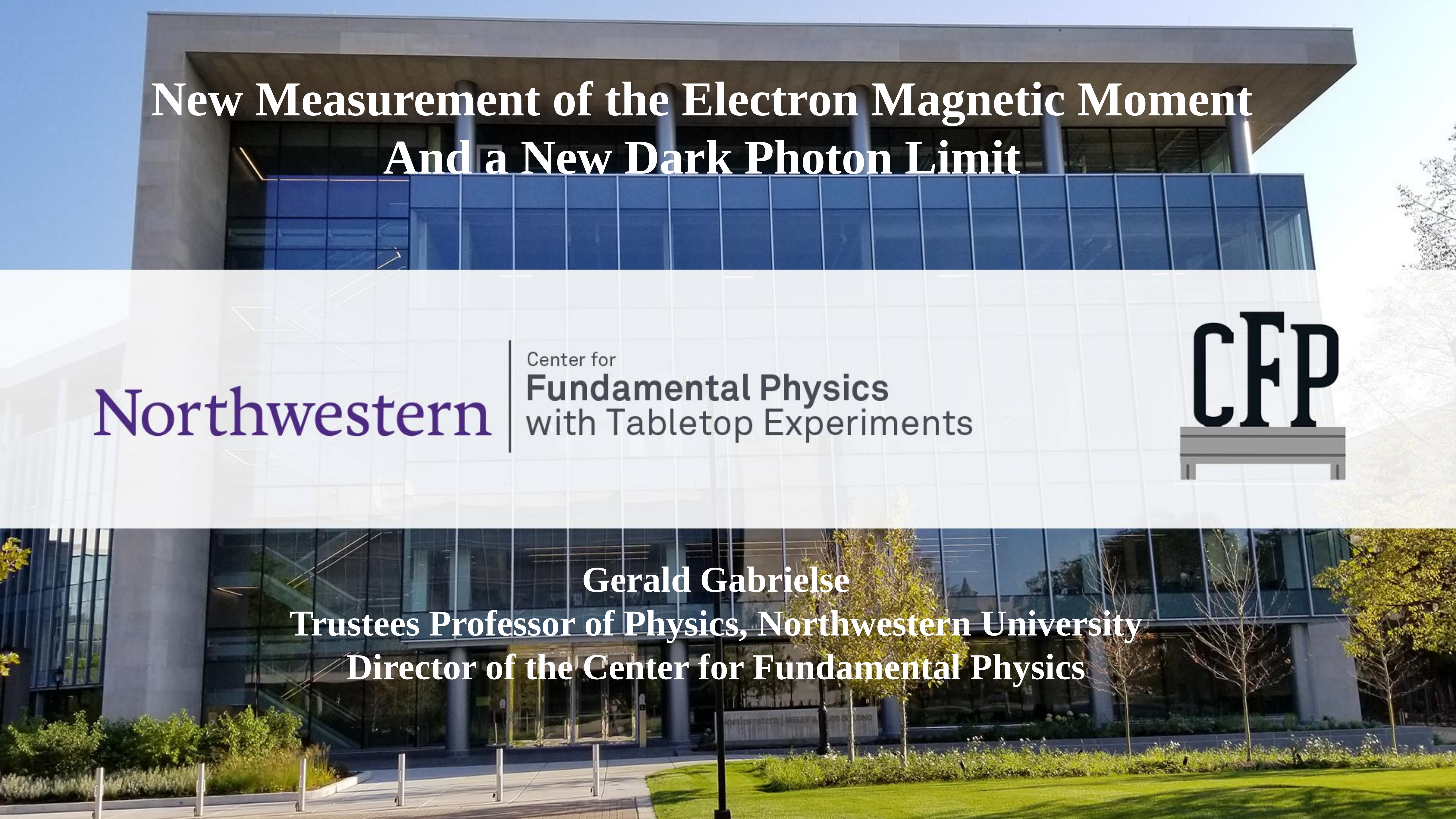


New Measurement of the Electron Magnetic Moment
And a New Dark Photon Limit

Northwestern | Center for Fundamental Physics with Tabletop Experiments

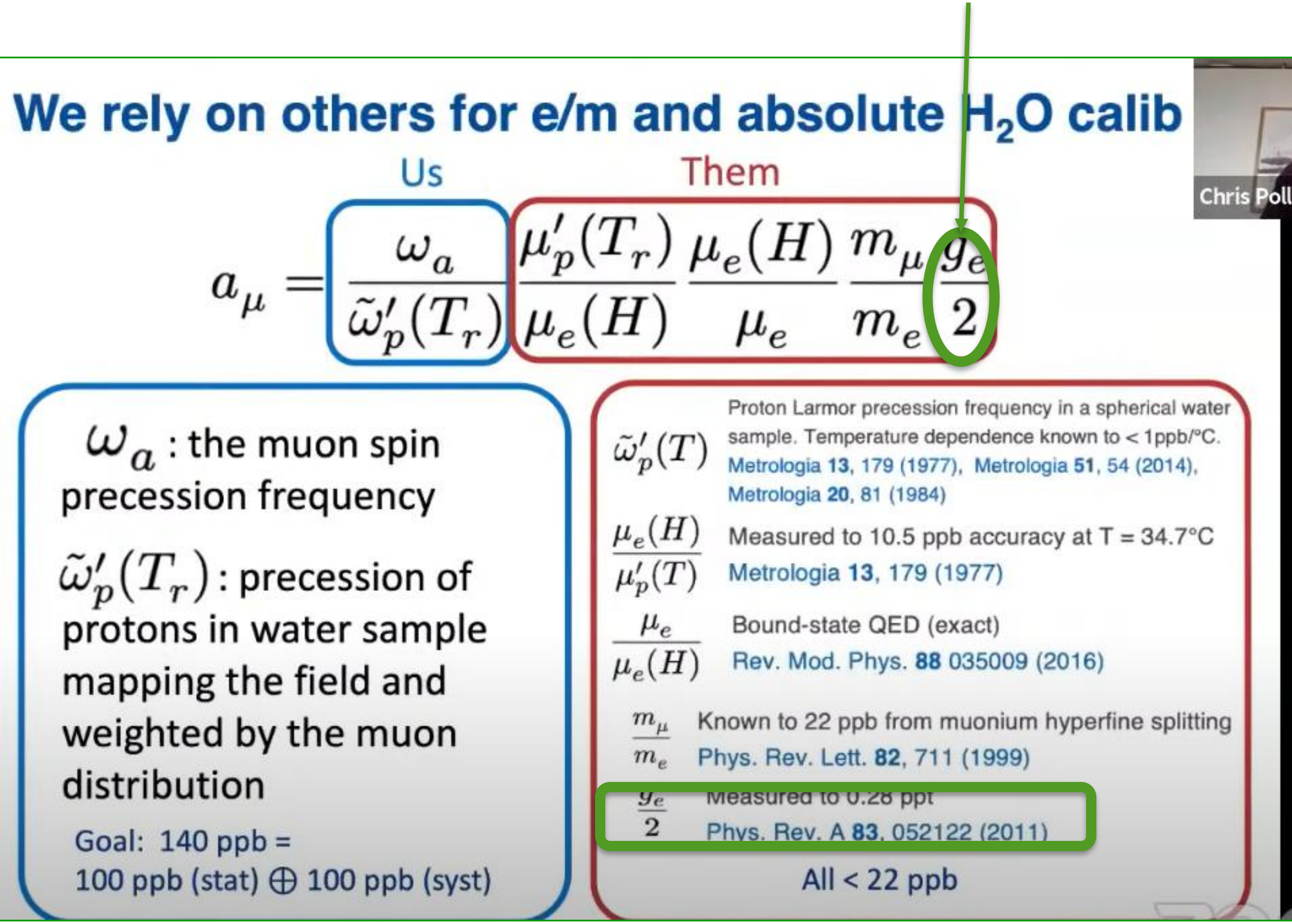
CFP

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

Congratulations to Your Muon Collaboration

- For your impressive new measurements
- For stimulating important lattice calculations
- For persuading Fermilab that the muon magnetic moment is important
- For barging a large storage ring from Brookhaven to Fermilab

We are Proud to Contribute to Your Muon Magnetic Moment



We rely on others for e/m and absolute H_2O calib

$$a_\mu = \overset{\text{Us}}{\boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}}\ \overset{\text{Them}}{\boxed{\frac{\mu'_p(T_r)}{\mu_e(H)}\ \frac{\mu_e(H)}{\mu_e}\ \frac{m_\mu}{m_e}\ \boxed{\frac{g_e}{2}}}}$$

ω_a : the muon spin precession frequency

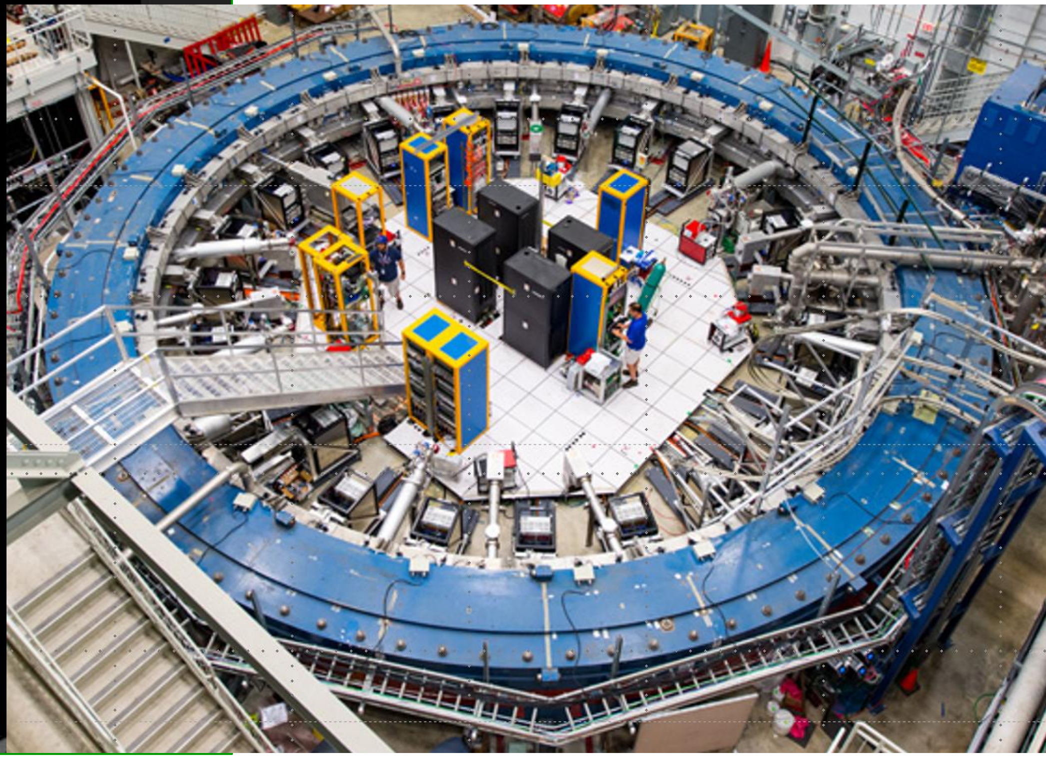
$\tilde{\omega}'_p(T_r)$: precession of protons in water sample mapping the field and weighted by the muon distribution

Goal: 140 ppb =
100 ppb (stat) ⊕ 100 ppb (syst)

$\tilde{\omega}'_p(T)$	Proton Larmor precession frequency in a spherical water sample. Temperature dependence known to < 1ppb/°C. Metrologia **13**, 179 (1977), Metrologia **51**, 54 (2014), Metrologia **20**, 81 (1984)
$\frac{\mu_e(H)}{\mu'_p(T)}$	Measured to 10.5 ppb accuracy at T = 34.7°C Metrologia **13**, 179 (1977)
$\frac{\mu_e}{\mu_e(H)}$	Bound-state QED (exact) Rev. Mod. Phys. **88** 035009 (2016)
$\frac{m_\mu}{m_e}$	Known to 22 ppb from muonium hyperfine splitting Phys. Rev. Lett. **82**, 711 (1999)
$\frac{g_e}{2}$	Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)

All < 22 ppb

Chris Polly



New Measurement of the Electron Magnetic Moment

New: PRL **130**, 071801 (2023) $-\frac{\mu}{\mu_B} = \frac{g}{2} = 1.001\,159\,652\,180\,59(13)$ [0.13 ppt],

Newer: Measurement now underway seeks to improve by a factor of 10 to 30.
Compare electron and positron 200x more precisely – CPT test

Motivations:

- Test the most precise prediction of the SM with the most accurate measurement of a property of an elementary particle
- Look to see if something is missing from the SM
- Check fine structure constant (given that there are measurement inconsistencies)
- Provide the $g_e/2$ used to determine the muon magnetic moment
- Check the 5σ discrepancy between the muon measurement and calculation using the electron ← going away?

Spinoff measurement: 75 times lower limit for meV dark photons PRL **129**, 261801 (2022)

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

Standard Model's Most Precise Prediction

electron

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

$$\frac{e\hbar}{2m} \longrightarrow$$

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

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

magnetic moment in Bohr magnetons

prediction requires a measured fine structure constant

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

Dirac 1

QED

$C_2 = 0.5$

$C_4 = -0.328\,478\,444\,002\,54\,(33)$

$C_6 = 1.181\,234\,016\,815\,(10)$

$C_8 = -1.911\,321\,391\,8(12)$ 891

$C_{10} = 6.74\,(16)$ Kinoshita, Nio, … 12672

exact + mass ratios

Feynman diagrams

Hadronic $a_{hadronic} = 1.693\,(11) \times 10^{-12}$

Weak $a_{weak} = 0.03053\,(23) \times 10^{-12}$

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**

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

$$+ \ \mathrm{a}_{hadronic} + \ a_{weak}$$

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 …

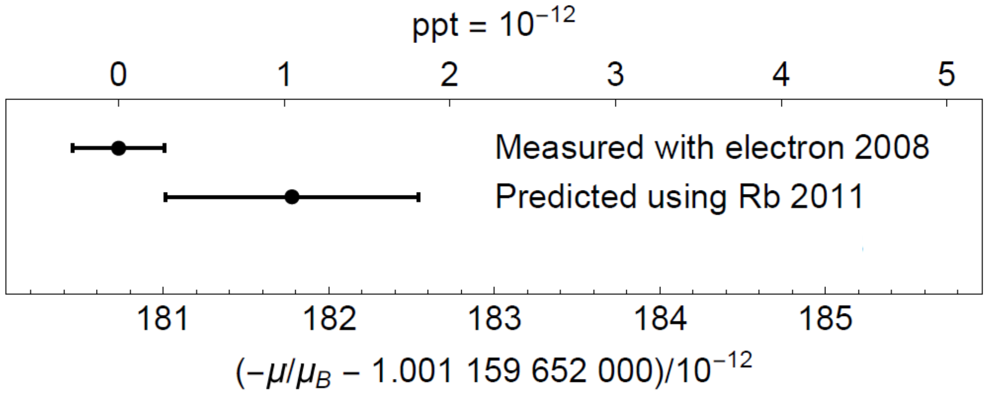
10th Order QED calculated numerically for the first time (Nio, Kinoshita, ...)

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

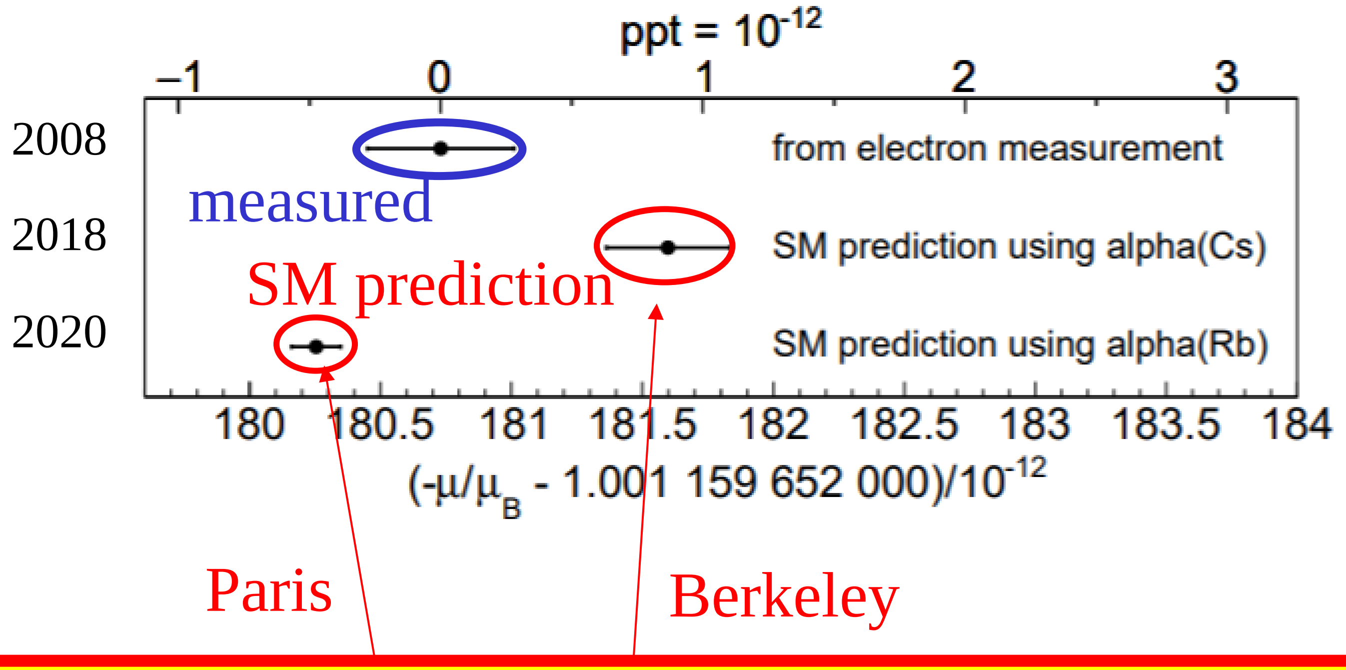
Standard Model calculation → became 10 times more accurate than the measurement uncertainty in μ/μ_B

2011: New α Measurement – accurate enough to test SM

Good agreement between measured and predicted μ/μ_B



☹ 2018 and 2020: “More Precise” α Measurements ☹



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

- α discrepancy limits the SM test
- Perhaps best 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.

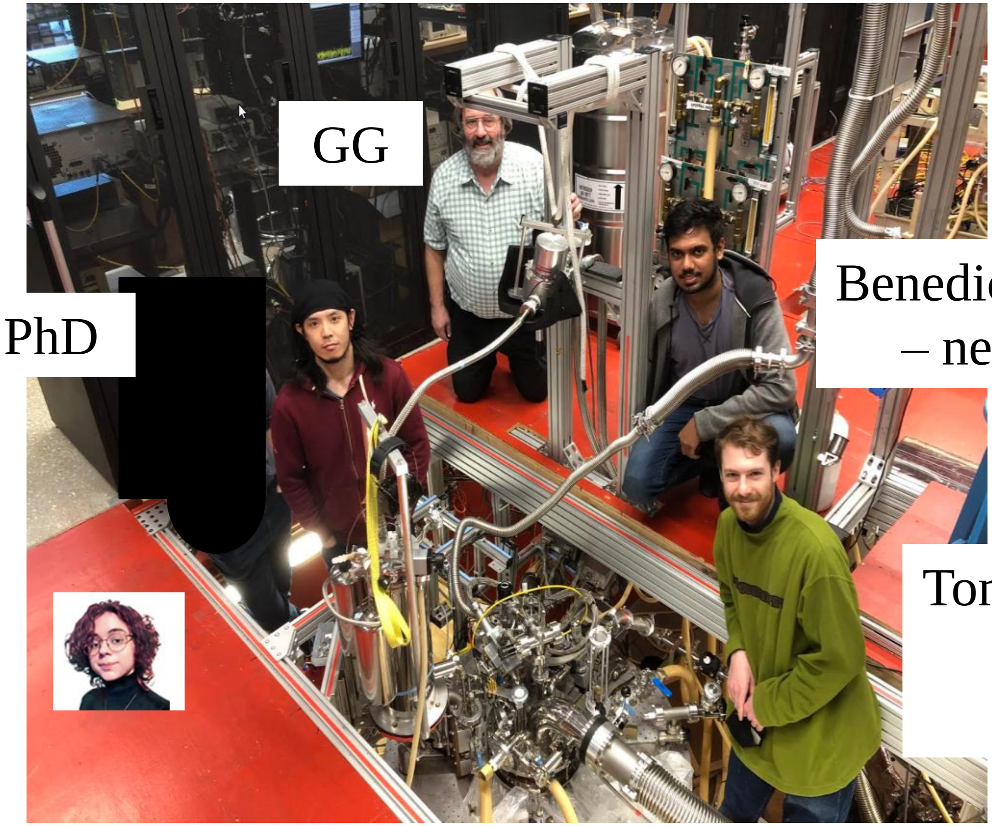
C. Arbelez, R. Cepedello, R. M. Fonseca, and M. Hirsch, $(g-2)$ anomalies and neutrino mass, 2020.

(and more)

2023 Measurement of the Electron Magnetic Moment

First more accurate measurement since 2008

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



[redacted]

GG

Dr. Xing Fan – PhD

Benedict Sukra
– next generation

Lily Sousa – next
generation

Tom Myers
– positron
and electron

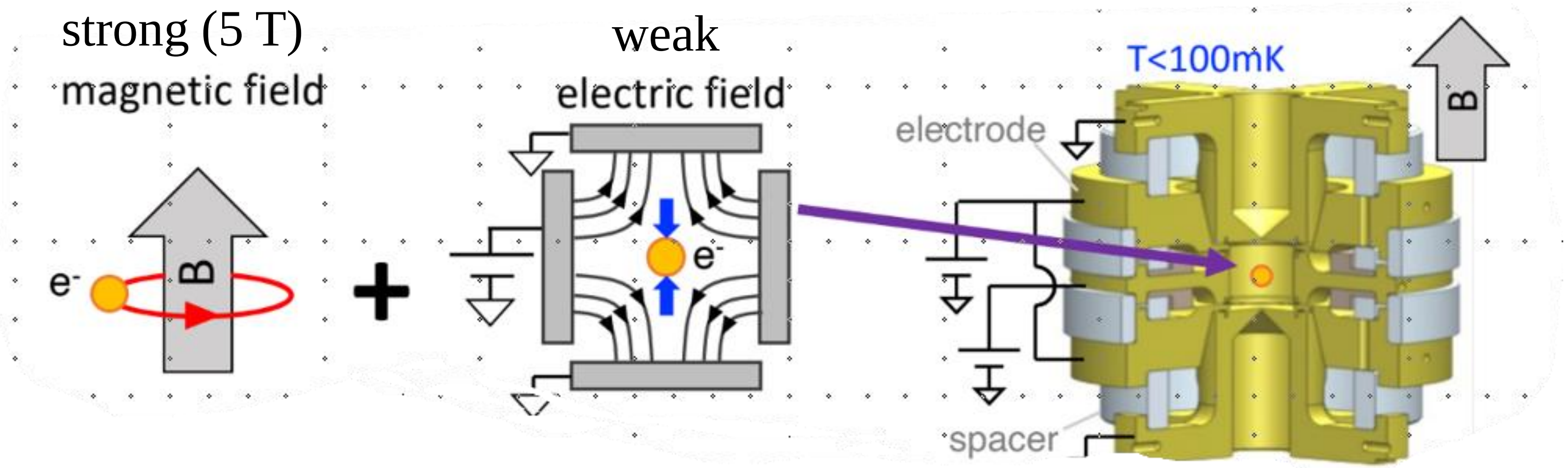
N$F: Lepton moments QM: cavities for qubits Templeton: SQUID development

Measuring the Electron Magnetic Moment

One electron (or positron) in Penning trap for months

strong (5 T)

weak



- 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

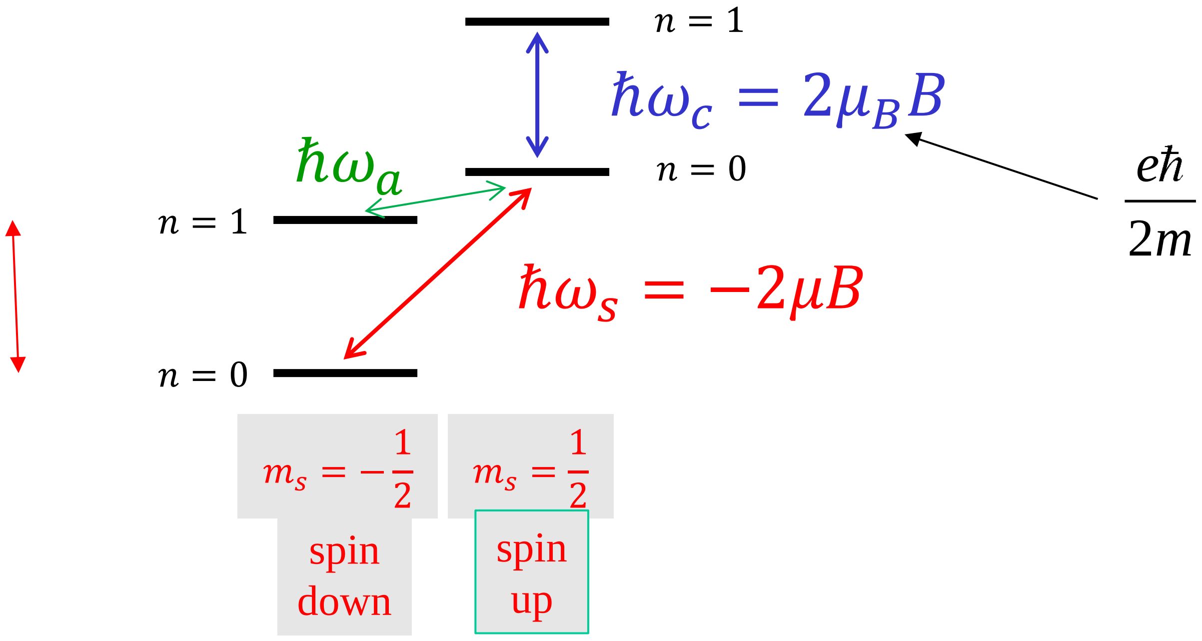
→ inhibits spontaneous emission

One-Electron Quantum Cyclotron

One electron cooled into its lowest cyclotron and spin states

$h\upsilon_c = k_B$ 7.2 kelvin

7.2 K >> 30 mK



$n = 1$

$\hbar\omega_c = 2\mu_B B$

$n = 0$

$\frac{e\hbar}{2m}$

$\hbar\omega_a$

$n = 1$

$\hbar\omega_s = -2\mu B$

$n = 0$

$m_s = -\frac{1}{2}$

spin
down

$m_s = \frac{1}{2}$

spin
up

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

except drift between measurements of the two frequencies

Brown-Gabrielse Invariance Theorem

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

Big Focus I. Magnetic Field Stability

→ In pursuit of the Expected Lineshape

2008 Measurement: both resonances were broader than expected

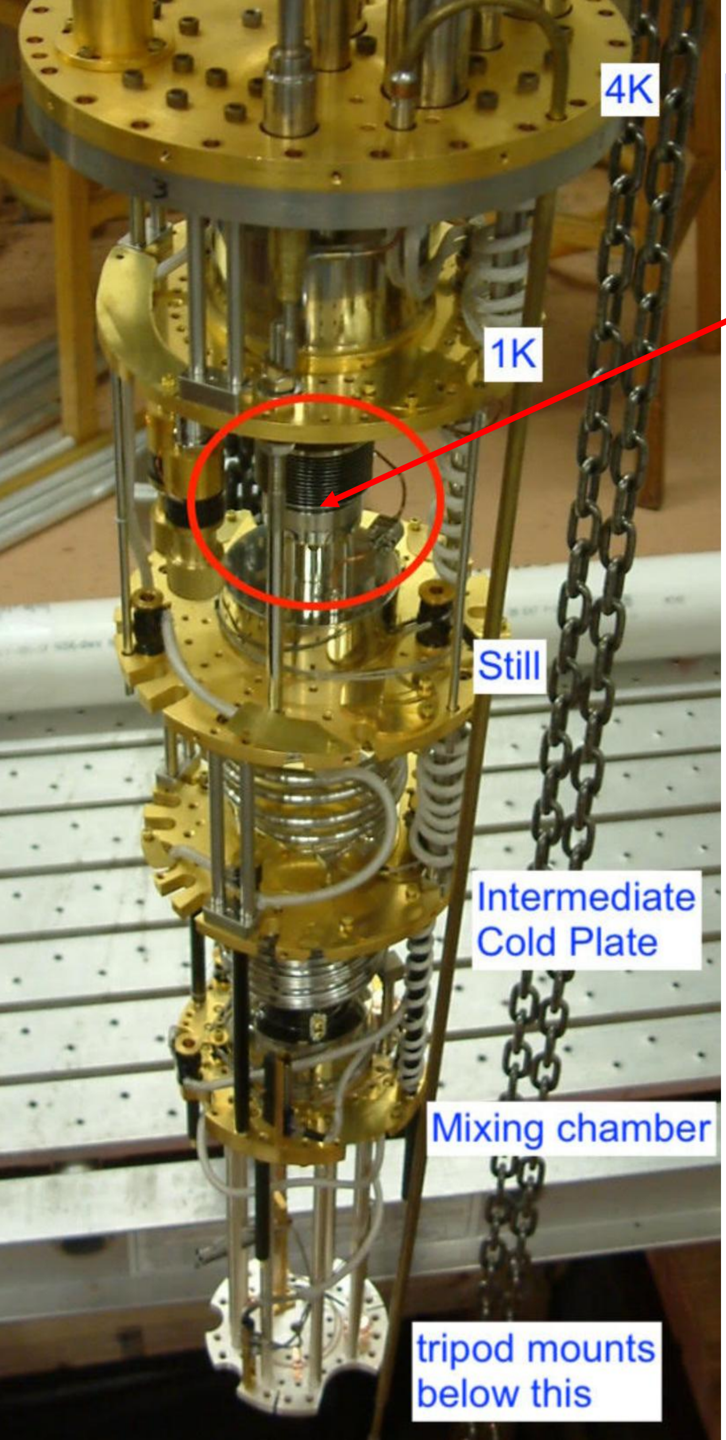
Hypothesis: broadening came from fluctuations in the magnetic field

$\omega_a \sim B \;\; and \;\; \omega_c \sim \mathrm{B}$ → broadening fractionally about the same

Magnetic field stability was thus a big focus for the new measurement

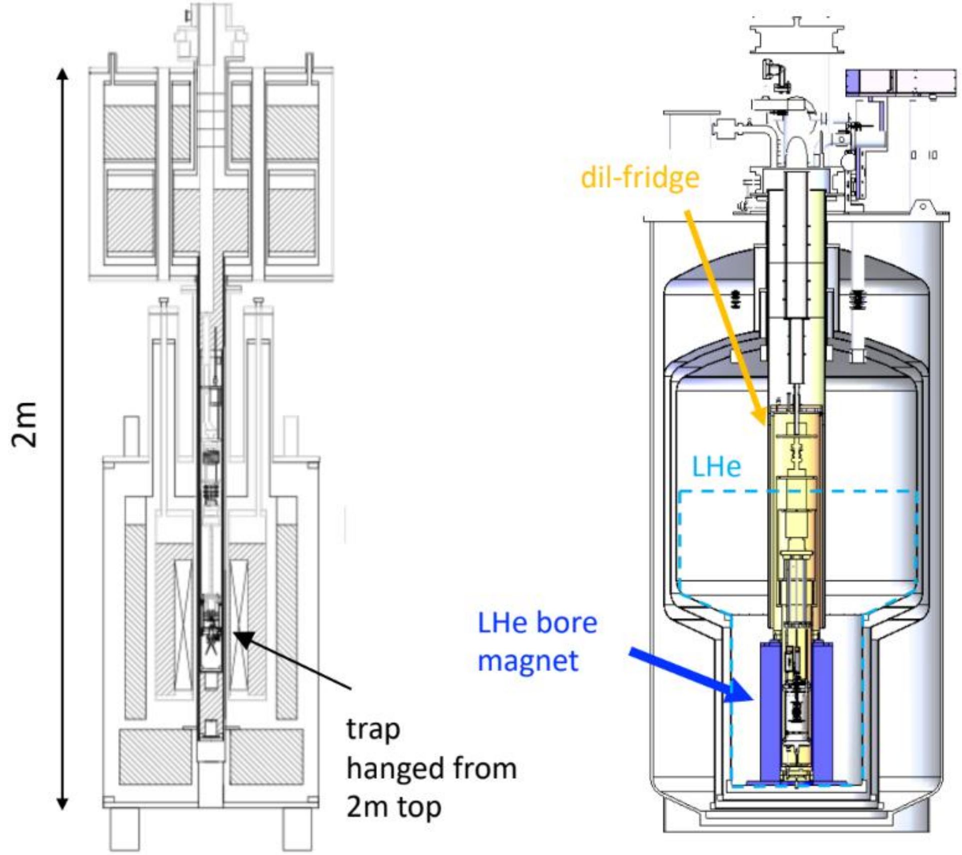
- New superconducting solenoid, dewar and dilution refrigerator
- Silver trap electrodes to minimize nuclear paramagetism that makes B fluctuate with small temperature fluctuations
- Use gas ^{3}He probe to adjust a dozen shim coils to make B homogeneous → movements of the electron do not change B much
- Self-shielding superconducting solenoid – invented for this purpose, now used in MRI imaging systems

“Flexible Dilution Refrigerator”



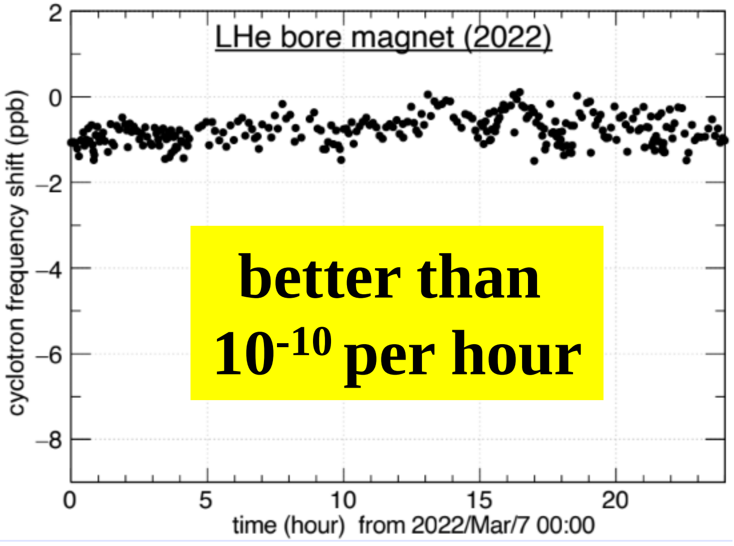
flexible hangers allow the refrigerated trap (at 50 mK) to rest mechanically upon the superconducing solenoid coil (4.2 K)

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



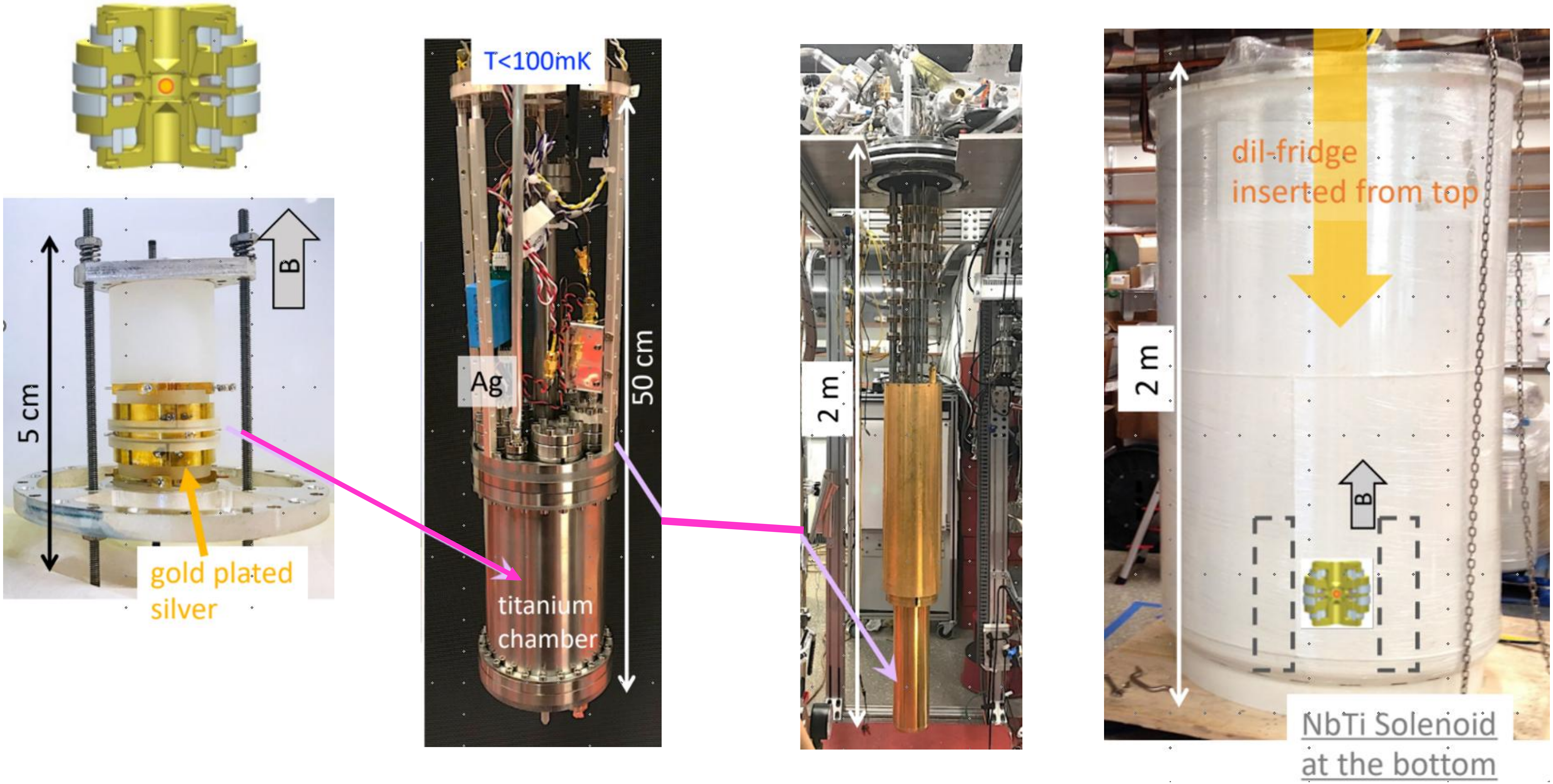
Very Successful

ΔB/B stable to 10^{-9}



better than 10^{-10} per hour

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

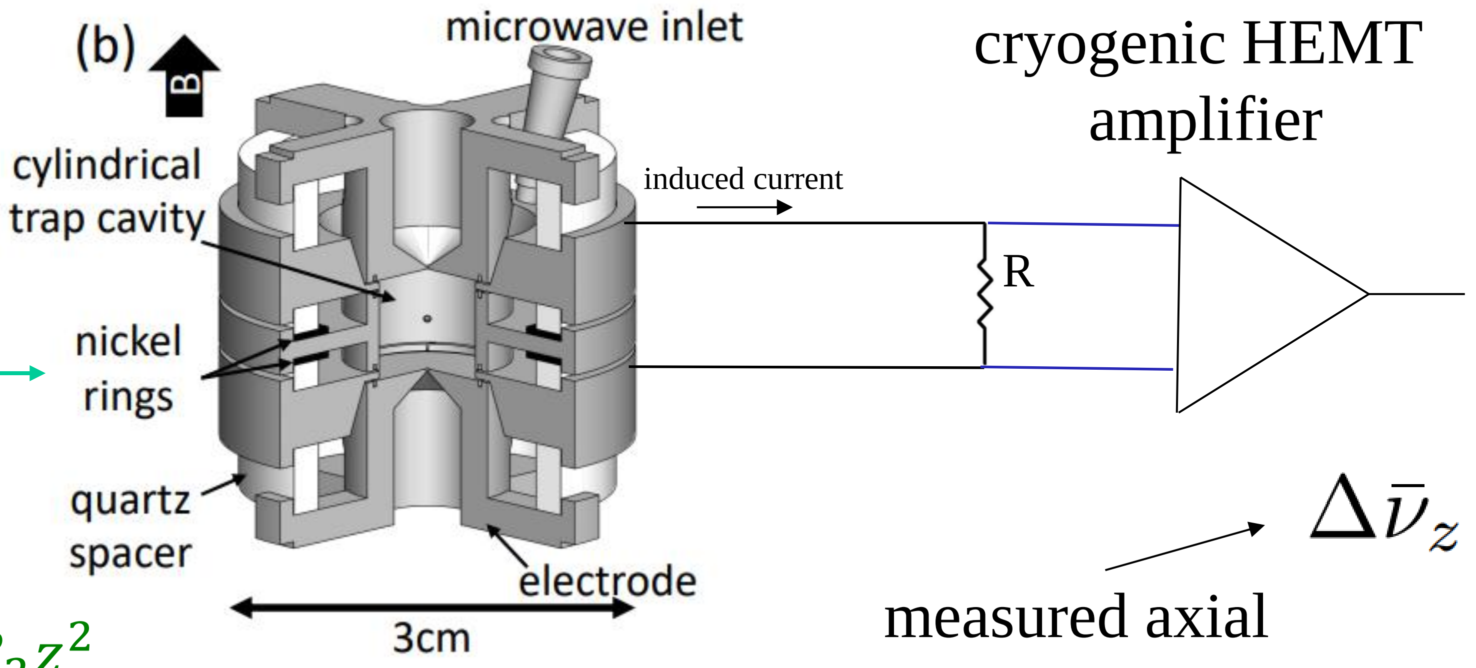


QND Determination of Cyclotron State (n) and Spin State (m_s)

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

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

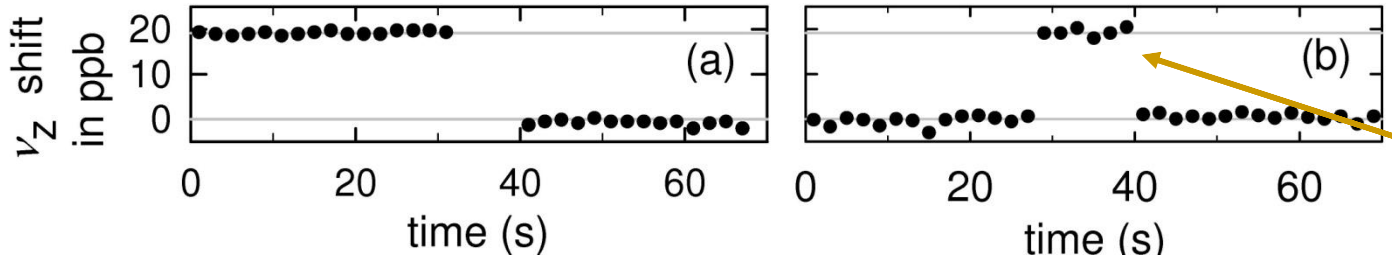
measured axial
frequency shift

cyclotron
quantum
number

spin
quantum
number

spin flip

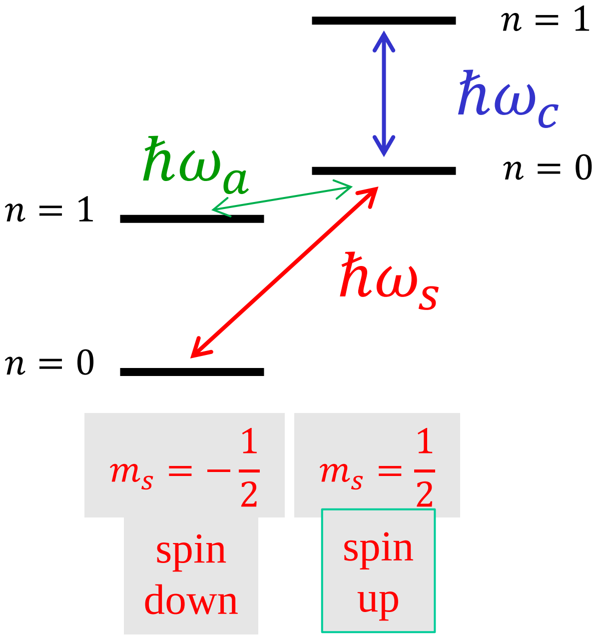
cyclotron excitation

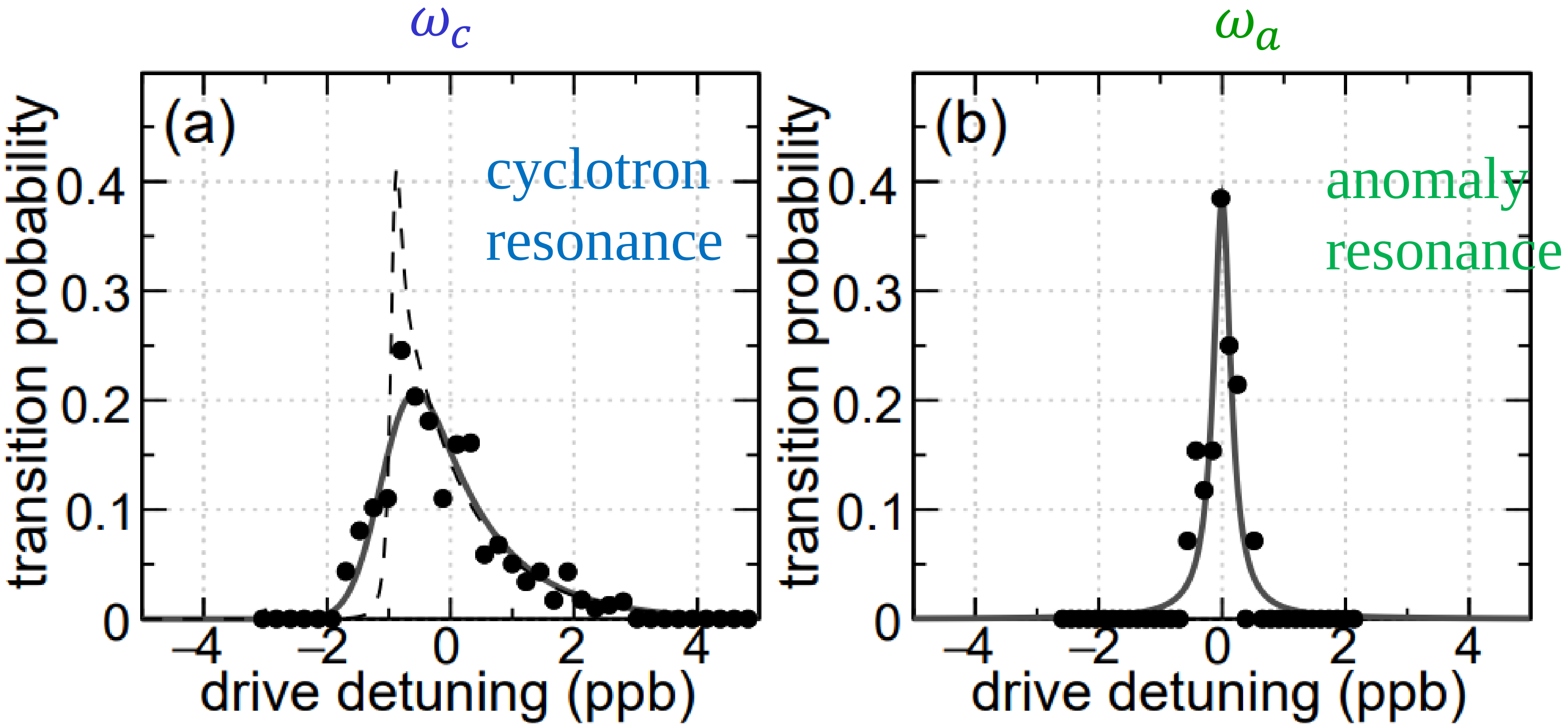


100 times
cavity-inhibited
spontaneous
emission

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

Big Focus II. Cavity Shifts

Interaction of the electron cyclotron motion and the electromagnetic modes of the trap cavity

Good news: Spontaneous emission from the excited cyclotron state
is inhibited by a factor of about 100

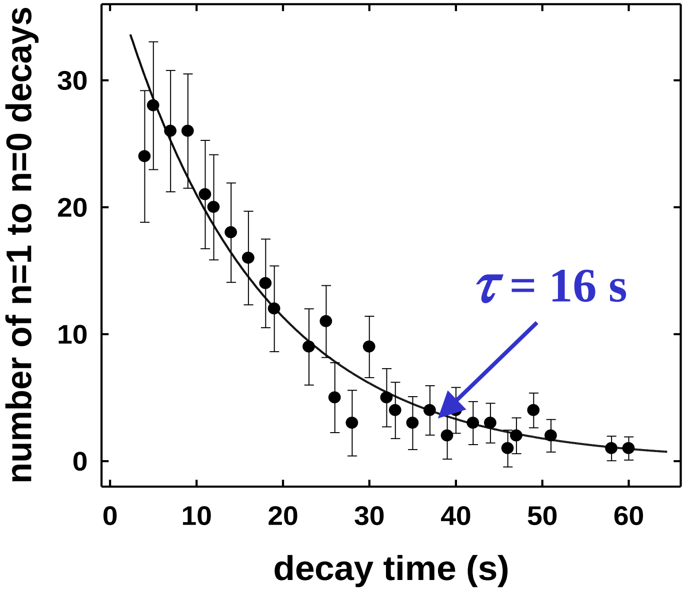
→ Gives us the averaging time we need to observe one-quantum cyclotron transitions

Bad news: coupling of the cavity modes “oscillators” to the cyclotron oscillator
shifts the measured cyclotron frequency ω_c

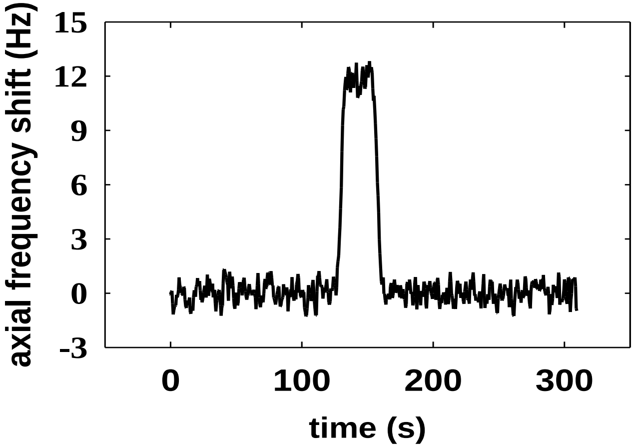
→ The only correction to our measurement

Cavity-Inhibited Spontaneous Emission

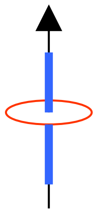
Purcell
Kleppner
Gabrielse and Dehmelt



measure time in excited state



Free Space

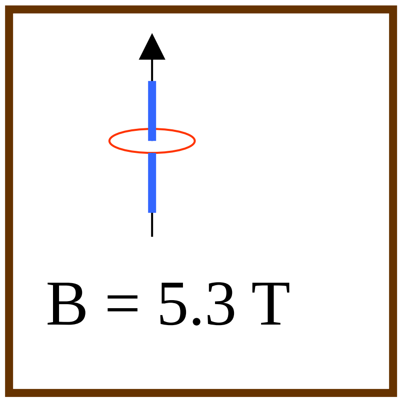


B = 5.3 T

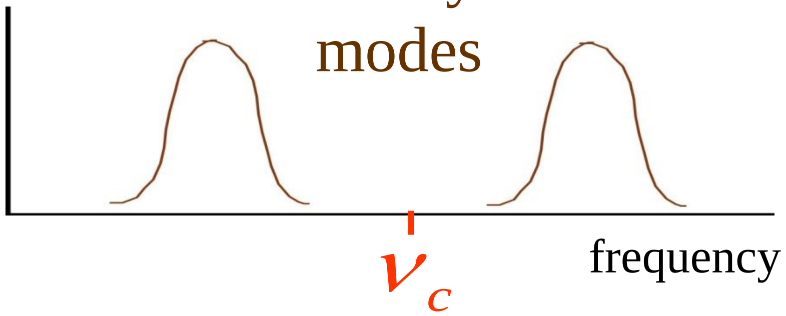
$$\gamma = \frac{1}{75\ ms}$$

inhibited
By 210!

Within
Trap Cavity



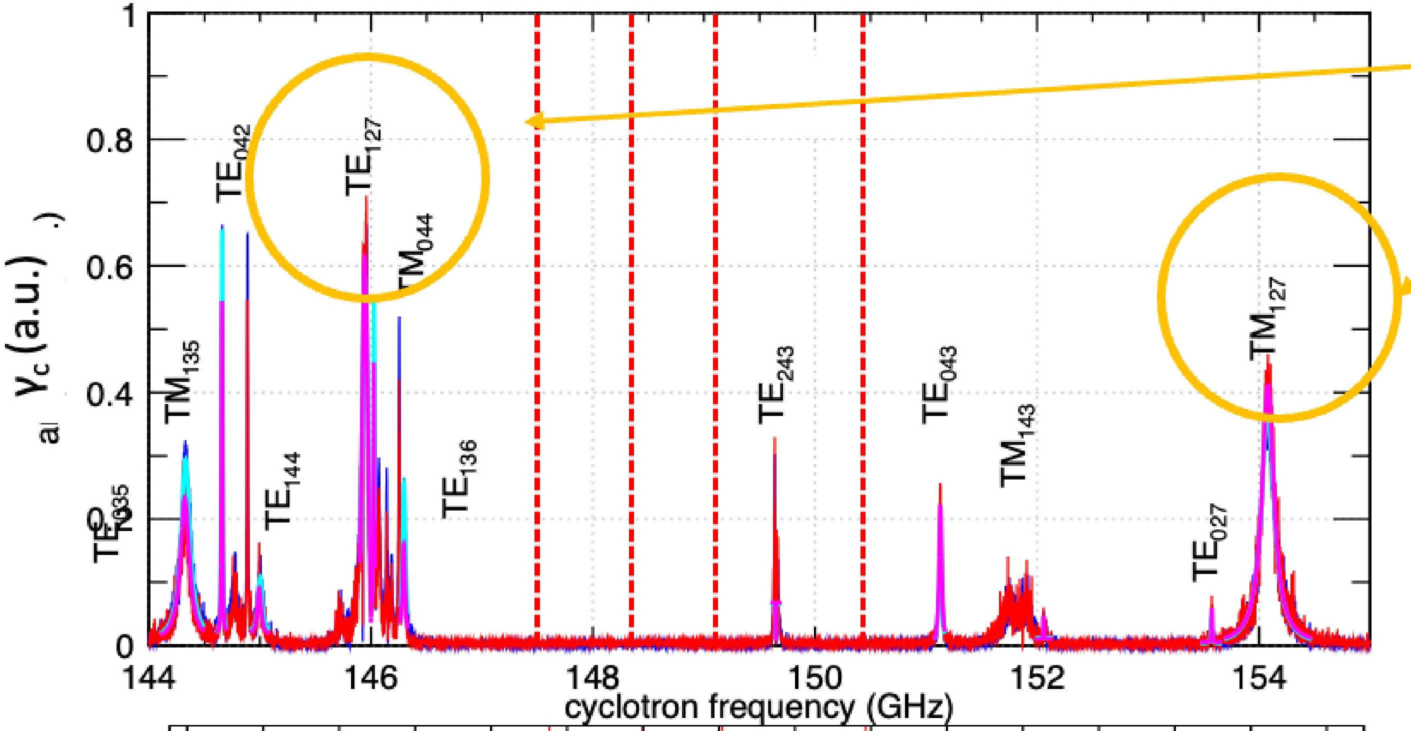
$$\gamma = \frac{1}{16\ \text{sec}}$$



Good news
→ narrower
lineshapes

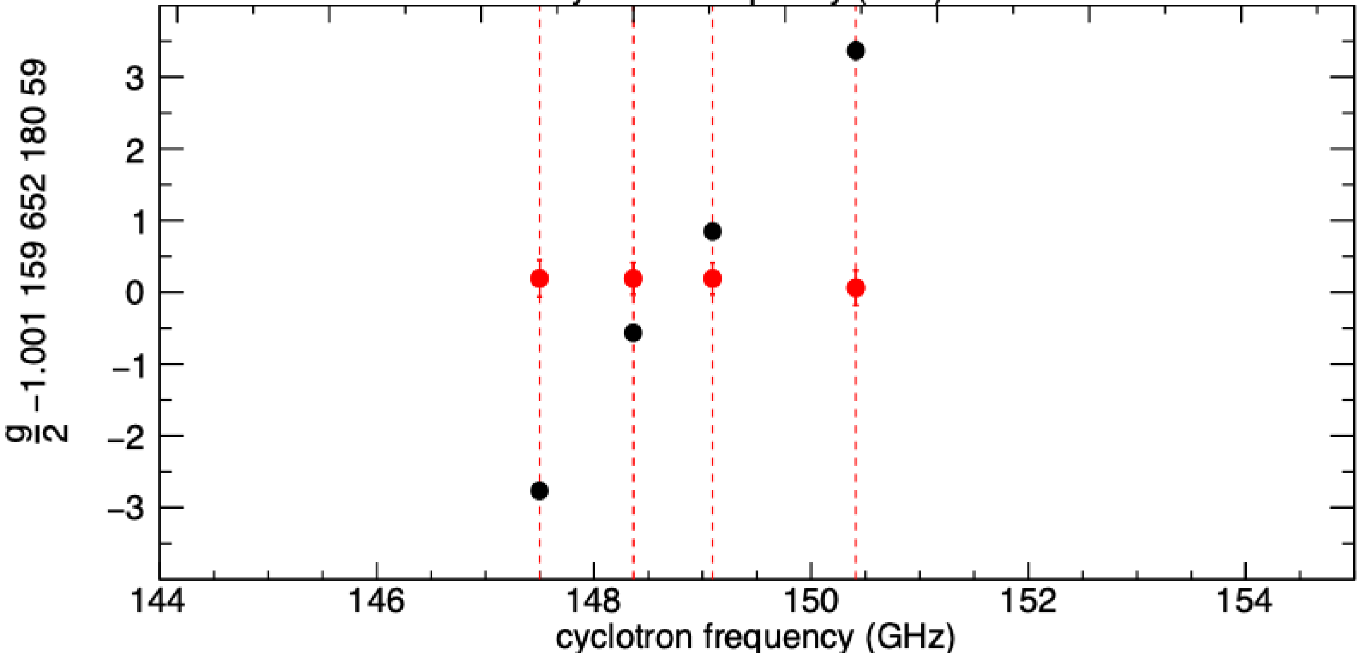
Gabrielse

Measured trap cavity mode spectrum



strongly coupled modes

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

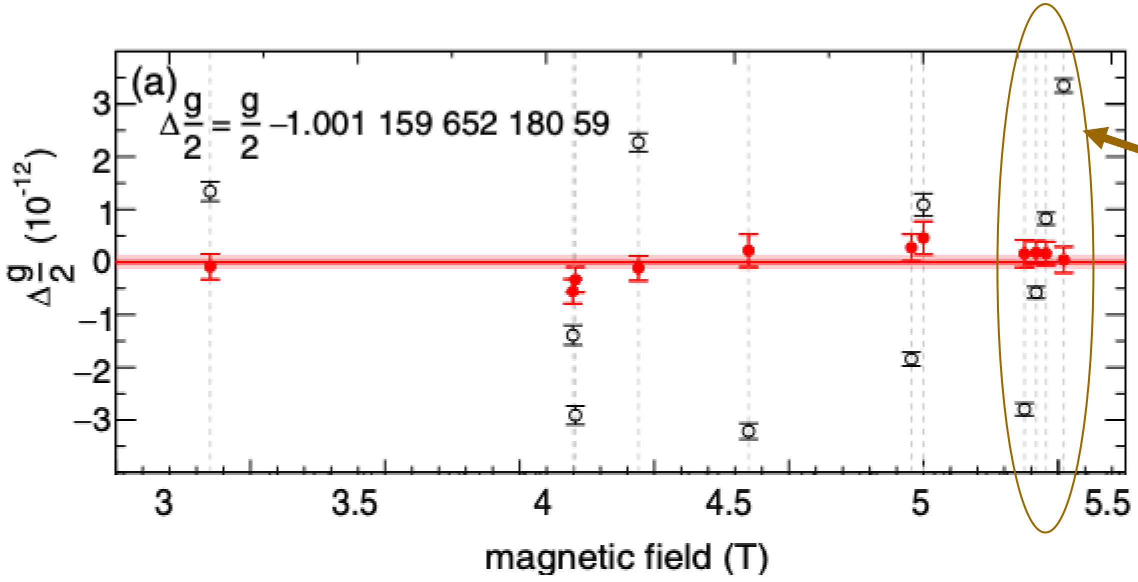


before correction
after correction

Also Checked Over a Very Broad Range

○ before cavity correction

● after cavity correction



graph on previous page

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

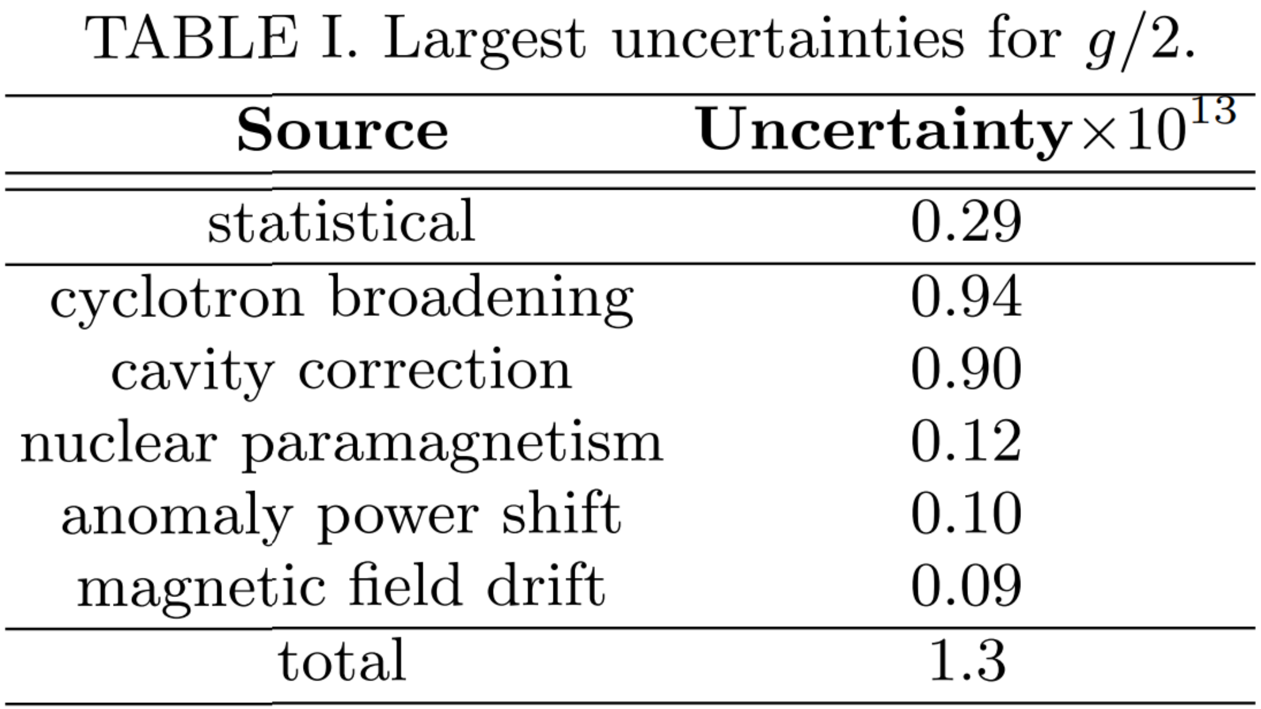
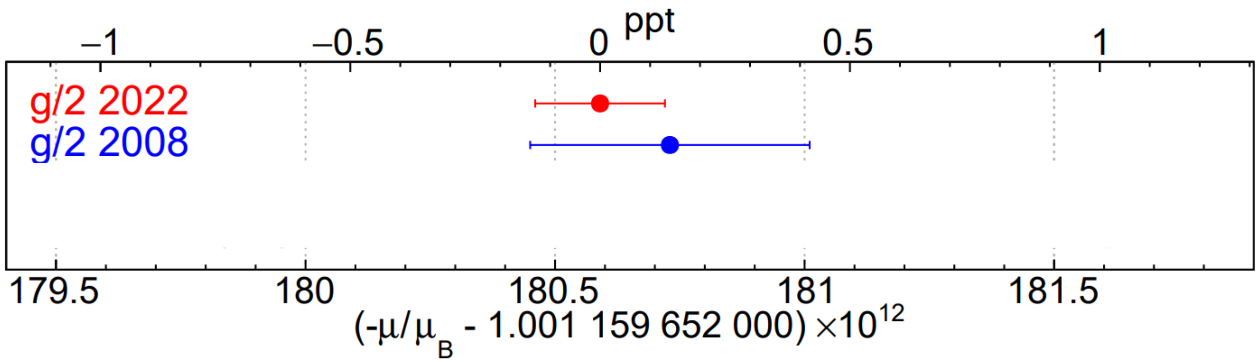


TABLE I. Largest uncertainties for $g/2$.

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

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



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

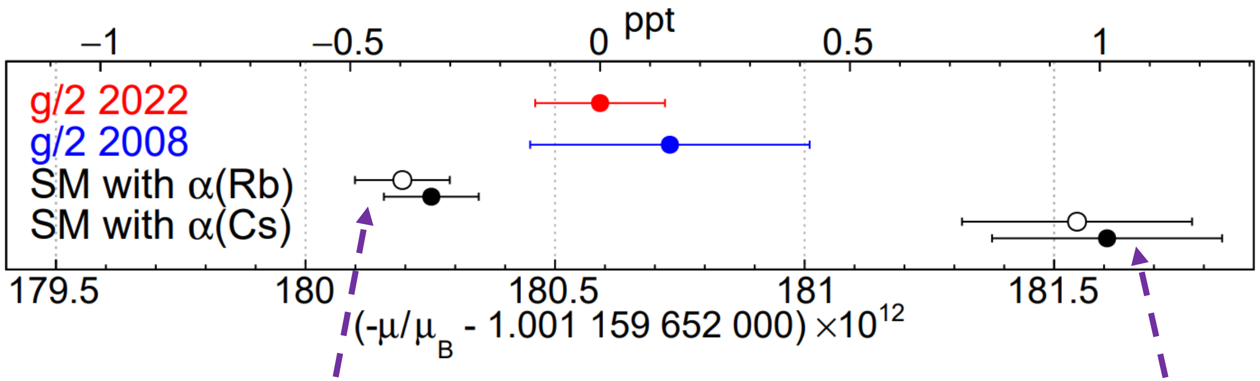
1.3 parts in 10^{13}

- 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: $\mu/\mu_B = -g/2$ 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 ☹

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

$$\frac{g}{2}(\mathrm{Rb}) = 1.001\ 159\ 652\ 180\ 254\ \overset{C_{10}}{(12)}\ \overset{\text{hadronic}}{(11)}\ \overset{\alpha\ \text{measurement}}{(93)}$$

Nature **588**, 61 (2020)

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

Science **360** 191 (2018)

↑

difference is 1344

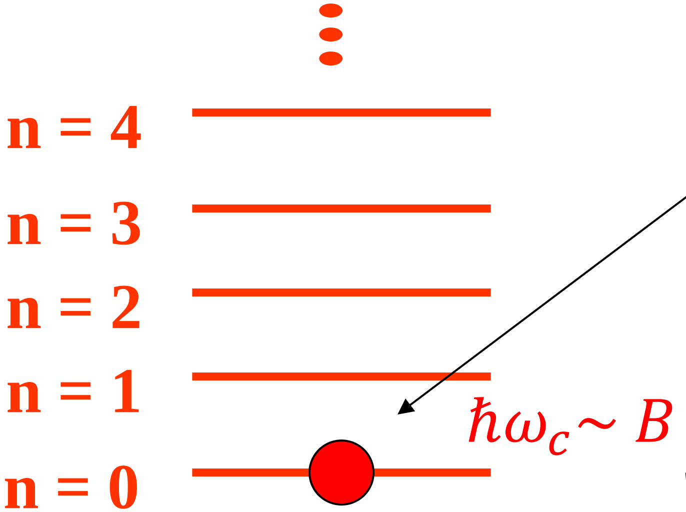
Please someone measure the fine structure constant with a new method!!!!!

Spin off: 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

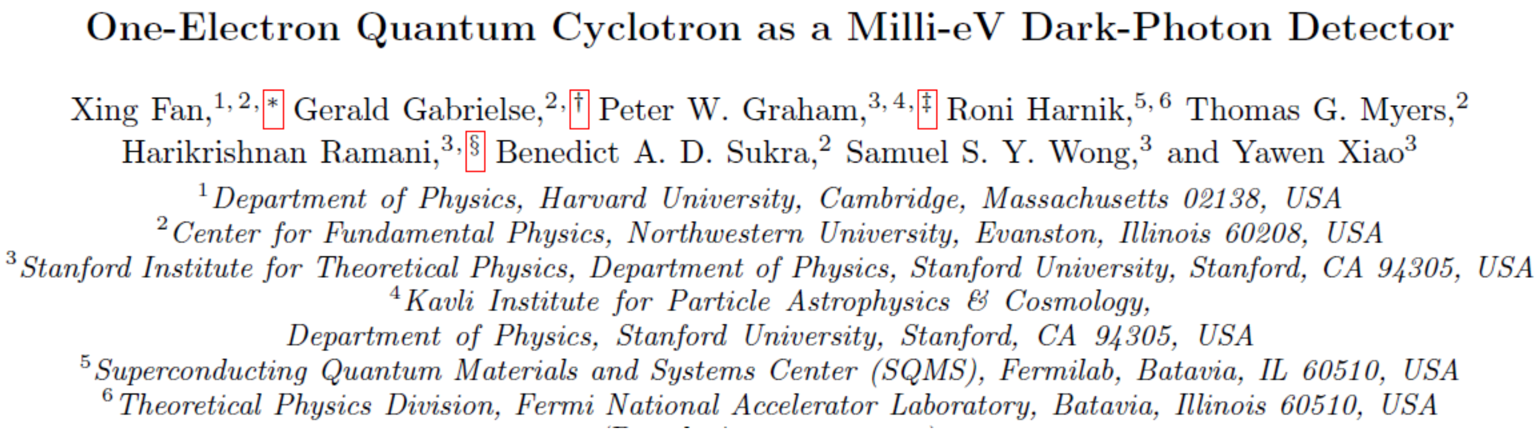
Non-gravitational window into dark matter → search for the kinetically mixed photon

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]
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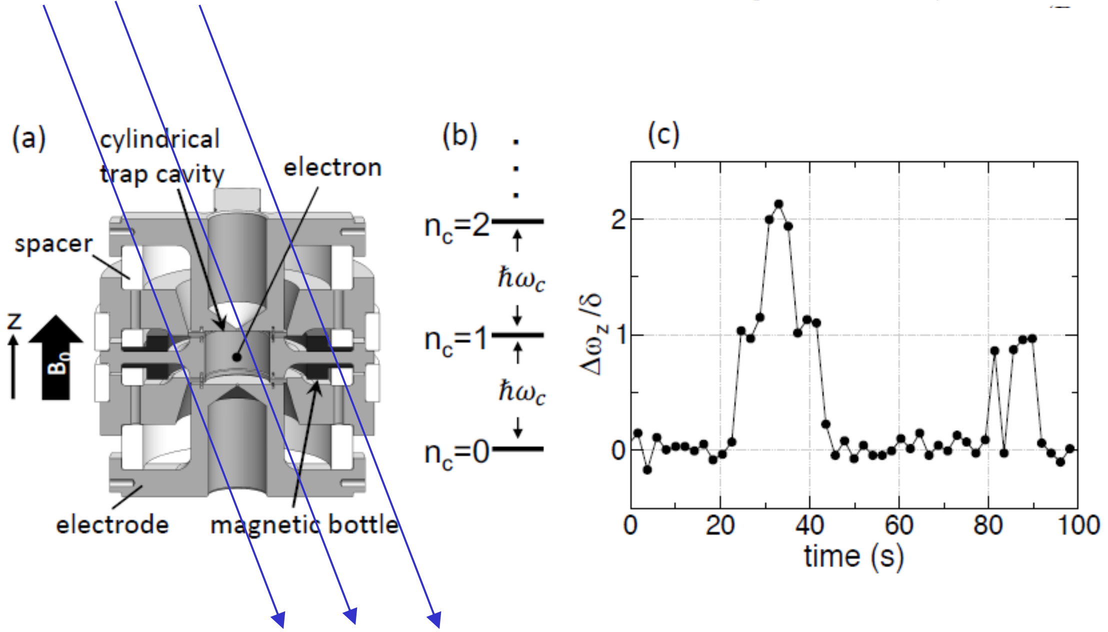
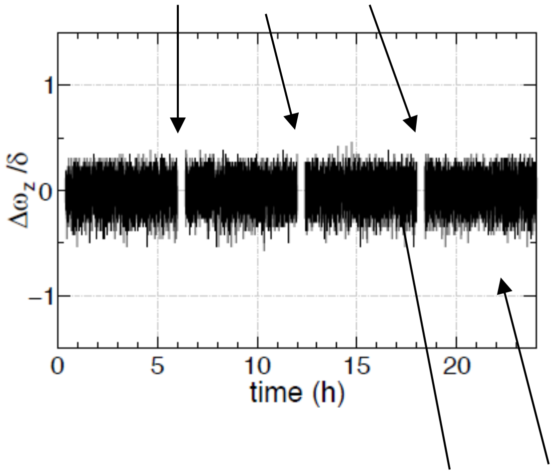
Department of Physics, Stanford University, Stanford, CA 94305, USA
[5]*Superconducting Quantum Materials and Systems Center (SQMS), Fermilab, Batavia, IL 60510, USA*
[6]*Theoretical Physics Division, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

dark photons



one-photon excitations
are easily observed

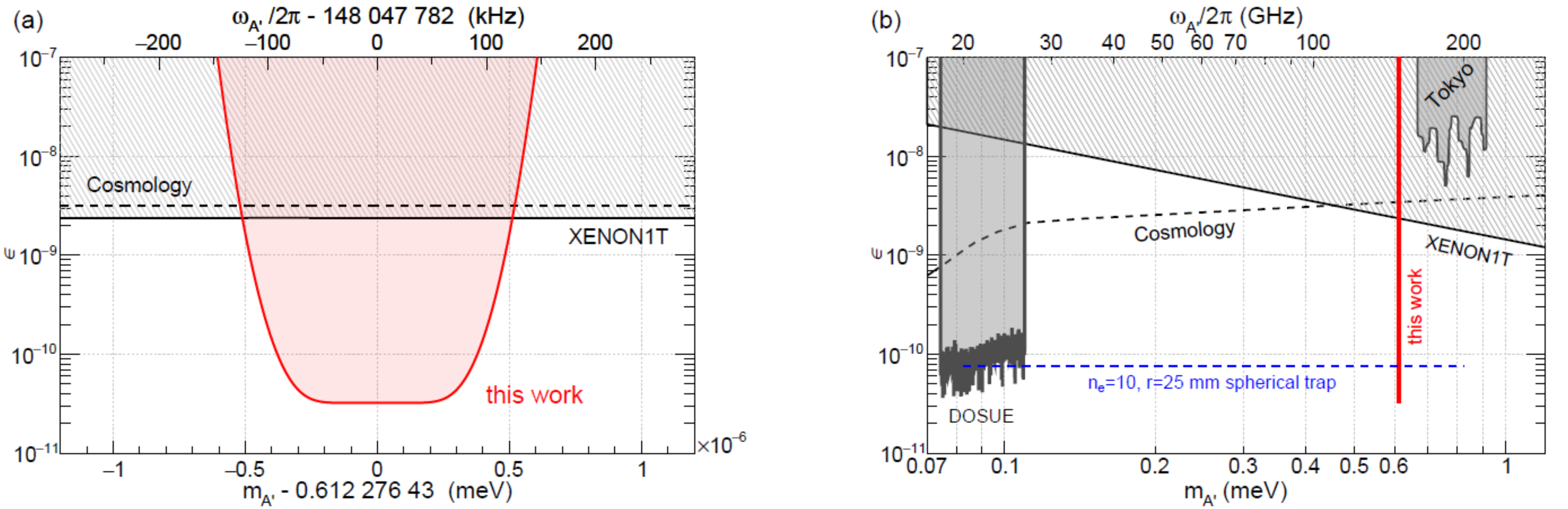
checking the qubit



searching for dark photons

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

Demonstration Measurement



↑

75

↓

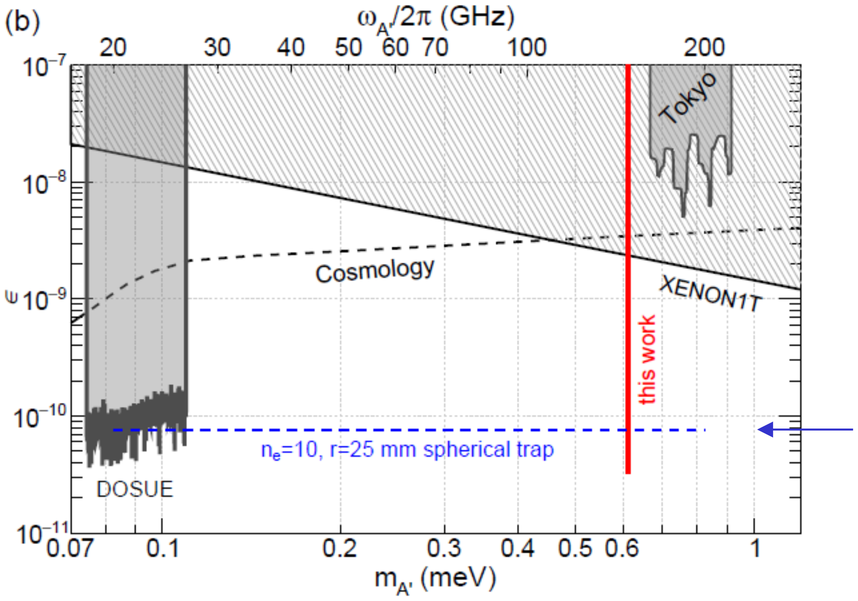
greatly
improved
limit
☺

⟷

very narrow
search range
☹

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

SQMS Low-Loss Cavity Development is Extremely Important



proposed scan range and sensitivity

- Lower microwave cavity loss → dark photon makes a longer excitation that can be detected more sensitively

- Lower matching cavity loss → use SQUID for much more sensitive one-photon detection, faster scan rate

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

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

Test of the most precise prediction of the SM → improved by a factor of 10

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

Best lepton CPT test → improved by a factor of 200

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

New Ideas that Enable

(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

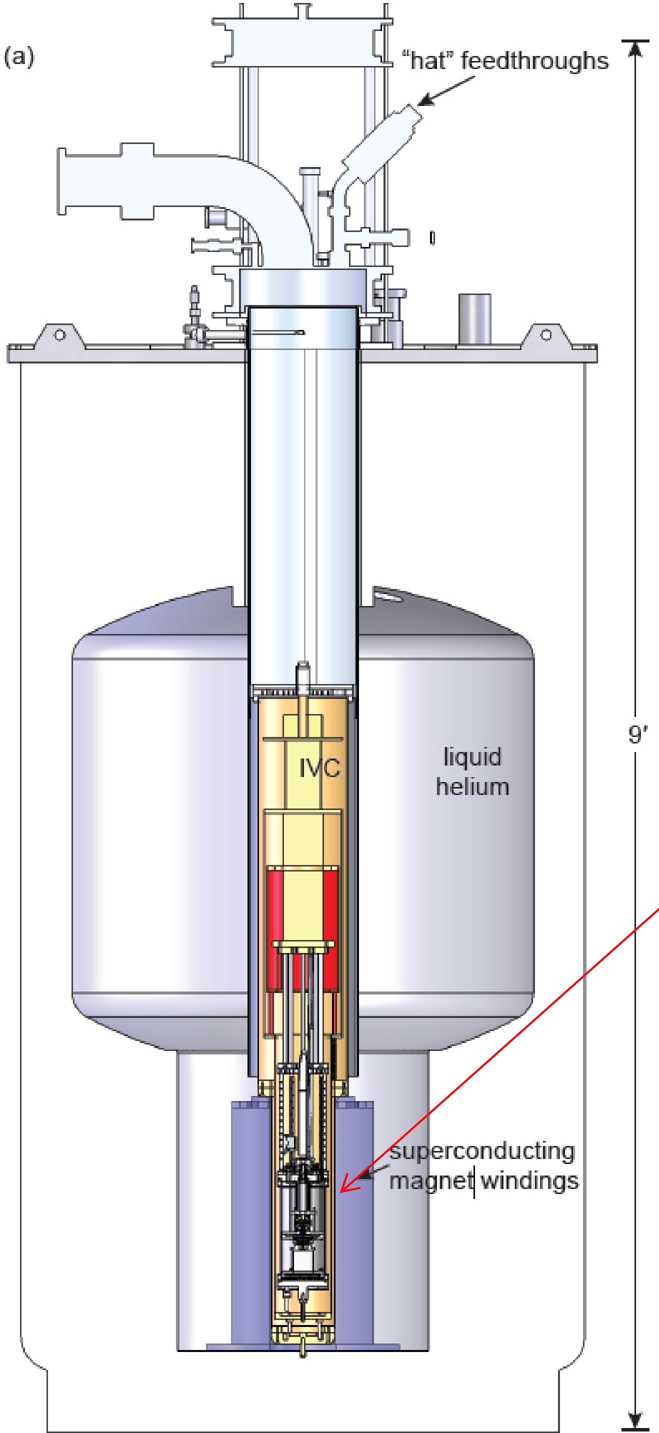
- **Quantum-limited** (nearly) with a 200 MHz SQUID for the QND detection
  → reduce electron and positron temperature by a factor of 25
  → requires 1kG B field near a 50 kG B field (actively shielded solenoid)

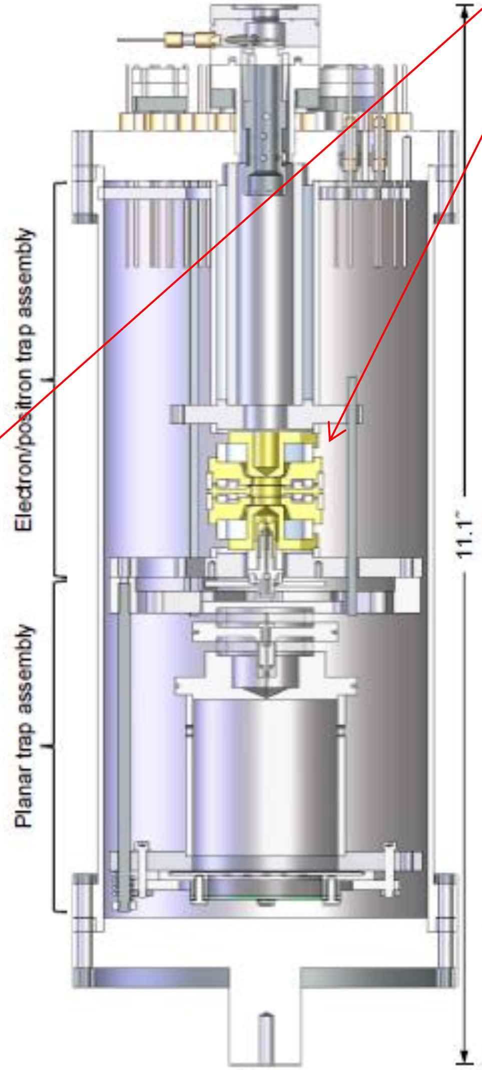
- Detector backaction circumvention

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

New Positron and Electron Apparatus

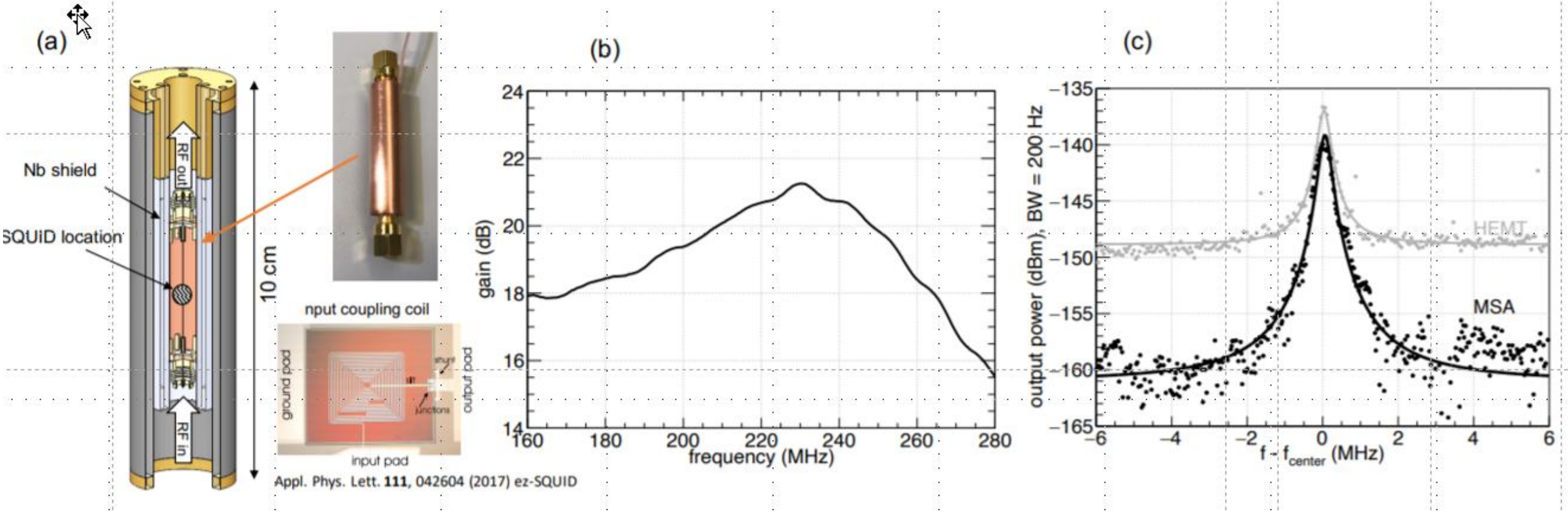
electron trap





200 MHz SQUID Detector

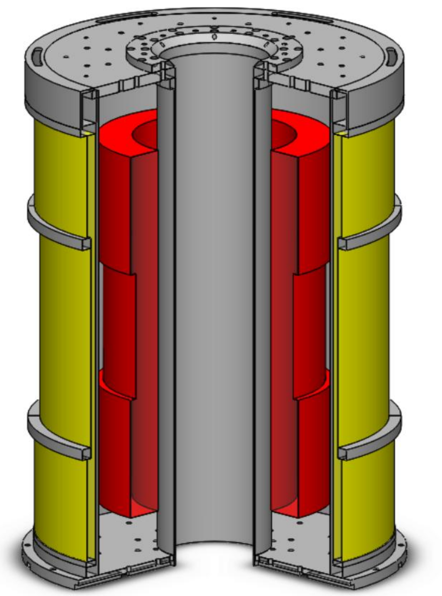
- Better electron qubit readout
- Close to quantum limit rather than being thermally limited



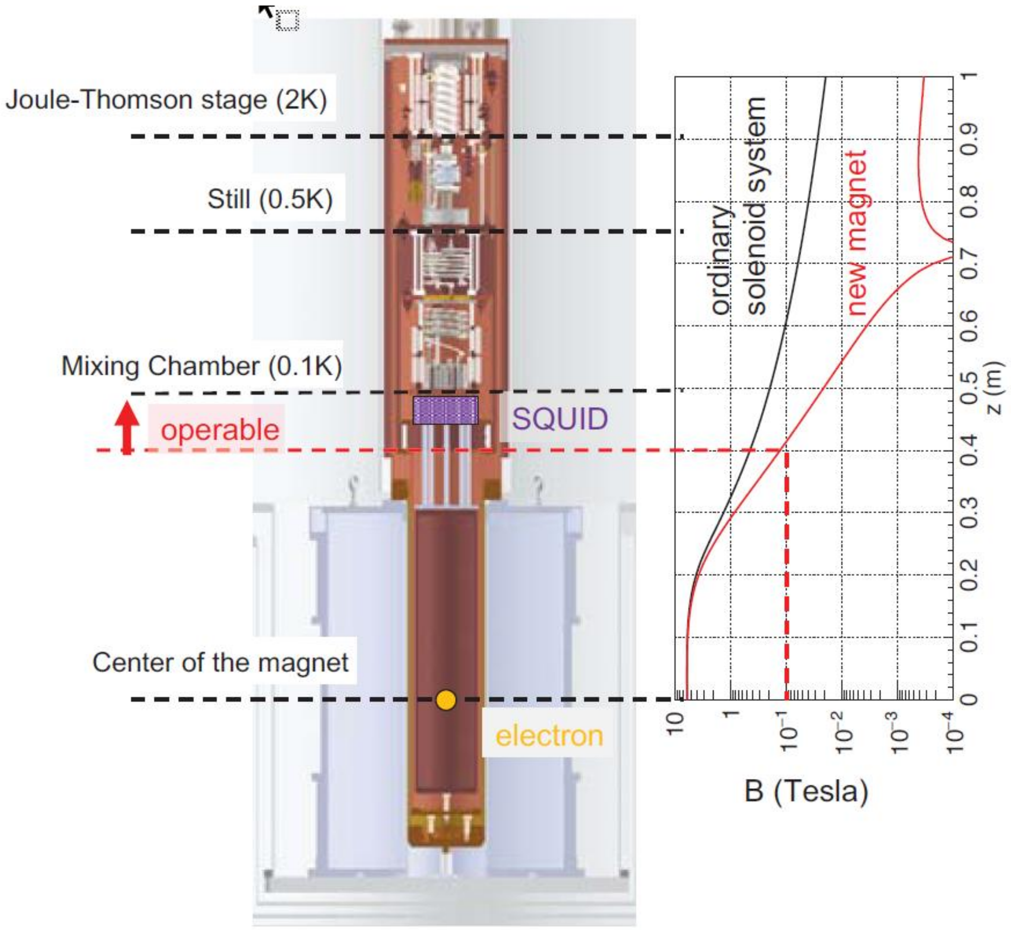
Appl. Phys. Lett. **111**, 042604 (2017) ez-SQUID

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

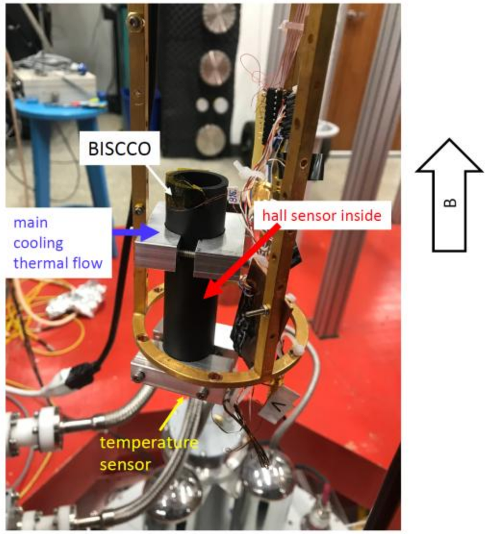
Add a high-temperature superconducting shield layer to get a lower trapped flux within the shields

- 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

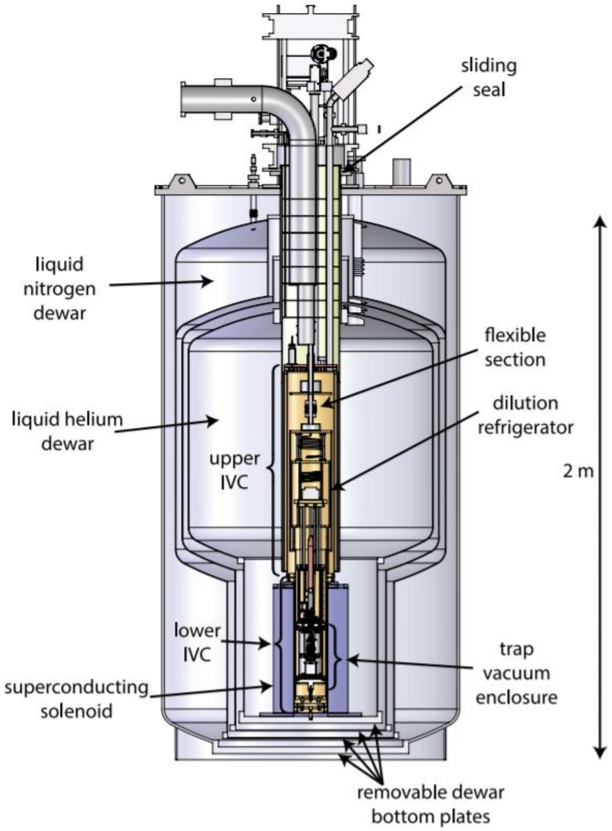
Initial cryogenic tests are very promising

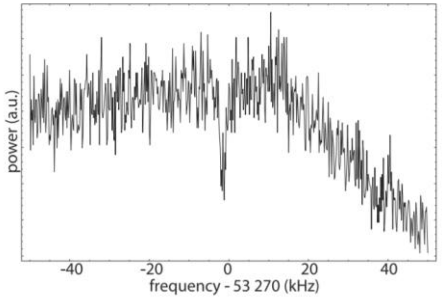


Positron Accumulation from “Student Source”

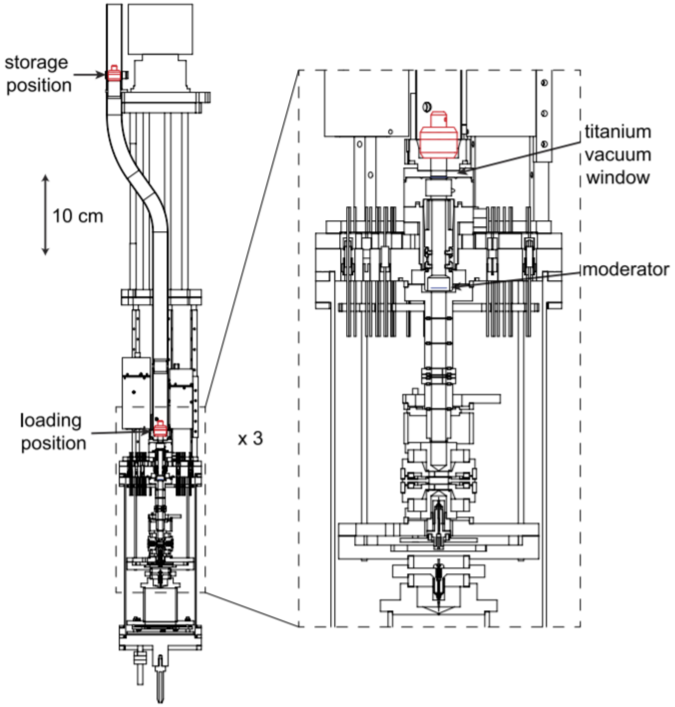
6.5 micro-Curie → 150 positrons/min/mCi

(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!

Conclusion

2023 Measurement of the Electron Magnetic Moment: $\mu/\mu_B = -g/2$ to 1.3 parts in 10^{13}

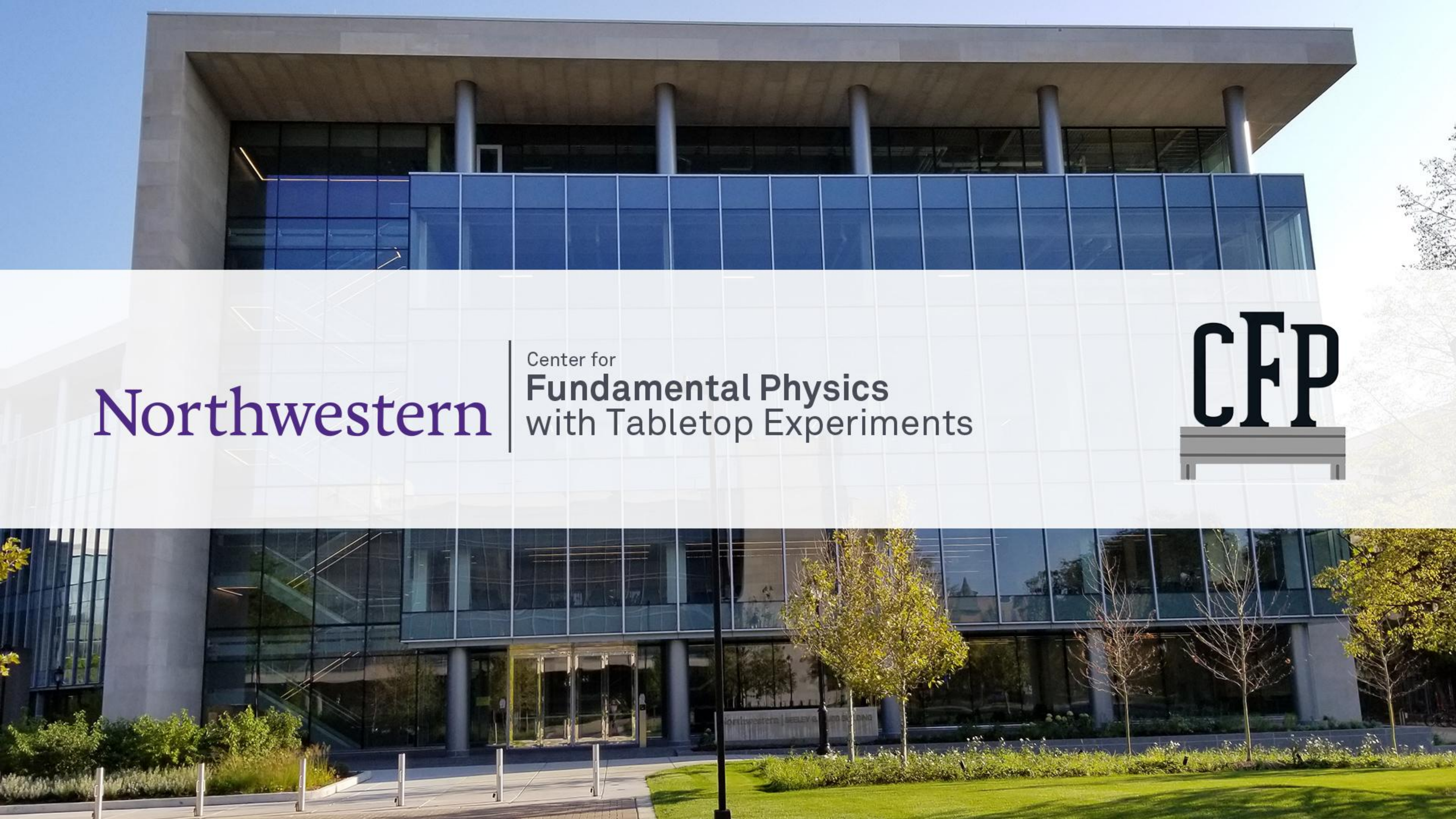
- Most precisely determined property of an elementary particle
- Tests the most precise prediction of the Standard Model of Particle Physics
- Sensitive test for BSM physics

S**pin off: 75x Lower Dark Photon Limit**

- Could be turned into a broad search
- ArXiv paper suggests big improvements are likely possible

New Measurement Underway Seeks 30x improved measurement of μ/μ_B

- Quantum-limited detector
- Special relativity QND coupling (instead of magnetic gradient)



Northwestern

Center for
Fundamental Physics
with Tabletop Experiments

CFP