

# Future prospects for axion haloscopes

Multiple cavities and really strong magnets

DBT

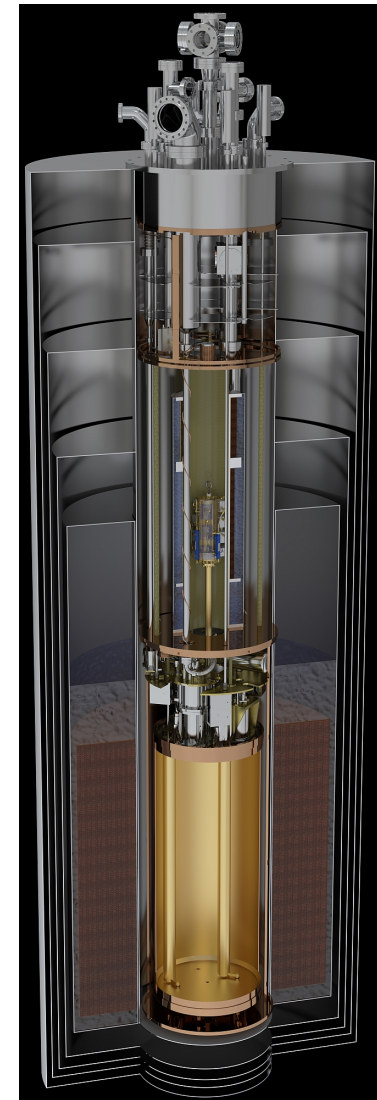
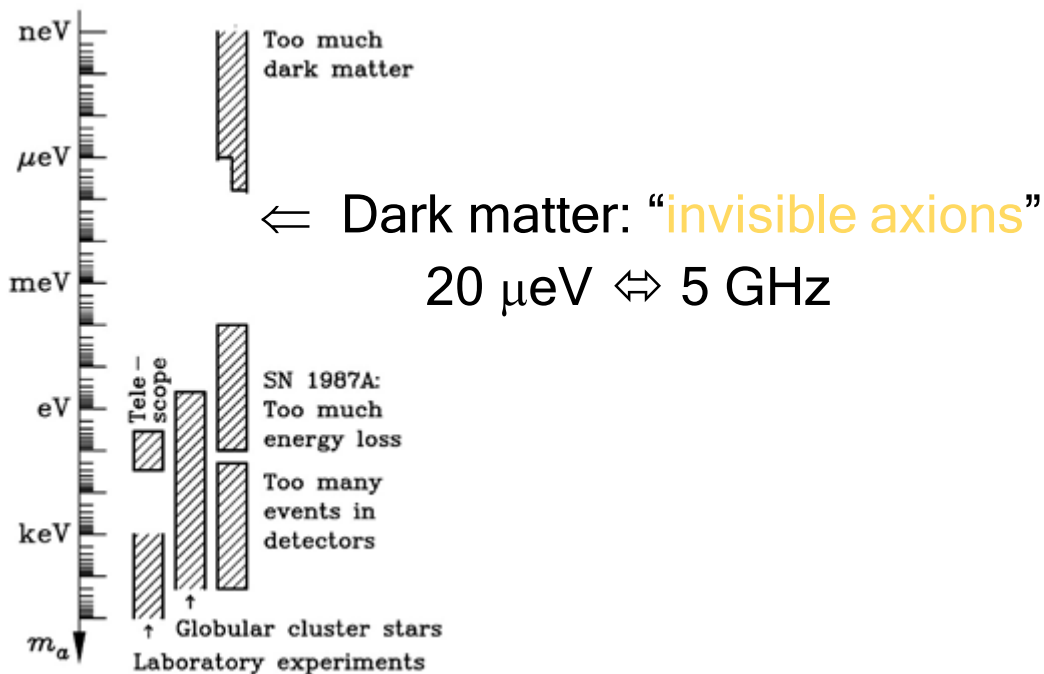
University of Florida

for the ADMX collaboration  
(with Mark Bird, Ian Dixon,  
Seungyong Hahn, Huub  
Weijers,  
and Ziad Melhem)



# Background

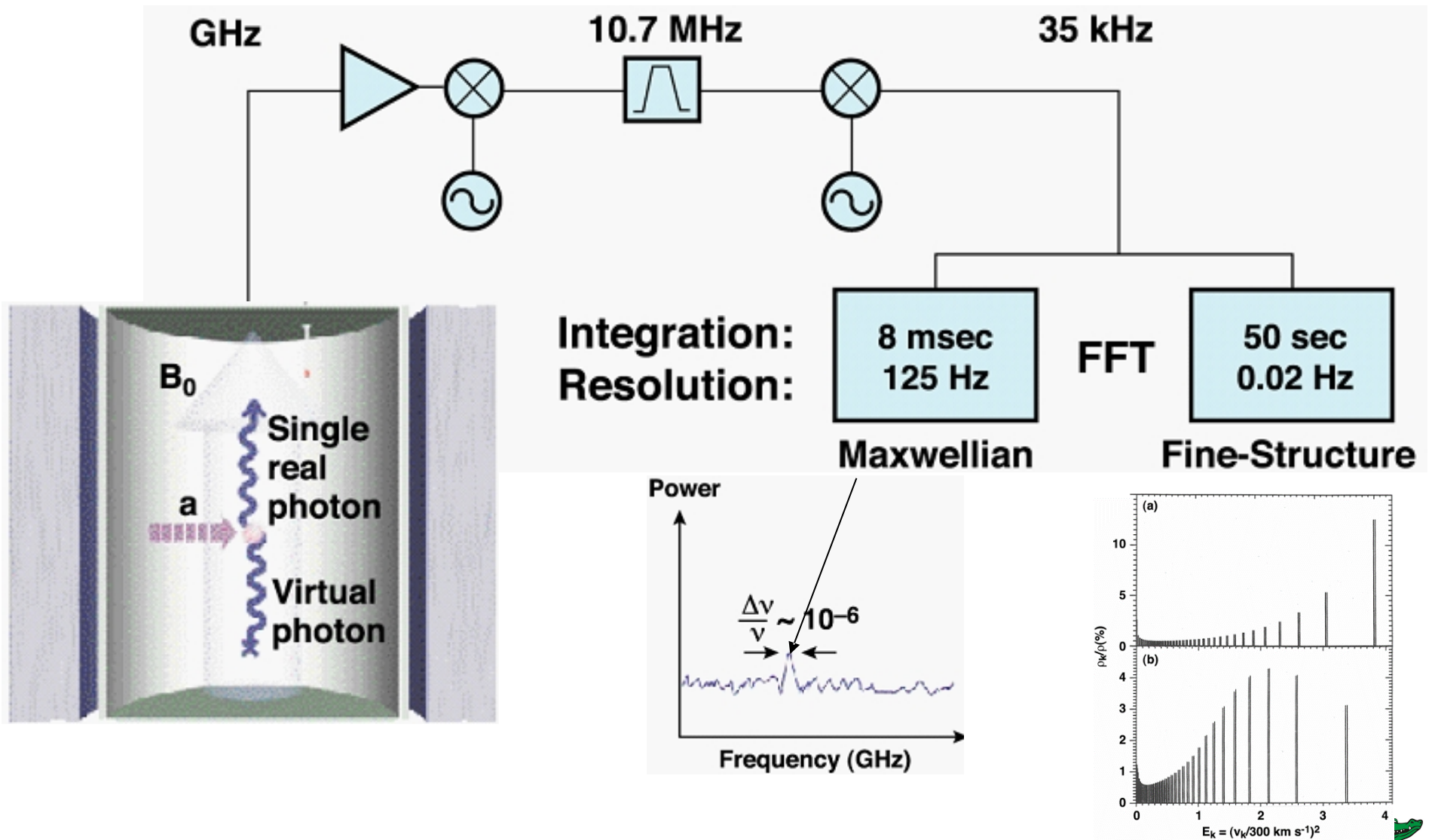
- Good evidence for dark matter in the universe
- The axion is a promising candidate
  - Strong CP problem -> PQ -> axion
  - Invisible axion
- Sikivie's axion haloscope made the axion visible
- As we heard this morning, ADMX is sensitive to the most weakly coupled (DFSZ) axions



ADMX



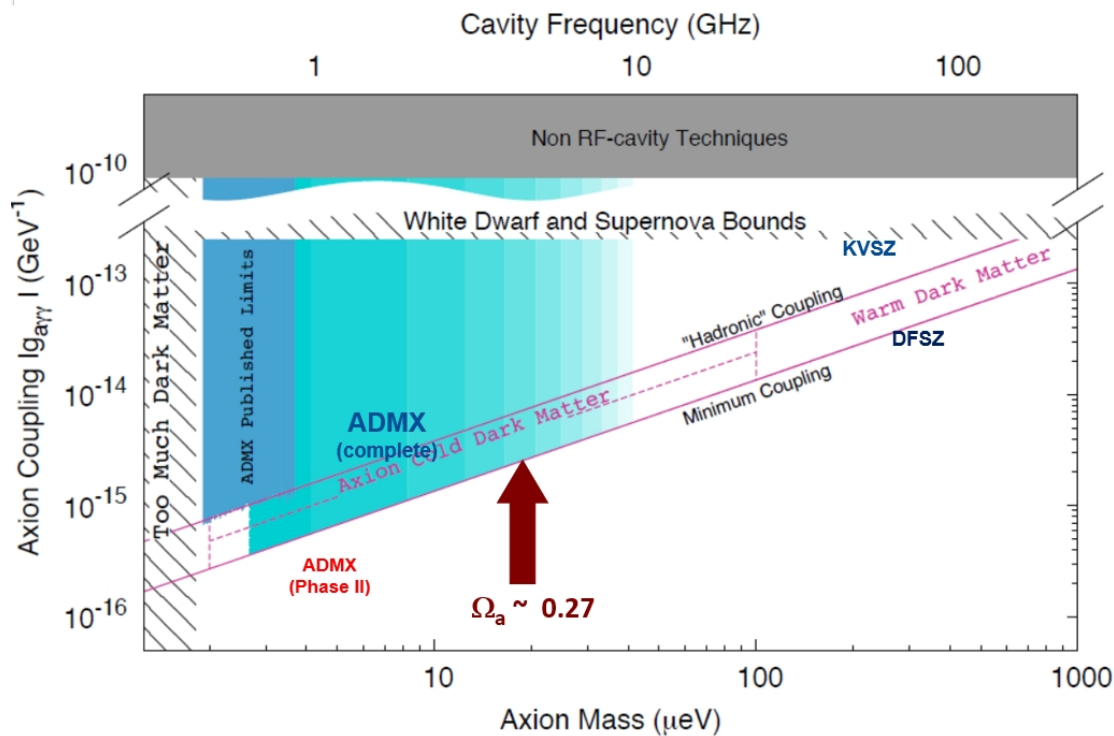
# Cavity axion detector



# ADMX should procure a new magnet

Higher field → Smaller volume → Search higher frequencies,

$$\frac{r}{1 \text{ cm}} = \frac{11.5 \text{ GHz}}{f}$$



## The signals are very weak

- Power from the cavity goes as  $B^2 V$

$$P = 130 \text{ yW} \left( \frac{V}{200 \ell} \right) \left( \frac{B_0}{8 \text{ Tesla}} \right)^2 \left( \frac{C_{nl}}{0.5} \right) \left( \frac{g_\gamma}{0.36} \right)^2 \cdot \left( \frac{\rho_a}{0.5 \text{ yg/cm}^3} \right) \left( \frac{f_a}{1 \text{ GHz}} \right) \left( \frac{Q_L}{100,000} \right)$$

- $1 \text{ GHz} \Leftrightarrow 4 \text{ } \mu\text{eV} \Leftrightarrow 50 \text{ mK}$
- 130 yW is about 200 photons/sec
- Axion signal ( $mc^2 + \text{kinetic energy}$ )  $\sim \text{kHz}$  in width @ GHz
- $C_{nl}$  is a form factor, overlap of  $\vec{E} \cdot \vec{B}_0$  in the cavity  $\sim 0.5$
- $g_\gamma \sim 0.36$  (DFSZ) while  $g_\gamma \sim 0.97$  (KSVZ)
- $Q_L \sim 120,000 (\text{GHz}/f)^{2/3}$  (ASE) so bandwidth is 10 kHz



# Search rate set by radiometer equation

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$$\frac{s}{n} = \frac{P}{kT_n} \sqrt{\frac{t}{\Delta f}}$$

- Search rate is set by desired snr, emitted power<sup>2</sup>, cavity  $Q$ , and system noise temperature

$$\frac{df}{dt} = 3 \text{ GHz/yr} \left( \frac{5}{s/n} \right)^2 \left( \frac{V}{200 \ell} \right)^2 \left( \frac{B_0}{8 \text{ Tesla}} \right)^4 \left( \frac{C_{nl}}{0.5} \right)^2 \left( \frac{g_\gamma}{0.36} \right)^4 \cdot \left( \frac{\rho_a}{0.5 \cdot 10^{-24} \text{ g/cm}^3} \right)^2 \left( \frac{f_a}{1 \text{ GHz}} \right)^2 \left( \frac{Q_L}{100,000} \right) \left( \frac{100 \text{ mK}}{T_n} \right)^2$$

- SQUID amplifiers have excess noise about half their physical temperature ( $\sim 100 \text{ mK}$ )
- When  $hf \sim kT$ , shot noise appears
- System noise temperature  $\sim T + T/2 + hf/k$



# Strawman: Single cavity

- Single cylinder, 8 T field; change size to resonate at search frequency

$$P = 130 \text{ yW} \left( \frac{1 \text{ GHz}}{f} \right)^{2.67}$$

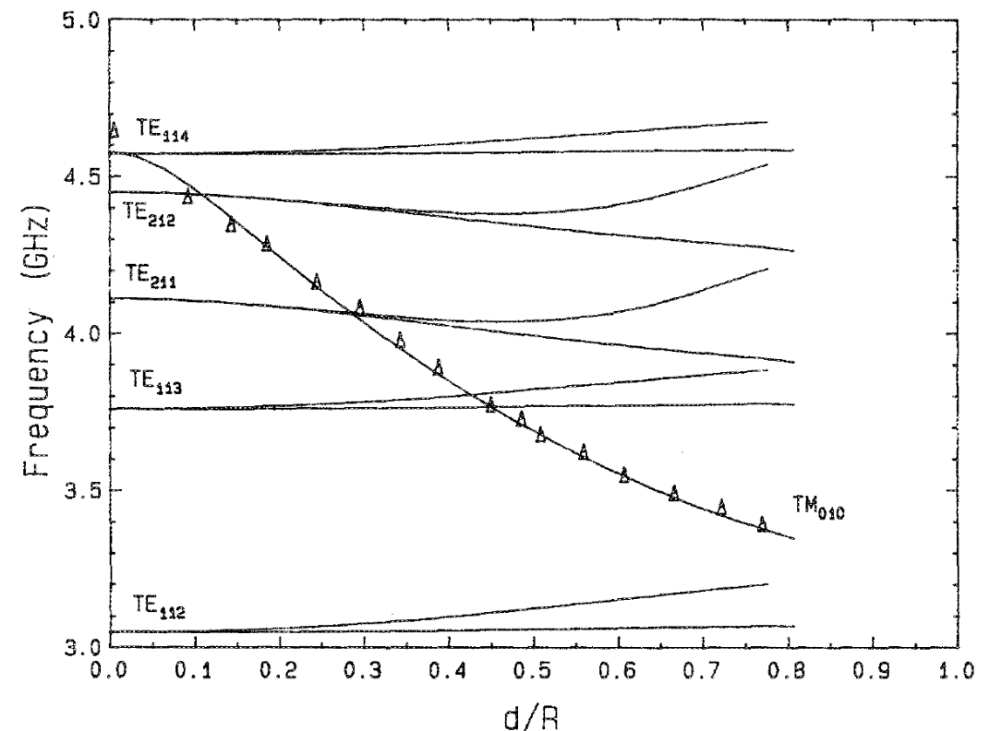
- Volume decreases as  $f^{-3}$ , the  $Q$  decreases as  $f^{-2/3}$  while the mass increases as  $f$

- Length as well as diameter changes because the cavity cannot get too long

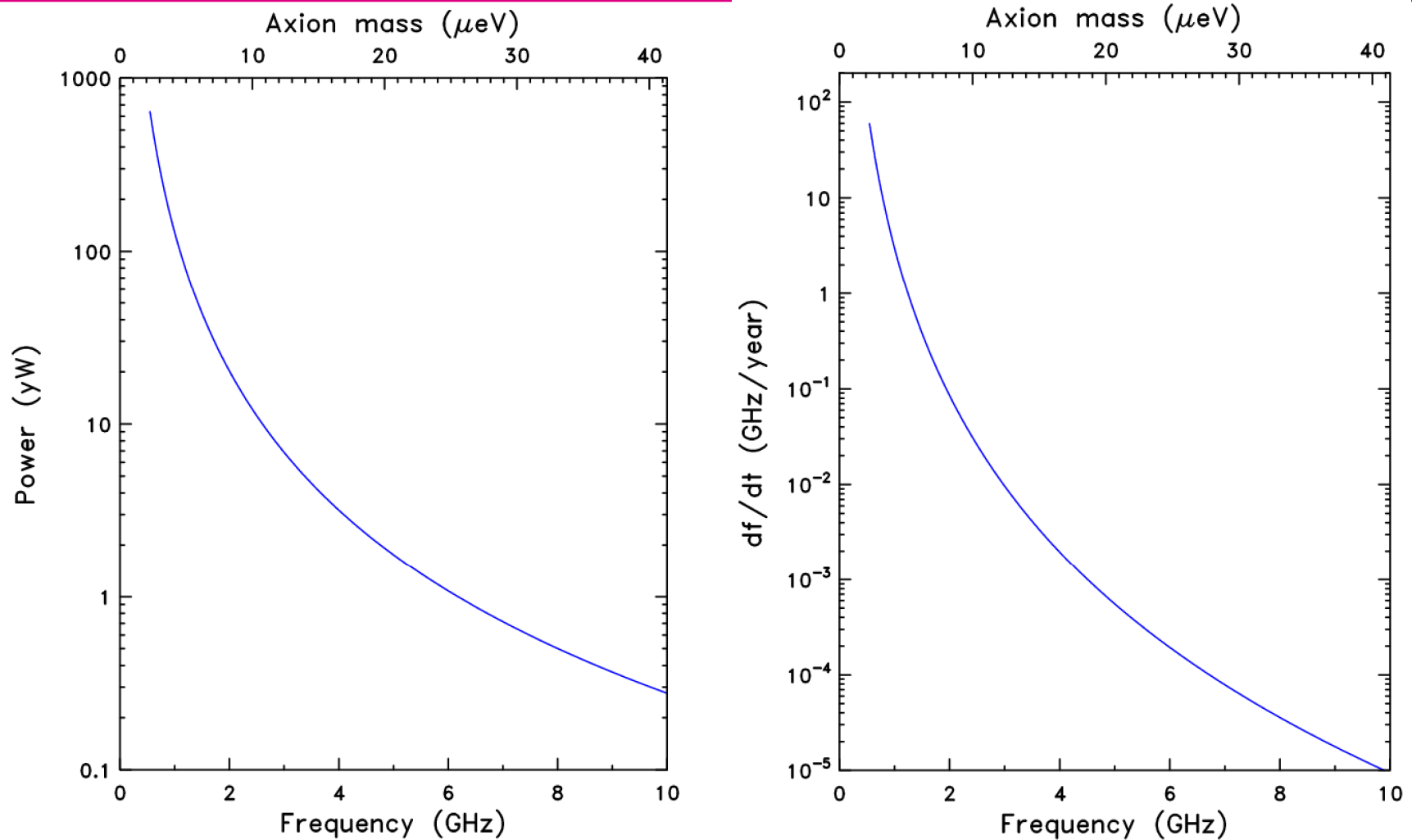
- The longer the cavity, the more TE/TEM modes there are

- Typically:

$$L \sim 4.4r$$



# Strawman: Single cavity



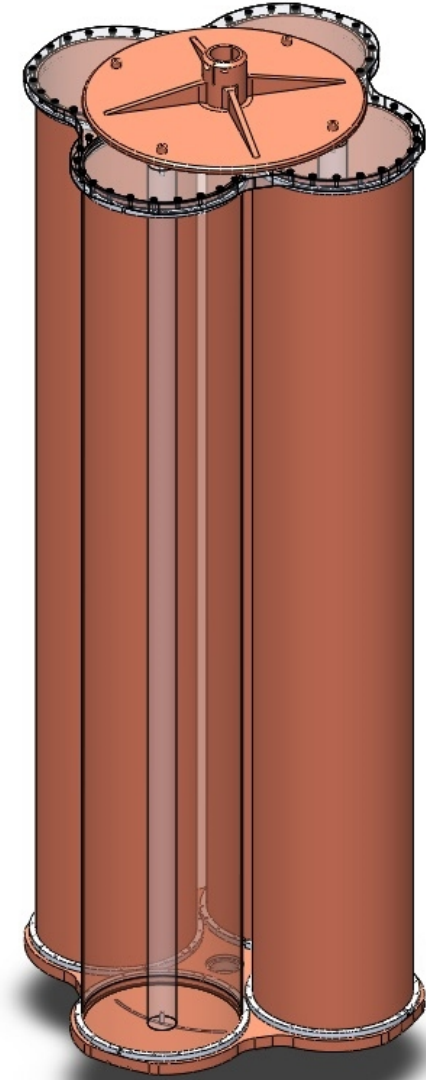
- Power and scan rate decrease as frequency goes up ☹️
- Just the opposite of what we want.



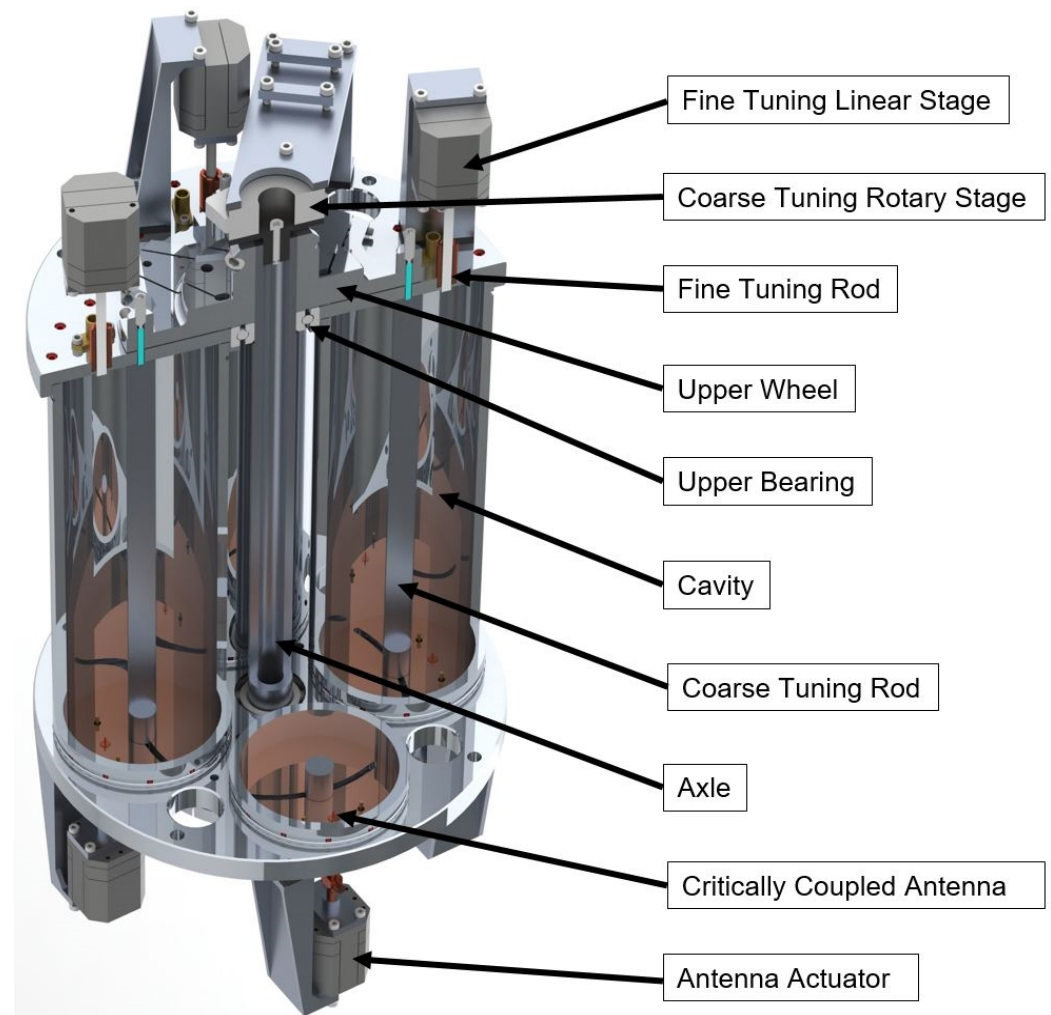
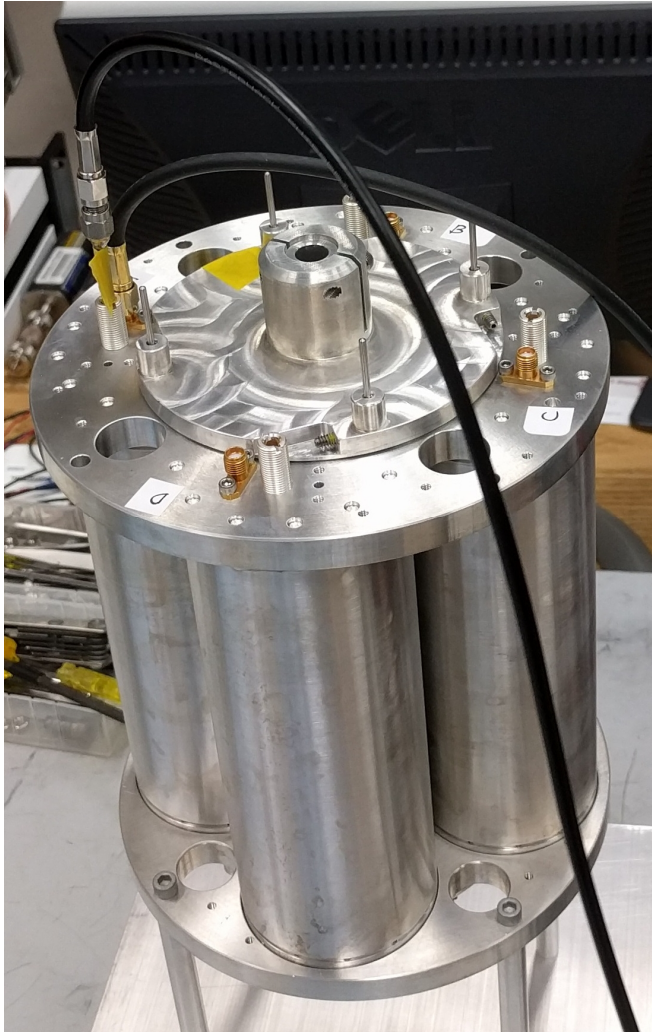
# Multiple cavities

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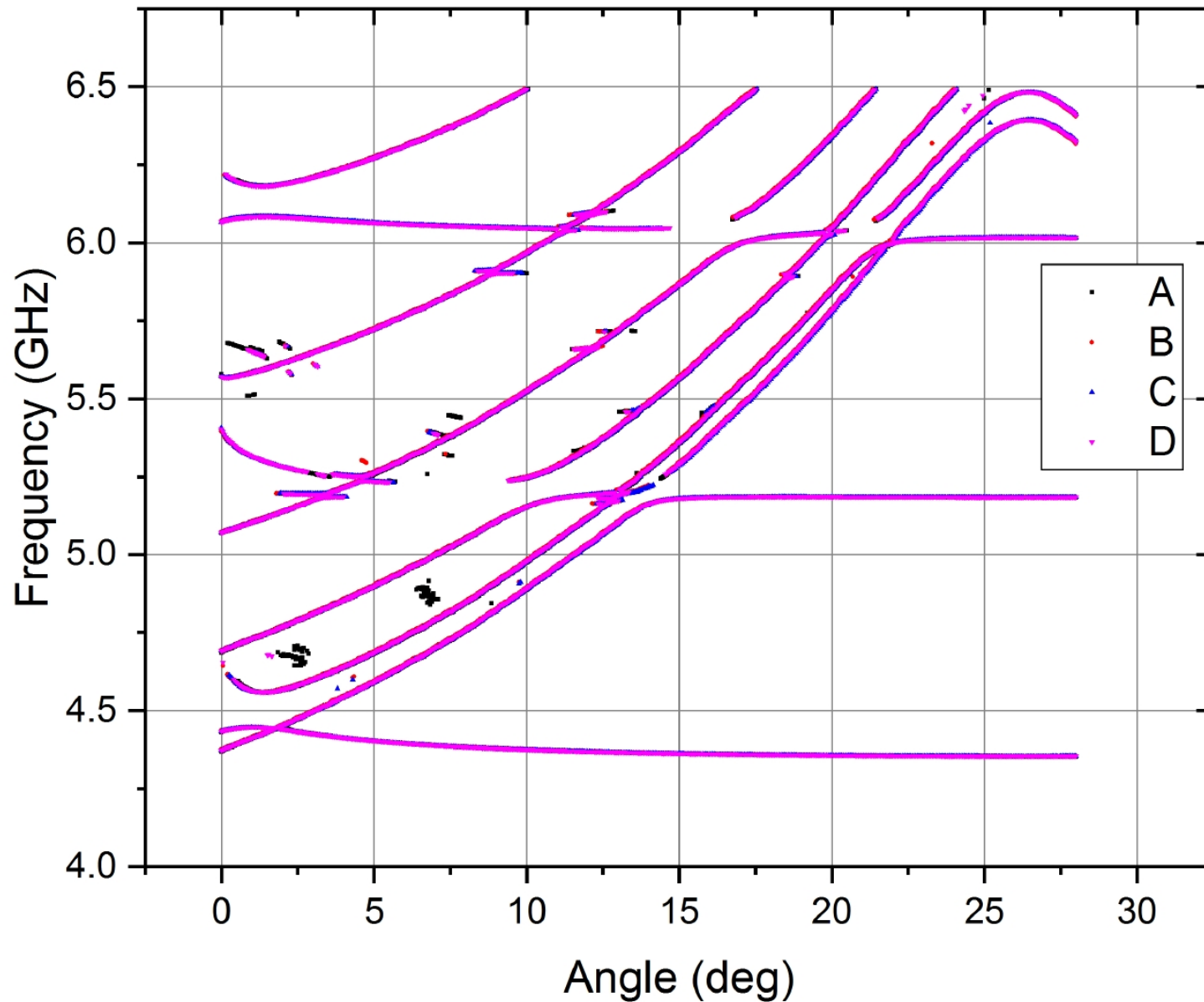
- Fix 1: Use multiple cavities, tuned together and added in phase
- 4 cavities will allow search over 1.4–2 GHz (5.8–8.3  $\mu\text{eV}$ )
- To start fall 2019



# Prototype: 1/3 scale model



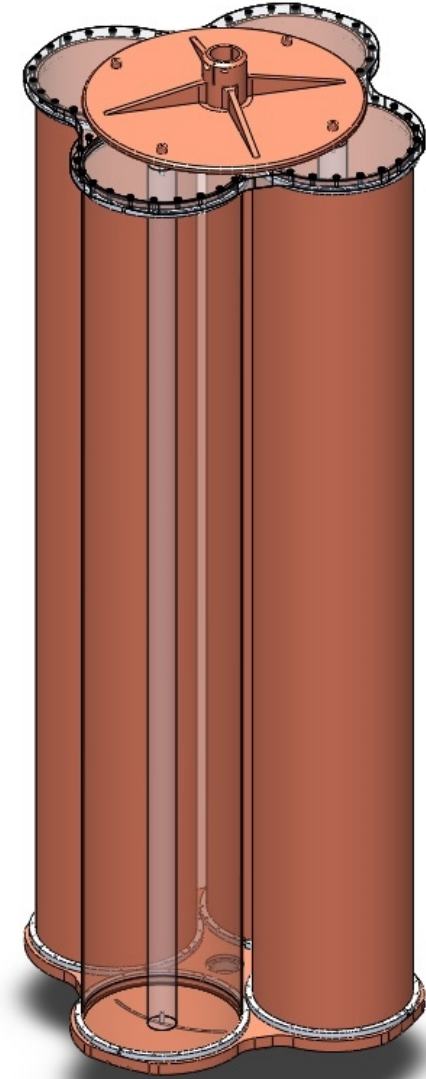
All four cavities track each other reasonably well (servo matches them within  $Q/20$ )



## Above 2 GHz

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- Can use ~16 cavities to cover to 6 GHz
- Complexity reduced at a given frequency if volume of high-field space is decreased
- Lower volume means weaker signal, so need to compensate with higher field
- $B^2V$  is the factor to maintain
- So a stronger magnet is needed!



# Goals and requirements

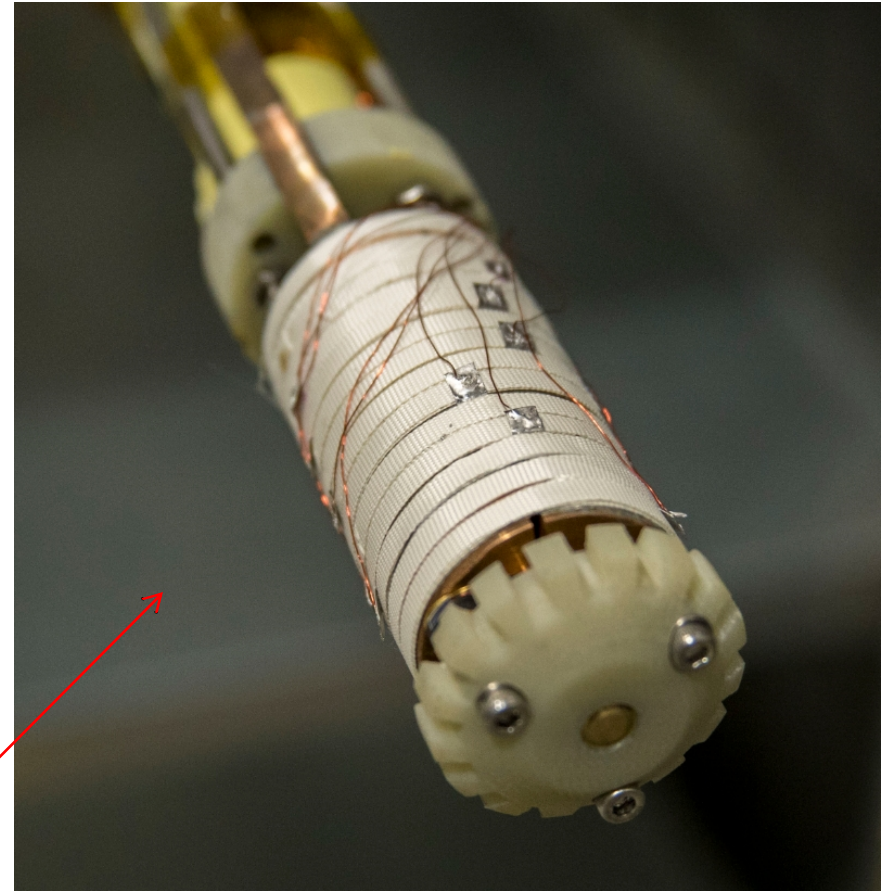
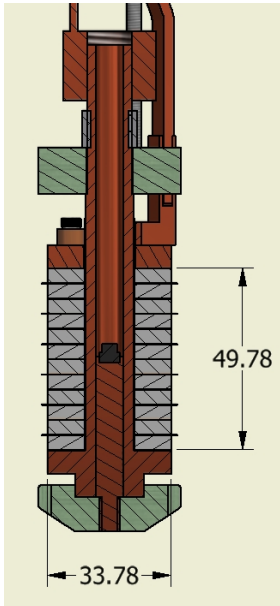
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- The design must be sensitive to the most weakly coupled axions (DFSZ) and be able to detect axions with mass up to  $\sim 40 \mu\text{eV}$ 
  - Cavity resonance: up to  $\sim 10 \text{ GHz} \Leftrightarrow 40 \mu\text{eV}$
- Measurement times and scan rates similar to current ADMX
- Magnet must be
  - Able to go to max field and stay there for 3 months
  - Reliable. A quench damages SQUID amplifier; destroys circulators; deforms cavity
- Magnet requirements strongly connected to cavity, RF system, and cryogenics
- Integrated dilution fridge:  $800 \mu\text{W}$  at  $100 \text{ mK}$
- Integrated “bucking coil” to provide zero-field region for SQUID/JPA



# NHMFL No-Insulation Magnet Technology

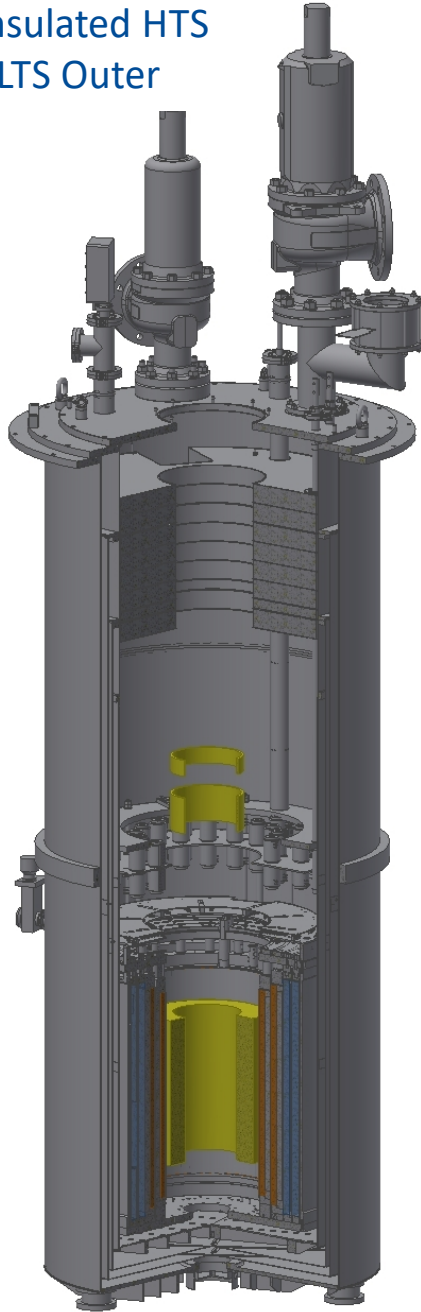
- 42.5 T test magnet
  - Total central field = 42.5 T
    - No-insulation coil = 11.5 T
    - Resistive magnet = 31.0 T
  - Reached 1151 A/mm<sup>2</sup>
  - HTS tape thickness = 42  $\mu$ m (5  $\mu$ m Cu on each side)



Seungyong Hahn and Ian Dixon

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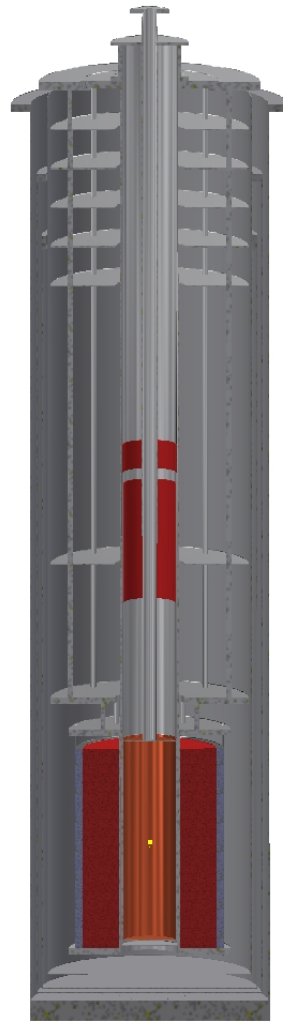
26 T Insulated HTS  
w/ LTS Outer



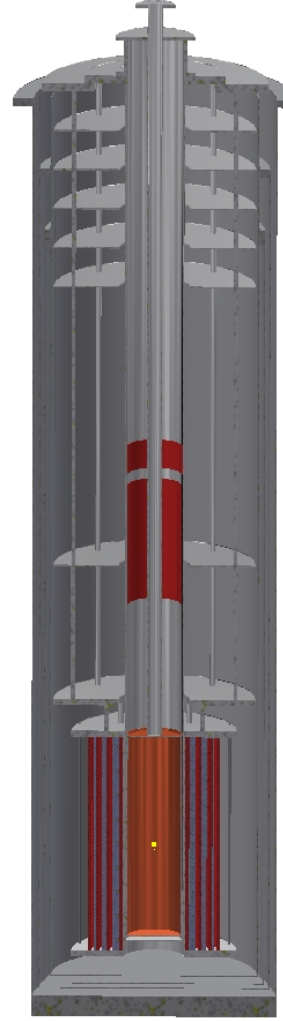
1  
m



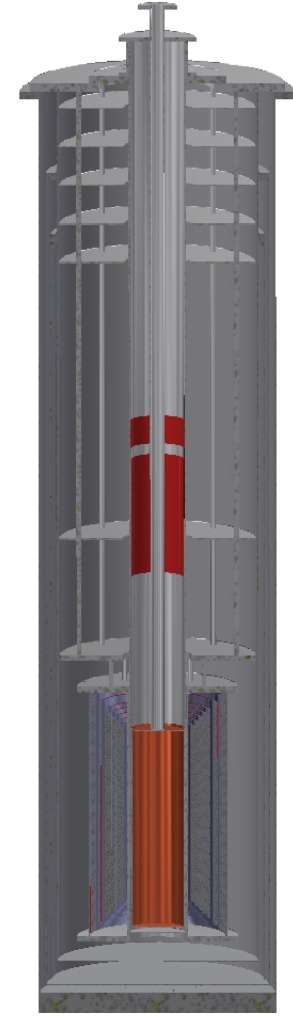
30 T Single No-  
Insulation Coil



31 T 4-Coil HTS  
No-Insulation



30 T Cabled  
HTS Coil



ADMX



So now lets see how useful various magnet designs are

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$$P = 130 \text{ yW} \left( \frac{V}{200 \ell} \right) \left( \frac{B_0}{8 \text{ Tesla}} \right)^2 \left( \frac{C_{nl}}{0.5} \right) \left( \frac{g_\gamma}{0.36} \right)^2 \cdot \left( \frac{\rho_a}{0.5 \text{ yg/cm}^3} \right) \left( \frac{f_a}{1 \text{ GHz}} \right) \left( \frac{Q_L}{100,000} \right)$$

$$\frac{df}{dt} = 3 \text{ GHz/yr} \left( \frac{5}{s/n} \right)^2 \left( \frac{V}{200 \ell} \right)^2 \left( \frac{B_0}{8 \text{ Tesla}} \right)^4 \left( \frac{C_{nl}}{0.5} \right)^2 \left( \frac{g_\gamma}{0.36} \right)^4 \cdot \left( \frac{\rho_a}{0.5 \cdot 10^{-24} \text{ g/cm}^3} \right)^2 \left( \frac{f_a}{1 \text{ GHz}} \right)^2 \left( \frac{Q_L}{100,000} \right) \left( \frac{100 \text{ mK}}{T_n} \right)^2$$



# ADMX

| Magnet | Diam | TM <sub>010</sub><br>freq | B<br>T | Cavities | Total V<br>liters | Tnoise<br>K | P<br>yW | Time for<br>an oactive<br>months |
|--------|------|---------------------------|--------|----------|-------------------|-------------|---------|----------------------------------|
| ADMX   | 42   | 0.55                      | 7.4    | 1        | 138               | 0.17        | 107     | 16                               |
| ADMX   | 17   | 1.3                       | 7.4    | 4        | 95                | 0.19        | 240     | 14                               |



## “NMR” magnet, including latest Bruker

| Magnet     | Diam | TM <sub>010</sub> | B   | Cavities | Total V | Tnoise | P   | Time for<br>an octive<br>months |
|------------|------|-------------------|-----|----------|---------|--------|-----|---------------------------------|
|            | cm   | freq              | T   |          | liters  | K      | yW  |                                 |
| ADMX       | 42   | 0.55              | 7.4 | 1        | 138     | 0.17   | 107 | 16                              |
| ADMX       | 17   | 1.3               | 7.4 | 4        | 95      | 0.19   | 240 | 14                              |
| "NMR"      | 5    | 4.3               | 18  | 1        | 0.3     | 0.17   | 3   | 38269                           |
| Bruker NMR | 5    | 4.3               | 28  | 1        | 0.3     | 0.17   | 8   | 6536                            |



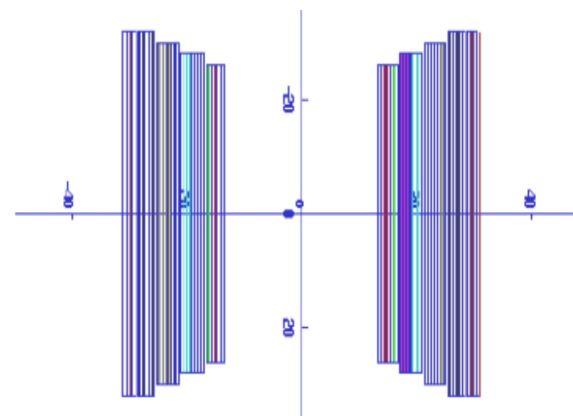
## 32 T, 6 inch diameter NI ReBCO design from NHMFL

| Magnet     | Diam | $TM_{010}$ | B   | Cavities | Total V | Tnoise | P   | Time for<br>an oactive<br>months |
|------------|------|------------|-----|----------|---------|--------|-----|----------------------------------|
|            | cm   | freq       | T   |          | liters  | K      | yW  |                                  |
| ADMX       | 42   | 0.55       | 7.4 | 1        | 138     | 0.17   | 107 | 16                               |
| ADMX       | 17   | 1.3        | 7.4 | 4        | 95      | 0.19   | 240 | 14                               |
| "NMR"      | 5    | 4.3        | 18  | 1        | 0.3     | 0.17   | 3   | 38269                            |
| Bruker NMR | 5    | 4.3        | 28  | 1        | 0.3     | 0.17   | 8   | 6536                             |
| NI ReBaCuO | 15   | 1.5        | 32  | 1        | 7       | 0.17   | 134 | 15                               |
| NI ReBaCuO | 6    | 3.6        | 32  | 4        | 5       | 0.24   | 297 | 20                               |



# Large diameter NbTi/Nb<sub>3</sub>Sn magnet

| Magnet                 | Diam<br>cm | TM <sub>010</sub><br>freq | B<br>T | Cavities | Total V<br>liters | Tnoise<br>K | P<br>yW | Time for<br>an oactive<br>months |
|------------------------|------------|---------------------------|--------|----------|-------------------|-------------|---------|----------------------------------|
| ADMX                   | 42         | 0.55                      | 7.4    | 1        | 138               | 0.17        | 107     | 16                               |
| ADMX                   | 17         | 1.3                       | 7.4    | 4        | 95                | 0.19        | 240     | 14                               |
| "NMR"                  | 5          | 4.3                       | 18     | 1        | 0.3               | 0.17        | 3       | 38269                            |
| Bruker NMR             | 5          | 4.3                       | 28     | 1        | 0.3               | 0.17        | 8       | 6536                             |
| NI ReBaCuO             | 15         | 1.5                       | 32     | 1        | 7                 | 0.17        | 134     | 15                               |
| NI ReBaCuO             | 6          | 3.6                       | 32     | 4        | 5                 | 0.24        | 297     | 20                               |
| Big Nb <sub>3</sub> Sn | 120        | 0.19                      | 15     | 1        | 565               | 0.31        | 701     | 0.5                              |
| Big Nb <sub>3</sub> Sn | 13         | 1.8                       | 15     | 64       | 430               | 0.81        | 10234   | 0.3                              |

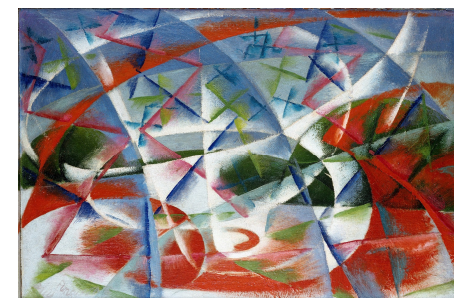


ADMX



# Futurism

| Magnet        | Diam | TM <sub>010</sub><br>freq | B<br>T | Cavities | Total V<br>liters | Tnoise<br>K | P<br>yW | Time for<br>an oactive<br>months |
|---------------|------|---------------------------|--------|----------|-------------------|-------------|---------|----------------------------------|
| ADMX          | 42   | 0.55                      | 7.4    | 1        | 138               | 0.17        | 107     | 16                               |
| ADMX          | 17   | 1.3                       | 7.4    | 4        | 95                | 0.19        | 240     | 14                               |
| "NMR"         | 5    | 4.3                       | 18     | 1        | 0.3               | 0.17        | 3       | 38269                            |
| Bruker NMR    | 5    | 4.3                       | 28     | 1        | 0.3               | 0.17        | 8       | 6536                             |
| NI ReBaCuO    | 15   | 1.5                       | 32     | 1        | 7                 | 0.17        | 134     | 15                               |
| NI ReBaCuO    | 6    | 3.6                       | 32     | 4        | 5                 | 0.24        | 297     | 20                               |
| Big Nb3Sn     | 120  | 0.19                      | 15     | 1        | 565               | 0.31        | 701     | 0.5                              |
| Big Nb3Sn     | 13   | 1.8                       | 15     | 64       | 430               | 0.81        | 10234   | 0.3                              |
| 55 T NI ReBCO | 14   | 1.6                       | 55     | 1        | 2                 | 0.14        | 122     | 11                               |



# Conclusions

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- As we heard this morning, ADMX is operating at DFSZ sensitivity
- Technology in hand to detect the axion if the mass is in the 1.2 to 8.3 meV range ( $mc^2/h = 0.33$  to 2 GHz)
- A 32 T HTSC magnet could allow a search up to 40  $\mu\text{eV}$  (10 GHz)

He who controls  
magnetism will control  
the universe

- It is an exciting time for axion researchers!



THE END

ADMX

