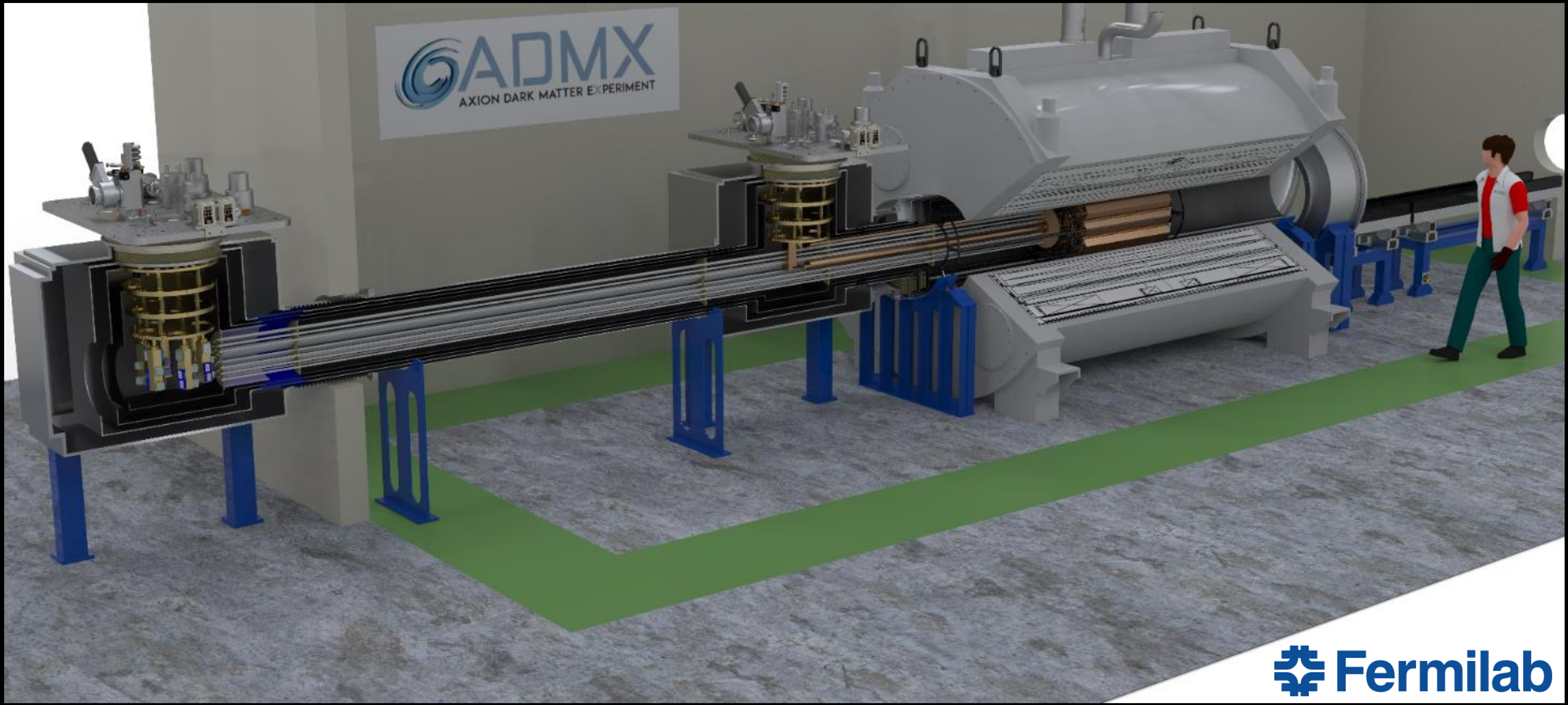


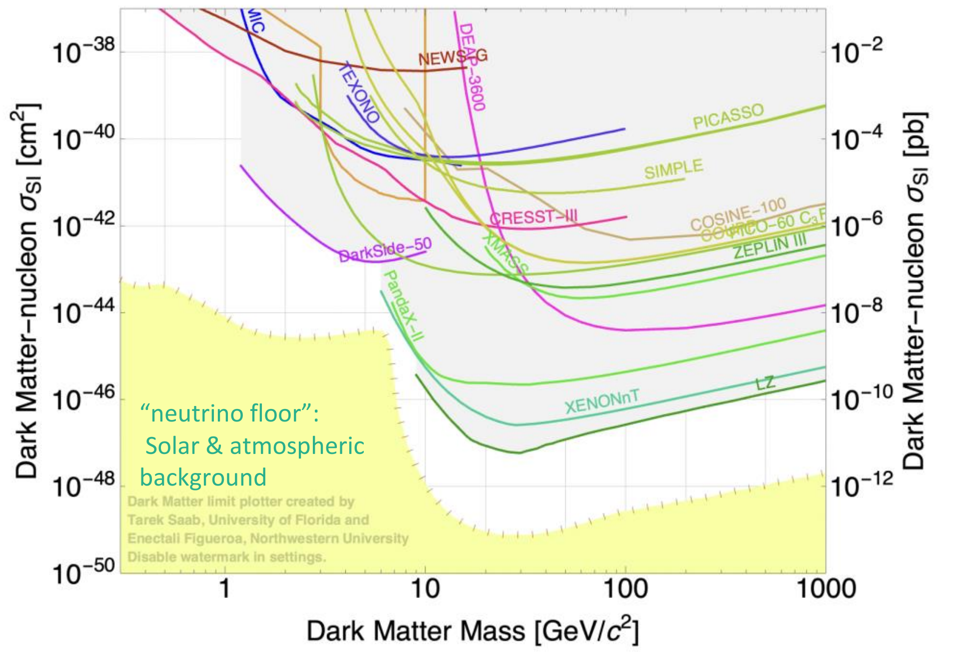
Plans for Fermilab Dark Wave Lab

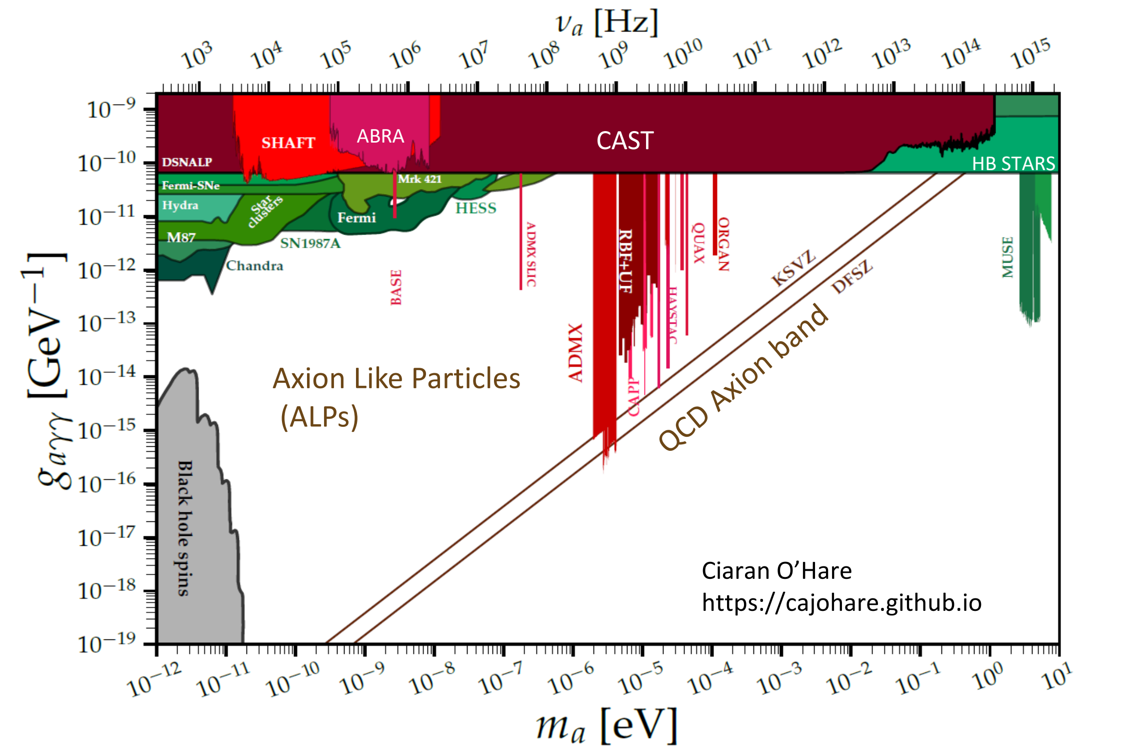
Andrew Sonnenschein, *Fermilab*
Axions 2024
University of Florida
26-April-2024

Dark Matter Searches: WIMPs Vs Axions

- WIMPs and WIMP-like
  - Field started with Goodman and Witten PRD 1985, "Detectability of Certain Dark Matter Candidates".
  - First experiments by Avignone & Caldwell groups in 1987.
  - Dramatic progress in attempted WIMP detection from 1987- 2020. Most models previously considered promising are now excluded.
- Axions and ALPs
  - Field starts with Sikivie 1983 PRL "Experimental Tests of Invisible axion", followed by Sullivan and Tanner experiments.
  - Relatively few completed experiments between 1983-2020. Dominated by one technique.
  - New techniques needed to reach required sensitivity.

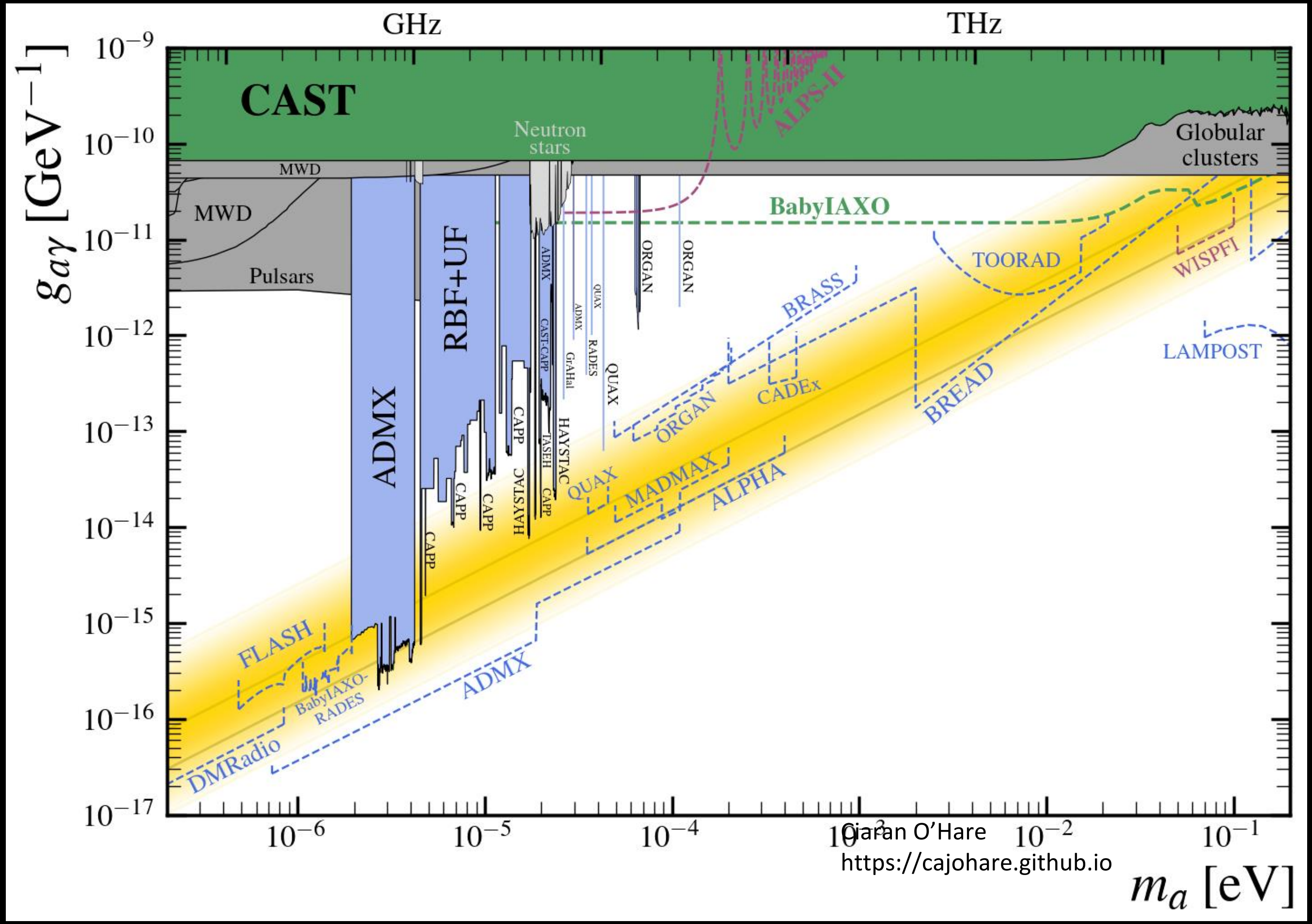
> 100 completed projects/ experiments





Axion Detection– Future Program

- Experimental axion search field is bursting with new ideas.
- Future program claims to cover QCD axion band from ~10^{-9} eV to 1 eV using a combination of techniques.
- Very ambitious!
- Similar to what happened in WIMP field in the 1990s-2020s
- Not clear how long this will take!



Need for National Lab/ University Partnerships

- Techniques exploring axion-photon coupling generally benefit from highest possible magnetic field strength and volume (signal ~ B^2V) and lowest possible temperature for noise reduction.
- Most successful experiments so far– ADMX, CAST, CAPP required large investments in magnet and cryo infrastructure.
- One lesson from ADMX-- difficult to build and maintain reliable systems at this scale over long running periods in a university environment.
- Requirements for large-scale infrastructure, technical support and safety best met at a national lab, while universities provide sophisticated sensor development, prototyping and data analysis.
- By leveraging lab resources, university groups can progress quickly from initial concept to a working experiment.

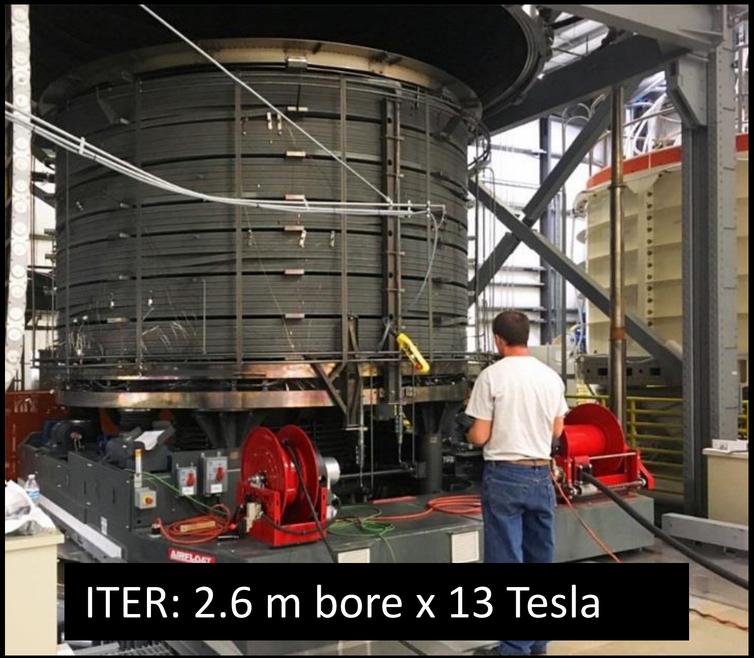
ADMX-G2 Operations

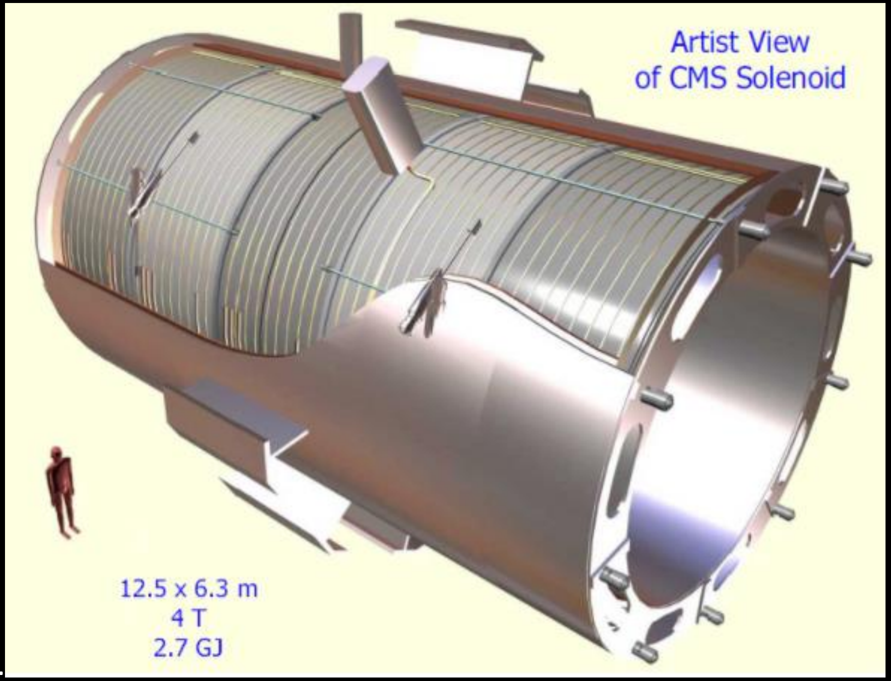
Large Volume Magnets

- How to use large volume solenoids to detect axions?

B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15

Compilation by Mark Bird, NHMFL


ITER: 2.6 m bore x 13 Tesla

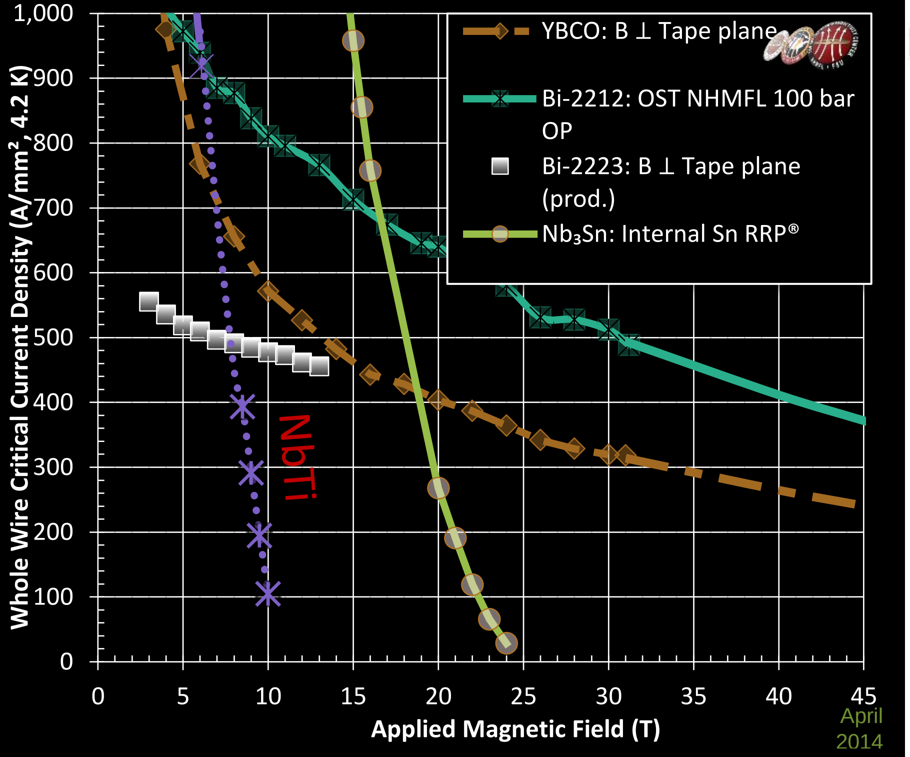


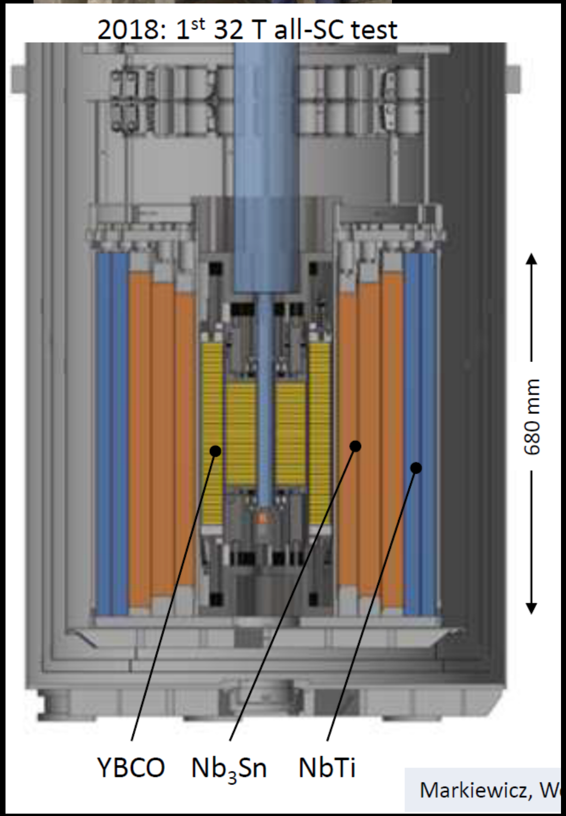
High Field Magnets

- Current ADMX magnet
  - 8.5-Tesla x 60 cm solenoid (normally operated at 7.6 Tesla)
  - Nb-Ti superconductor at 4 Kelvin.
- A step up to higher field requires different superconductor technology.
  - NbTi -> 10 Tesla
  - Nb_3Sn -> 15 Tesla
  - BI-2212, YBCO -> 30 Tesla or more, but technology is not yet mature.
  - 30 mm diameter magnet x 30 tesla at National High Magnetic Field Lab (Tallahassee) in 2019.
  - Meter scale 20-tesla magnet demonstrated by Commonwealth Fusion Systems in Fall 2021.

ADMX 7.6 Tesla NbTi

NHMFL 30 Tesla YBCO



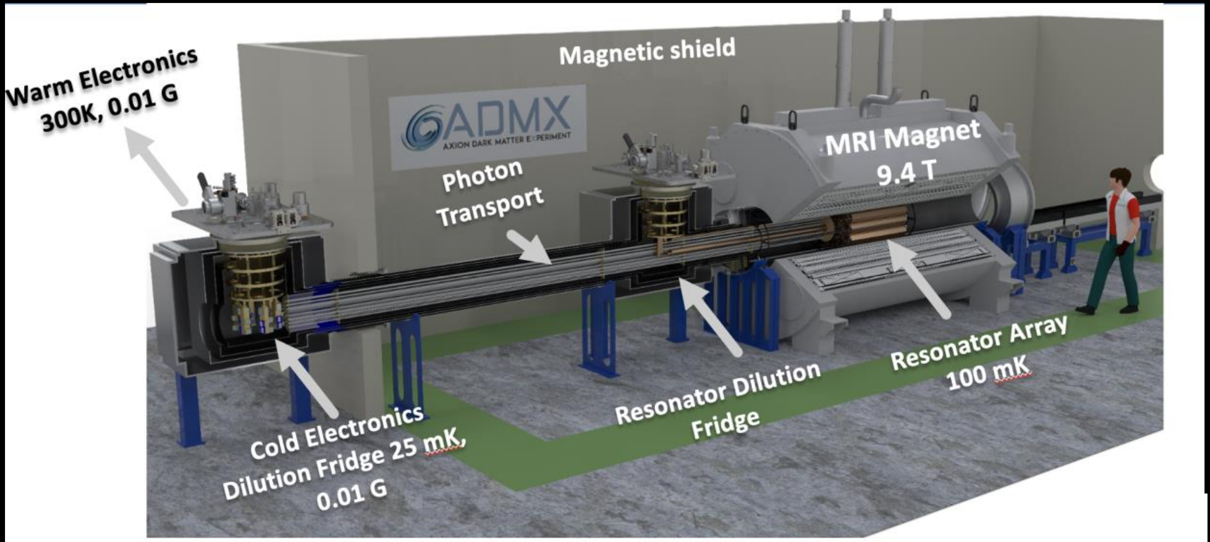


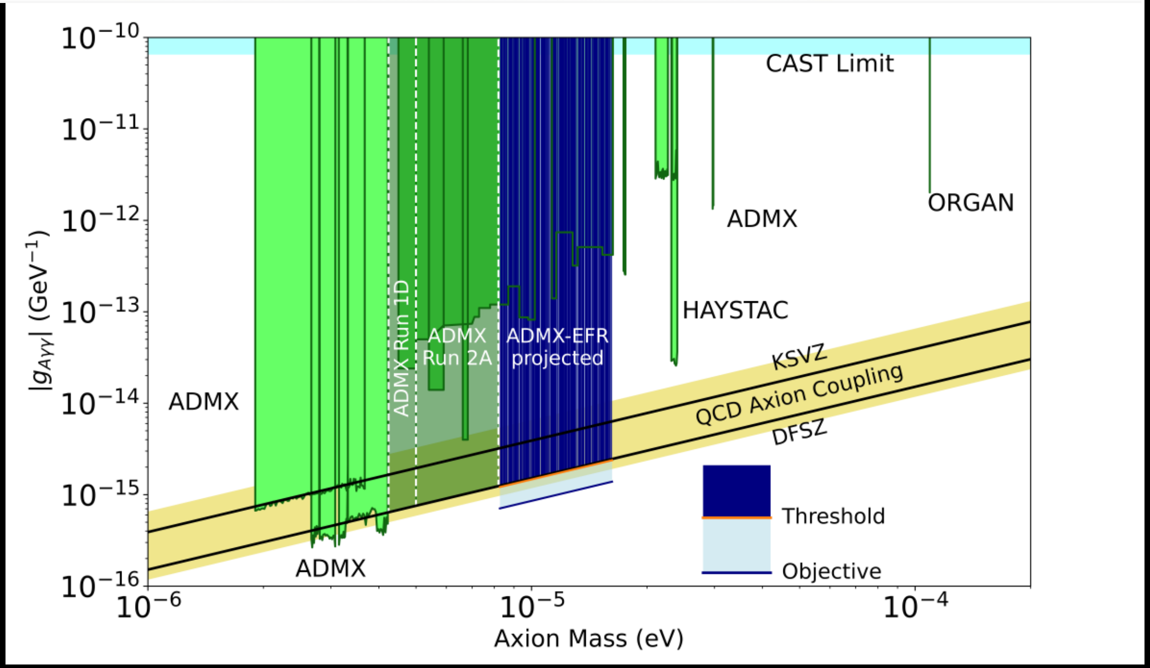
Proposal: Dark Wave Laboratory at Fermilab

- We propose to provide a facility able to host several small scale and at least one larger scale axion search experiment.
- We will begin by installing the 9.4 Tesla MRI magnet selected for the ADMX-EFR experiment. This magnet is significantly larger than needed for the ADMX-EFR detector alone and, with careful planning, may host one or more smaller additional experiments.
- The cryogenic system and magnetic shielding will also be planned to allow for additional experiments.
- The Dark Wave Lab will include shop, assembly and testing areas and will have robust, reliable infrastructure for operating cryogenic equipment.
- A mechanism will be put in place for proposal of new experiments to share space in the magnet.
- Over time, responding to identified needs, additional magnets and cryostats will be installed in the Dark Wave Lab.

ADMX-EFR and its 9.4 Tesla MRI Magnet

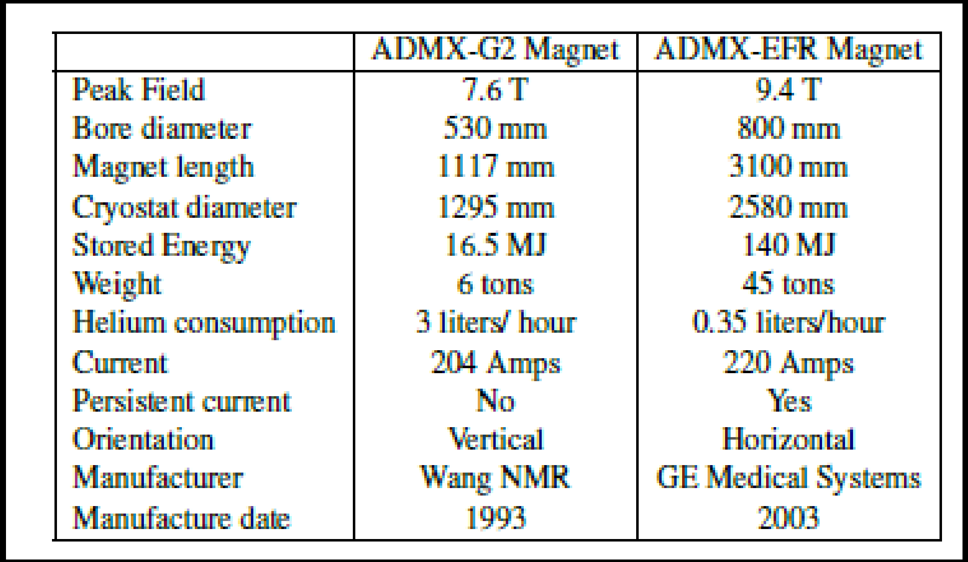
- ADMX-EFR is the proposed next step for ADMX collaboration after currently operating ADMX-G2 experiment at U. Washington.
- Design studies and magnet testing funded by DOE Dark Matter New Initiatives program in 2019-2025.
- Will use an 18-cavity array with coherent signal combining to scan for QCD axion in 2-4 GHz range (8.3-16.5 μeV in mass)
- See talk by Carosi in this Workshop.





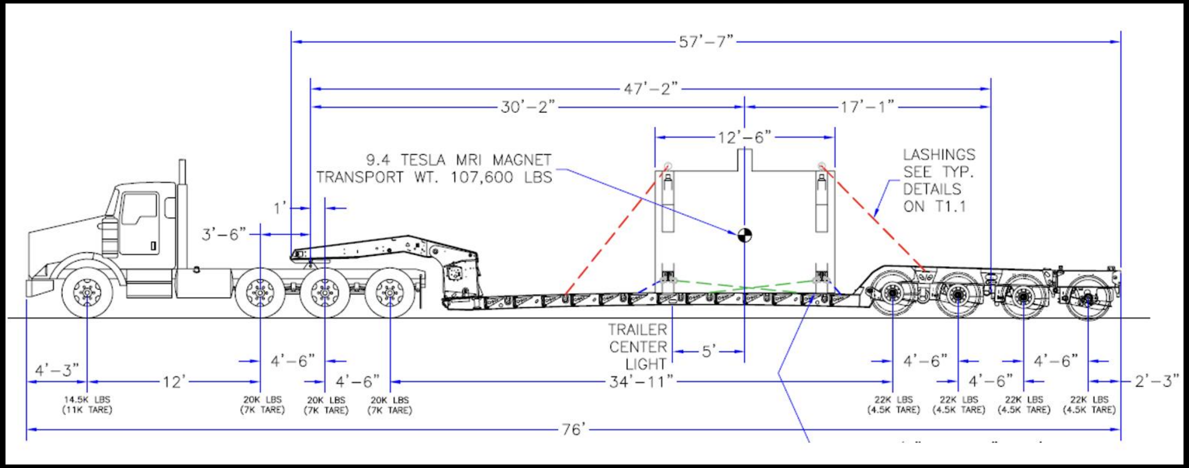
9.4 Tesla MRI Magnet from University of Illinois, Chicago

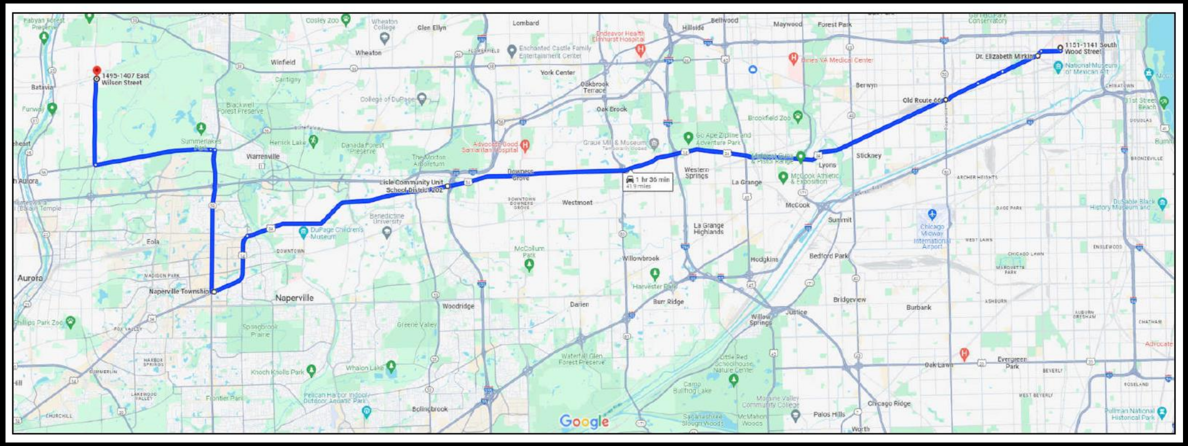
- ADMX-EFR will reuse a 9.4 Tesla, 800 mm bore MRI magnet currently at University of Illinois Chicago medical center. Was world's highest field whole-body MRI magnet when installed in 2003.
- Current status: final sign off by Fermilab and UIC purchasing and legal departments complete. Rigging plans being reviewed. Preparing for magnet move in late May/ Early June.
- Magnet is currently warm and at zero field. We will reinstall at Fermilab and ramp to full field as a test of magnet reliability.
- An opportunity to do axion physics before start of ADMX-EFR.

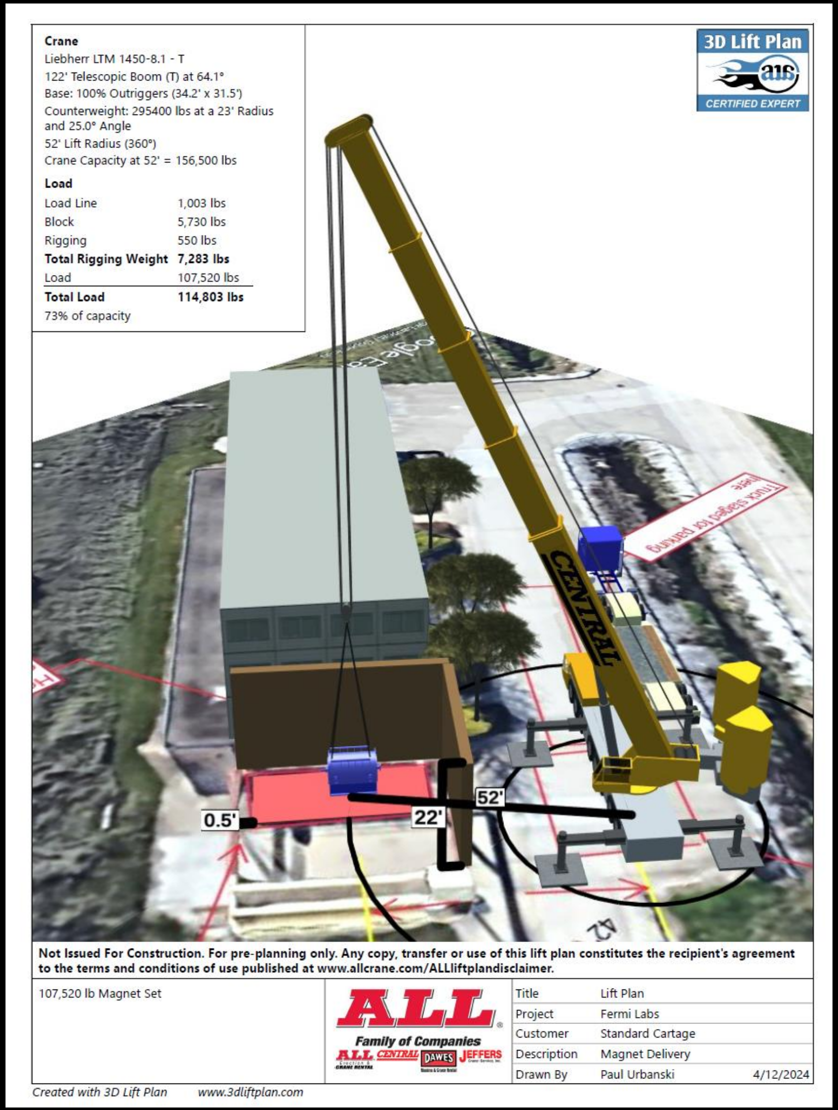


	ADMX-G2 Magnet	ADMX-EFR Magnet
Peak Field	7.6 T	9.4 T
Bore diameter	530 mm	800 mm
Magnet length	1117 mm	3100 mm
Cryostat diameter	1295 mm	2580 mm
Stored Energy	16.5 MJ	140 MJ
Weight	6 tons	45 tons
Helium consumption	3 liters/ hour	0.35 liters/hour
Current	204 Amps	220 Amps
Persistent current	No	Yes
Orientation	Vertical	Horizontal
Manufacturer	Wang NMR	GE Medical Systems
Manufacture date	1993	2003

Magnet Coming to Fermilab This Summer





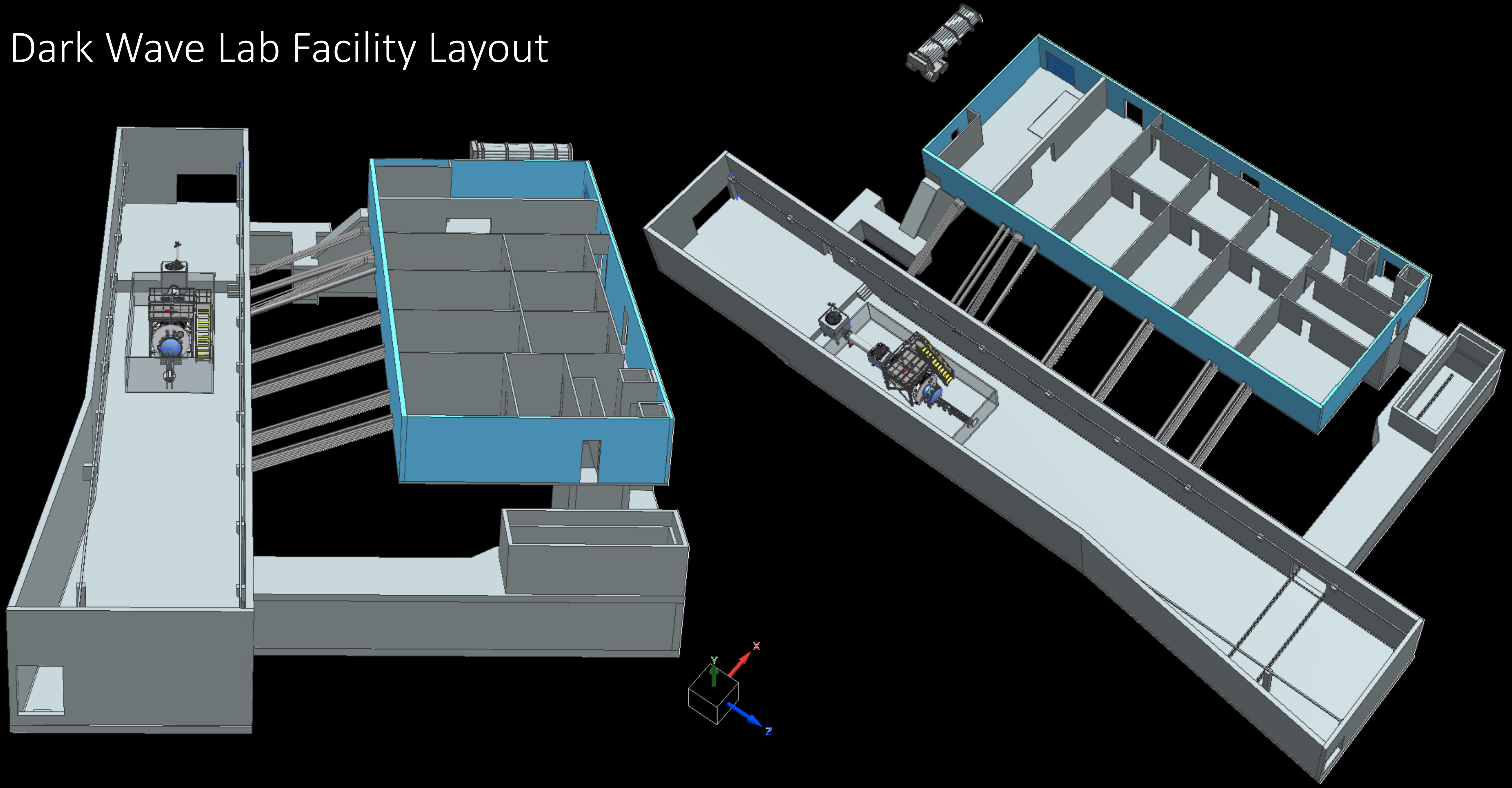


Nearly 3-hour transport via air-ride truck. Max speed ~35 mph.
Mostly smooth roads. Many stops. No railroad crossings.
Test transport limited accelerations to <0.95 g

Site for Dark Wave Lab: PW8 Hall

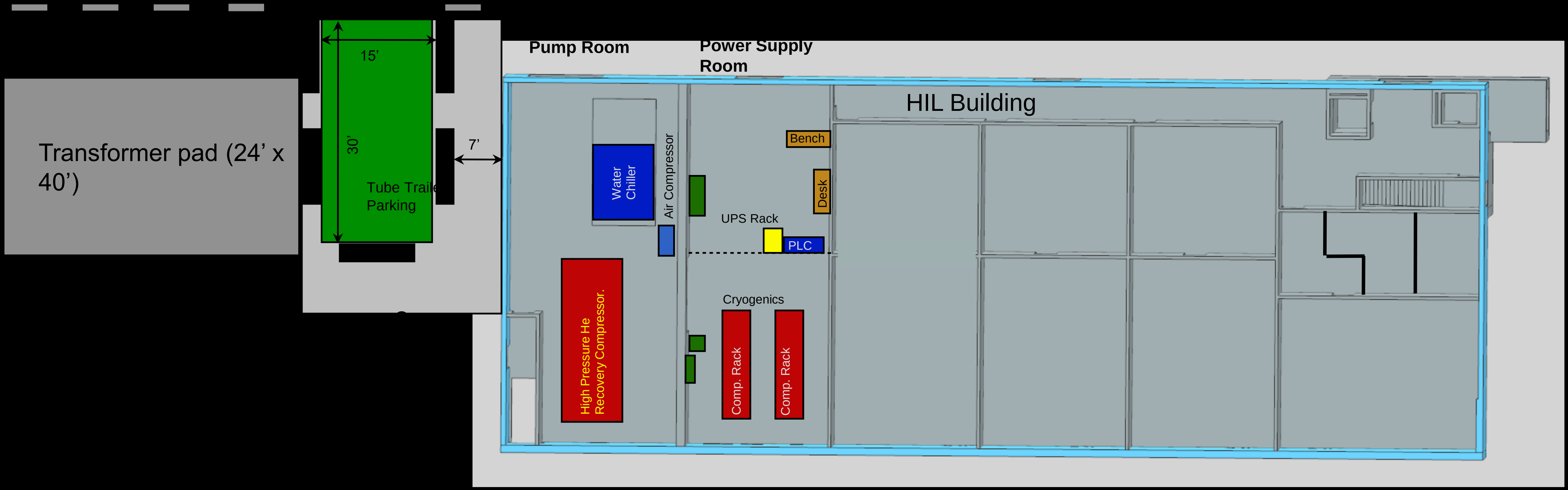
- Fermilab cleared out the PW8 hall for use by ADMX-EFR.
- Had been used for storage last 25 years after discovery of Tao neutrino in DONUT experiment.
- 13,000 square ft available space including adjacent HIL service building— enough for multiple magnets plus significant testing facilities, office and meeting space.
- Could benefit from renovation. Focusing now on putting in reliable services such as helium recovery, chilled water, electrical power.

Dark Wave Lab Facility Layout

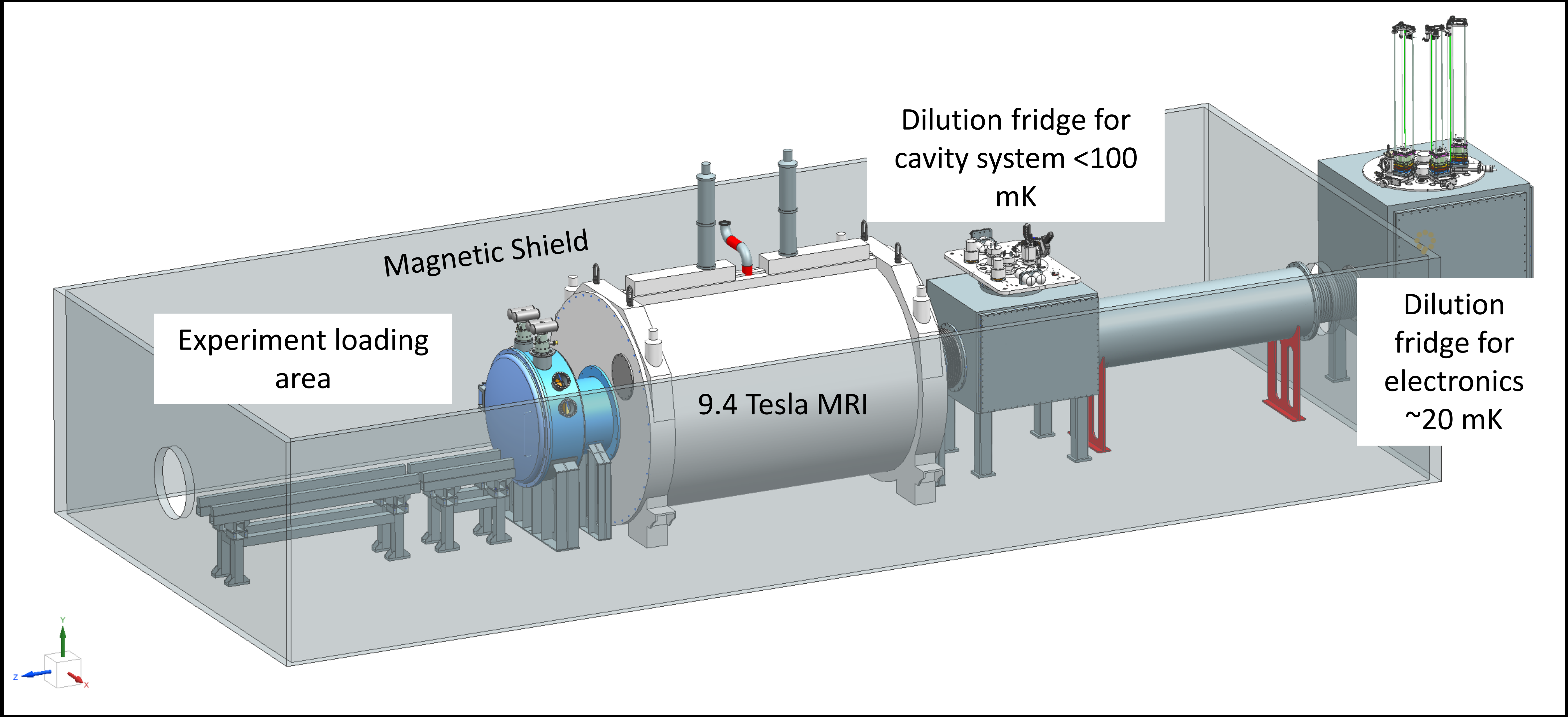


Office/ Service Building for Dark Wave Lab

- 8,000 Square ft building outside the stray magnetic field
- Utilities and control systems
- Helium compressors
- Control room, meeting rooms, rest rooms, shop and benchtop assembly areas
- Small test cryostats

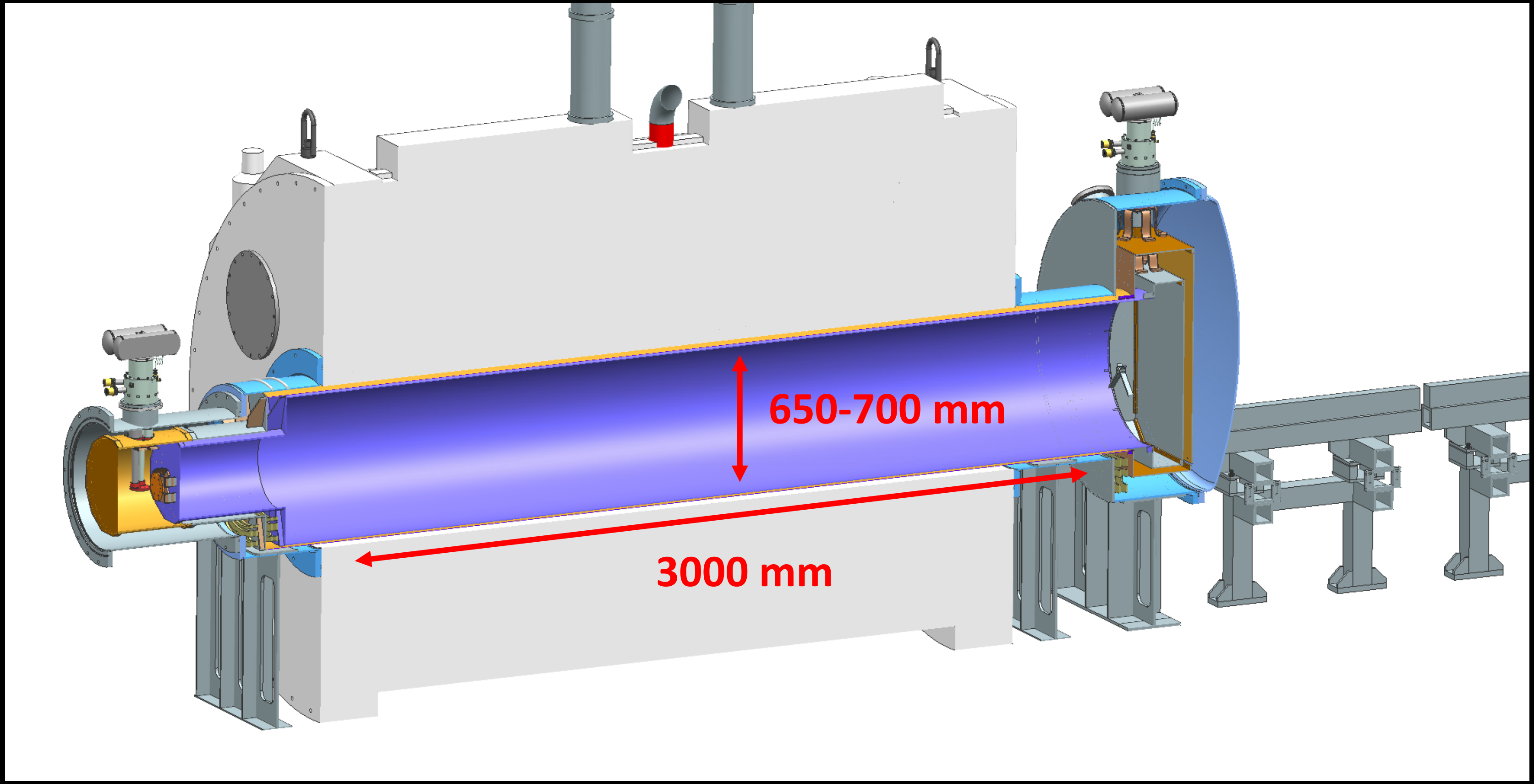


ADMX-EFR Cryogenic System With 2 Dilution Refrigerators



4-Kelvin System For Early Experiments (2027?)

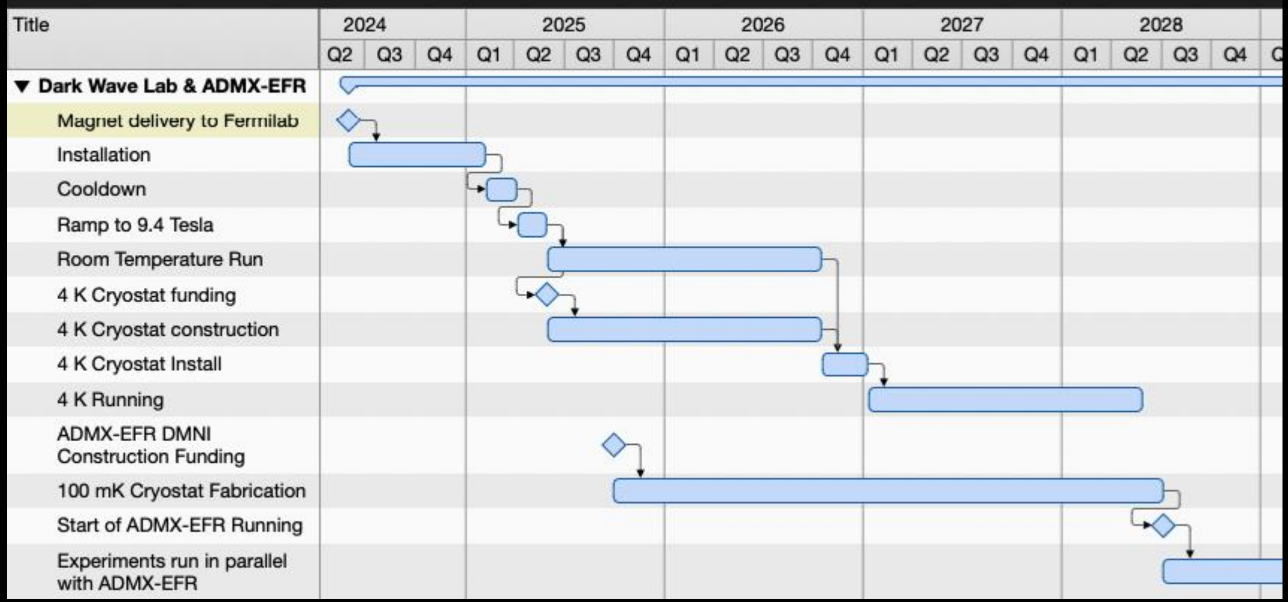
- Relatively low-cost system to provide 4 Kelvin environment for early experiments.
- Payload can be inserted into bore through the side access hatch using a rail-track system. Rails (not shown here) are attached to the inside of the PT2 shield.
- No zero field region in initial plan– ok for transistor amplifiers.
- Could provide sub-K cooling for electronics package with small sorption fridge.



Notional Schedule for Dark Wave Lab Operations

preliminary schedule concept

- 9.4 Tesla solenoid delivery to Fermilab late May/ Early June 2024.
- ~ 1 year to commission magnet.
- **Potential to run room-temperature pilot experiments in 2025-2026.**
- A **4-Kelvin cryostat could be available in 2027,** enabling more sensitive experiments.



- ADMX-EFR project includes large 100-mK cryostat, which could be ready as soon as 2028 (depends on on DMNI funding decision). May allow space for one or more additional experiment packages to run in parallel with ADMX-EFR.
- It may be sensible to plan for one or more additional magnets for use beyond 2030.

Dark Wave Lab Workshop April 15-16 2024

- https://indico.fnal.gov/event/63051/
- Assessment of community interest in common facilities.
  - What experiments would likely be proposed and what facilities are needed for them?
  - Gather material for White Paper and presentation to Fermilab Physics Advisory Committee.
- Identify best near-term uses (2025- 2028) for 9.4 Tesla MRI magnet with bore at room temperature or 4 kelvin.
- Form new experiment collaborations & expand the field of potential Dark Wave Lab users.
  - There are quite a few interesting experiment ideas in this field that are not yet being seriously pursued. More good ideas than people or funding.
  - Theorists meet experimentalists- maybe someone will work on your idea.

~80 participants from US and international labs and universities

Early projects for Dark Wave Lab

- We identified ~10 projects that could go into the 9.4 Tesla MRI magnet before the start of ADMX-EFR.
- Most not sensitive to QCD axion band but would search for ALPs while developing detector technologies.
- Significant interest in tests with room temperature magnet bore– could start as soon as 2025.
- Some groups are ready now– have room temperature prototypes operating without a magnetic field.
- 4 Kelvin experiments beginning in 2027.
- 100 mK experiments in parallel with ADMX-EFR as soon as 2028– depends on DMNI funding timeline.

Experiment	Collaboration	Type	Room Temp?	4 Kelvin
ADMX-EFR	ADMX	Cavity	■	■
GigaBREAD	BREAD	Dish	■	■
ADMX-SLIC	Florida + ?	LC	■	■
ADMX-VERA	Stanford, Washington, LLNL	Cavity	■	■
Orpheus	Washington	Dielectric Disc	■	■
MADMAX	MADMAX	Dielectric Disc	■	■
ORGAN	UWa, Swinburn	Reentrant cavity	■	■
TBD	Florida + Uwa+ Swinburne?	Reentrant cavity	■	■
SC Cavities 2-10 GHz	SQMS, CAPP?	Cavity		■
Large 300 MHz Cavity	ADMX?	Cavity	■	■

Dark Wave Lab Summary

- Goal is to help realize ambitions of axion search field on a reasonable cost and time scale.
- Give community access to large scale magnet and cryo facilities.
- Workshop outcomes:
  - Strong interest from US and international groups– 20 talks on possible experiments.
  - About 9 projects would make early use of magnet with room temperature or 4 K bore.
  - Test prototype detectors and search for ALPs.

Next steps: White Paper, Presentations to Fermilab PAC.

Additional Slides

Axion Electrodynamics

- Axions interact weakly with photons – small axion to photon coupling $g_{a\gamma\gamma}$
- Besides the normal electric field E(x,t) and magnetic field B(x,t), there is an axion field a(x,t).
- Maxwell's equations modified with new terms to include effects of a.
- The new field is always multiplied by the very small $g_{a\gamma\gamma}$

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t} \right)$$

$$\nabla \cdot \mathbf{B} = 0$$

- There are plane wave solutions for the $a(x,t)$, oscillating with a frequency corresponding to the axion mass ($\omega_a = m_a c^2 / \hbar$).

$$a(x,t) \propto \sqrt{\rho_{DM}} \cos(\omega_a t - kx)$$

Large Background Magnetic Field

- First step to discover axions: get a big magnet

- In the presence of a static magnetic field B_0, the axion field sources an effective oscillating electric current J_a

$$J_a = g_{a\gamma\gamma} B_0 \frac{\partial a}{\partial t}$$

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g_{a\gamma\gamma} \left(\cancelto{0}{\mathbf{E} \times \nabla a} - \overbrace{\mathbf{B} \frac{\partial a}{\partial t}}^{J_a} \right)$$

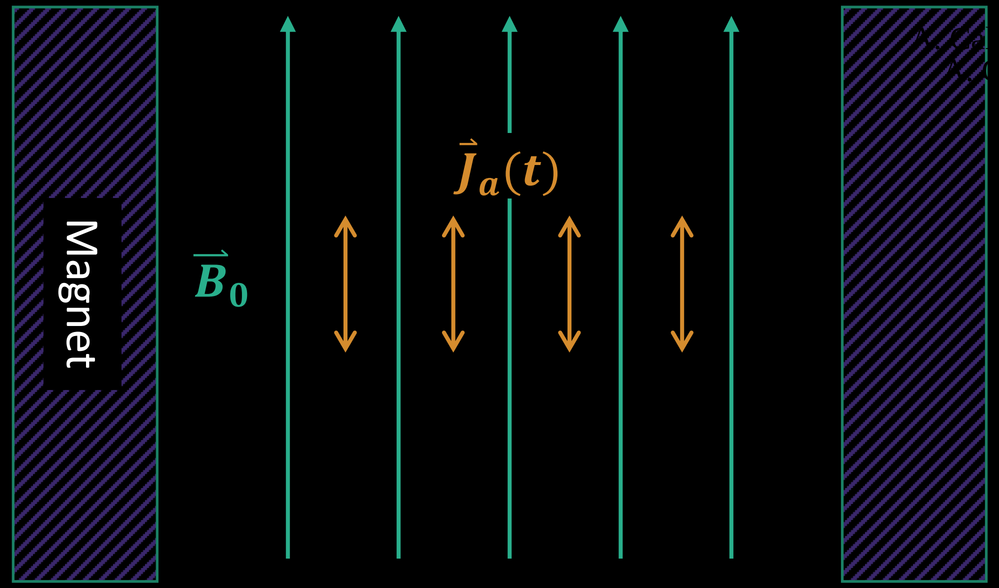
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times B - \frac{\partial E}{\partial t} = J_a$$

Oscillating Fictitious Current

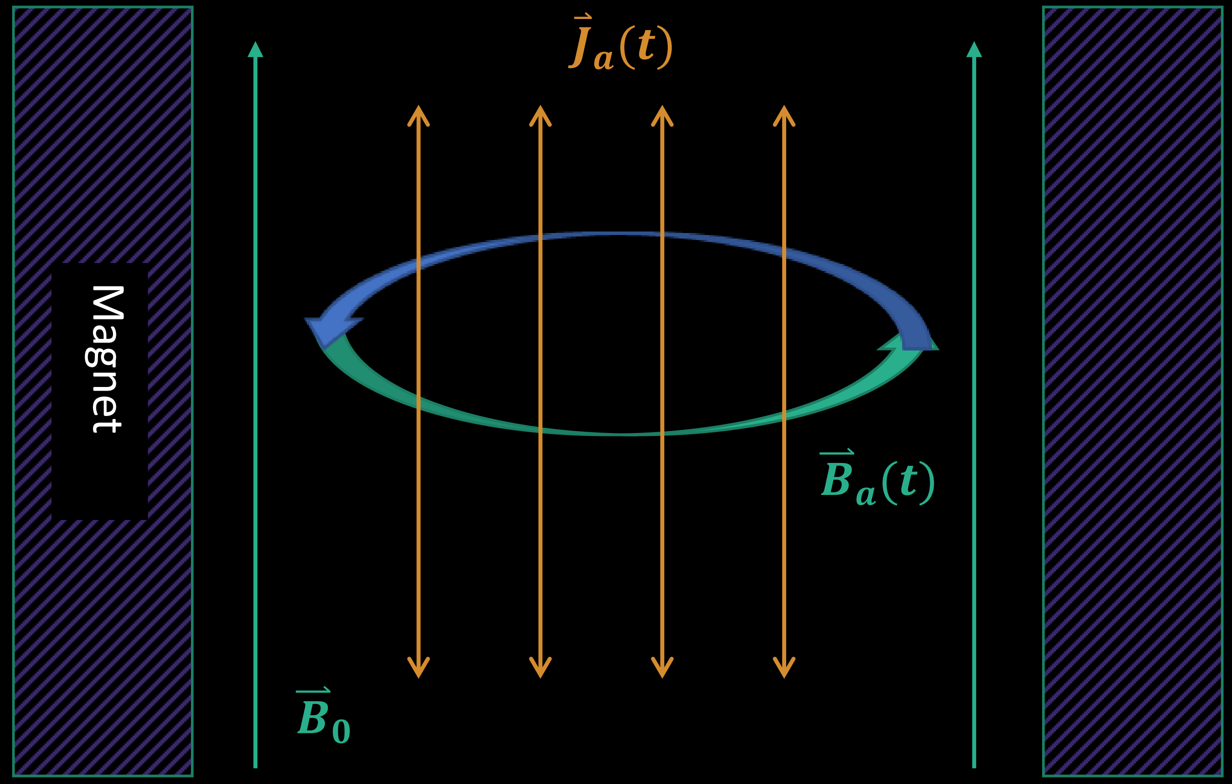
- Will produce the same electromagnetic response as a normal electric current.
- Oscillates at frequency ω_a determined by axion mass

$$\omega_a = \frac{m_a c^2}{\hbar}$$



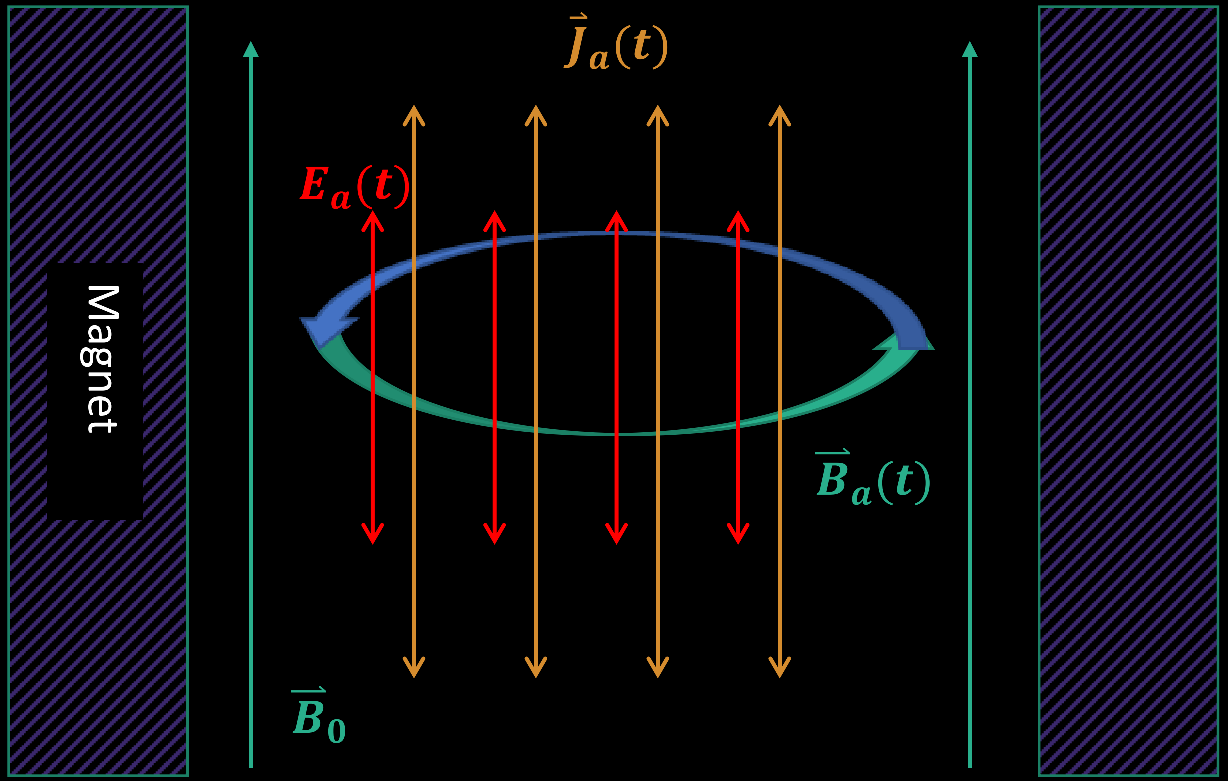
Electric and Magnetic Field Response

- The fictitious AC current $J_a(t)$ can source real oscillating magnetic field $\vec{B}_a(t)$



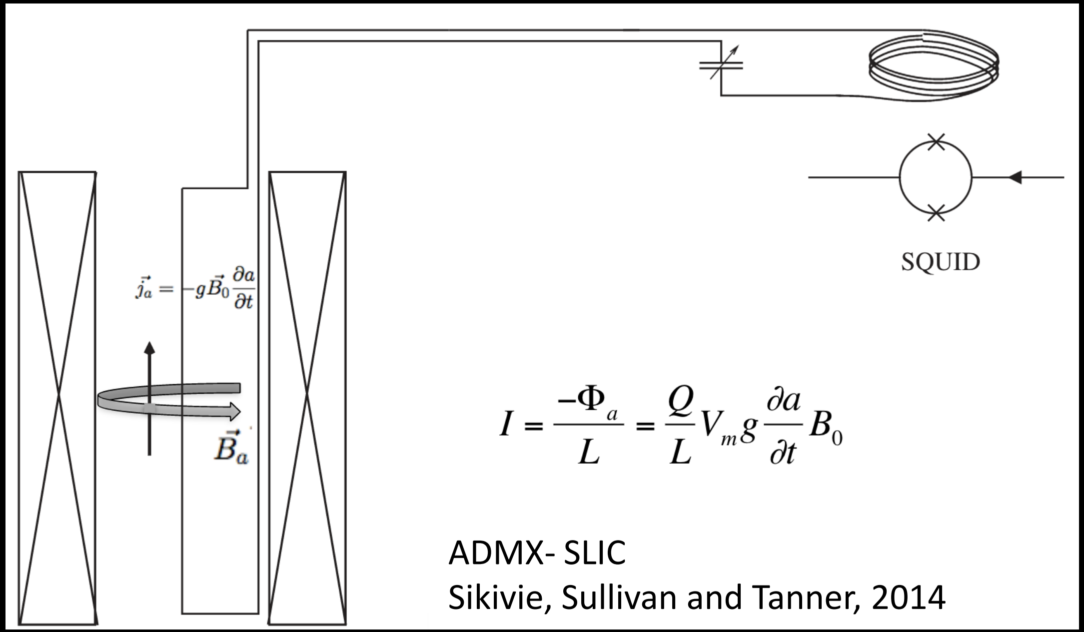
Electric and Magnetic Field Response

- There is also an oscillating electric field in the axial direction $E_a(t)$
- Relative strength of the oscillating electric and magnetic fields depends on boundary conditions & and size of apparatus compared to axion wavelength

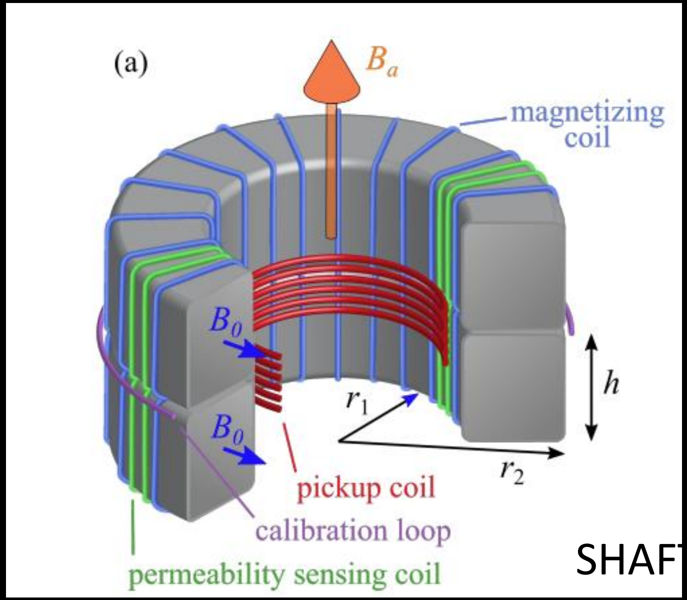


Axion Detection Through Magnetic Flux

- Collect the magnetic flux sourced by $\boldsymbol{J_a}$ with a transformer coil and measure induced current with a SQUID.
- Works for solenoidal magnets (ADMX-SLIC, DMRADIO) or toroidal (ABRACADABRA, SHAFT)
- Sensitive to light axions with wavelength big compared to magnet size.



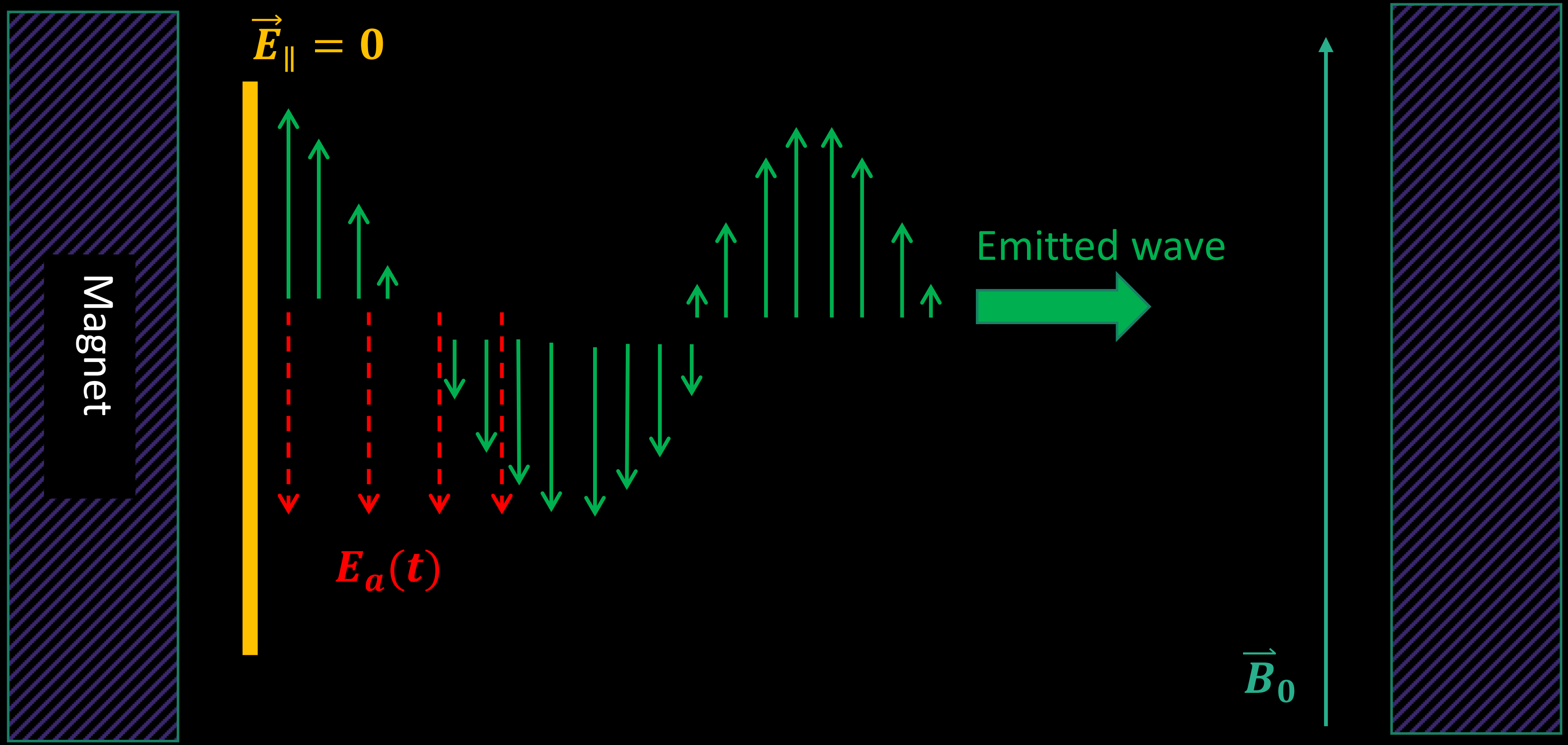
ADMX- SLIC
Sikivie, Sullivan and Tanner, 2014



Gramolin et al., Nature Physics 17, 79-84, 2021

Emission of Electromagnetic Wave From Conducting Surface

- Insert a conducting surface into the magnet bore.
- Currents will appear in the conductor driven by the axion induced electric field oscillations.
- A traveling electromagnetic wave is emitted from the surface to satisfy boundary conditions.



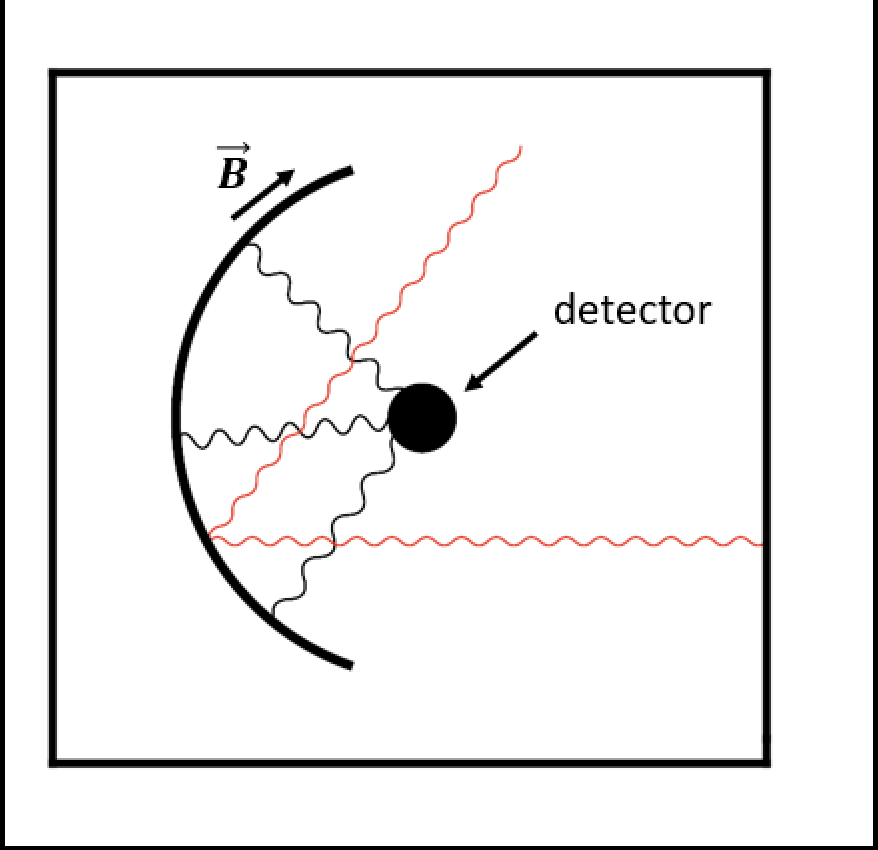
“Dish Antenna” Experiments

- Arrange for the axion induced surface emission to be focused onto a detector.

- Signal is very weak. Only around 10^{-26} watts for a big magnet.

$$P_{signal} = 8.27 \cdot 10^{-26} W \cdot \left(\frac{A}{10\ m^2}\right)\left(\frac{B_{\|}}{10\ \mathrm{Tesla}}\right)^2 \left(\frac{\rho_{DM}}{0.3\ GeV/cm^3}\right)\left(\frac{g_{a\gamma\gamma}}{3.92 \cdot 10^{-16}\ GeV^{-1}}\right)^2 \left(\frac{1\ \mu eV}{m_a}\right)^2$$

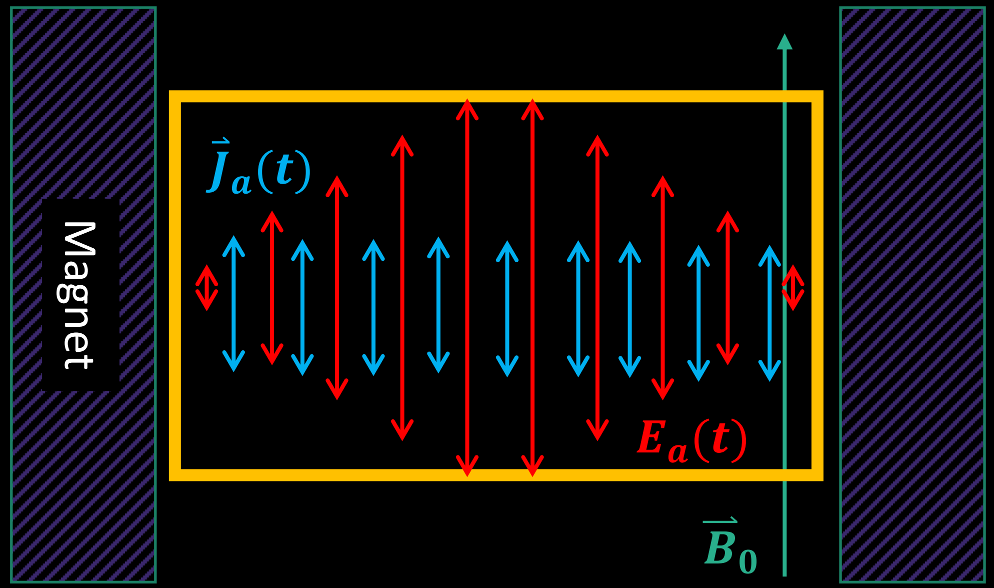
- More on this later…



Horns, Jaeckel, Lindner, Lobanov, Redondo and Ringwald, 2012

Signal Enhancement in a Resonant Cavity

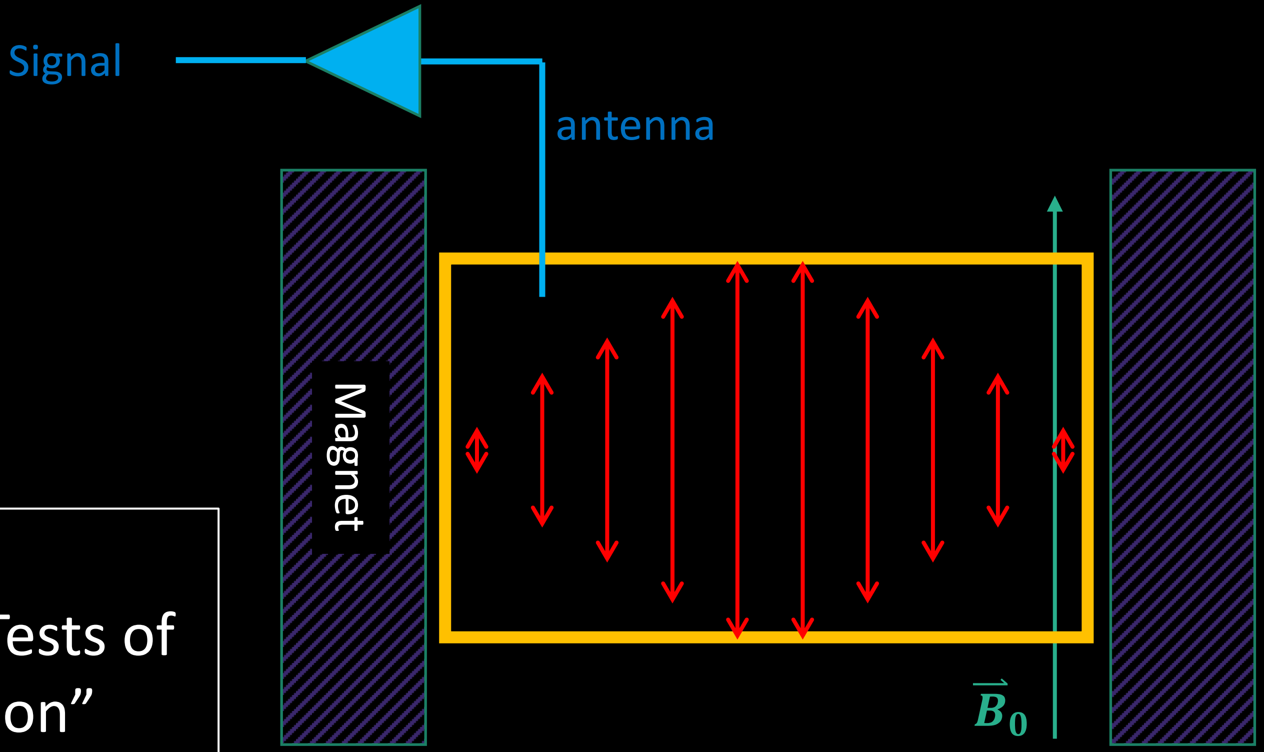
- Build a metal box (cavity) inside the magnet
- The conducting cavity walls emit radiation
- Cavity will resonate at discrete frequencies when integer number of wavelengths fit inside.
- Resonance condition when $\omega_{cavity} = \omega_{axion} = \frac{m_a c^2}{\hbar}$ ➡ Power enhancement!



Pumped Cavity Mode

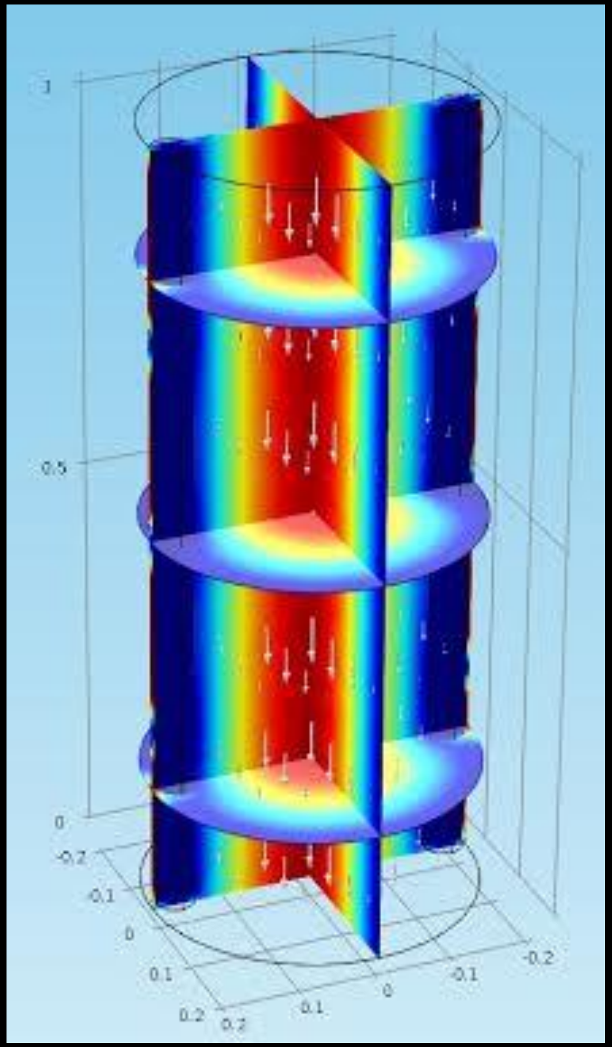
- Power buildup occurs when cavity resonance frequency is matched to axion mass.
- Signal Power ~10^{-22}-10^{-23} W at 1 GHz for typical cavity and magnet parameters.
- Three orders of magnitude more than a non-resonant dish antenna.

<u>Experiments</u>
RBF (1980s)
U Florida
ADMX
HAYSTAC
CAPP/CULTASK
KLASH
CAST- RADES

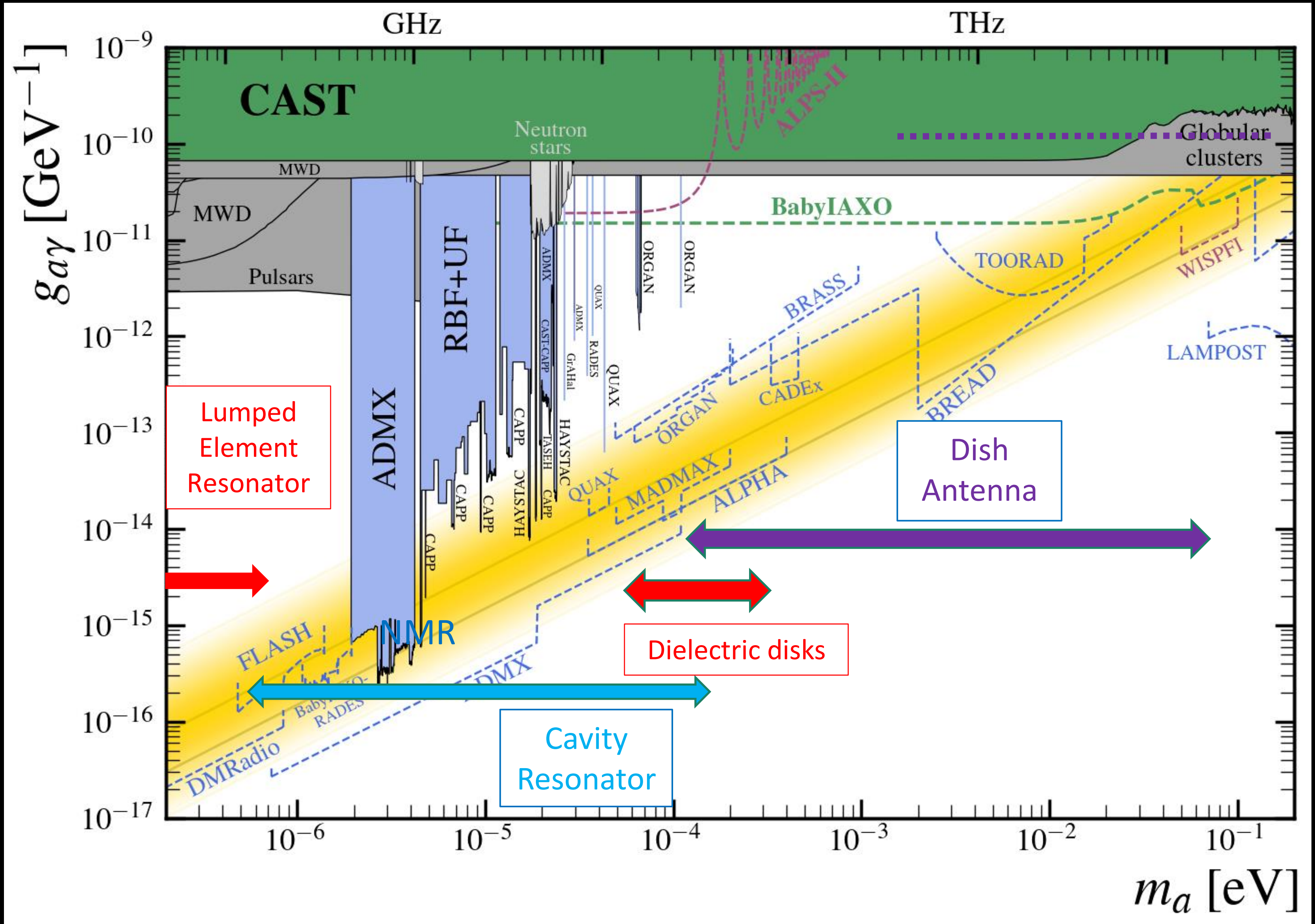


Pierre Sikivie, “Experimental Tests of the Invisible Axion” 1983 PRL

TM_{010} Mode



Complementarity of Detection Techniques



Extension of Sensitivity to Higher Frequency

- Effective scan rate of ADMX ≈ 1 MHz/ day
- As we move up in frequency **f**,
  - Volume *per cavity* decreases as 1/$\mathbf{f}^3$
  - Resonator quality factor decreases as 1/$\mathbf{f}^{2/3}$
  - Noise power from Standard Quantum Limit increases as **f**.
- Need to increase number of cavities, magnetic field, Q to maintain signal power as frequency increases.

Scan Rate Vs Frequency & other parameters

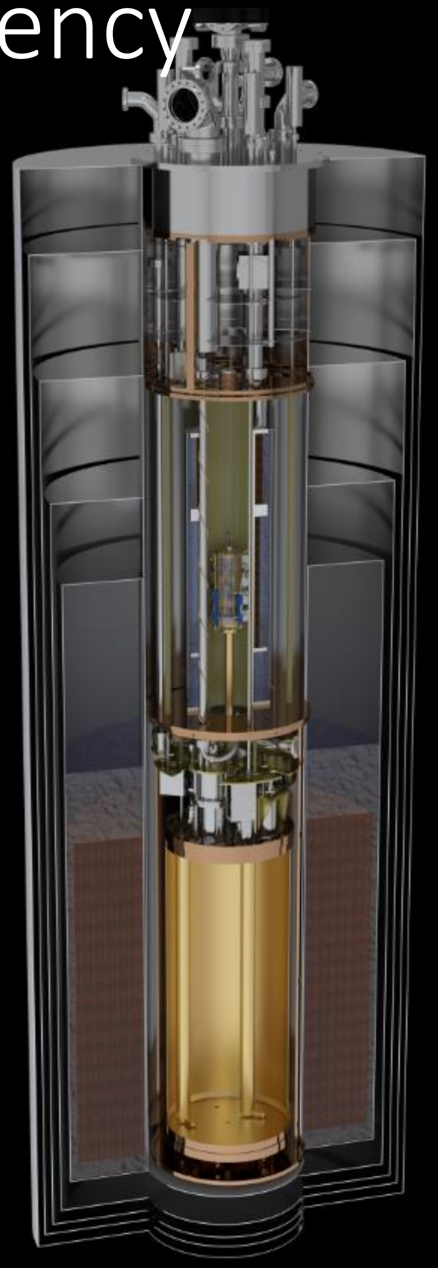
$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year}\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{1\ \mathrm{GHz}}\right)^2\left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2\left(\frac{B_0}{8\ \mathrm{T}}\right)^4\left(\frac{V}{100\mathrm{l}}\right)^2\left(\frac{Q_L}{10^5}\right)\left(\frac{C_{010}}{0.5}\right)^2\left(\frac{0.2\ K}{T_{sys}}\right)^2$$

Stronger Magnet

More Detector Volume: Array of Resonators

Higher Q: Superconducting or Dielectric Resonators

Lower Noise Amplifiers

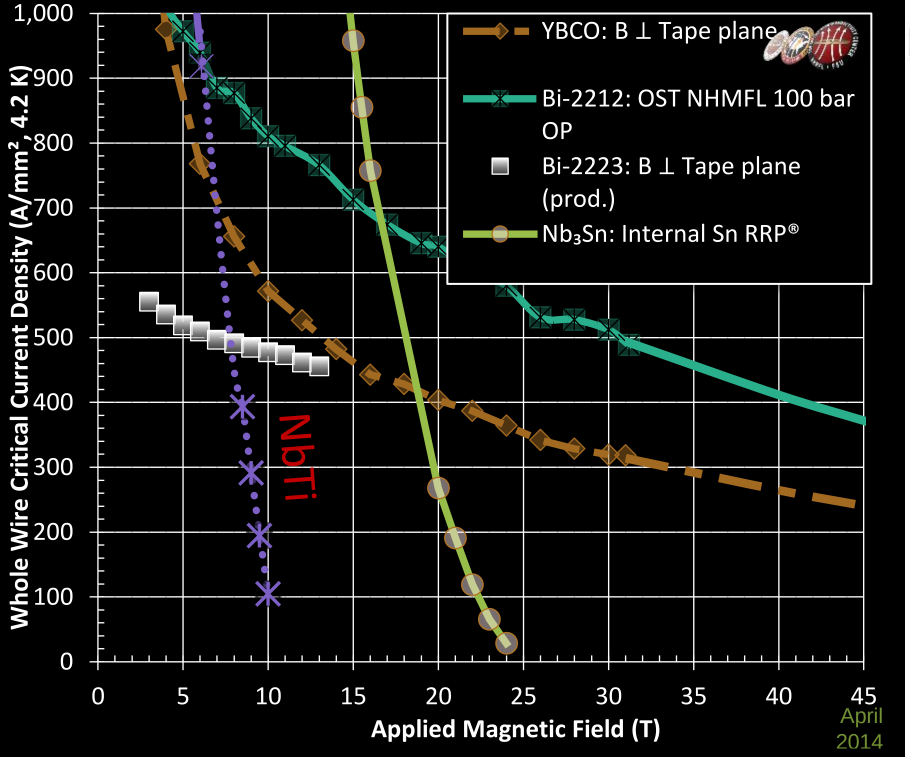


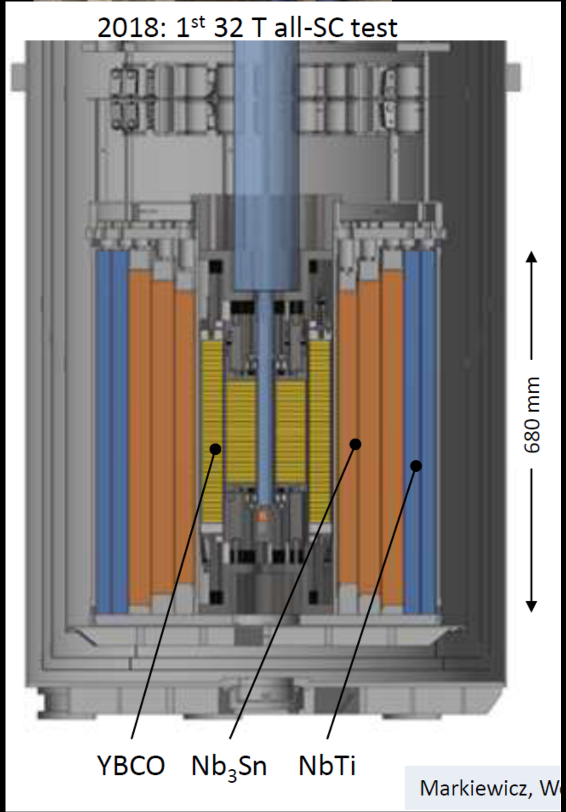
Magnets

- Current ADMX magnet
  - 8.5-Tesla x 60 cm solenoid (normally operated at 7.6 Tesla)
  - Nb-Ti superconductor at 4 Kelvin
  - 25 years old-- Manufactured in 1993 by Wang NMR, Livermore CA.
- A step up to higher field requires different superconductor technology.
  - NbTi -> 10 Tesla
  - Nb_3Sn -> 15 Tesla
  - BI-2212, YBCO -> 30 Tesla or more, but technology is not yet mature.
  - 30 mm diameter magnet x 30 tesla at National High Magnetic Field Lab (Tallahassee) in 2019.
  - Meter scale 20-tesla magnet demonstrated by Commonwealth Fusion Systems in Fall 2021.

ADMX 7.6 Tesla NbTi

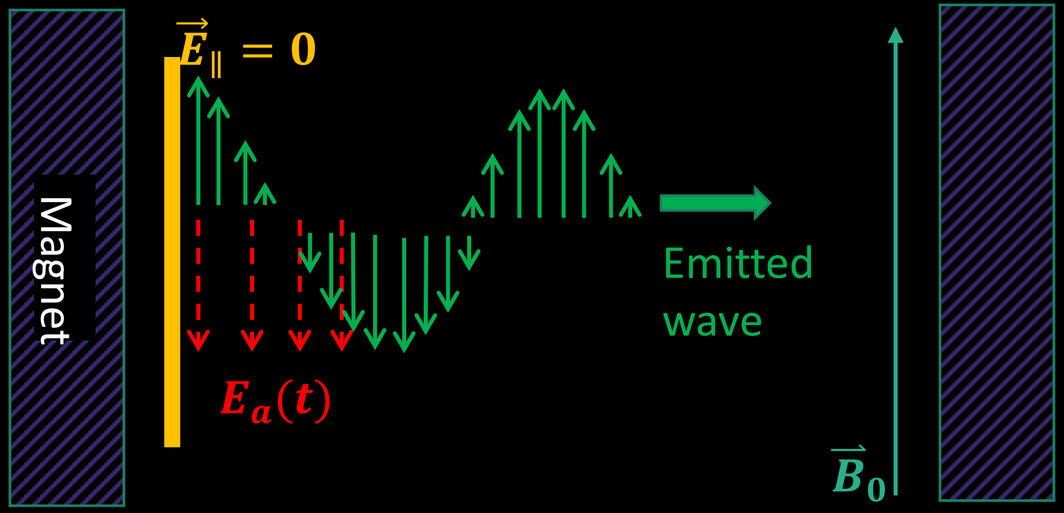
NHMFL 30 Tesla YBCO





Axion Induced Radiation from A Magnetized Metal Slab

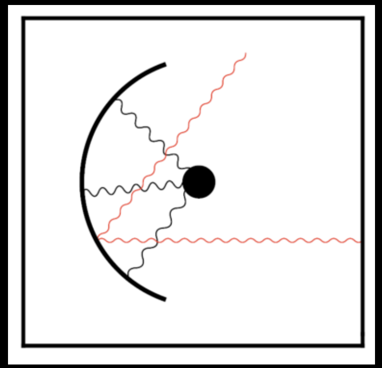
- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space
- A conducting surface in this field emits a plane wave perpendicular to surface.



- Radiated power is very low:

$$P_{signal} = 8.27 \cdot 10^{-26} W \cdot \left(\frac{A}{10\ m^2}\right)\left(\frac{B_{\parallel}}{10\ \text{Tesla}}\right)^2\left(\frac{\rho_{DM}}{0.3\ GeV/cm^3}\right)\left(\frac{g_{a\gamma\gamma}}{3.92 \cdot 10^{-16}\ GeV^{-1}}\right)^2\left(\frac{1\ \mu eV}{m_a}\right)^2$$

- But no detector tuning is required!



“Dish antenna” (Horns et al., 2012)