Overview on Precision Measurement

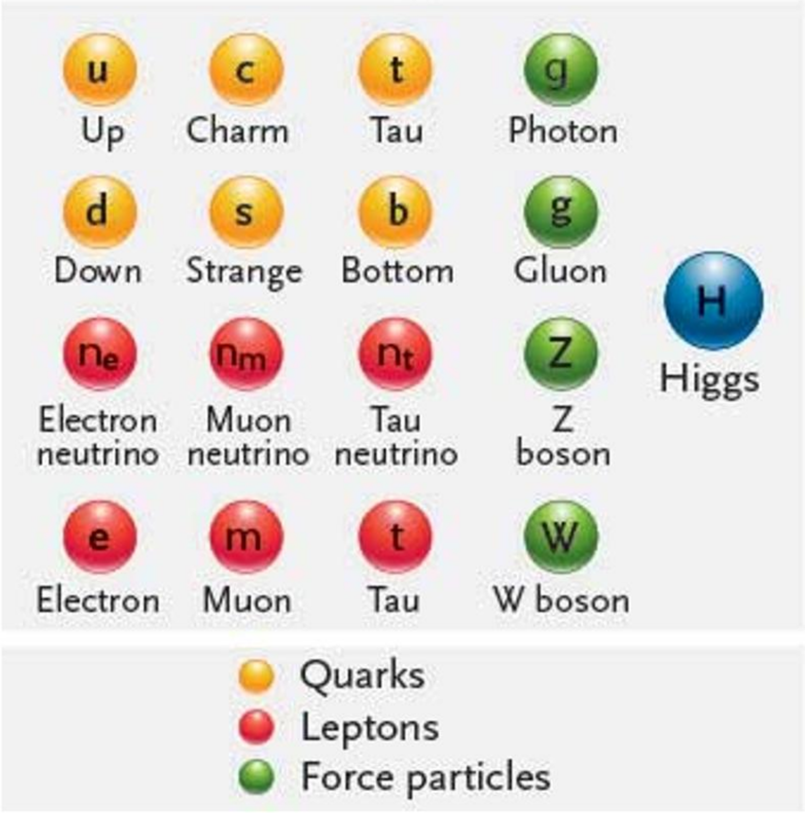
Northwestern | Center for Fundamental Physics with Tabletop Experiments

CFP

Gerald Gabrielse
Trustees Professor of Physics, Northwestern University
Director of the Center for Fundamental Physics

Fundamental Physics Motivation: Probing the Great Mystery of the "Standard Model"

The Standard Model → the "triumph and the great frustration of modern physics!



- Particles
- Interactions
- Symmetries C, P, T, CP, CPT
- Quantum field theory → CPT → Lorentz invariance

Incredibly precise predictions **and** Inconsistent with our universe

The Mystery of the Standard Model

Great triumph: The Standard Model has survived all laboratory tests of its predictions ☺

Great frustration: The Standard Model is incomplete or wrong ☹

- Cannot explain how a universe survives the big bang
- Cannot baryon rather than antibaryon universe?
- Gravity does not fit well (can’t be renormalized)
- Cannot explain inflation
- Cannot explain dark energy
- No dark matter has been identified

Our approach: Test the most precise predictions of the Standard Model
→ Look for evidence of new physics beyond the Standard Model

Fundamental Physics with Tabletop Measurementgs

- Testing the most precise predictions of the Standard Model (SM)
- Testing the fundamental symmetries of the Standard Model
- Seach for physics beyond the Standard Model (BSM)
- Search for symmetry violations
- Search for missing or new particles
- Measure fundamental constants

APS

Topical Group on Precision Measurement & Fundamental Constants

The Topical Group on Precision Measurement & Fundamental Constants is a subunit of the American Physical Society. Its objective is to serve as a focus for research related to investigating and testing the fundamental laws of physics and their underlying connections, determining fundamental constants, and developing and improving basic measurement standards, with special emphasis on the high precision experiments that are characteristic of such research.

quantum
nondestructive
cold

use precision rather than high energy

I prefer "Fundamental Physics" to "Precision Measurmeents"

Center for Fundamental Physics
with Tabletop Experiments

Compare with Other APS Topical Groups

TOPICAL GROUPS			
Compression (GCCM)	427	469	543
Data Science (GDS)	1245	1533	1399
Energy Research & Applications (GERA)	725	768	721
Few-Body Systems (GFB)	329	307	328
Hadronic Physics (GHP)	593	628	576
Instrument & Measurement Science (GIMS)	553	609	592
Magnetism (GMAG)	1,139	1,231	1,218
Medial Physics (GMED)	508	518	486
Plasma Astrophysics (GPAP)	464	477	424
Physics of Climate (GPC)	571	630	596
Physics Education Research (GPER)	630	702	747
Fundamental Constants (GPMFC)	521	557	547
Quantum Materials Synthesis (GQMS)	N/A	N/A	N/A
Statistical & Non-Linear (GSNP)	1,203	1,280	1,302

DIVISIONS			
Atomic, Molecular & Optical (DAMOP)	3,188	3,327	3,322
Astrophysics (DAP)	2,799	2,899	2,725
Biological Physics (DBIO)	1,969	2,188	2,160
Condensed Matter Physics (DCMP)	6,324	6,731	6,568
Computational Physics (DCOMP)	2,920	2,928	2,765
Chemical Physics (DCP)	1,314	1,317	1,222
Fluid Dynamics (DFD)	3,432	3,250	3,299
Gravitation (DGRAV)	1,590	1,651	1,526
Laser Science (DLS)	1,145	1,204	1,080
Materials Physics (DMP)	2,844	2,979	2,802
Nuclear Physics (DNP)	2,764	2,812	2,559
Physics of Beams (DPB)	1,086	1,070	1,001
Particles & Fields (DPF)	3,410	3,448	3,100
Polymer Physics (DPOLY)	1,245	1,351	1,371
Plasma Physics (DPP)	2,584	2,652	2,422
Quantum Information (DQI)	2,864	3,321	3,539
Soft Matter (DSOFT)	1,980	2,127	2,147

Challenges

Measurements often take many years because of the high precision

Infrequent papers

Cost – much lower than high energy physics
– much higher than most low energy experiments

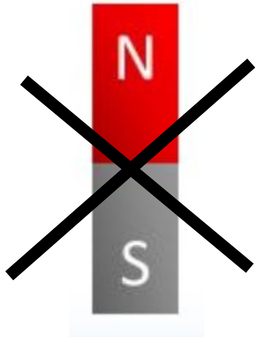
Hard to get a career launched – cost, time to build apparatus

Tenure can be difficult – need many papers and “home run”

e.g. Electron magnetic moment measurement -- 14 PhD thesis
nearly 40 years

The Electron has Magnetic and Electric Dipole Moments

Magnetic dipole moment $\vec{\mu} = \mu \frac{\vec{S}}{\hbar / 2}$



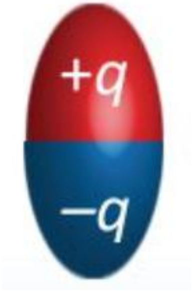
but: no magnetic charges

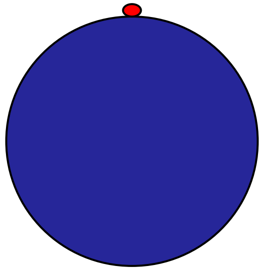
but: no electron size
no rotation

Most precise prediction of the Standard Model

Sensitive to BSM physics

Electric dipole moment $\vec{d} = d \frac{\vec{S}}{\hbar / 2}$

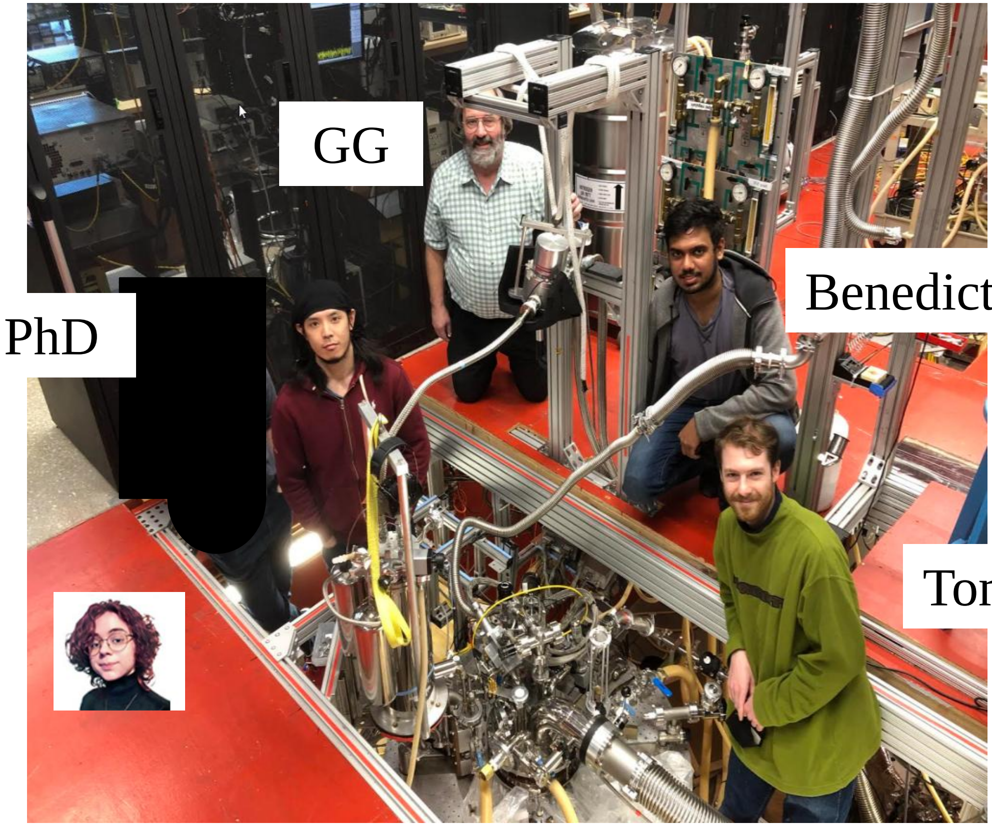




Too small to measure ← Standard Model
Bigger ← BSM Models

New Measurement of the Electron Magnetic Moment and a New Dark Photon Limit

Gerald Gabrielse
Board of Trustees Professor and Director of the Center for Fundamental Physics (CFP),
Department of Physics and Astronomy, Northwestern University



N$F: Lepton moments QM: cavities for qubits Templeton: SQUID development

Standard Model's Most Precise Prediction

prediction requires a measured fine structure constant

electron

$$\vec{\mu} = \mu \frac{\vec{S}}{\hbar/2}$$

$$\frac{e\hbar}{2m} \rightarrow -\frac{\mu}{\mu_B} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots$$

$$+ a_{hadronic} + a_{weak}$$

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

magnetic moment in Bohr magnetons

Dirac	1		
QED	$C_2 = 0.5$		
	$C_4 = -0.328\,478\,444\,002\,54\,(33)$	exact + mass ratios	
	$C_6 = 1.181\,234\,016\,815\,(10)$		
	$C_8 = -1.911\,321\,391\,8(12)$		891
	$C_{10} = 6.74\,(16)$	Kinoshita, Nio, …	12672
Hadronic	$a_{hadronic} = 1.693\,(11) \times 10^{-12}$		
Weak	$a_{weak} = 0.03053\,(23) \times 10^{-12}$		

Feynman diagrams

1987 – Dehmelt finished – import step forward

any keV electrons → 4.2 K electron

classical cyclotron orbits - measured frequency depends on energy
- spontaneous emission limits measurement time
- magnetic gradient

1987 – Gabrielse – quest for a quantum system

ongoing

4.2 K electron → 10 μK

quantum cyclotron – ground state and first excited state
– inhibited spontaneous emission (20 sec lifetime)
– QND detection
– special relativity (eliminate magnetic gradient)
– quantum-limited detector
– backaction circumvention

2006-2008: First fully quantum measurements of μ/μ_B

- 15 times more accurate than 1987 measurement
- Took about 20 years and ≅10 Harvard PhD Students

- **Good agreement between measured and predicted μ/μ_B**
  - SM theory calculations much less accurate than electron measurement
  - Fine structure constant 20x less accurate than needed to test SM
- **For 12 years determine α using measured μ/μ_B and Standard Model calculation**

$$-\frac{\mu}{\mu_B} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots$$

$$+ a_{hadronic} + a_{weak}$$

After 2008: Important Theory Developments

Stefano Laporta
891 4-loop diagrams

8th Order QED calculated analytically to 1100 digits → instead of 4 !!!

C_8 = -1.912 98 (84) → C_8 = -1.912 245 764 926 445 574 152 647 167 439 830 054 060 873 …

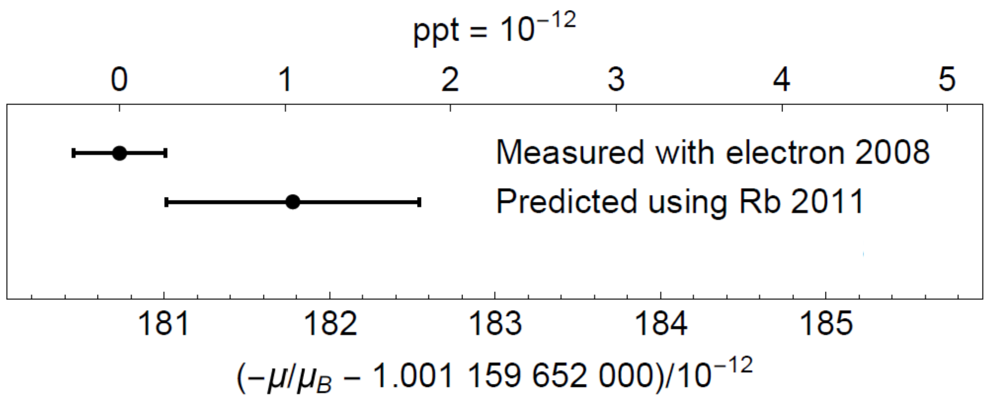
10th Order QED calculated numerically for the first time (Nio, Kinoshita, ...)

C_{10} = unknown → C_{10} = 6.74 (16)   12,670 Feynman diagrams

Standard Model calculation → became 10 times more accurate than the measurement uncertainty in μ/μ_B

2011: New α Measurement – accurate enough to test SM

Good agreement between measured and predicted μ/μ_B



$$-\frac{\mu}{\mu_B} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ \ldots$$

$$+ \ a_{hadronic} + \ a_{weak}$$

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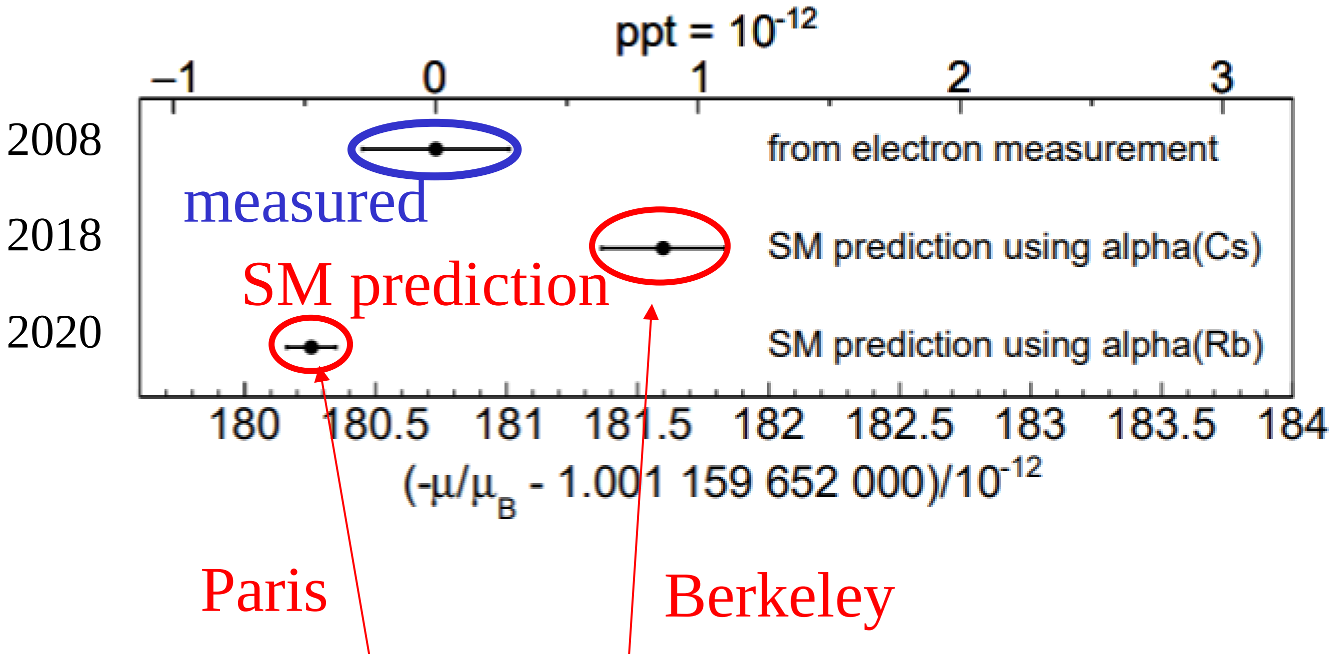
☹ 2018 and 2020: "More Precise" α Measurements ☹



☹ Discrepancy due entirely to measured α values ☹
that differ by > 5σ

- α discrepancy limits the SM test
- Perhapsbest α is again from μ/μ_B plus SM

Theoretical "Explanations"

S. Gardner and X. Yan, LIght scalars with lepton number to solve the $(g-2)_e$ anomaly, 2019.

J. Liu, C. E. M. Wagner, and X.-P. Wang, Journal of High Energy Physics **2019**, 8 (2019).

H. Davoudiasl and W. J. Marciano, Phys. Rev. D **98**, 075011 (2018).

A. Crivellin, M. Hoferichter, and P. Schmidt-Wellenburg, Phys. Rev. D **98**, 113002 (2018).

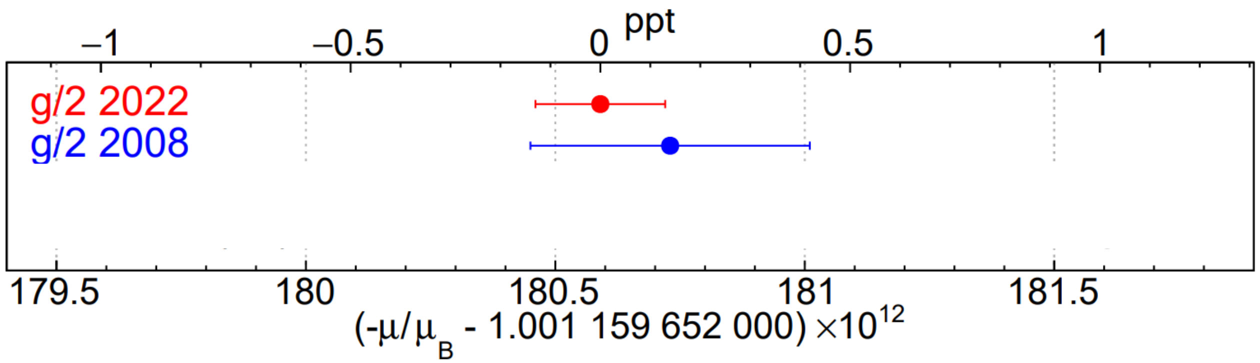
X.-F. Han, T. Li, L. Wang, and Y. Zhang, Phys. Rev. D **99**, 095034 (2019).

S. Jana, V. P. K., W. Rodejohann, and S. Saad, Dark matter assisted lepton anomalous magnetic moments and neutrino masses, 2020.

C. Arbelez, R. Cepedello, R. M. Fonseca, and M. Hirsch, $(g-2)$ anomalies and neutrino mass, 2020.

(and more)

Unblinded Measurement Determines μ/μ_B = -g/2 to 1.3 parts in 10^{13}



$$\frac{g}{2} = 1.001\,159\,652\,180\,59\,(13) \quad [0.13 \text{ ppt}]$$

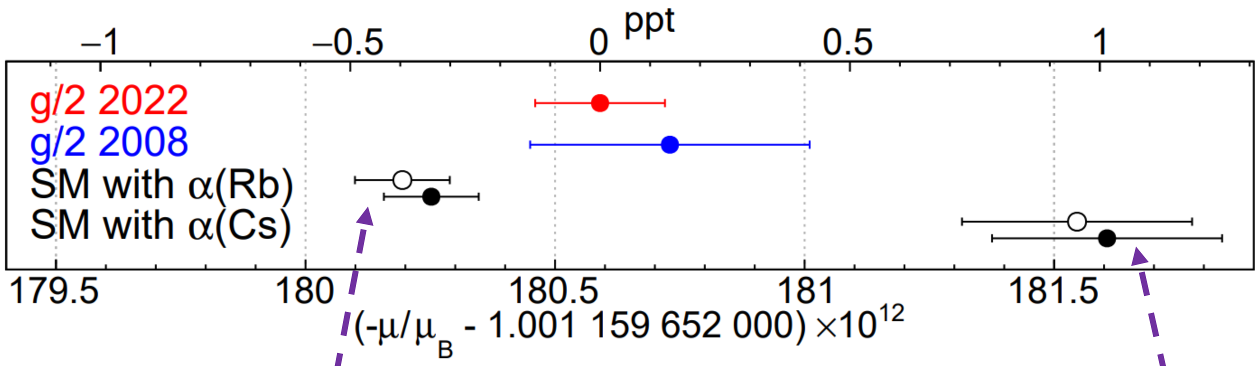
1.3 parts in 10^{13}

- Most precisely determined property of an elementary particle
- Tests the most precise prediction of the Standard Model of Particle Physics
- Sensitive test for BSM physics

“Measurement of the Electron Magnetic Moment”
X. Fan, T.G. Myers, B.A.D. Sukra, G. Gabrielse
Phys. Rev. Lett. **130**, 071801 (2023)

Compare with SM Prediction: μ/μ_B = -g/2 to 1.3 parts in 10^{13}

- Most precisely determined property of an elementary particle
- Tests the most precise prediction of the Standard Model of Particle Physics
- Sensitive test for BSM physics



$$\frac{g}{2} = 1.001\,159\,652\,180\,59\,(13) \quad [0.13 \text{ ppt}]$$

1.3 parts in 10^{13}

Problem: Disagreeing values of the fine structure constant produce "two SM predictions" of μ/μ_B

"Measurement of the Electron Magnetic Moment"

X. Fan, T.G. Myers, B.A.D. Sukra, G. Gabrielse

Phys. Rev. Lett. **130**, 071801 (2023)

☹ Two Predictions Using Two Fine Structure Constant Values ☹

The SM needs the fine structure constant as input → the "best" two alpha measurements disagree by 5 standard deviations ☹

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

C_{10} hadronic α measurement

$$\frac{g}{2}(\text{Rb}) = 1.001\ 159\ 652\ 180\ 254\ (12)\ (11)\ (93)$$

Nature **588**, 61 (2020)

$$\frac{g}{2}(\text{Cs}) = 1.001\ 159\ 652\ 181\ 598\ (12)\ (11)\ (234)$$

Science **360** 191 (2018)

difference is 1344

Please someone measure the fine structure constant with a new method!!!!!

2023 Measurement of Electron Magnetic Moment in Bohr Magnetons

- New apparatus
- New people
- New university
- New state
- Blind measurement

→ First more accurate (2.4x) measurement since 2008

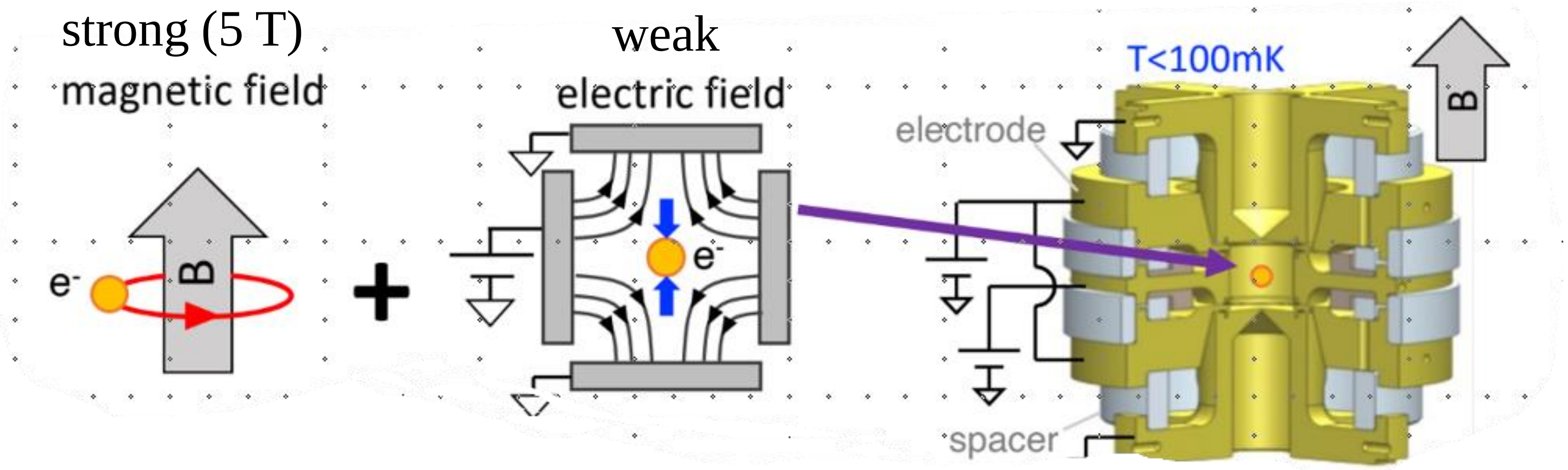
2025 New Measurement Underway

- New apparatus and quantum methods

→ 10x to 30x more precise measurement
→ 200x more stringent lepton CPT test

Measuring the Electron Magnetic Moment

One electron (or positron) in Penning trap for months



- B produced by a 4.2 K superconducting solenoid
- More than 10 shim coils to make B spatially uniform
- Tuned shims using gas ^{3}He NMR probe

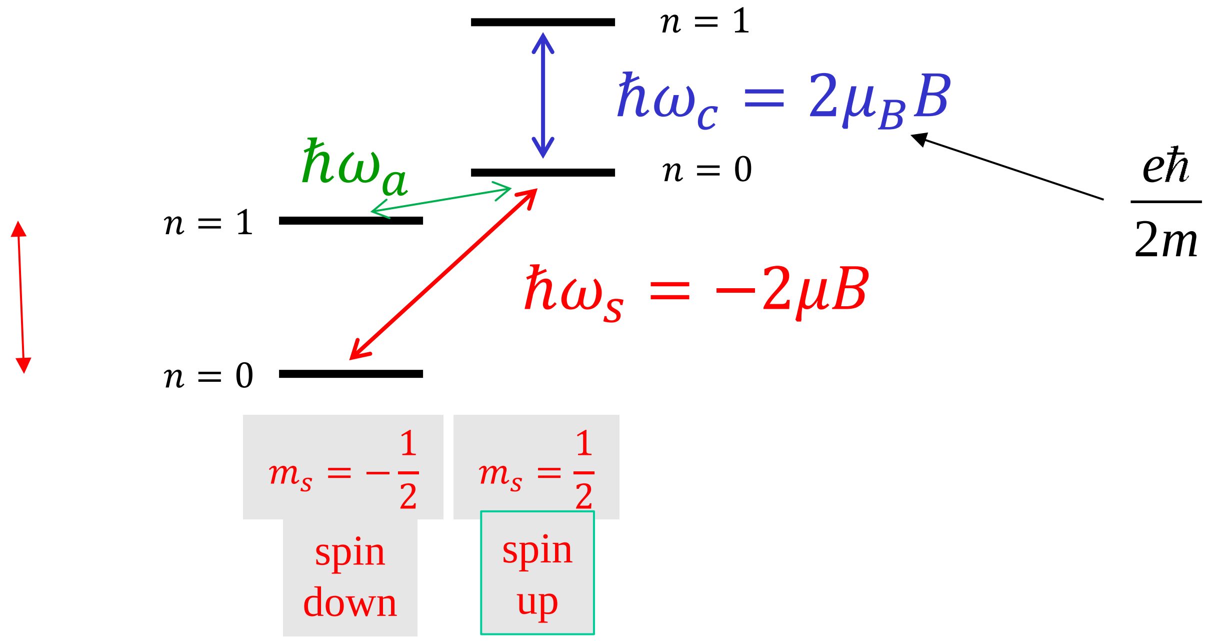
cooled to 30 mK << 7/2 K using a dilution refrigerator

Cylindrical trap microwave cavity
→ inhibits spontaneous emission

One-Electron Quantum Cyclotron

One electron cooled into its lowest cyclotron and spin states

$h\nu_c = k_B \; 7.2$ kelvin



7.2 K >> 30 mK

Measure a ratio of frequencies → use quantum jump spectroscopy

$$-\frac{\mu}{\mu_B} = \frac{\omega_s}{\omega_c} = 1 + \frac{\omega_a}{\omega_c}$$

magnetic field cancels out ☺

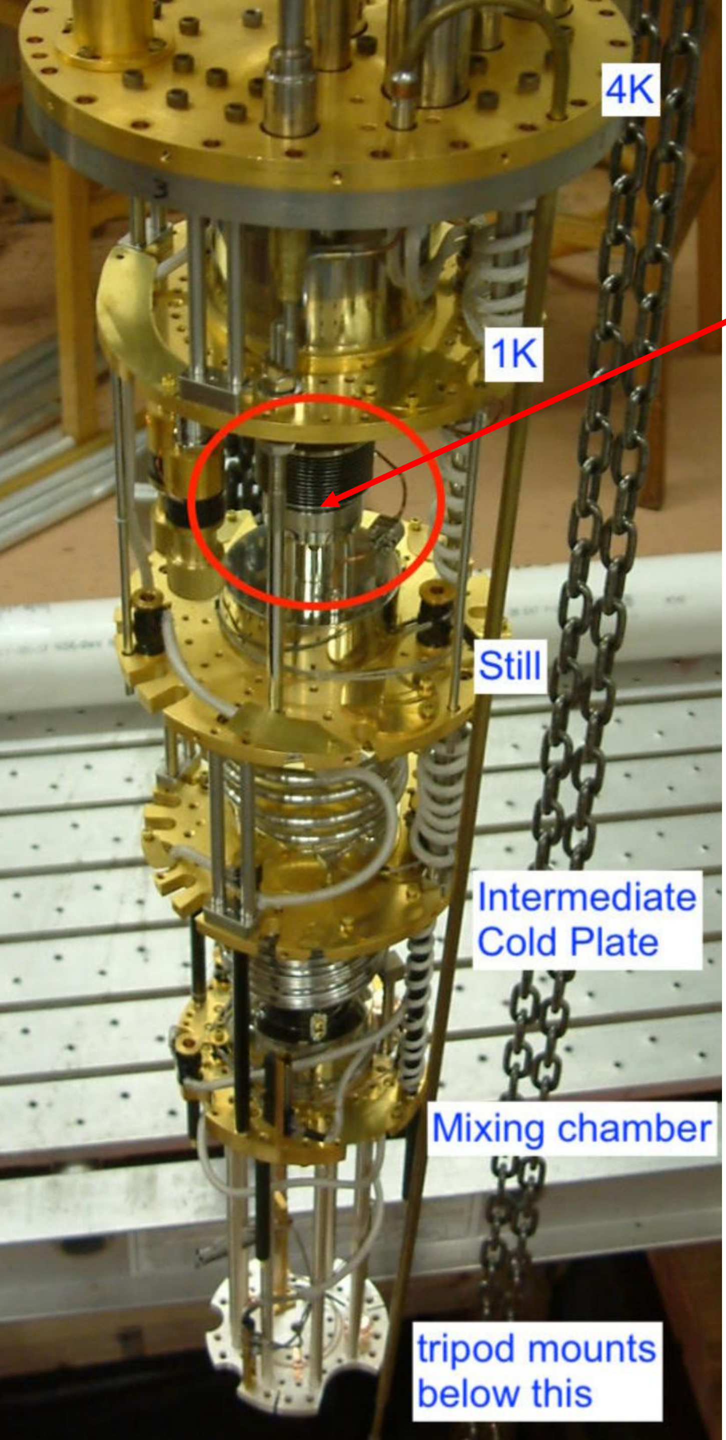
$\omega_a \sim B$ *and* $\omega_c \sim$ B

(actually, more subtle)

Brown-Gabrielse Invariance Theorem

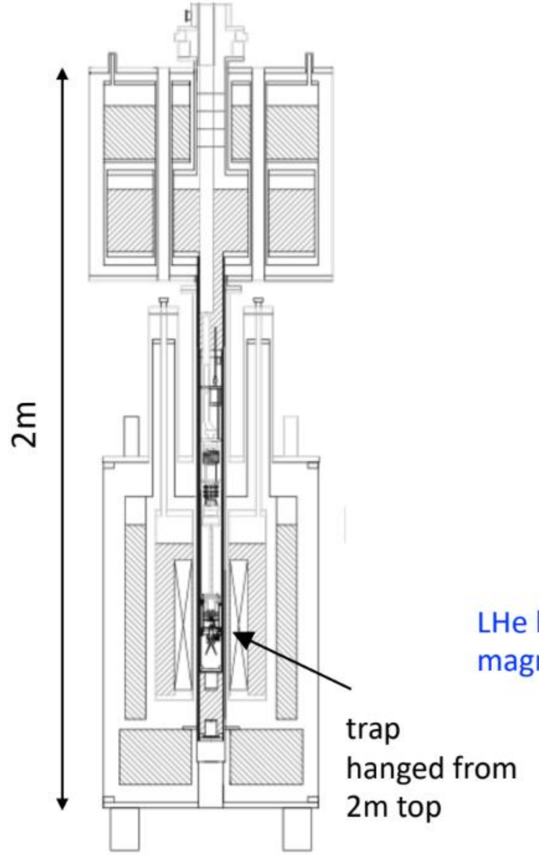
$$\nu_c = \sqrt{(\bar{\nu}_c)^2 + (\bar{\nu}_z)^2 + (\bar{\nu}_m)^2}$$

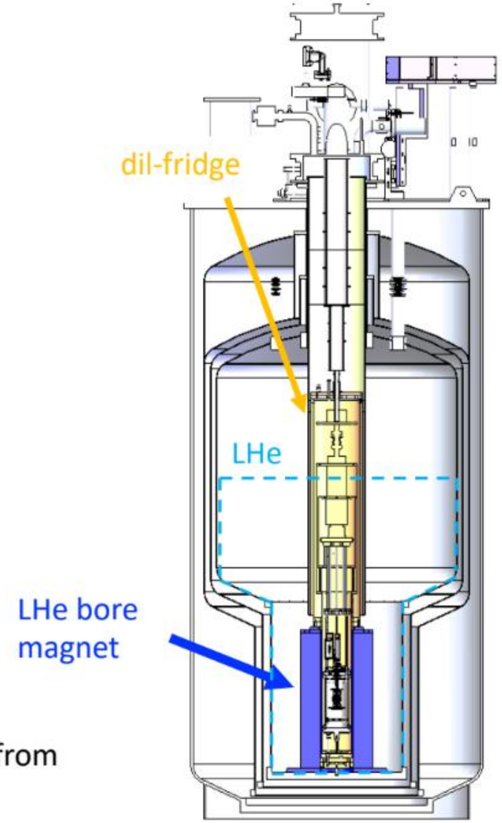
“Flexible Dilution Refrigerator”



flexible hangers allow the refrigerated trap (at 50 mK) to rest mechanically upon the superconducing solenoid coil (4.2 K)

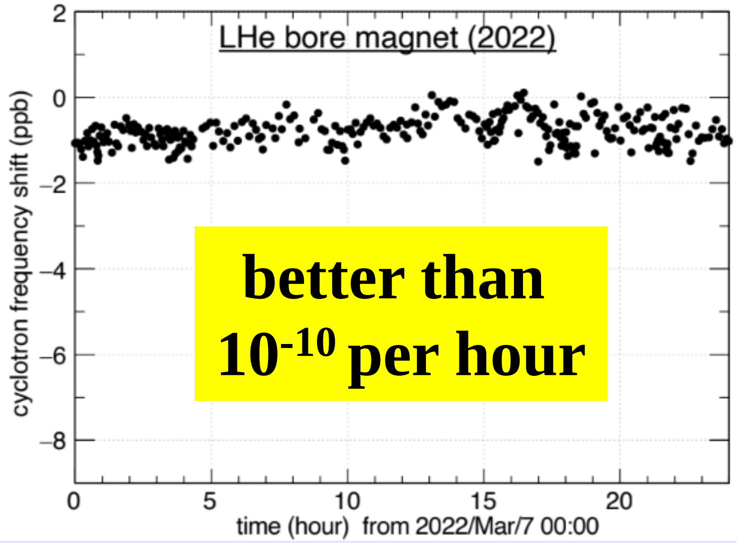
→ the electron in its trap does not move with respect to the solenoid producing the magnetic field



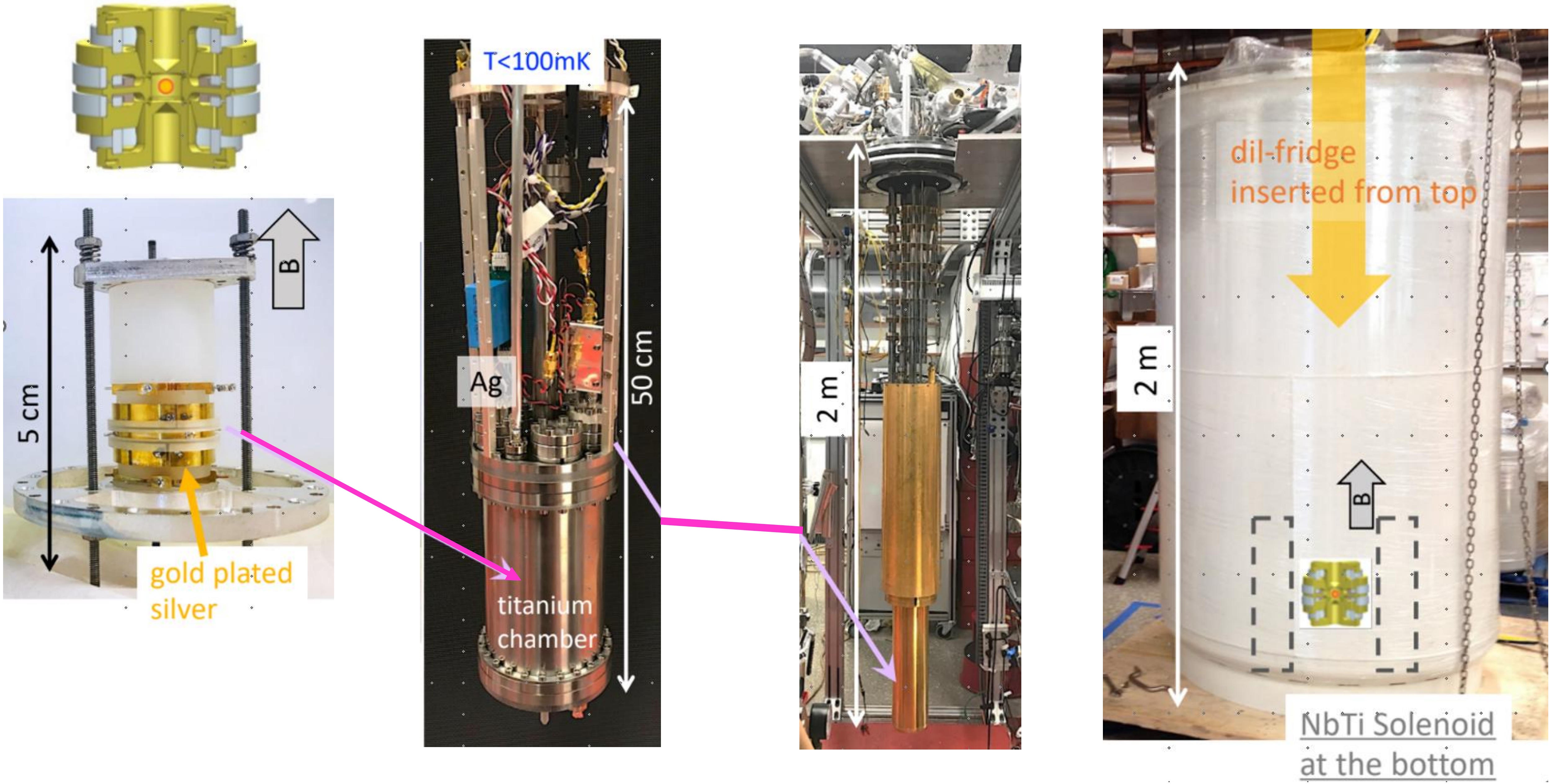


Very Successful

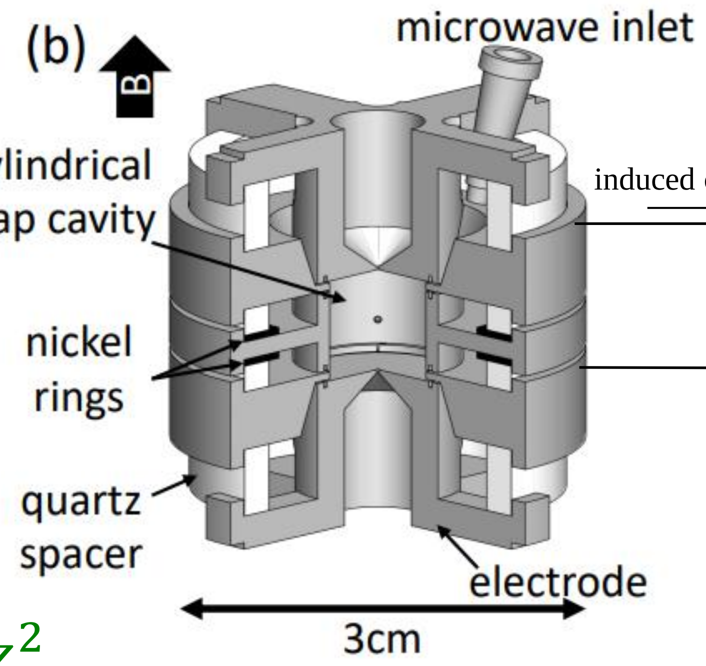
ΔB/B stable to 10^{-9}



Entirely "New" Apparatus → 7 years for design to operation



QND Determination of Cyclotron State (n) and Spin State (m_s)

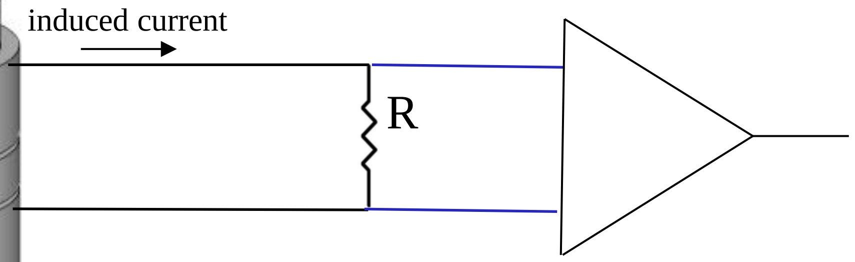


magnetic bottle gradient

$\Delta\vec{B} = B_2 z^2$

$\Delta H = -\mu B_2 z^2$

cryogenic HEMT amplifier



Fourier transform the amplified signal to get the axial frequency and small shifts

$$\Delta\bar{\nu}_z \approx 1.3\,(n + m_s)\ \text{Hz}$$

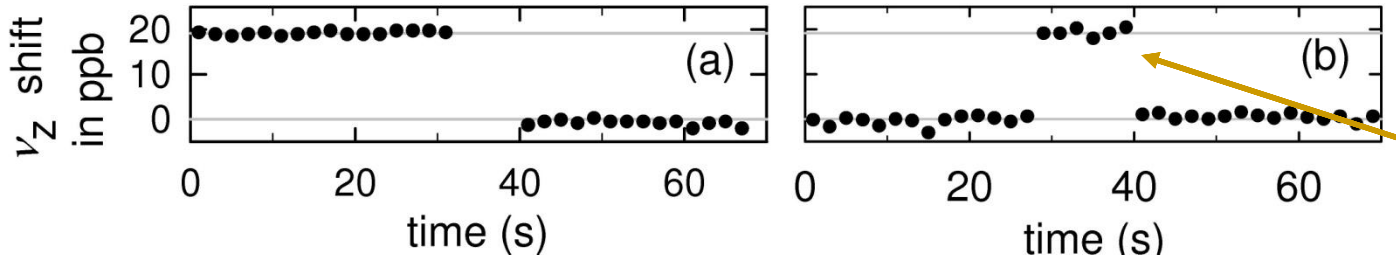
measured axial frequency shift

cyclotron quantum number

spin quantum number

spin flip

cyclotron excitation



100 times cavity-inhibited spontaneous emission

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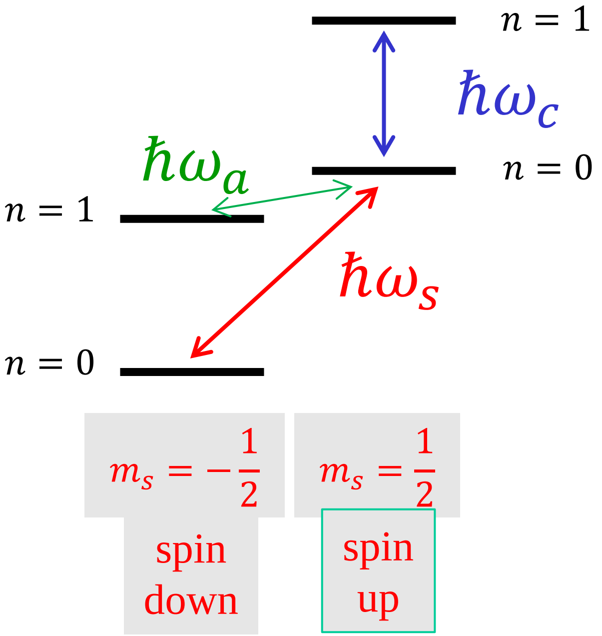
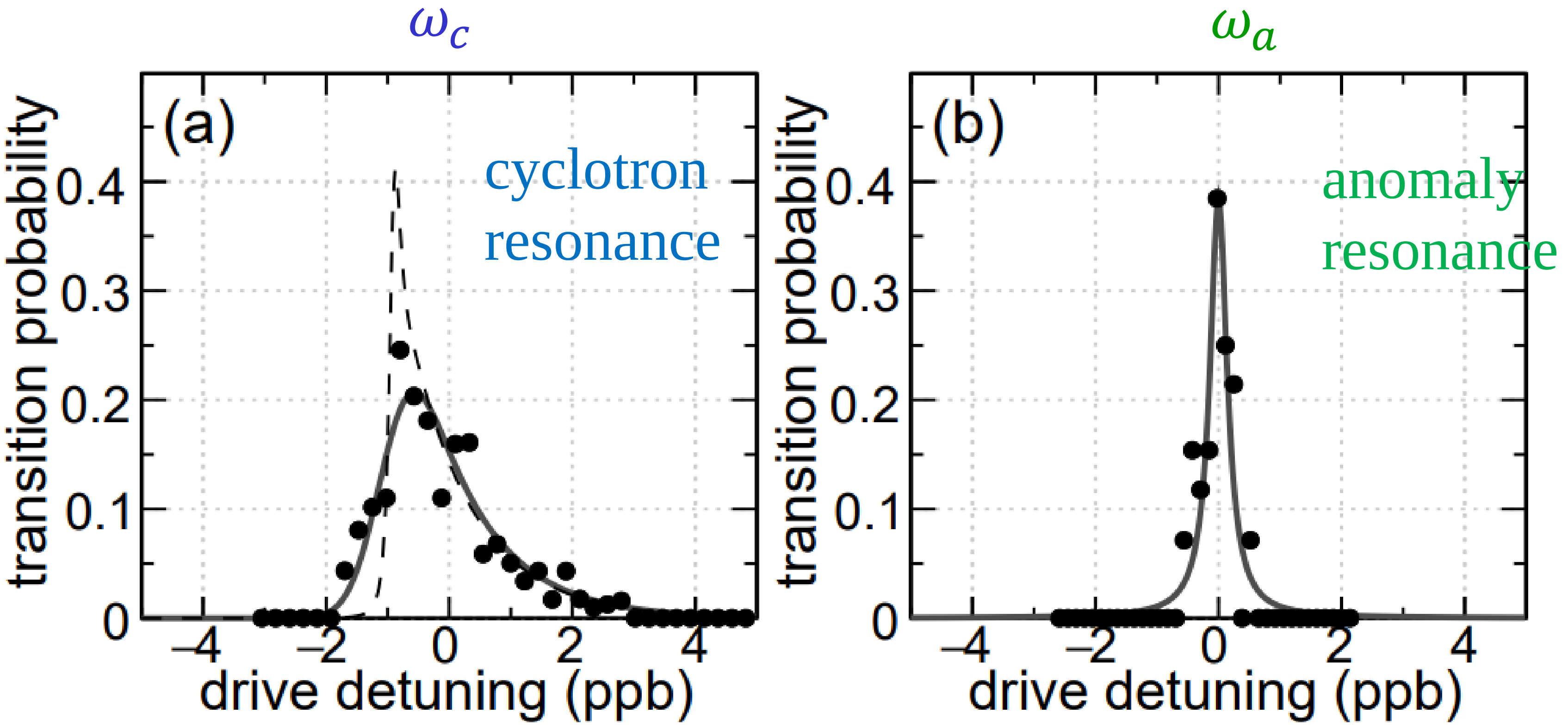
Observed Quantum Jump Lineshapes

count the number of quantum jumps as a function of drive frequency





$$-\frac{\mu}{\mu_B} = 1 + \frac{\omega_a}{\omega_c}$$

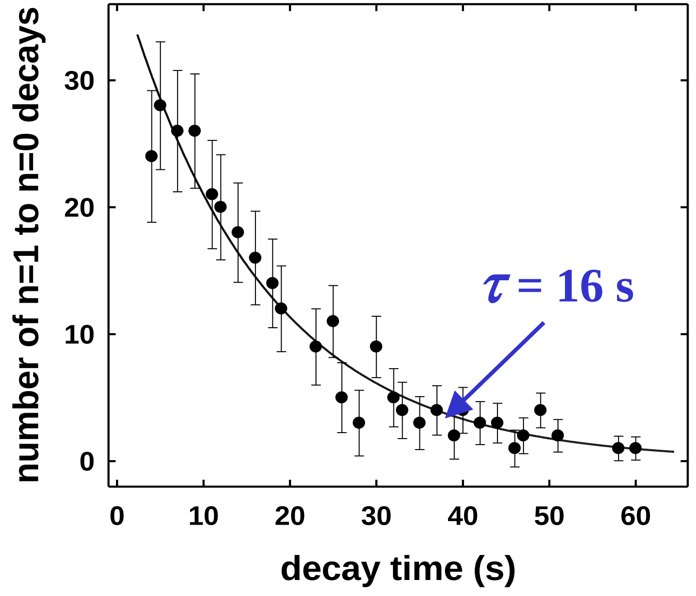
☹ broadened version of the asymmetric lineshape ☹

☺ Expected lineshape ☺

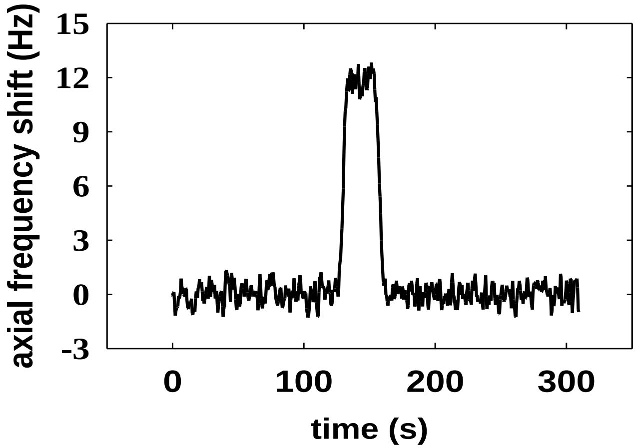
Hypothesis: → There is a B fluctuation spectrum
→ The two motions average the fluctuations in B with a very different time constant

Cavity-Inhibited Spontaneous Emission

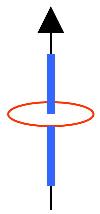
Purcell
Kleppner
Gabrielse and Dehmelt



measure time in excited state



Free Space

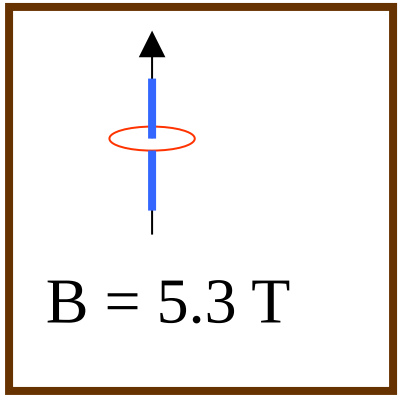


B = 5.3 T

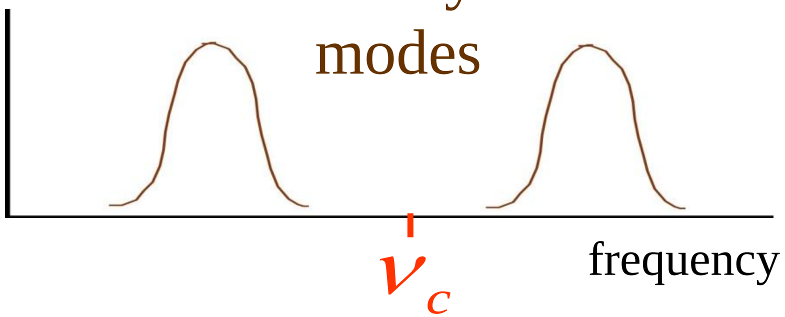
$$\gamma = \frac{1}{75\ ms}$$

inhibited
By 210!

Within
Trap Cavity



$$\gamma = \frac{1}{16\ \text{sec}}$$



Good news
→ narrower
lineshapes

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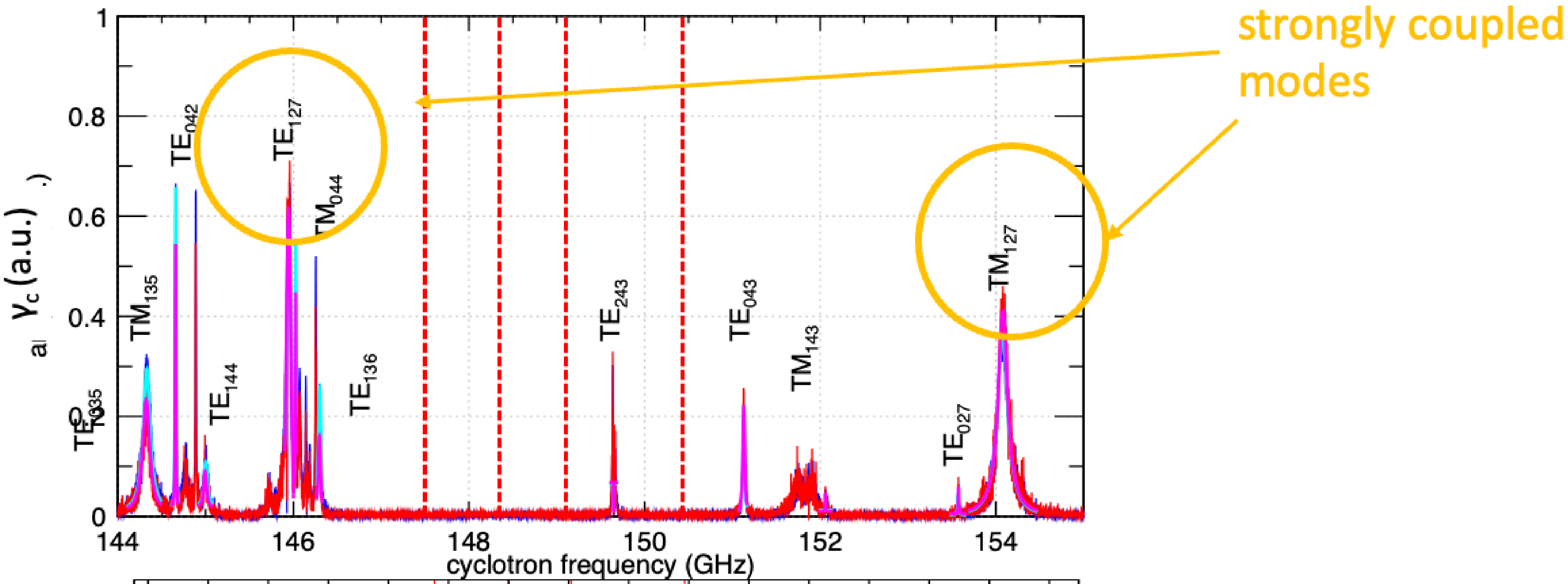
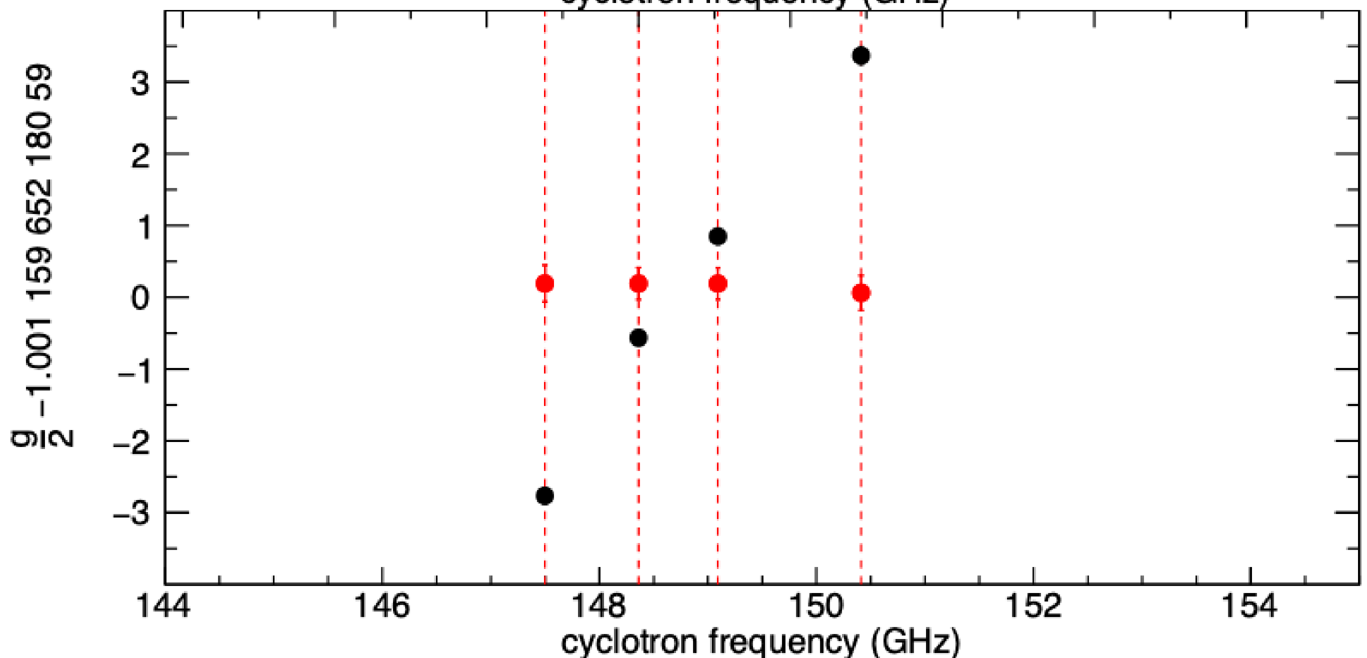
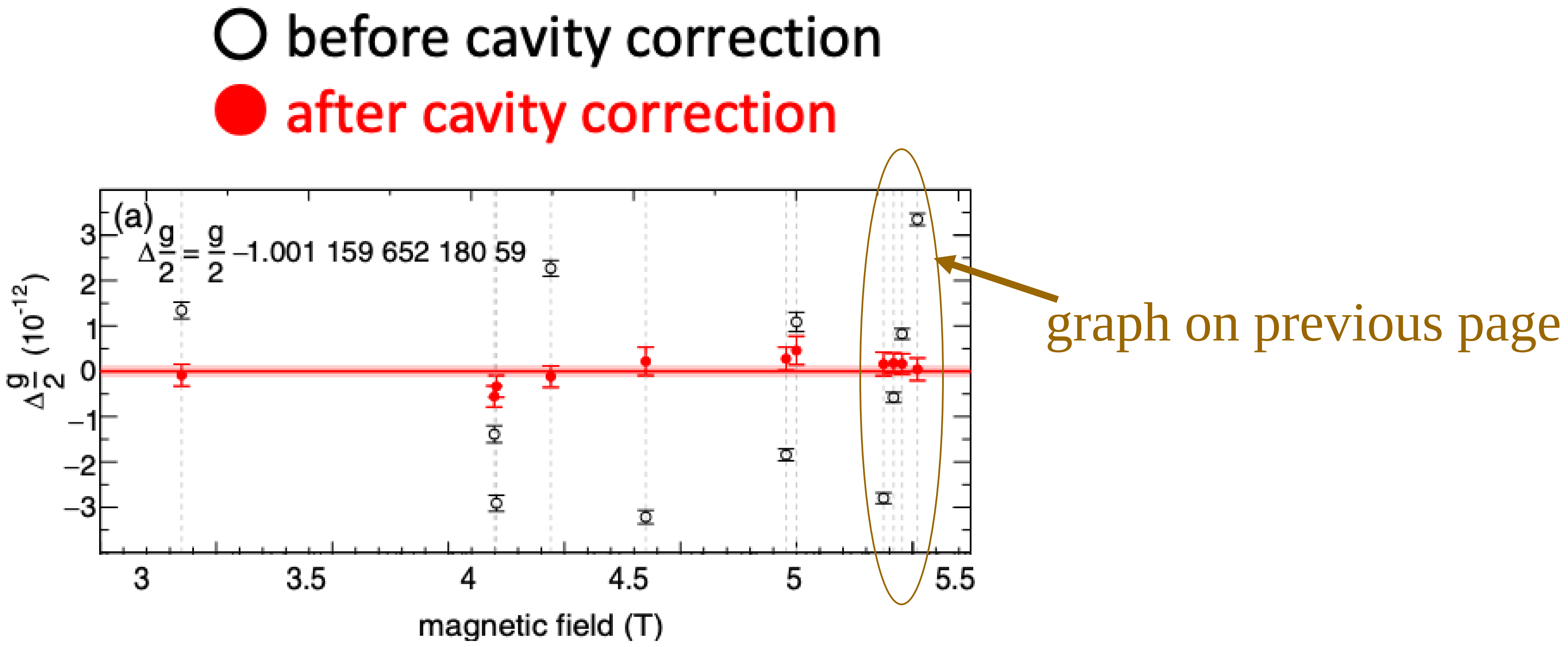
Measured trap cavity mode spectrum



Uncorrected and corrected $g/2 = -\mu/\mu_B$



Also Checked Over a Very Broad Range



This large range includes interactions with many different cavity radiation modes
→ suggests that the one correction to our measured magnetic moment is under good control

Cavity Shifts and Cyclotron Broadening → Largest Uncertainties

TABLE I. Largest uncertainties for $g/2$.

Source	**Uncertainty**$\times 10^{13}$
statistical	0.29
cyclotron broadening	0.94
cavity correction	0.90
nuclear paramagnetism	0.12
anomaly power shift	0.10
magnetic field drift	0.09
total	1.3

Launch of New Measurements of the Electron and Positron Magnetic Moments in Bohr Magnetons

New cryogenic system (dewar, superconducting solenoid, dilution refrigerator) took 7 years and 3 companies to go from design start to operation.

Now underway

Enabling New Ideas

(to determine electron and positron magnetic moments to 1 part in 10^{14})

- QND detection with special relativity instead of magnetic gradient
  → reduce systematic errors from magnetic gradient line broadening

- Quantum-limited (nearly) with a 200 MHz SQUID for the QND detection
  → reduce electron and positron temperature by a factor of 25
  → requires 1kG B field near a 50 kG B field (actively shielded solenoid)

- Detector backaction circumvention

- Smaller trap for better detection efficiency
- More harmonic cylindrical Penning trap
- Higher Q trap cavity at 150 GHz
- Renormalized calculation of cavity shifts

Opportunity: Measure Electron and Positron Magnetic Moments 10x More Accurately

Best lepton CPT test → improved by a factor of 200

Test of the most precise prediction of the SM → improved by a factor of 50

Requires also: fine structure constant error → reduced by a factor of 10
fine structure constant discrepancy → reduced by a factor of 50

New cryogenic system (dewar, superconducting solenoid, dilution refrigerator)
→operating well (7 years from design start to operation, 3 companies)

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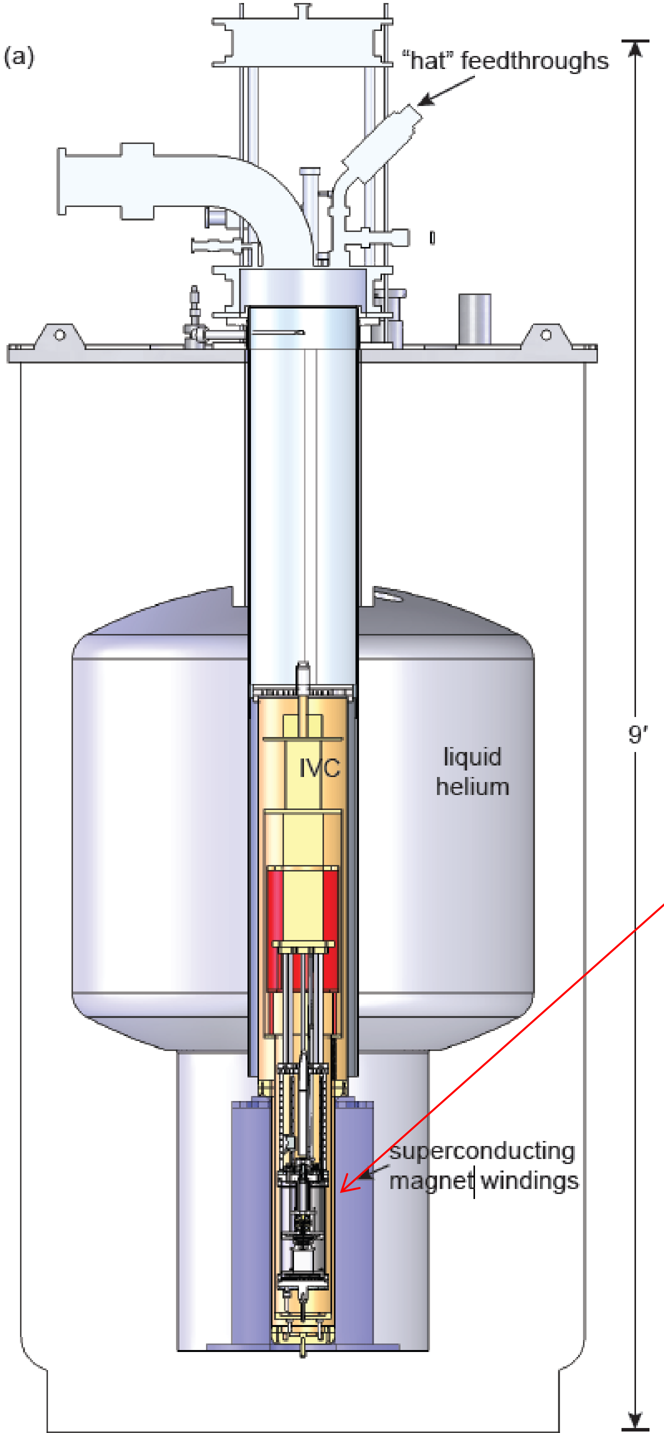
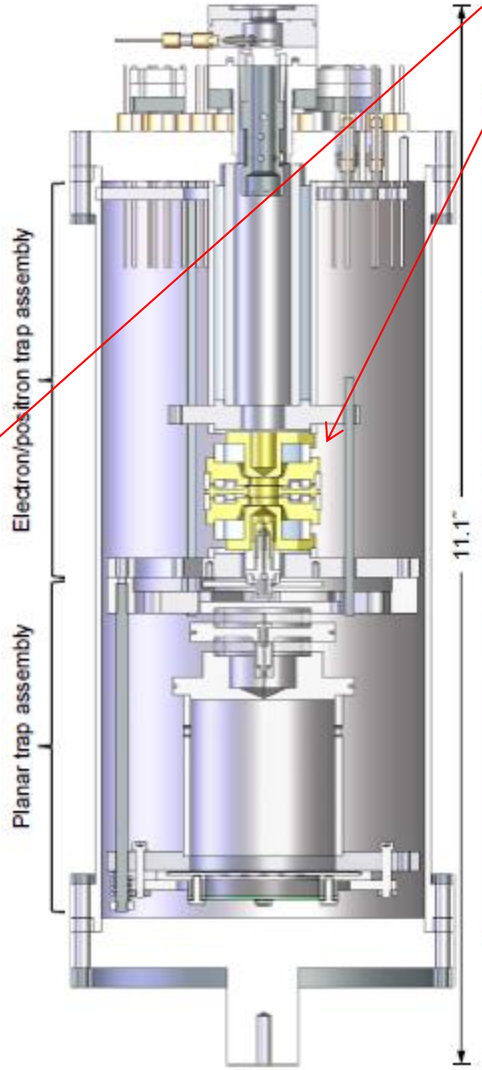
New Positron and Electron Apparatus

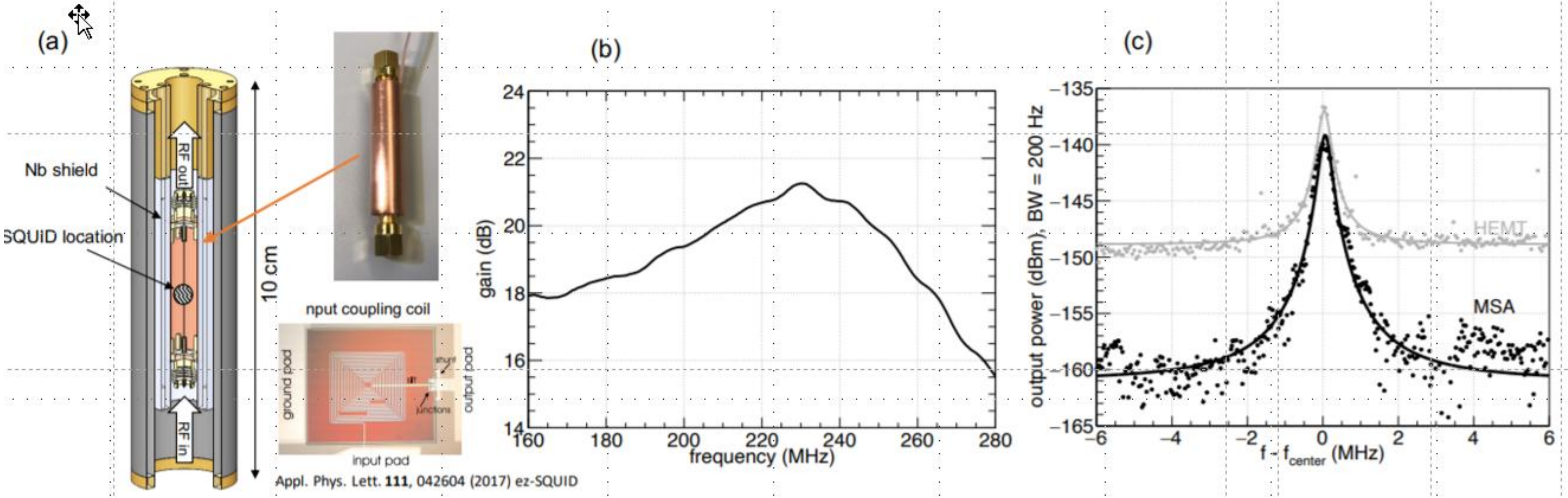


electron trap



200 MHz SQUID Detector

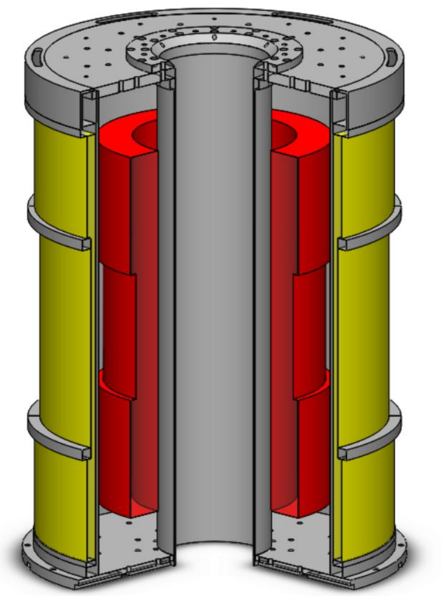
- Better electron qubit readout
- Close to quantum limit rather than being thermally limited

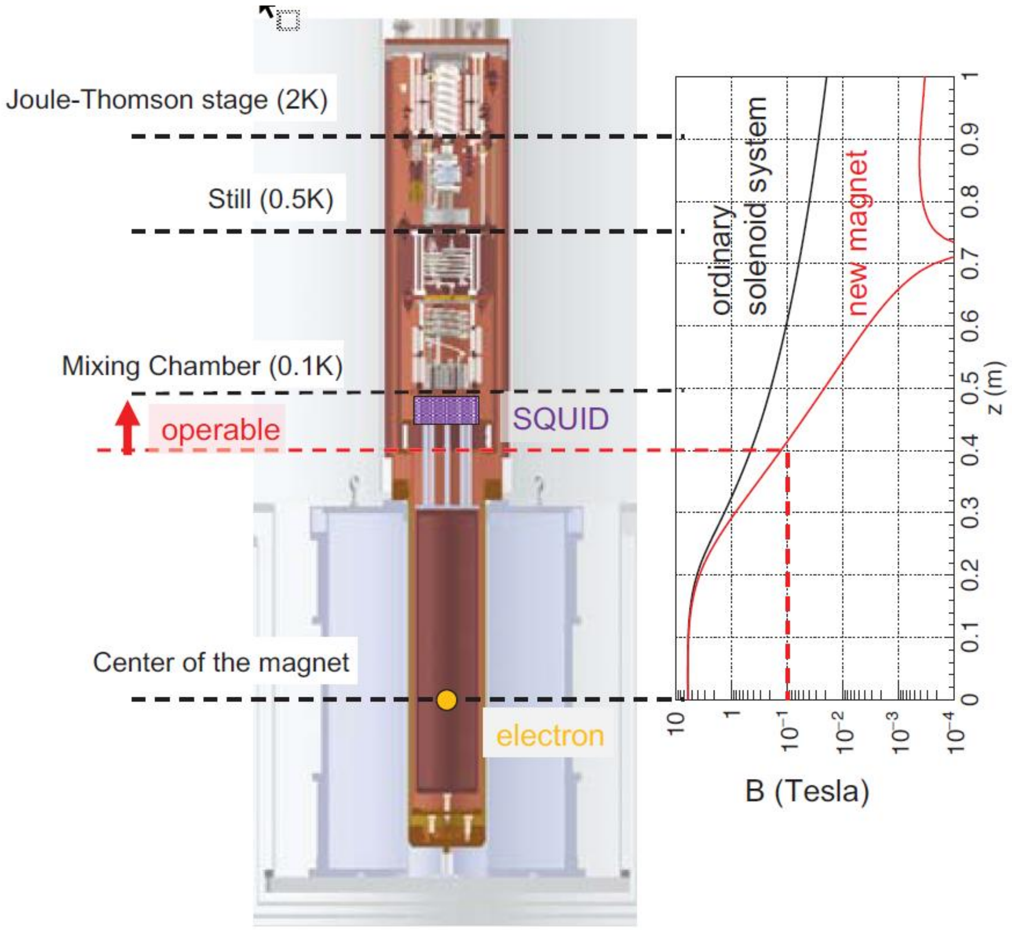


Appl. Phys. Lett. **111**, 042604 (2017) ez-SQUID

looks promising

New Solenoid System with Active Shielding





- two coaxial solenoids
- B in opposite directions

much lower field 40 cm away
→ SQUID location

High Temperature Shield for SQUID

Nb shield below 9 K

→ $S \sim 10^6$

→ Traps flux within the shield as lowered into the cryogenic system

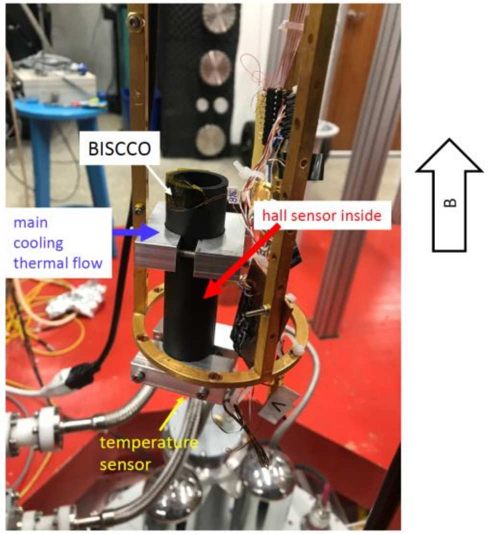
Add a high-temperature superconducting shield layer
to get a lower trapped flux within the shields

- B must stay on to stay stable
- Hard to buck out the field in the detection region without making a big heat load
- This shield will keep inside field near 0 until the Nb becomes superconducting

$Bi_{1.8}Pb_{0.26}Sr_2Ca_2Cu_3O_{10+x}$ (Pb-doped BISCCO)

$T_c = 108$ K

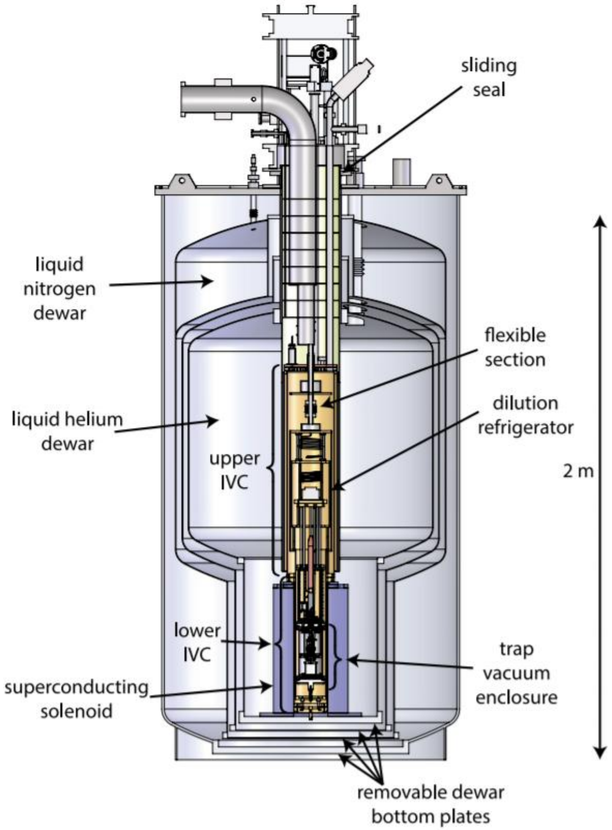
Initial cryogenic tests are very promising

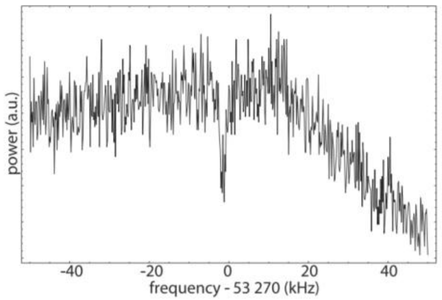


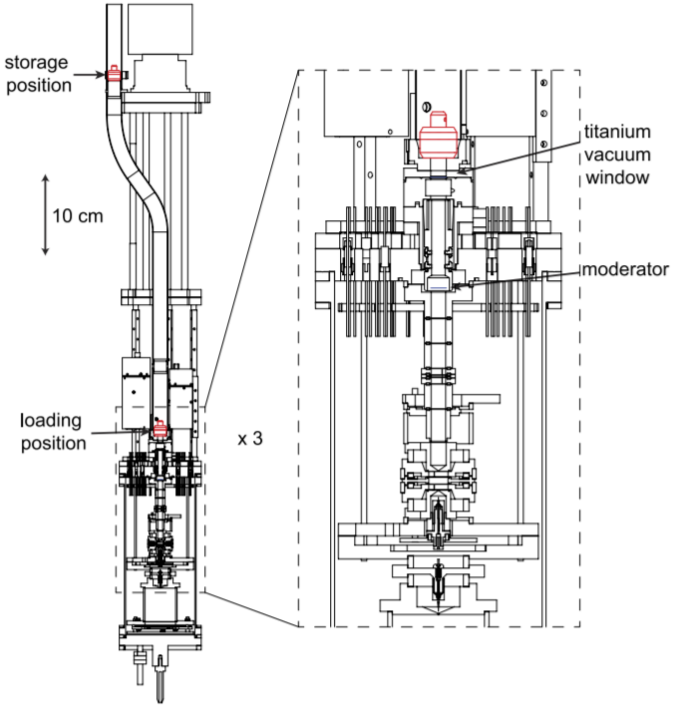
Positron Accumulation from “Student Source”

6.5 micro-Curie → 150 positrons/min/mCi

(10 micro-Curie triggers licensing requirements)







signal from ~150
trapped positrons

Need Fine Structure Constant Measured to 13 ppt (to Make Use of a 10x More Accurate Measurement)

$$\alpha^2 = \frac{2R_\infty}{c}\frac{A(x)}{A(e)}\frac{h}{M(x)}$$

Rydberg constant	8.7 ppt			
	13 ppt			
discrepancy	33 ppt	→	13 ppt	?????
A(e)	29 ppt	→	13 ppt	
A(Rb)	75 ppt	→	13 ppt	
A(Cs)	65 ppt	→	13 ppt	
h/M(Rb)	141 ppt	→	13 ppt	← Discrepancy reduced by 50
h/M(Cs)	400 ppt	→	13 ppt	

Need Help!

How the Fine Structure Constant is Determined

$$\alpha \equiv \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \longrightarrow \alpha^2 = \frac{2R_\infty}{c}\frac{A(x)}{A(e)}\frac{h}{M(x)}$$

hydrogen spectroscopy

MPQ 2018: $R_\infty = 10\,973\,731.568\,076\,(096)\ m^{-1}$ [8.7 ppt]

Orsay 2018: $R_\infty = 10\,973\,731.568\,530\,(140)\ m^{-1}$ [13 ppt]

33 ppt disagreement does not affect alpha (yet)

33 ppt discrep

mass ratios

Germany 2014: $A(e) = 0.000\,548\,579\,909\,070\,(16)$ [29 ppt]

FSU 2011: $A(Rb) = 86.909\,180\,5319\,(65)$ [75 ppt]

$A(Cs) = 132.905\,451\,9615\,(86)$ [65 ppt]

atom recoil

4.59135925890(65) 141 ppt

$$\frac{h}{M_{Rb}} = 2c^2\frac{f_{recoil}}{(f)^2}$$

Rb Paris 2011: $h/M(Rb) = 4.591\,359\,272\,9\,(57) \times 10^{-9}\ m^2/s$ [1200 ppt]

Cs Berkeley 2018: $h/M(Cs) = 3.002\,369\,472\,1\,(12) \times 10^{-9}\ m^2/s$ [400 ppt],

less precise

Excited by the Opportunity to Measure the Electron Magnetic Moment 10x More Accurately!

- Test most precise prediction of the SM
- Extremely sensitive test for BSM physics
- Most accurate determination of a property of an elementary particle
- Most precise confrontation of theory and experiment
- First check for BSM physics that may be present for muons
- Most precise QED test (to 10^{th} order)
- Most sensitive test of the fundamental CPT invariance of the SM with leptons

- The 1-particle quantum methods are elegant and FUN!

Muon Magnetic Moment

$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1 + a_{QED}(\alpha) + \delta a_{SM:Hadronic+Weak} + \delta a_{New\,Physics}$$

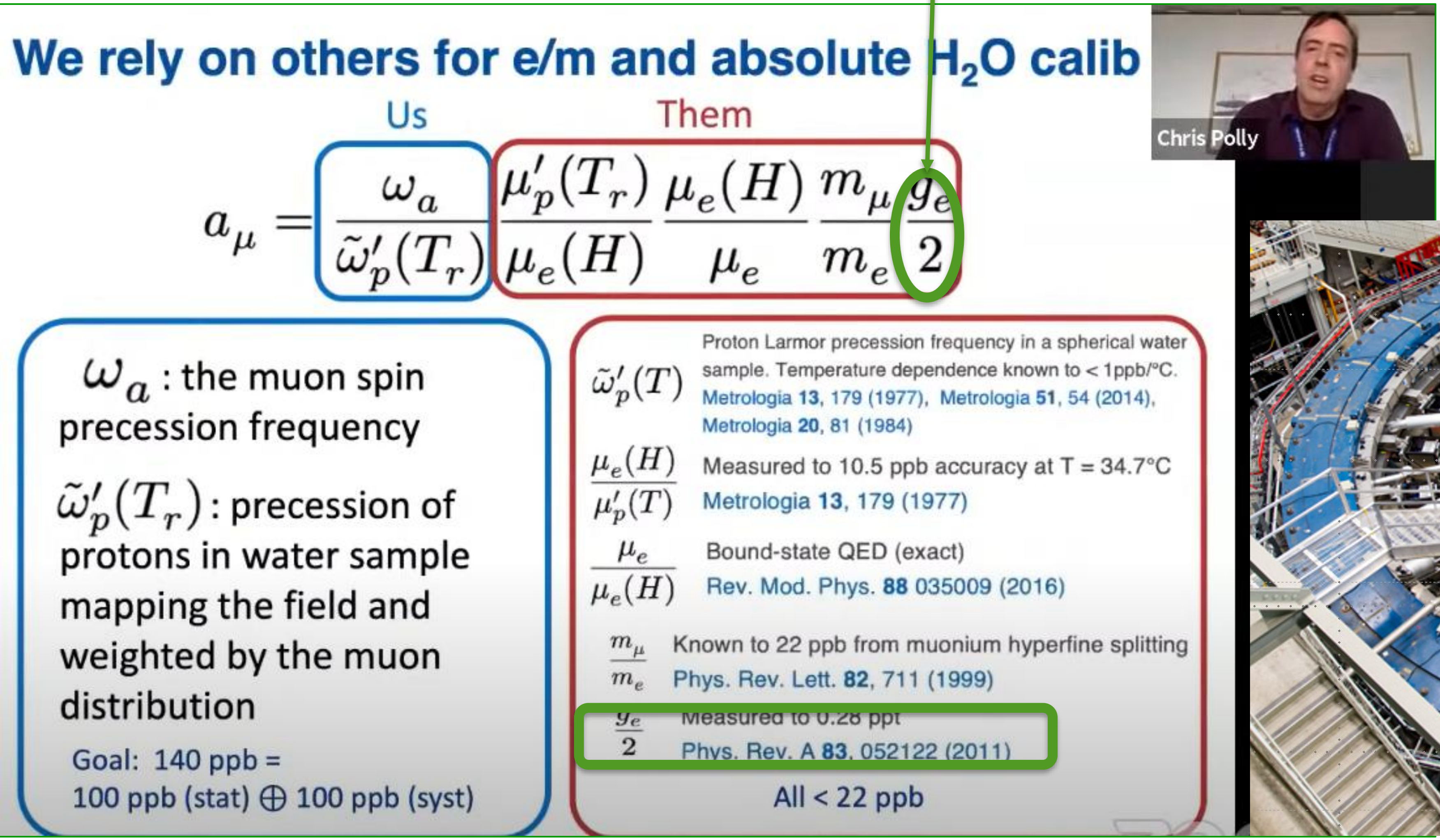
40,000 times bigger than for electron

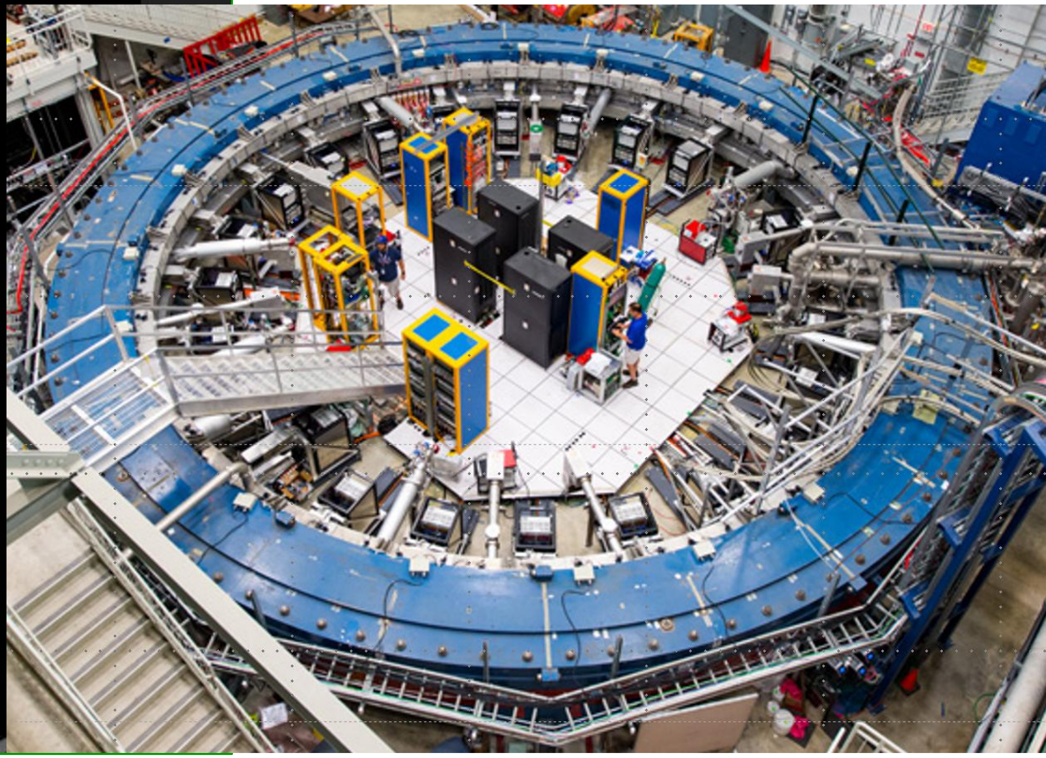
BAD

40,000 times bigger than for electron

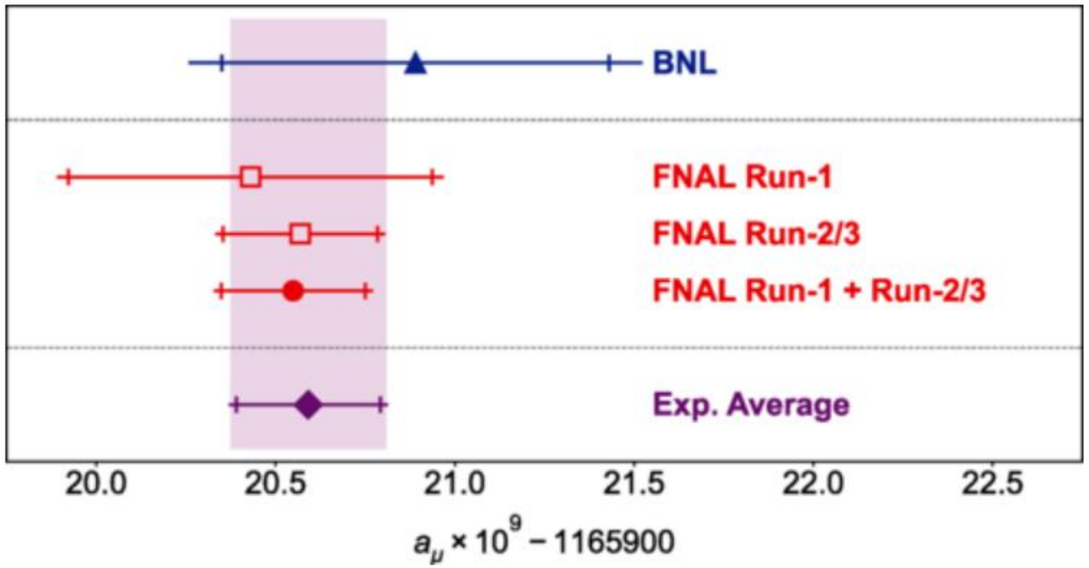
GOOD

Muon Magnetic Moment Measurement Relies upon Our Measurement





Comparison and Importance for the Measurement of Muon Magnetic Moment



expect a 2 times improvement coming

PRL **131,** 161802 (2023) $g_\mu/2 = 1.101\ 165\ 920\ 550\ 00\ (24\ 000)$ [200.00 ppt]

PRL **131**, 071801 (2023) $g_e/2 = 1.001\ 159\ 652\ 180\ 59\ (00\ 013)$ [000.13 ppt]

We Can Check the 5 σ Disagreement between Muon g Measurement and "SM Prediction"?

$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1 + a_{QED}(\alpha) + \delta a_{SM:Hadronic+Weak} + \delta a_{New\,Physics}$$

$(m_\mu/m_e)^2 \sim 40{,}000$ ← muon more sensitive to "new physics"

$\div 1540$ ← how much more accurately we measure

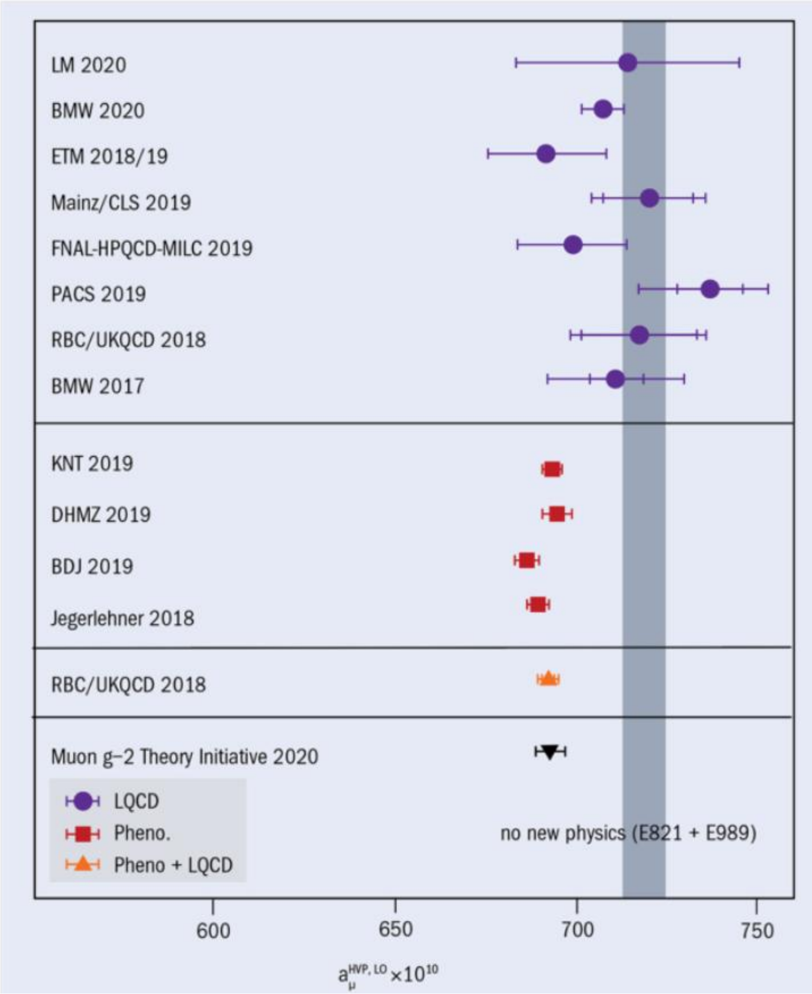
$\div 5$ ← 5 σ disagreement is now seen (probably)

→ If we can reduce the electron g uncertainty by 5 times more should be able to have the precision to see a 5σ effect (or not)

Also need: Independent measurement of α improved by this factor

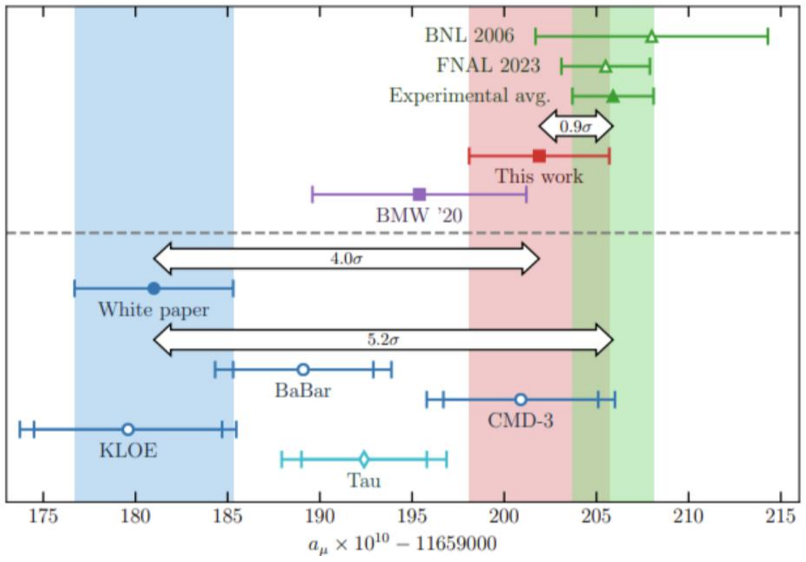
Intriguing Lattice QCD Calculations → Could Reduce the 5-Sigma Discrepancy?

hadronic contribution to theory



Must be extrapolated to

- infinite integration volume
- vanishing mess spacing



T Aoyama *et al.* 2020 *Phys. Rept.* **887** 1–166
(adapted in CERN Couried)

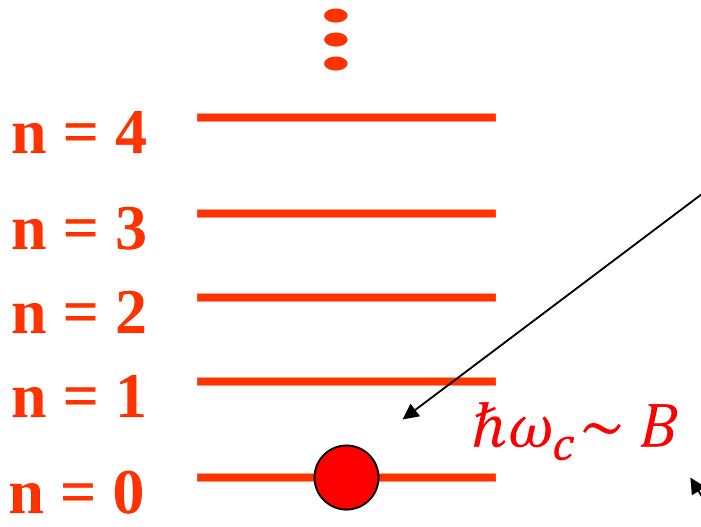
Using the One-Electron Quantum Cyclotron to Search for Dark Photons

New Quantum Detector for meV Dark Photons and 75-Times Lower Limit

dark photon – proposed mediator of force between dark matter particles → unknown mass
– kinetically mixes with Standard Model photon → unknown coupling strength

Non-gravitational window into dark matter → search for the kinetically mixed photon

one-electron quantum cyclotron



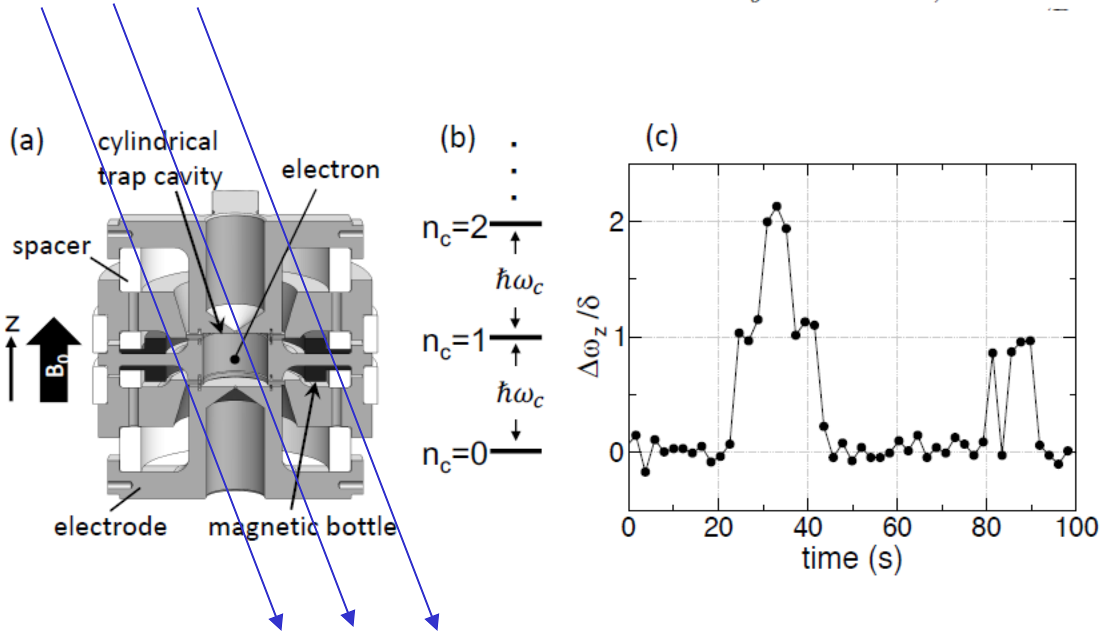
- one-photon sensitivity
- no background at all
- meV dark photon are largely missing

tune B to search

One-Electron Quantum Cyclotron as a Milli-eV Dark-Photon Detector

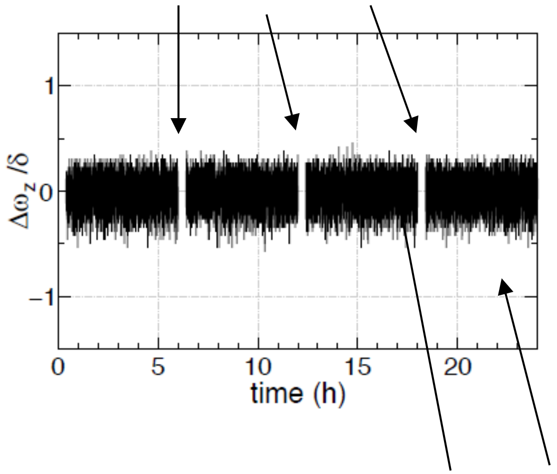
Xing Fan,[1,2,*] Gerald Gabrielse,[2,†] Peter W. Graham,[3,4,‡] Roni Harnik,[5,6] Thomas G. Myers,[2]
Harikrishnan Ramani,[3,§] Benedict A. D. Sukra,[2] Samuel S. Y. Wong,[3] and Yawen Xiao[3]
[1]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[2]Center for Fundamental Physics, Northwestern University, Evanston, Illinois 60208, USA
[3]Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA
[4]Kavli Institute for Particle Astrophysics & Cosmology,
Department of Physics, Stanford University, Stanford, CA 94305, USA
[5]Superconducting Quantum Materials and Systems Center (SQMS), Fermilab, Batavia, IL 60510, USA
[6]Theoretical Physics Division, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

dark photons



one-photon excitations
are easily observed

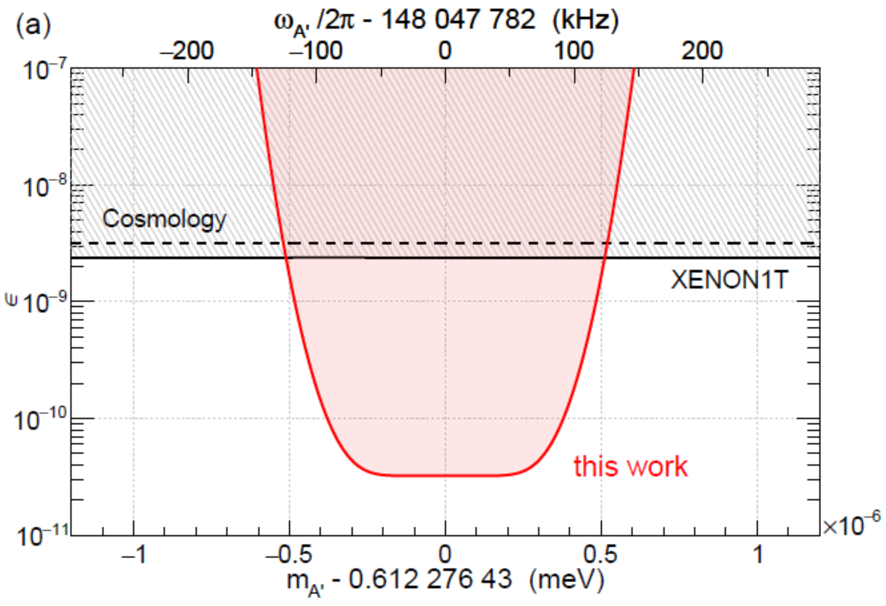
checking the qubit

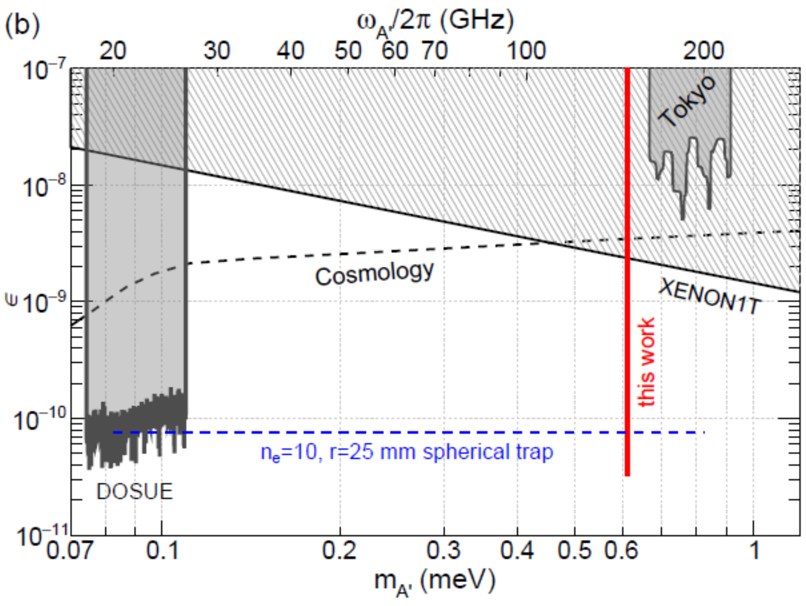


searching for dark photons

Phys. Rev. Lett. **129**, 261801 (2022)

Demonstration Measurement





↑
75
↓

greatly improved limit
☺

⟷

very narrow search range
☹

Demo apparatus used was built for extremely high magnetic field stability → NOT to be scanned

Should Design and Build a Purpose-Built Dark Photon Search Apparatus

- Magnetic field can be swept in a reasonable way
- Refrigerator cooled
- Spherical trap or some other focusing shape
- More sensitive detection
- Use 10 or more electrons

Could also be used to search for axions

"Highly Excited Electron Cyclotron for QCD Axion and Dark-Photon Detection"
X. Fan, G. Gabrielse, P. W. Graham, H. Ramani, S. S. Y. Wong, Y. Xiao, (2024). arXiv:2410.05549

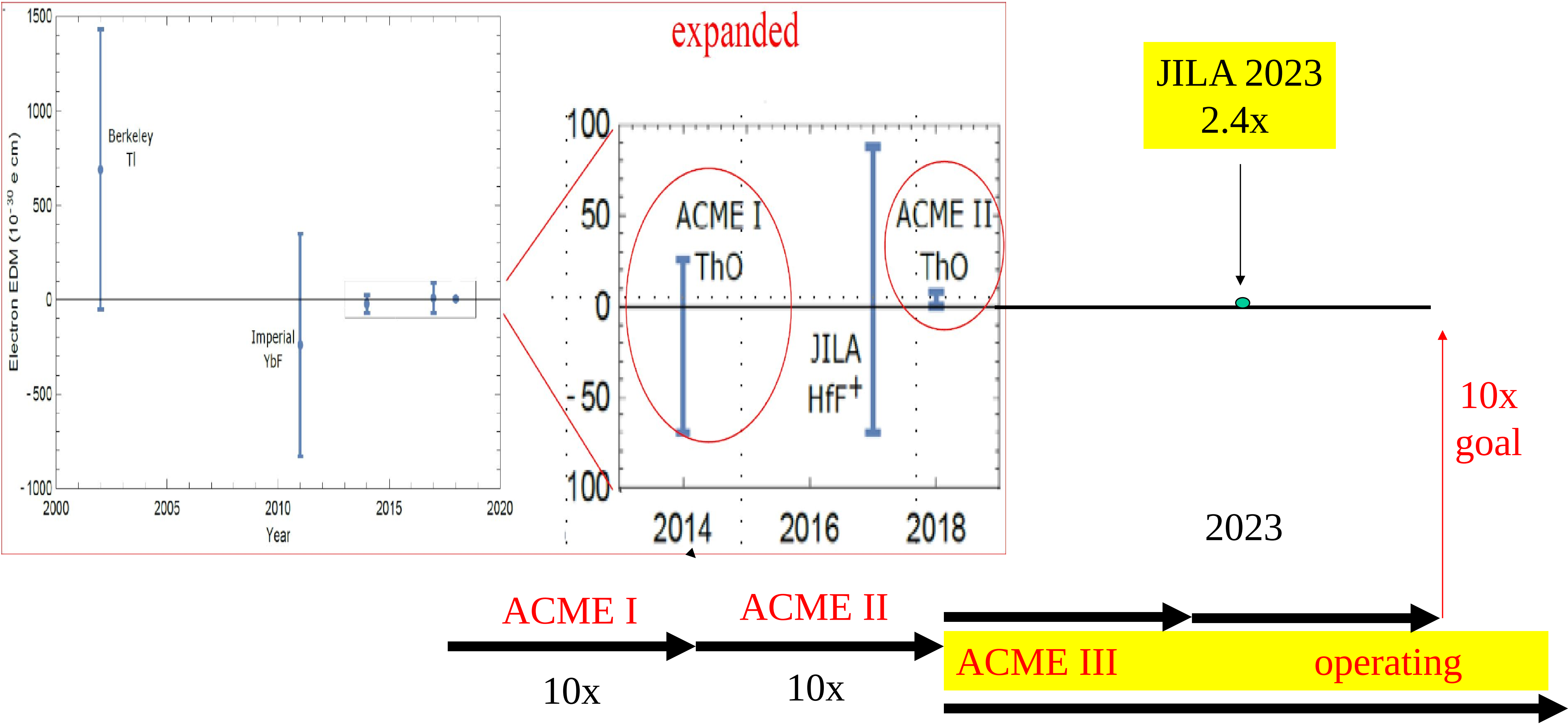
Launch of New Electron EDM Measurement
ACME III

Harvard, Northwestern, U. Chicago

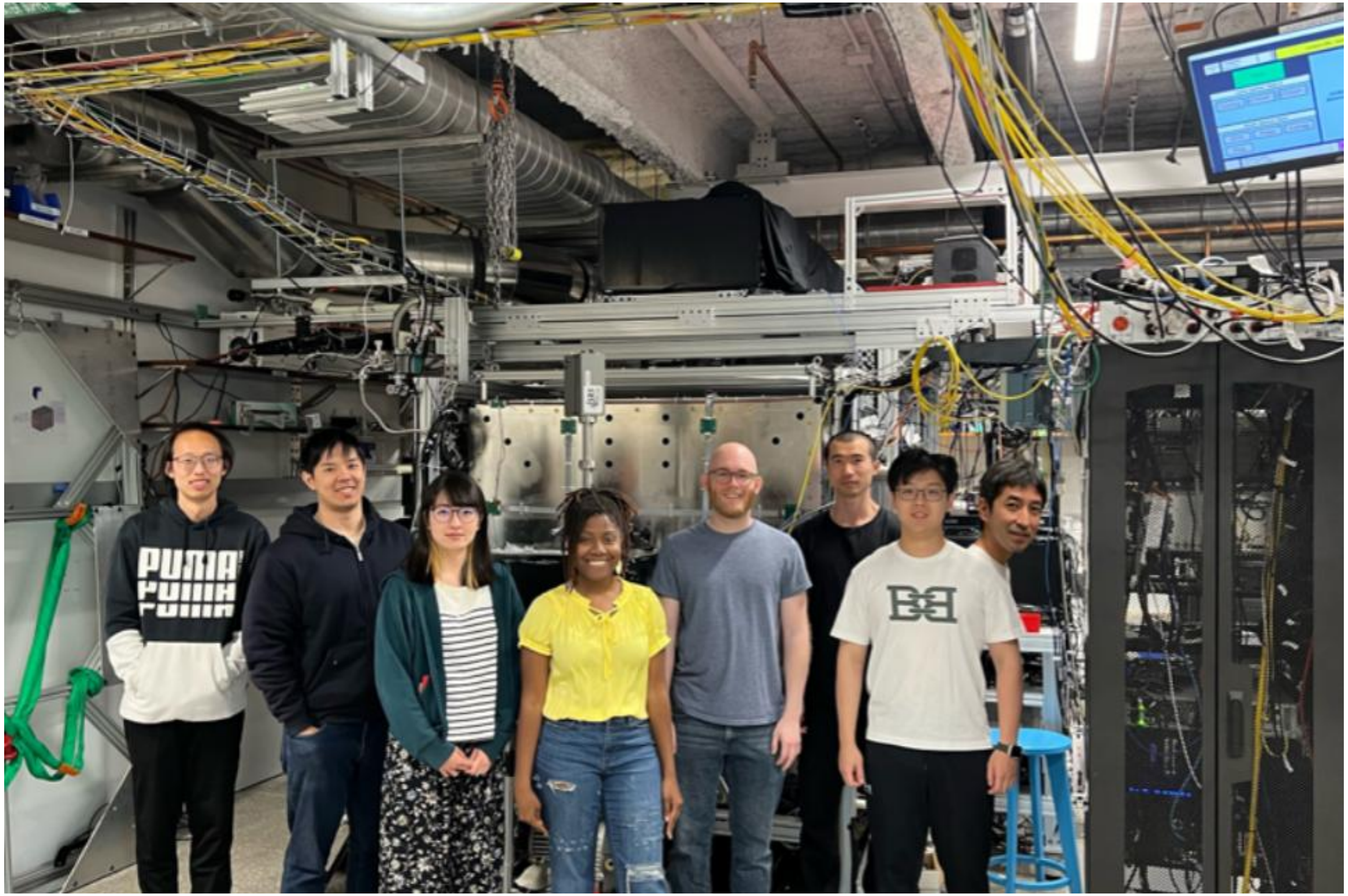
→ search for BSM physics i.e. beyond the Standard Model (SM)

New measurement goal: 100x → 3000x improved sensitivity (10x current sensitivity)

Electron Electric Dipole Moment – History and Status



ACME III: The Young and the Vigorous (and others ☺)



S. Liu X. Fan A. Hiramoto M. Watts C. Diver P. Hu Z. Han T. Masuda

J. Doyle

D. DeMille

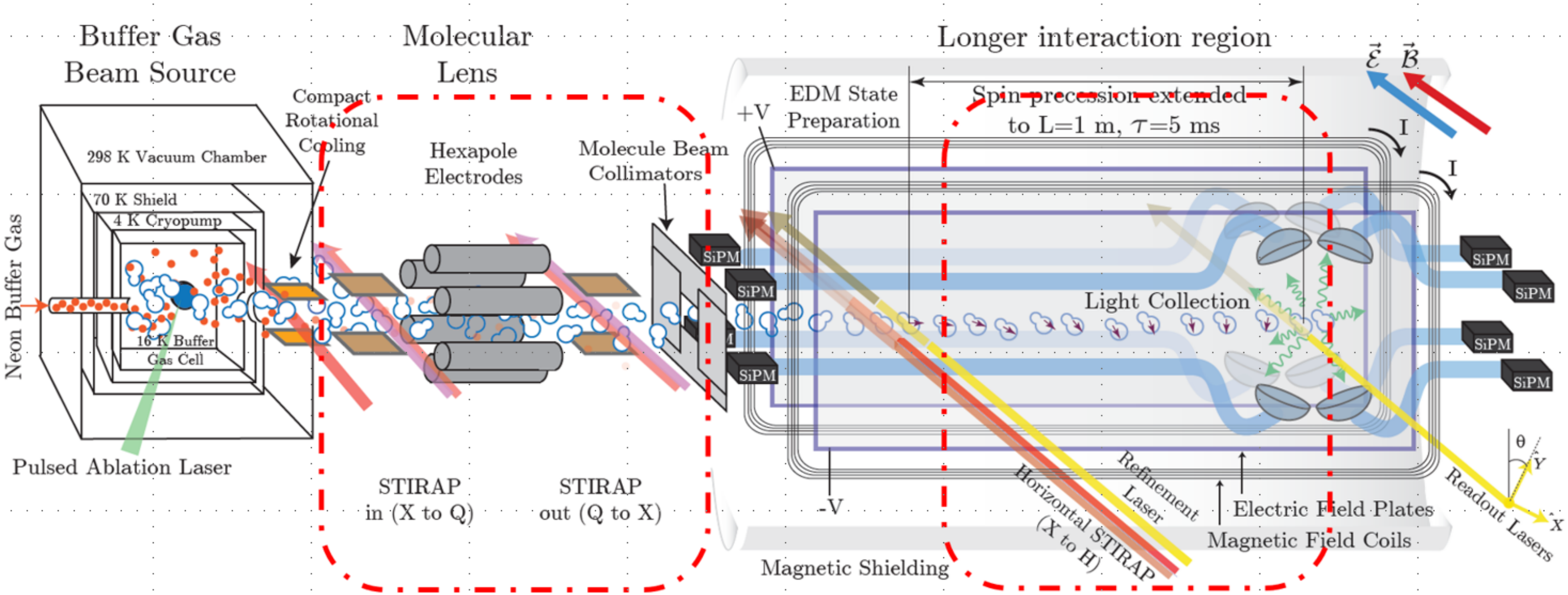
G. Gabrielse

K. Yoshimura

N. Sasao

S. Uetake

We have been very busy between 2018 and 2024



Almost entirely new ACME III Apparatus

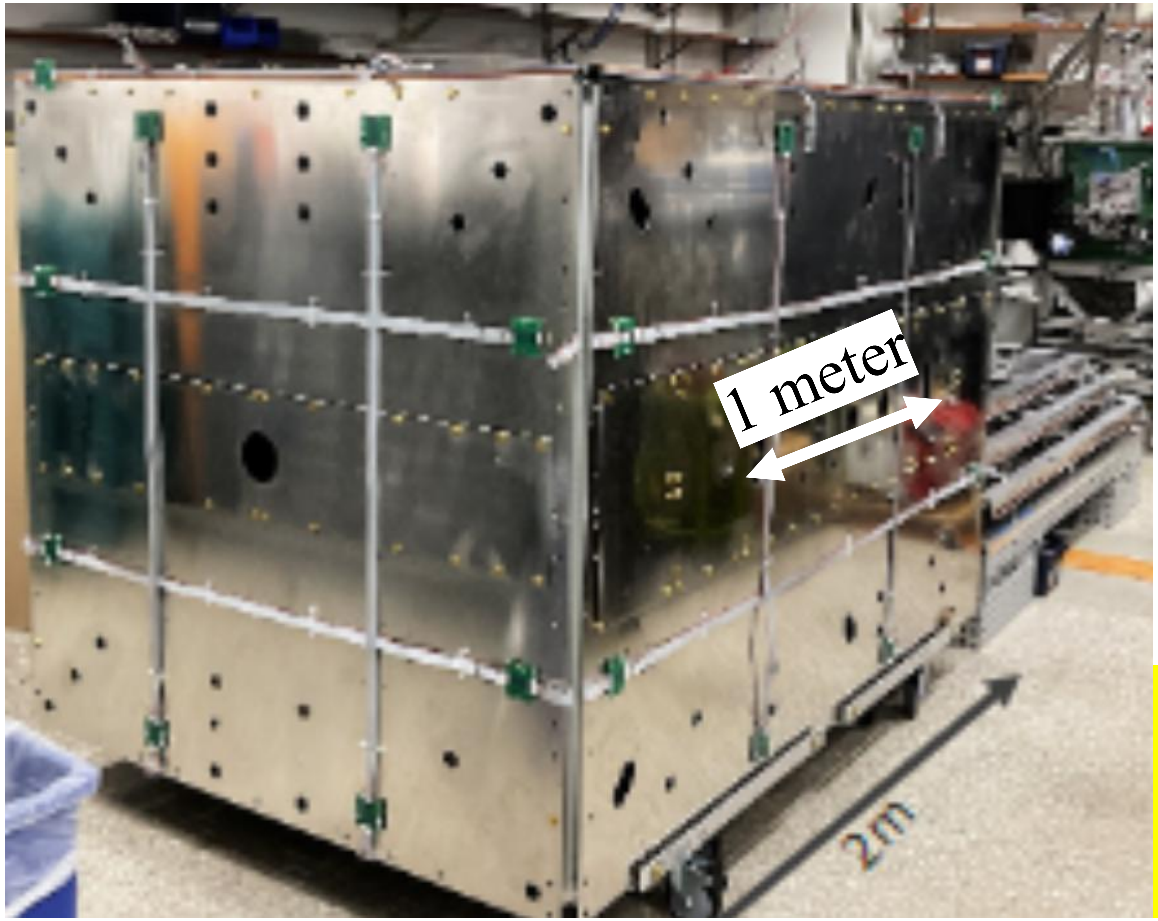
New location: Harvard University → Northwestern University

Overview: Demonstrated ACME III Sensitivity Improvements

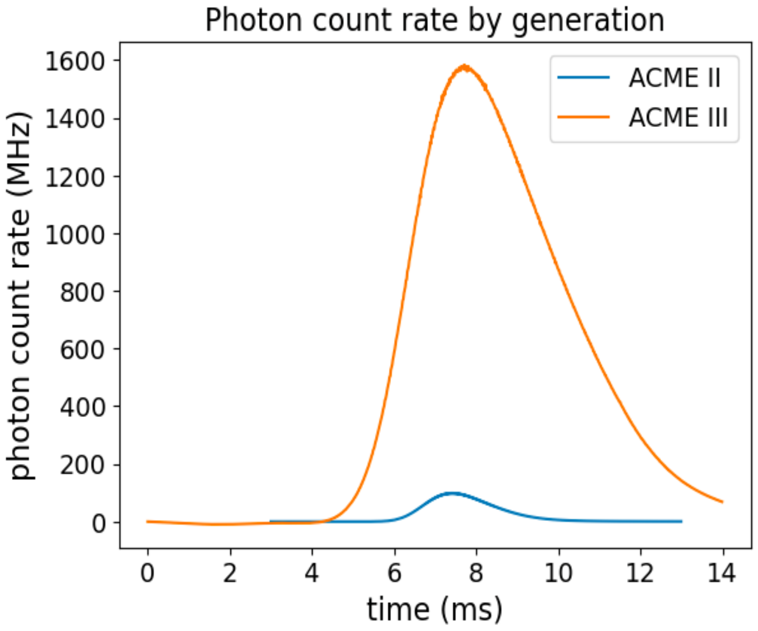
Shot noise limit;

$$\delta d_e = \frac{\hbar}{2\tau\mathcal{E}_{\mathrm{eff}}\sqrt{N}}$$

5x larger



precession time
5x longer
(20 cm → 1 m)

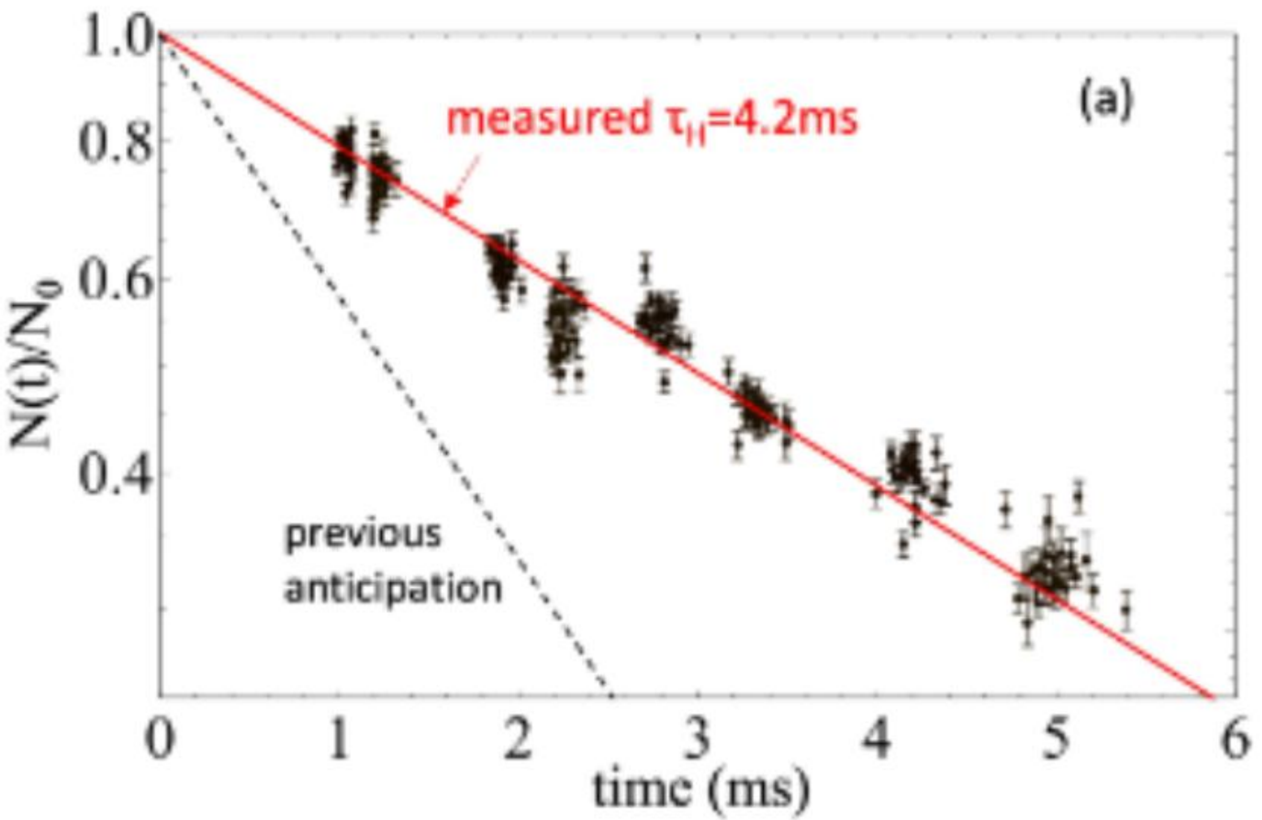


anticipated
5 x 5 = 25

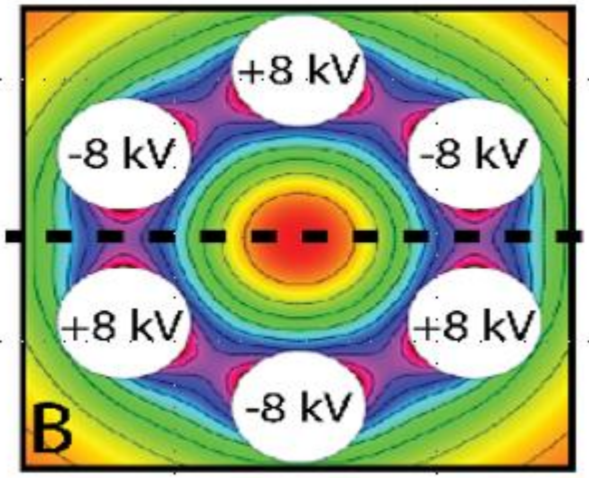
10 x increase
over 2023 limit

Longer H State Lifetime ← science state

→ Allows a much longer precession time time



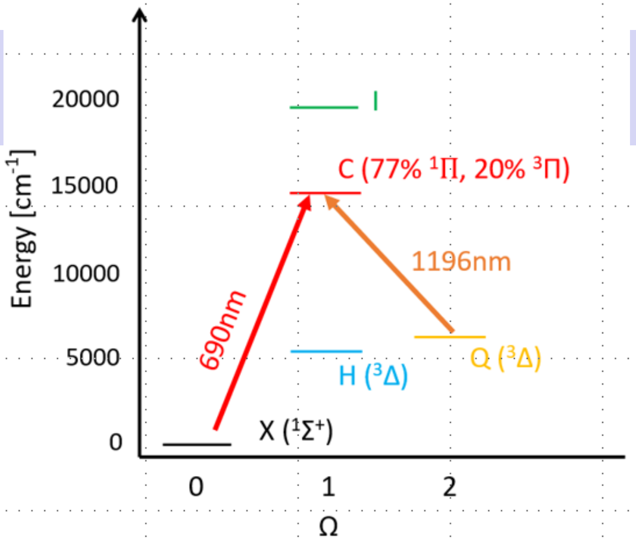
D. G. Ang, C. Meisenhelder, C. D. Panda, X. Wu, D. DeMille, J. M. Doyle, and G. Gabrielse. Measurement of the $H^3\Delta_1$ radiative lifetime in ThO. Phys. Rev. A, **106**, 022808 (2022).



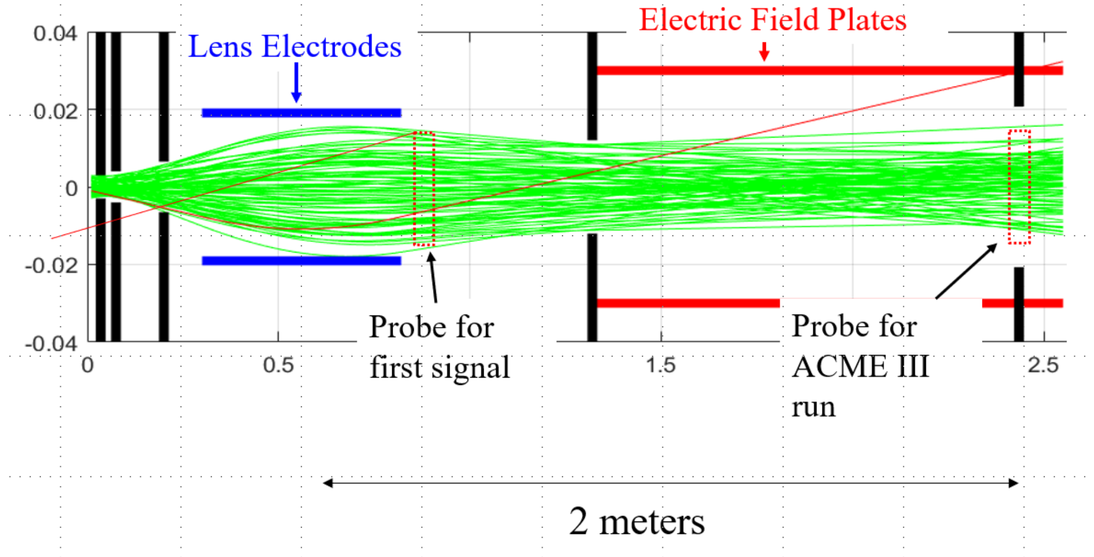
Electrostatic Lens

rod diameter 19 mm

rod spacing 9.5 mm



STIRAP: populate Q by X-C
probe Q-C see C→X



- Captures more ThO molecules from source
- Makes it unnecessary to increase the radial dimensions by a factor of 5

"The metastable Q $^3\Delta_2$ state of ThO: a new resource for the ACME electron EDM search"
X. Wu, Z. Han, J. Chow, D. G. Ang, C Meisenhelder, C. D. Panda, E. P. West, G. Gabrielse, J. M. Doyle, and D. DeMille. New Journal of Physics, 22 023013 (2020).

Systematic Error Control Requires Lower Magnetic Fields over a much Larger Volume that for ACME II

700 micro-G
= 70 nT

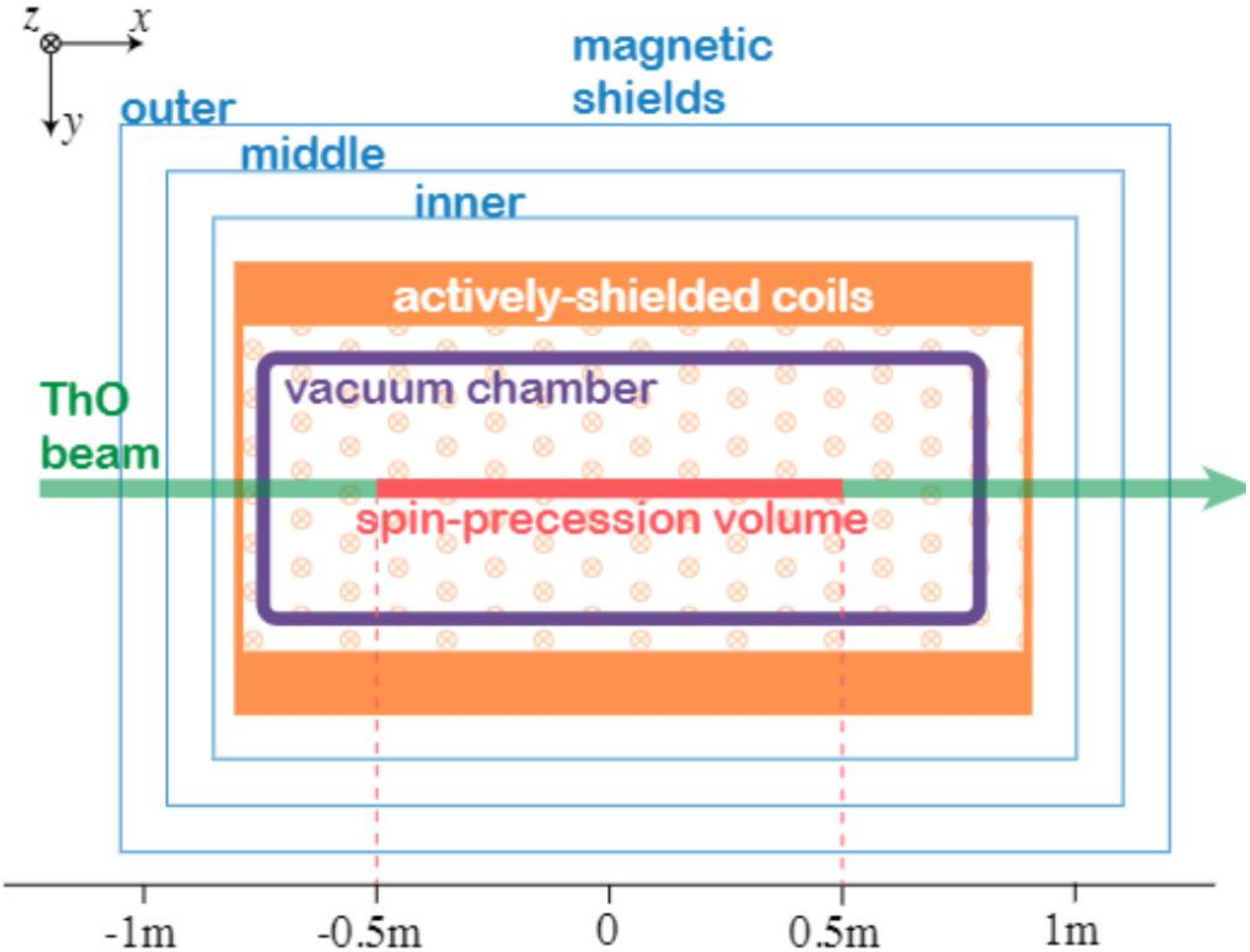
ACME II: Residual field of 100 micro-G = 20 nT
using 5 layers of mu-metal shields

100 micro-G
= 10 nT

ACME III: Need residual field of 10 micro-G = 1 nT
5x longer precession volume
3 layers of mu-metal shields
gradient 1 micro-G / cm
tons of mu-metal, demountable for reannealing if needed

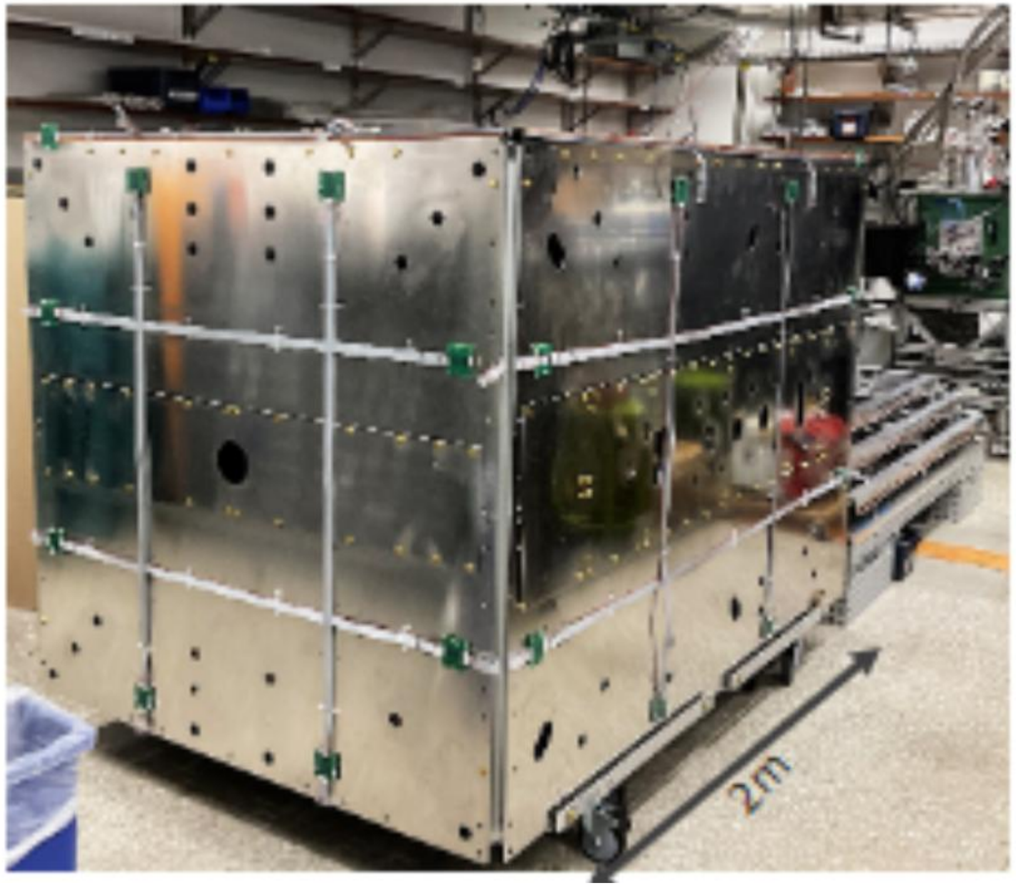
cost and weight reduction

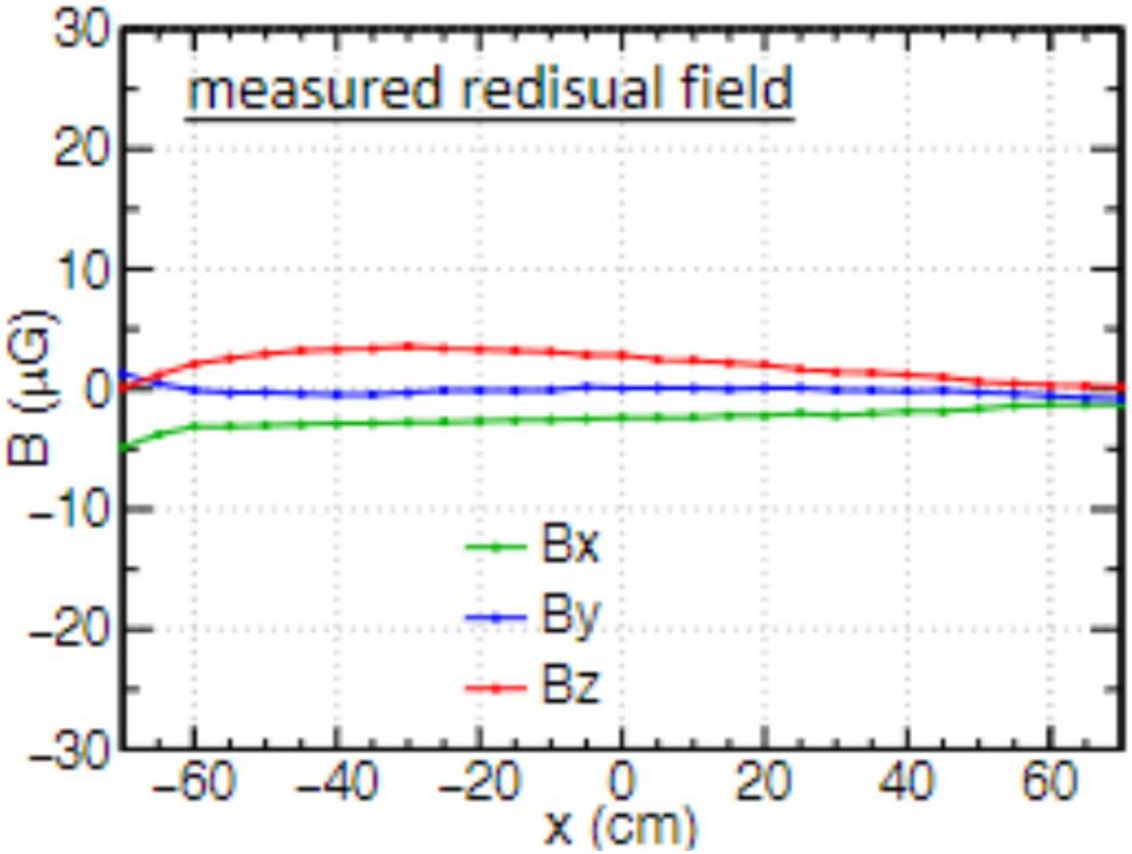
Coils that produce this field is also designed to cancel out any residual field from the mu-metal shields


z
x
y
magnetic
shields
outer
middle
inner
actively-shielded coils
ThO
beam
vacuum chamber
spin-precession volume
-1m
-0.5m
0
0.5m
1m

3 layers of mu metal shielding (demountable) B field below 1 nT (10 micro-G)

108 degaussing coils





Ouch: Inserted field plates and supports → residual field increased to 3 nT
→ We cancelled this field using our internal field coils

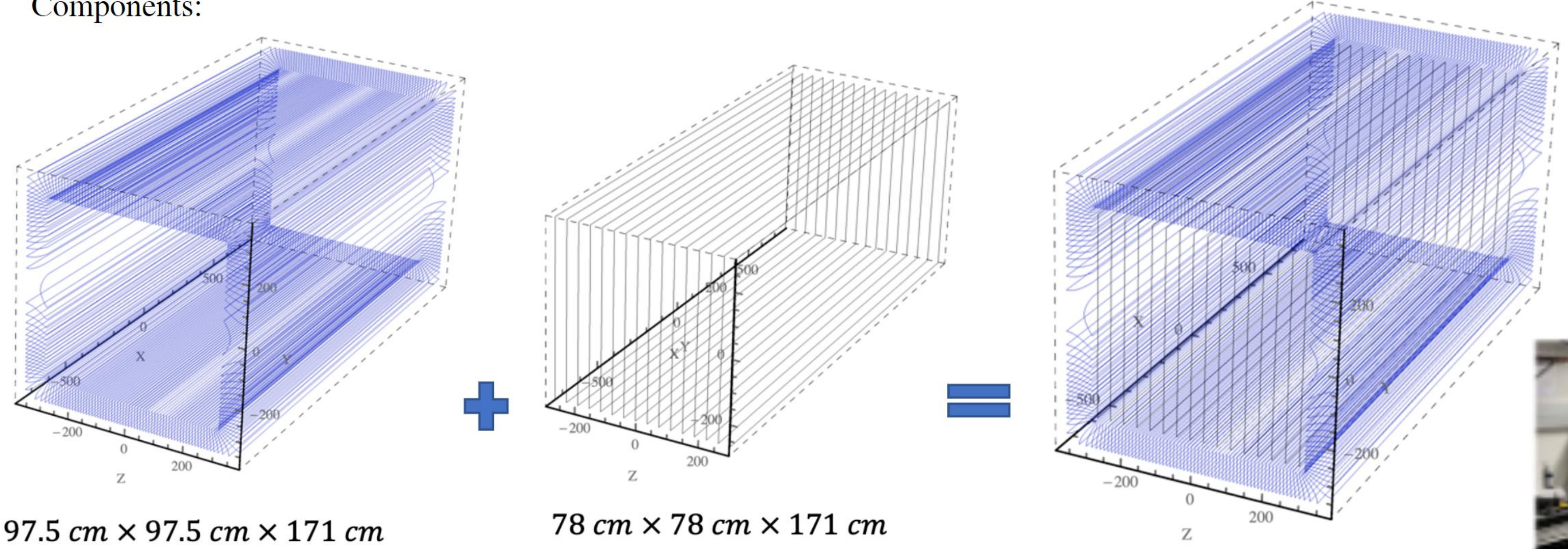
magnetism?? shields??

Manuscript finished and should be submitted in the next couple of weeks

Cos Theta Coil with Active Shielding

ACME II: field at shield is ~1.5 times the produced field
ACME III: field at shield is ~ 4% of the produced field

Components:



$97.5\ cm \times 97.5\ cm \times 171\ cm$

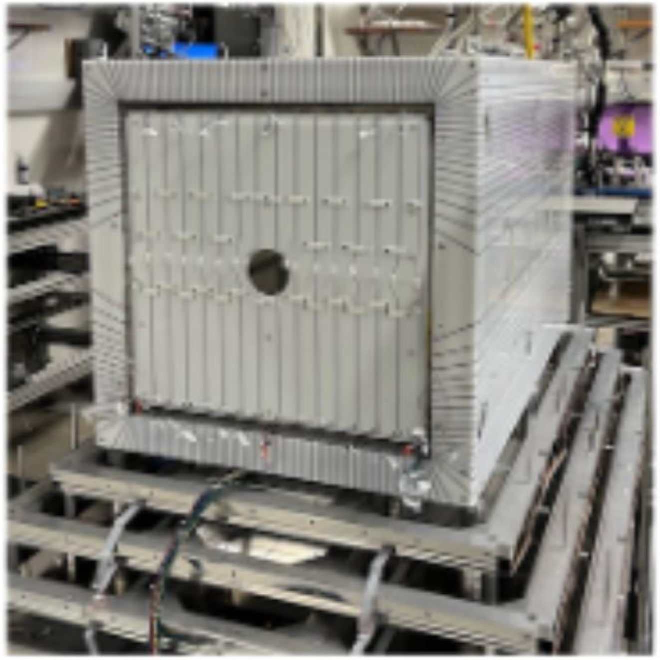
- Outer Coil (Blue)
  - Inner Layer
  - Outer Layer

$78\ cm \times 78\ cm \times 171\ cm$

- Inner Coil (Black)

- Whole Coil (Black+Blue)

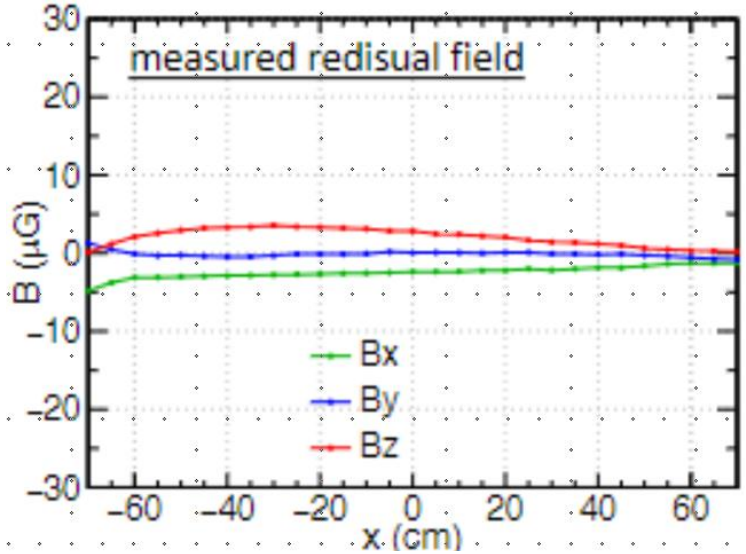
mA → 100 micro-G (10 nT)



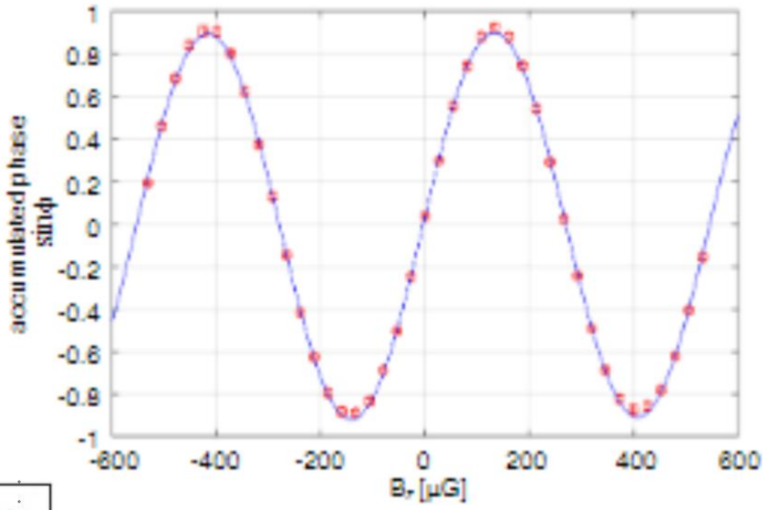
→ Internal B switching for more than a day without degaussing does not add to residual magnetism of the shields

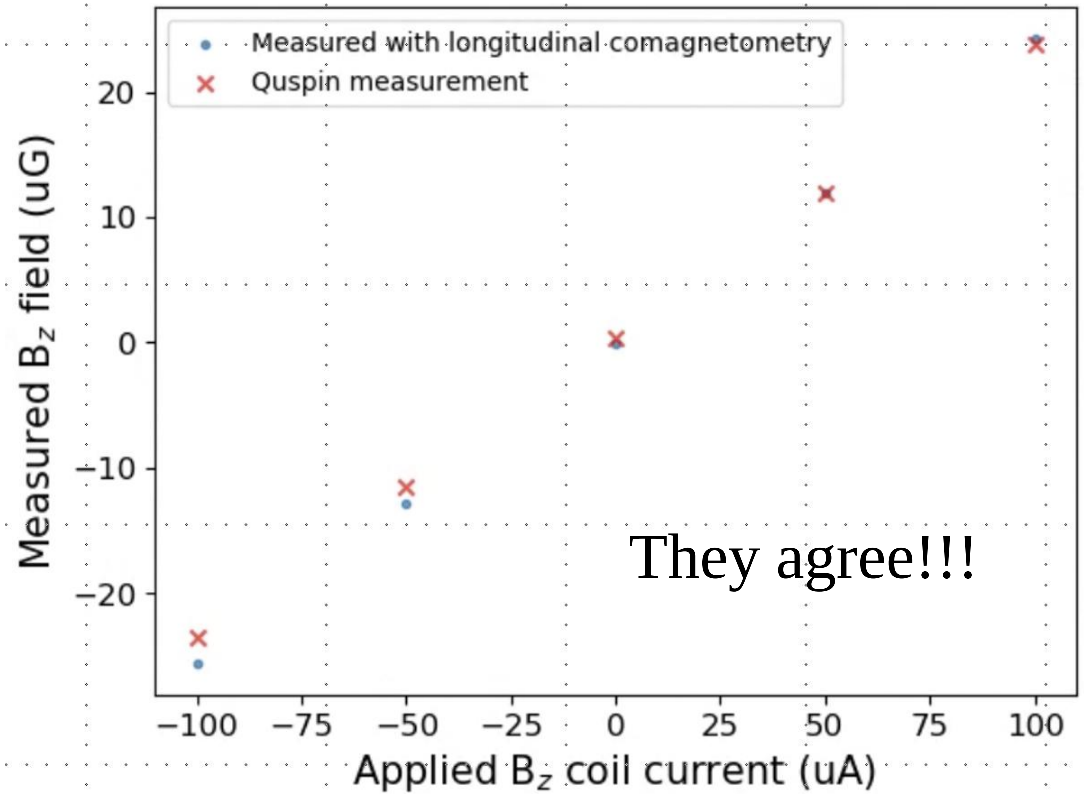
Magnetometry

Array of 8 x 3 Rb magnetometers



ThO Q-state magnetometry





They agree!!!

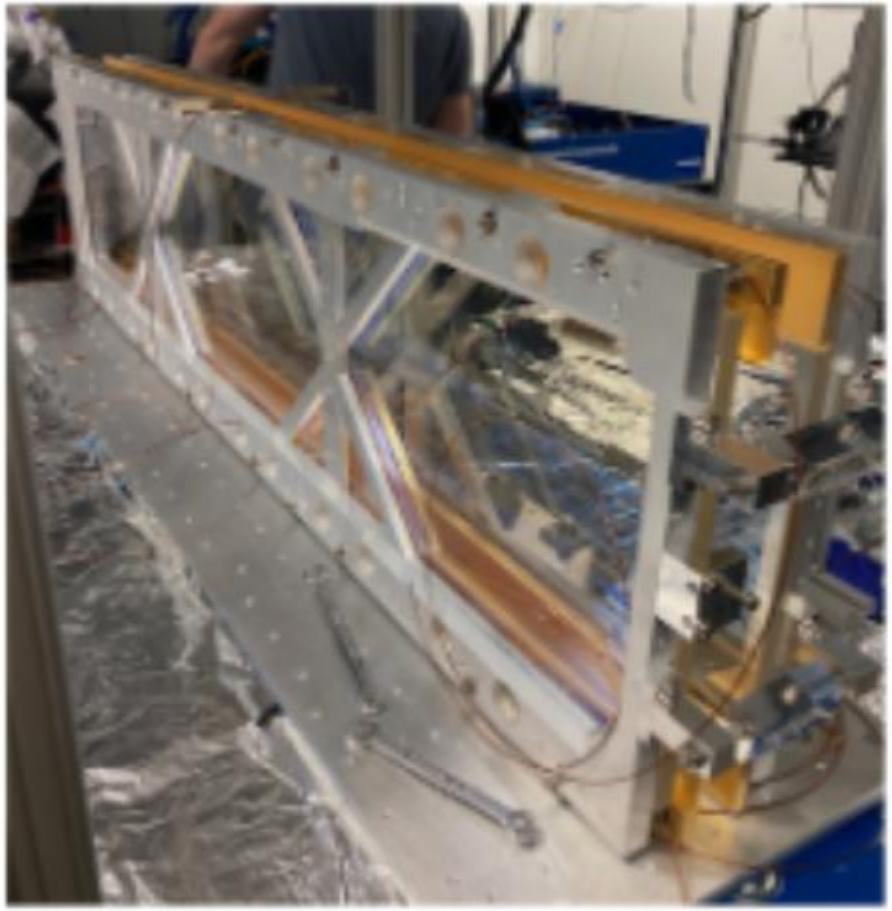
Achieving the shot noise limit (after ACME III)

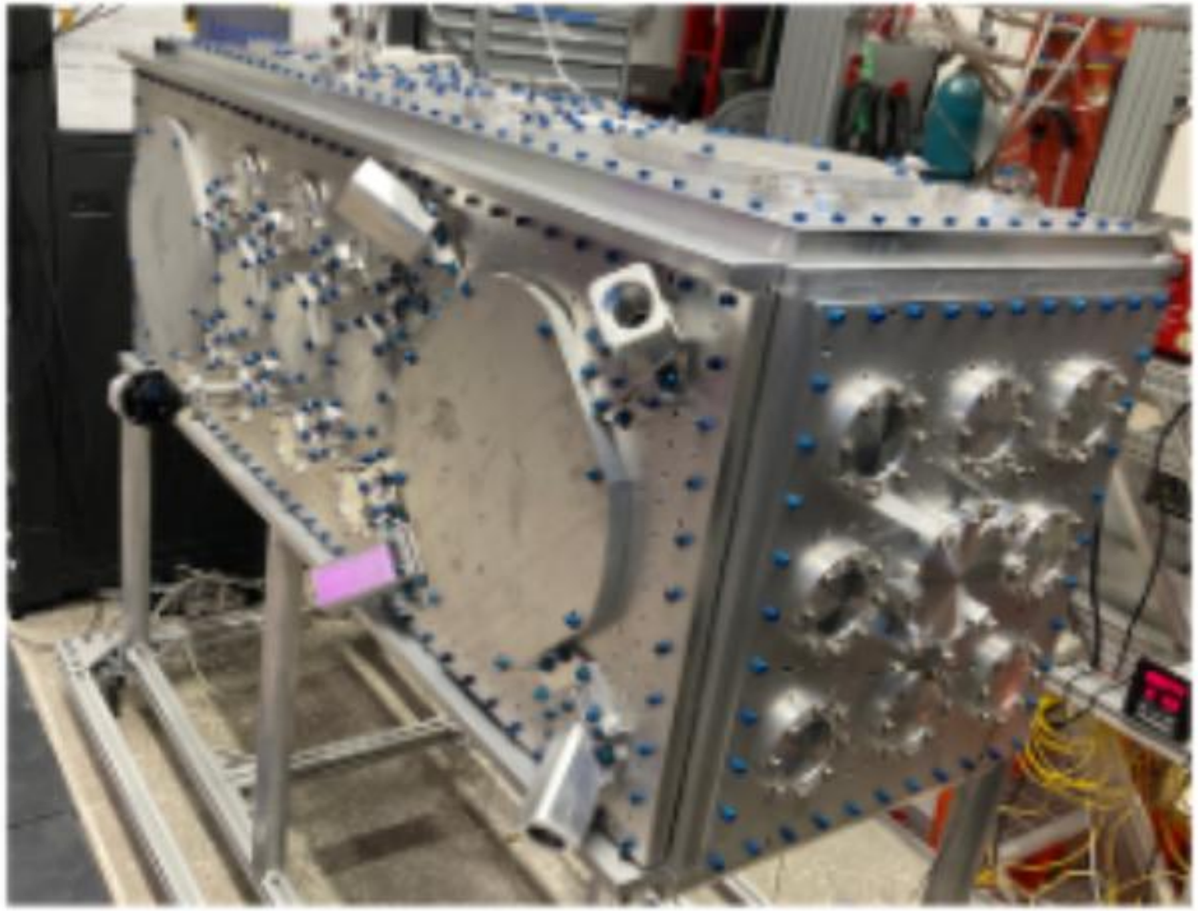
- Faulty firmware that was fixed
- Proper synchronization of data acquisition clocks

C D Panda, C Meisenhelder, M Verma, D G Ang, J Chow, Z Lasner, X Wu, D DeMille, J M Doyle, and G Gabrielse. “Attaining the shot-noise-limit in the acme measurement of the electron electric dipole moment”. Journal of Physics B: Atomic, Molecular and Optical Physics, **52**, 235003 (2019)..

1.3 meter glass field plates

1.5 m vacuum chamber





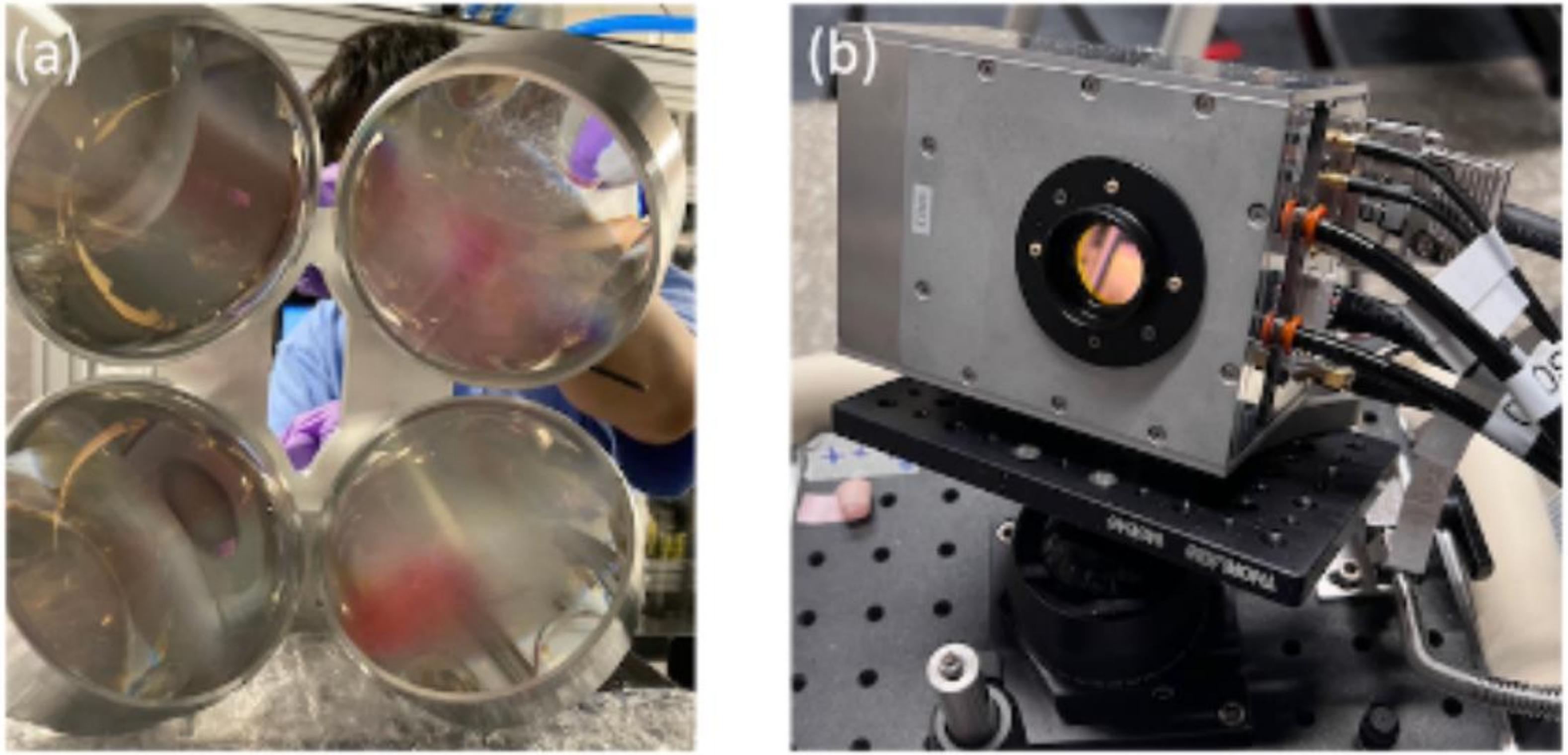
- low birefringence (Schott SF57HTUltra)
- 200x lower stress optic coefficient
- low stress mounting

low magnetism (~10 micro-Gauss)

1 nT

8 x 3 Rb magnetometers

Increased Light Correction, SIPM rather than PMTs



Demonstrated ACME III Improvements: More Detail

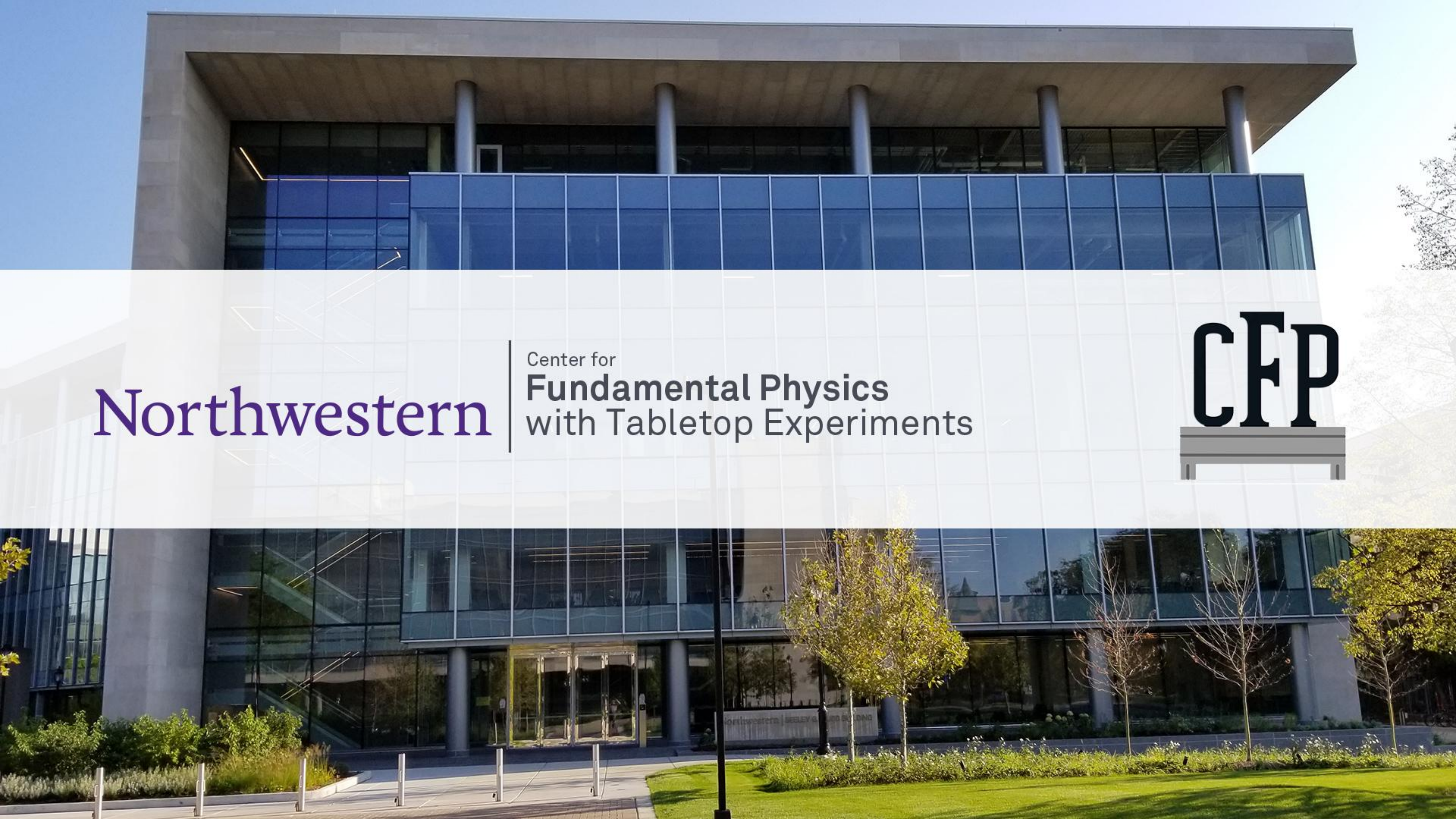
Demonstrated Improvement	Signal Gain	τ Gain	EDM sensitivity Gain
Longer Precession Time	0.3	5	2.7
Electrostatic Lens	12	1	3.5
SiPM Detector	2.7	1	1.6
Improved collection optics	1.7	1	1.3
Eliminated Timing Jitter Noise	1	1	1.7
Load-lock target change	1.4	1	1.2
Total	23	5	41
ACME II Daily Statistical Sensitivity (e cm)			$\sim 1 \times 10^{-29}$
ACME III Daily Sensitivity(e cm)			$\sim 3 \times 10^{-31}$

After 6 Years of Design and Construction → ACME III is Operating

Looks promising that ACME III could measure electron EDM ~ 4×10^{-31} e-cm

→ 25 times more sensitively than 2018 ACME II measurement

→ 10 times more sensitively than the 2023 JILA measurement


Northwestern
Center for
Fundamental Physics
with Tabletop Experiments
CFP