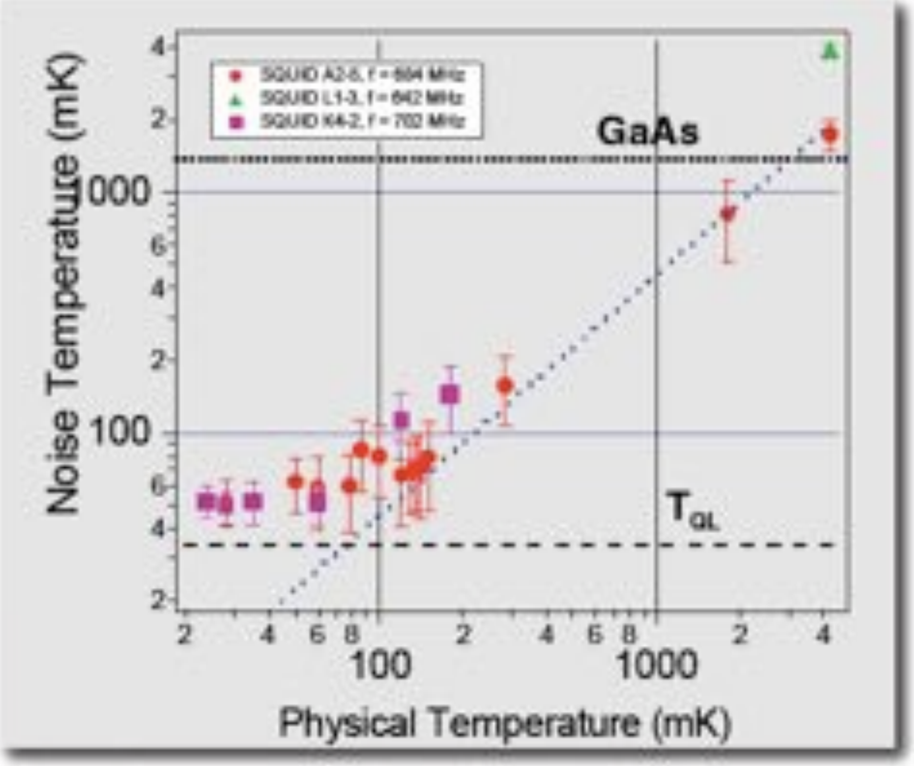
ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

The SQL can be evaded by

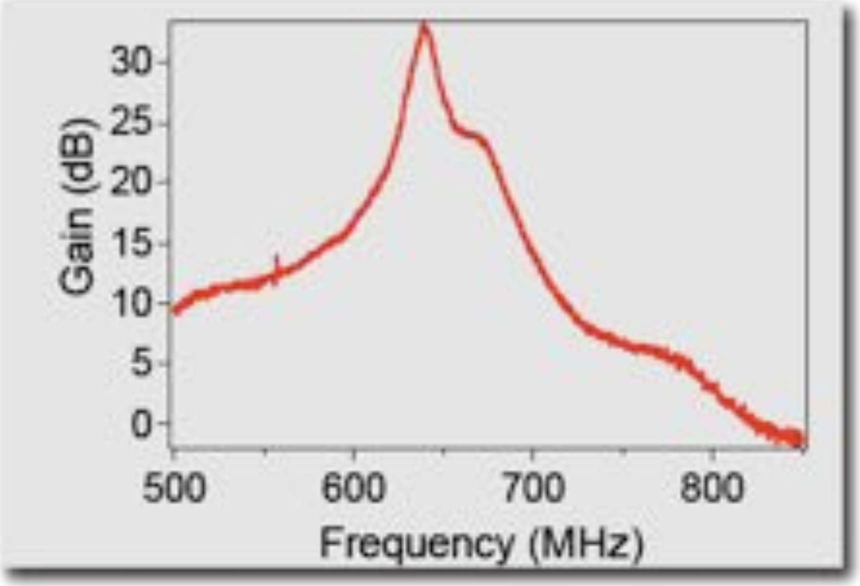
- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)

Microstrip SQUID amplifiers *(John Clarke, UCB Physics)*



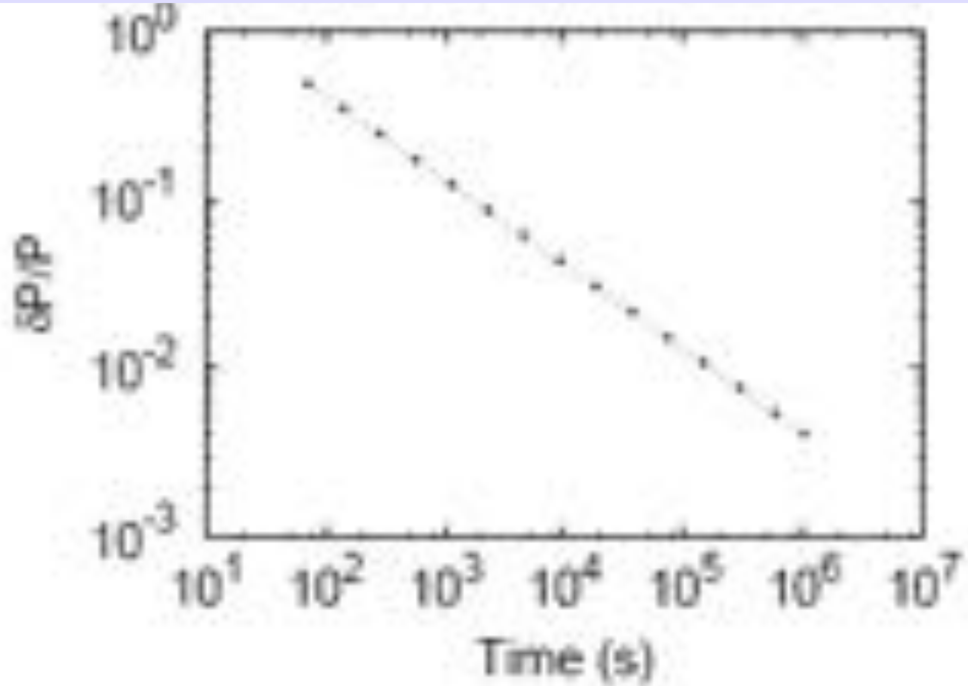


More than an order of magnitude quieter than current GaAs HFET amplifier



But ideally amplifiers can be quieter still & beat the SQL

ADMX is the world's quietest spectral receiver



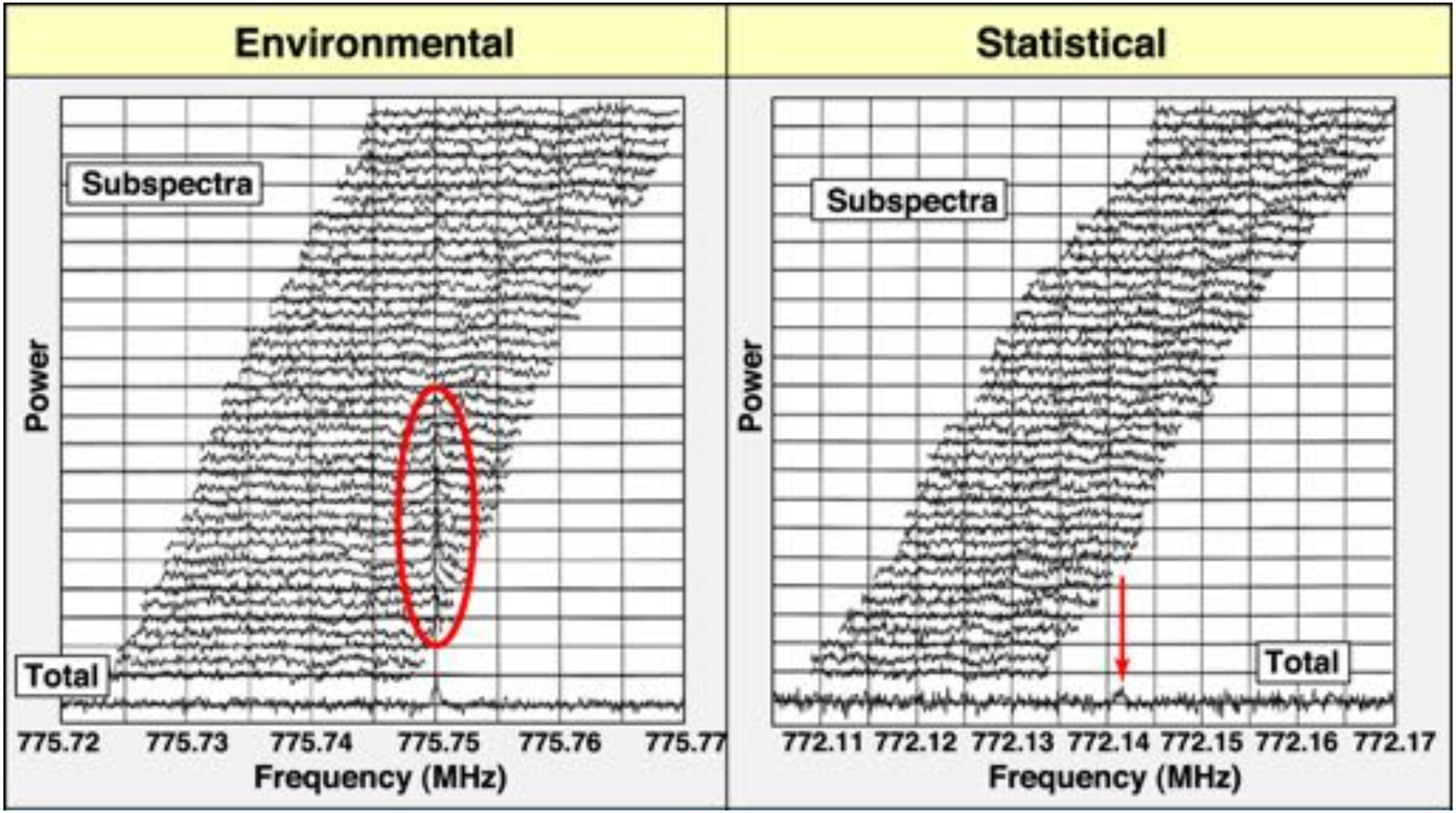
Dicke Radiometer equation:

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

Systematics-limited for signals of 10^{-26} W – 10^{-3} of DFSZ axion power.

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

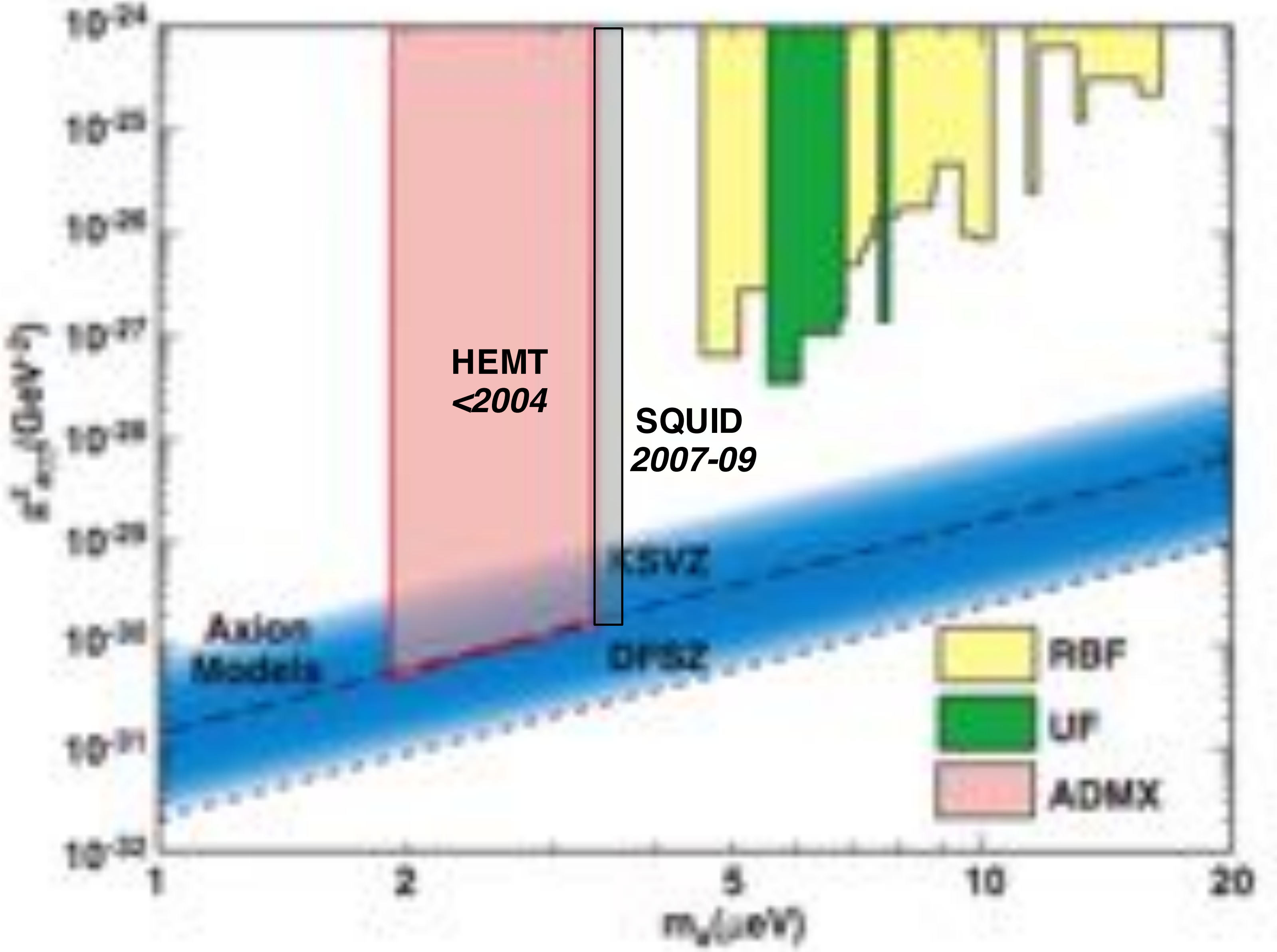
What does the data look like, and candidates?



Signal maximizes in the wings, and furthermore is episodic ⟶ Radio peak

Distributed over many subspectra (good), but didn't repeat ⟶ Statistical peak

Limits on the axion after twenty years



Team ADMX-HF – Extreme Axion Experiment (X3)

Yale University (experiment site)

Steve Lamoreaux, Ling Zhong, Ben Brubaker, Sid Cahn, Kelly Backes

UC Berkeley

Karl van Bibber, Saad Al Kenany, Maria Simanovskaia, Samantha Lewis, Jaben Root, Nicholas Rapidis,

CU Boulder/JILA

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

Lawrence Livermore National Lab

Gianpaolo Carosi, Tim Shokair

NSF

HEISING-SIMONS
FOUNDATION

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

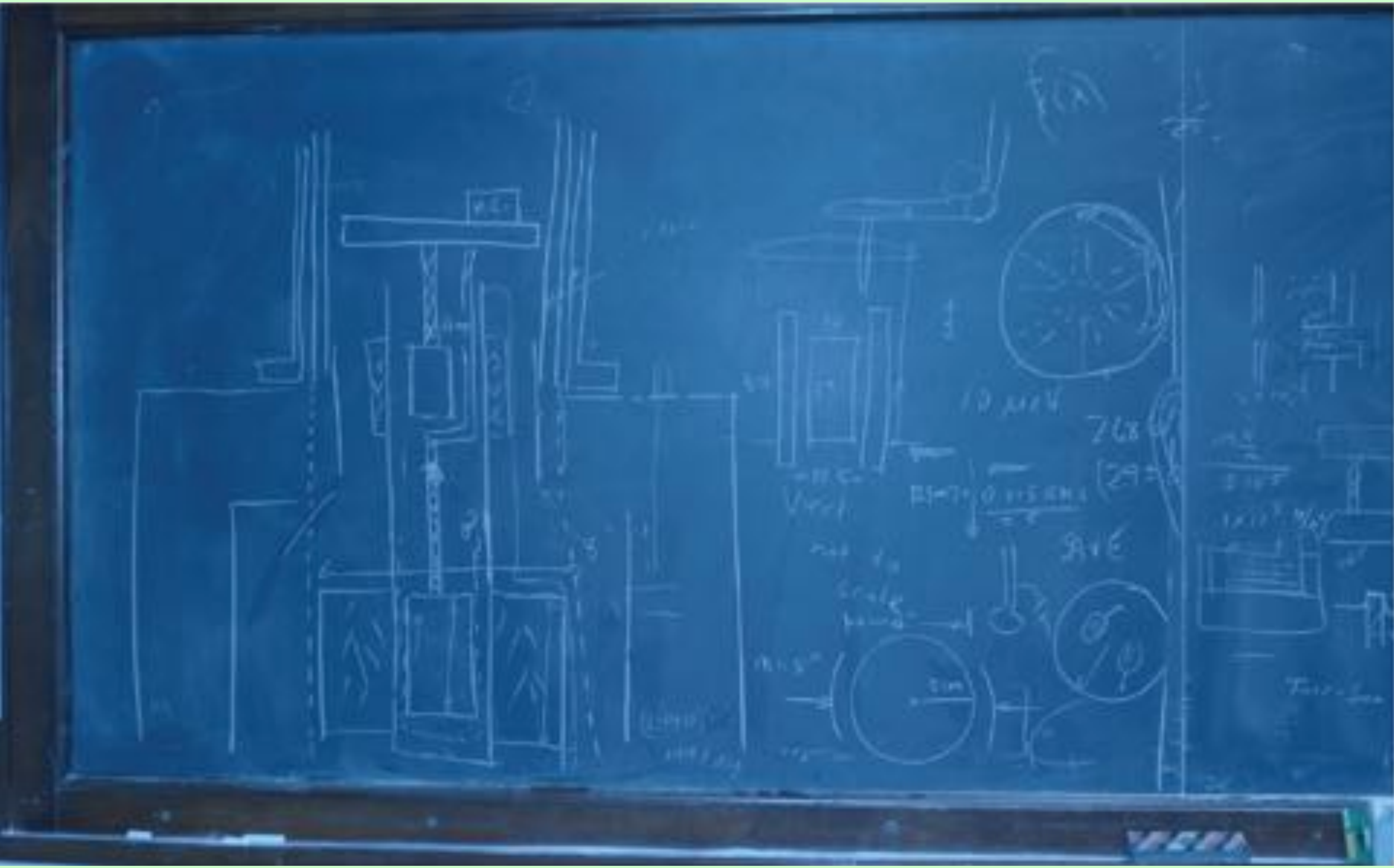
X3 Rationale and Goals

- Both *Innovation Test-bench* and *Data Pathfinder*
- Identify and resolve challenges for 5–25 GHz (20–100 μeV)
- Develop new cavity and amplifier technologies, validate in ops

$$P_{SIG} = \eta\, g_{a\gamma\gamma}^{2} \left(\frac{\rho_a}{m_a}\right) B^{2} Q_C V C_{nml}$$

$$SNR = \frac{P_{SIG}}{k_B T_{SYS}} \sqrt{\frac{t}{\Delta\nu_a}}$$

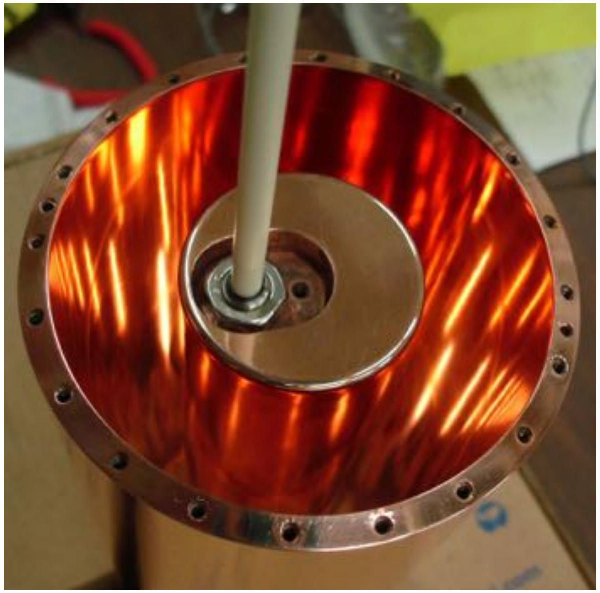
Our original “Technical Design Report”

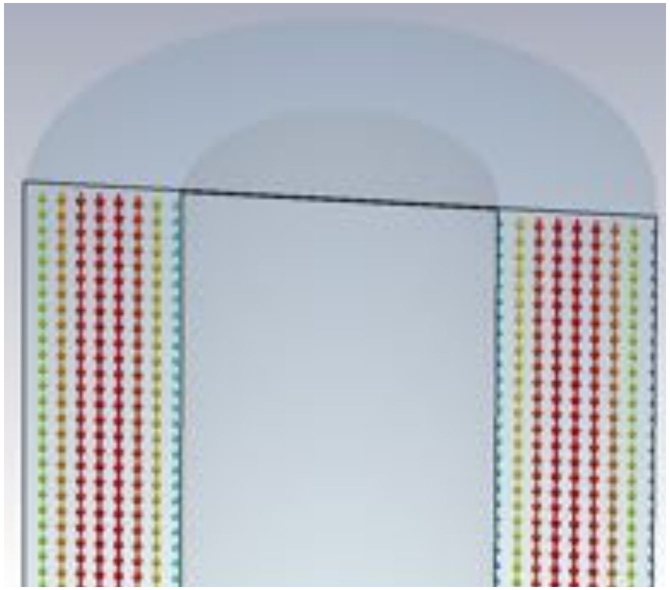


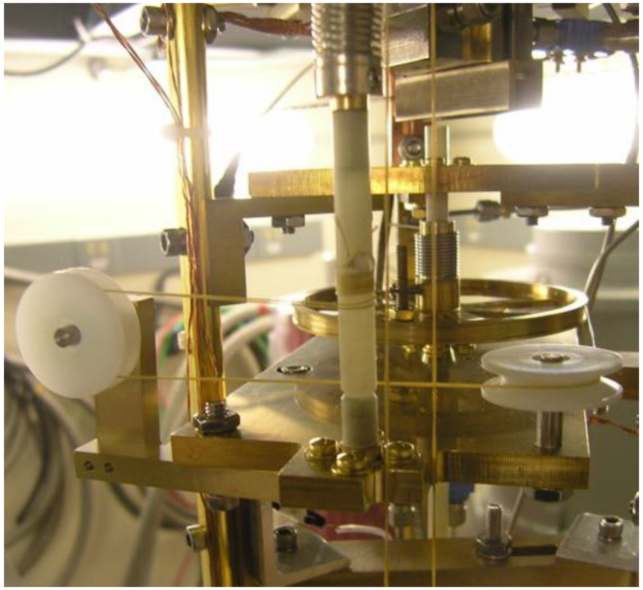
And that’s about how it looks now …

Microwave Cavity

- Cu body with off-axis tuning rod
- Tunable over 3.6 – 5.8 GHz
- $Q_C \sim 20{,}000$
- Stepping motors and Kevlar lines used for motion

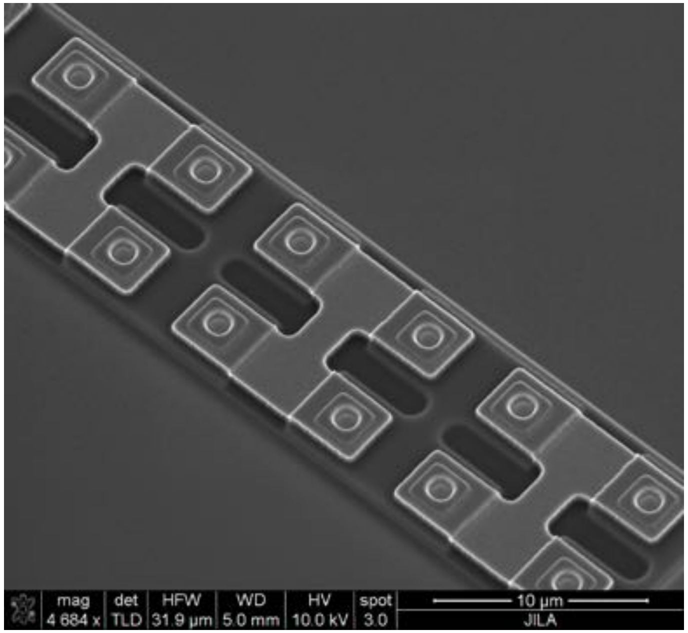


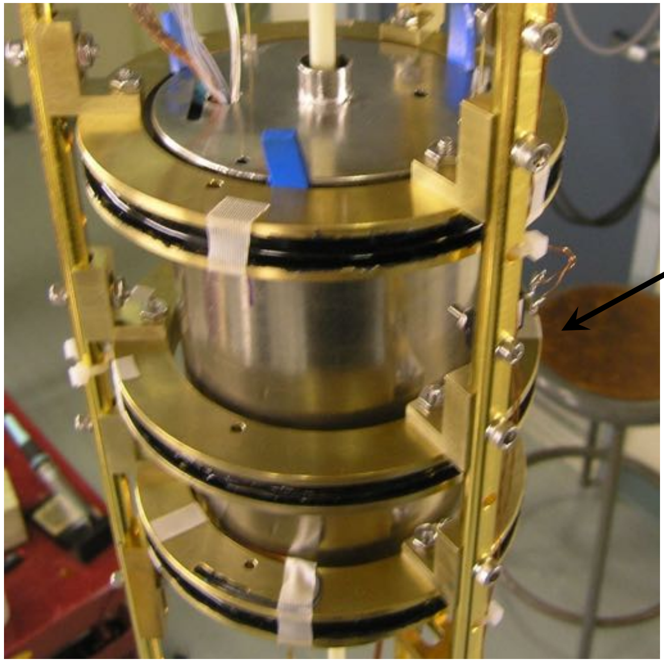




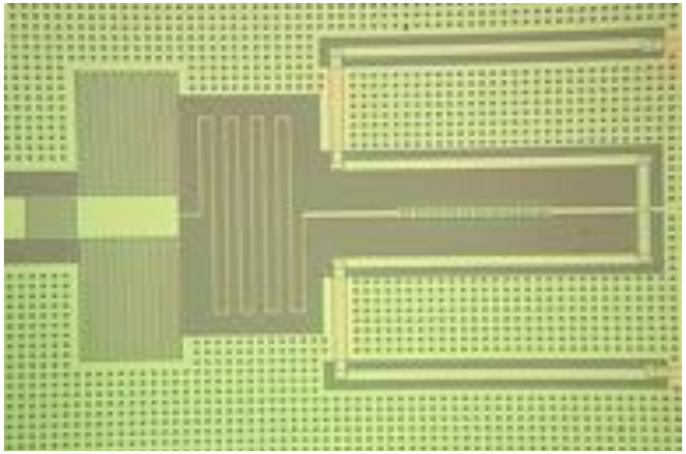
Josephson Parametric Amplifiers

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

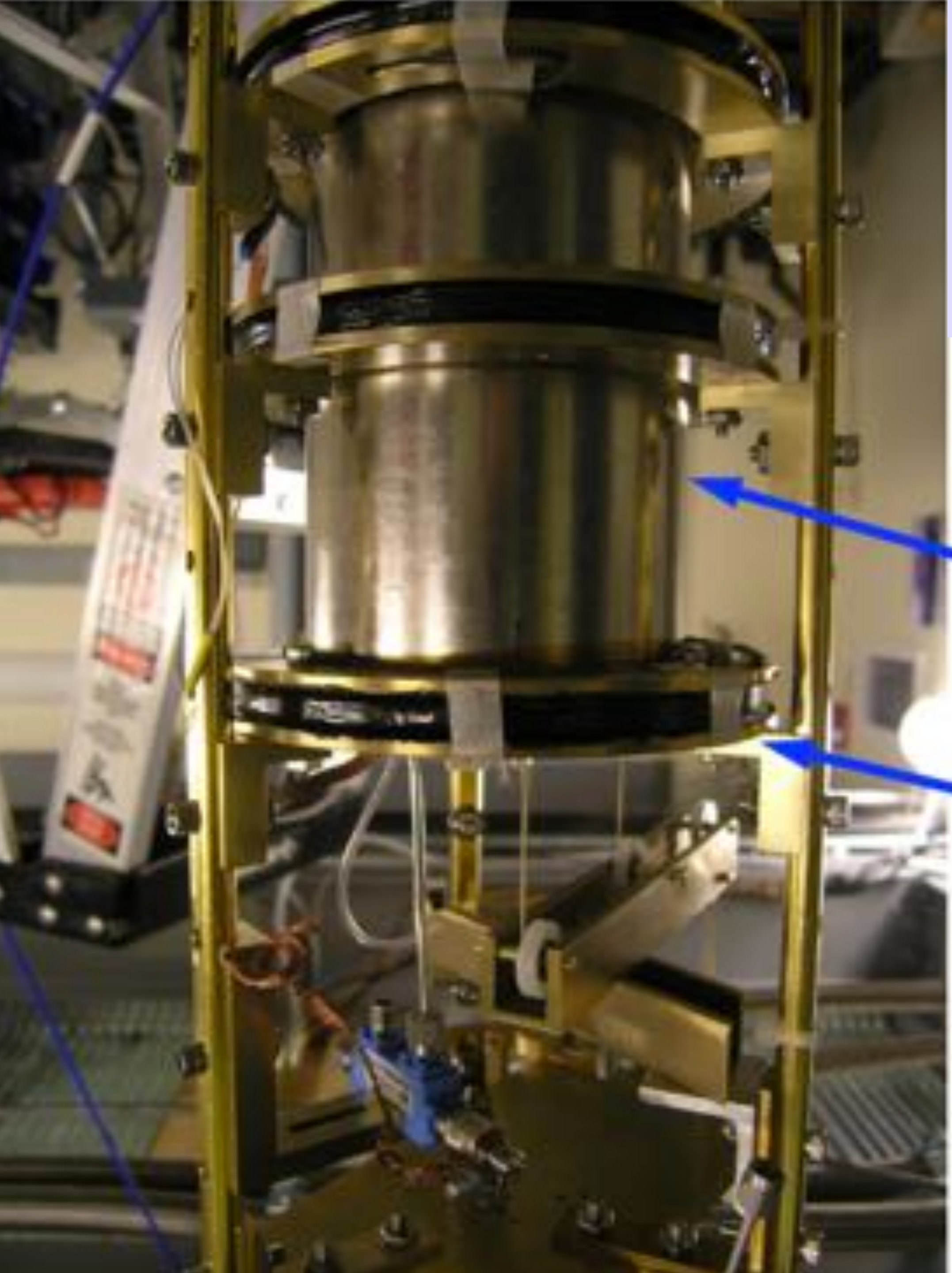




Persistent coils for field cancellation



JPAs require a magnetic Field-free environment

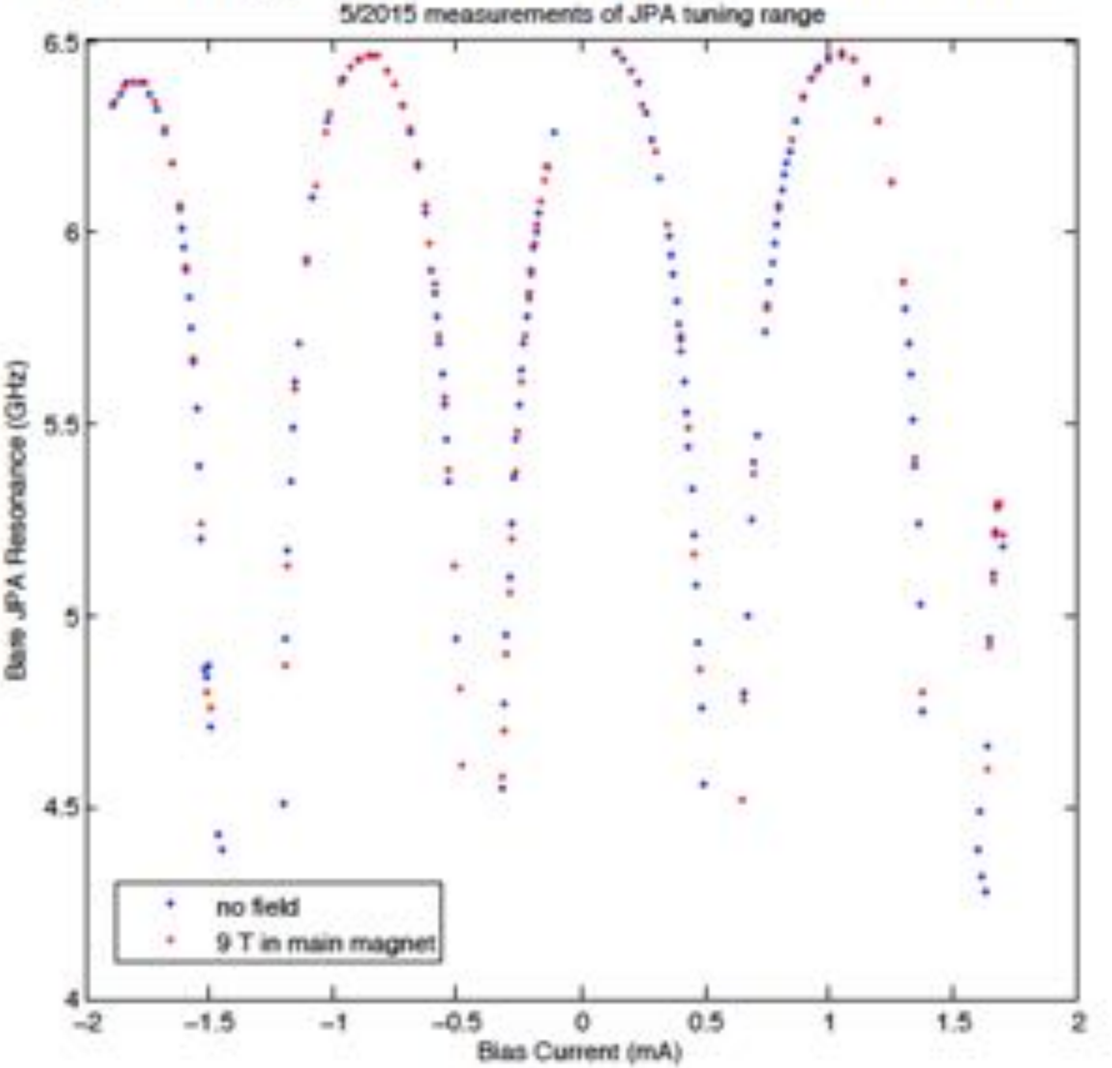


Double-wall cryoperm with superconducting lead foil inside

Persistent coils (4) to eliminate gradients of remnant field

The JPA cannister is surrounded by a magnetic compensation coil, part of the main magnet to take out most of the fringe field

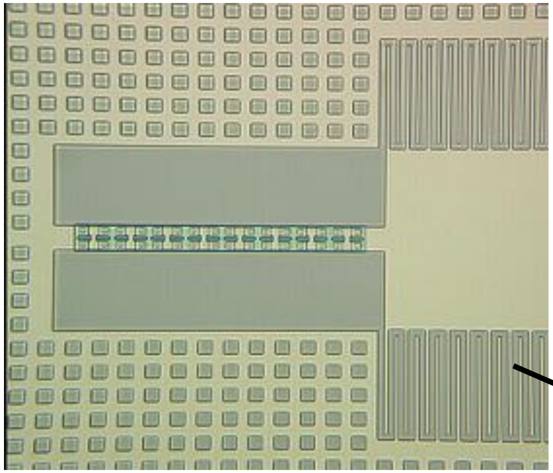
Efficacy of the magnetic shielding system for the JPAs



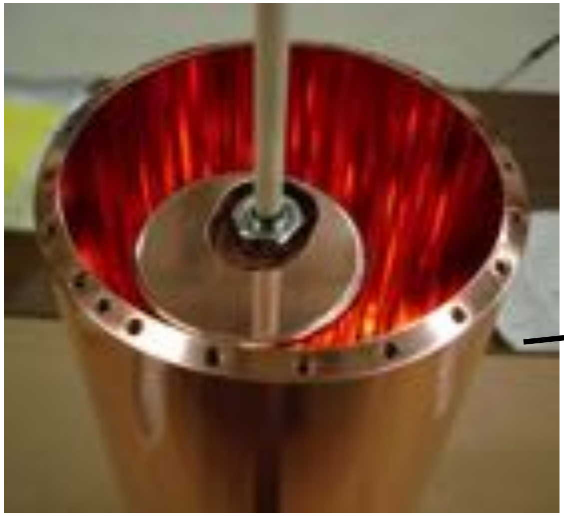
By looking at the shift of the JPA frequency curve between B = 0 T and B = 9 T (see interleaved points), we conclude that the field at the JPA changes < 0.01 flux quantum as the magnet is ramped. Thus the magnetic shielding is working very well.

Integration of the Experiment at Yale (I)

Josephson Parametric Amplifier



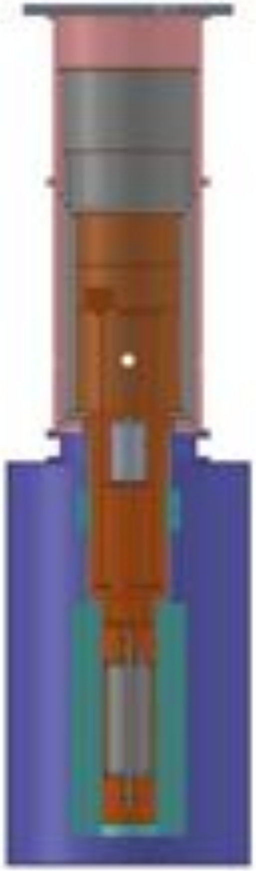
Microwave Cavity (copper)



^{3}He/^{4}He Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet

ADMX-HF design : small, highly capable, flexible



CMI Inc.,
Cryogen-free magnet
NbTi 9 T

- Experiment located at Yale
- 9 T magnet (17.5 cm × 40 cm)
- Copper microwave cavities (initially)
- VeriCold Dilution Refrigerator (25 mK)
- Josephson Parametric Ampifiers (JPA)
- R&D on cavities at UC Berkeley & LLNL
- R&D on amplifiers at JILA/Colorado

Integration (II) and Infrastructure Details

Superconducting magnet

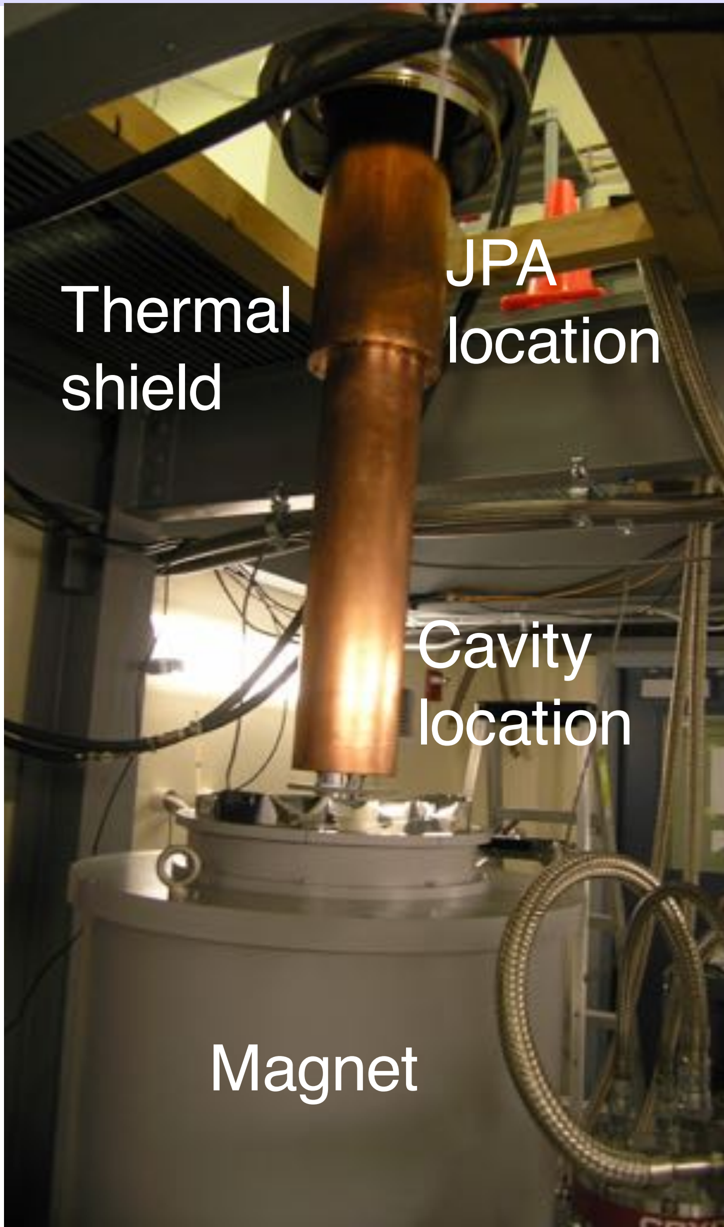
- Made by Cryomagnetics, Inc.
- Maximum field of 9.4 T
- Large bore
- Dry system

Dilution refrigerator

- 25 mK base temperature
- Experiment operates at 100 mK to stabilize the JPA
- Thermal shield contains gantry, JPA, and cavity

Data analysis

- Two analysis sites: Yale and Berkeley



AMAZING TEST BY MICKEY MANTLE PROVES TIMEX WATCHES ARE REALLY RUGGED...

Unusual Verified* Shock Test Proves Timex Can Take A Licking Yet Keep On Ticking

V-CONIC MOVEMENT

WATERPROOF*

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ONE YEAR GUARANTEE

US TIME

TIMEX

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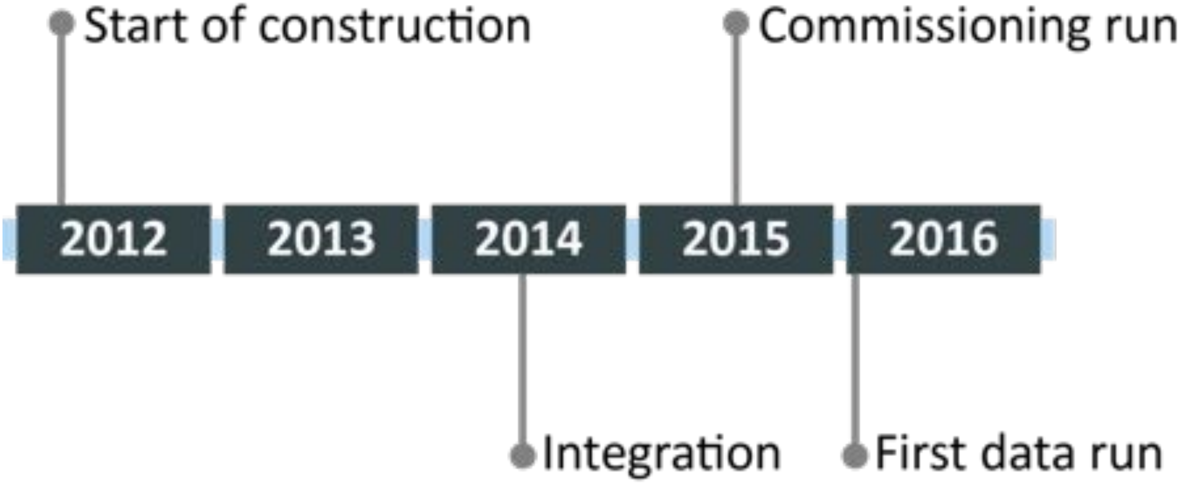
"It takes a licking, and keeps on ticking!"

John Cameron Swazey,
Timex commercials,
1950's & 60's

Snowstorm knocked out Yale's central power station

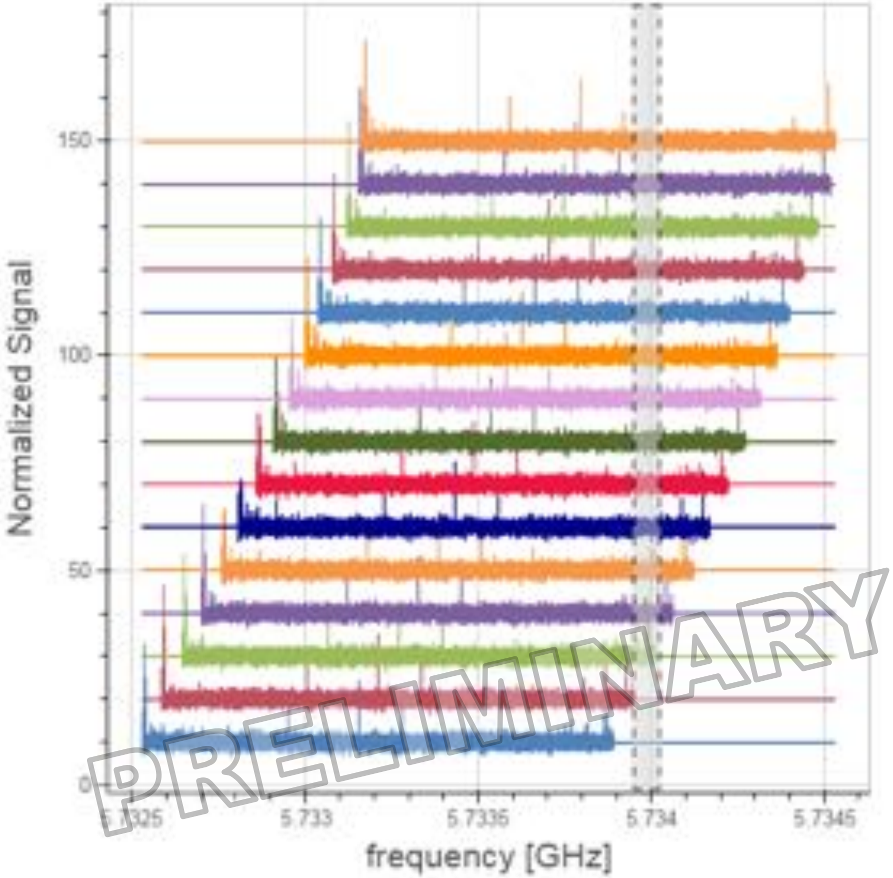
- Experienced a magnet quench in early March
- Surprisingly little damage
- Repairs complete, experiment back in operation mid-May

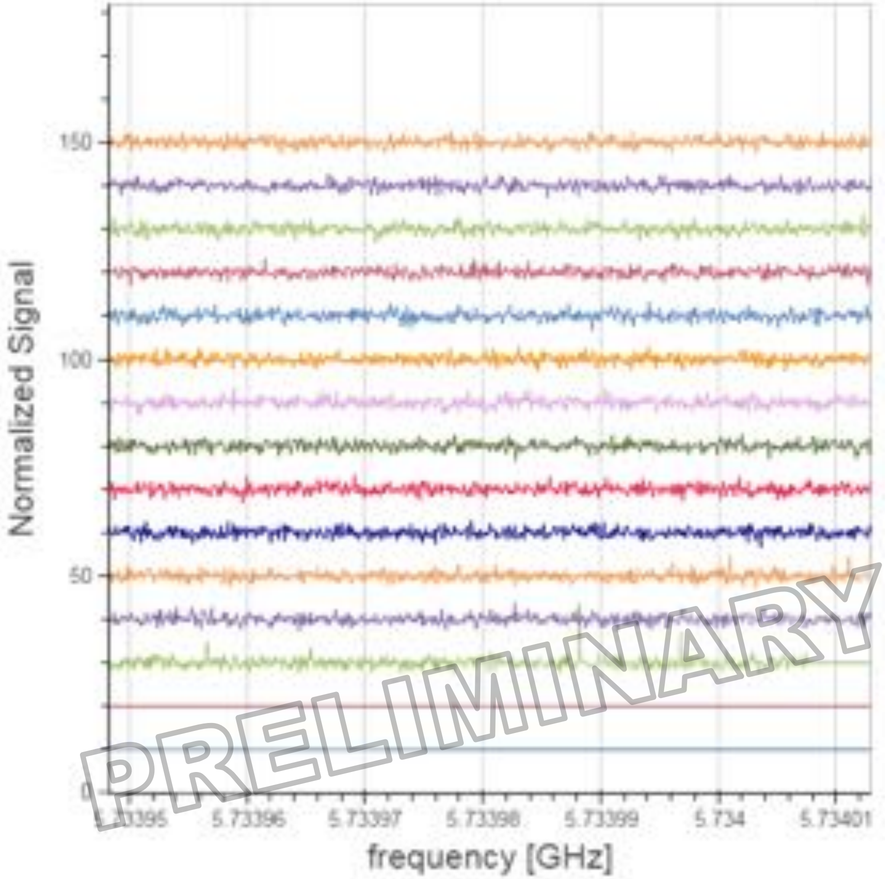
Project timeline & first data run



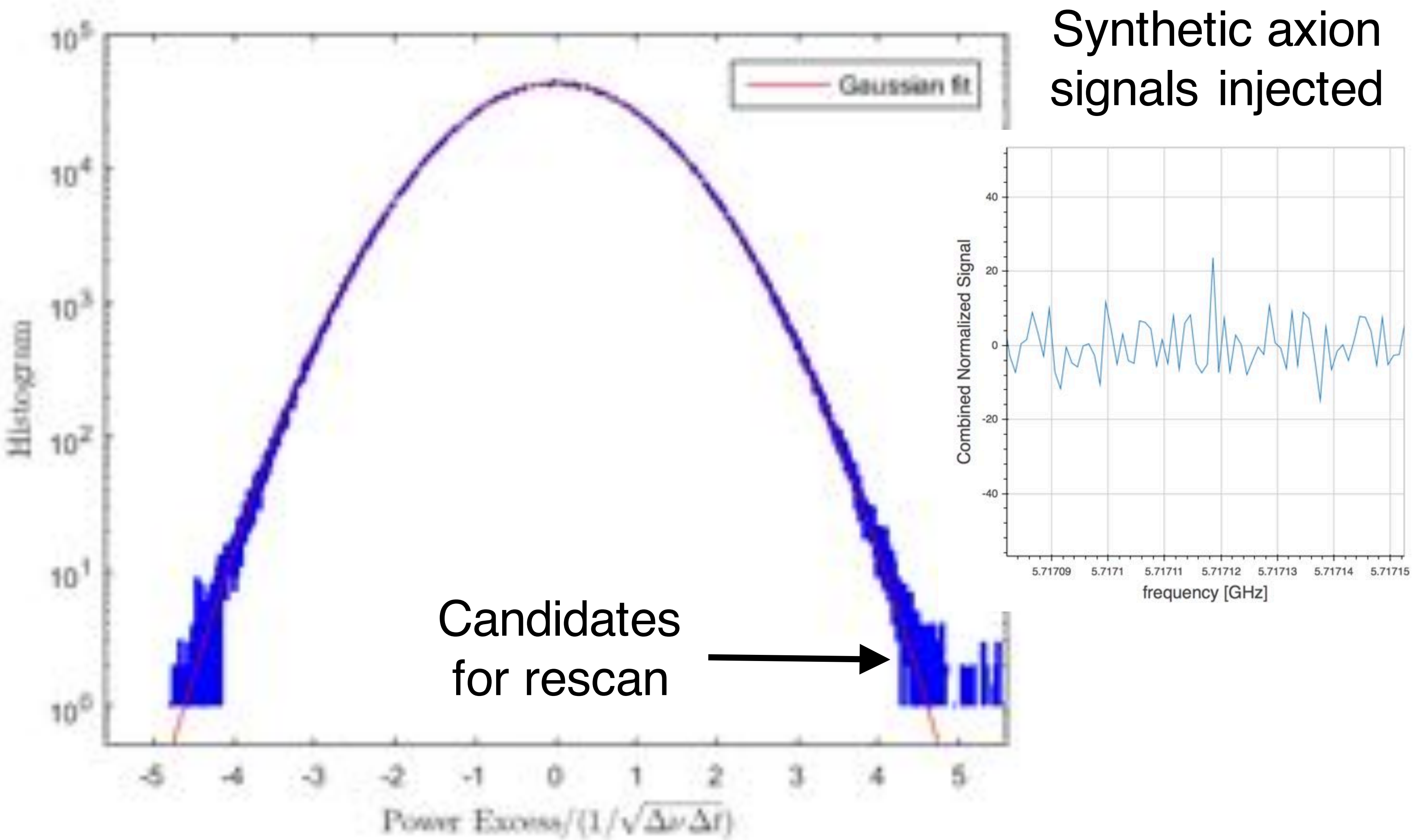
- First run in $f \sim$ 6 GHz range (Jan – July 2016)
- $T_{SYS} \sim 1100$ mK ($\sim 3.5\, T_{SQL}$; “hot rod” problem)
- Reach $g_{a\gamma\gamma} \sim 2.5$ KSVZ, ~ 2 KSVZ with new thermal link
- The first data run should conclude by the end of July

Preliminary Data





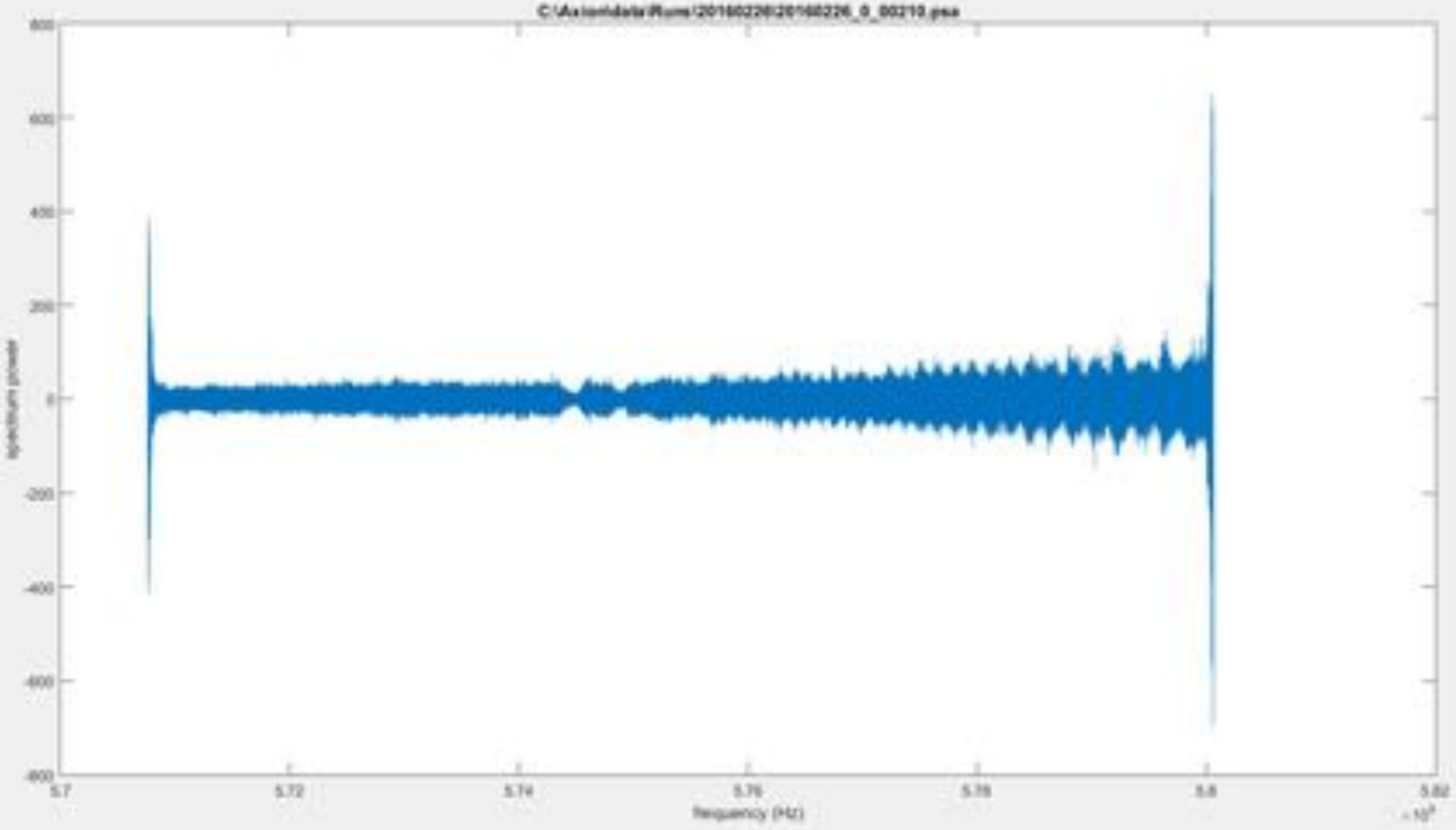
Data quality appears very good



Synthetic axion signals injected

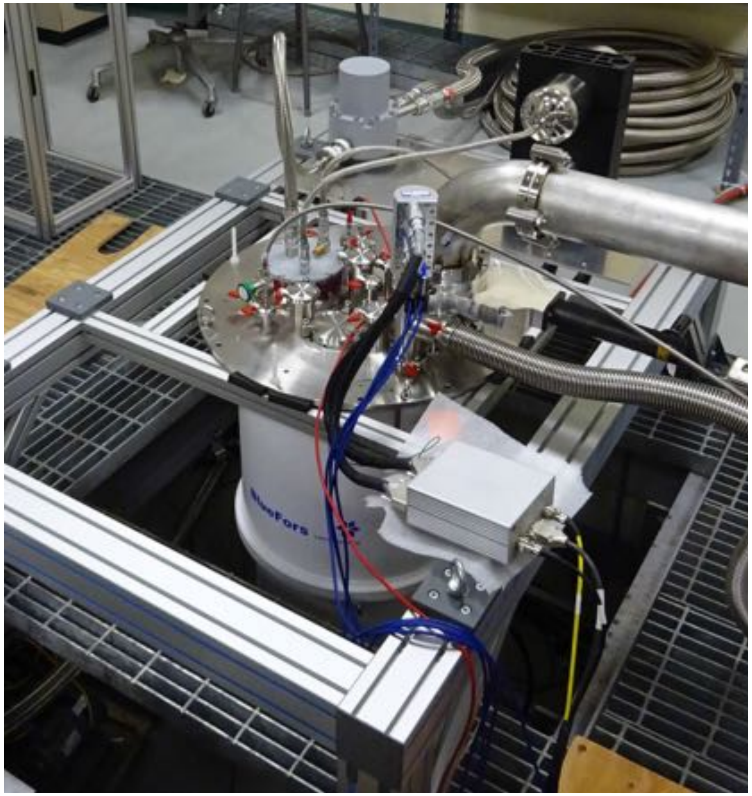
Candidates for rescan

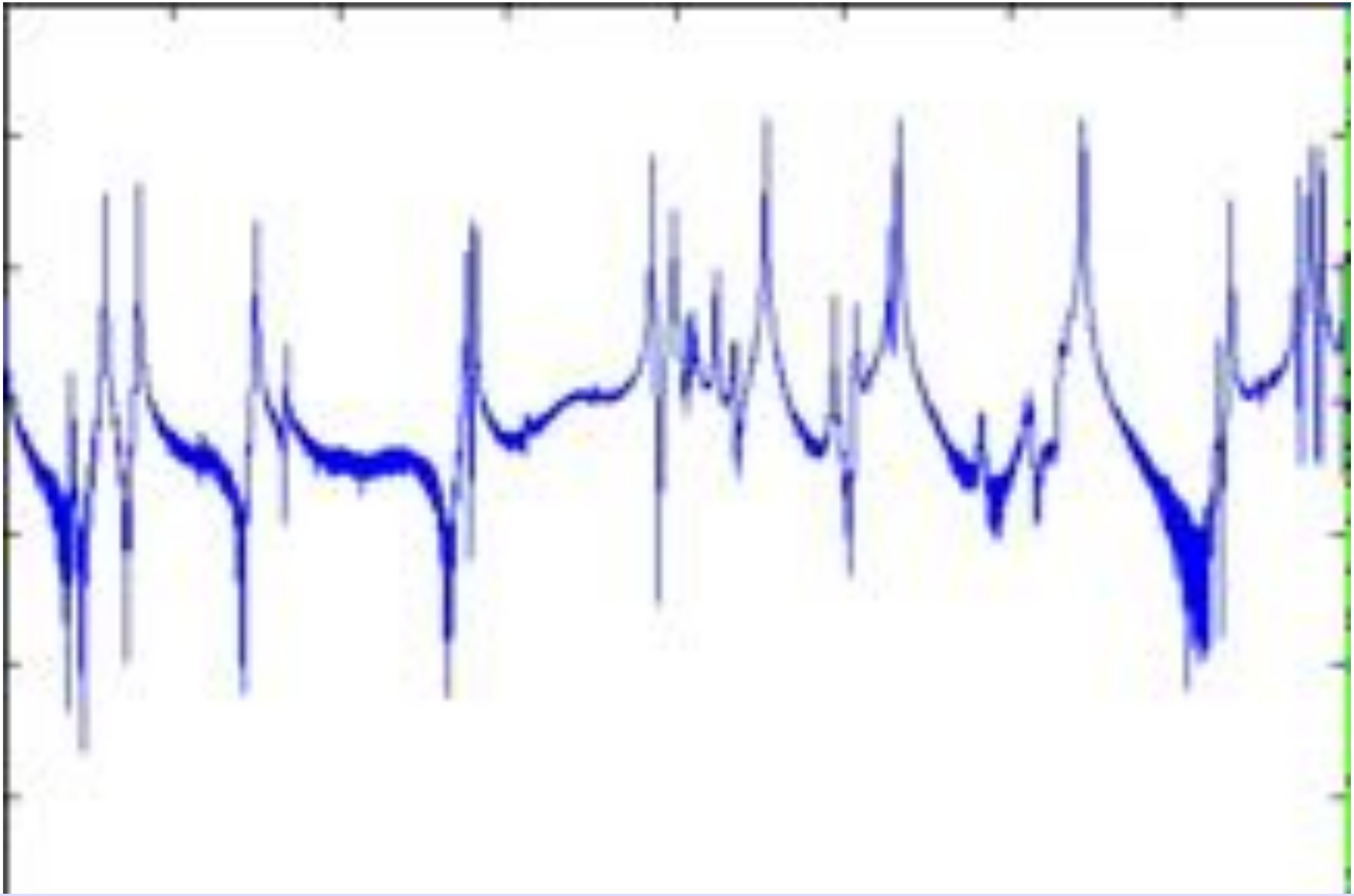
SNR increasing with coaddition of subspectra



The near-term program

- Higher frequency run with “hot rod” mitigation (early fall 2016)
- Swap in Blue Fors fridge
- Deploy, run squeezed-vacuum state receiver (early 2017)
  - Will take significant rework of exp’t
  - To reduce $T_{SYS} < T_{SQL}$
  - To our knowledge, only LIGO/GEO have employed squeezed-states in an actual operating experiment
- Microwave cavity enhancements (mid-2017)

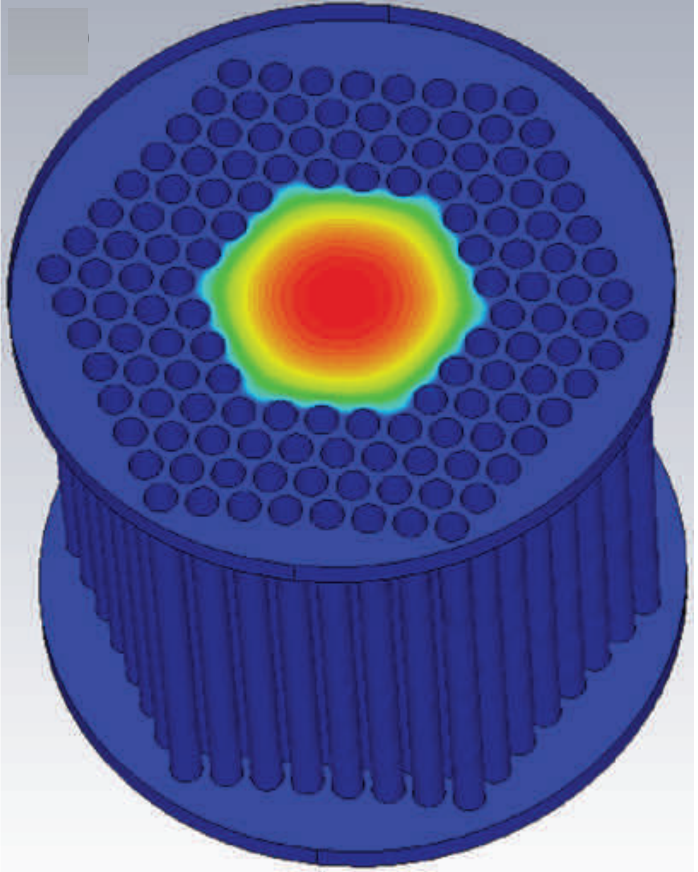


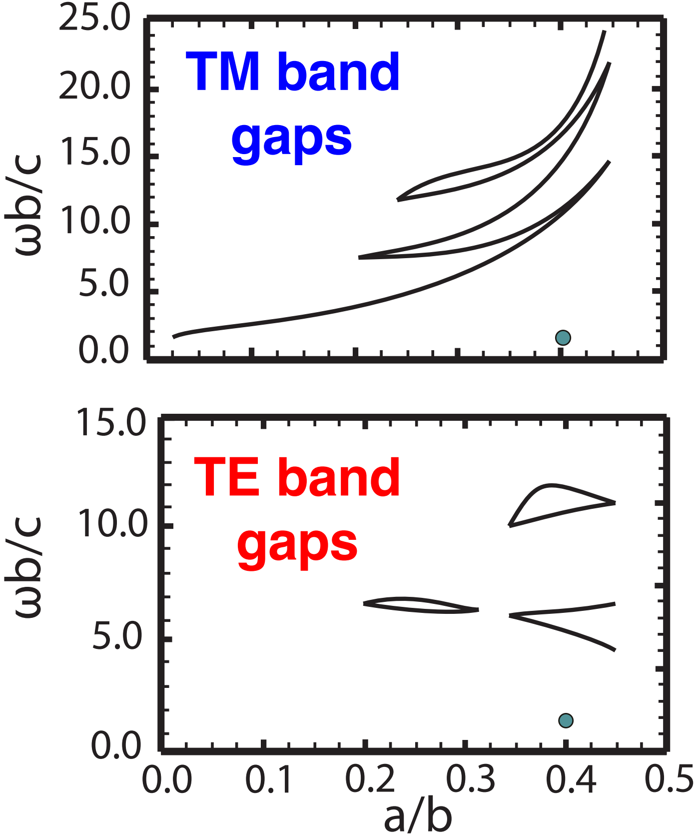


The Scourge of Mode Crossings

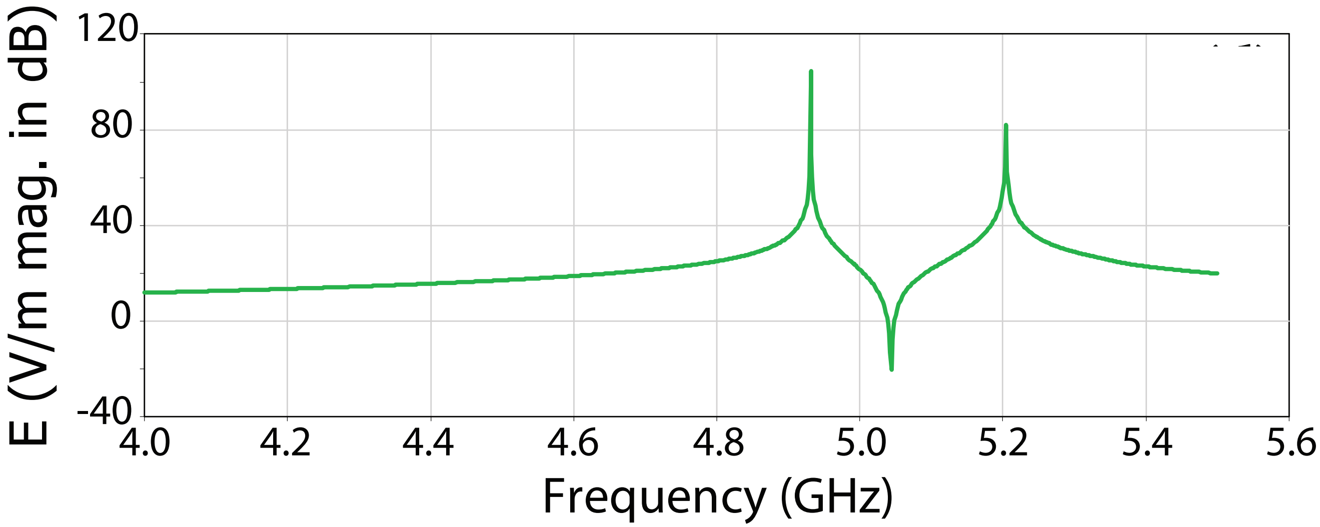
Photonic Band Gap Resonators

(Samantha Lewis)





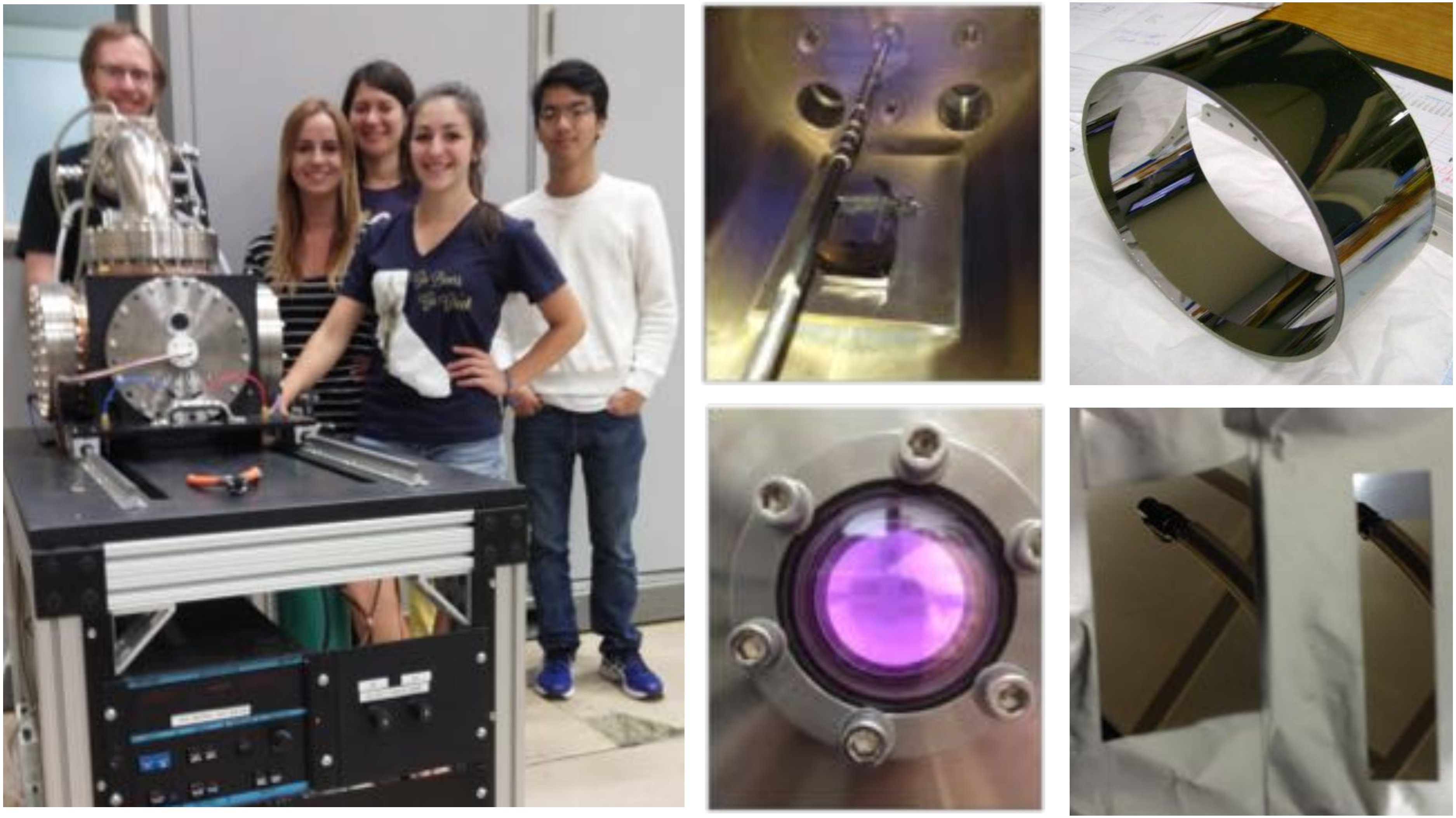
Open structure designed to trap TM modes, but allow TE modes to radiate away



Cleanses the spectrum of the forest of mode crossings, and thus dramatically accelerates the scan rate of the experiment

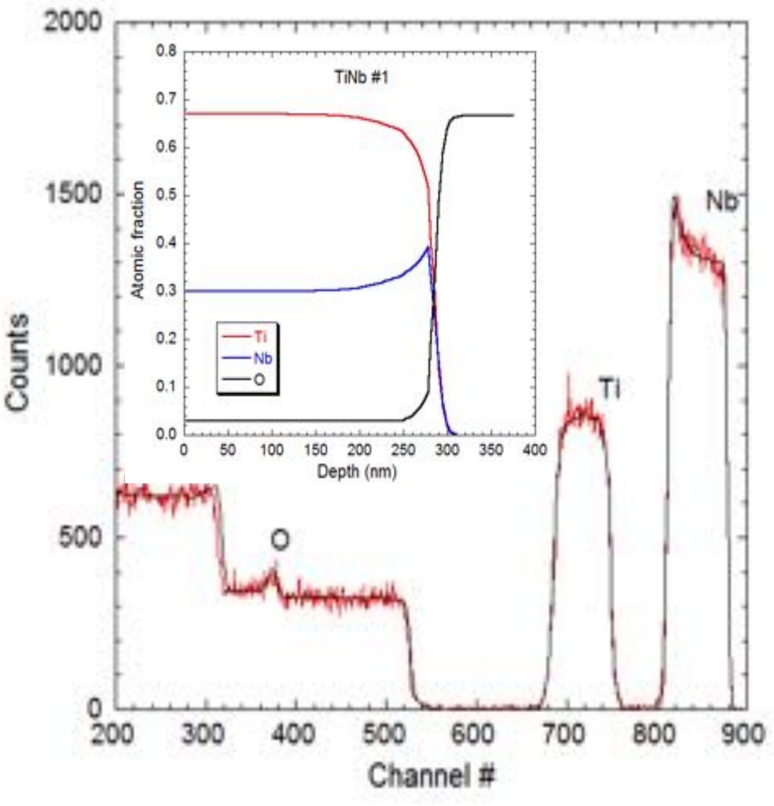
Thin-film Type-II superconducting cavities to improve Q

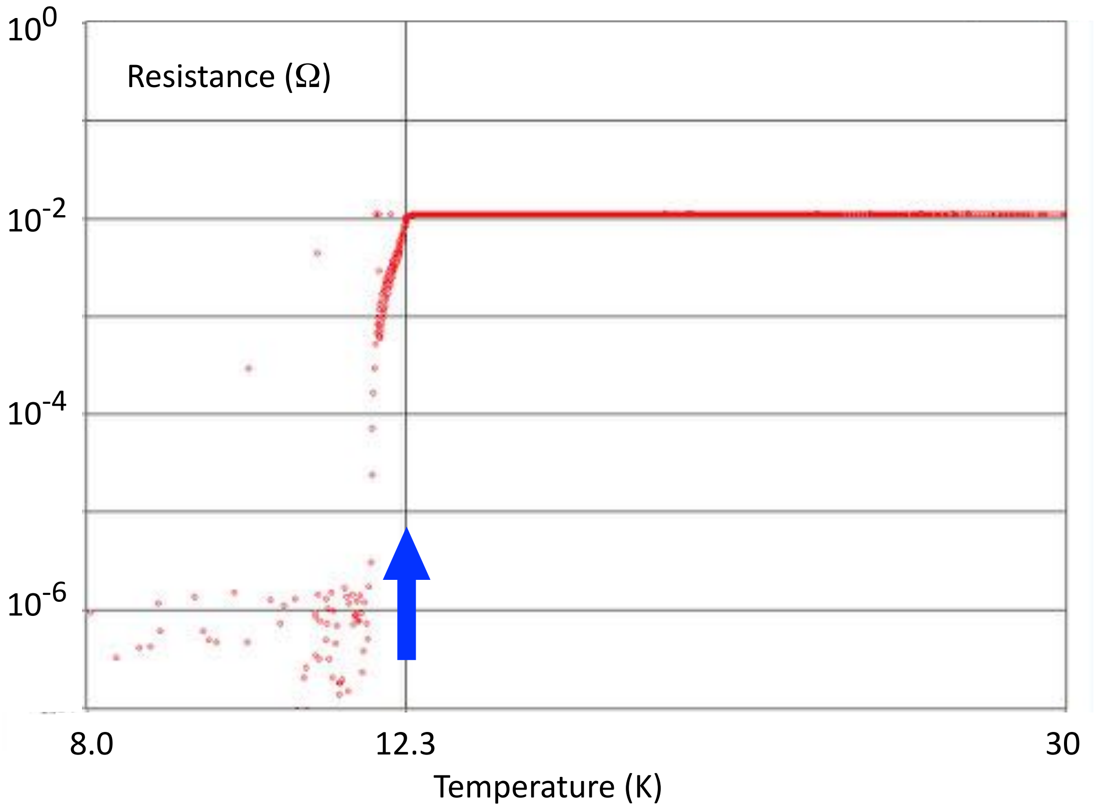
(Maria Simanovskaia)



Thin NbTiN films have been successfully made

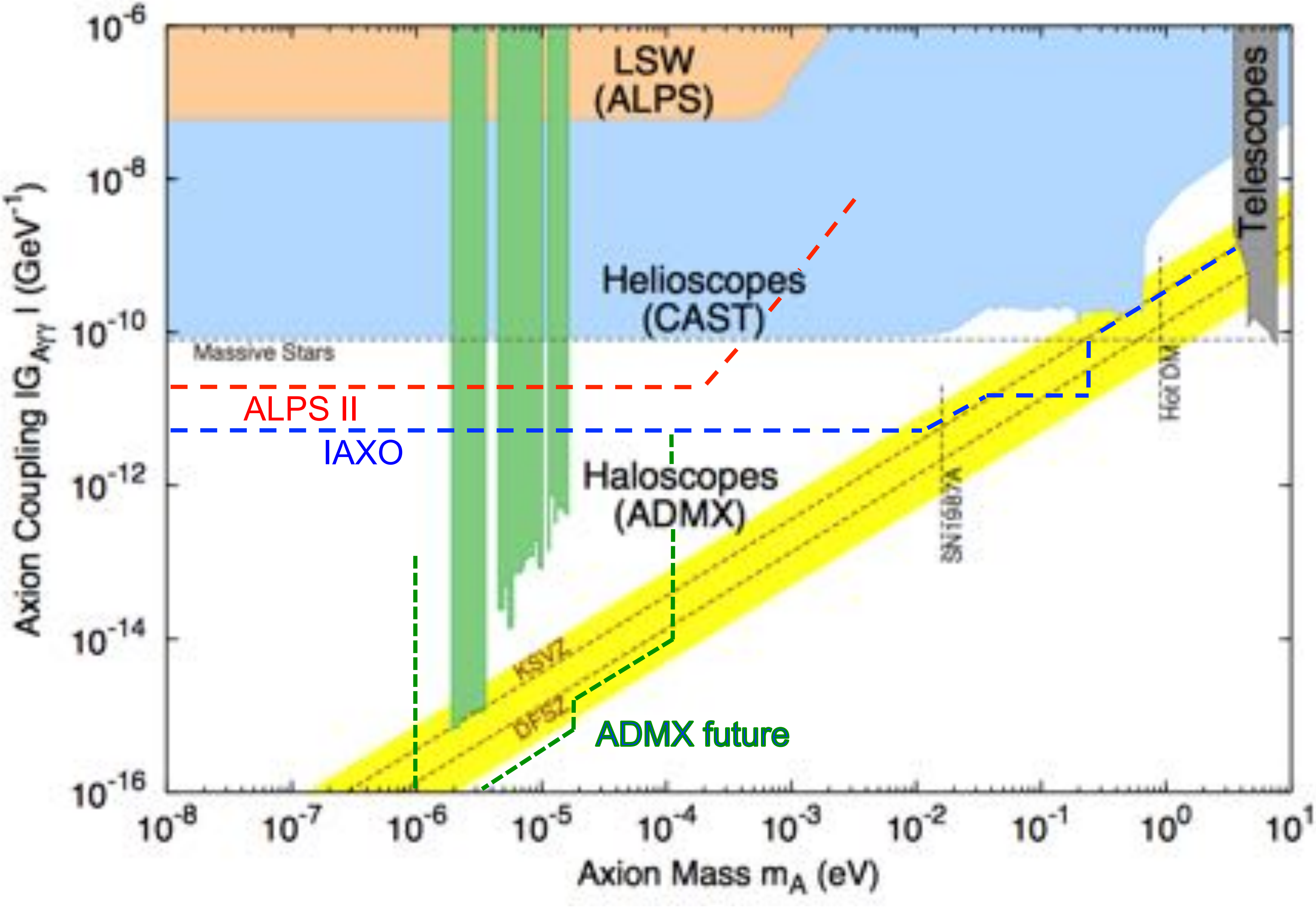
$Nb_{0.30}Ti_{0.67}O_{0.03}$: 280 nm



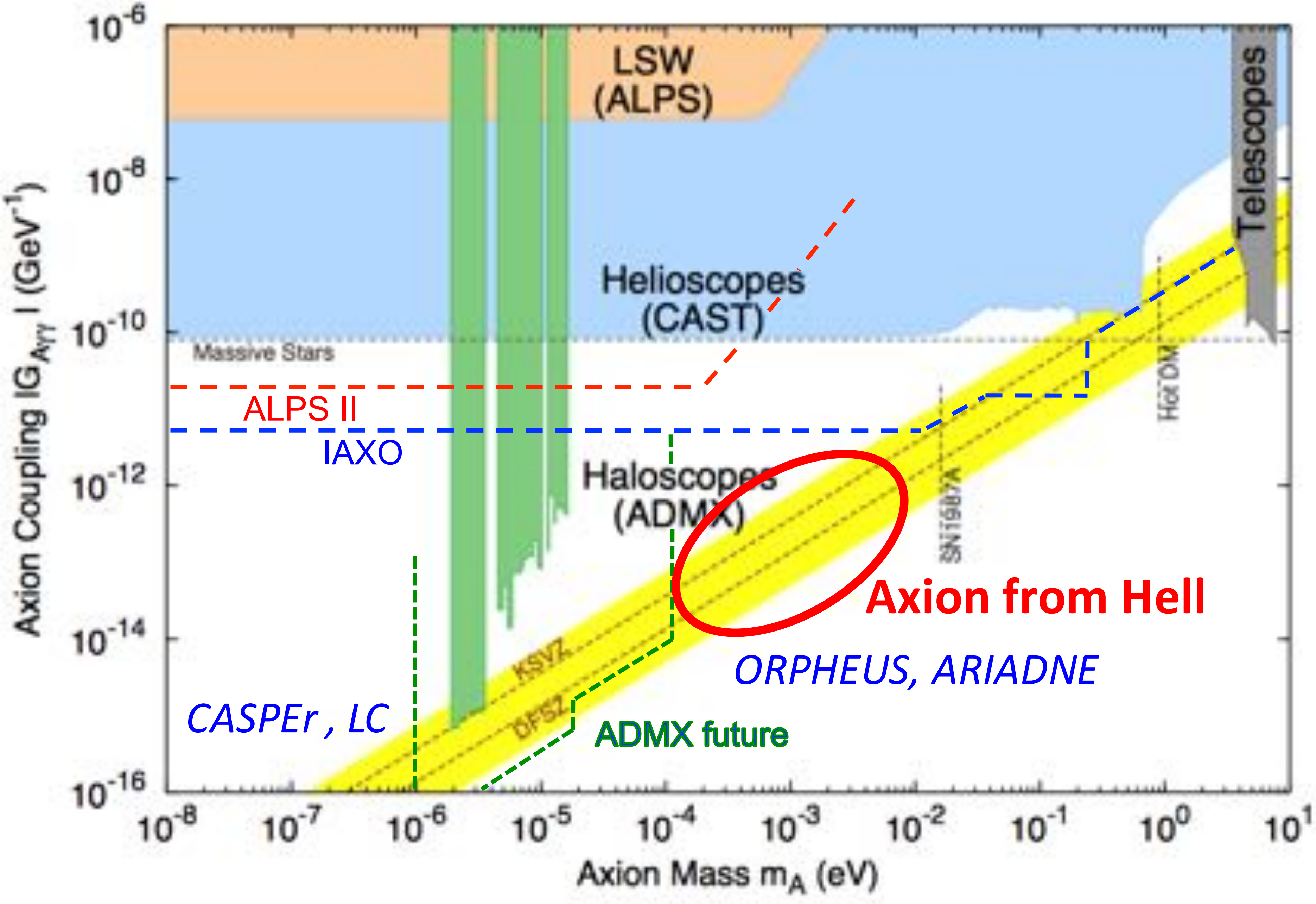


We are also pursuing Dielectric Bragg Resonators to improve Q

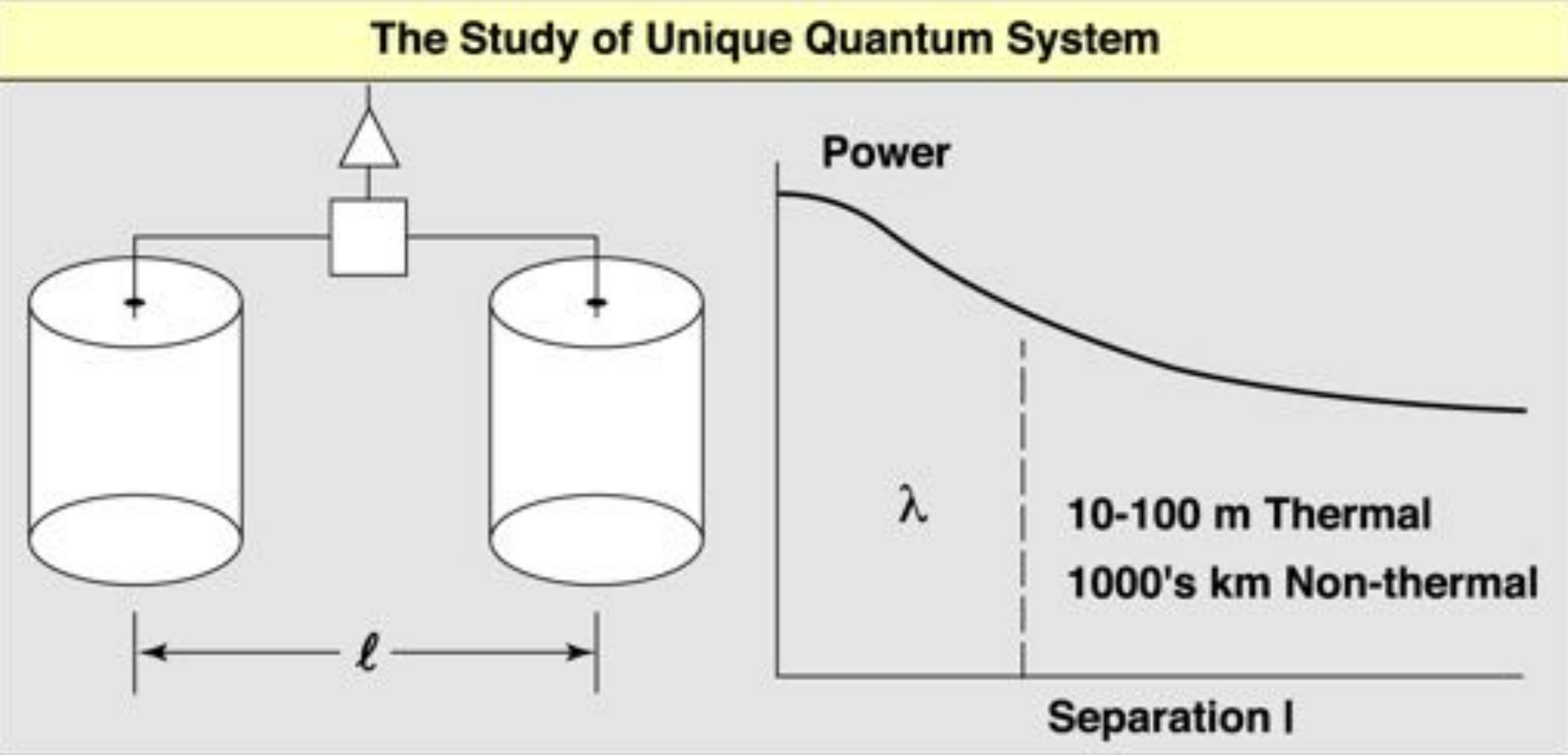
Excluded $g_{A\gamma\gamma}$ vs. m_A with all experimental & observational constraints



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

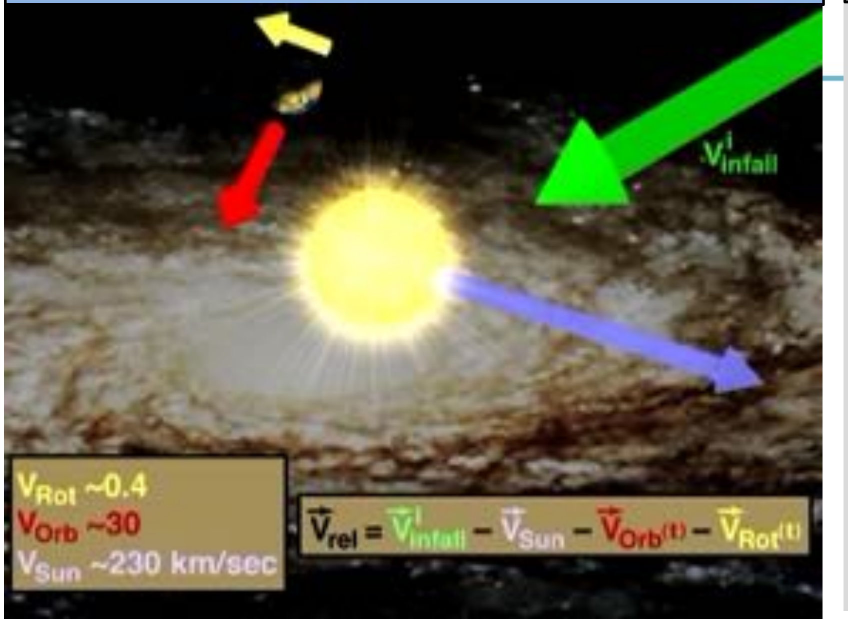


And if the axion be found?

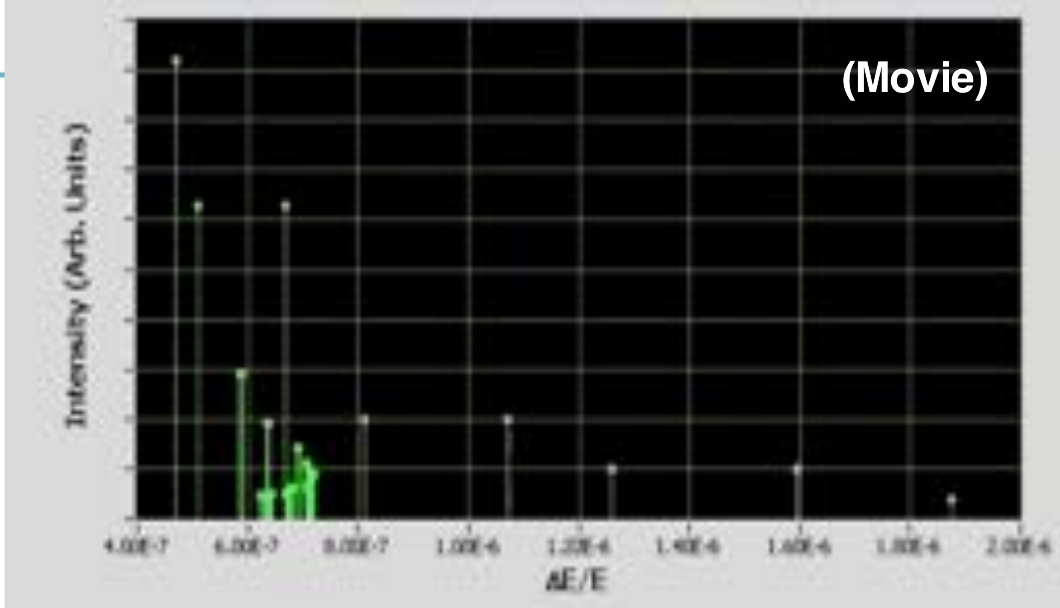


And should the axion possess very narrow fine-structure, it would constitute a “movie” of the formation of our Milky Way galaxy.

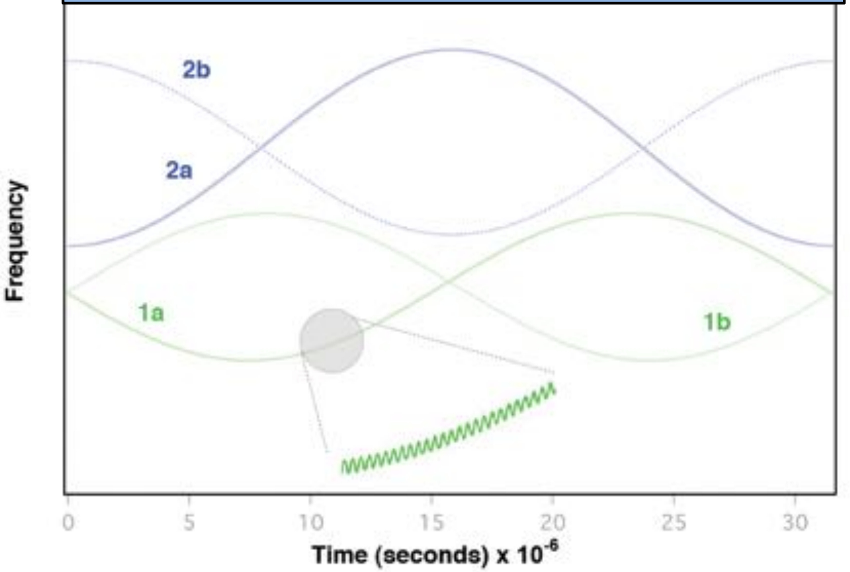
Modulation of one infall line



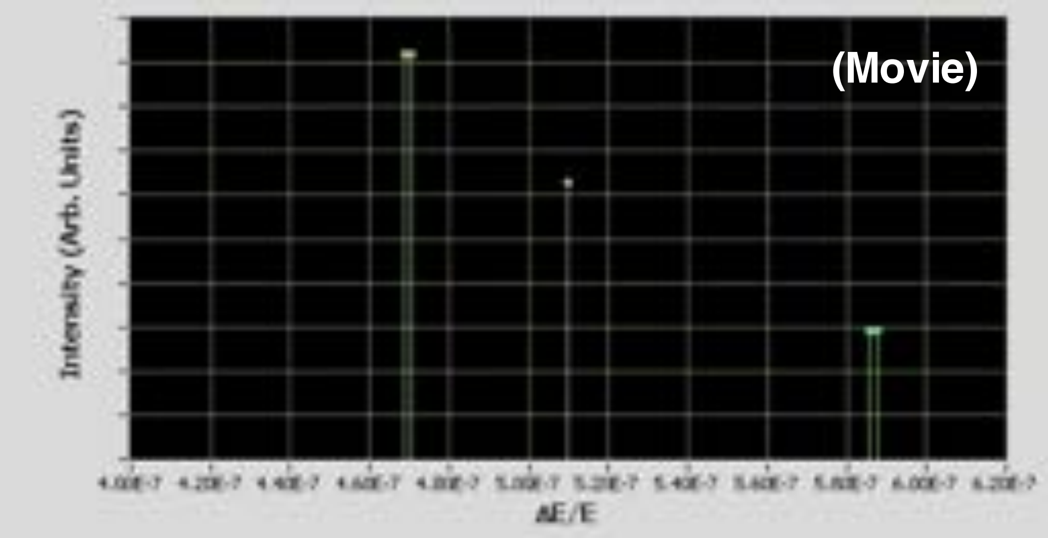
Annual Modulation: Earth's orbit around Sun


(Movie)

Vector DM Flow is uniquely determined



Daily Modulation: Earth's spin on its axis


(Movie)

We wish to gratefully acknowledge support from

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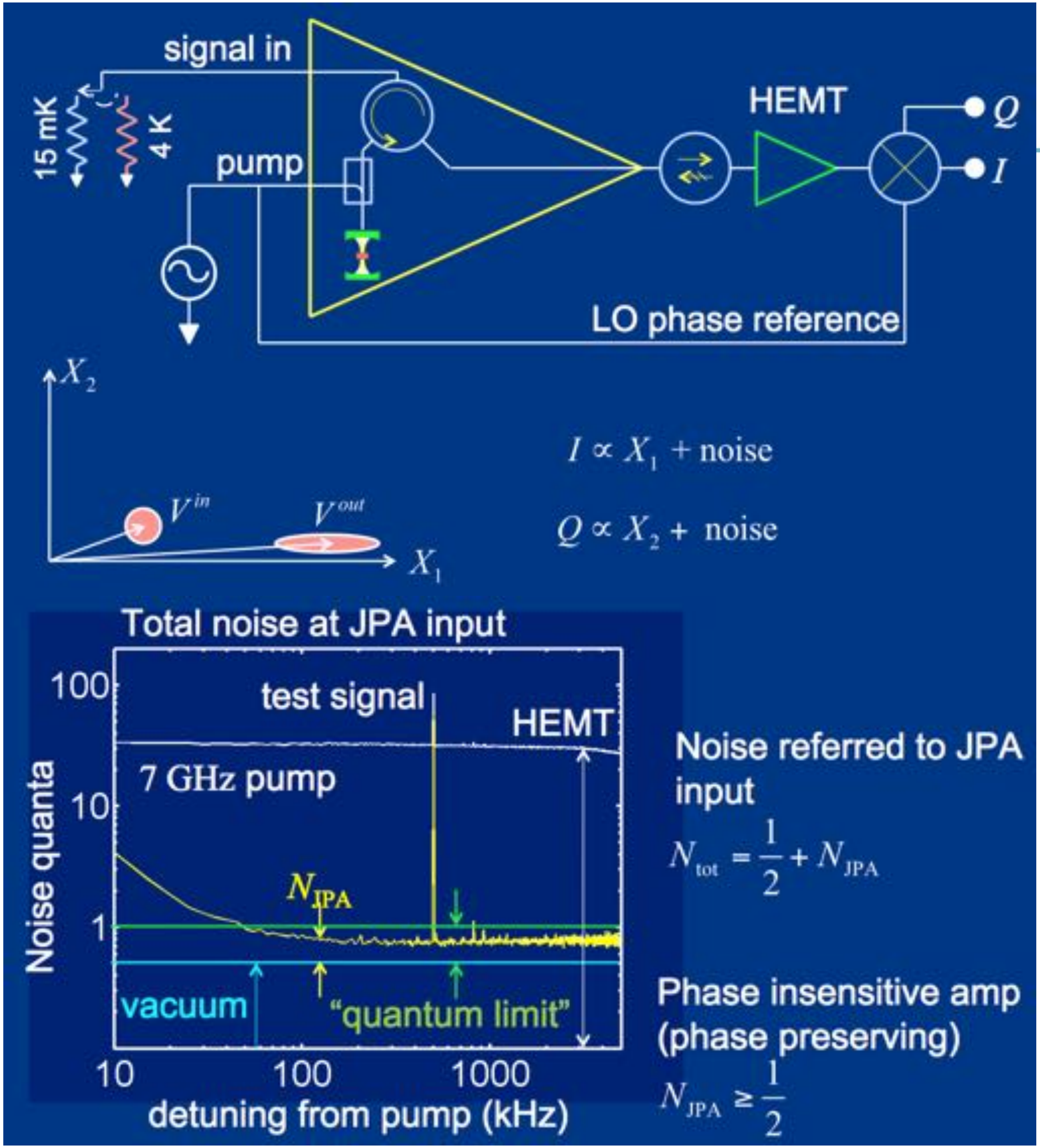
The US Department of Energy

The Heising-Simons Foundation

Additional Slides

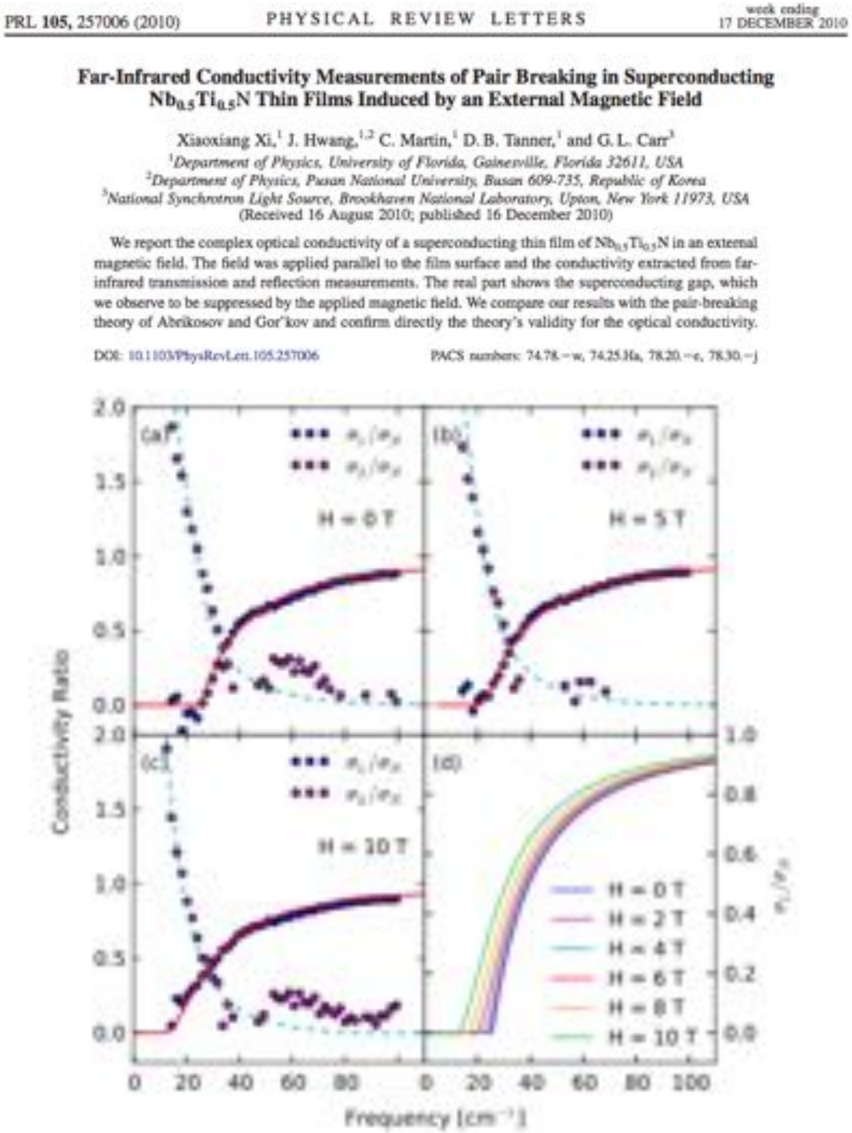
Josephson Parametric Amplifiers (JPA)

Konrad Lehnert, JILA/CU



- Natural for higher frequencies
- Broadly & easily tunable
- Operates at the SQL or below (squeezing)
- ADMX-HF initially utilize an existing and proven system design
  - 4-8 GHz
  - Quantum-limited T

Thin-film Type-II superconductors appear promising



PRL **105**, 257006 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Far-Infrared Conductivity Measurements of Pair Breaking in Superconducting $Nb_{0.5}Ti_{0.5}N$ Thin Films Induced by an External Magnetic Field

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We report the complex optical conductivity of a superconducting thin film of $Nb_{0.5}Ti_{0.5}N$ in an external magnetic field. The field was applied parallel to the film surface and the conductivity extracted from far-infrared transmission and reflection measurements. The real part shows the superconducting gap, which we observe to be suppressed by the applied magnetic field. We compare our results with the pair-breaking theory of Abrikosov and Gor'kov and confirm directly the theory's validity for the optical conductivity.

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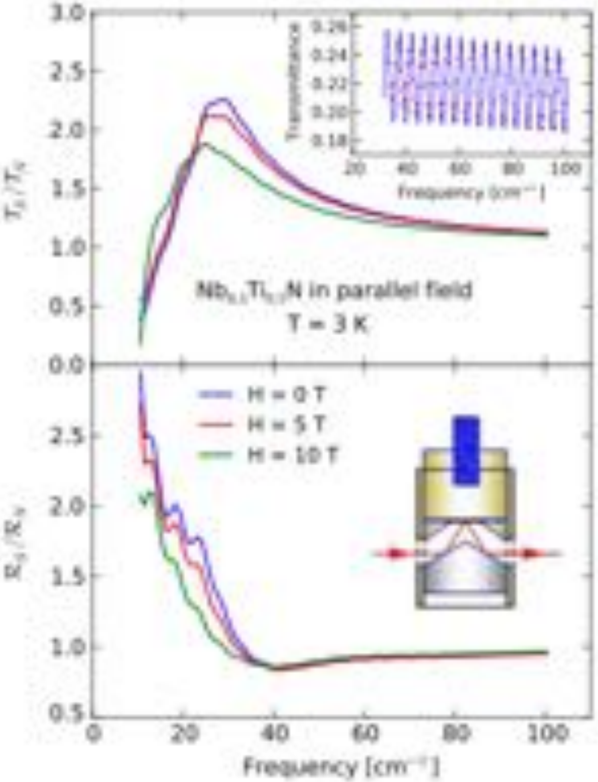


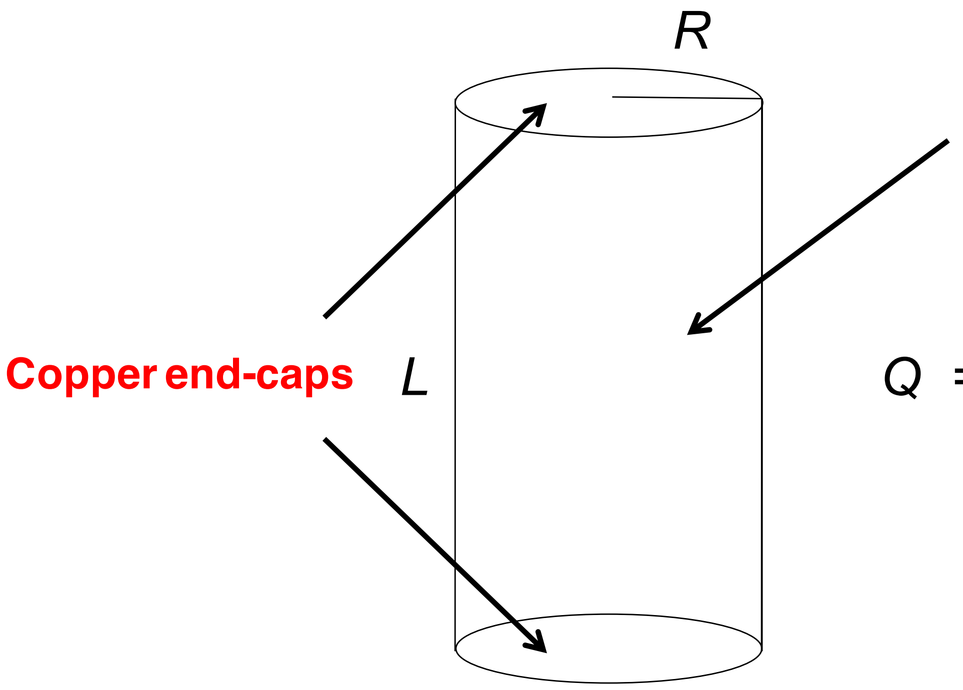
10 nm $Nb_{0.5}Ti_{0.5}N$ is perfect

Supports $B_{||}$ up to 10 Tesla

Q of the TM_{010} mode for a conventional Cu cavity:

$$Q = \frac{L/R}{1 + \mathbf{L/R}} \cdot \frac{R}{\delta}$$

The concept of a hybrid superconducting cavity:



Thin-film superconducting barrel

$$Q = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

This term goes away for a superconducting barrel

$$\boxed{Q_{hybrid} = (1 + L/R) \cdot Q_{cu}}$$

For typical ADMX cavity, L/R = 5, enhancement factor = 6