A comprehensive QCD axion search strategy needs major investments in HEP magnet facilities

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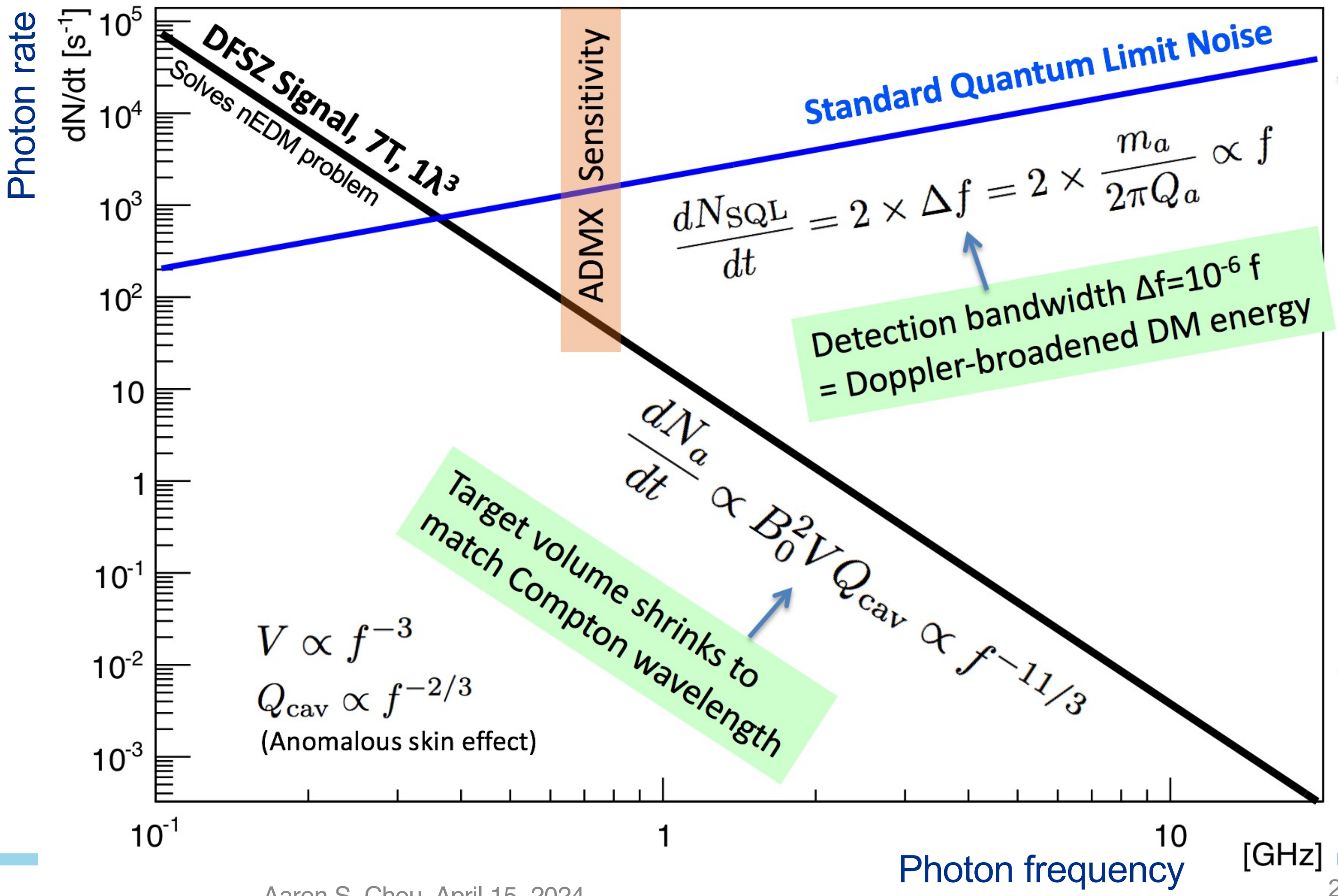
Fermilab
Dark Wave Lab Workshop
April 15, 2024

$$g \propto \frac{1}{(B^2 V)^{1/2}} \left(\frac{R_{\mathrm{bkgd}}}{t} \right)^{1/4}$$

- Fiction: axion experiments are cheaper than WIMP experiments
- Reality: pathfinder axion/ALP experiments are cheaper than full-scale WIMP experiments
- **We need to get serious if we want to discover the QCD axion within the next 10,000 years!**

The predicted axion DM signal/noise ratio in cavity experiments plummets as the axion mass increases → SQL readout is not scalable.



Effective
DCR = 10^4/s

Need
DCR < 10^{-2}/s

SC qubits as single photon detectors. No quantum noise!

Fermilab/Chicago/Stanford

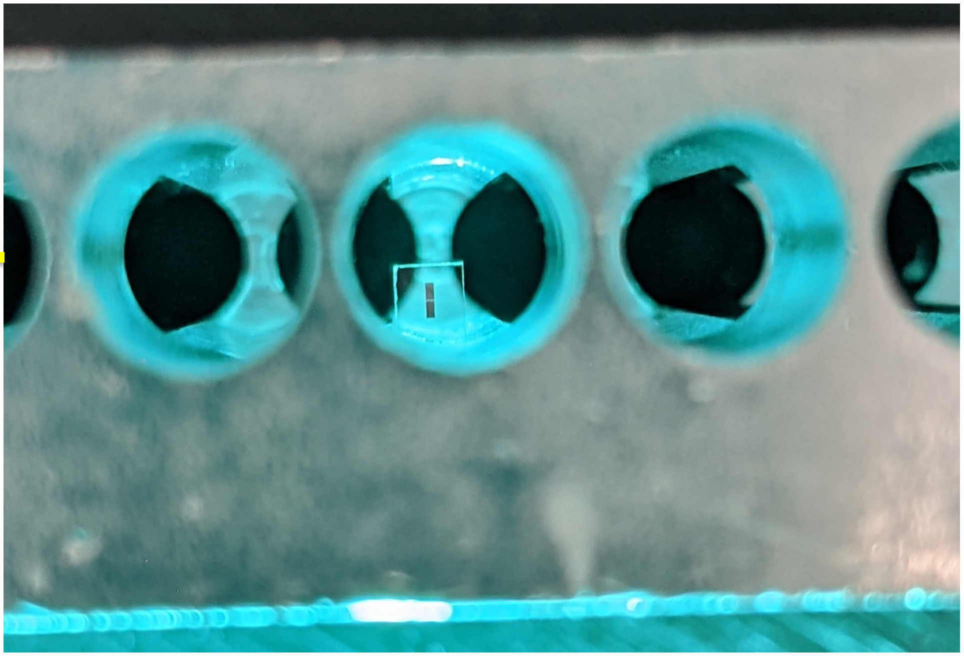
Nested sapphire cavity compatible with high B field needed for axion search: Q>10^6,
¼-wave layers reflect photon waves back to center

(based on design from INFN/QUAX)

SQuAD (Superconducting Qubits for Axion Darkmatter)

Installed in 10 mK dilution refrigerator and 14T solenoid magnet at Fermilab

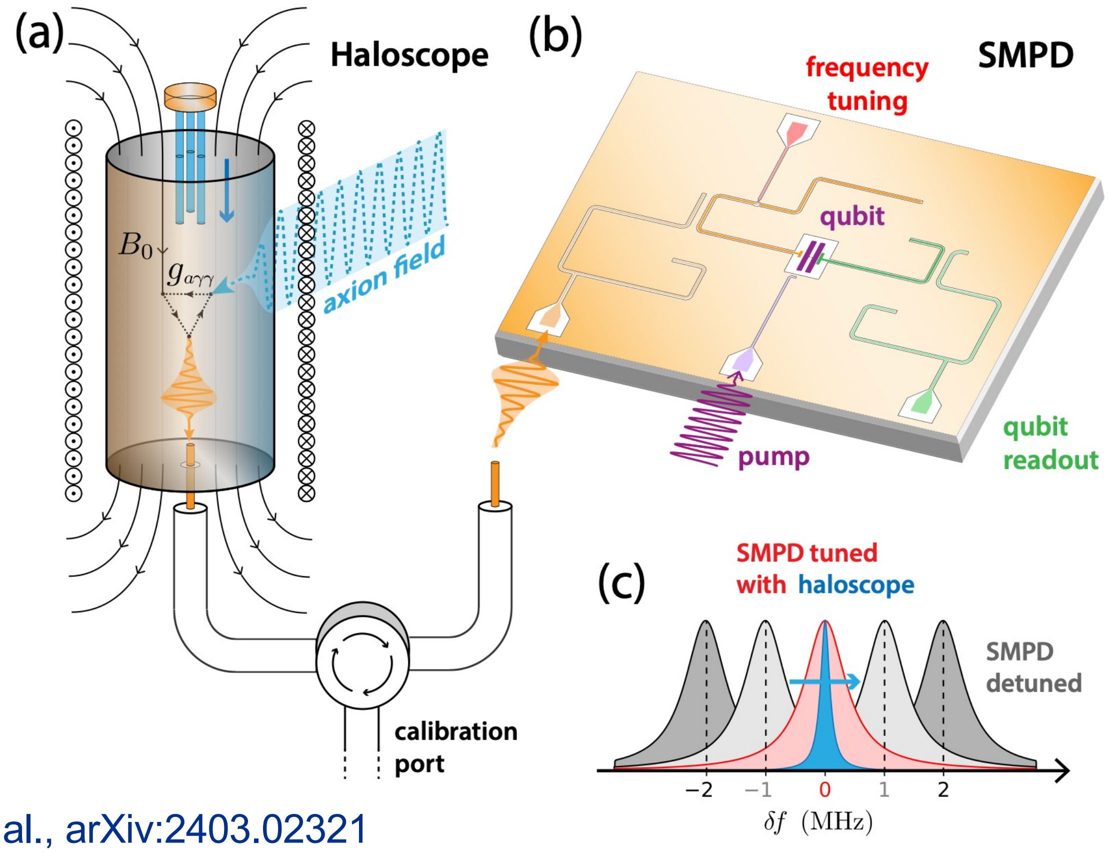
Quantum readout electronics in remote, magnetically-shielded region



Transmon qubit performs quantum non-demolition single photon counting with noise **36x lower than zero-point noise, 1300x speed-up.**
Achieved 1 Hz DCR.

A.V. Dixit et al., *Phys.Rev.Lett.* 126 (2021)

Patrice Bertet’s remote single microwave photon receiver deployed in axion search



Photon is detected via a controlled-X gate, exciting the qubit **g→e** only when a signal photon is present.

Technical complications:

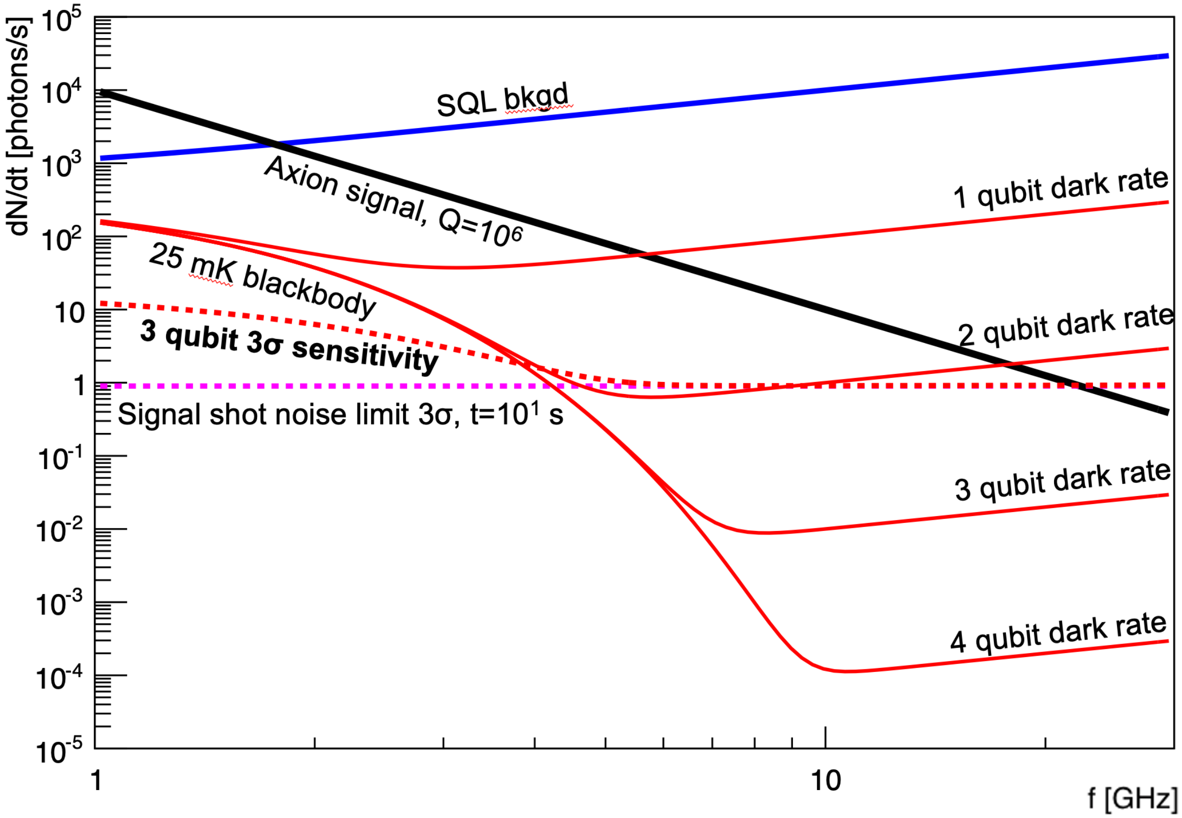
- **Remote photon buffer resonator must be co-tuned** with SQUID to match the frequency of the axion cavity.
- Large **dark count rate ~100/s** from poor thermalization of rf lines, spontaneous heating of the qubit state, but better than SQL!

C. Braggio et al., arXiv:2403.02321 (SQMS)

Signal rate sensitivity is determined by the integration time budget:

if $Q_c=10^6$ then have maximum t=10 s at each tuning to get 1 octave in mass, i.e. using 10^6 tunings in 1 year

Assume that quantum sensors will continue to improve until experiments are **no longer background-limited.**



For t = 10 s, the minimum observable signal rate is R_s=1 Hz

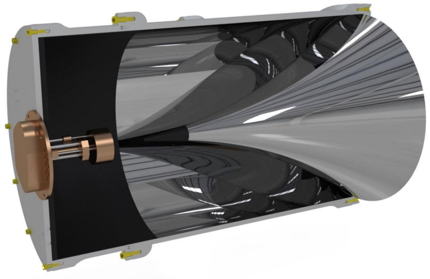
(Signal shot noise limit, need to count 9 ± 3 photons for 3σ sensitivity)

Once DCR is sufficiently low, cavity experiments are still **signal limited at higher frequencies**:

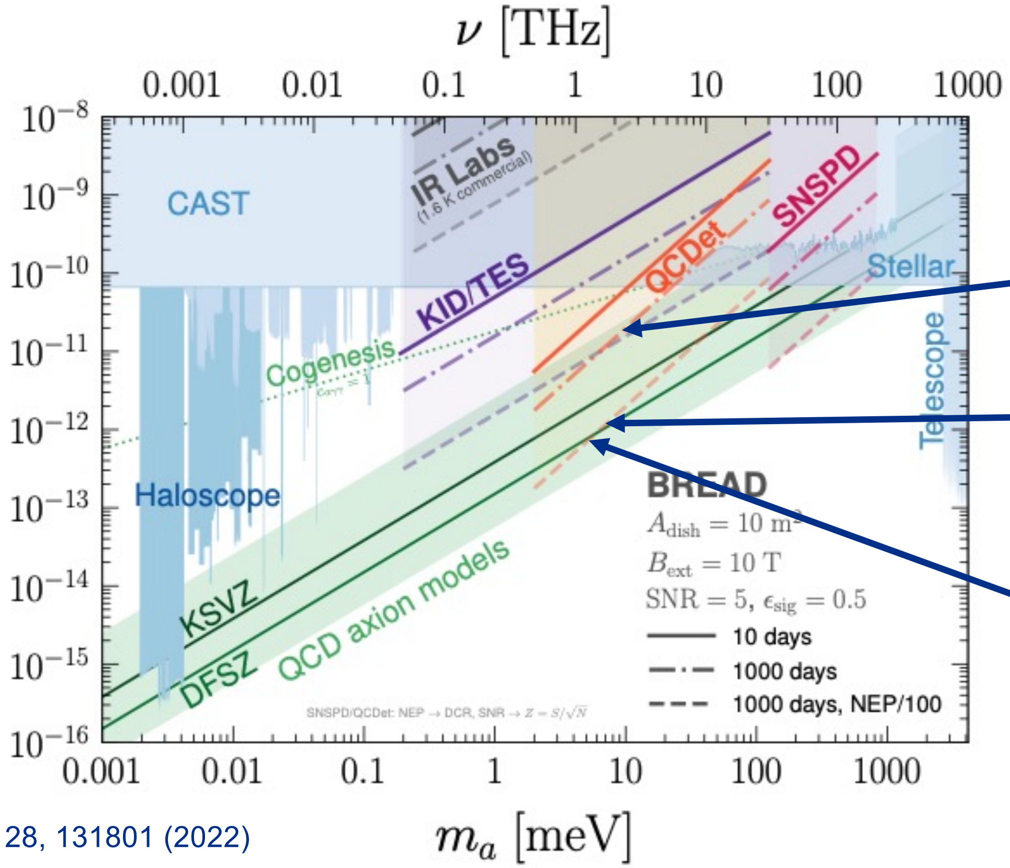
Need larger B^2V for cavity experiments!

Broadband dish expts: use longer integration time to see smaller signal rates

These are now background limited → Need to reduce best SPD dark count rates by factor 10^4 !!!



BREAD sensitivity to photon-axion coupling



J. Liu, et al., PRL 128, 131801 (2022)

Dark Count Rates:

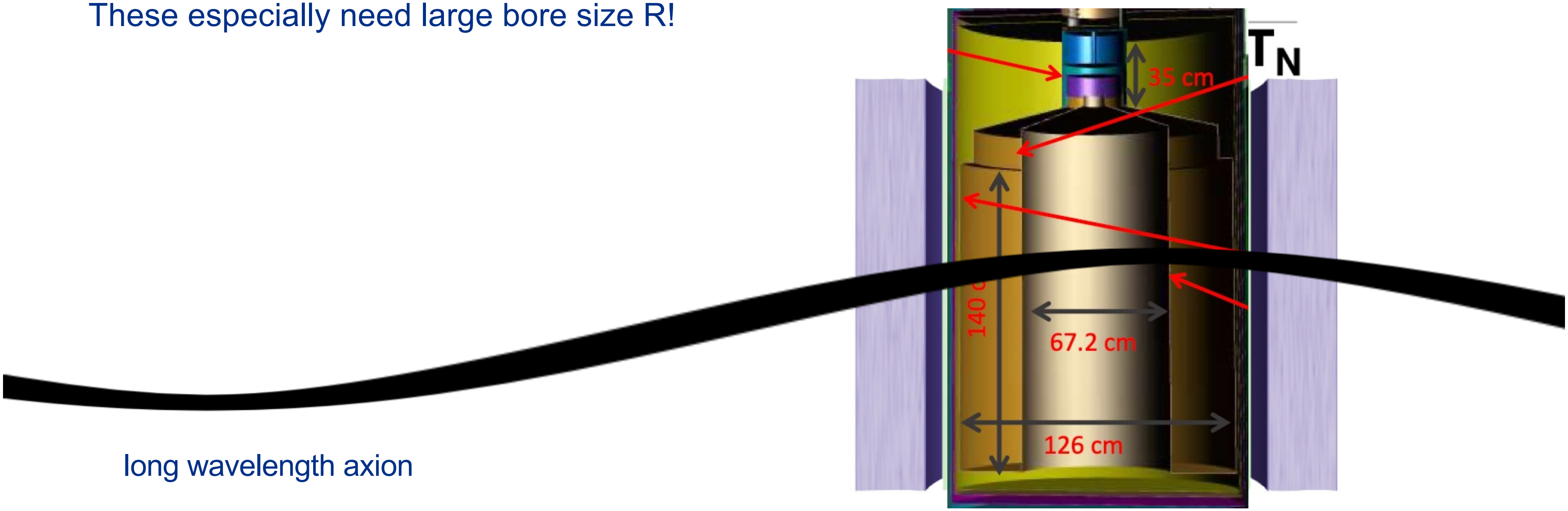
DCR=1 Hz
10^8 counts in t=10^8 s

DCR=10^{-4} Hz **(!)**
10^4 counts in t=10^8 s

Signal rate
$R_s \sim 10^{-6}$ Hz
100 counts in t=10^8 s
R_s limit ~ sqrt(R_b / t)

Need larger B^2V for dish antenna experiments!

Lumped element experiments at lower frequencies have sign**al rates that scale as B^2V (mR)^2** due to the high-pass filtering from the antenna response.
These especially need large bore size R!



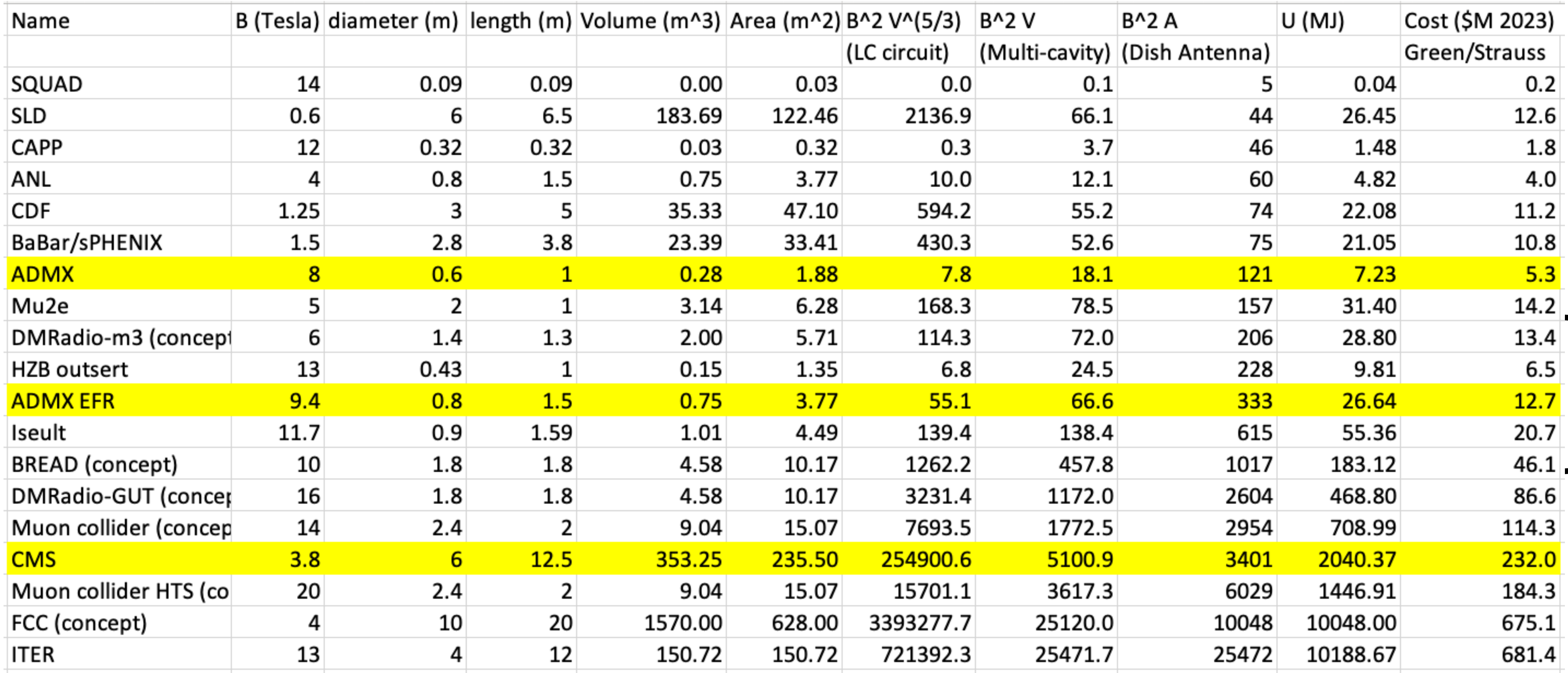
DMRadio-GUT baseline design:
B=16T, V=10 m^3

Need larger $B^2V \times R^2$ for LC experiments!

What we really need for all experiments are bigger magnets

$$C(M\$) = 0.95[E(MJ)]^{0.67}$$

Green/Strauss doi: 10.1109/TASC.2008.921279



Name	B (Tesla)	diameter (m)	length (m)	Volume (m^3)	Area (m^2)	B^2 V^(5/3)	B^2 V	B^2 A	U (MJ)	Cost ($M 2023)
						(LC circuit)	(Multi-cavity)	(Dish Antenna)		Green/Strauss
SQUAD	14	0.09	0.09	0.00	0.03	0.0	0.1	5	0.04	0.2
SLD	0.6	6	6.5	183.69	122.46	2136.9	66.1	44	26.45	12.6
CAPP	12	0.32	0.32	0.03	0.32	0.3	3.7	46	1.48	1.8
ANL	4	0.8	1.5	0.75	3.77	10.0	12.1	60	4.82	4.0
CDF	1.25	3	5	35.33	47.10	594.2	55.2	74	22.08	11.2
BaBar/sPHENIX	1.5	2.8	3.8	23.39	33.41	430.3	52.6	75	21.05	10.8
ADMX	8	0.6	1	0.28	1.88	7.8	18.1	121	7.23	5.3
Mu2e	5	2	1	3.14	6.28	168.3	78.5	157	31.40	14.2
DMRadio-m3 (concep	6	1.4	1.3	2.00	5.71	114.3	72.0	206	28.80	13.4
HZB outsert	13	0.43	1	0.15	1.35	6.8	24.5	228	9.81	6.5
ADMX EFR	9.4	0.8	1.5	0.75	3.77	55.1	66.6	333	26.64	12.7
Iseult	11.7	0.9	1.59	1.01	4.49	139.4	138.4	615	55.36	20.7
BREAD (concept)	10	1.8	1.8	4.58	10.17	1262.2	457.8	1017	183.12	46.1
DMRadio-GUT (conce	16	1.8	1.8	4.58	10.17	3231.4	1172.0	2604	468.80	86.6
Muon collider (concep	14	2.4	2	9.04	15.07	7693.5	1772.5	2954	708.99	114.3
CMS	3.8	6	12.5	353.25	235.50	254900.6	5100.9	3401	2040.37	232.0
Muon collider HTS (co	20	2.4	2	9.04	15.07	15701.1	3617.3	6029	1446.91	184.3
FCC (concept)	4	10	20	1570.00	628.00	3393277.7	25120.0	10048	10048.00	675.1
ITER	13	4	12	150.72	150.72	721392.3	25471.7	25472	10188.67	681.4

Barely reach QCD axion with a lot of hand-waving

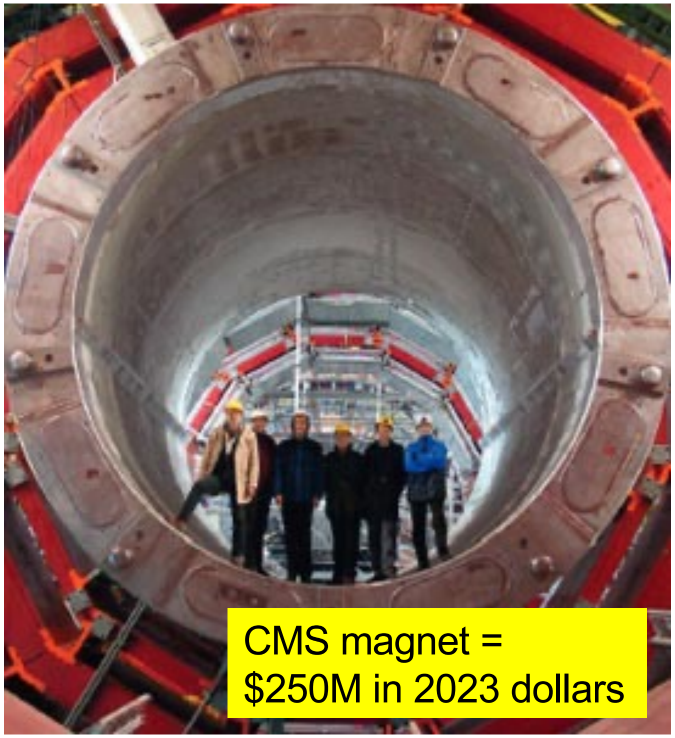
Decisively reach axion (g=0.3)

Push to g=0.1 !

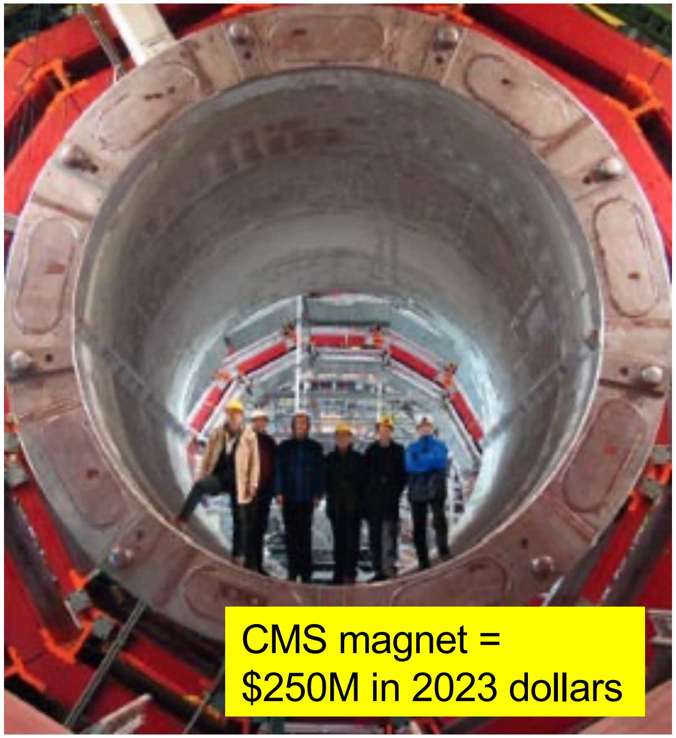
The Dark Wave Lab magnet will be best magnet available for axion searches for the near future. What comes next???

Build $500M-scale magnet user facilities, hosting many experiments?

CMS magnet? They need similar for muon collider tracker, need 10x scale-up for FCC detector



CMS magnet =
$250M in 2023 dollars



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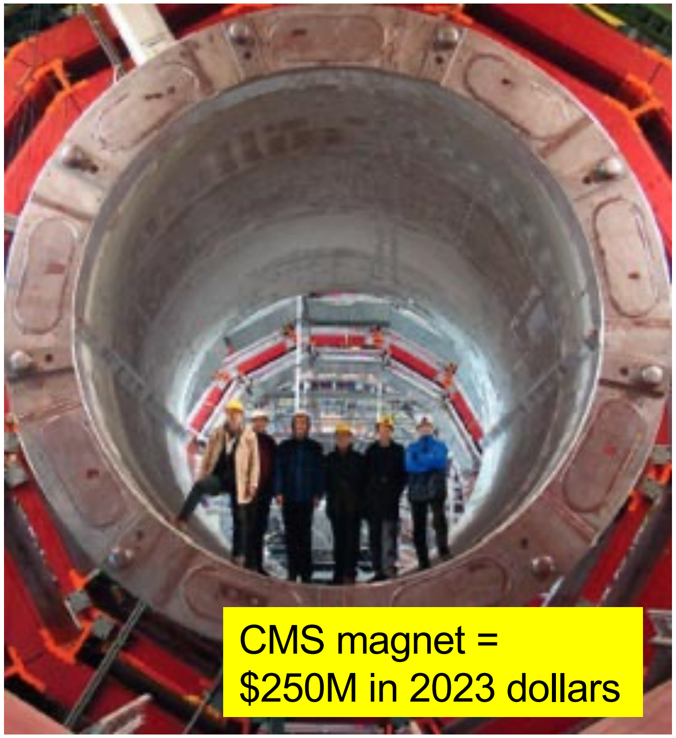


CMS magnet =
$250M in 2023 dollars

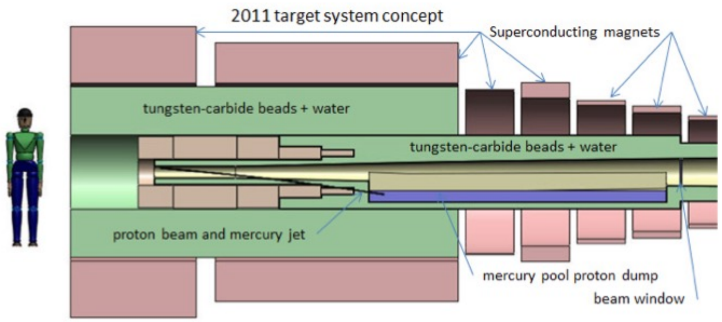
Magnets of this scale take **10 years to build**, so if we want them, we better start planning now!
Who are our partners?

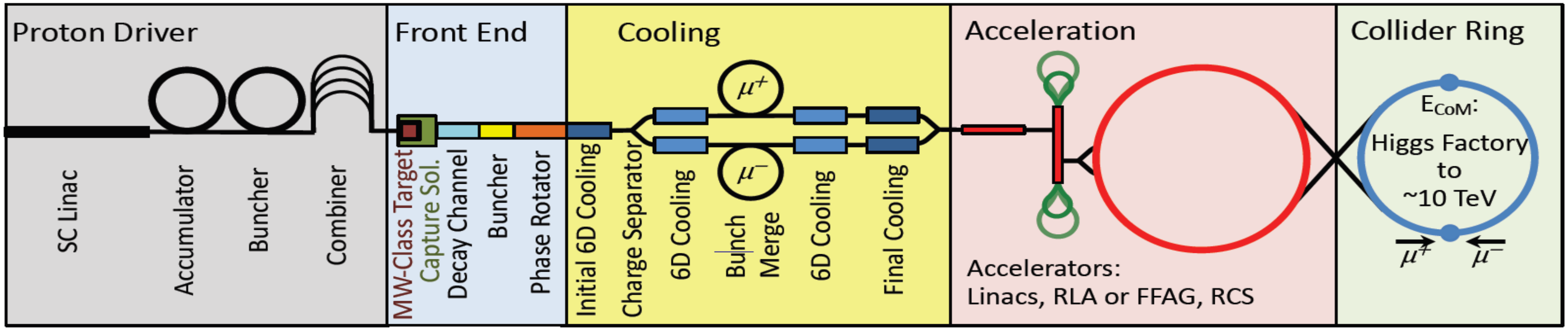
Muon Collider Facility Overview

J.S. Berg
Fermilab ACE Science Workshop
June, 2023

Needs 20 T, 2m bore solenoid to focus the pion beam, >$200M

- Proton driver creating high-power proton beam
- Front end: create pions at target, capture muons, convert to buncl
- Cooling: reduce emittance, combine into one bunch
- Acceleration: increase energy
- Collider ring





Axion experiments go here

Multi-prong strategy provides many stakeholders, broad science program,

Energy Frontier:
Muon Collider,
Tracking detector magnets

Cosmic Frontier:
Axion Dark Matter

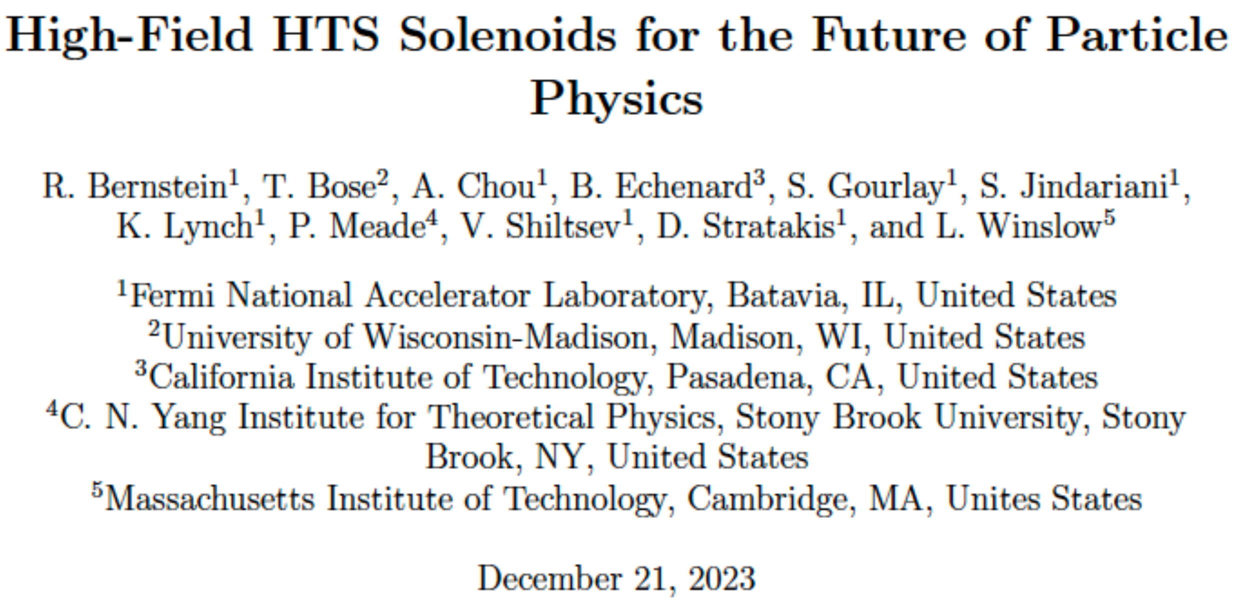
Accelerator Frontier:
Magnet R&D,
Muon Collider,
Accelerator Complex Evolution

Rare/Precision Frontier:
Charged Lepton Flavor Violation

Non-HEP:
Plasma fusion,
High field MRI,
Quantum magnetic materials, High-Tc superconductivity, etc.

Bring home the gold ($$$) !

Letter to NASEM EPP2024 co-signed by several former Snowmass frontier conveners



High-Field HTS Solenoids for the Future of Particle Physics

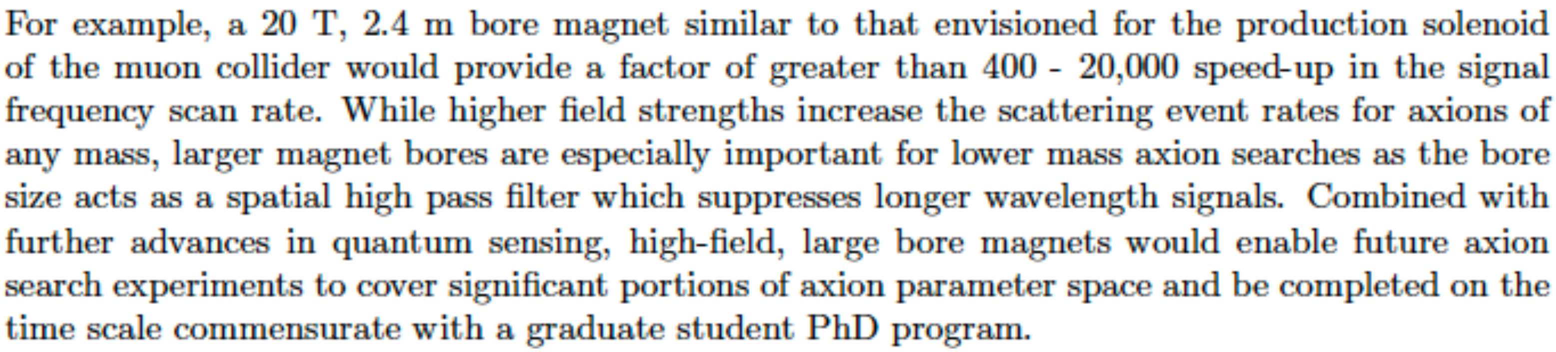
R. Bernstein[1], T. Bose[2], A. Chou[1], B. Echenard[3], S. Gourlay[1], S. Jindariani[1],
K. Lynch[1], P. Meade[4], V. Shiltsev[1], D. Stratakis[1], and L. Winslow[5]

[1]Fermi National Accelerator Laboratory, Batavia, IL, United States
[2]University of Wisconsin-Madison, Madison, WI, United States
[3]California Institute of Technology, Pasadena, CA, United States
[4]C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY, United States
[5]Massachusetts Institute of Technology, Cambridge, MA, Unites States

December 21, 2023

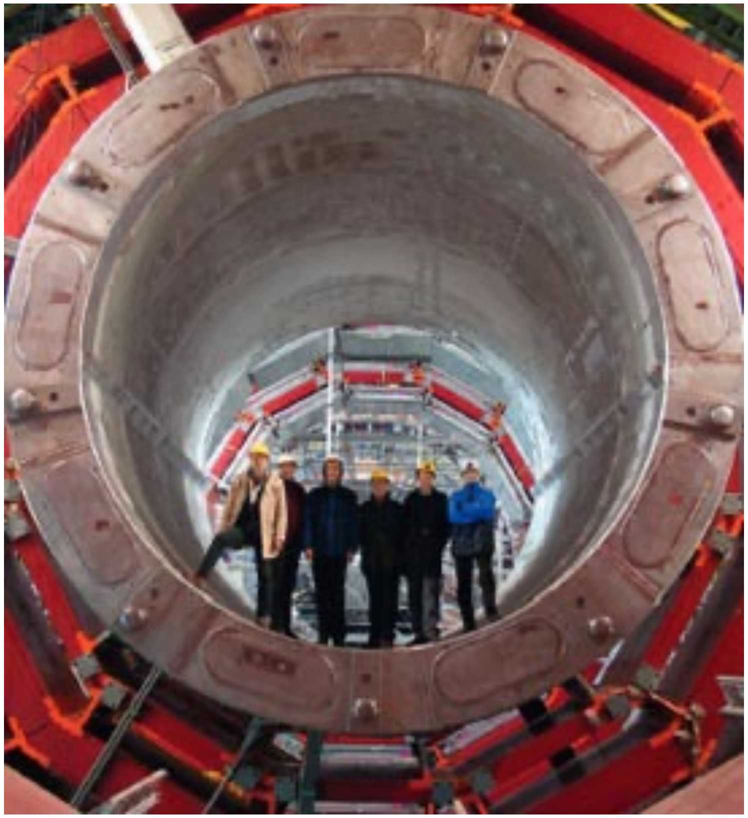
HEP science case also communicated to NASEM High Magnetic Field Science study, 2024

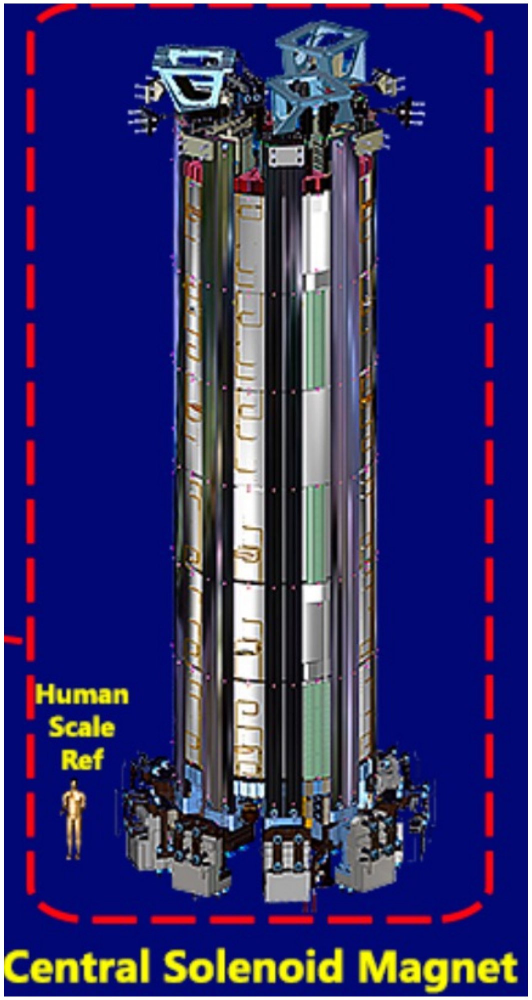
Excerpt:



For example, a 20 T, 2.4 m bore magnet similar to that envisioned for the production solenoid of the muon collider would provide a factor of greater than 400 - 20,000 speed-up in the signal frequency scan rate. While higher field strengths increase the scattering event rates for axions of any mass, larger magnet bores are especially important for lower mass axion searches as the bore size acts as a spatial high pass filter which suppresses longer wavelength signals. Combined with further advances in quantum sensing, high-field, large bore magnets would enable future axion search experiments to cover significant portions of axion parameter space and be completed on the time scale commensurate with a graduate student PhD program.

The Dark Wave Lab is the first step towards future HEP magnet user facilities





Need 100x stored energy to reduce integration time from 10,000 years to 1 year