Particle Astrophysics in a Can: The ADMX-HF Experiment

Presented by S.K. Lamoreaux

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Tim Shokair, Gp Carosi, LBNL

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FEATURES ARCHIVE

21 OCTOBER 2010 | Contemporary Art | Article

Andy Warhol's *Campbell's Soup Can (Tomato)*, 1962

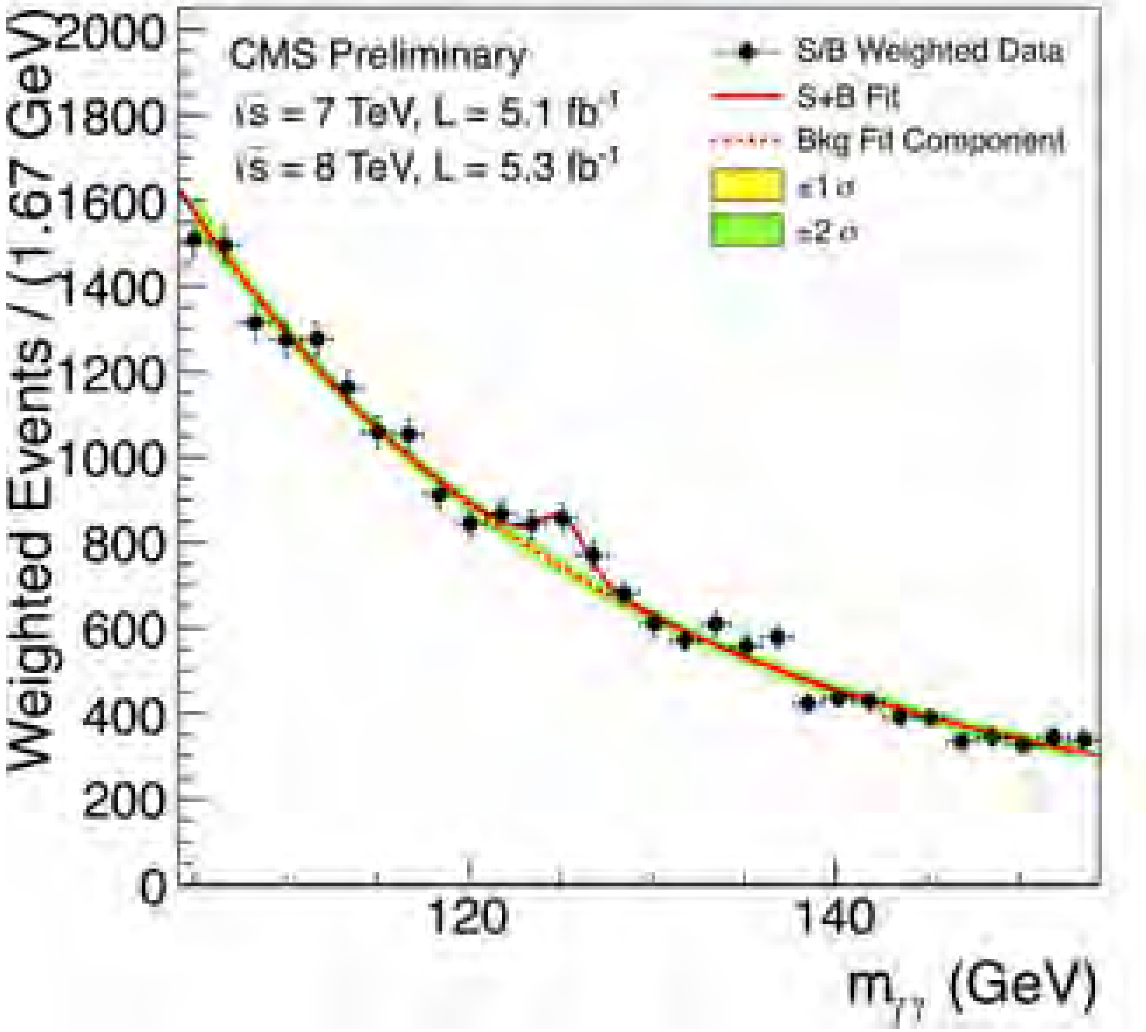
With *Campbell's Soup Can (Tomato)* Andy Warhol takes as his subject a ubiquitous staple food found in millions of American homes and turns it into high art. With the unique candor he displayed in the best of his early Pop art works he appropriates the curved lines and iconic graphic imagery of a tin of canned soup and re-examines them in the context of their pure visual qualities.

Andy Warhol's *Campbell's Soup Cans* transformed him into an overnight sensation when they were first exhibited in Los Angeles in 1962. It was his first one-person exhibition organized by Irving Blum, the legendary and visionary director of the Ferus Gallery. The exhibition featured thirty-two "portraits" of soup cans, each identical except for the flavor inscribed on their labels. These revolutionary paintings were displayed on a small narrow shelf that ran along the wall of the gallery in a way that suggested not only a gallery rail but also the long shelves in a grocery store. With these works, Warhol took on the tradition of still life painting, declaring a familiar household brand of packaged food a legitimate subject in the age of Post-War economic recovery.

Lot 12, Sale 2355
Andy Warhol (1928-1987)
Campbell's Soup Can (Tomato)
Price Realized: $9,042,500

The *32 Campbell's Soup Cans* are now in the collection of the Museum of Modern Art in New York. At the same time he produced this series, he also produced less than a dozen of what Irving Blum called "early versions", single canvases that are virtually identical to the ones included in the exhibition except for the absence of metallic paint. The present work is one of these "early versions". Warhol had just started using silkscreen that year, which makes *Campbell's Soup Can (Tomato)* among the earliest examples of the medium through which he would forever transform the landscape of late 20th Century art. Furthermore, in using the commercial process of silkscreen to render this seemingly banal subject, and mediating it through a factory-based production system, Warhol questioned the sacrosanct notion of artistic subjectivity as well. The Ferus exhibition sparked heated criticism and even outrage from numerous critics and visitors, and catapulted Warhol and the challenge of Pop art into the public consciousness.

Of all the varieties of soup that Warhol produced, *Tomato* was his most valued. Not only did it have a strong resonance for the artist, it was also the very first


CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
m_γγ (GeV)

standard model

- Amazingly successful in the “gauge” sector*
- Many problems in “flavor” sector— considerable success in correlating data but at the expense of many phenomenological input parameters

(* except the overall phase of the quark mass matrix is physically meaningful)

The Strong CP Problem

It is well known that the usual Lagrangian of the electromagnetic field

$$-\frac{1}{4}F_{\mu\nu}F_{\mu\nu} = \frac{1}{2}(\boldsymbol{E}^2 - \boldsymbol{B}^2)$$

can in principle be supplemented by another Lorentz scalar [151]

$$F_{\mu\nu}\tilde{F}_{\mu\nu}, \quad \tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\kappa\lambda}F_{\kappa\lambda}.$$

This scalar violates both P and T invariance, which can most easily be seen from its three dimensional form:

$$F_{\mu\nu}\tilde{F}_{\mu\nu} = -4\boldsymbol{E}\cdot\boldsymbol{B}.$$

However, being a total four-divergence, this scalar generates no observable effects in electrodynamics.

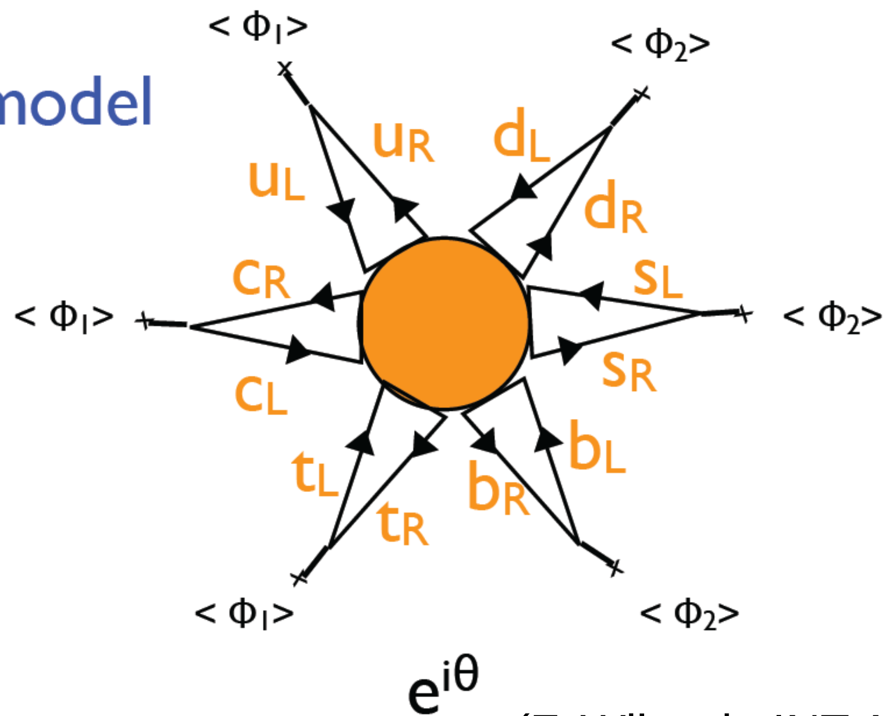
In quantum chromodynamics (QCD) the situation is quite different. Due to the self-interaction of the gluon vector potential A_μ^a, the field configurations which do not fall off rapidly enough at infinity play a prominent role in the theory. Therefore, an analogous four-divergence is no longer harmless. The corresponding possible P and T violating term in the QCD Lagrangian is usually written as

$$L_\theta = -\theta\,(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu} \tag{5.3}$$

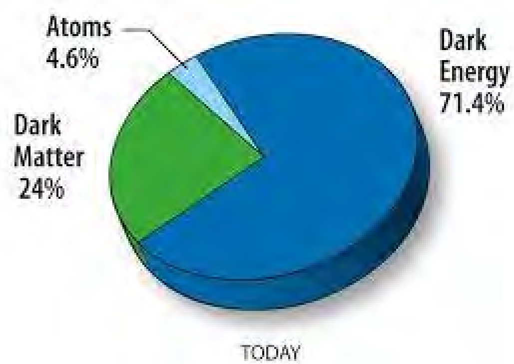
and is called the θ term. Here α_s is the gluon coupling constant, a QCD analogue of the fine structure constant $\alpha = 1/137$ in electrodynamics.

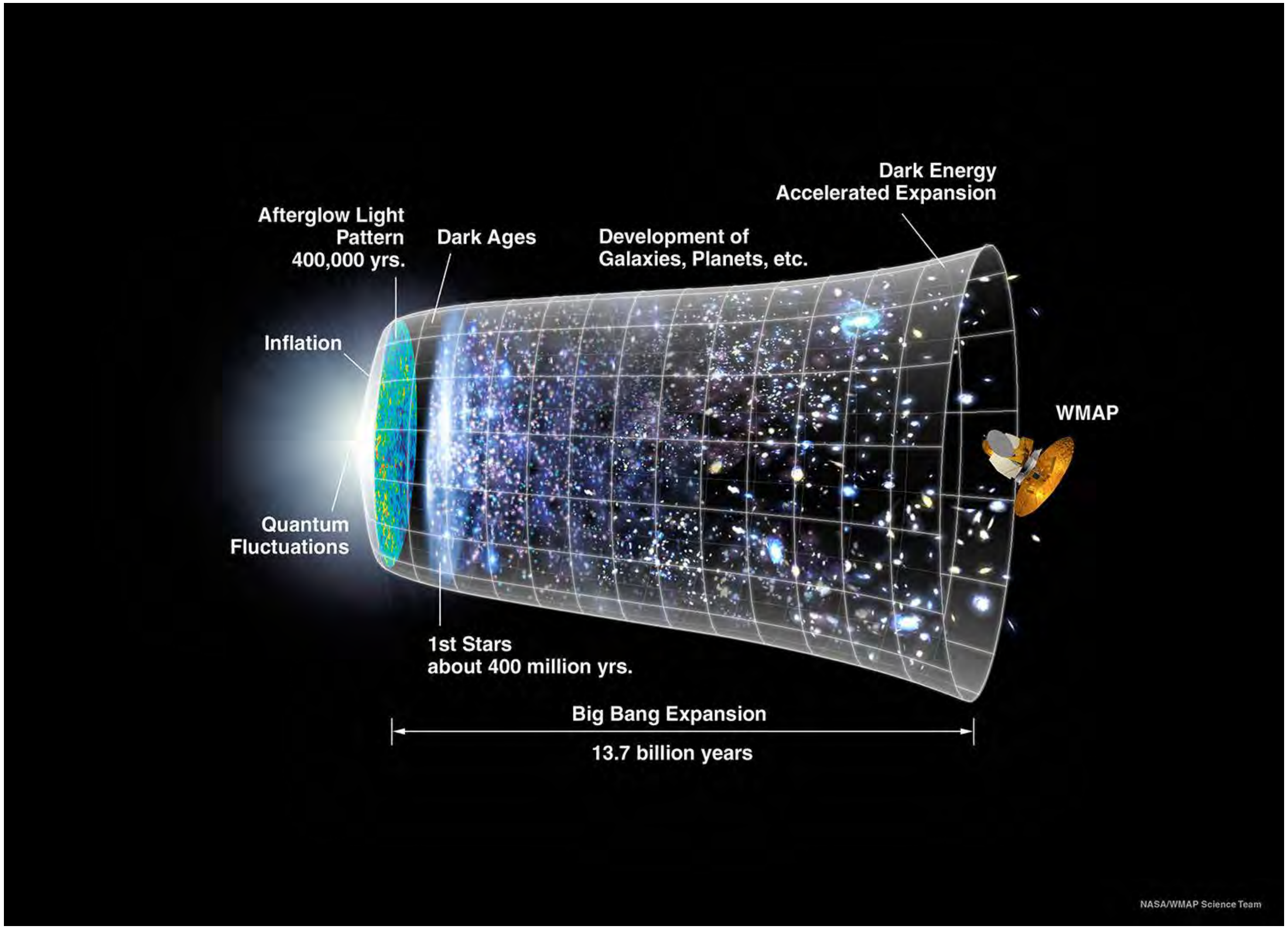
- θ is small based on experiment: $\sim 10^{-9}$
- Can set it to zero however standard model CP violation will induce, diverges at 14th order
- Peccei and Quinn: a new symmetry $U(1)_{PQ}$ implying the existence of a new particle (Wilczek, Weinberg)

minimal PQ model



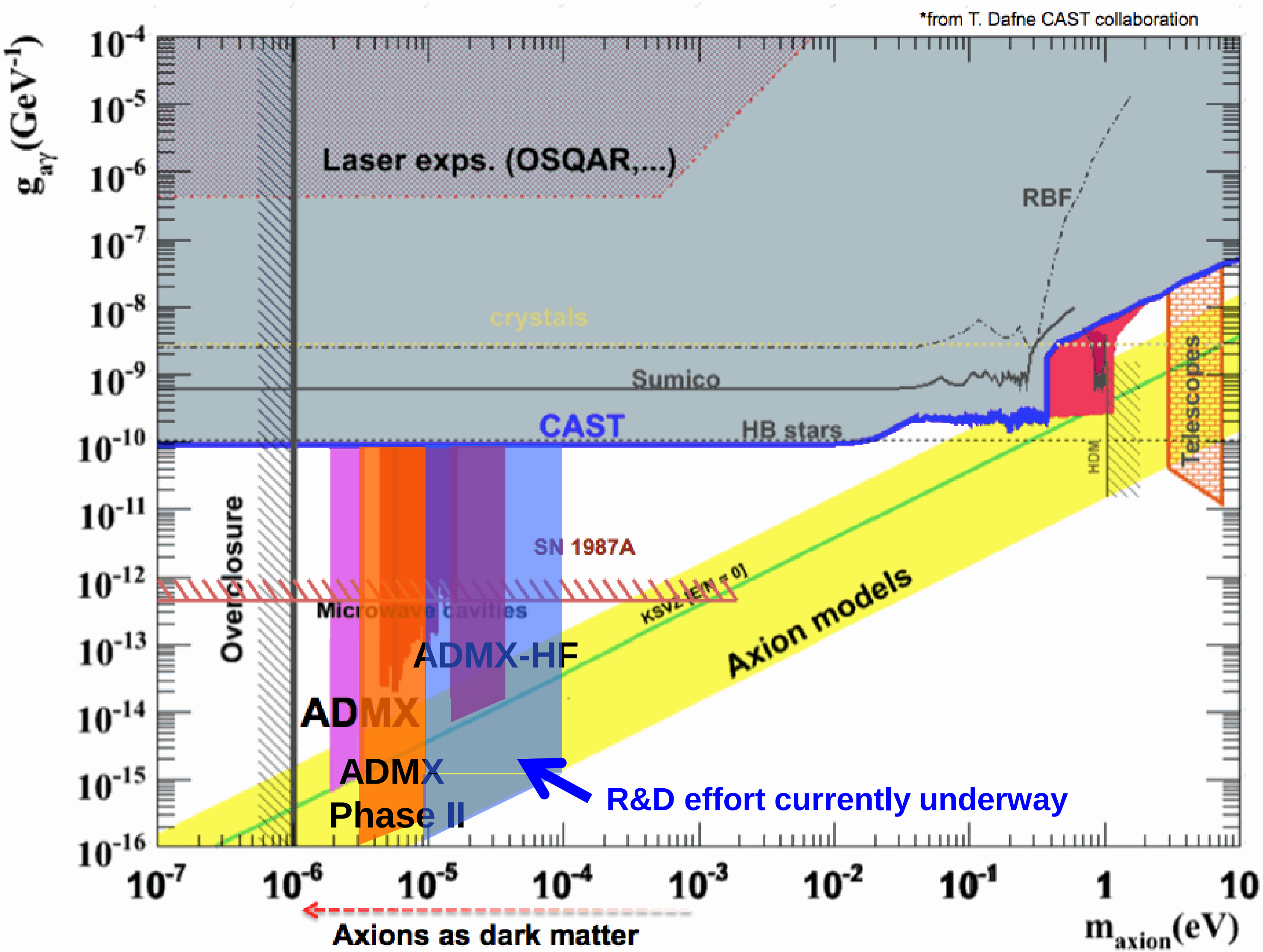
(F. Wilczek, INT Axion Workshop)


Atoms
4.6%
Dark
Energy
71.4%
Dark
Matter
24%
TODAY


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

The Dark Matter Problem

- Dark matter is in fact (nearly) invisible matter except via its gravitational effect
- Gravitationally bound to galaxies ($v/c \sim 10^{-3}$) to account for rotation velocity/distance anomalies
- Can't be neutrinos (Fermi velocity is too high)
- Assumed to be particles; the higher the mass the higher the temperature (velocity is specified)
- Main focus has been on WIMPs or supersymmetric particles: increasing sensitivity of EDM experiments together with lack of an LHC signal is disfavoring supersymmetry as an explanation of anything
- The Axion, long known as a possible solution, is receiving renewed attention
- The Axion has other applications in astrophysics



*from T. Dafne CAST collaboration
$g_{a\gamma}$ (GeV^{-1})
Laser exps. (OSQAR,...)
RBF
crystals
Sumico
CAST
HB stars
HDM
Telescopes
SN 1987A
Overclosure
Microwave cavities
KSVZ (E/N = 0)
Axion models
ADMX-HF
ADMX
ADMX
Phase II
R&D effort currently underway
Axions as dark matter
m_{axion} (eV)

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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Received 14 September 1982

The production of axions in the early universe is studied. Axion models which break the $U(1)_{PQ}$ symmetry above 10^{12} GeV are found to produce an unacceptably large axion energy density.

$$d^2\phi_A/dt^2 + 3H(t)d\phi_A/dt + m_A^2(T)\phi_A = 0$$

<u>Relic Dark Matter Axions</u> : (Preskill, Wise, Wilczek; Abbott, Sikive; Dine, Fischler)

Axions will interact with an EM field

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

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(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2N}{12\pi^2}\frac{a}{v}F_{\mu\nu}\tilde{F}^{\mu\nu} + \tfrac{1}{2}\partial_\mu a\,\partial^\mu a - \tfrac{1}{2}m_a{}^2a^2[1 + O(a^2/v^2)]$$

$$\nabla\cdot\vec{E} = \frac{e^2N}{3\pi^2 v}\vec{B}\cdot\nabla a, \quad \nabla\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = \frac{e^2N}{3\pi^2 v}\left[\vec{E}\times\nabla a - \vec{B}\frac{\partial a}{\partial t}\right], \quad \Box a = \frac{e^2N}{3\pi^2 v}\vec{E}\cdot\vec{B} - m_a{}^2 a$$

$$\mathcal{L} = \frac{1}{2}\epsilon_0 \mathbf{E}^2 - \frac{1}{2\mu_0}\mathbf{B}^2 - \frac{3}{4}\xi \frac{\alpha}{2\pi\mu_0 c}\frac{a}{f_a/N}\,\mathbf{E}\cdot\mathbf{B}$$

$$\xi \simeq \frac{4}{3}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right) \qquad z = m_u/m_d$$

	E/N	ξ
DFSZ	8/3	0.97
KSVZ	0	-2.59

$$\nabla\cdot\mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla\times\mathbf{B} = \mu_0\epsilon_0\frac{\partial\mathbf{E}}{\partial t} + \mu_0\mathbf{j}$$

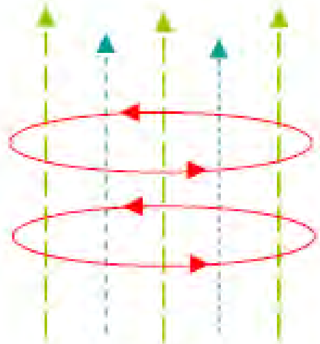
$$\rho = \frac{3}{4}\xi\frac{\alpha}{2\pi\mu_0 c}\frac{a}{f_a/N}\,\mathbf{B}\cdot\nabla a$$

$$\mathbf{j} = \frac{3}{4}\xi\frac{\alpha}{2\pi\mu_0 c}\frac{a}{f_a/N}\left(\mathbf{E}\times\nabla a - \mathbf{B}\frac{\partial a}{\partial t}\right)$$

$$\boldsymbol{\nabla}^2\boldsymbol{E} - \boldsymbol{\mu\epsilon}\,\partial^2\boldsymbol{E}/\partial t^2 = \boldsymbol{\mu\kappa B_0}\,\partial^2 \boldsymbol{a}/\partial t^2$$

Galactic Dark Matter Axions $\quad \frac{\partial a}{\partial t} \simeq m_a a \qquad \nabla a \simeq m_a v a \qquad v \sim 10^{-3}c$

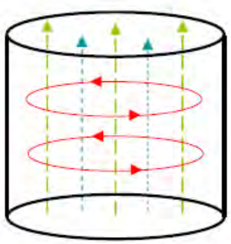
Constant Fields in Laboratory $\quad \mathbf{B}_{\text{lab}} \gg \frac{1}{c}\mathbf{E}_{\text{lab}}$



$$\nabla \times \mathbf{E} = -i\omega \mathbf{B}$$

For $D \sim \hbar / m_a$ $\qquad \frac{E}{c} \sim B$

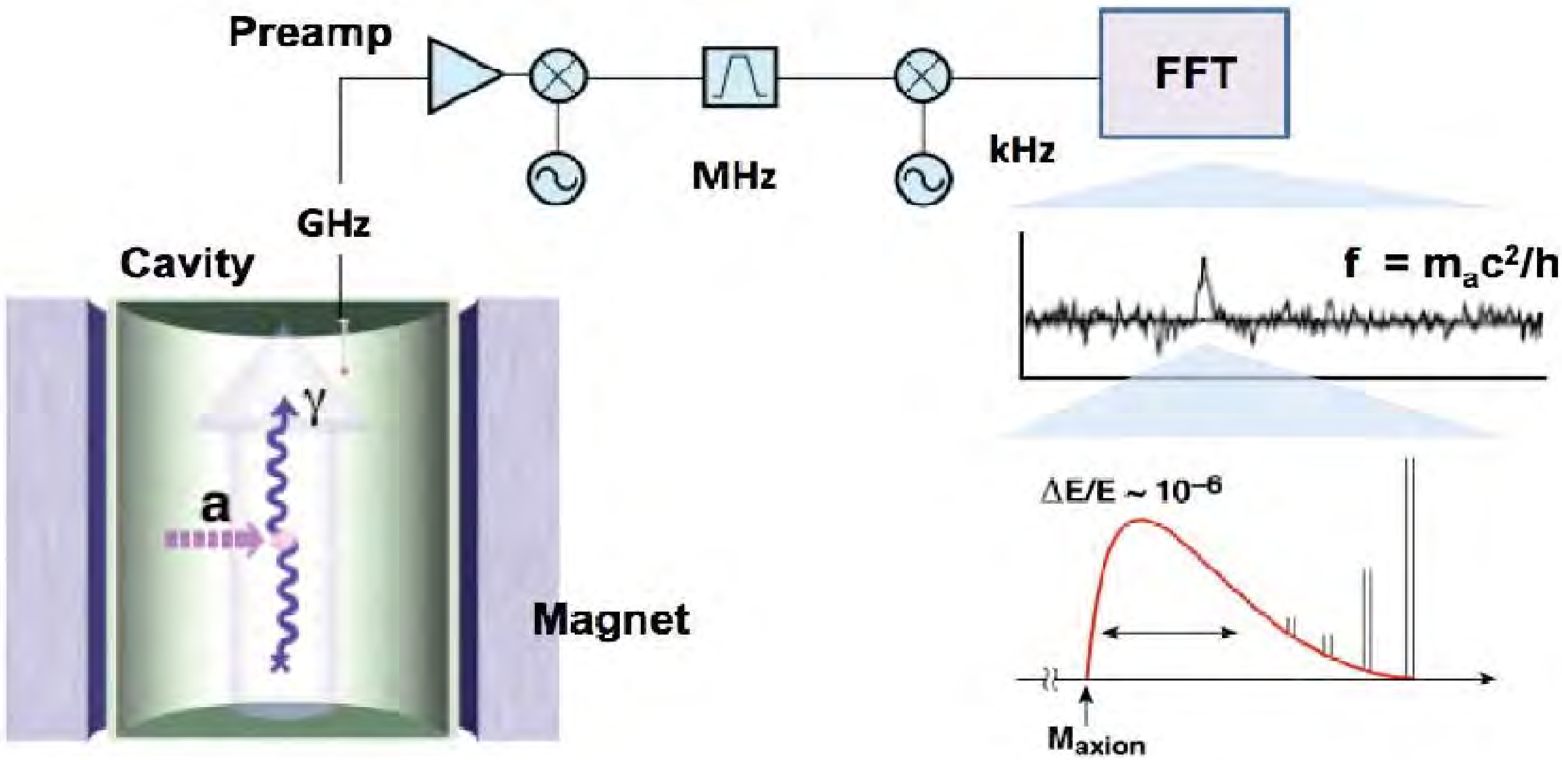
- Resonant Cavity TM_{010}



$\omega_{010} \simeq 4.8\ c / D$

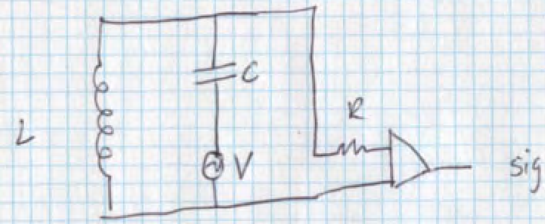
f_a /N	D
10^{12} GeV	15 cm
10^{16} GeV	1.5 km

Basic Experiment



$$P_{sig} = g^2_{a\gamma\gamma}\left(\frac{\rho_a}{m_a}\right) B_0^2 V\, C\, Q$$

10^{-24} W is an interesting power level



Assume loss is due to receiver.

$V \propto \quad g_{\gamma a} \; B_0$

$$I = \frac{V}{\frac{1}{i\omega C} + \frac{1}{1/R + 1/i\omega L}} = \frac{V\, i\omega C}{1 + \frac{i\omega C}{1/R + \frac{1}{i\omega L}}}$$

$$= \frac{V\, i\omega C}{i\omega L/R - \omega^2 LC + 1}\left(1 + \frac{i\omega L}{R}\right)$$

$$\rightarrow \text{on resonance} = \frac{V(i\omega C)}{i\omega L/R}\left(1 + i\omega L/R\right)$$

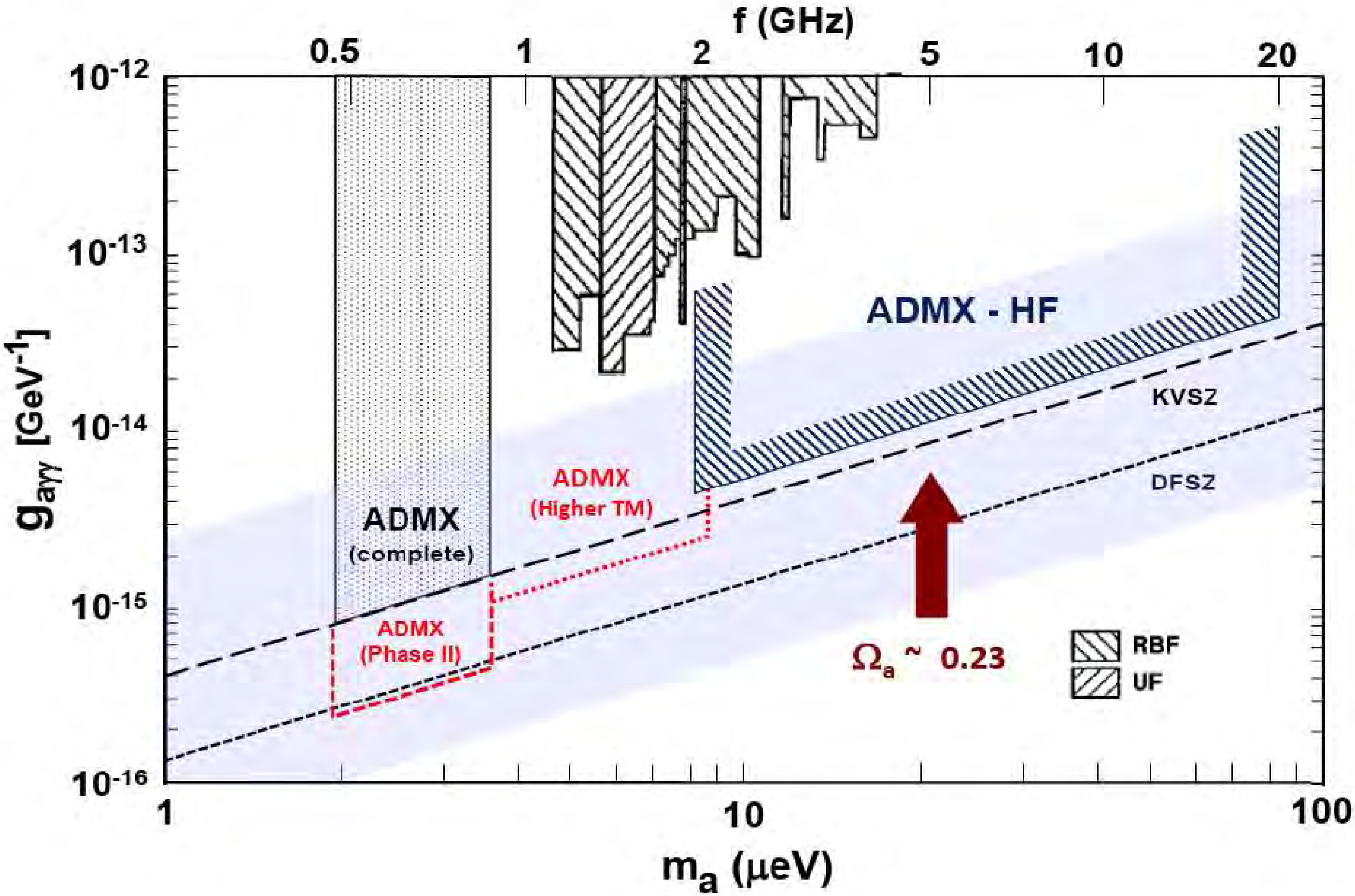
$$\frac{R}{\omega L} = Q$$

$$= \frac{V(i\omega C)}{i/Q}\left(1 + i/Q\right)$$

$$V_C = I\,\frac{1}{i\omega C} = \frac{V(1+iQ)}{i/Q} \simeq -iQV$$

$$\text{Power: } \frac{1}{2}\frac{V_C^2}{R} = \frac{1}{2}\frac{Q^2V^2}{R} = \frac{1}{2}\frac{Q^2V^2}{Q\omega L} = \frac{1}{2}\frac{Q}{\omega L}V^2 = U\frac{\omega}{Q}$$

$$\frac{1}{\omega L} = \omega C \qquad U = \frac{1}{2}CV^2$$


f (GHz)
0.5
1
2
5
10
20
10-12
10-13
10-14
10-15
10-16
gaγγ [GeV-1]
ADMX - HF
KVSZ
DFSZ
ADMX
(Higher TM)
ADMX
(complete)
ADMX
(Phase II)
Ωa ~ 0.23
RBF
UF
1
10
100
ma (μeV)

How Much *Q*?

- Perhaps we want the cavity bandwidth to match the galactic axion effective bandwidth: “Maxwell-Boltzmann Distribution” and cavity interaction time both contribute to Q_a *2R=D* cavity diameter

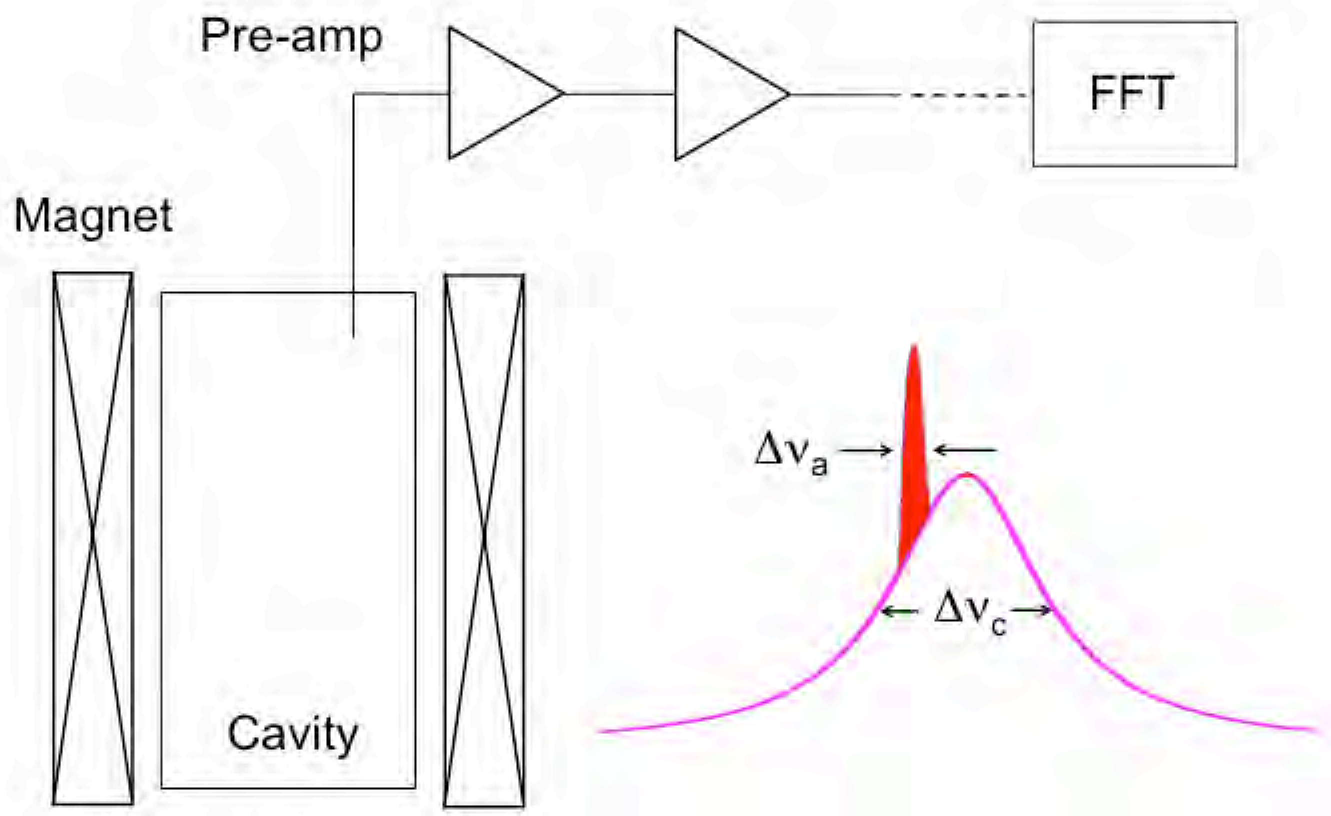
- If the interaction time is for a random uncorrelated field (size of cavity)

$$Q_a = \frac{f}{\delta f} = 2 f \tau = 2 \frac{(11.5 GHz \cdot cm)}{R} \frac{2R}{3 \times 10^7 cm/s} \approx 1500$$

Neglects coherence length: approximately ½ de Broglie wavelength

$$Q_a = \frac{f}{\delta f} = 2 f \tau = 2 \frac{m_a c^2}{h} \frac{h/(2 m_a v)}{v} = v^{-2} c^2 = \beta^{-2} = 10^6$$

Which applies when the coherence length >> *R*



Pre-amp
FFT
Magnet
Cavity
$\Delta\nu_a$
$\Delta\nu_c$

$Q_L^{-1}=Q_w^{-1}+Q_o^{-1}$ is the "loaded Q"
High Q *(low bandwidth)* limits maximum scan speed

Intrinsic cavity wall loss and output power coupling loss (optimum signal to noise when coupling is approximately equal to wall loss)

$$Q_L^{-1}=Q_w^{-1}+Q_o^{-1}$$

No real reason to not reduce Q_W^{-1} *to near-zero*
(some technical questions, e.g. amplifier stability).

We can make Q_L *anything we want*

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

Dicke Radiometer equation

$$P \propto g^2 \cdot B^2 V \cdot \min(Q_L, Q_a)$$

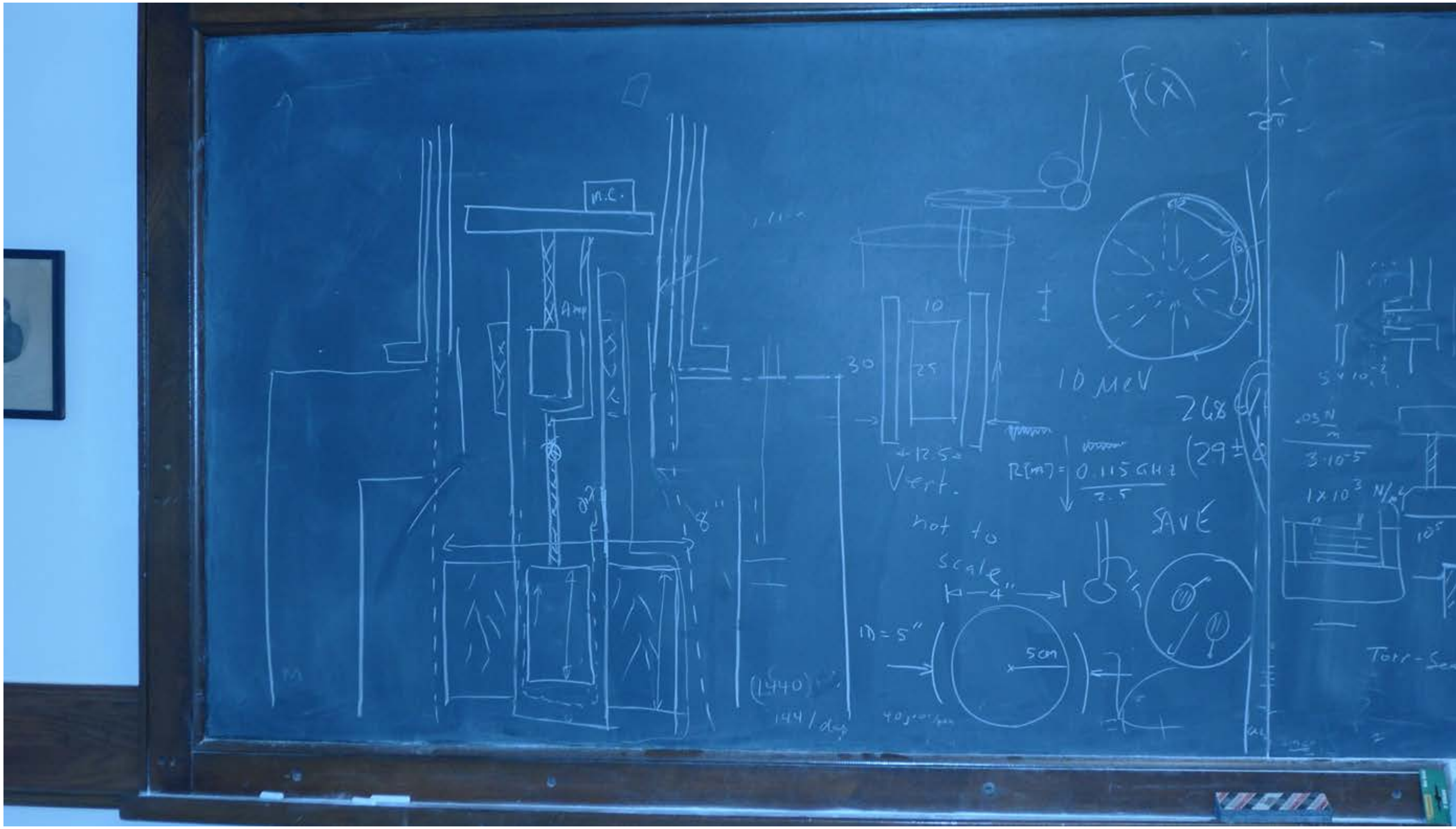
$$\frac{1}{f} \cdot \frac{df}{dt} \propto g^4 \cdot B^4 V^2 \cdot \min(Q_L, Q_a)$$

For copper cavities, $Q_a \sim 10^6$, whereas $Q_L \sim 50{,}000$

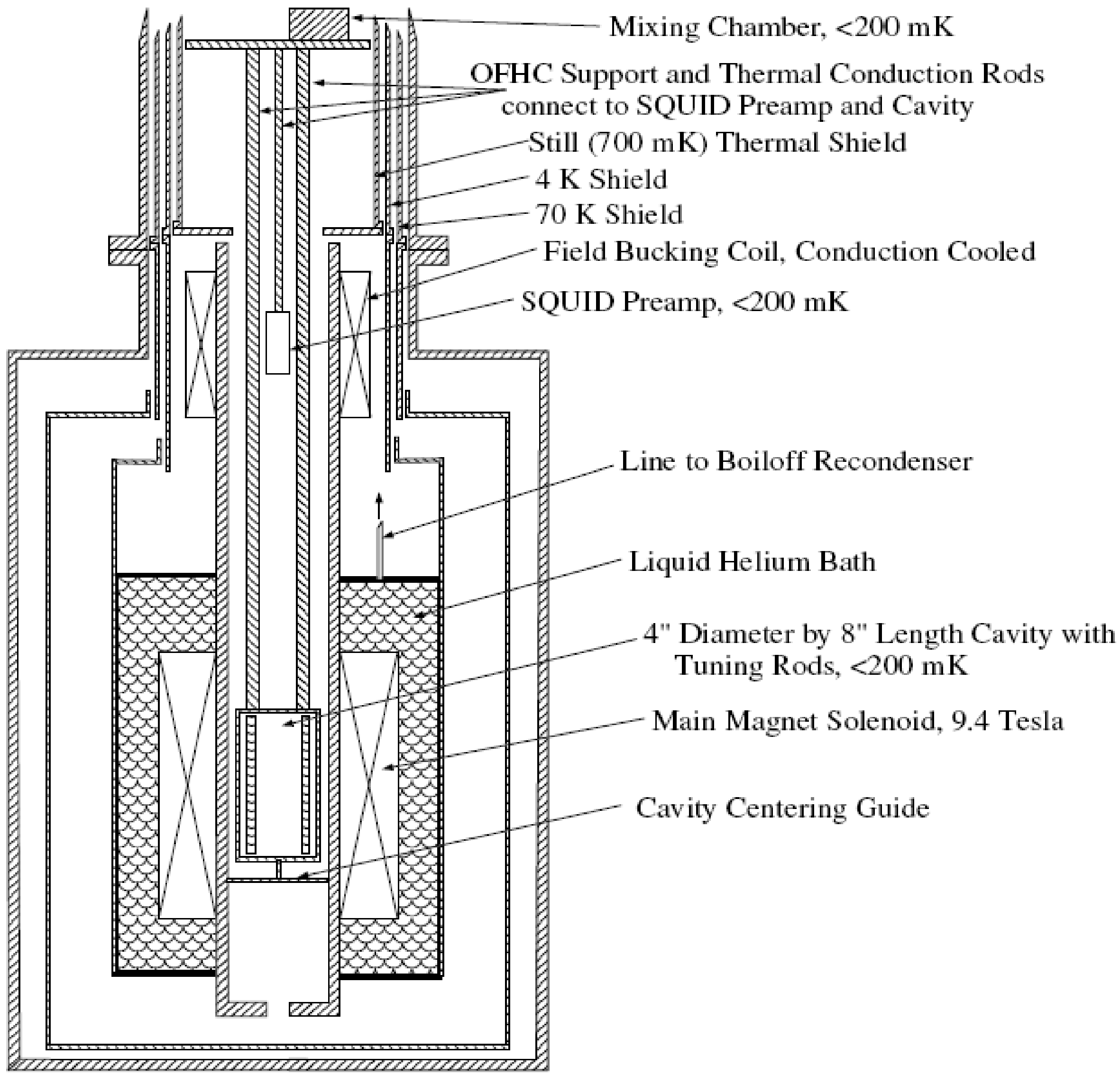
If you could increase Q_L by a factor of *e.g.* x10 :

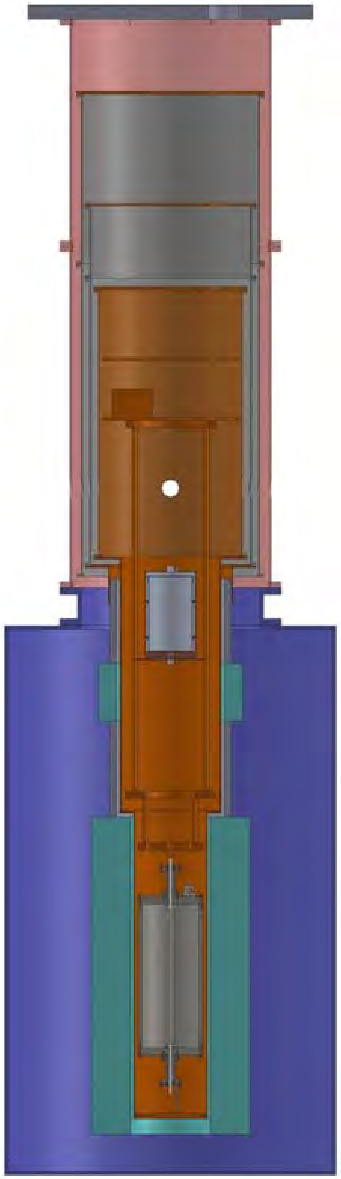
- P would increase by x10
- df/dt would increase by x10 *(for constant g)*
- g would improve by ÷1.8 *(for constant scan speed)*

*slides from Karl van Bibber

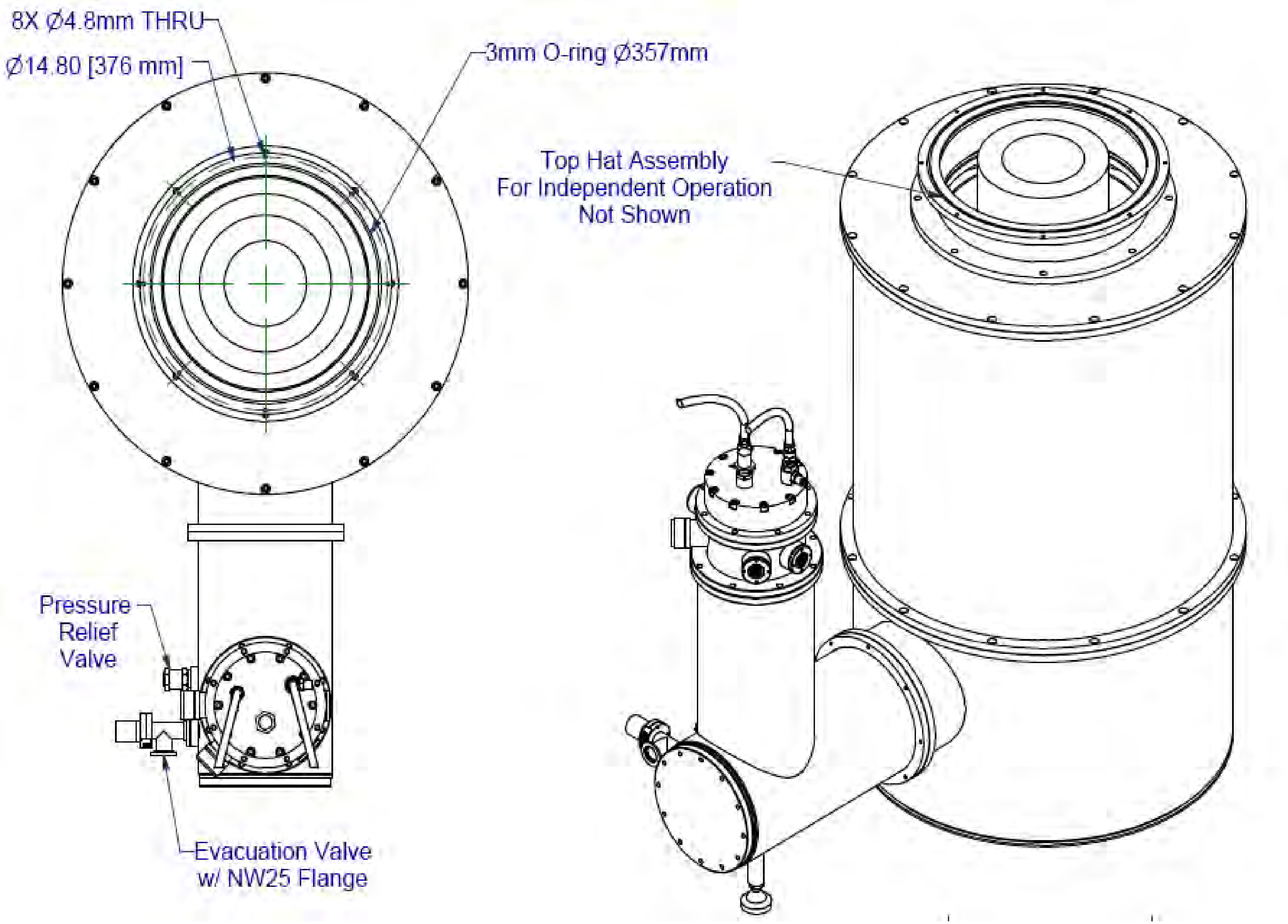

m.c.
Amp
8"
30
10
25
12.5
Vert.
not to scale
4"
ID = 5"
5cm
(1440)
144/day
10 MeV
268
0.115 GHz
2.5
SAVE
f(x)
1x10^3
Torr-Sea

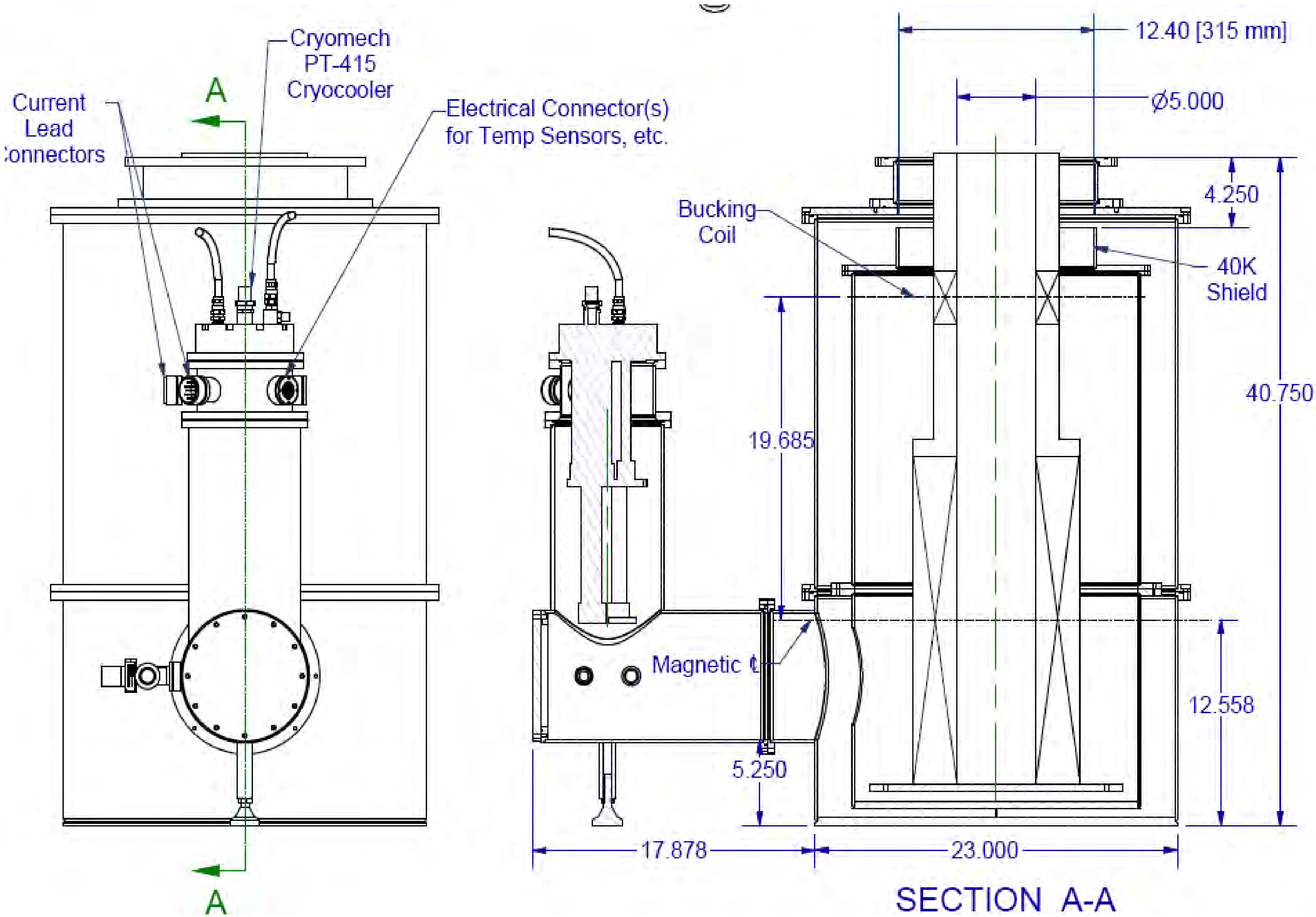
Overall Scheme



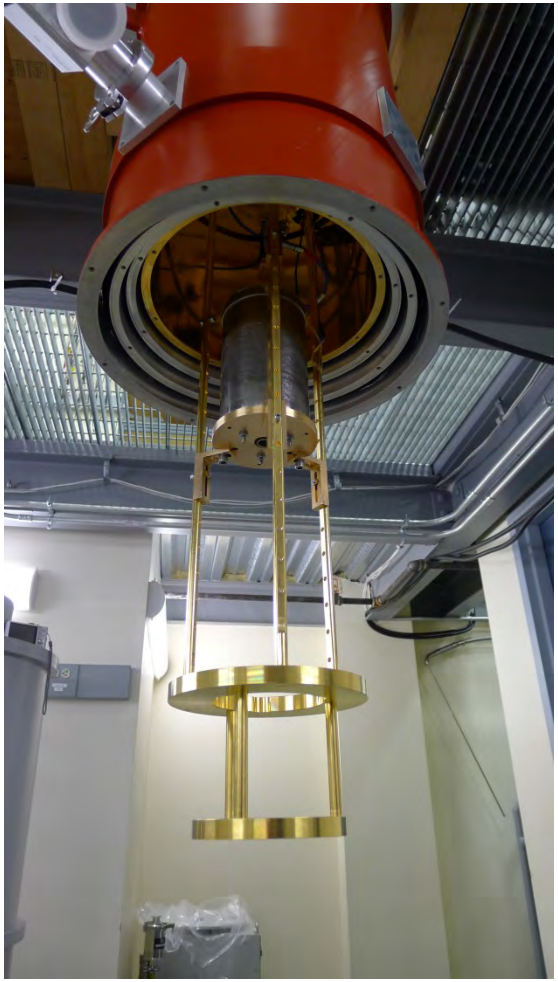


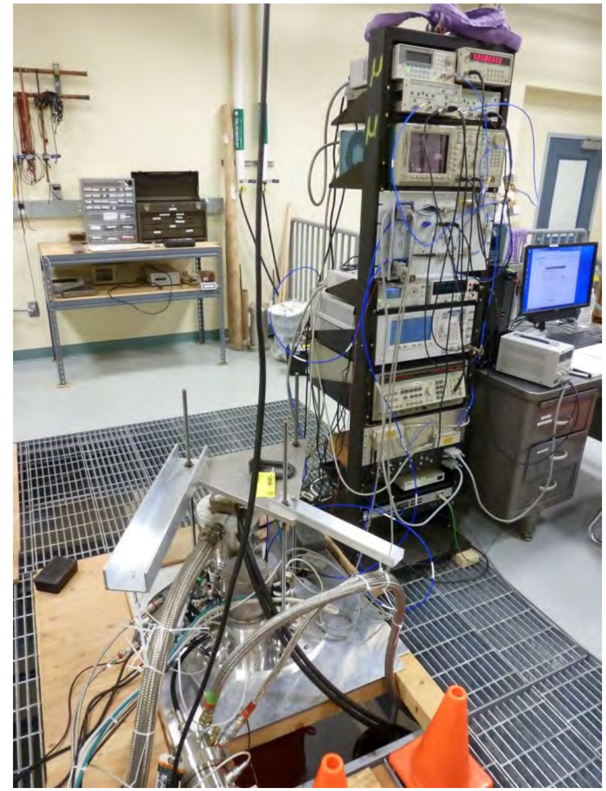
Cryomagnetics Magnet: Being Fabricated



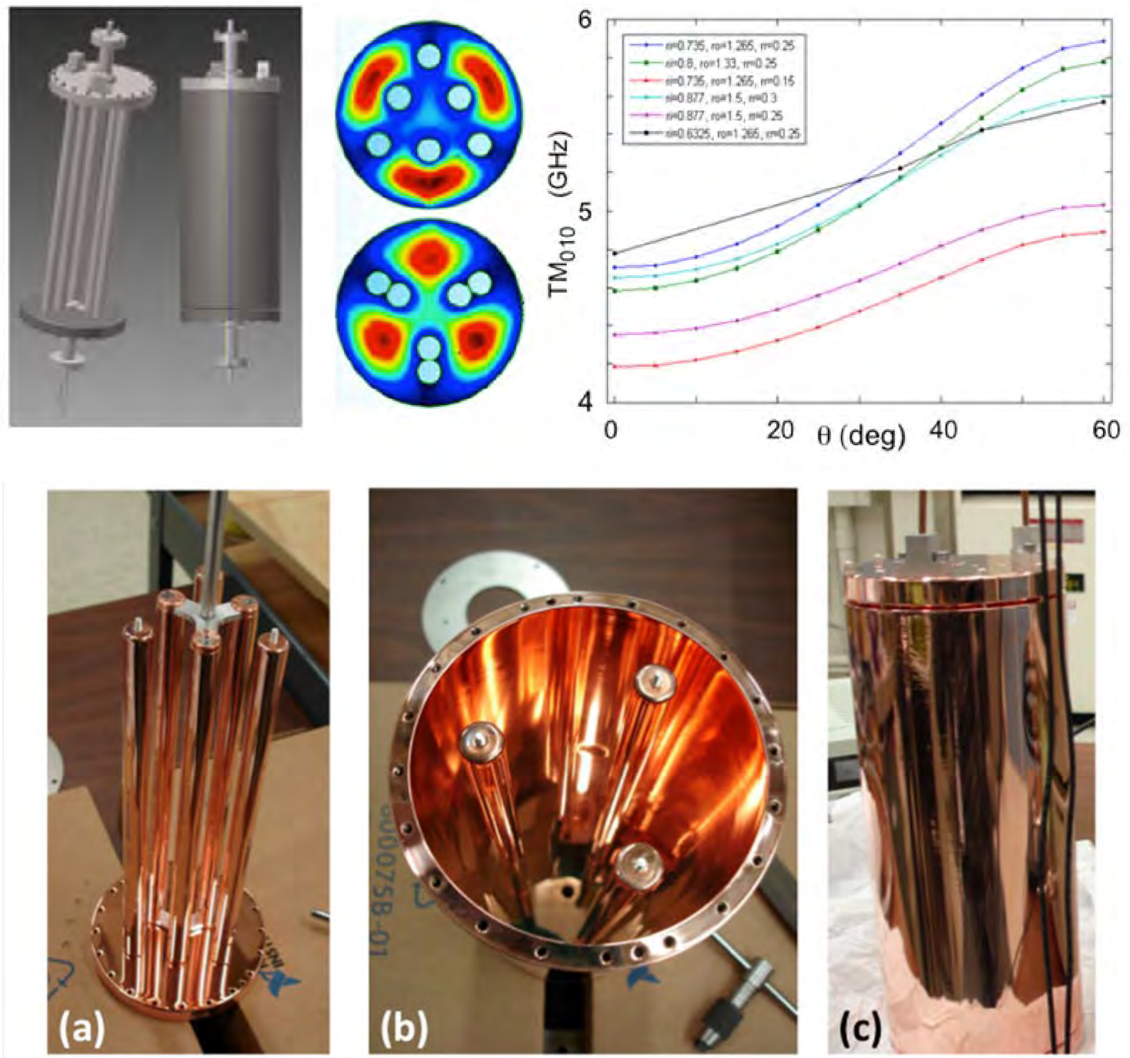


Current Lead Connectors
A
Cryomech PT-415 Cryocooler
Electrical Connector(s) for Temp Sensors, etc.
A
Bucking Coil
12.40 [315 mm]
Ø5.000
4.250
40K Shield
19.685
40.750
Magnetic ℄
12.558
5.250
17.878
23.000
SECTION A-A





The Cavity



The Amplifier

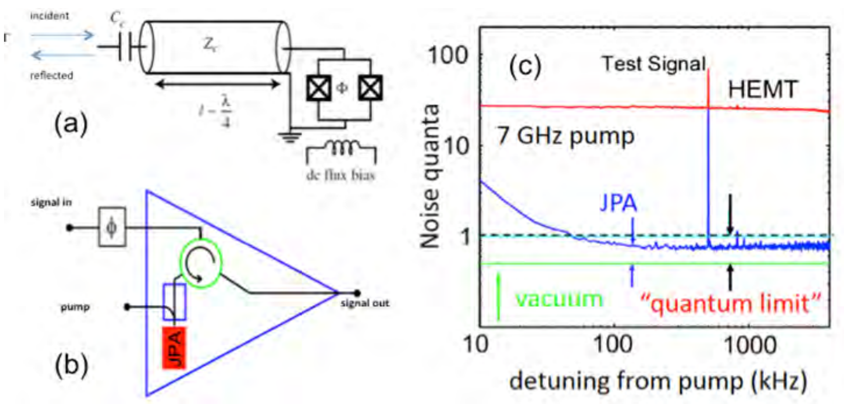
- HEMT amplifier fed by Josephson Parameteric Array; can achieve "standard quantum limit" for noise

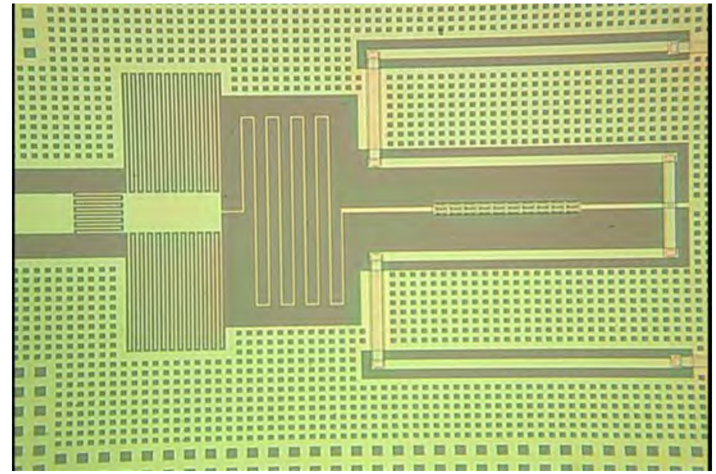
$$[p_f, q_f] = \frac{i\hbar}{2} = [Gp_0, Gq_0] + [p_g, q_g] = \frac{iG^2\hbar}{2} + [p_g, q_g]$$

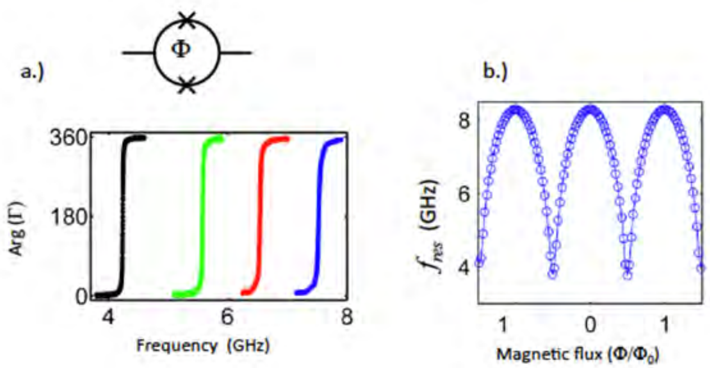
$$[p_g, q_g] = \frac{i(1 - G^2)\hbar}{2}$$

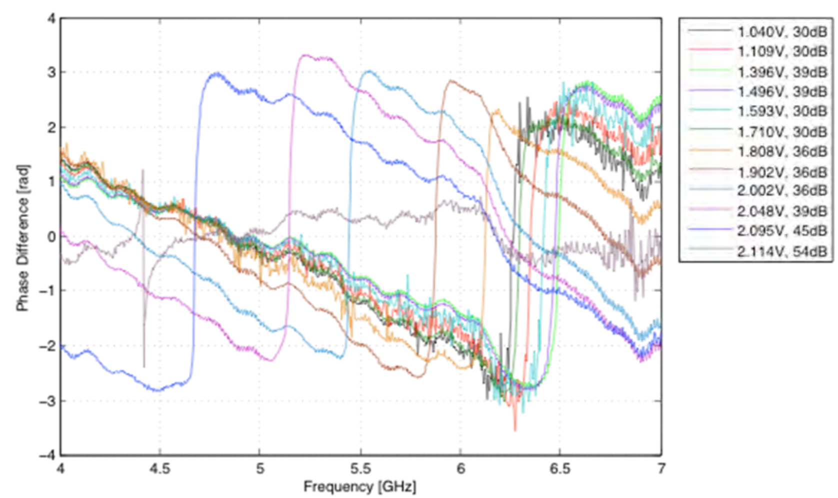
$$\langle|\Delta p_g|^2\rangle\langle|\Delta q_g|^2\rangle \geq \frac{(G^2 - 1)^2\hbar^2}{4}$$

$$\frac{1}{G^2}\left[\frac{G^2 h\nu}{2} + \frac{(G^2 - 1)h\nu}{2}\right] = \frac{h\nu}{2} + \frac{(G^2 - 1)h\nu}{2G^2} \approx 2 \times \frac{h\nu}{2}$$


incident
reflected
C_c
Z_c
$l \sim \frac{\lambda}{4}$
Φ
dc flux bias
(a)
signal in
pump
JPA
signal out
(b)
(c)
Test Signal
HEMT
7 GHz pump
JPA
vacuum
"quantum limit"
100
10
1
Noise quanta
10
100
1000
detuning from pump (kHz)

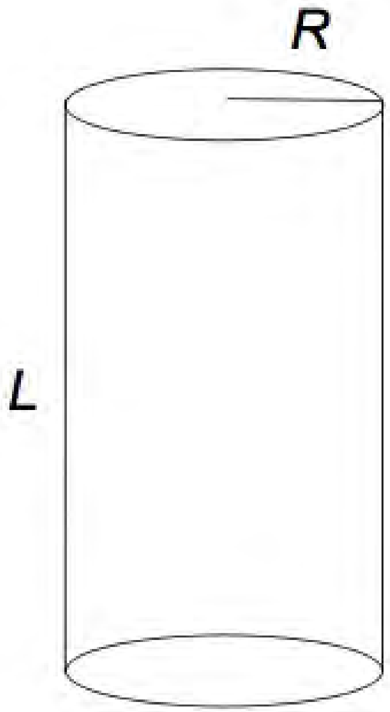



a.)
Φ
360
180
0
Arg (Γ)
4
6
8
Frequency (GHz)
b.)
8
6
4
f_{res} (GHz)
1
0
1
Magnetic flux (Φ/Φ$_0$)


Phase Difference [rad]
Frequency [GHz]
4
4.5
5
5.5
6
6.5
7
1.040V, 30dB
1.109V, 30dB
1.396V, 39dB
1.496V, 39dB
1.593V, 30dB
1.710V, 30dB
1.808V, 36dB
1.902V, 36dB
2.002V, 36dB
2.048V, 39dB
2.095V, 45dB
2.114V, 54dB

The “Hybrid” superconducting cavity concept

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



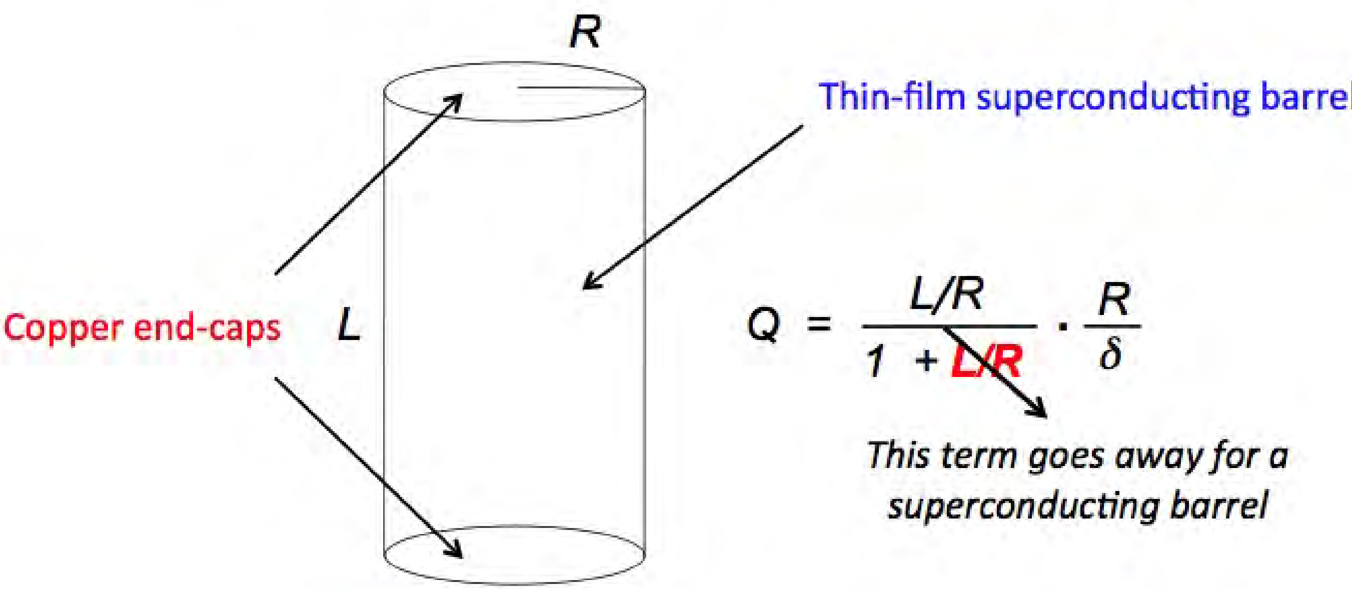
$$Q = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

Skin depth of Copper

***slides from Karl van Bibber**

The “Hybrid” superconducting cavity concept

The concept of a hybrid superconducting cavity:



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

This term goes away for a superconducting barrel

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

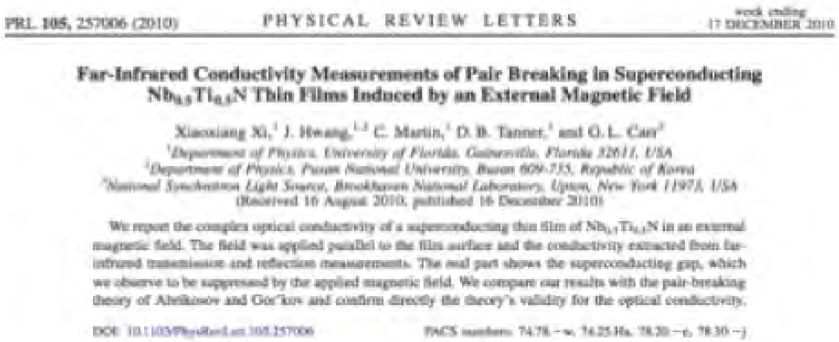
For typical ADMX cavity, L/R = 5, enhancement factor = 6

***slides from Karl van Bibber**

Superconducting Films

- A bulk superconductor expels fields from the interior; for type II, a “normal” layer forms near the surface, separated by a thin transition layer (Abrikosov) between the regions
- For a thin film, the entire layer is in a mixed state, if the applied field is nearly perpendicular to the thin direction
- This thin film provides a superconducting boundary condition
- D. Tanner suggests that this can be used to improve cavity *Q* for ADMX experiments

The science of thin-film superconductors is mature



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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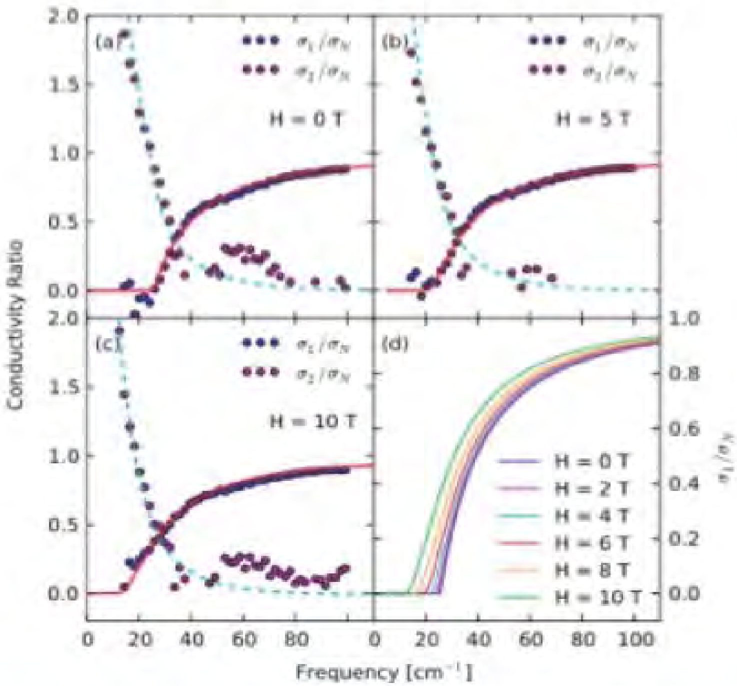
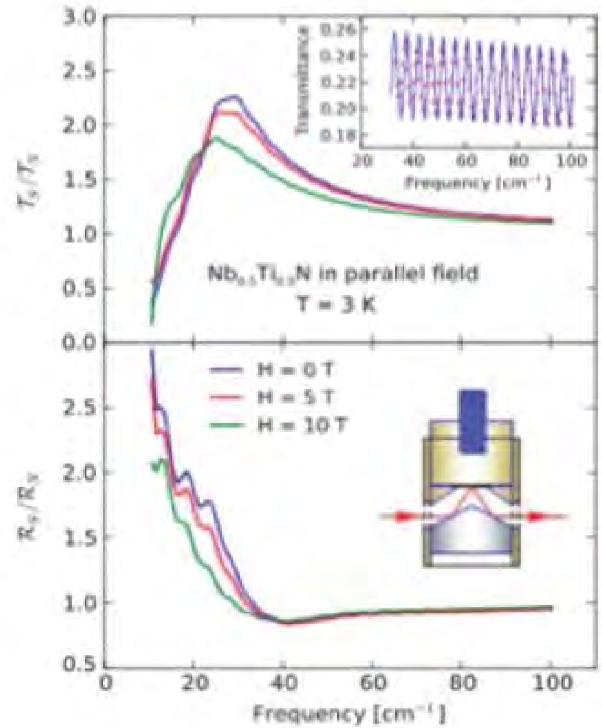
We report the complex optical conductivity of a superconducting thin film of $Nb_{0.5}Ti_{0.5}N$ in an external magnetic field. The field was applied parallel to the film surface and the conductivity extracted from far-infrared transmission and reflection measurements. The real part shows the superconducting 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.

DOI: 10.1103/PhysRevLett.105.257006 PACS numbers: 74.78.−w, 74.25.Ha, 78.20.−e, 78.30.−j



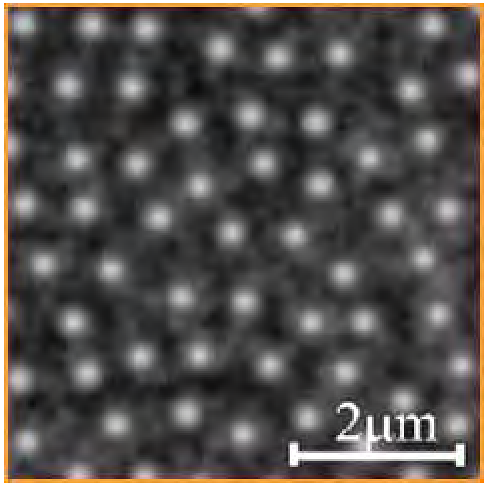


10 nm $Nb_{0.5}Ti_{0.5}N$ is perfect

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

- **Magnetic-force microscopy of Vortex Lattice, 2002**
- Magnetic Force Microscopy
  Nb film, 40G, 4.3K

  A. Volodin et al.
  Katholieke Universiteit Leuven
  Europhys. Lett. 58, 582 (2002)

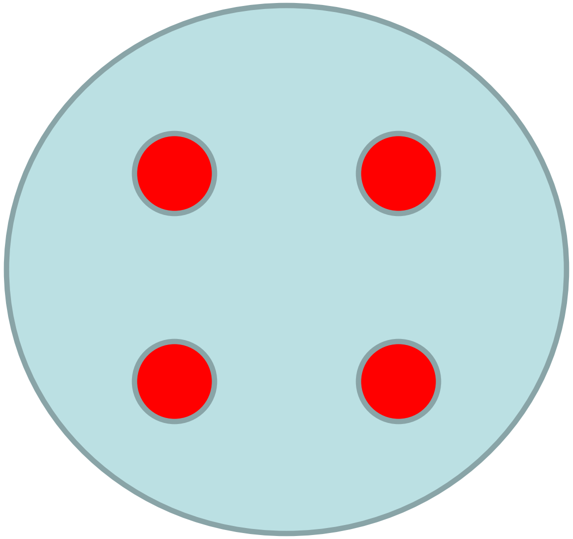


Requirements

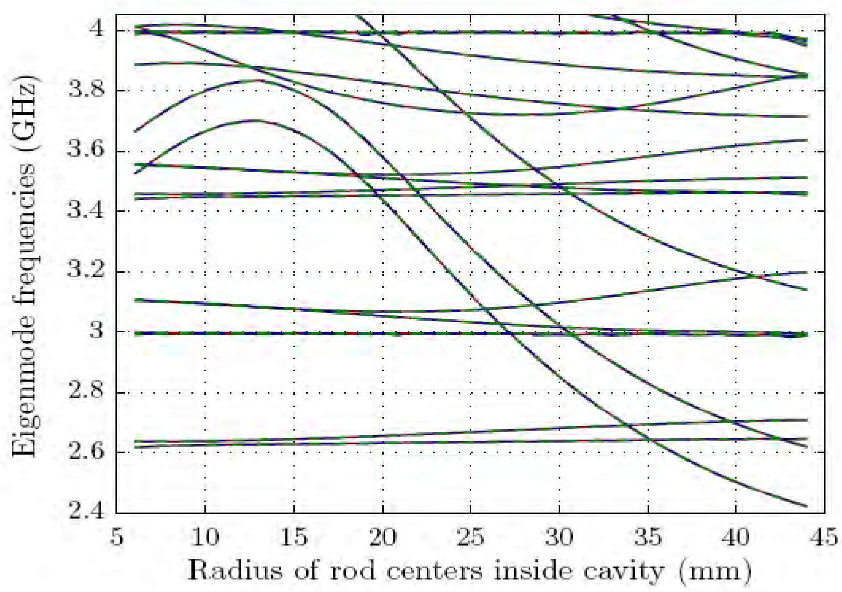
- Strong field must be parallel to surface
- Perpendicular field forms vorticies in plane of film
- Require a very homogeneous magnet and precision alignment
- Main cylinder and tuning rods coatings can be effective; cylinder endcaps are perpendicular to field

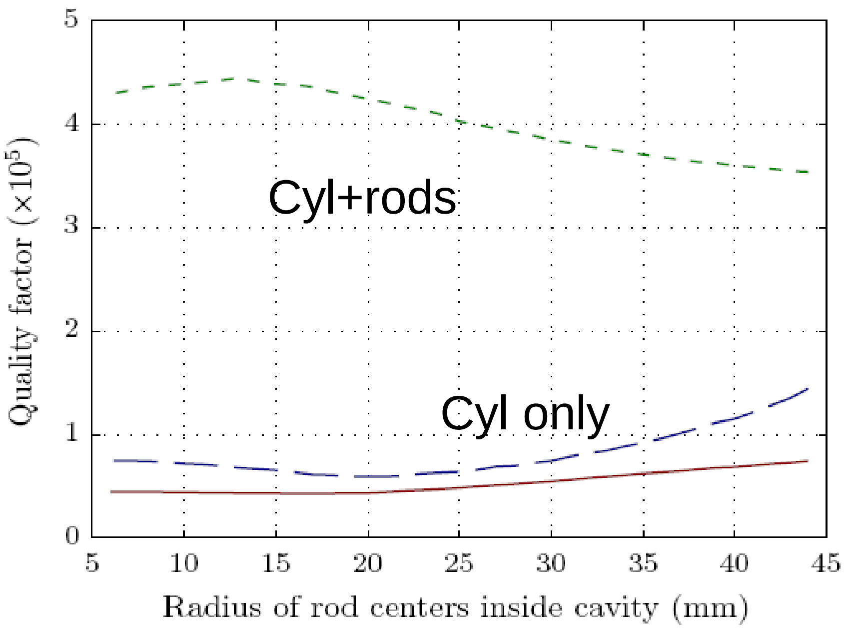
How Well Can We Do?

- Need to consider tuning rods
- Case study: 1 cm rods, Cu, 4 symmetrically placed



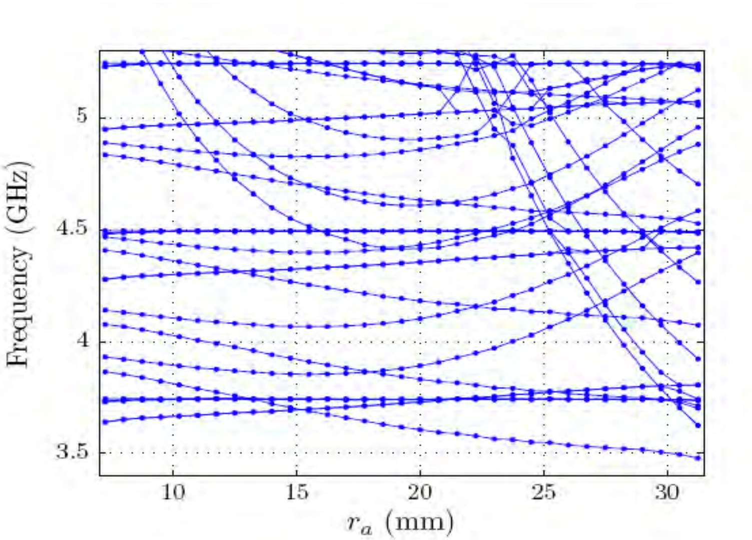
Comsol Results

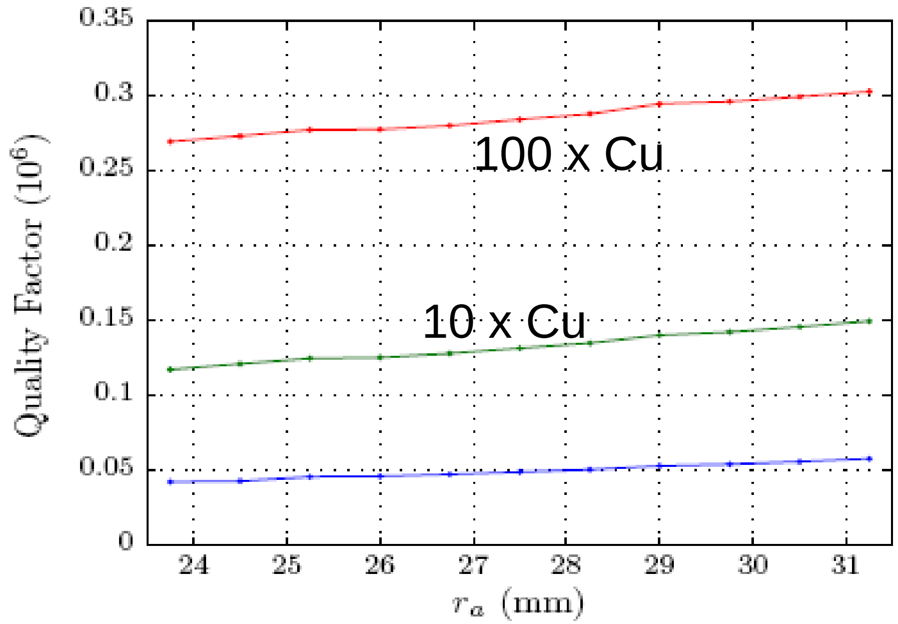




10 cm diameter, 15 cm long cavity; effect of coating only the cylinder and both cylinder/tuning rods with superconductor

20 cm long, 7.5 cm dia cavity, 4   1 cm rods

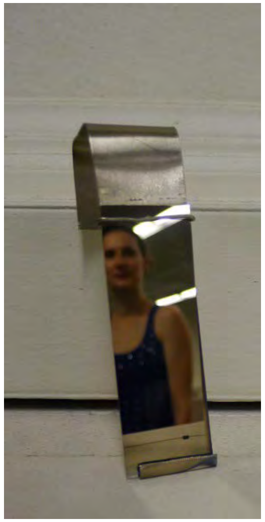




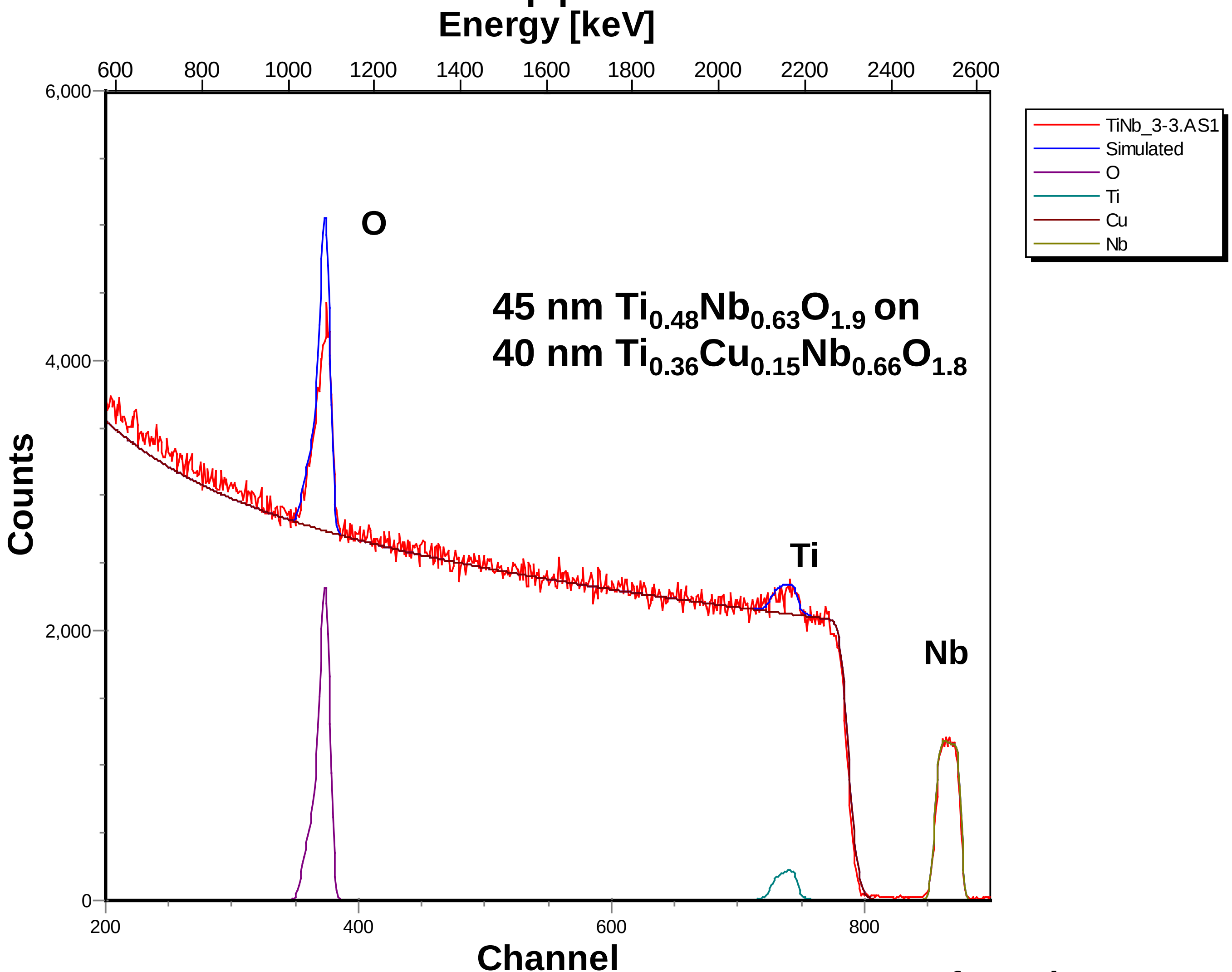
Requirements

- Need 100 times better conductivity than Cu in the anomalous skin depth region
- At any frequency other than “0”, a superconductor presents a finite resistance
- Vortices increase this resistance, and the vortex density is proportional to the perpendicular field
- <100 G perpendicular field is required– need well-designed magnet, careful alignment (.01 T/10 T=.001 radians=.06 deg)
- Magnet has been designed and built for ADMX-HF, by Cryomagnetics, Oak Ridge

R&D has already begun on NbTiN superconducting coatings

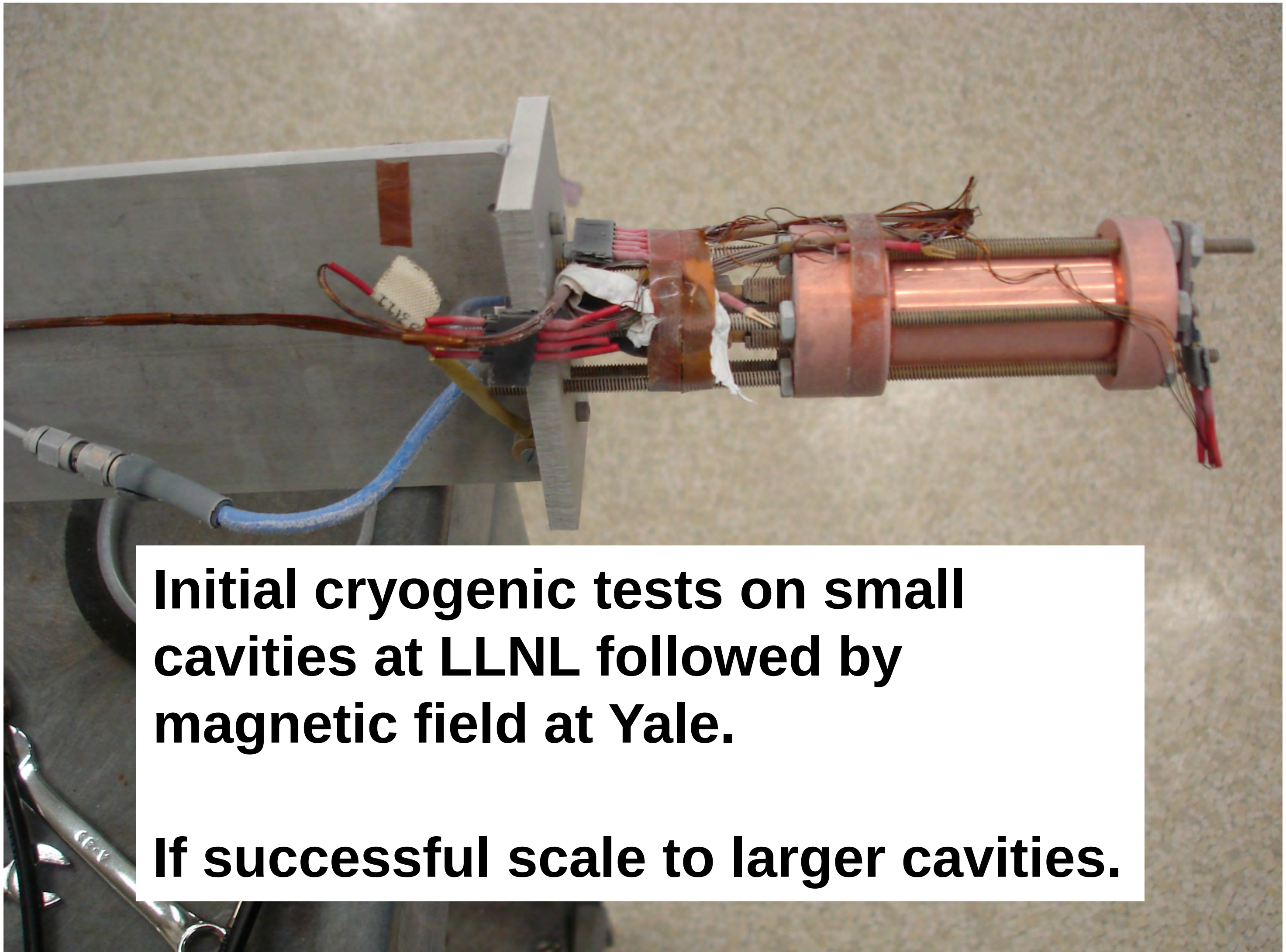


Rutherford backscattering of 20 min NbTi deposition on copper foil



***courtesy of Dr. Kin Man Yu of LBNL**

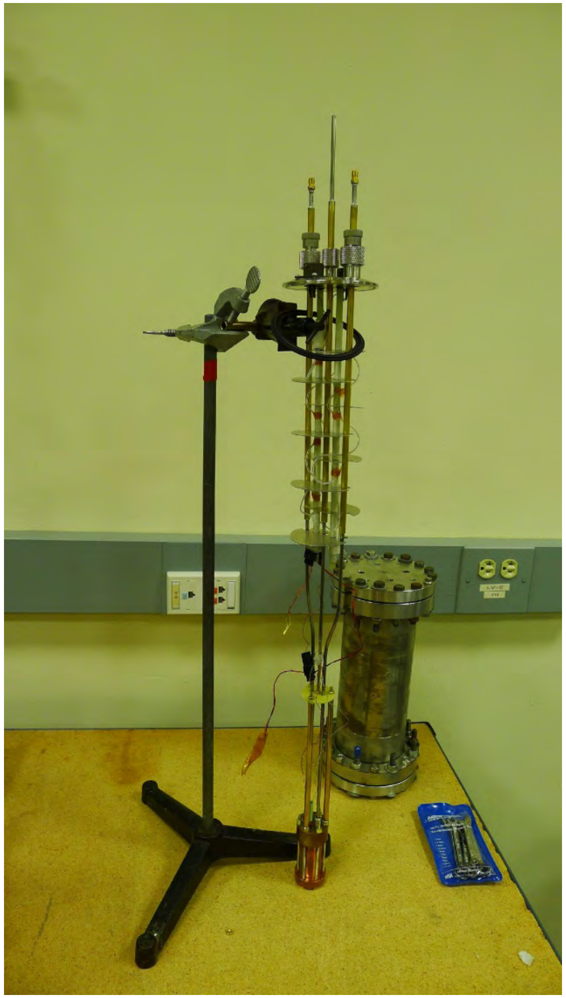
Superconducting coatings will be placed on 1” cavity barrels

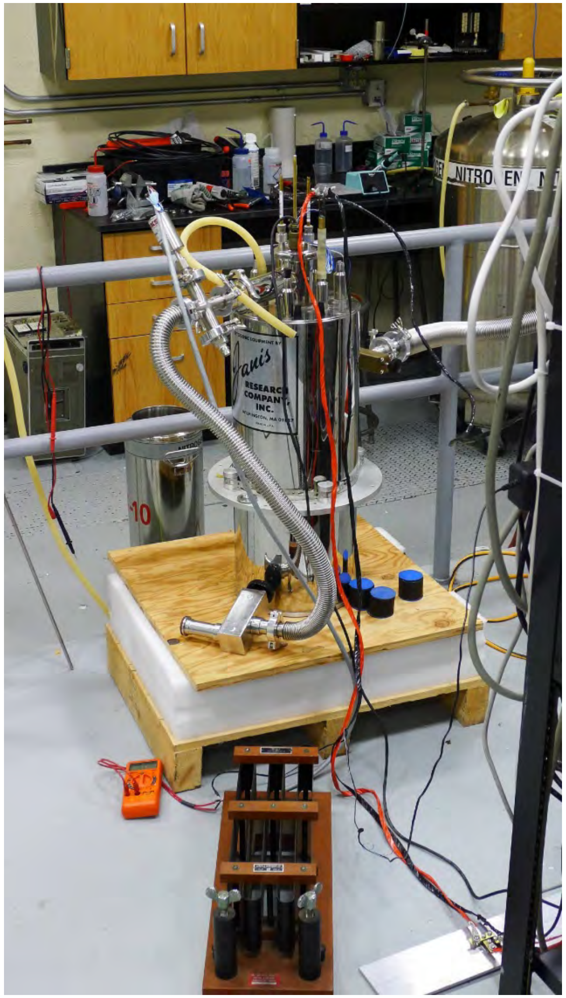


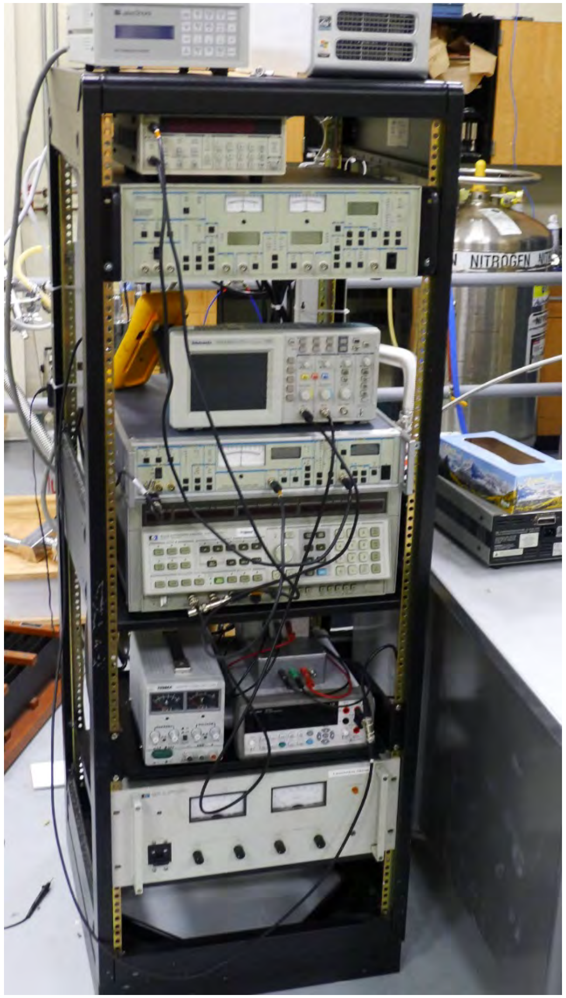
Initial cryogenic tests on small cavities at LLNL followed by magnetic field at Yale.

If successful scale to larger cavities.

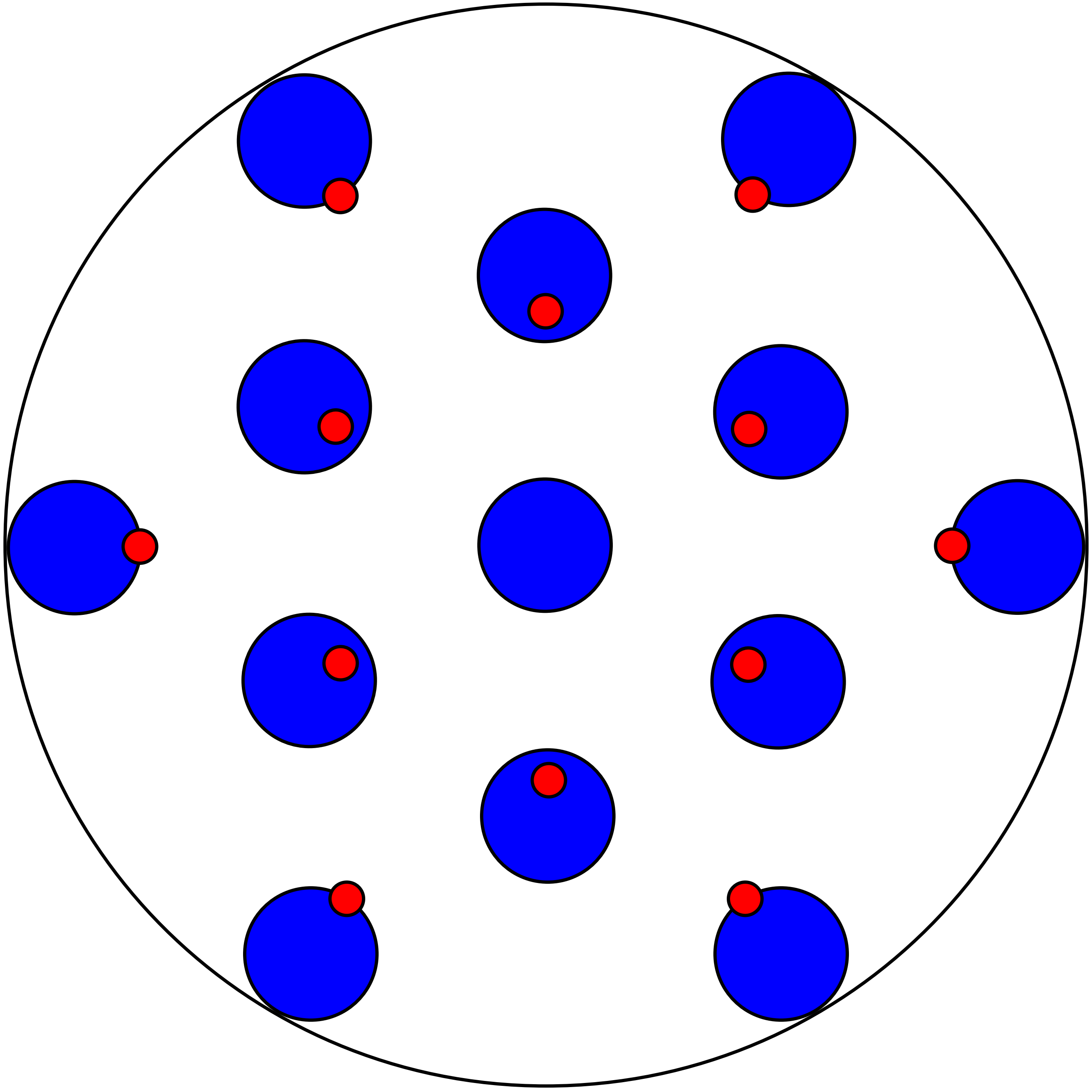
Test Apparatus at Yale



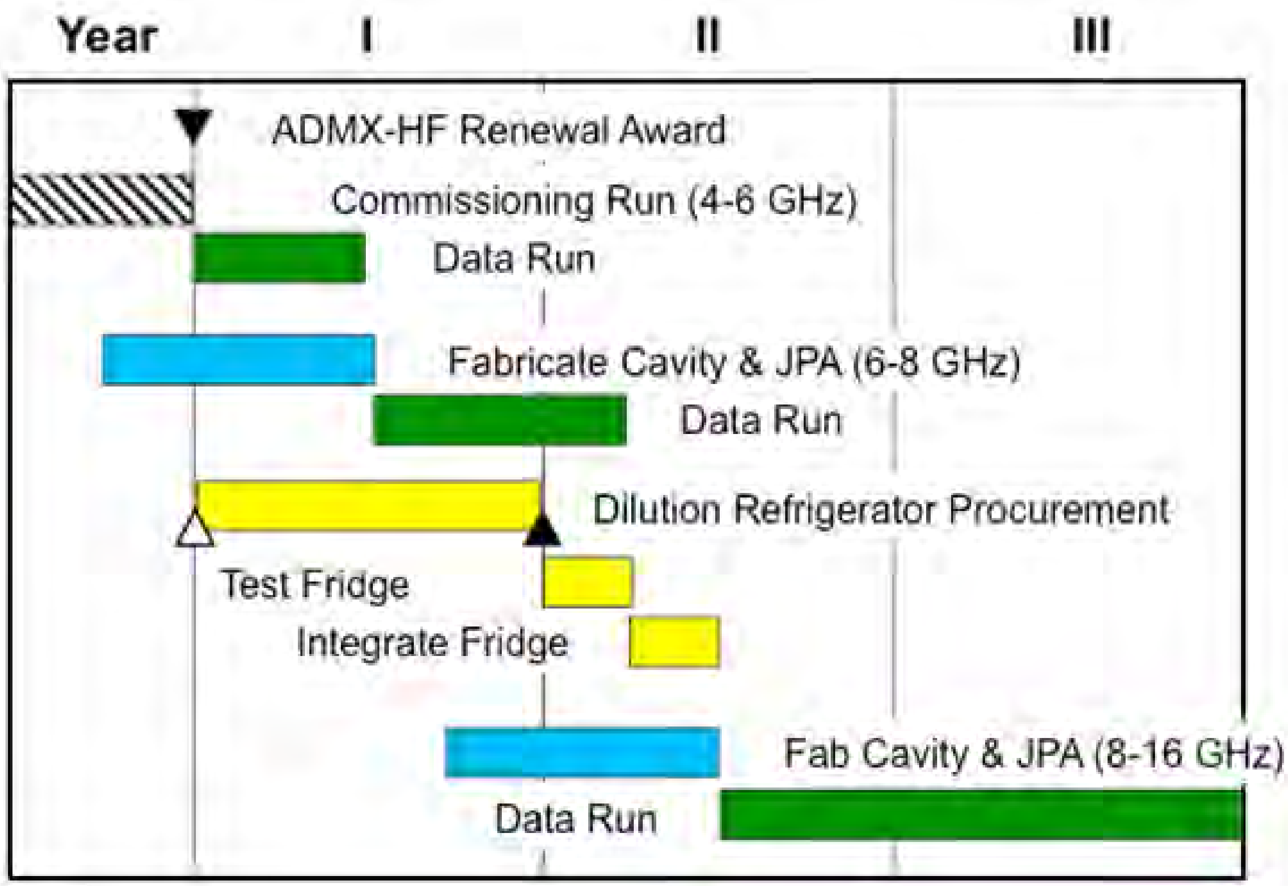




Improved Higher Frequency Cavity



Schedule


Year
I
II
III
ADMX-HF Renewal Award
Commissioning Run (4-6 GHz)
Data Run
Fabricate Cavity & JPA (6-8 GHz)
Data Run
Dilution Refrigerator Procurement
Test Fridge
Integrate Fridge
Fab Cavity & JPA (8-16 GHz)
Data Run