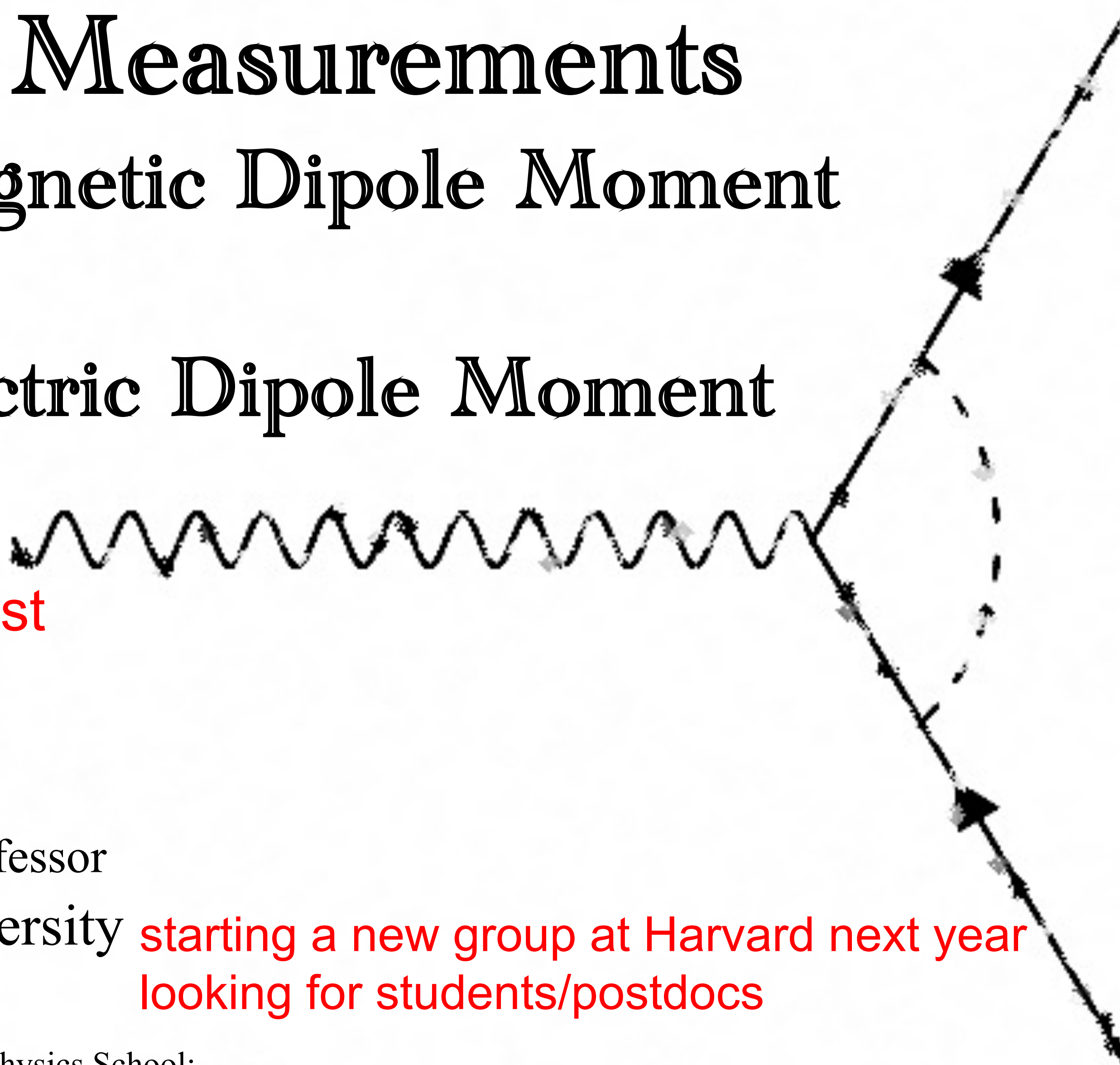
Precision Measurements

Electron Magnetic Dipole Moment
and
Electron Electric Dipole Moment



I am not a muon-ist

Xing Fan

Research Assistant Professor

Northwestern University

starting a new group at Harvard next year
looking for students/postdocs

2024 Sep 3 Muon International Physics School:
Simon Eidelman School on Muon Dipole Moments and Hadronic Effects

What is Precision Measurement?

precision measurement tools

THORLABS

Products Home / Lab Supplies / General Tools / Precision Measuring Tools

Precision Measuring Tools

- Caliper, Micrometer, and Indicator Available
- High-Resolution Digital Readouts
- Display Imperial or Metric Units

Related Items

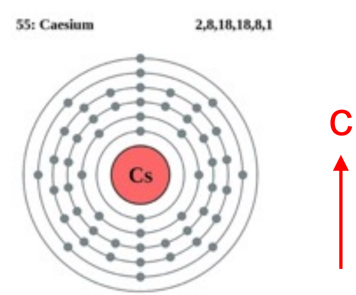
What is Measurement?

170 cm

= 1.7m

$$= 1.7 \times c \times \left(\frac{1\ \mathrm{sec}}{299\,792\,458}\right)$$

$$= 1.7 \times c \times \left(\frac{1}{299\,792\,458} \times \frac{9\,192\,631\,770}{\nu_{Cs}\ (\mathrm{Hz})}\right)$$



travel of light in $1/\nu_{Cs}$

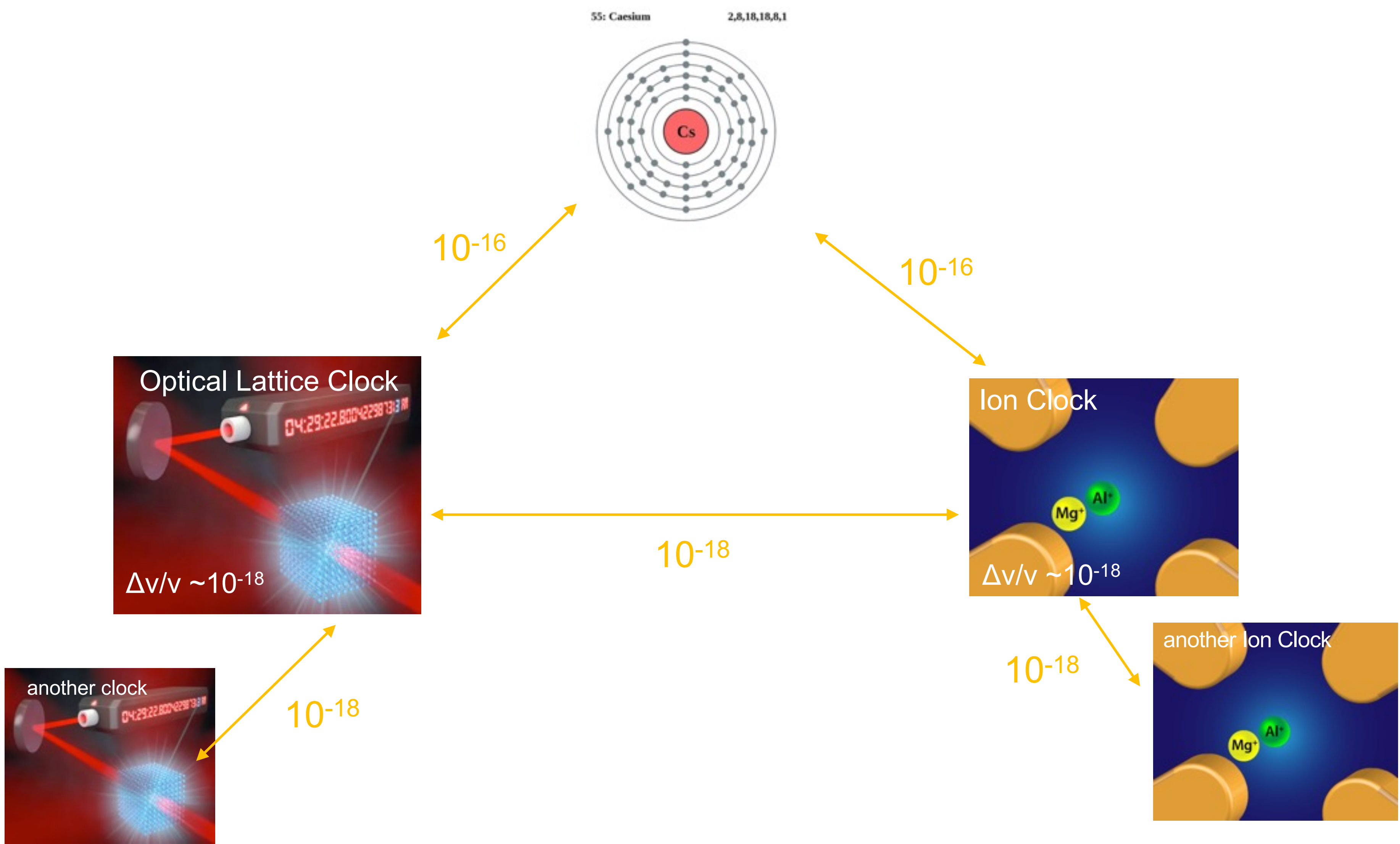
multiply by $\frac{9\,192\,631\,770}{299\,792\,458}$

to get 1 m

What is Measurement?

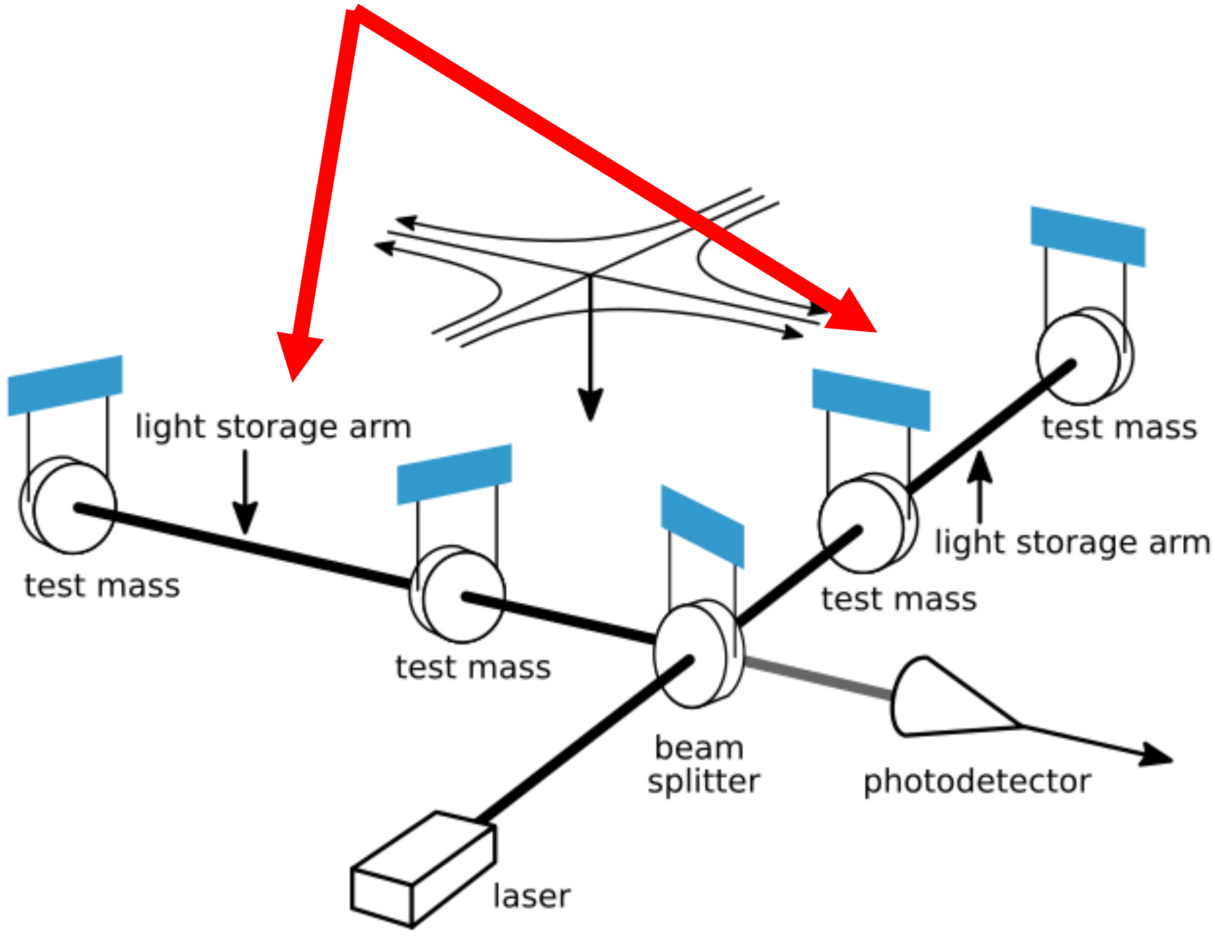
- always relative

Cs Clock
$\Delta\nu/\nu \sim 10^{-16}$



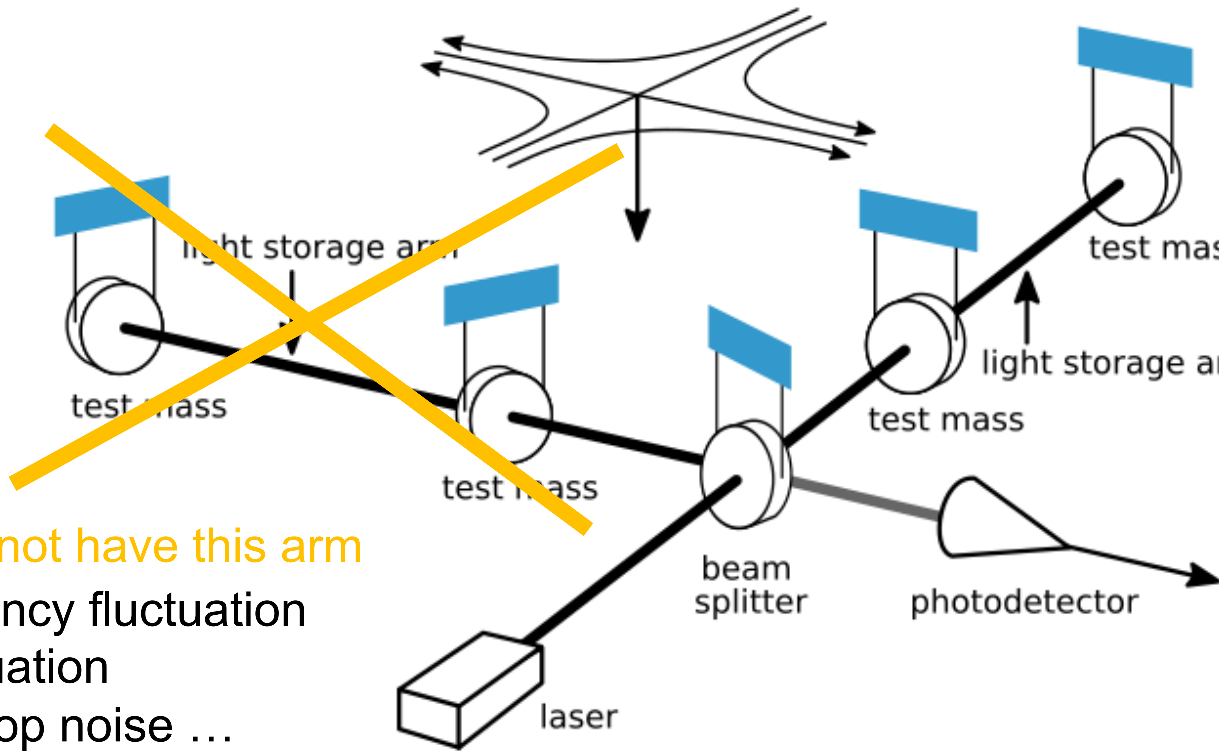
Gravitational Wave Detector

two stable arms → common mode cancellation



Common Mode Cancellation

- Make the system insensitive to what you do not want to see



If we did not have this arm

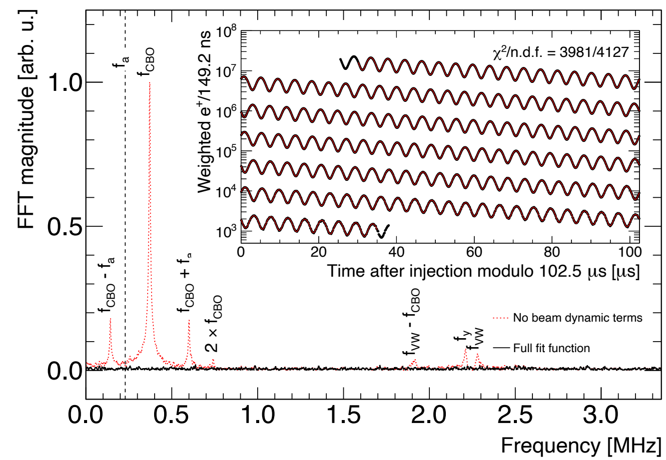
laser frequency fluctuation
power fluctuation
feedback loop noise …

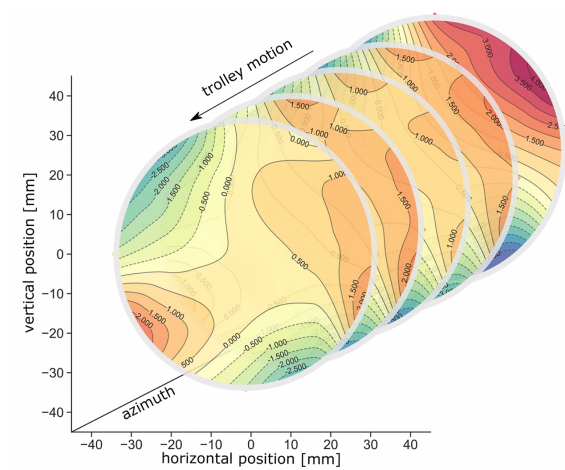
Always Have Two Good Measurements

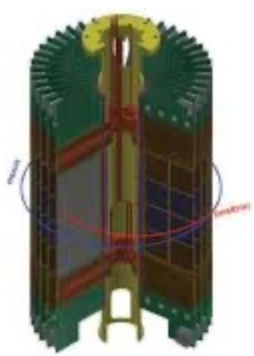
measure spin frequency

$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{m_\mu}{e}\frac{\nu_a}{B}$$

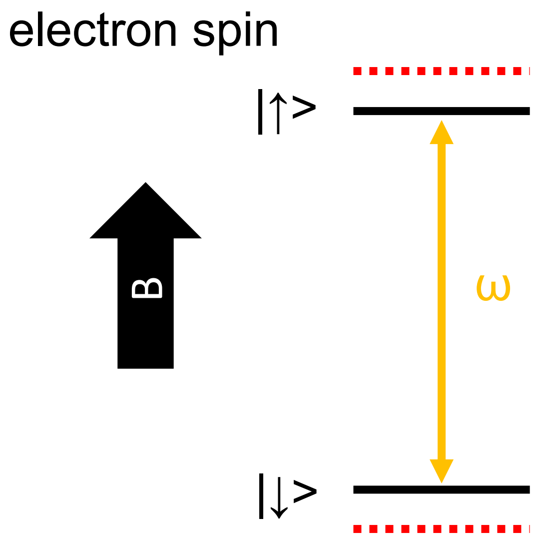
measure cyclotron frequency
(=magnetic field)

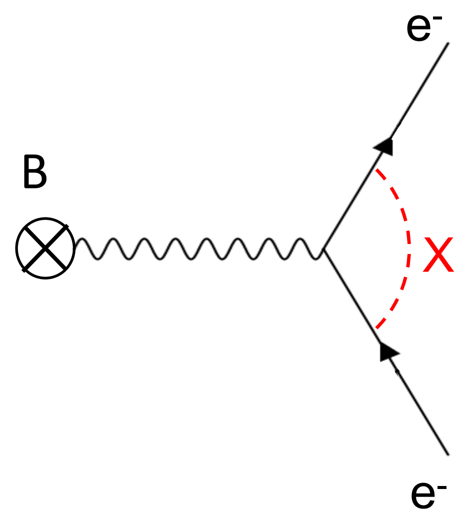






AMO picture





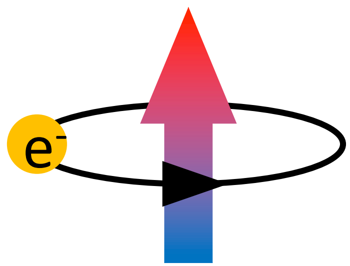
$$\delta\omega = \frac{\omega}{Q} = \frac{1}{\tau}$$

→clock measurement for new physics search

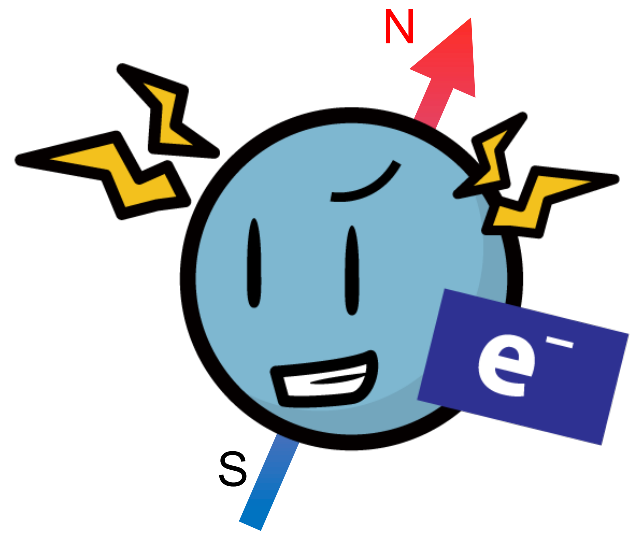
Magnetic Dipole Moment (MDM)

- Magnetic moment of an orbiting charge

angular momentum $\boldsymbol{L}$

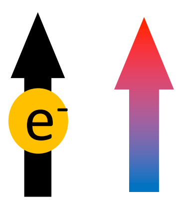


$$\boldsymbol{\mu} = \frac{-e}{2m}\boldsymbol{L}$$



- An electron has a spin $\boldsymbol{S} = \frac{\hbar}{2}$

$\boldsymbol{S} = \frac{\hbar}{2}$



$$\boldsymbol{\mu} = \frac{-e}{2m} \times \frac{\hbar}{2} \; ? \times g$$

$g_e/2$= 1.001 159 652 180…

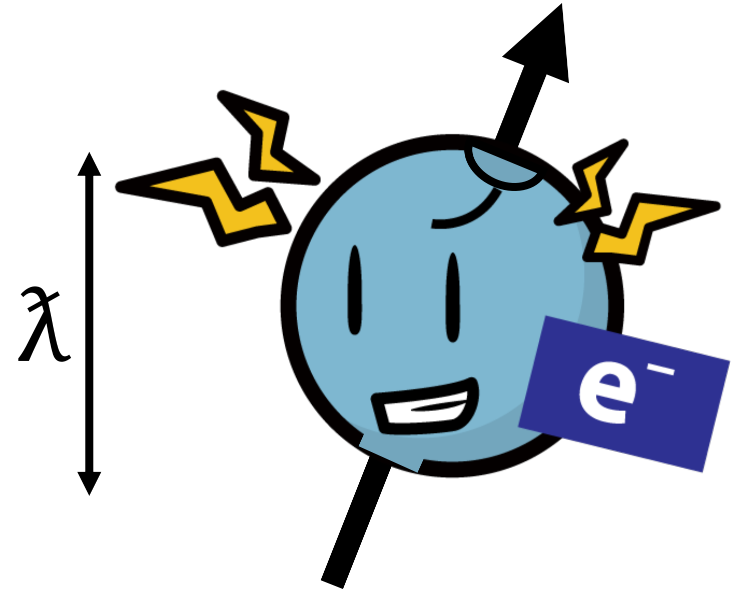
>13,000 Feynman diagrams

Electric Dipole Moment (EDM)

- electron's Compton length
  $\lambdabar = \hbar/mc$

- EDM's natural size should be
  $d_e \sim \lambdabar \times e \times \mathcal{O}(1)$

  I take the last constant to be 1/4
  (will explain why shortly)



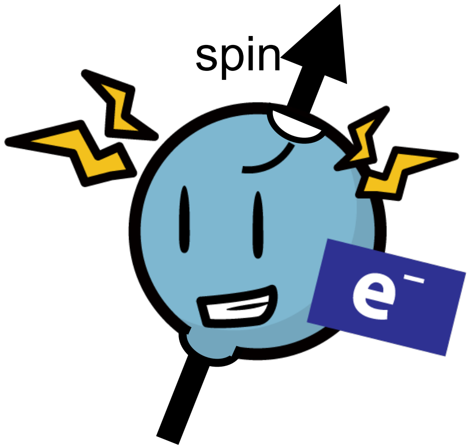
unit: charge × length

- so, $d_e = e\lambdabar/4 = e\hbar/4mc$ ~~?~~ $\times\eta$

$|\eta| < 1.1\times10^{-18}$ (ACME II, $|d_e| < 1.1\times10^{-29}$ e•cm)
$|\eta| < 4.4\times10^{-19}$ (JILA II, $|d_e| < 4.1\times10^{-30}$ e•cm)
SM Prediction: $|\eta| \leqq 10^{-24}$

What is η? Why so small?

$$\boldsymbol{\mu} = \frac{-e\hbar}{4m} \times g \qquad \boldsymbol{d_e} = \frac{-e\hbar}{4mc} \times \eta$$



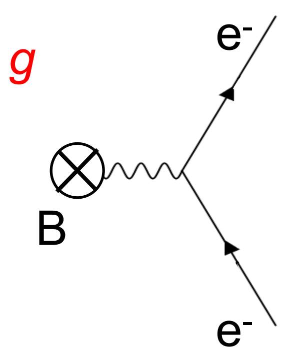
$$\mathcal{H} = -\boldsymbol{\mu} \cdot \vec{B} - \boldsymbol{d_e} \cdot \vec{E}$$

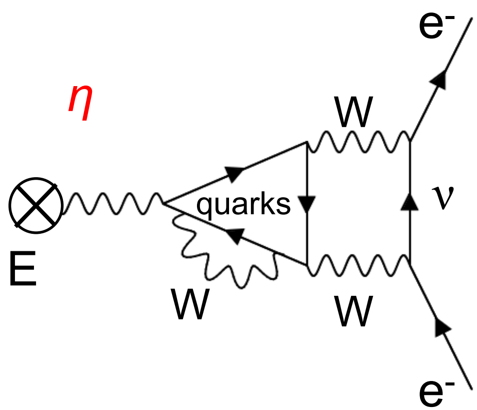
$$= \frac{e\hbar}{2m} \left(\frac{g}{2} \vec{\sigma} \cdot \vec{B} + \frac{\eta}{2} \vec{\sigma} \cdot \vec{E}/c \right)$$

Bohr magneton

EDM is protected by the Charge-Parity symmetry (CP symmetry)

required Feynman diagram in SM



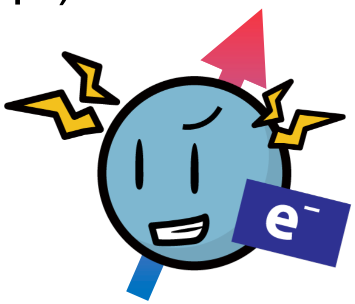


Electron/Muon MDM/EDM

Electron MDM

g/2(theory)= 1.001 159 652 180 25(10)

g/2(exp.)= 1.001 159 652 180 59(13)



13 digits

Muon MDM

g/2(theory)= 1.001 165 918 10(43)

white paper value

g/2(exp.)= 1.001 165 920 59(22)

10 digits

Electron EDM

$\eta/2(\text{theory}) < 10^{-24}$

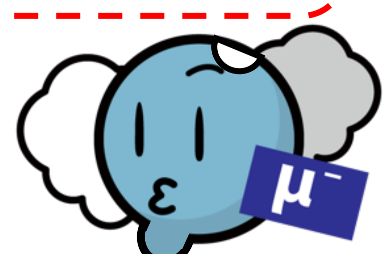
$\eta/2(\text{exp.}) < 10^{-18}$

Muon EDM

$\eta/2(\text{theory}) < 10^{-9}$

$\eta/2(\text{exp}) < 2 \times 10^{-7}$

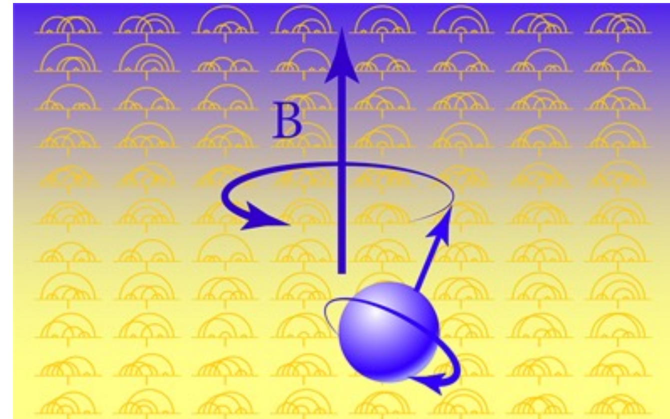
a little



Very Important Difference btw electron/muon

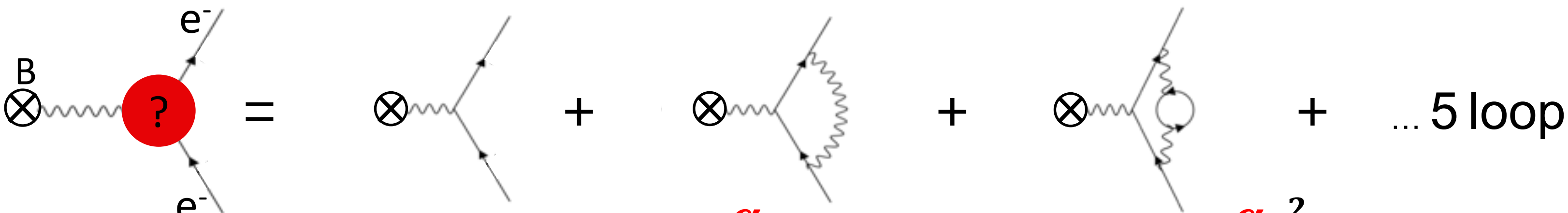
lifetime of electron is infinite!

Standard Model calculation



$g_e/2$(theory)= 1.001 159 652 180 25(10)

Most precise prediction of the Standard Model



$$g = 2 + \left(\frac{\alpha}{\pi}\right) + -0.656\ldots \times \left(\frac{\alpha}{\pi}\right)^2 + \cdots$$

fine structure constant
measured using Rb or Cs

error mostly
from α

QED contribution:	1.001 159 652 178 526 (093)
QCD contribution:	0.000 000 000 001 693 (012)
weak contribution:	0.000 000 000 000 031 (000)

Two Inconsistent α Measurements

$$\alpha^{-1}(\mathrm{Rb}) = 137.035\,999\,\underline{206\,(11)}$$
$$\alpha^{-1}(\mathrm{Cs}) = 137.035\,999\,\underline{046\,(27)}$$

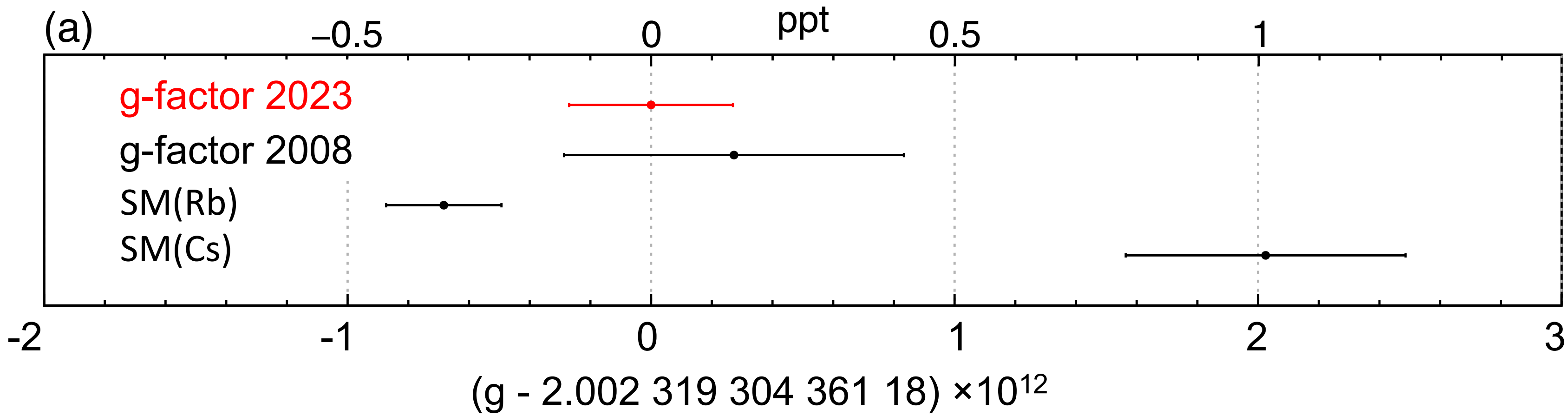
probably experimental reason?

S. Guellati-Khélifa (LKB, Rb)

H. Mueller (Berkeley, Cs)

new projects using Sr and Yb are being prepared
(private communication, Oxford, Northwestern)

Electron g's Current Situation



XF, et al, Phys. Rev. Lett. **130**, 071801 (2023)

α discrepancy contribution is negligible
in muon's g-factor
δa_{μ}(from α) ~0.1×10^{-11}

SM calculation

T. Kinoshita

M. Nio

S. Laporta

S. Volkov

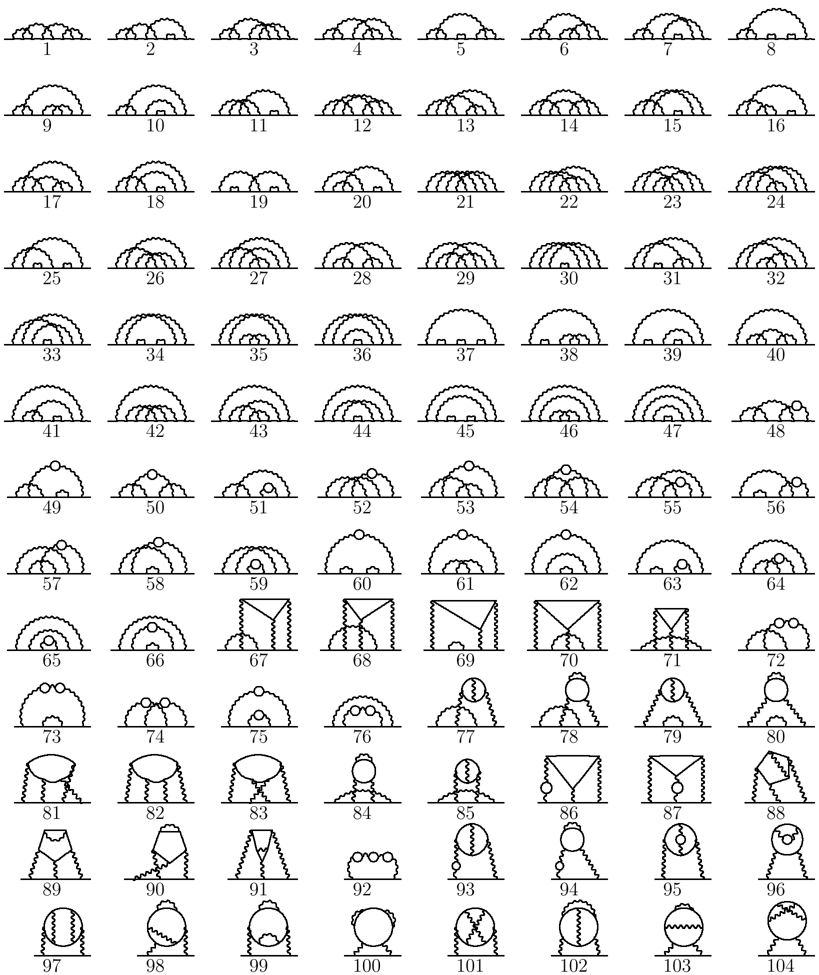
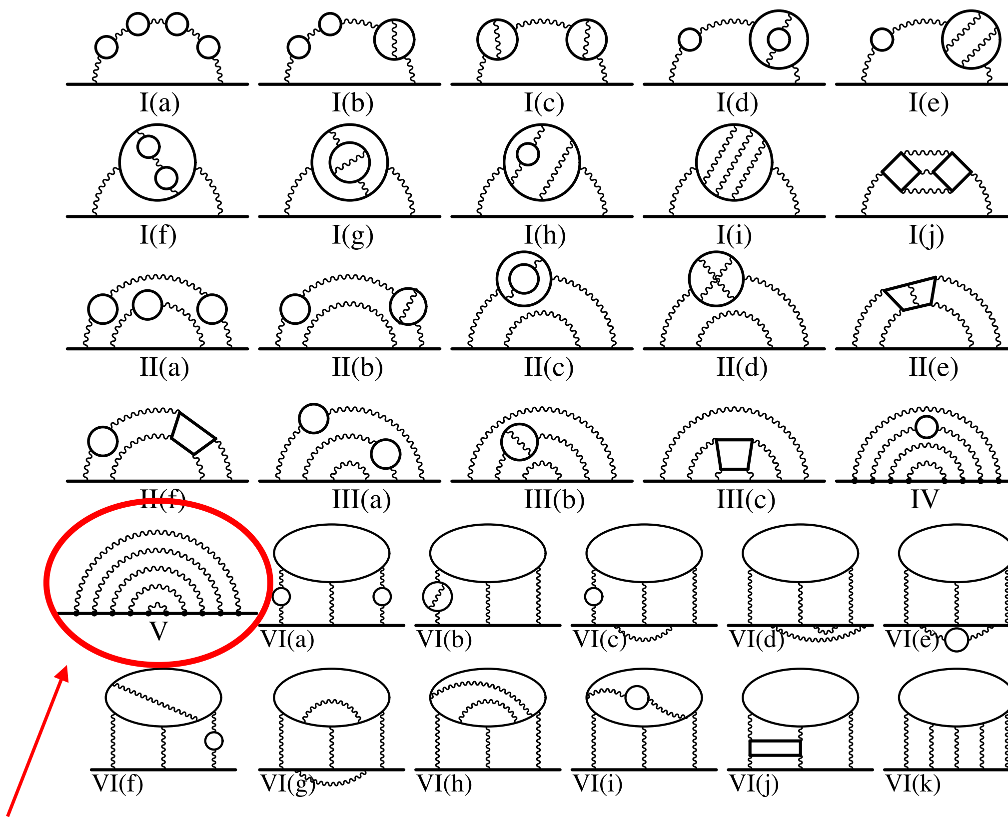
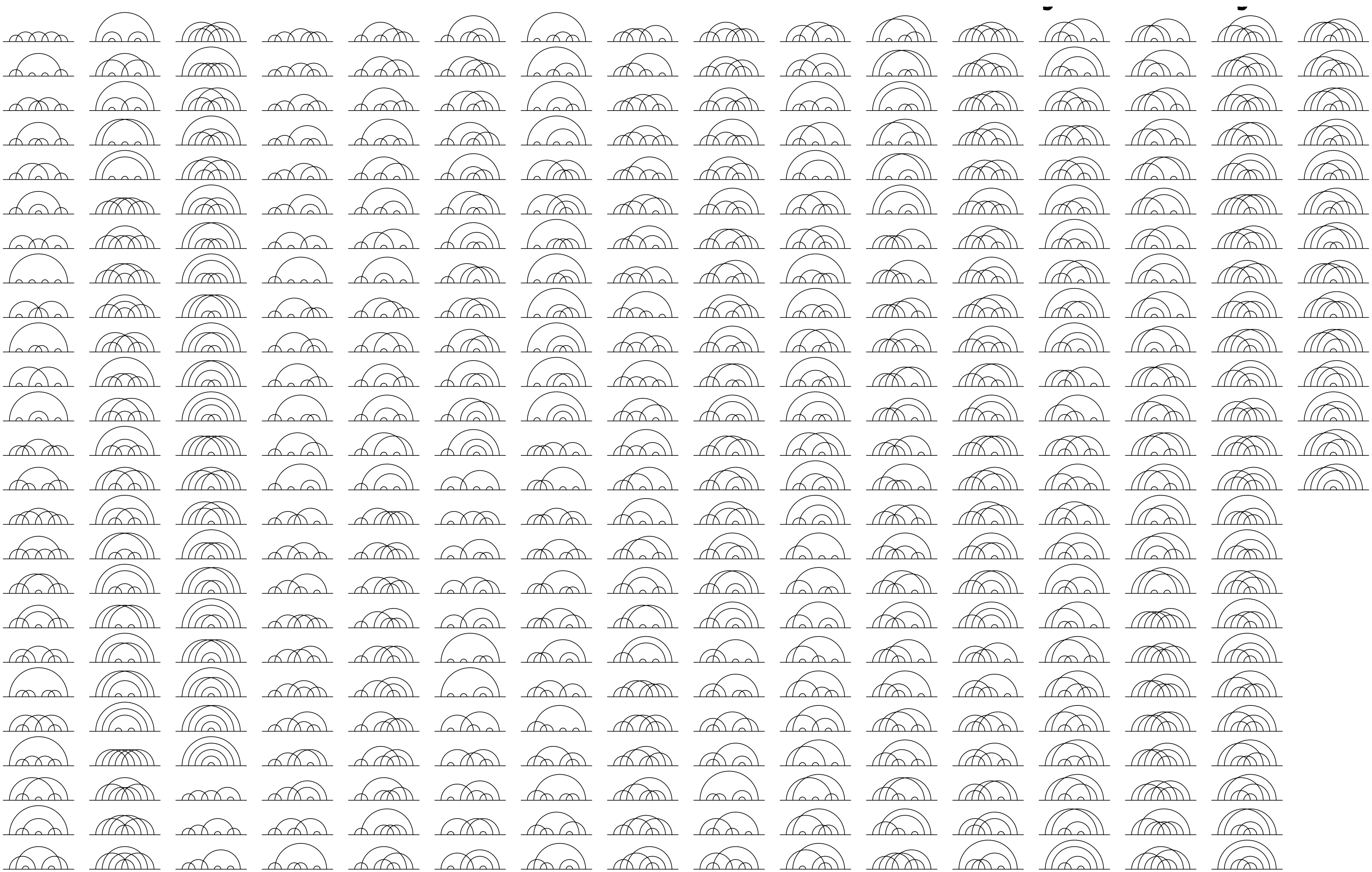


Fig. 1. The 4-loop self-mass diagrams.



I heard this type is most difficult

5 loop



What is an ideal g-factor measurement?

- Perfect B field
  very very homogeneous
  very very stable

electron is trying to realize them using an ion trap

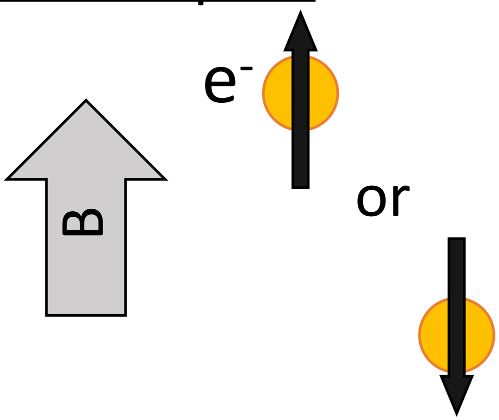
- Perfectly controlled particle's motion
  isolated in free space
  no movement
  isolated from environment

- high statistics
  many particles, not interacting with each other
  or perfectly controlled interaction (spin squeezing?)

not yet
long shot

Principle of g-factor measurement

In free space



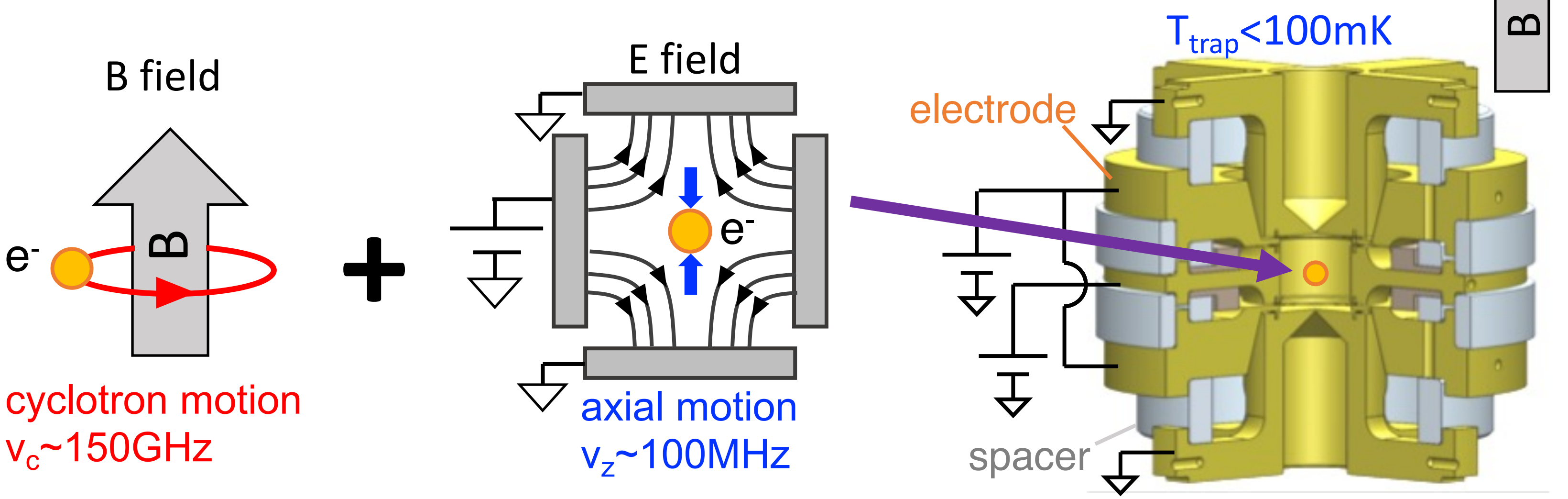
$$\Delta E_s = 2\mu \cdot B = \frac{g}{2} \times \frac{\hbar e B}{m}$$

spin precession energy $h\nu_s$

cyclotron motion energy $h\nu_c$

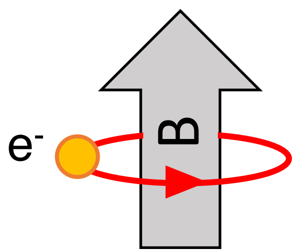
$$\frac{g}{2} = \frac{\nu_s}{\nu_c}$$

In a Penning trap



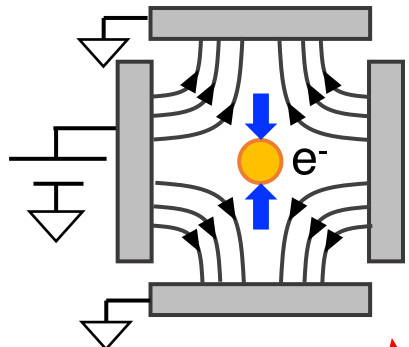
Electron's motion in a Penning Trap

magnetic field

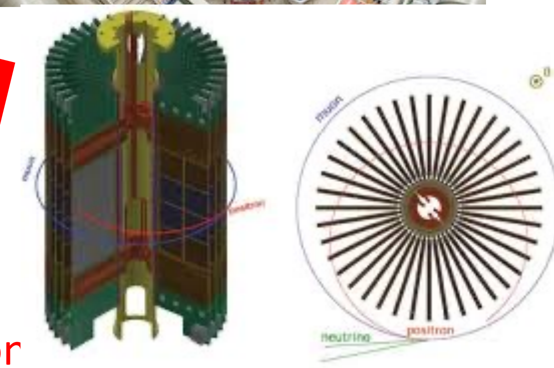


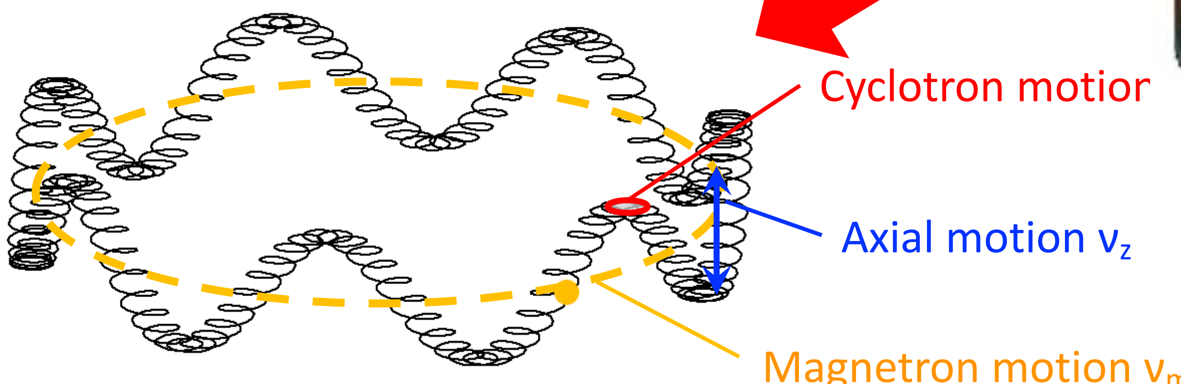
+

electric field



similar?





e.g. B=5.3T, V=33V

ν_c~150GHz >> ν_z~100MHz >> ν_m~50kHz

$\nu_s = \nu_c \times g/2$ ~150.17 GHz

Electron g-factor's direction

1. use single electron
   - Coulomb interaction is too large!

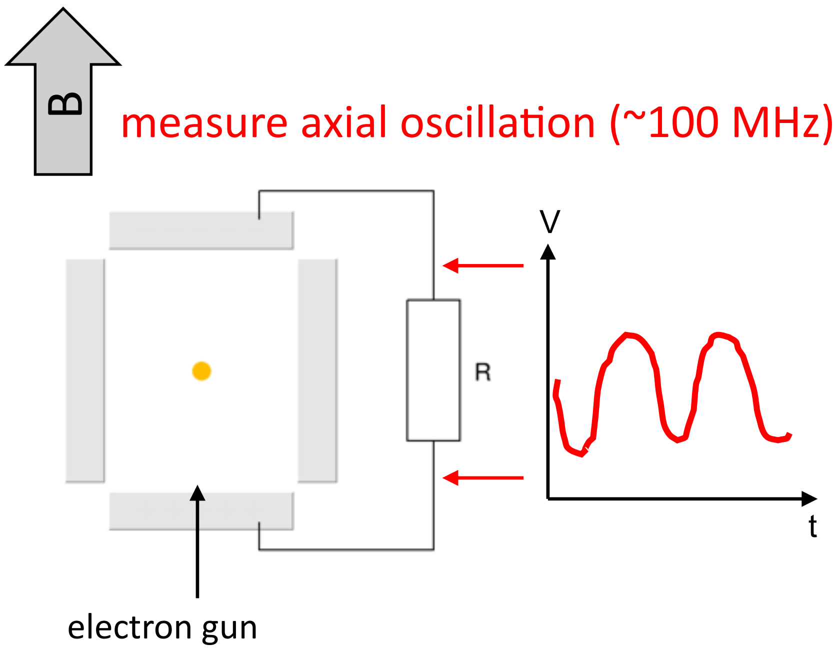
2. cool the motion as much as possible
   - suppressed systematic shifts

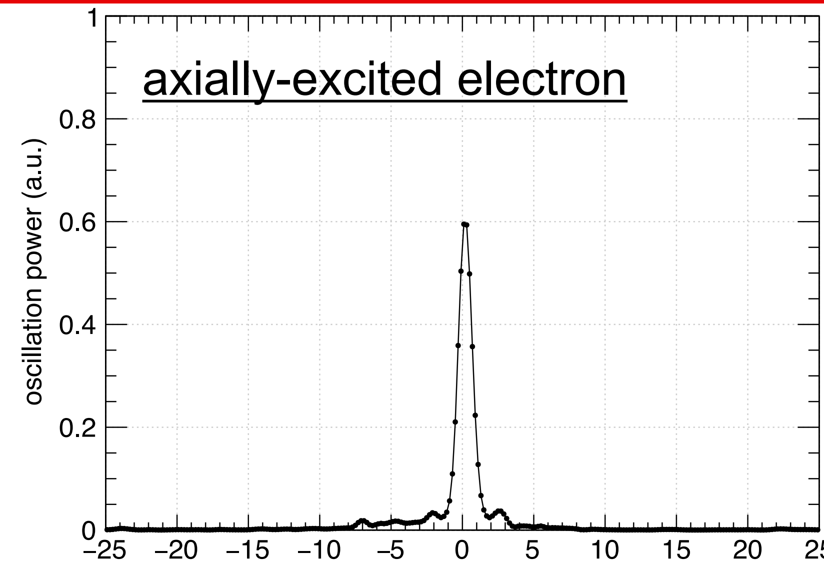
very Atomic Physics approach
(clock-approach)

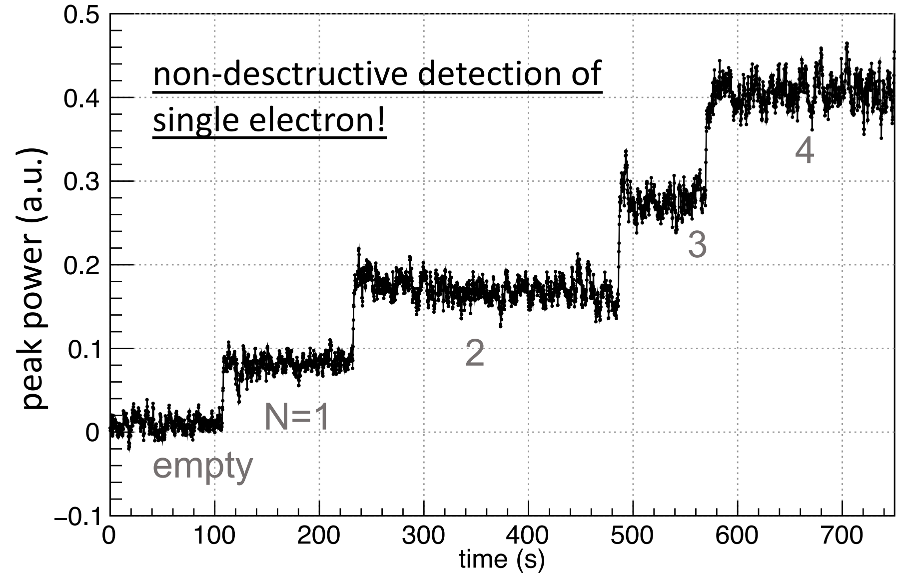
3. non-destructive detection
   - repeatability, reproducibility, high duty cycle

Electron Detection with Axial Motion

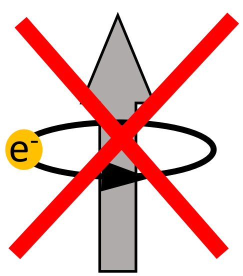
measure axial oscillation (~100 MHz)







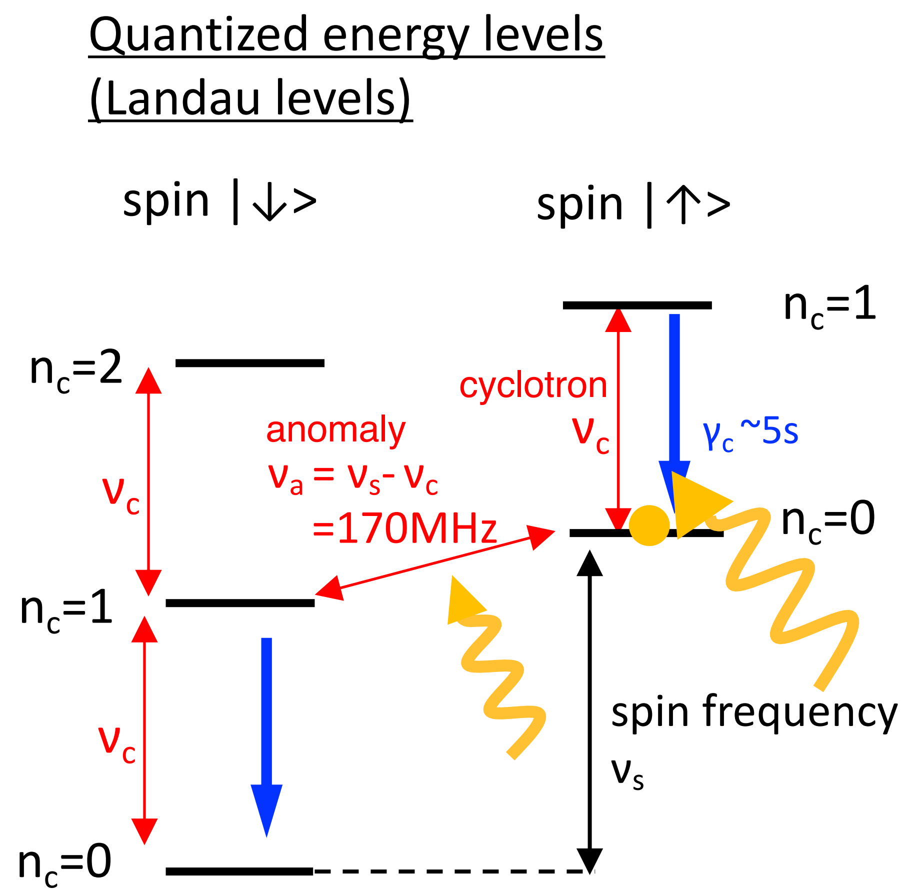
Quantum Cyclotron Motion



ν_c =150 GHz

$h\nu_c/k_B$ =7.2K

T_{trap}=100mK



Why Measure ν_a, not ν_s?

$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_a}{\nu_c}$$

~1.001

😣 measure this with 10^{-13} precision

🤗 measure this with 10^{-10} precision

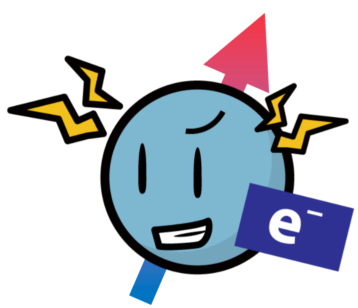
Quiz:
I am going to show you two kids.
Tell me which one is taller?

- measure the difference
- measure simultaneously
- measure at the same location

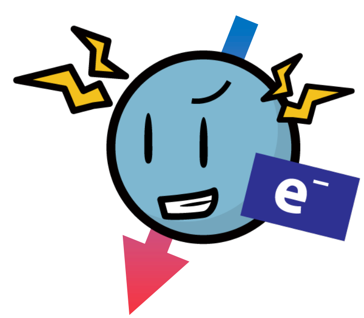
Disadvantage of electorn: spin measurement

- Unlike muon, measuring electron’s spin is not obvious!

electron→ need to detect magnetic interaction

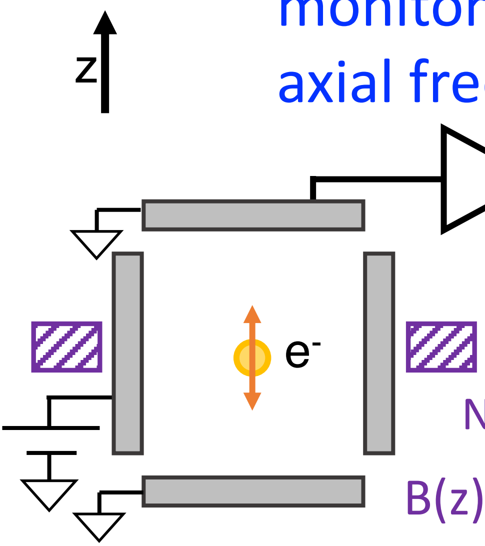


or



How to Detect Transition?

monitor
axial frequency ν_z



$B(z) = B_0 + B_2 z^2$

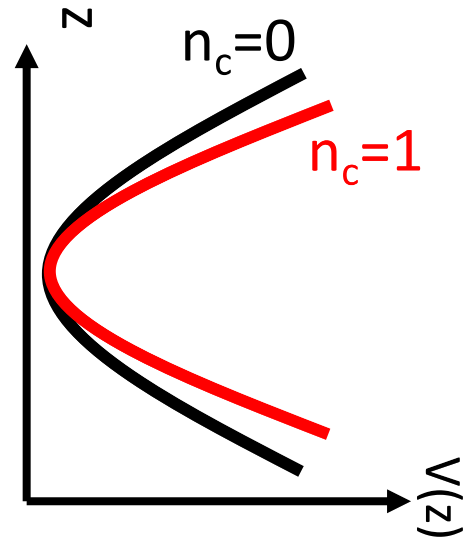
potential along *z*

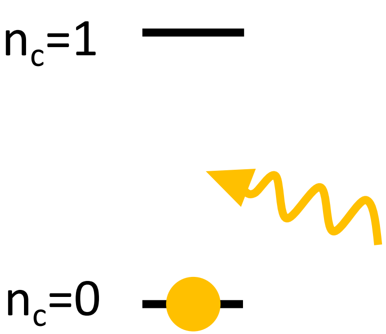
$$V(z) = eV_2 z^2 + \mu_{tot} B_2 z^2$$

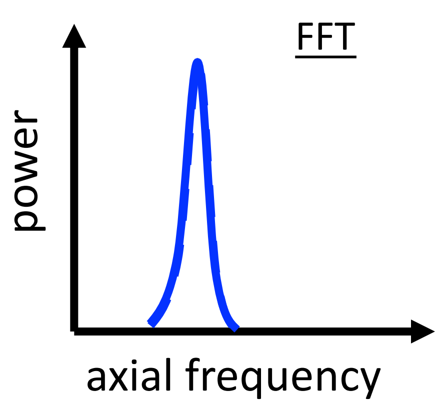
electric potential

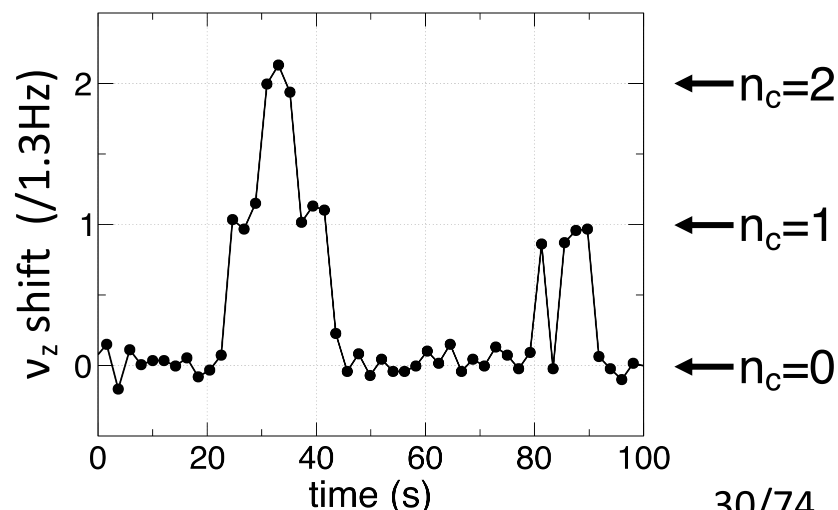
magnetic potential

$\mu_{tot} \propto n_c$

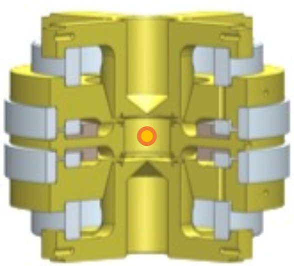




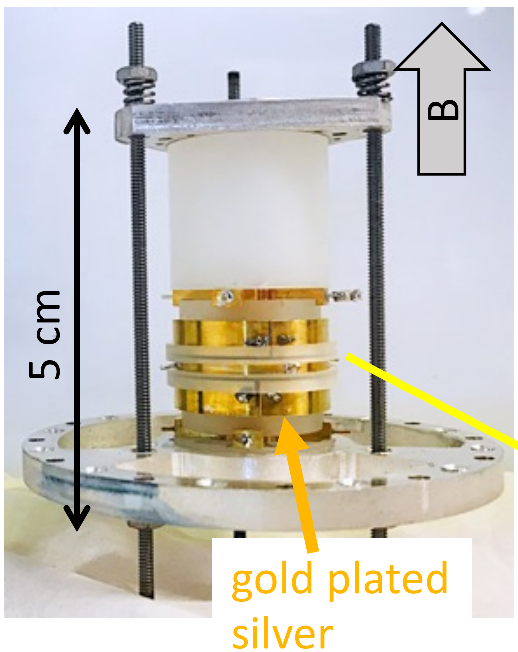




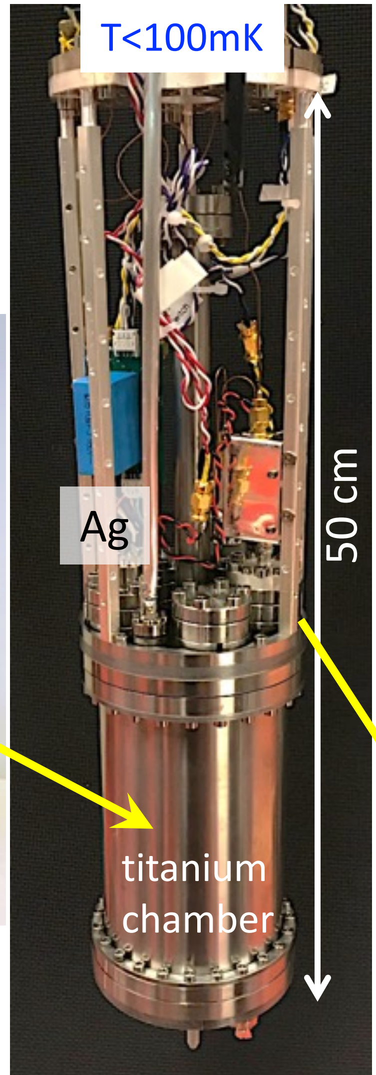
Apparatus



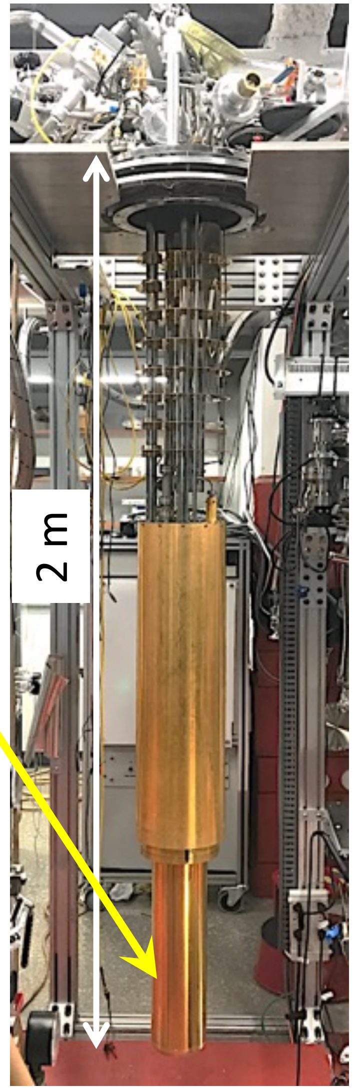
Penning trap



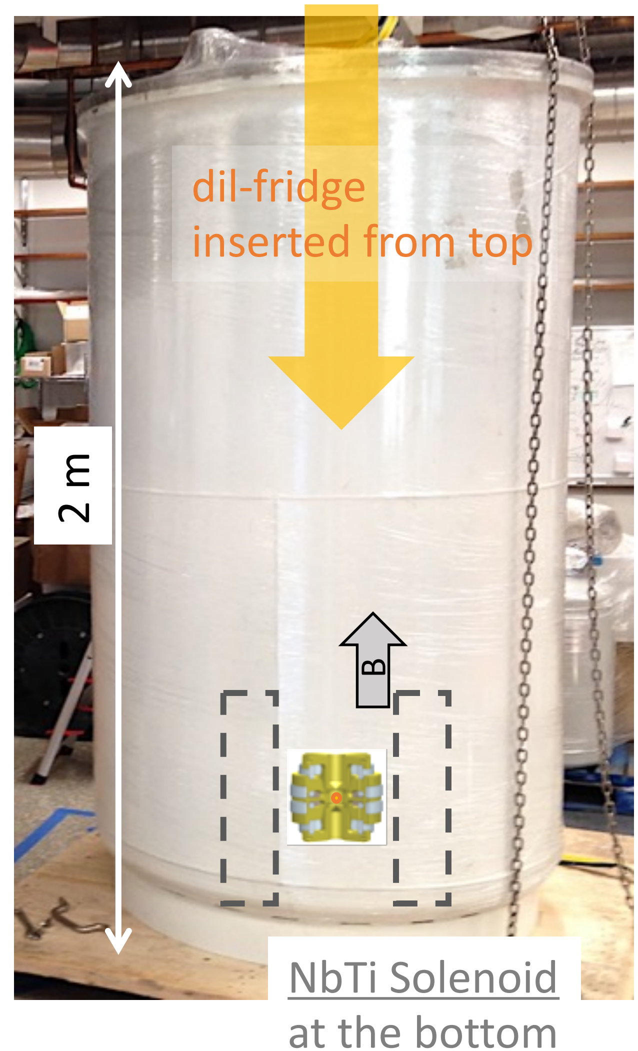
vacuum chamber



dilution fridge



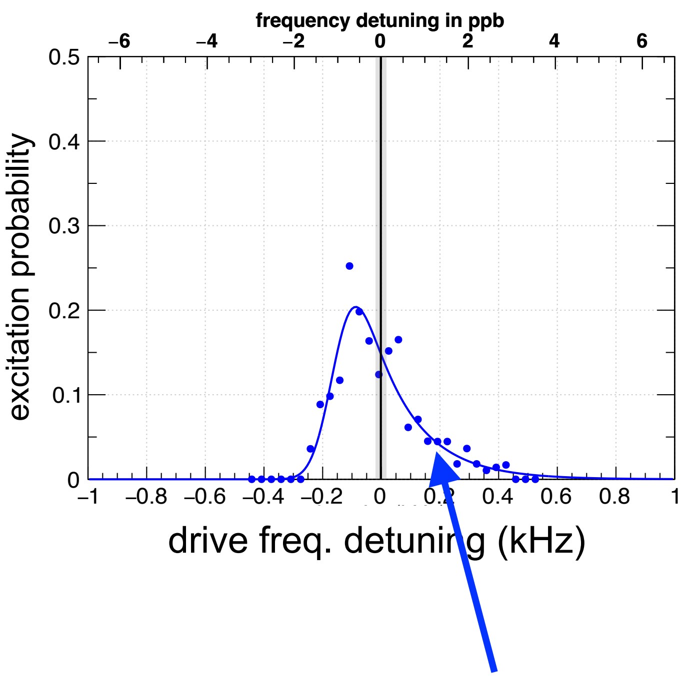
LHe Dewar with a magnet



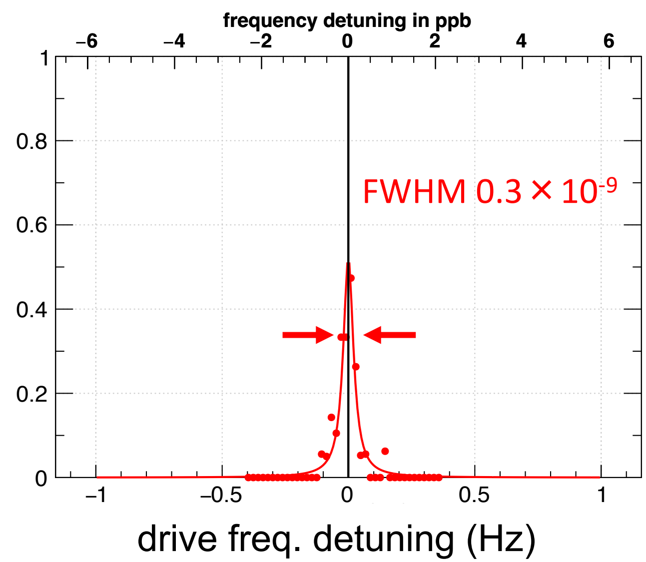
Spectroscopy
Transition Prob. vs Drive Freq

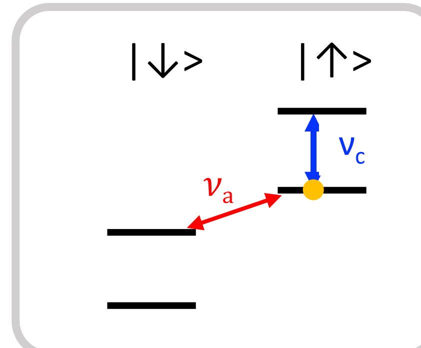
Apply drive, measure cyclotron and anomaly transition prob.

cyclotron



anomaly



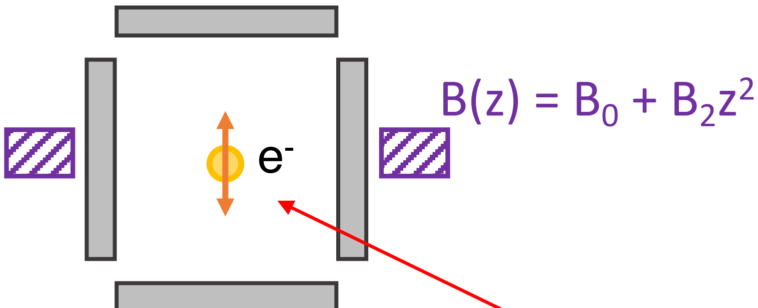


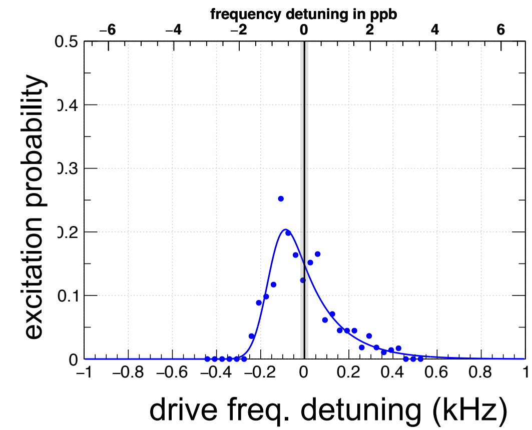
$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_a}{\nu_c}$$

linewidth dominated by axial motion’s temperature

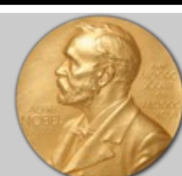
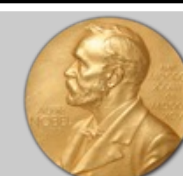
L. S. Brown, PRL 52, 2013 (1984), X. Fan and G. Gabrielse, PRL **126** 070402 (2021)

Need ground state cooling!

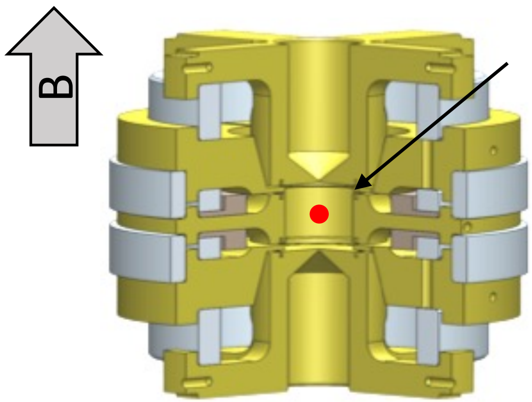




electron's thermal motion in magnetic field gradient dominates the linewidth

	first trap	Ground state cooling
ions	1953 Paul 	1989 Wineland 
electron	1959 Dehmelt 	never

Major Systematic Error: Cyclotron Image Charge Shift



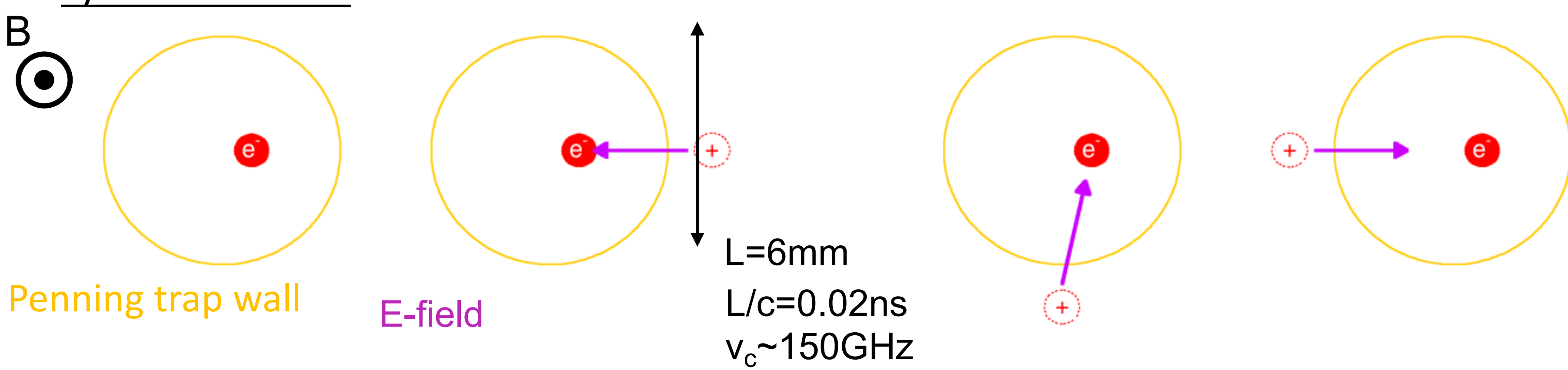
$$\frac{g}{2} = \frac{\nu_s}{\nu_c + \Delta\nu_c^{ICS}}$$

top view
cyclotron motion

positive image charge

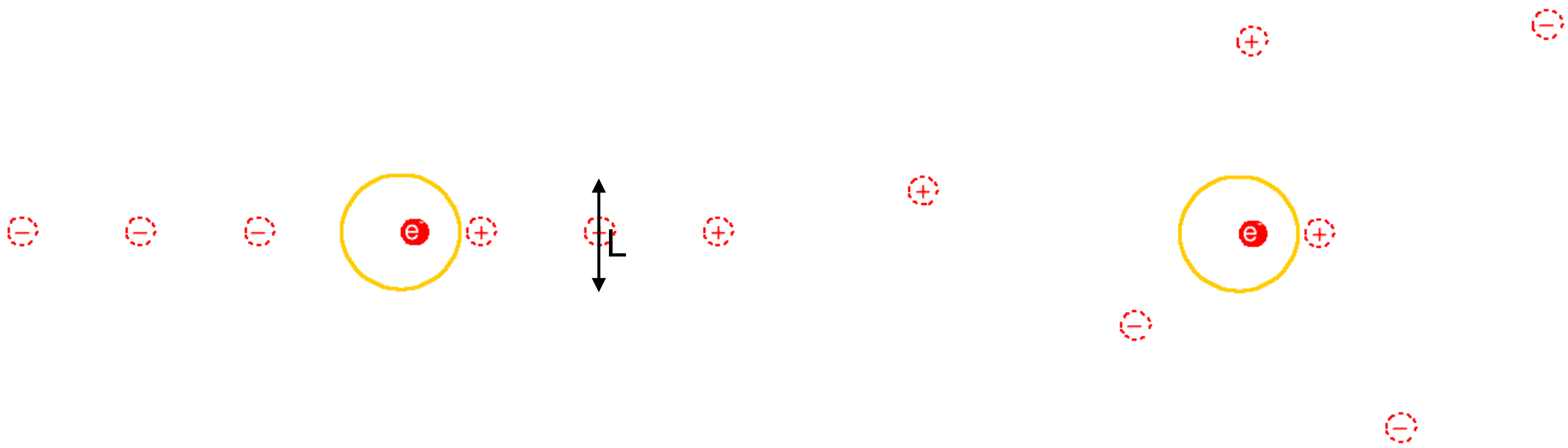
ν_c fast

ν_c very fast



Lowell S. Brown, et. al., Phys. Rev. Lett. 55, 44 (1985)

Image Charge of Image Charge…



ν_c = c/2L × n

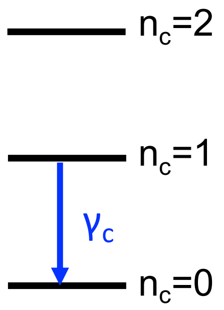
<u>large shift!</u>

ν_c ≠ c/2L × n

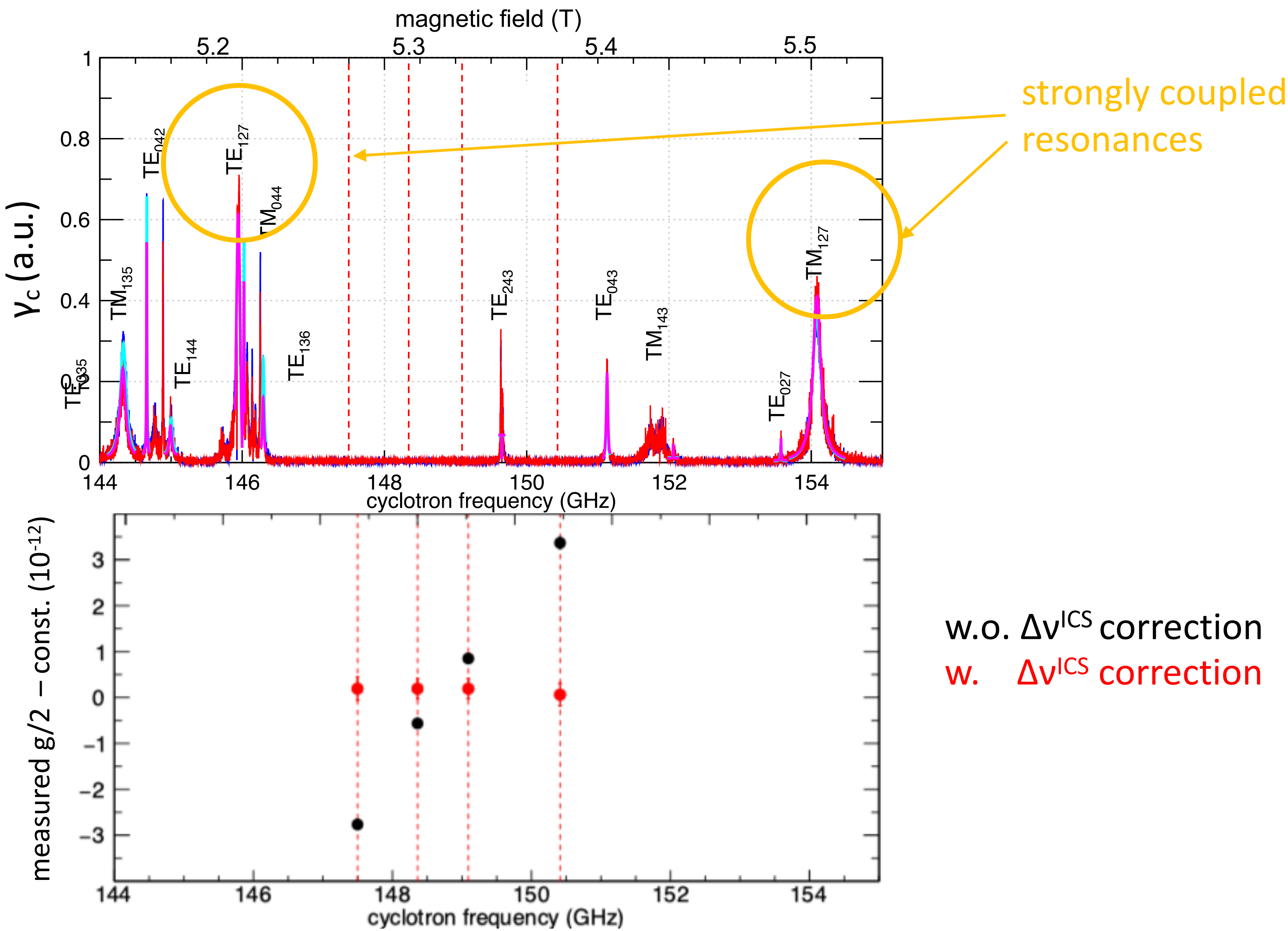
<u>small shift!</u>

- $\Delta\nu_c^{ICS}$ depends on trap cavity's resonance
  <u>=cavity QED</u>
  →measure cavity resonances and correct

Huge!

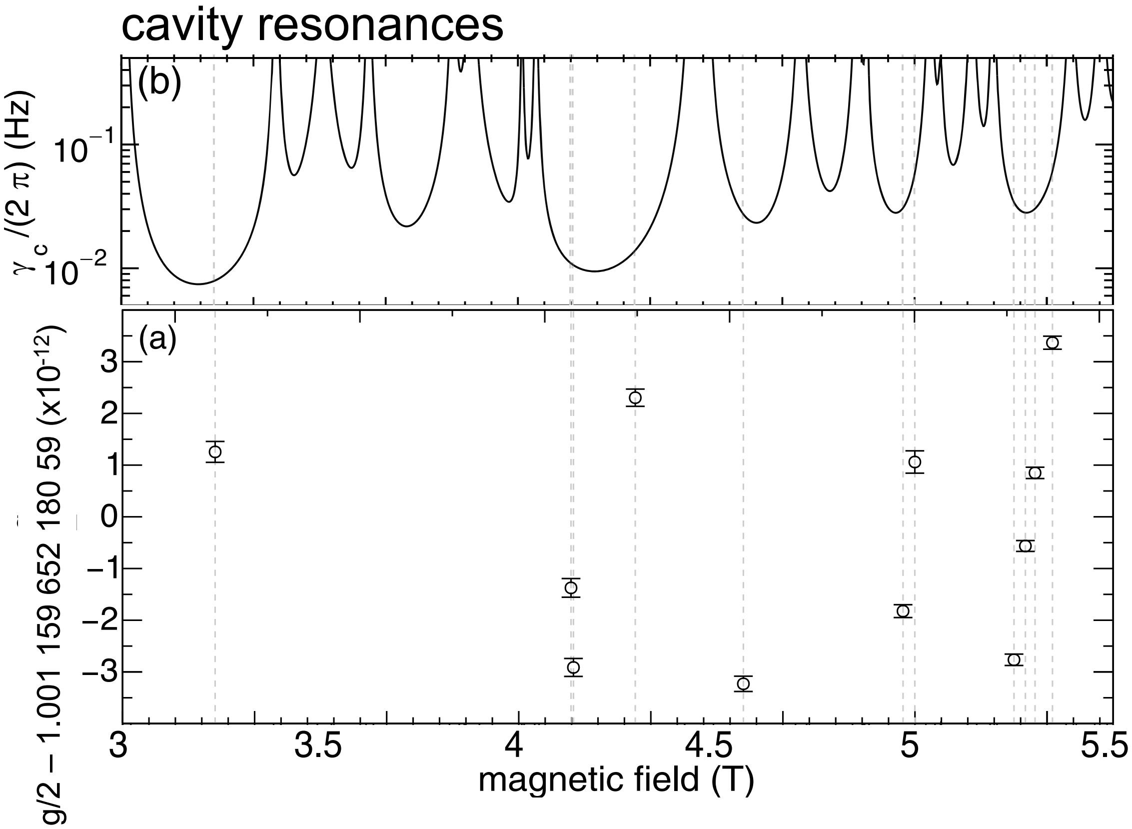


n_c=2
n_c=1
γ_c
n_c=0



magnetic field (T)
5.2
5.3
5.4
5.5
γ_c (a.u.)
1
0.8
0.6
0.4
0.2
0
TE_{042}
TE_{127}
TM_{044}
TM_{135}
TE_{035}
TE_{144}
TE_{136}
TE_{243}
TE_{043}
TM_{143}
TE_{027}
TM_{127}
144
146
148
150
152
154
cyclotron frequency (GHz)
strongly coupled resonances
measured g/2 – const. (10^{-12})
3
2
1
0
-1
-2
-3
144
146
148
150
152
154
cyclotron frequency (GHz)
w.o. $\Delta\nu^{ICS}$ correction
w. $\Delta\nu^{ICS}$ correction

Measurements at Different Fields



○ before image charge correction

● after image charge correction

χ^2/ndf=13.05/10, p=0.22

<u>average 11 fields from 3 T to 5.5T</u>

g/2 = 1.001 159 652 180 59 (13)

α^{-1} = 137.035 999 166 (15)

Reporting Precision in δg or δa?

$$a \equiv \frac{g}{2} - 1$$

~0.001 (for a)

~1.001 (for $\frac{g}{2}$)

PHYSICAL REVIEW LETTERS **130,** 071801 (2023)

Measurement of the Electron Magnetic Moment

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

a_e=1159 652 180 59 (13) × 10^{-14} (0.11 ppb)

X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]

VS

PHYSICAL REVIEW LETTERS **131,** 161802 (2023)

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

$g_\mu/2$=1.001 165 920 55 (24) (0.24 ppb)

$$a_\mu(\text{FNAL}) = 116\,592\,055(24) \times 10^{-11} \qquad (0.20\ \text{ppm}),$$

D. P. Aguillard,[33] T. Albahri,[30] D. Allspach,[7] A. Anisenkov,[4,a] K. Badgley,[7] S. Baeßler,[35,b] I. Bailey,[17,c] L. Bailey,[27] V. A. Baranov,[15,d] E. Barlas-Yucel,[28] T. Barrett,[6] E. Barzi,[7] F. Bedeschi,[10] M. Berz,[18] M. Bhattacharya,[7] H. P. Binney,[36] P. Bloom,[19] J. Bono,[7] E. Bottalico,[30] T. Bowcock,[30] S. Braun,[36] M. Bressler,[32] G. Cantatore,[12,e] R. M. Carey,[2] B. C. K. Casey,[7] D. Cauz,[26,f] R. Chakraborty,[29] A. Chapelain,[6] S. Chappa,[7] S. Charity,[30] C. Chen,[23,22] M. Cheng,[28] R. Chislett,[27] Z. Chu,[22,g] T. E. Chupp,[33] C. Claessens,[36] M. E. Convery,[7] S. Corrodi,[1] L. Cotrozzi,[10,h] J. D. Crnkovic,[7] S. Dabagov,[8,i] P. T. Debevec,[28] S. Di Falco,[10] G. Di Sciascio,[11] B. Drendel,[7] A. Driutti,[10,h] V. N. Duginov,[15,d] M. Eads,[20] A. Edmonds,[2] J. Esquivel,[7] M. Farooq,[33] R. Fatemi,[29] C. Ferrari,[10,j] M. Fertl,[14] A. T. Fienberg,[36] A. Fioretti,[10,j] D. Flay,[32] S. B. Foster,[2] H. Friedsam,[7] N. S. Froemming,[20] C. Gabbanini,[10,j] I. Gaines,[7] M. D. Galati,[10,h] S. Ganguly,[7] A. Garcia,[36] J. George,[32,k] L. K. Gibbons,[6] A. Gioiosa,[25,l] K. L. Giovanetti,[13] P. Girotti,[10] W. Gohn,[29] L. Goodenough,[7] T. Gorringe,[29] J. Grange,[33] S. Grant,[1,27] F. Gray,[21] S. Haciomeroglu,[5,m] T. Halewood-Leagas,[30] D. Hampai,[8] F. Han,[29] J. Hempstead,[36] D. W. Hertzog,[36] G. Hesketh,[27] E. Hess,[10] A. Hibbert,[30] Z. Hodge,[36] K. W. Hong,[35] R. Hong,[29,1] T. Hu,[23,22] Y. Hu,[22,g] M. Iacovacci,[9,n] M. Incagli,[10] P. Kammel,[36] M. Kargiantoulakis,[7] M. Karuza,[12,o] J. Kaspar,[36] D. Kawall,[32] L. Kelton,[29] A. Keshavarzi,[31] D. S. Kessler,[32] K. S. Khaw,[23,22] Z. Khechadoorian,[6] N. V. Khomutov,[15] B. Kiburg,[7] M. Kiburg,[7,19] O. Kim,[34] N. Kinnaird,[2] E. Kraegeloh,[33] V. A. Krylov,[15] N. A. Kuchinskiy,[15] K. R. Labe,[6] J. LaBounty,[36] M. Lancaster,[31] S. Lee,[5] B. Li,[22,1,p] D. Li,[22,q] L. Li,[22,g] I. Logashenko,[4,a] A. Lorente Campos,[29] Z. Lu,[22,g] A. Lucà,[7] G. Lukicov,[27] A. Lusiani,[10,r] A. L. Lyon,[7] B. MacCoy,[36] R. Madrak,[7] K. Makino,[18] S. Mastroianni,[9] J. P. Miller,[2] S. Miozzi,[11] B. Mitra,[34] J. P. Morgan,[7] W. M. Morse,[3] J. Mott,[7,2] A. Nath,[9,n] J. K. Ng,[23,22] H. Nguyen,[7] Y. Oksuzian,[1] Z. Omarov,[16,5] R. Osofsky,[36] S. Park,[5] G. Pauletta,[26,s] G. M. Piacentino,[25,t] R. N. Pilato,[30] K. T. Pitts,[28,u] B. Plaster,[29] D. Počanić,[35] N. Pohlman,[20] C. C. Polly,[7] J. Price,[30] B. Quinn,[34] M. U. H. Qureshi,[14] S. Ramachandran,[1,k] E. Ramberg,[7] R. Reimann,[14] B. L. Roberts,[2] D. L. Rubin,[6] L. Santi,[26,f] C. Schlesier,[28,v] A. Schreckenberger,[7] Y. K. Semertzidis,[5,16] D. Shemyakin,[4,a] M. Sorbara,[11,w] D. Stöckinger,[24] J. Stapleton,[7] D. Still,[7] C. Stoughton,[7] D. Stratakis,[7] H. E. Swanson,[36] G. Sweetmore,[31] D. A. Sweigart,[6] M. J. Syphers,[20] D. A. Tarazona,[6,30,18] T. Teubner,[30] A. E. Tewsley-Booth,[29,33] V. Tishchenko,[3] N. H. Tran,[2,x] W. Turner,[30] E. Valetov,[18] D. Vasilkova,[27,30] G. Venanzoni,[30,l] V. P. Volnykh,[15] T. Walton,[7] A. Weisskopf,[18] L. Welty-Rieger,[7] P. Winter,[1] Y. Wu,[1] B. Yu,[34] M. Yucel,[7] Y. Zeng,[23,22] and C. Zhang[30]

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C.M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[14,*], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[18,*], C.T.H. Davies[19], M. Della Morte[20], S.I. Eidelman[21,22,*], A.X. El-Khadra[23,24,*], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[1], M. Hayakawa[31,2], G. Herdoíza[32], D.W. Hertzog[33], A. Hoecker[34], M. Hoferichter[14,35,*], B.-L. Hoid[36], R.J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[26,37,*], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M.K. Marinković[46,47], P. Masjuan[48,49], A.S. Meyer[37], H.B. Meyer[12,13], T. Mibe[1,*], K. Miura[12,13,3], S.E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[12,*], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C.F. Redmer[12], B.L. Roberts[57,*], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[60,*], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18], M.N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C.A. Dominguez[67], A.E. Dorokhov[68], V.P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C.S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J.R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A.S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P.B. Mackenzie[24], W.J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E.T. Neil[77], A.V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A.E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E.P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A.S. Zhevlakov[78]

Why I chose to use g (not a)

1. fair comparison with EDM?

$$\mathcal{H} = -\boldsymbol{\mu} \cdot \vec{B} - \boldsymbol{d_e} \cdot \vec{E}$$

$$= \mu_B \left(\frac{g}{2} \vec{\sigma} \cdot \vec{B} + \frac{\eta}{2} \vec{\sigma} \cdot \frac{\vec{E}}{c} \right)$$

$$= \mu_B \left((1 + a) \vec{\sigma} \cdot \vec{B} + \frac{\eta}{2} \vec{\sigma} \cdot \frac{\vec{E}}{c} \right)$$

Why I chose to use g (not a)

2. ICS directly shifts g (and not a)

$$\frac{g}{2} = \frac{\nu_s}{\nu_c + \Delta\nu_c^{ICS}} \cong \frac{\nu_s}{\nu_c} \times \left(1 - \frac{\Delta\nu_c^{ICS}}{\nu_c}\right)$$

~10^{-13}

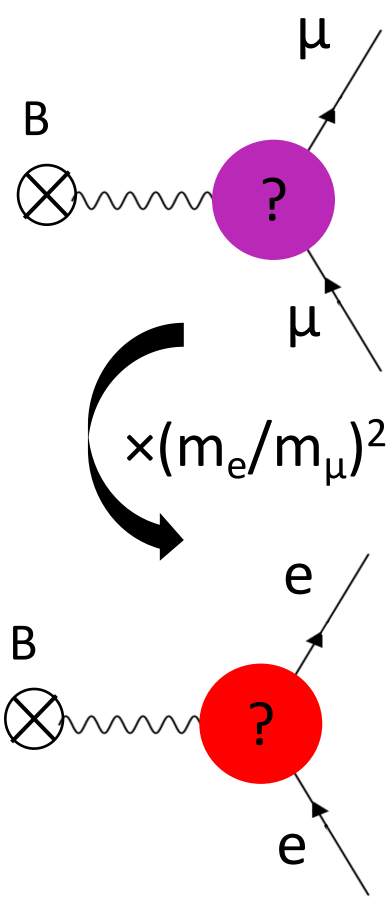
$$\frac{\Delta g}{g} = \frac{\Delta\nu_c^{ICS}}{\nu_c}$$

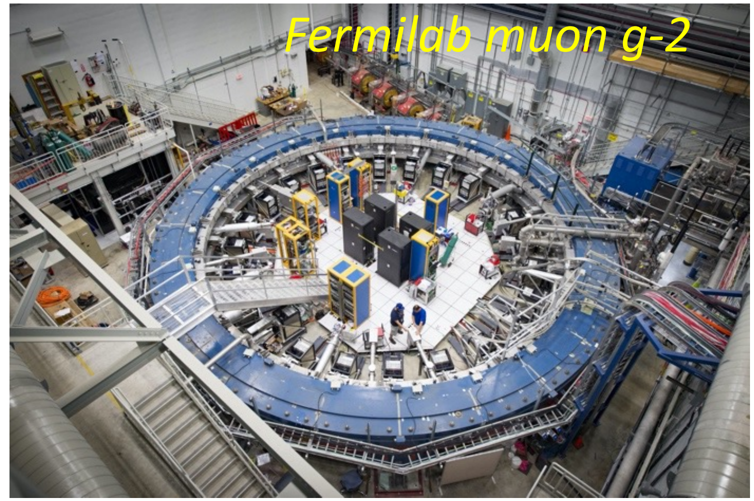
or

$$\frac{\Delta a}{a} = \frac{2}{g-2}\frac{\Delta\nu_c^{ICS}}{\nu_c}$$

i.e.
For some effects that shift only one of ν_c and ν_s using g seems more straightforward

Able to Check Muon g-2?





Phys. Rev. Lett. **131**, 161802 (2023) Physics reports **887**, 1 (2020)

$\Delta g_\mu = g_\mu^{\mathrm{exp}} - g_\mu^{\mathrm{theo.}} = 498(96) \times 10^{-11}$ 4.2σ

white paper value

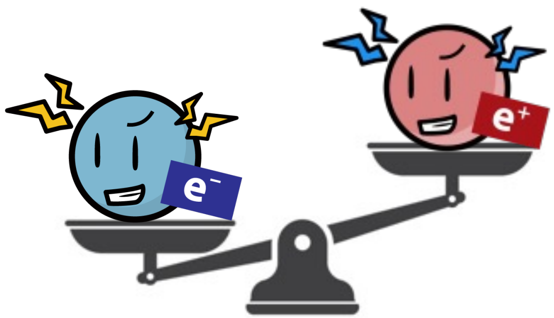
$\Delta g_e = \Delta g_\mu \times (m_e/m_\mu)^2 = 0.12(0.03) \times 10^{-12}$

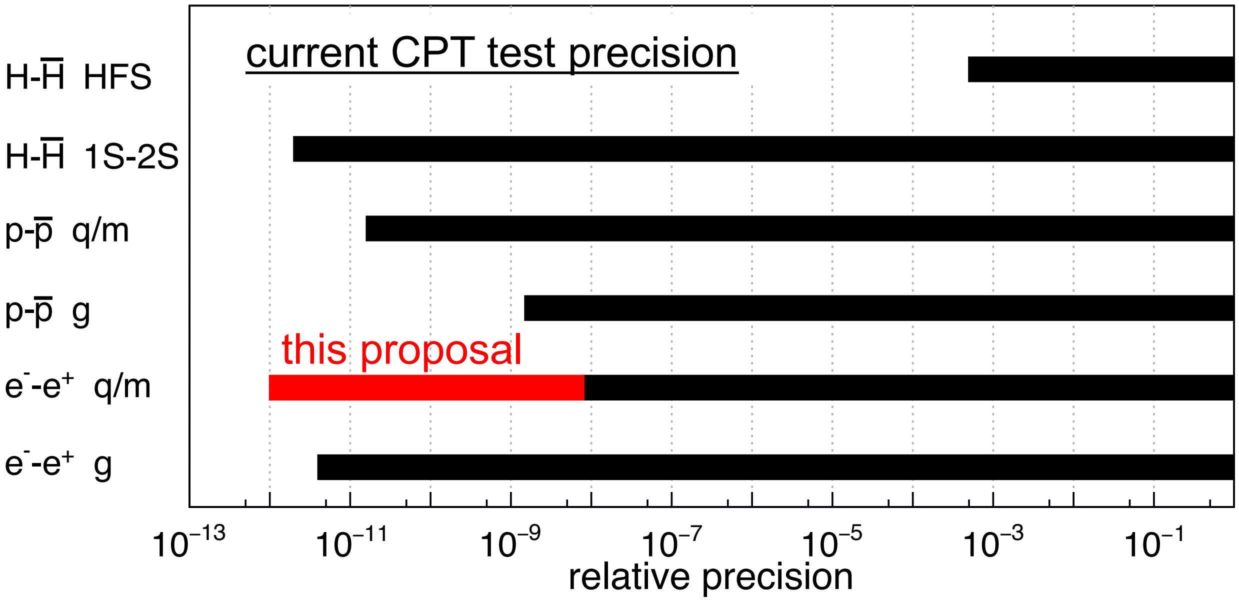
electron g-factor: $\sigma(g_e) = 0.26 \times 10^{-12}$

a factor of 5 improvement
to see muon's discrepancy

Positron's Measurement

- $g(e^+)$ measurement at the same precision
  - x30 better than ever, most precise lepton CPT test
- m_{e+}/m_{e-} at 10^{-11} precision
- x10,000 better than ever
- anti-gravity test at $\delta(\bar{g}/g)\sim0.03$ level





Collab. with Stefan Ulmer (HHU/CERN/RIKEN)

Take Home Messages

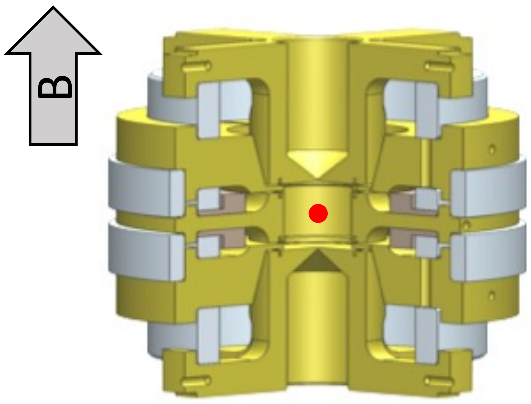
✓SIMPLIFY the experiment!

✓Think how to realize the IDEAL environment

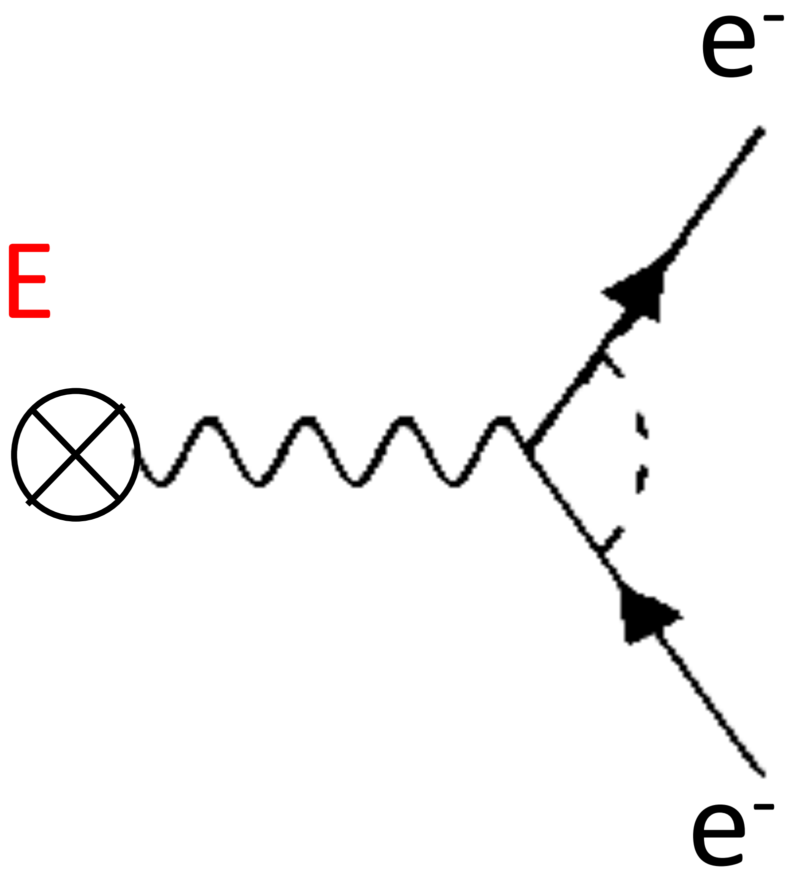
- Perfect B field
- Perfectly controlled particle's motion

partially realized

- high statistics   not realized yet



Electron Electric Dipole Moment

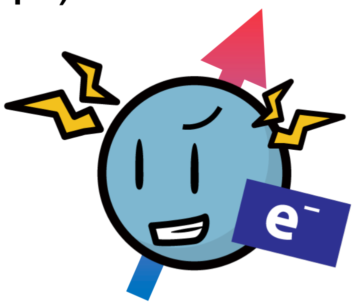


Electron/Muon MDM/EDM

Electron MDM

g/2(theory)= 1.001 159 652 180 25(10)

g/2(exp.)= 1.001 159 652 180 59(13)



Muon MDM

g/2(theory)= 1.001 165 918 10(43)

white paper value

g/2(exp.)= 1.001 165 920 59(22)

Electron EDM

$\eta/2$(theory) < 10^{-24}

$\eta/2$(exp.) < 10^{-18}

zero-consistent search (so far)

Muon EDM

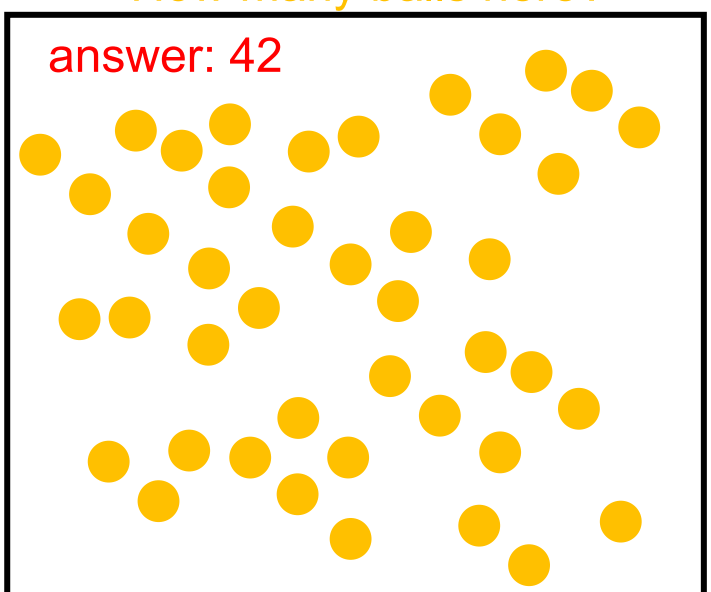
$\eta/2$(theory) < 10^{-9}

$\eta/2$(exp) < 2×10^{-7}

Electron EDM is a zero-consistent measurement

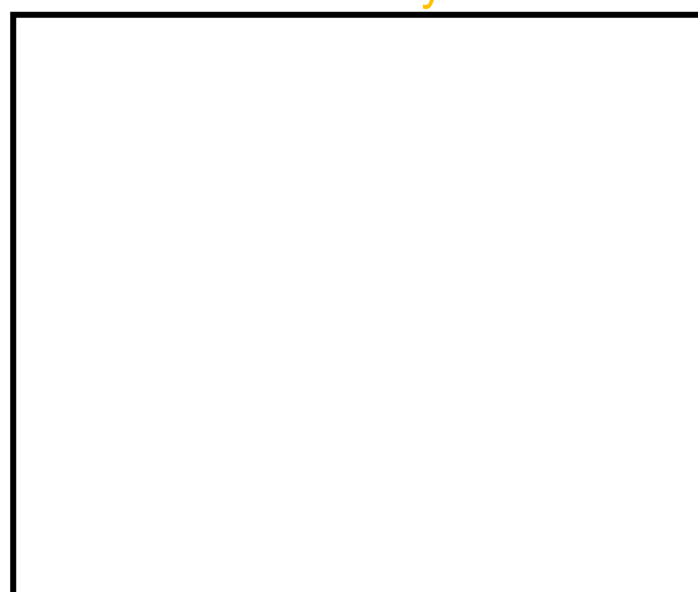
Measuring non-zero (g-factor)

How many balls here?



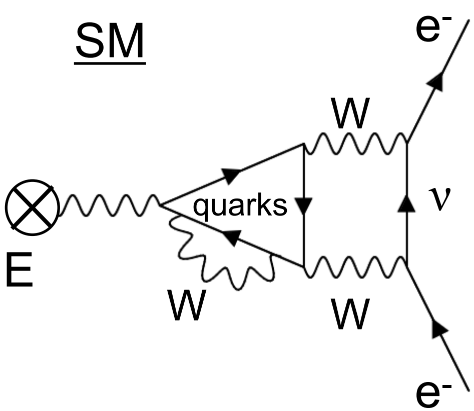
Measuring zero (EDM)

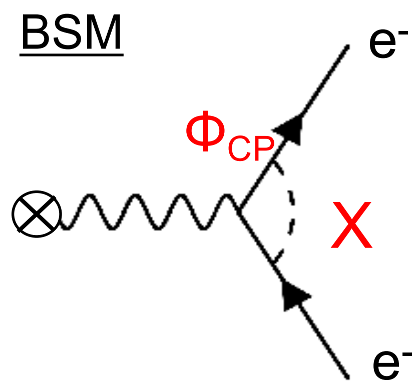
Is there any ball?

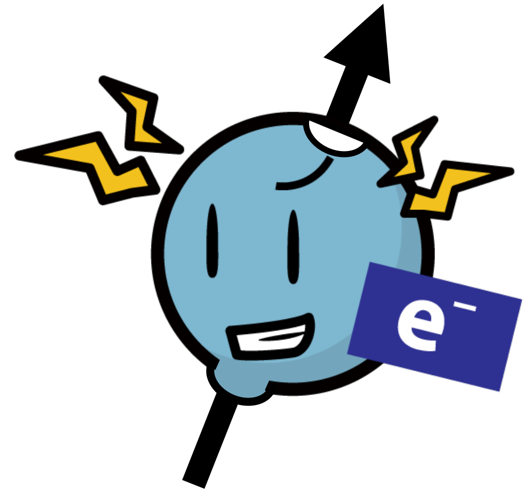


Electric Dipole Moment (EDM)

- violates CP-symmetry, very small in SM
- very sensitive to BSM physics







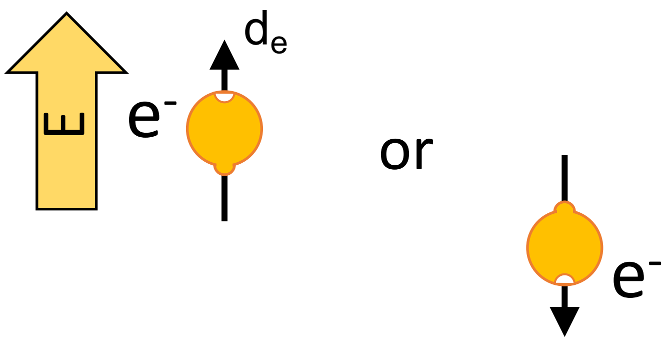
unit: charge × length
(e × cm)

$$\delta \frac{\eta}{2} \sim \frac{\alpha}{\pi}\left(\frac{m_e}{m_X}\right)^2 \sin \phi_{\mathrm{CP}}$$

for Φ_{CP}~1, sensitive to ~30TeV

Principle of EDM measurement

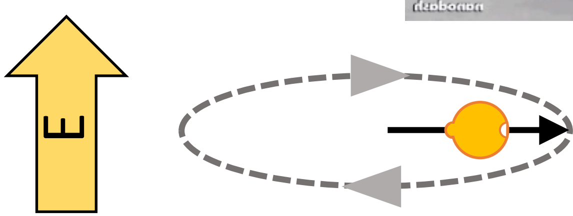
Apply an electric field



$$\Delta E = 2d_e \cdot E = \frac{\mu_B}{c}\eta E$$

$\hbar\omega_s$ precession energy

Experimentally



spin precession ω_s

$$\delta\omega_s = \frac{1}{\tau}\frac{1}{\sqrt{N}}$$

precession time (τ)

# of measured spins (N)

$$\rightarrow \delta\eta = \frac{\hbar c}{\mu_B}\frac{1}{E\,\tau\,\sqrt{N}}$$

Good Electron EDM search

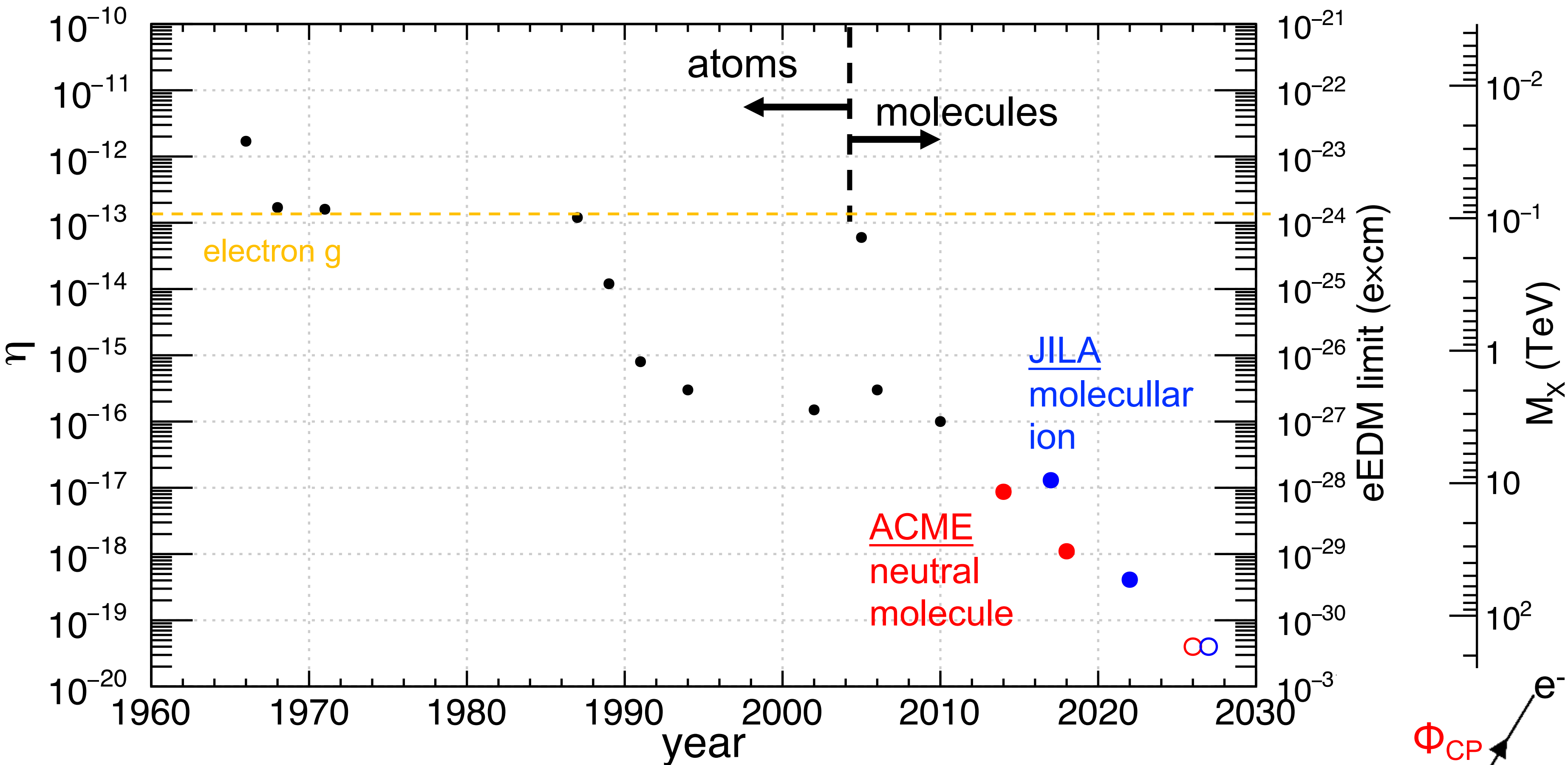
$$\delta\eta \propto \frac{1}{E\,\tau\,\sqrt{N}}$$

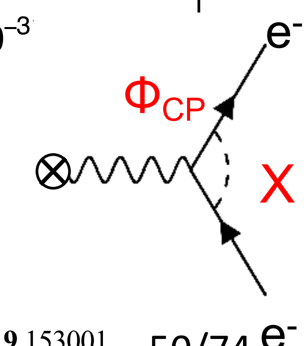
large electric field
- does not need to be accurate/precise

long coherence time

high statistics

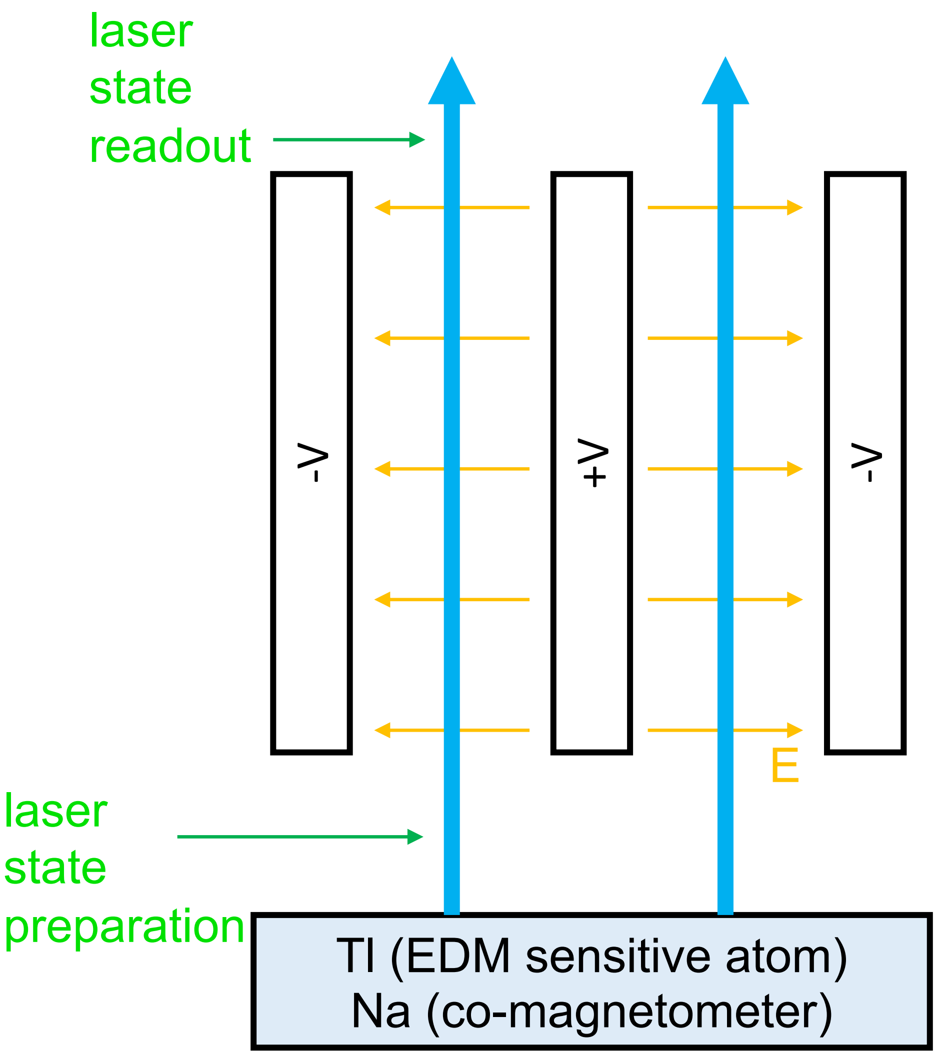
electron EDM History





Science **343**, 269 (2014) Phys. Rev. Lett. **119** 153001
Nature **562**, 355 (2018) Science, **381**,46 (2023)

EDM Experiment using Atoms



B-field change when flipping E-field
→ mimics EDM signal

- ✓ leakage current
- ✓ charging current
- ✓ imperfection of reversal
- ✓ Berry's phase
- ✓ motional E-field

etc…

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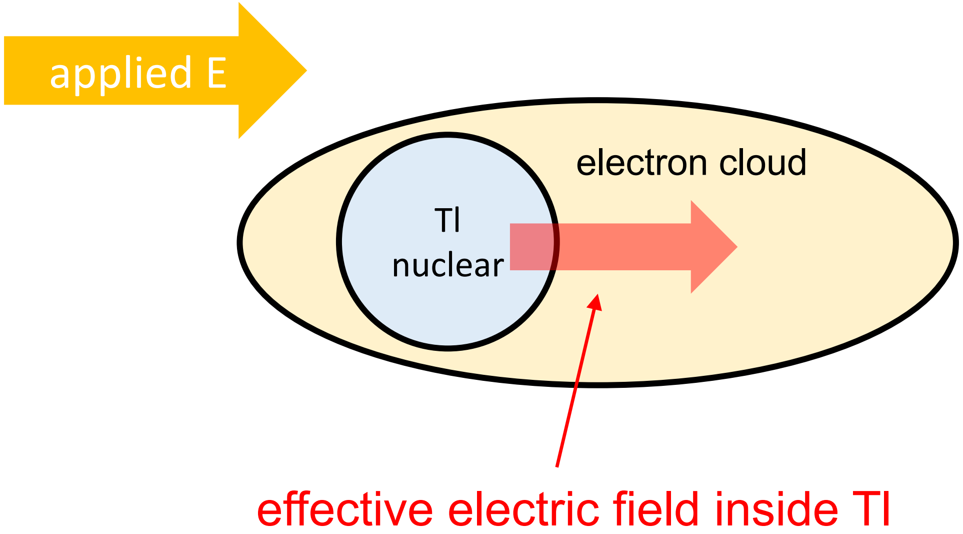
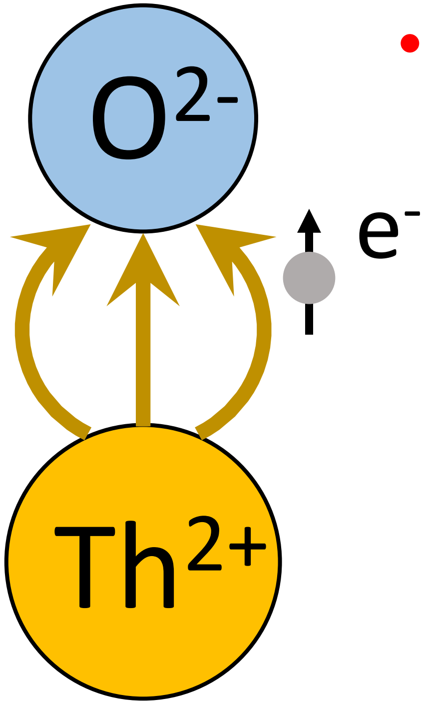
- Applied electric field: 100 kV/cm
- effective electric field in Tl: 60 MV/cm



polarized Tl works as an electric field amplifier!
Gain ~600

Molecule
Thorium Monooxide (ThO)



- Applied E-field: 100 V/cm
- effective E-field in ThO: 80 GV/cm

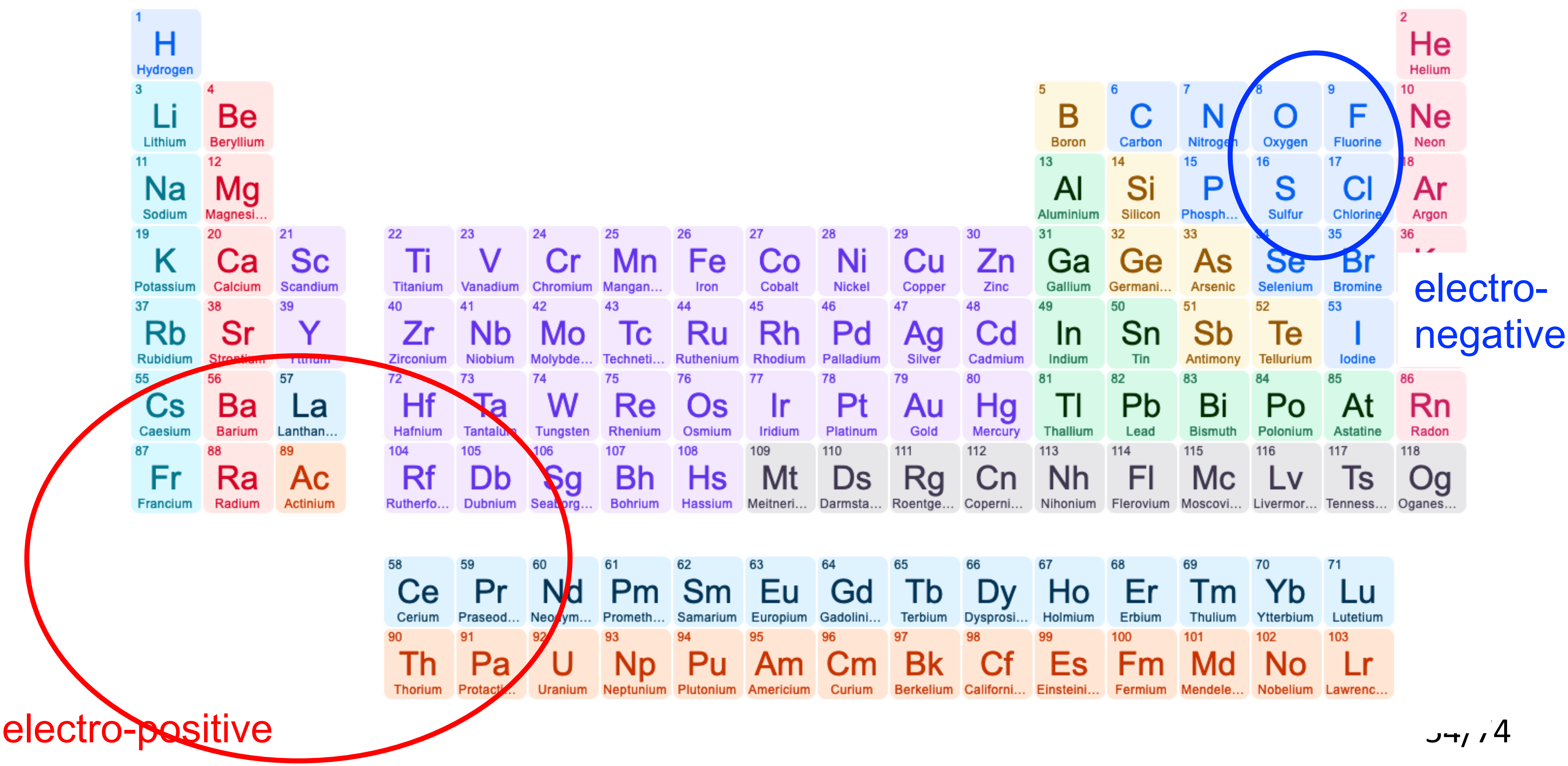
gain ~10^9

remember:

$$\delta\eta \propto \frac{1}{E\,\tau\,\sqrt{N}}$$

How did you choose?

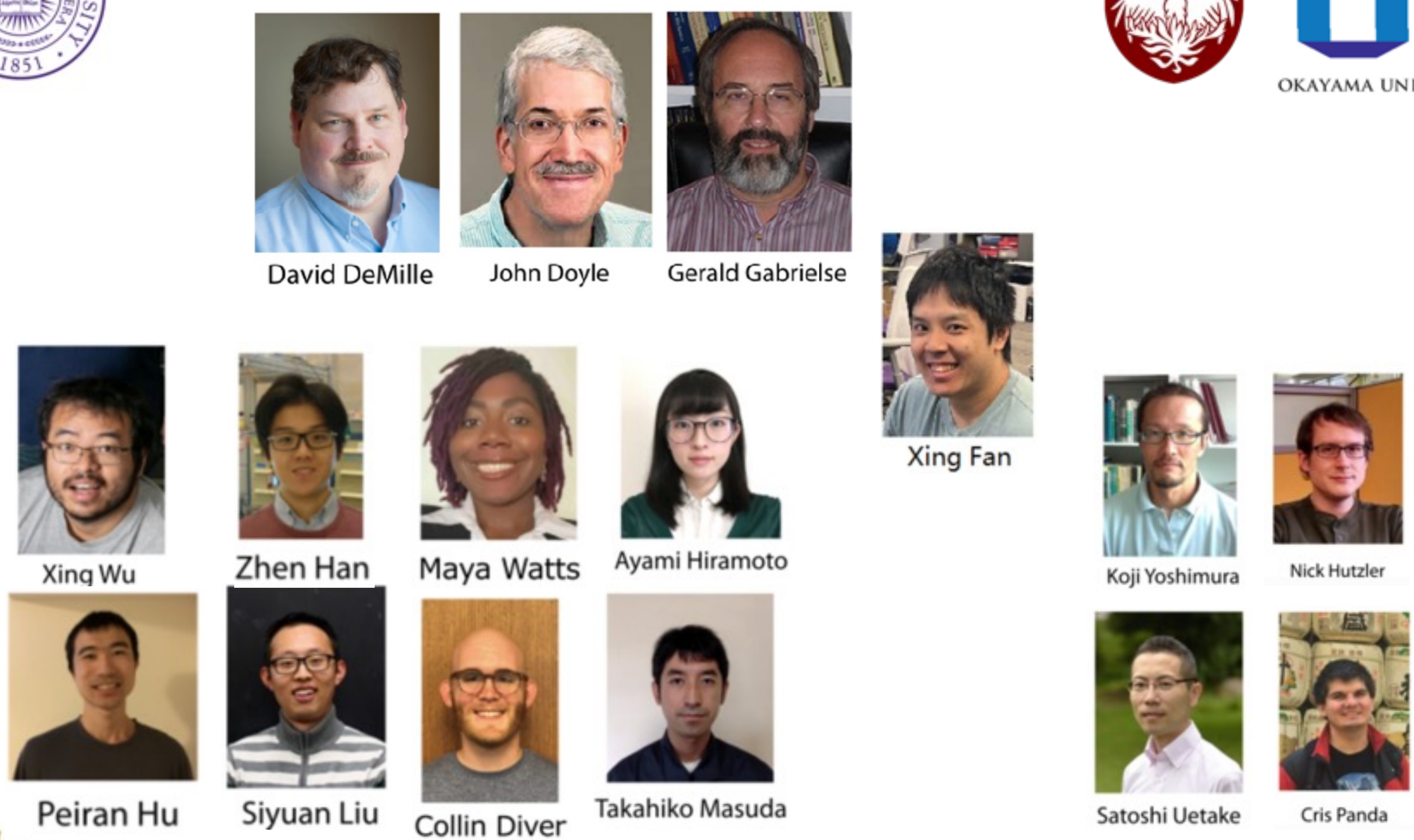
- many many details…



Measurement of the Electron's Electric Dipole Moment

ACME Collaboration

OKAYAMA UNIV.



NSF

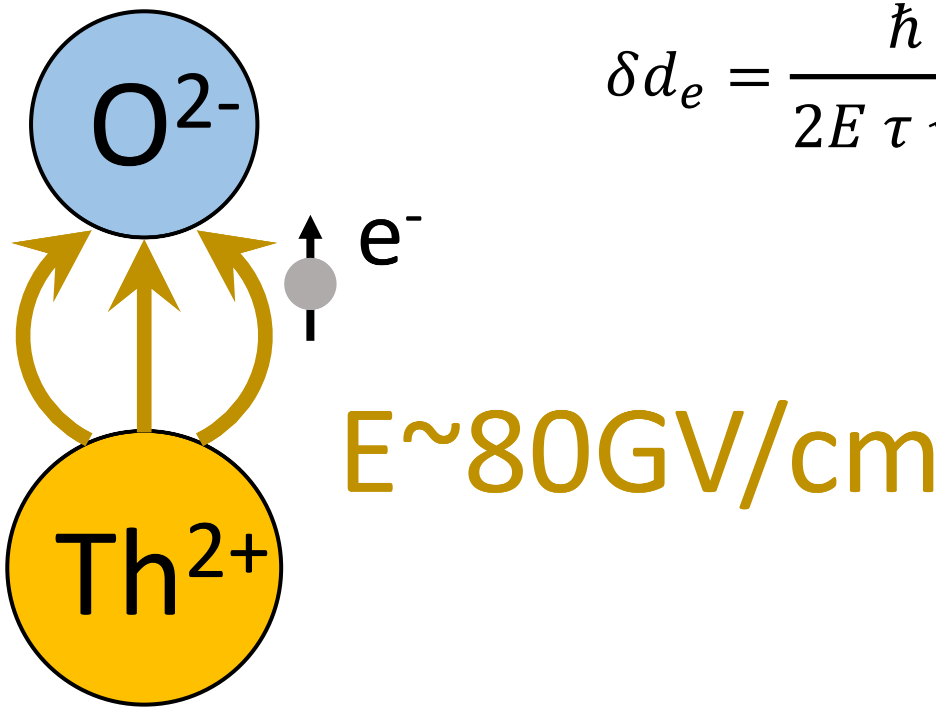
GORDON AND BETTY MOORE FOUNDATION

Alfred P. Sloan FOUNDATION

科研費 KAKENHI

ACME Collaboration
Thorium Monoxide: ThO

- E=80 GV/cm
- very easy to make = high N
- $^3\Delta_1$ state : long τ and B-insensitivity

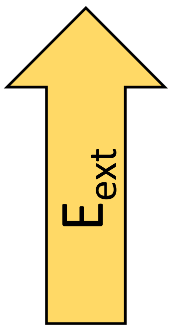


$$\delta d_e = \frac{\hbar}{2E\,\tau\,\sqrt{N}}$$

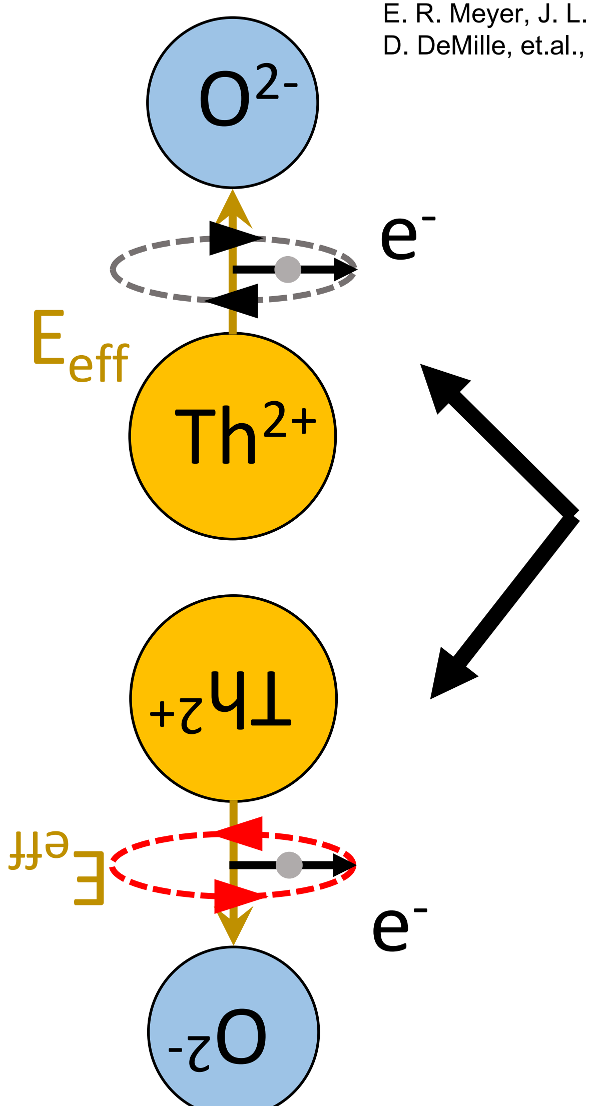
http://doylegroup.harvard.edu/edm

Molecule Axis Reversal
GOOD SWITCH!!

E. R. Meyer, J. L. Bohn, and M. P. Deskevich, PRA **73**, 062108 (2006)
D. DeMille, et.al., AIP Conference Proceedings, **596,** 72 (2001)

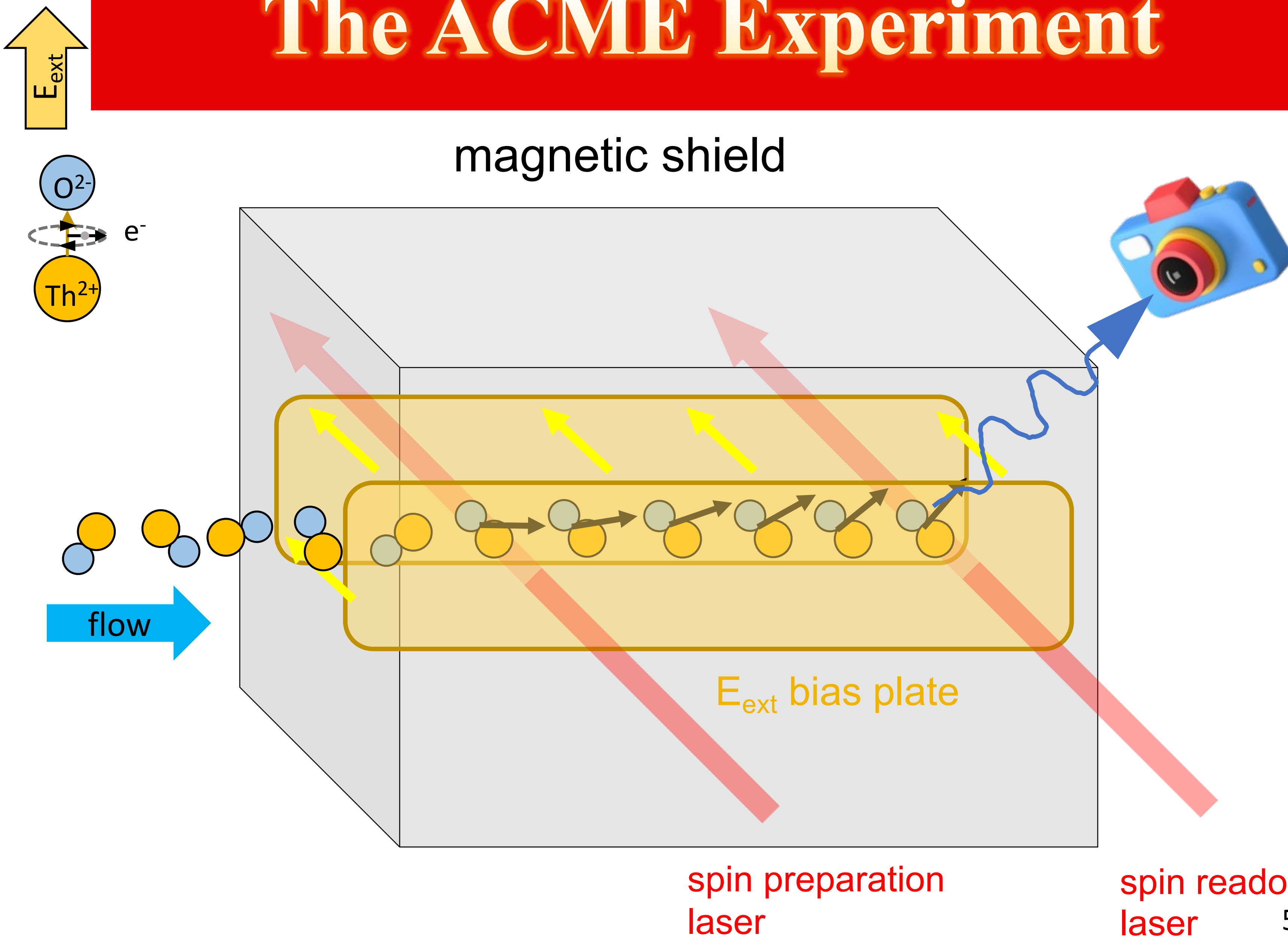


~100V/cm
<u>aligns molecule</u>

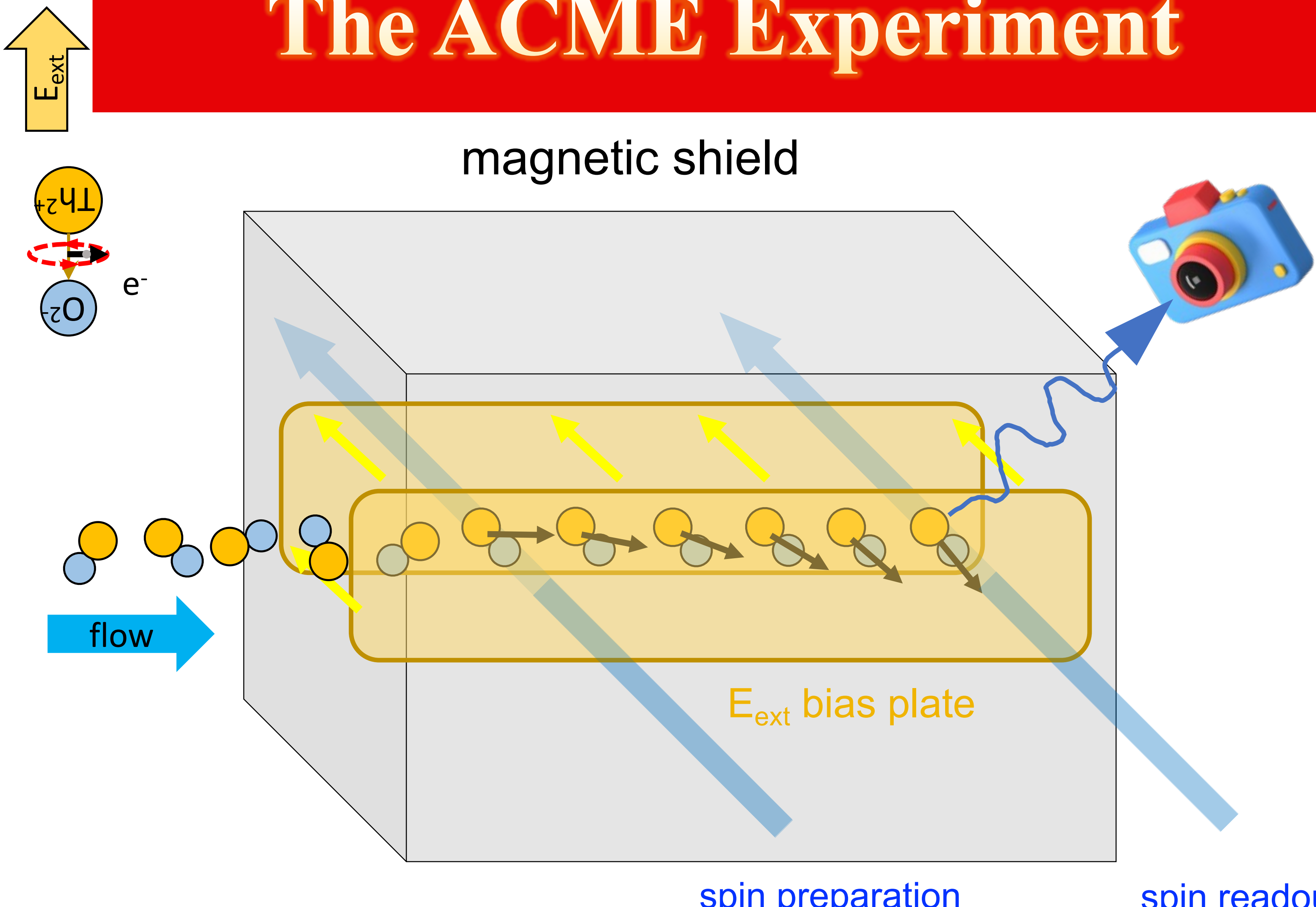


can select direction by
laser frequency detuning

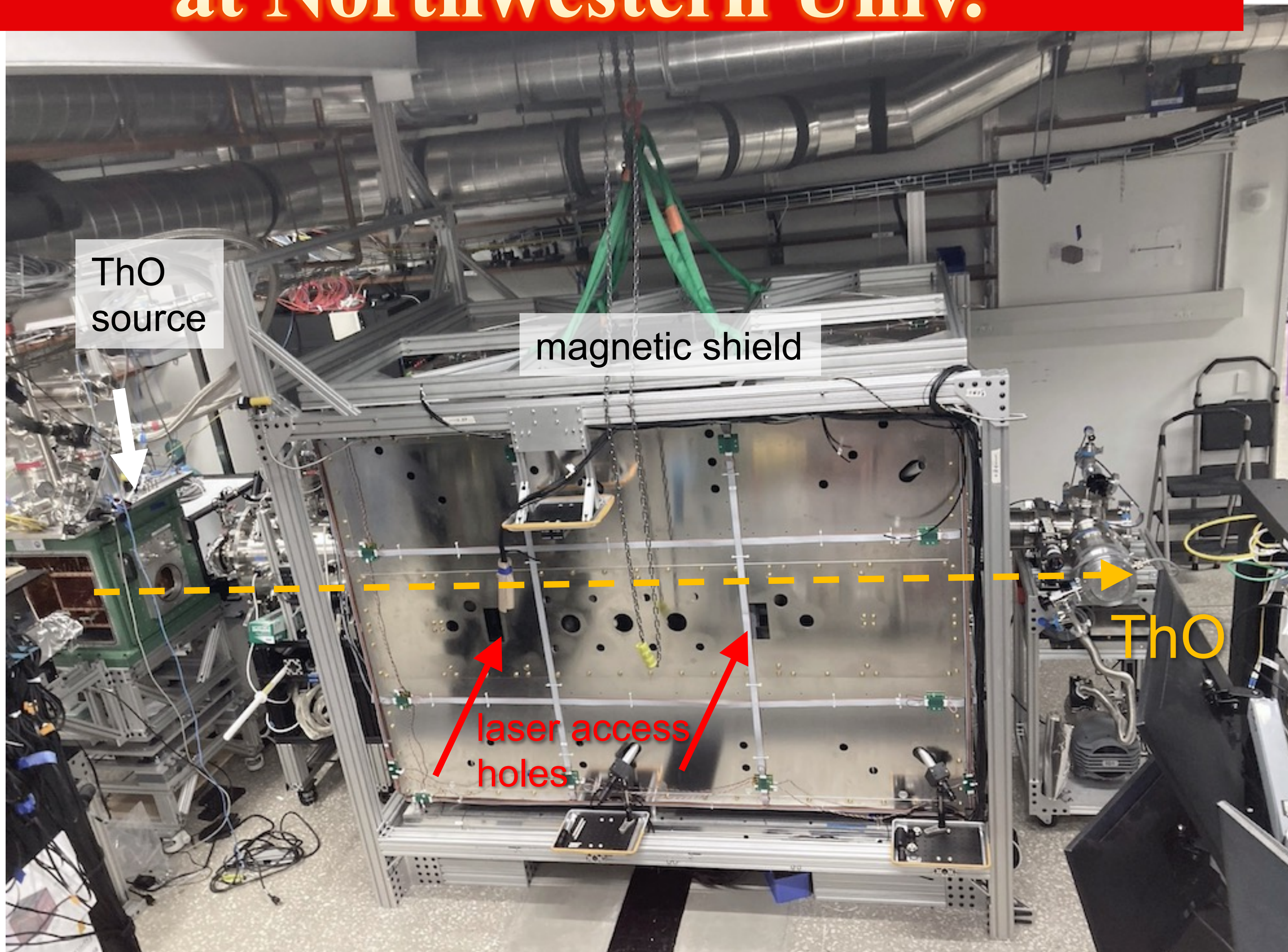
The ACME Experiment



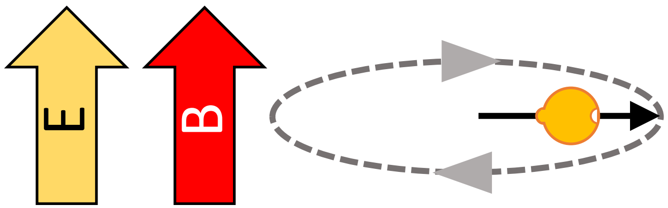
The ACME Experiment



Newly Constructed Beamline at Northwestern Univ.



Magnetic Field Control



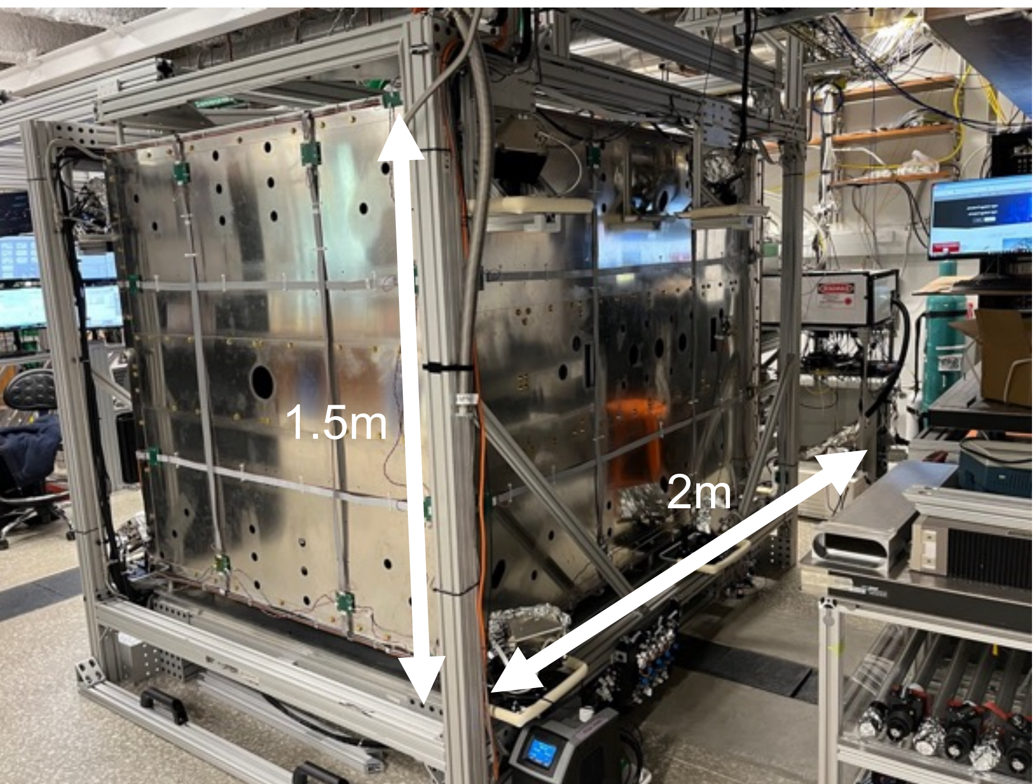
spin precession ω_s

$$\omega_s = \frac{2\,(d_e \cdot E + \mu \cdot B)}{\hbar}$$

B_{earth}=500mG ↔η=10^{-13}

(target: η <10^{-19})

*ThO $^3\Delta_1$ state and switching help a lot

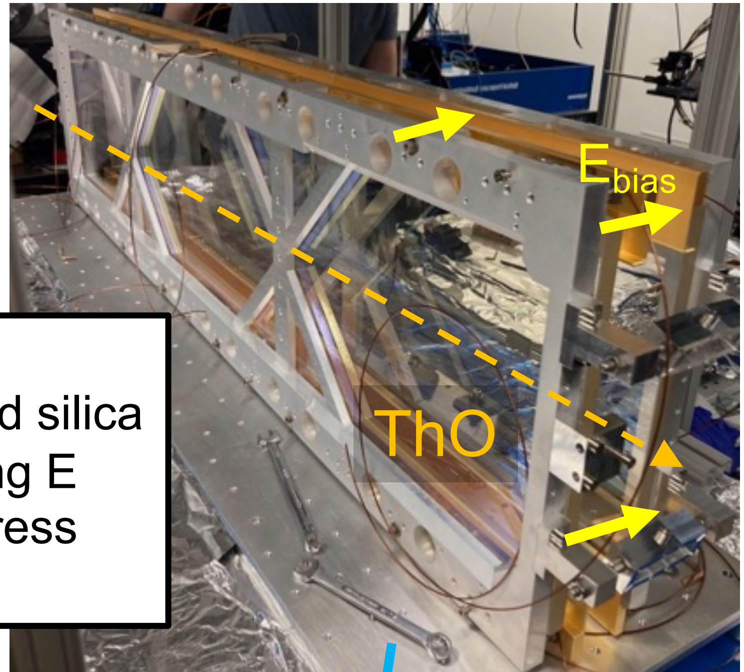


- 3-layer magnetic shield
- 3000 lbs = 1500kg
- 3,600 wire connections

✓ <30μG without active cancellation
✓ <5μG with active cancellation

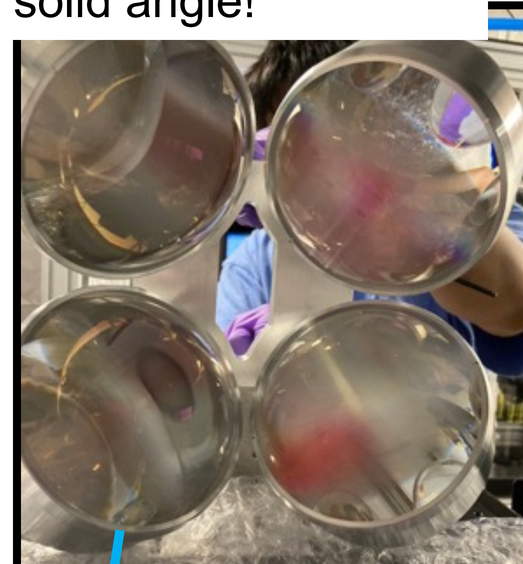
E-field plates

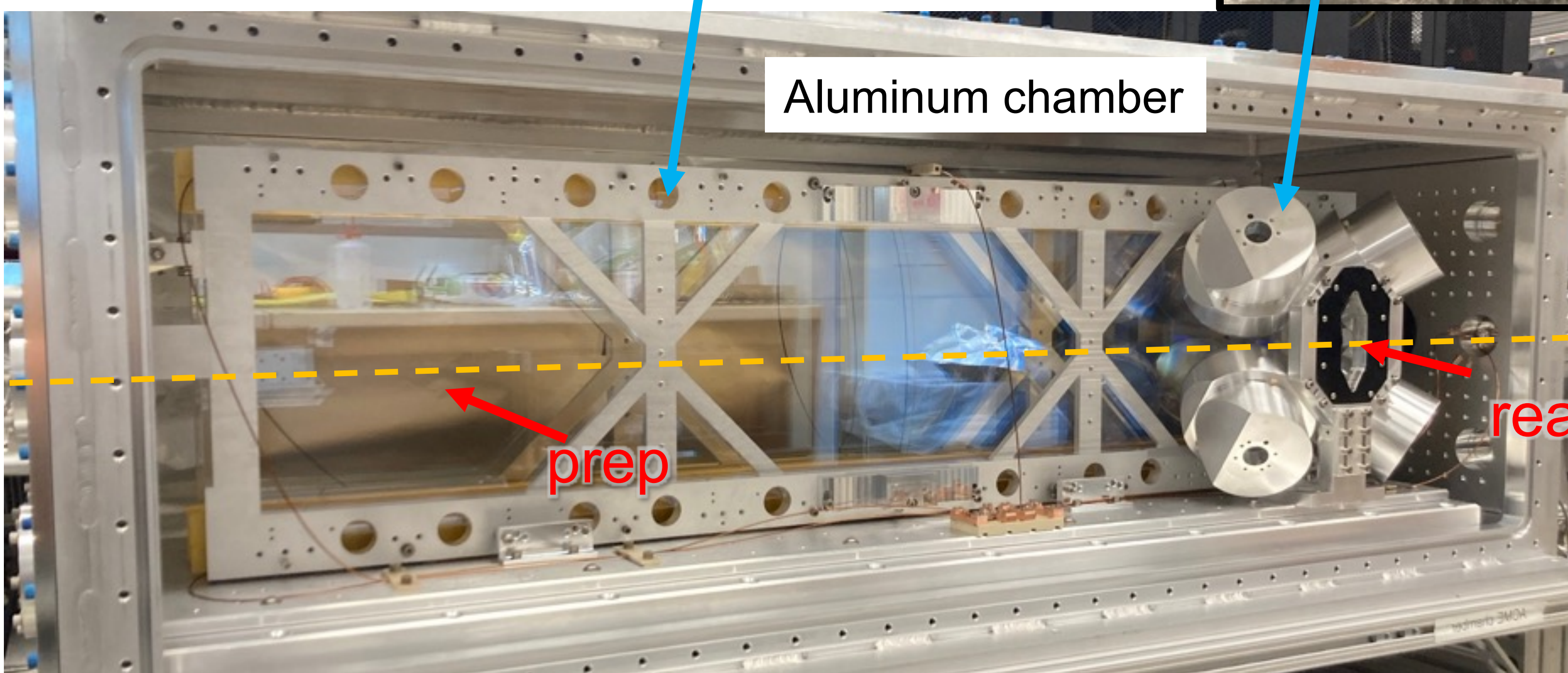
- ✓ ITO-coated fused silica
- ✓ low non-reversing E
- ✓ low mounting stress
- ✓ non-magnetic



fluorescence collection lens

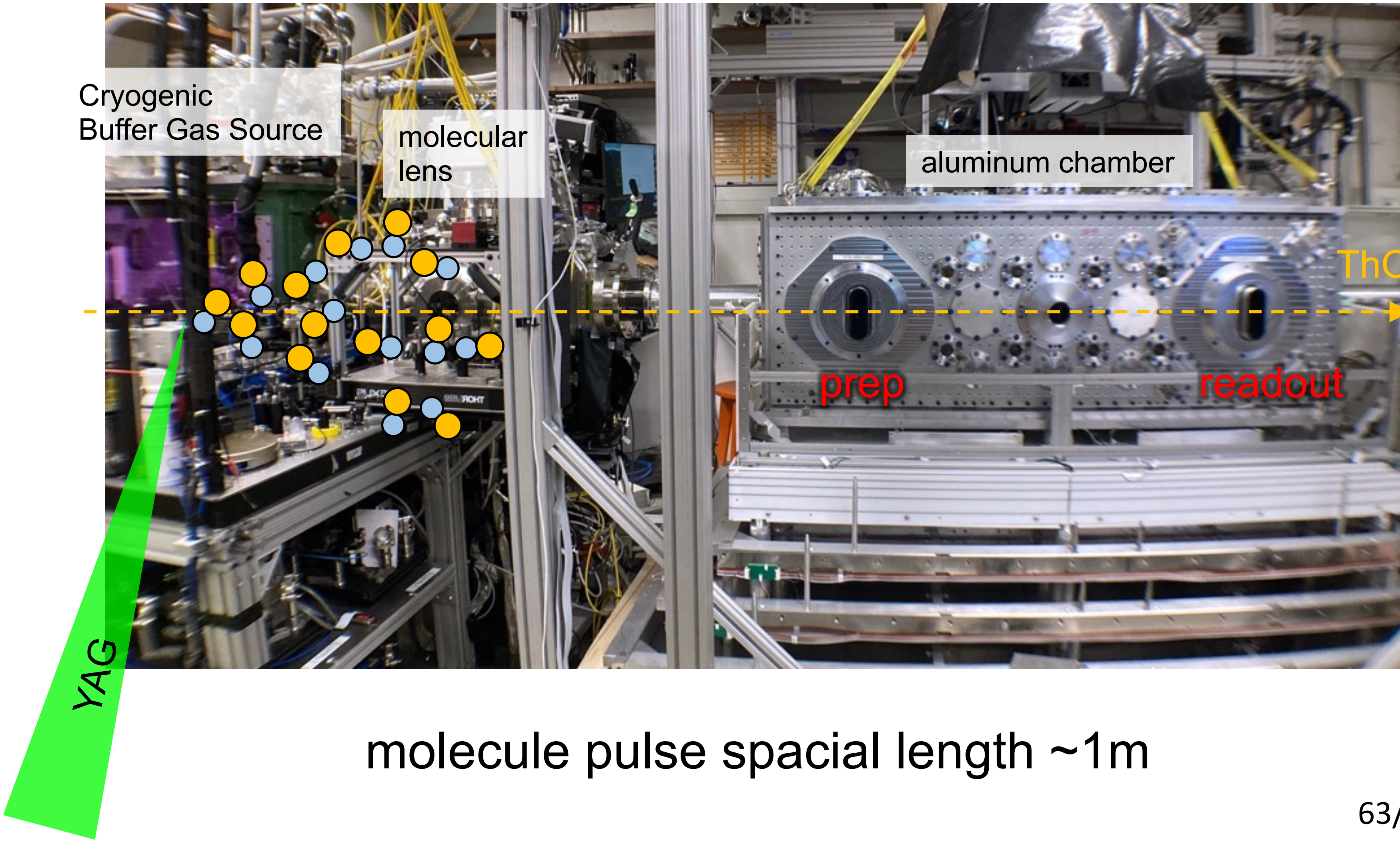
>30% solid angle!





The Whole Beamline

X Wu, et al, New J. Phys. 24 073043(2022)



molecule pulse spacial length ~1m

Dominant Systematic Errors

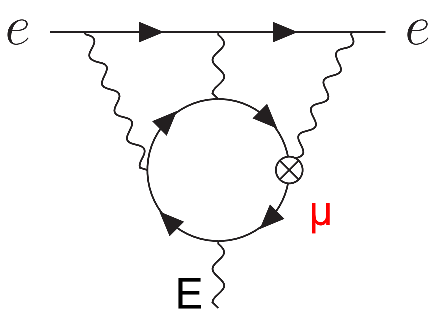
1. Imperfection of laser polarization
   × imperfection of E-field reversal
   × imperfection of laser beam shape

2. imperfection of laser frequency detuning
   × imperfection of magnetic field gradient
   × imperfection of electric field gradient

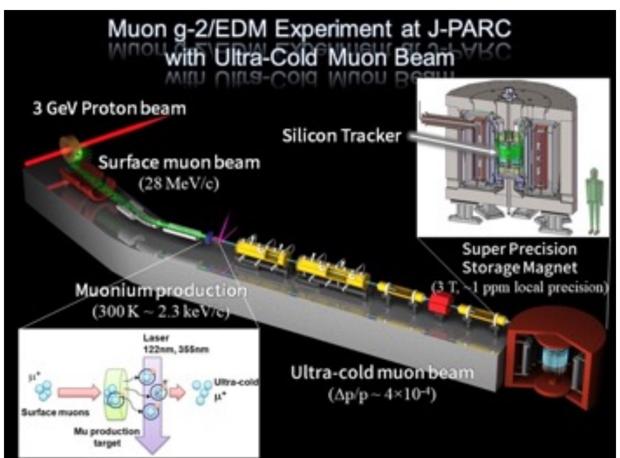
ALWAYS unexpected higher order coupling!
make everything perfect!

muon EDM limit from electron EDM

Phys. Rev. D 98, 113002
Phys. Rev. Lett. 128, 131803



PTEP 2019 (5), 053C02



The most stringent limit on μ EDM is currently from the electron EDM

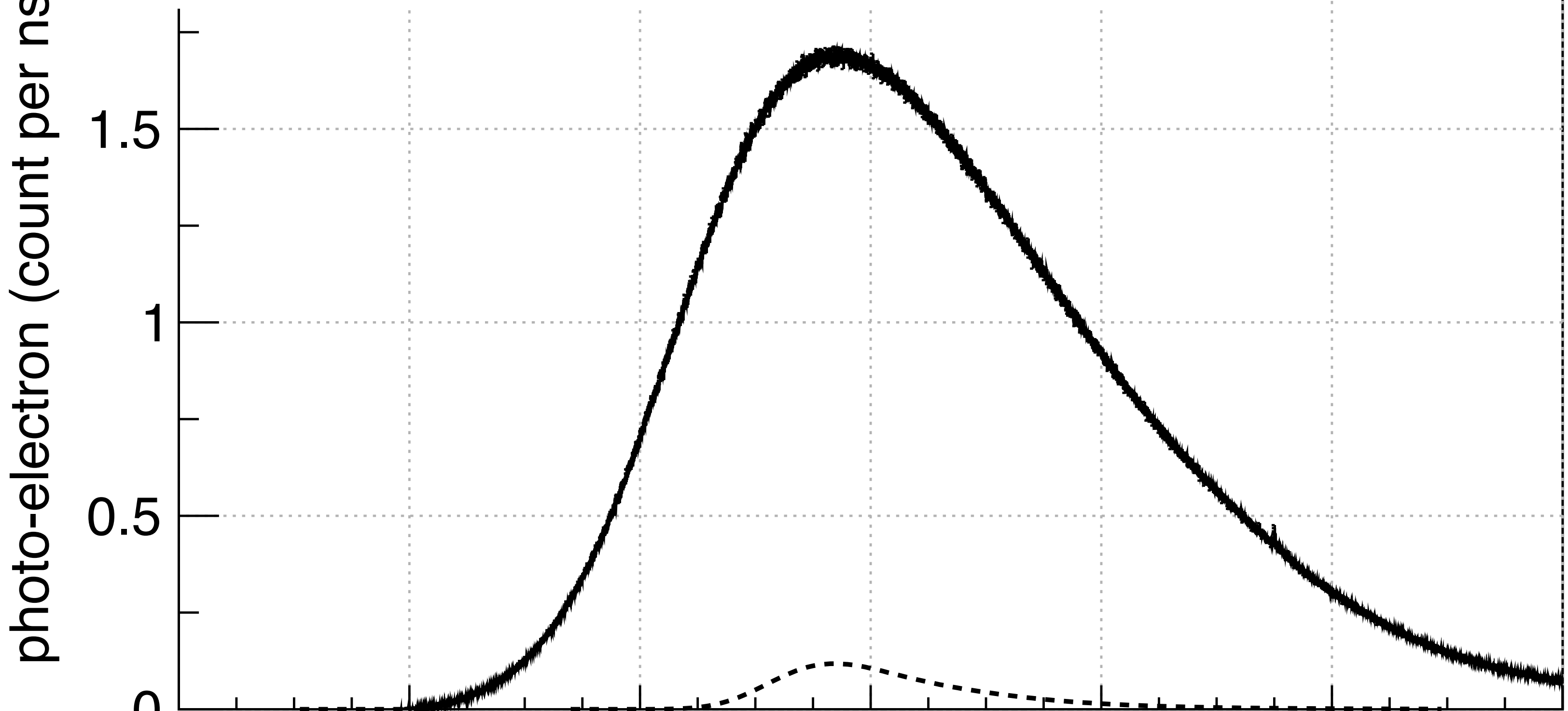
d_μ(BNL) $<1.8\times10^{-19}$ e cm
d_μ(ThO) $<2\times10^{-20}$ e cm
d_μ(HfF$^+$) $<1\times10^{-20}$ e cm

d_μ(FNAL) <~1×10^{-21} e cm
d_μ(J-PARC) $<1.5\times10^{-21}$ e cm
d_μ(PSI) $<6\times10^{-23}$ e cm
} projected

arXiv:2201.08729

Many New Devices

signal in the new beamline!
x30 higher than the previous generation!



<u>ACME 3 plan to publish a new eEDM result within 2 years</u>

Future EDM proposals

- laser cooled and trapped molecules

  SrOH, YbOH, RaOH

John Doyle

Nick Hutzler

Ronald Garcia Ruiz

- cryo-assembled molecules

  FrAg

David DeMille

- trapped molecular ions

  $^{232}ThF^{+}$ and $^{227}ThF^{+}$

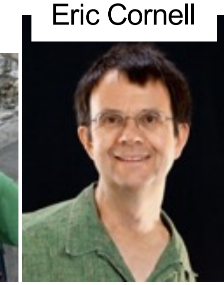
  nuclear EDM

Xing Fan

Stephan Malbrunot

Kia Boon Ng

Eric Cornell



- molecules in a cryomatrix

Eric Hessels

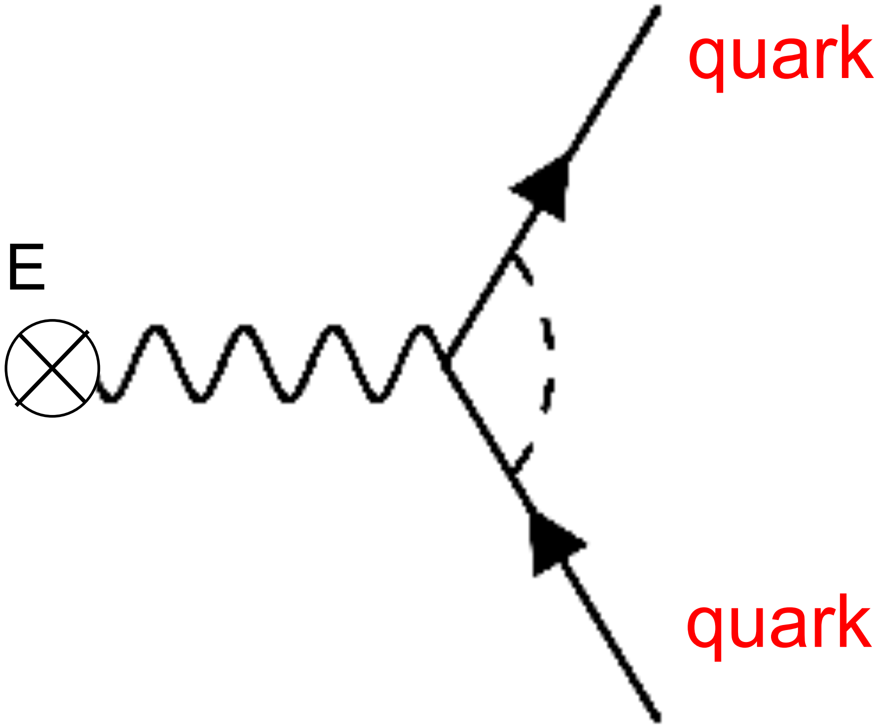
Amar Vutha

Europium

Take Home Messages

- Make the signal large!!! (large E)
- prepare good switches to isolate what you want to see!
- make everything perfect! systematic errors are always from higher order couplings!

Nuclear Electric Dipole Moment



CP-violation in Hadronic Sector

proposed work

$^{227}ThF^+$: Combining Best & Best & Best & Best & Best

Pear-shape Nuclear: $>10^3$ enhancement to Hadronic $\not{CP}$ effect

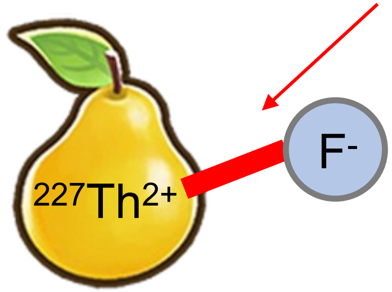
$^{227}ThF^+$

1. Pear-Nuclear

$\times 10^3$

2. Molecule's internal E-field

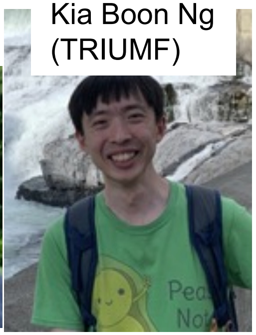
$\times 10^5$



3. EDM-state is the ground state!
4. insensitive to B-field fluctuation
5. Spectroscopy is done already!

Stephan Malbrunot (TRIUMF)

Kia Boon Ng (TRIUMF)

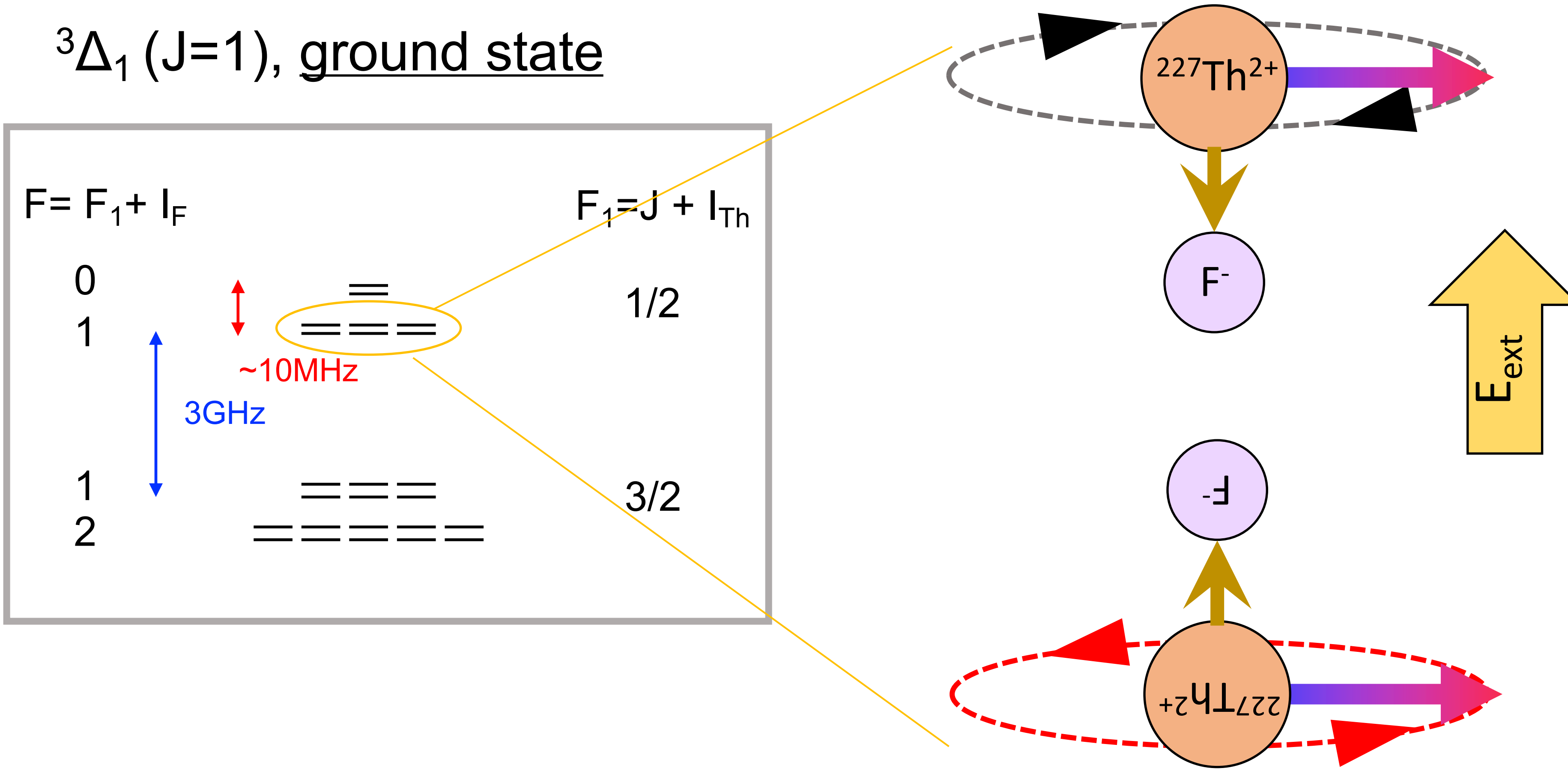


Eric Cornell (CU Boulder, JILA)

➢ can improve the current limit (=θ_{QCD} limit) with 1 molecule and 1 day of measurement

Same Spectroscopic E-reversal

$^3\Delta_1$ (J=1), ground state



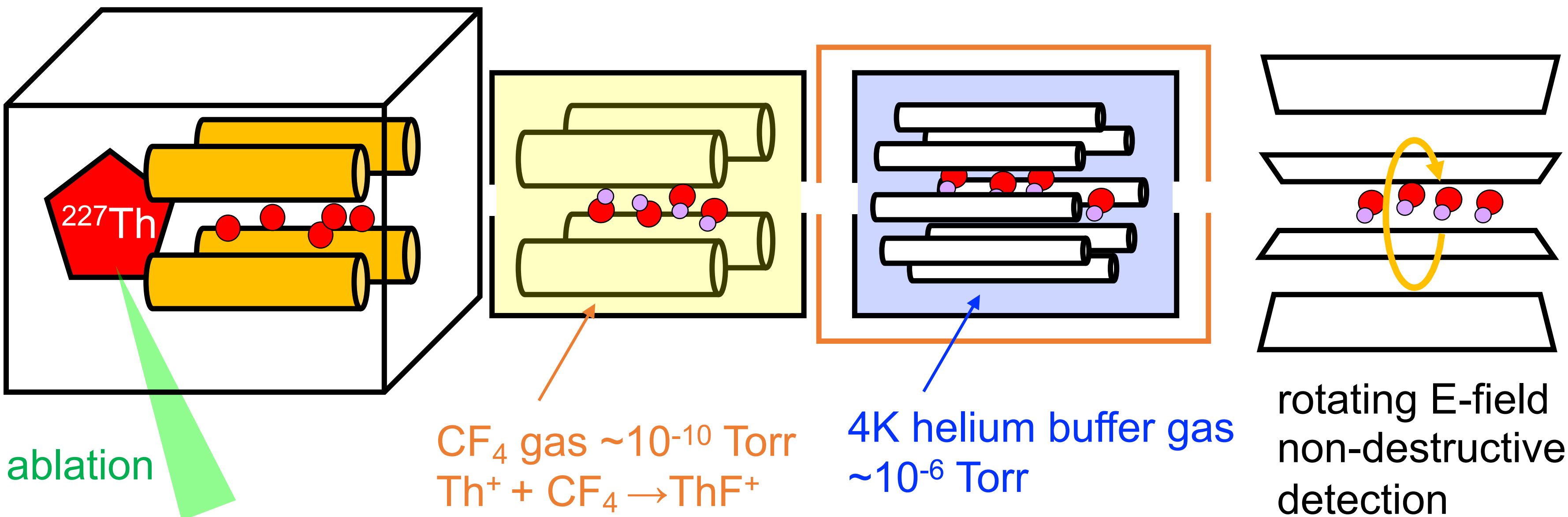
Beamline Schematics

1. $^{227}Th^{+}$ loading trap

2. $^{227}ThF^{+}$ creation

3. multipole trap rotational cooling

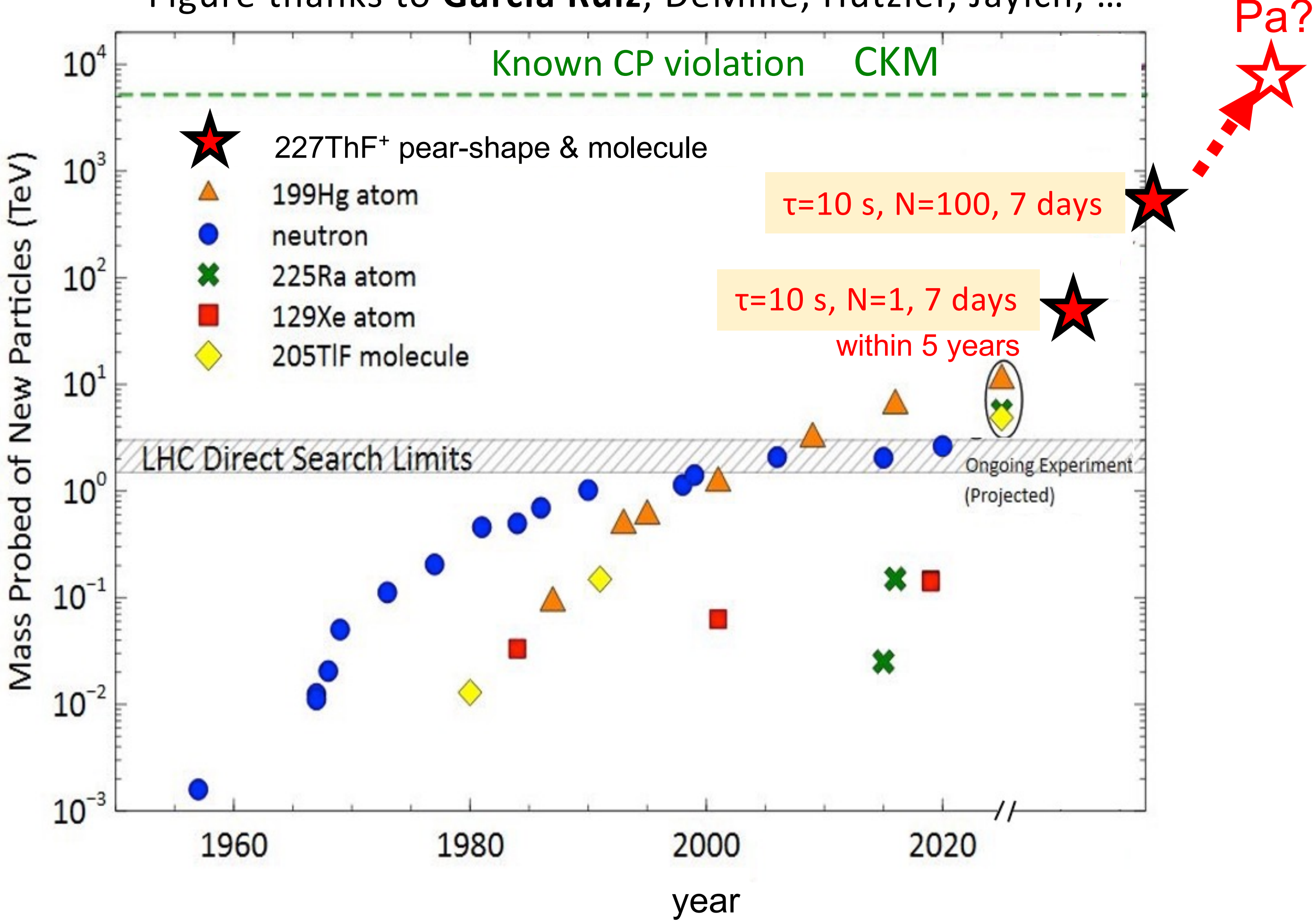
4. EDM measurement trap



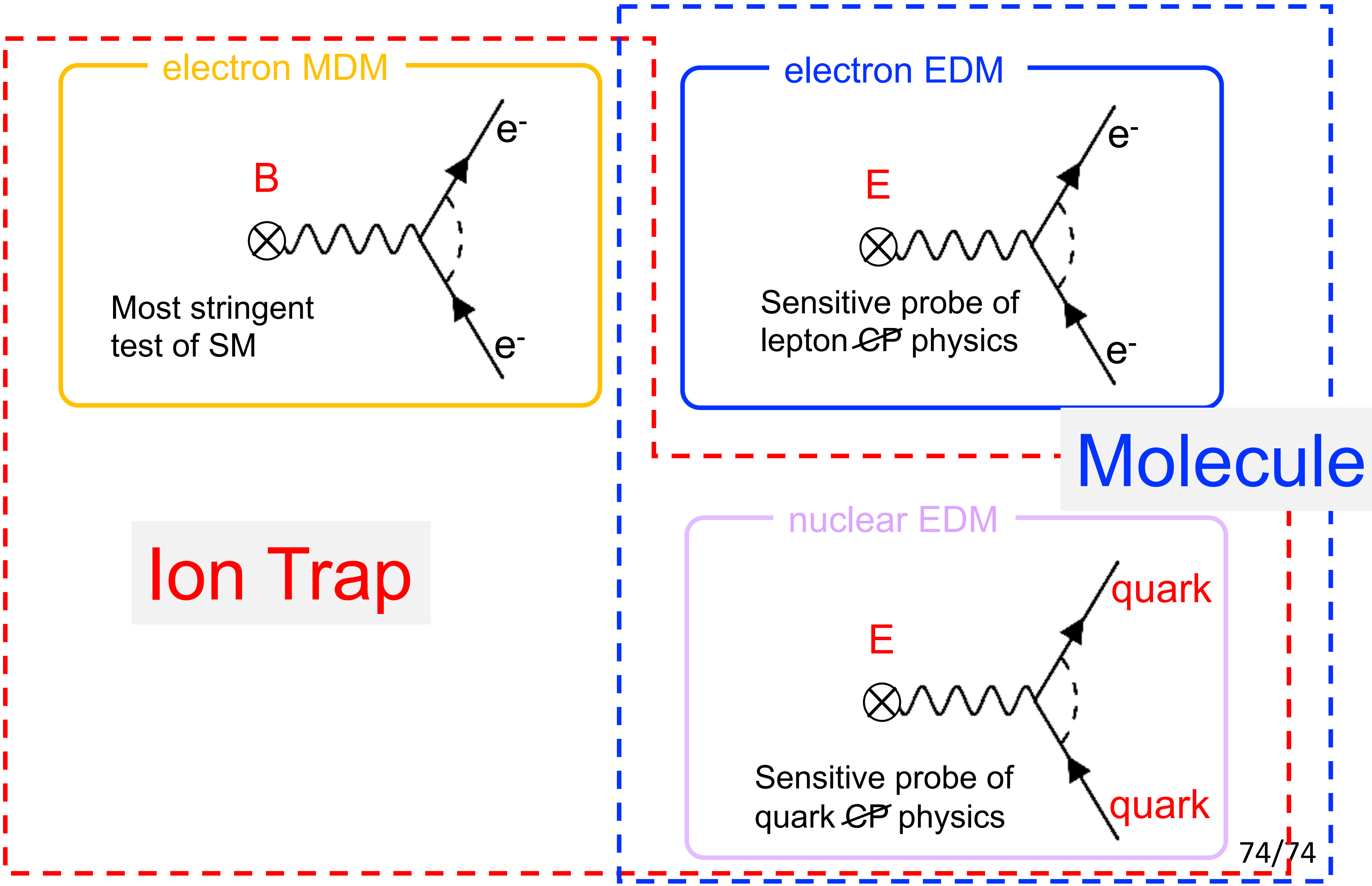
acknowledgement: RIKEN-Harvard partnership

Sensitivity

Figure thanks to **Garcia Ruiz**, DeMille, Hutzler, Jayich, …



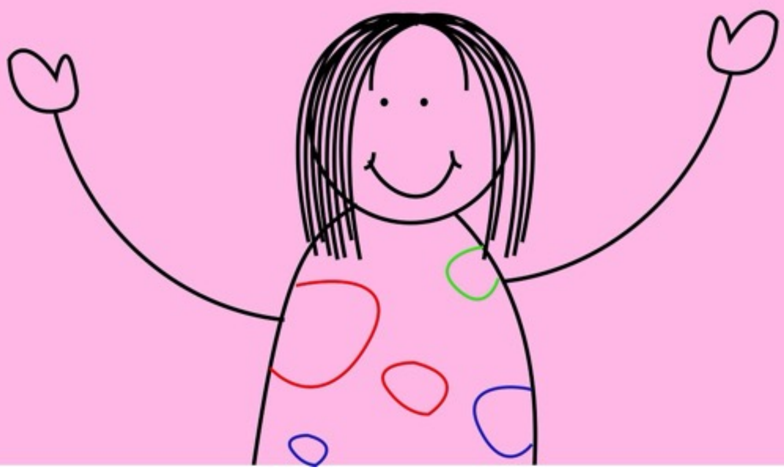
Summary: Probing BSM



starting at Harvard 2025 July

Looking for Students/Postdocs!

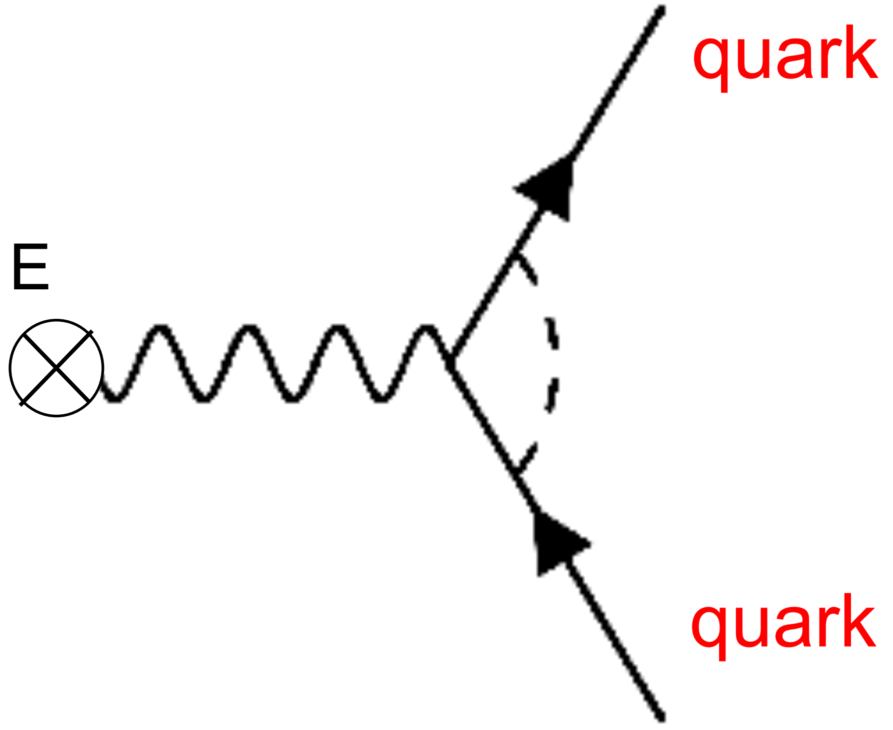
I got a job!



xing.x.fan@gmail.com

backup

Nuclear Electric Dipole Moment



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1. Pear-Nuclear

x10^3

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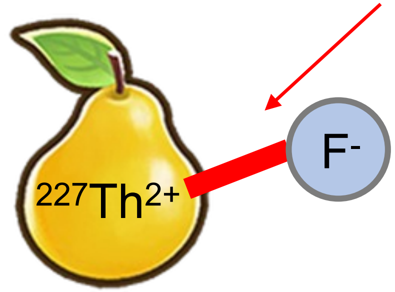
x10^5



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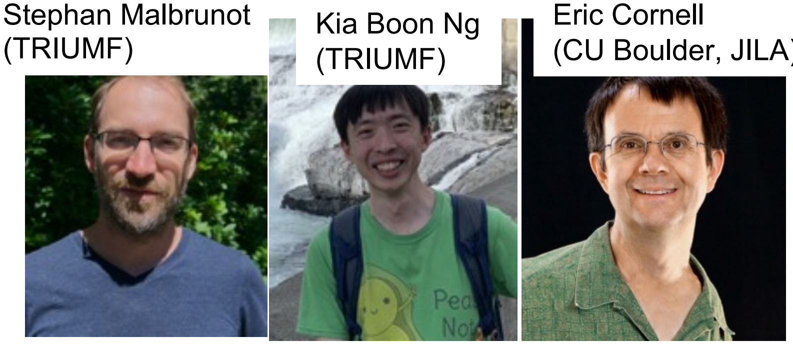
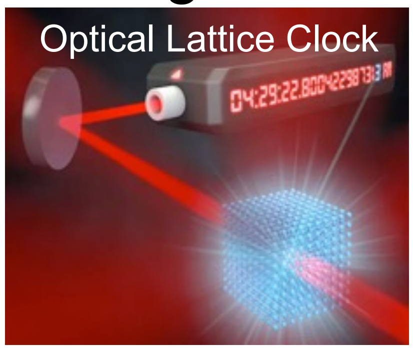
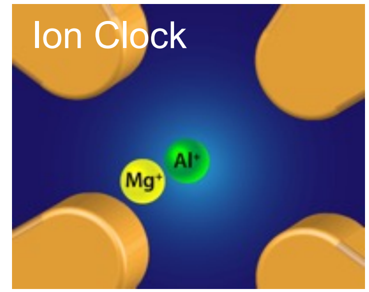
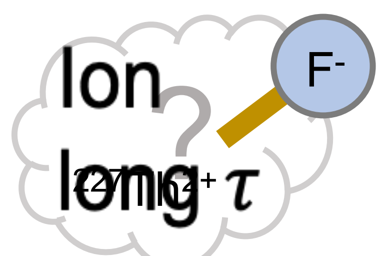


➢ can improve the current limit (=θ_{QCD} limit) with 1 molecule and 1 day of measurement

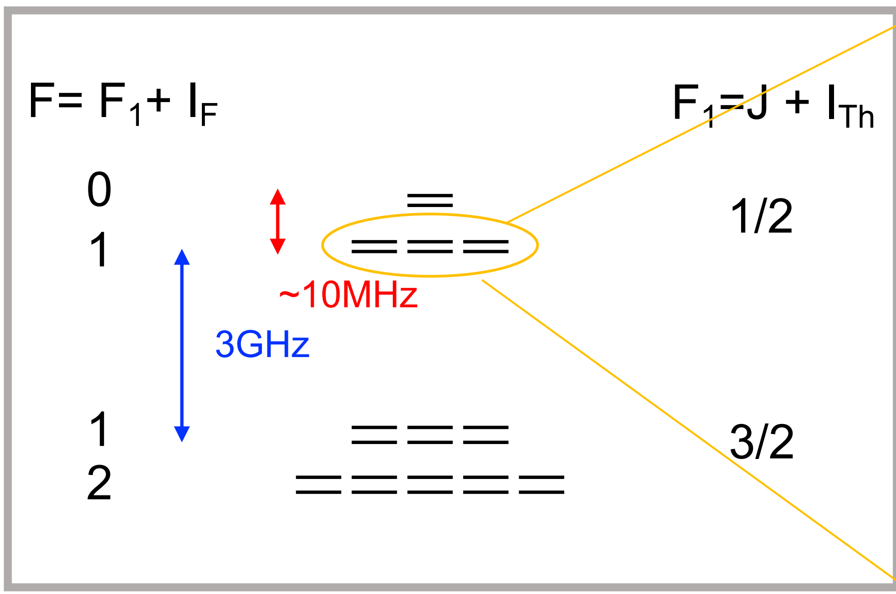
Neutral vs Ion

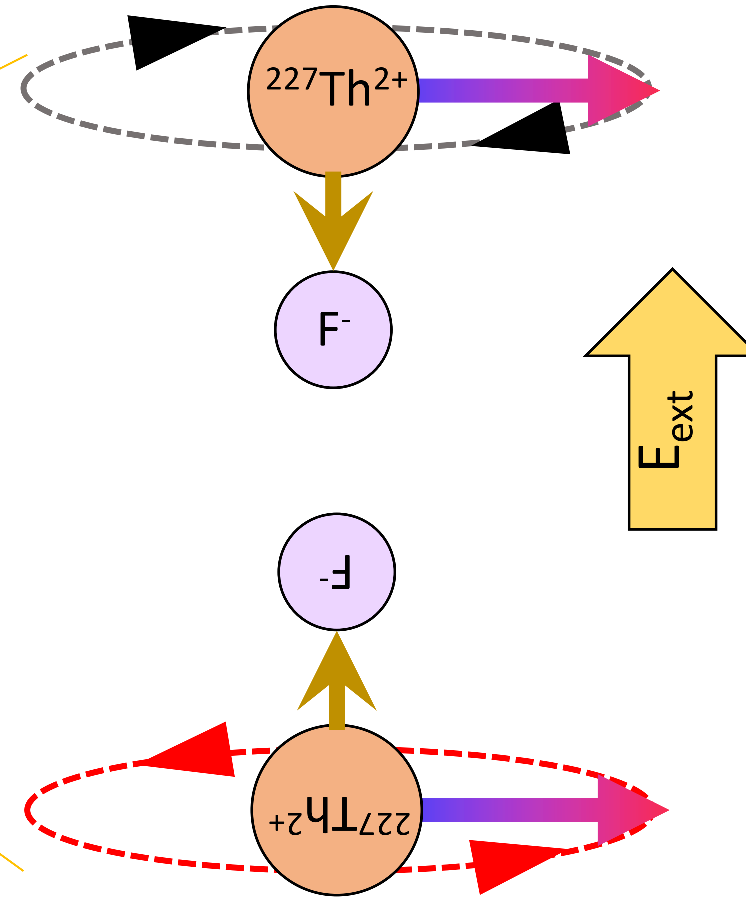
	neutral large N	Ion long τ
clock		
electron EDM	 ^{232}ThO	 $^{180}HfF^{+}$ $^{232}ThF^{+}$
nuclear EDM	 proposed: $^{225}RaOH$ $^{225}RaOCH_3$ etc	

$$\delta\omega = \frac{1}{\tau}\frac{1}{\sqrt{N}}$$

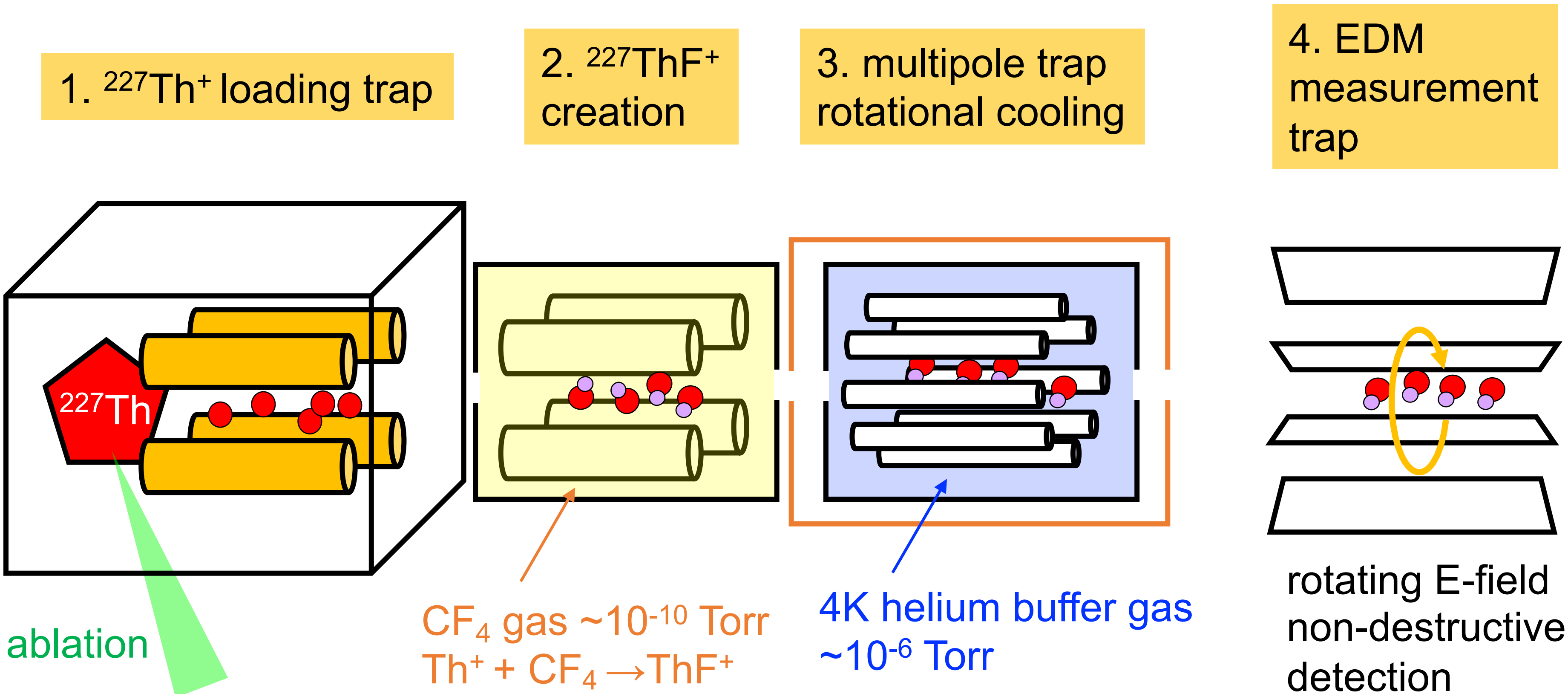
Same Spectroscopic E-reversal

$^3\Delta_1$ (J=1), ground state





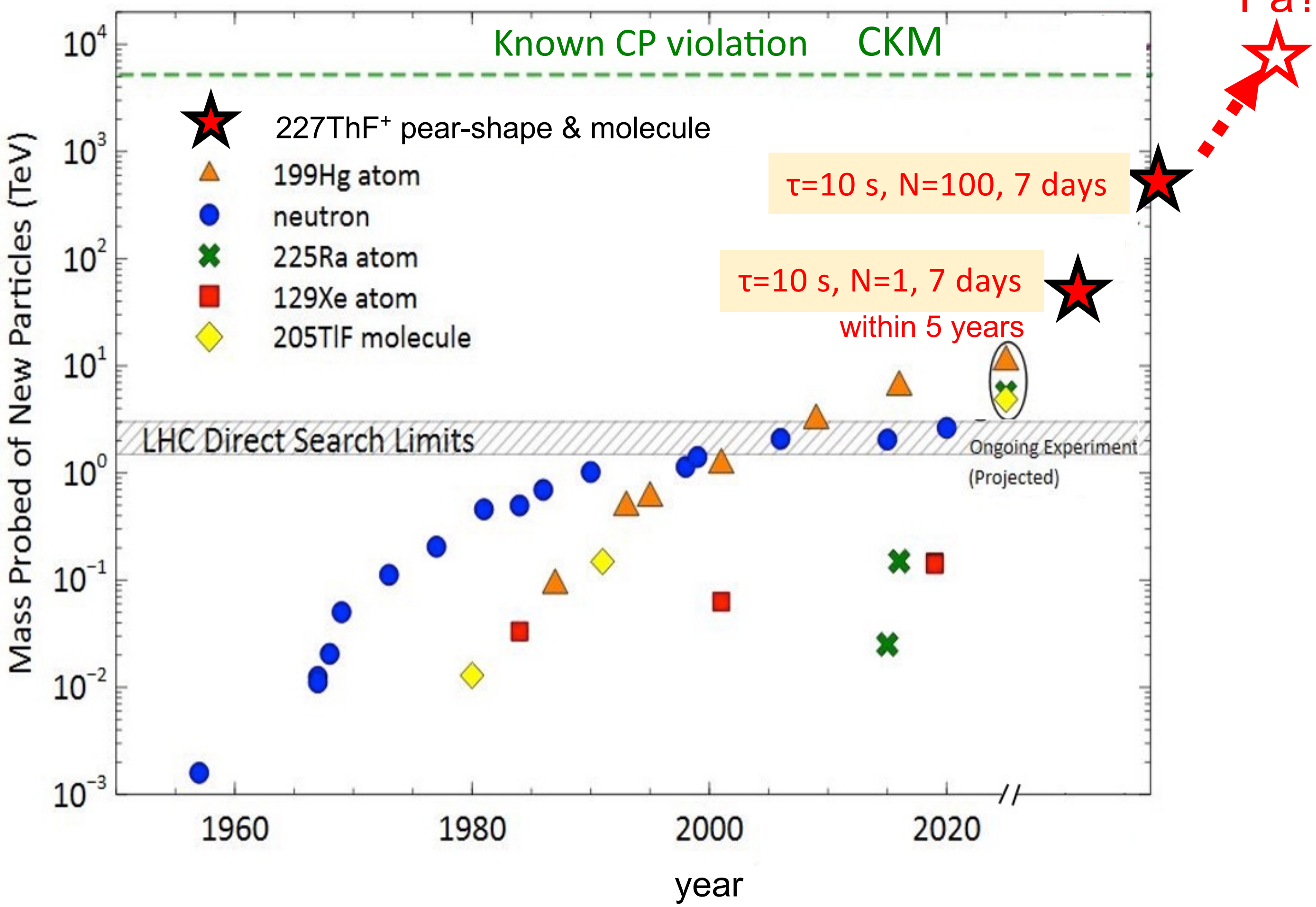
Beamline Schematics



new and exciting developments!

Sensitivity

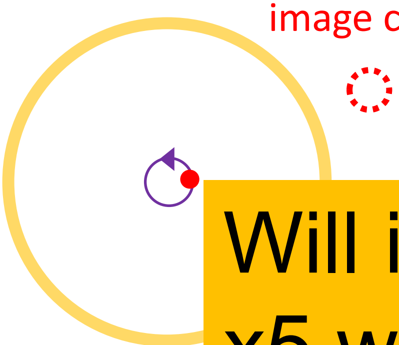
Figure thanks to **Garcia Ruiz**, DeMille, Hutzler, Jayich, …



Toward muon g-2 sensitivity
Image Charge Shift

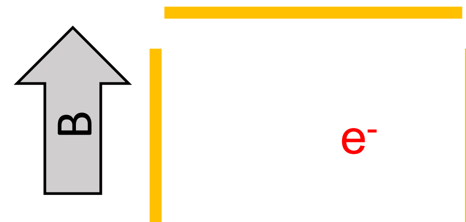
New Idea

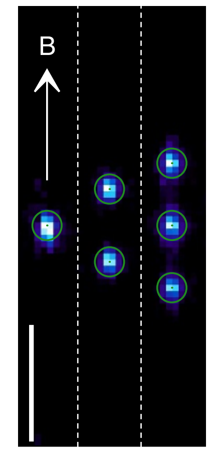
R. S. Van Dyck et. al.,
Phys. Rev. A 40, 6308 (1989)



$$\frac{g}{2} = \frac{\nu_s}{\nu_c + \Delta\nu_c^{ics}}$$

Penning trap 1D electron chain

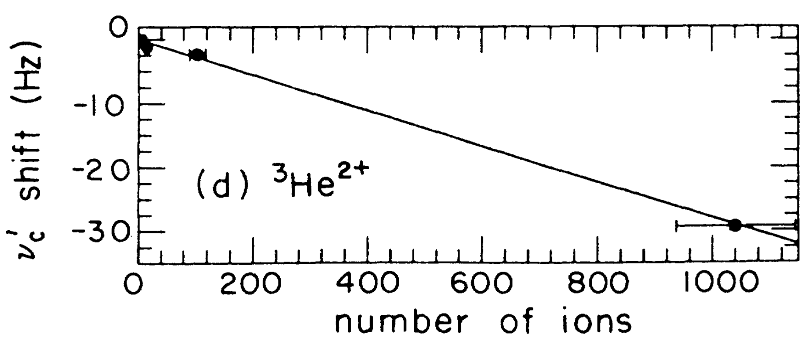


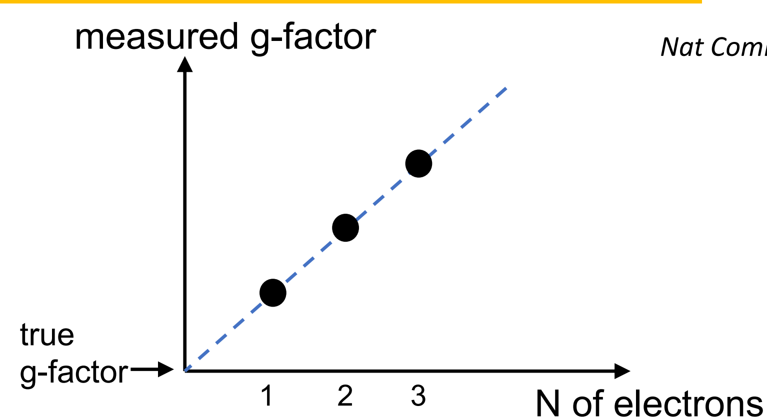


Ca+ ion

Nat Commun **4**, 2571 (2013)

Will improve electron's g-factor
x5 within 5 years
check muon g-2 in electron g-2





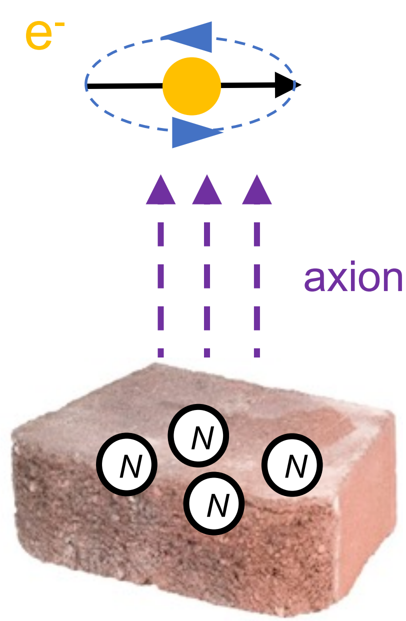
Earth-Sourced Axion-Nucleon-Electron Coupling

axion

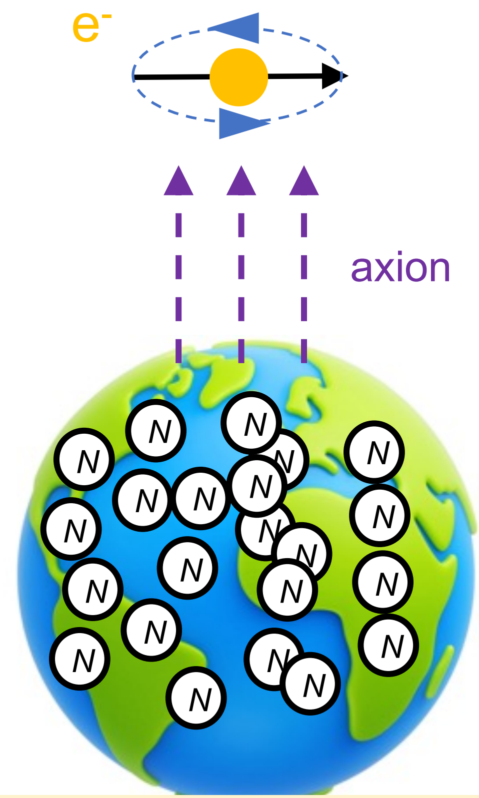
$$\mathcal{L} \supset g_s \phi \bar{N} N + c_\psi \frac{\partial_\mu \phi}{f_\phi} \bar{\psi} \gamma^\mu \gamma^5 \psi,$$

nucleon fermion

causes spin rotation near heavy block



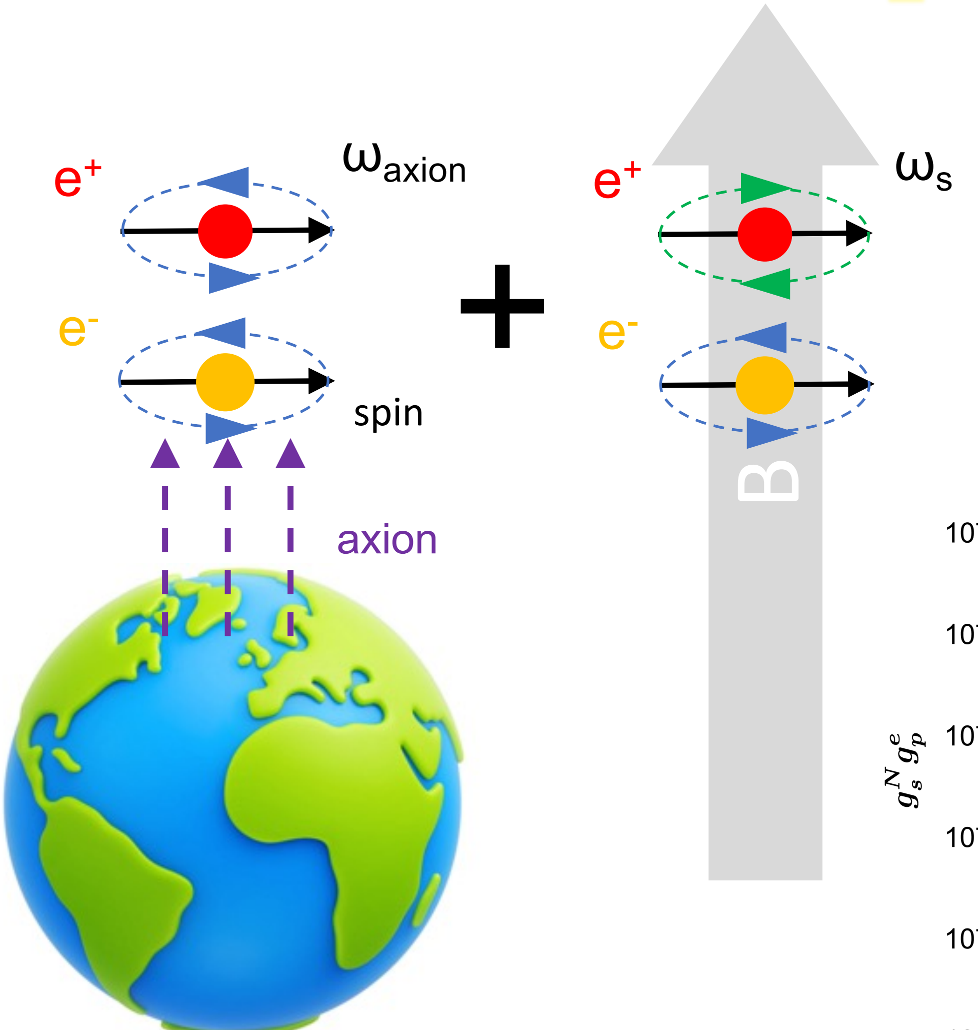
earth-source



much larger nucleon source
how to separate from static B?

Prateek Agrawal, et. al., Phys. Rev. D 108, 015017

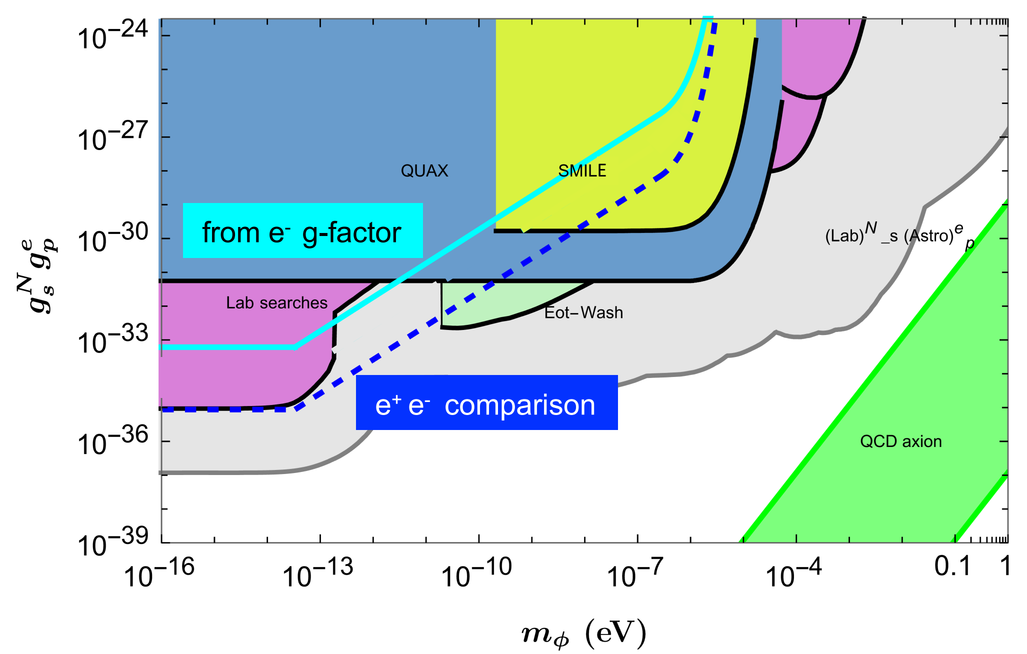
Penning Trap
Particle anti-particle Switch



XF and Mario Reig, arxiv:2310.18797

$$\omega_{tot}(e^+) = \omega_s - \omega_{axion}$$
$$\omega_{tot}(e^-) = \omega_s + \omega_{axion}$$

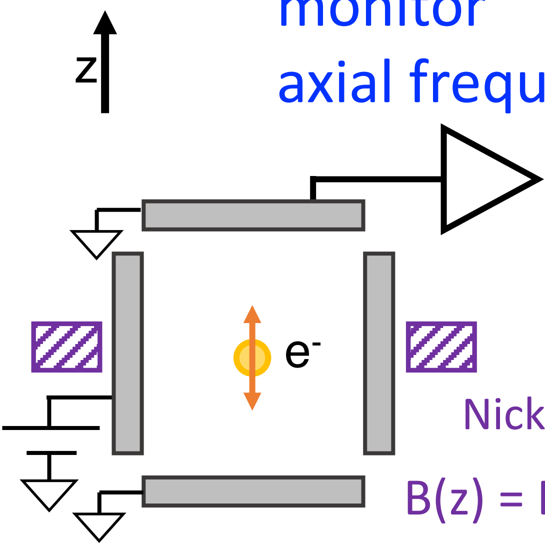
$e^+ e^-$ switch
isolates axion effect from *B*-field



How to Detect Transition?

Phys. Rev. Lett. 59 (1987) 26.

monitor
axial frequency ν_z



$B(z) = B_0 + B_2 z^2$

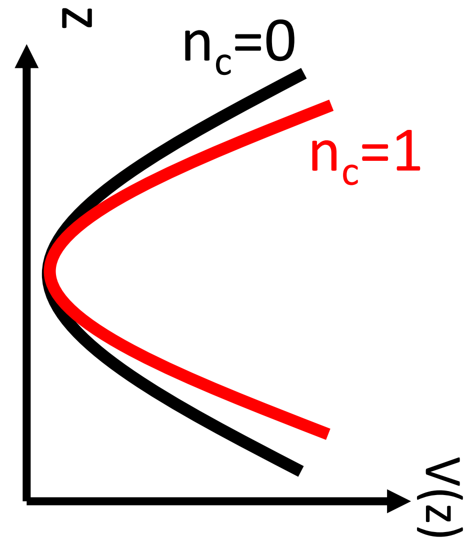
potential along *z*

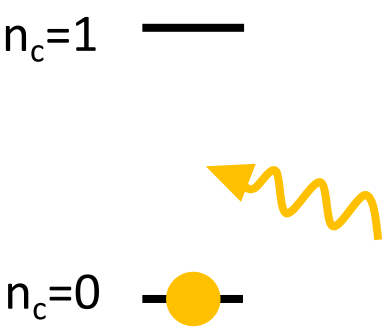
$$V(z) = eV_2 z^2 + \mu_{tot} B_2 z^2$$

electric potential

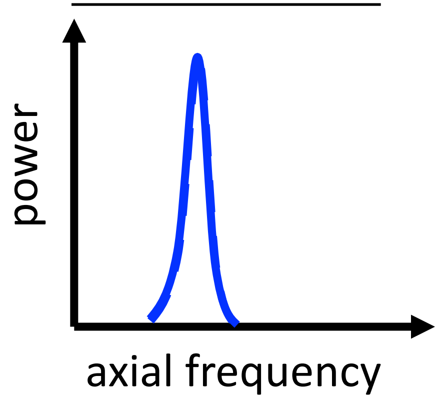
magnetic potential

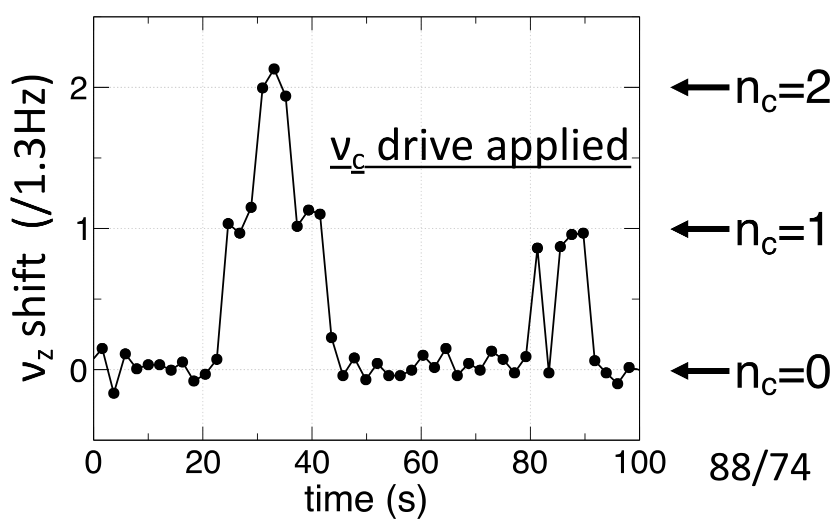
$\mu_{tot} \propto n_c$





Fourier spectrum of axial oscillation





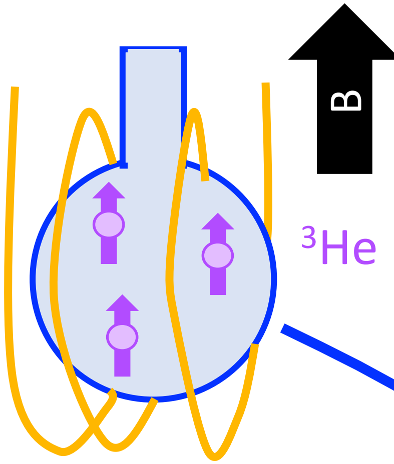
Cryogenic ^{3}He NMR Probe

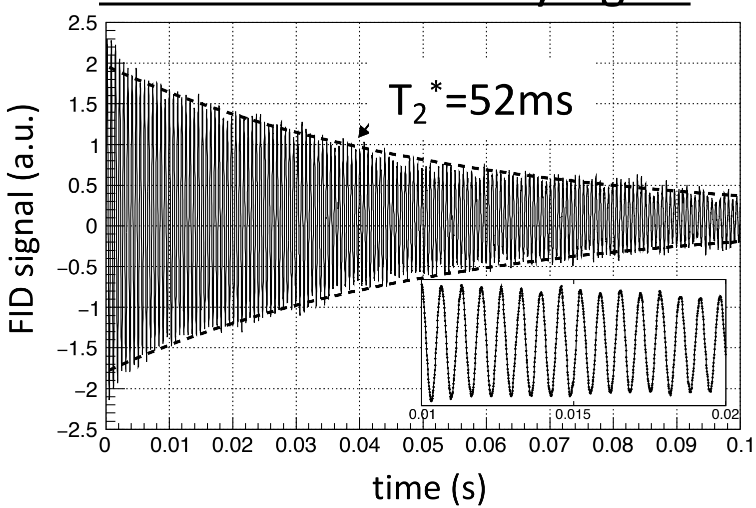
X.Fan, et al., Rev. Sci. Instrum. **90,** 083107 (2019)

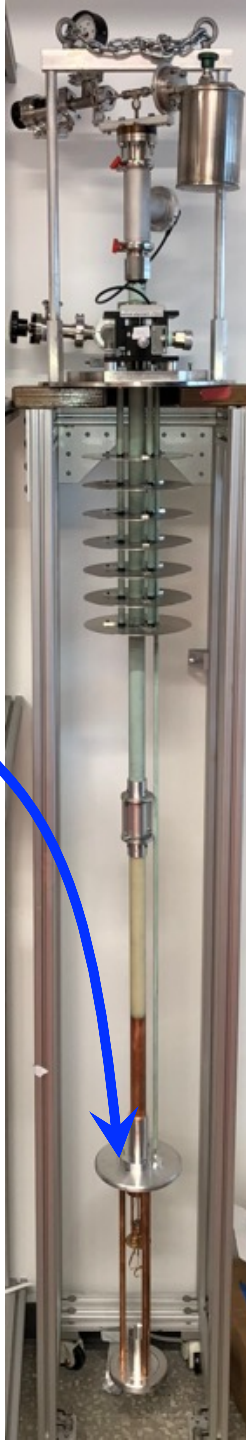
- Much faster/easy way to measure magnetic field/homogeneity

😩 Water-NMR probe does not work in the LHe-bore magnet
😄 invented a cryogenic ^{3}He NMR probe!
🎁 large signal with no optical pumping!

→ allows measurements of g/2 at many fields



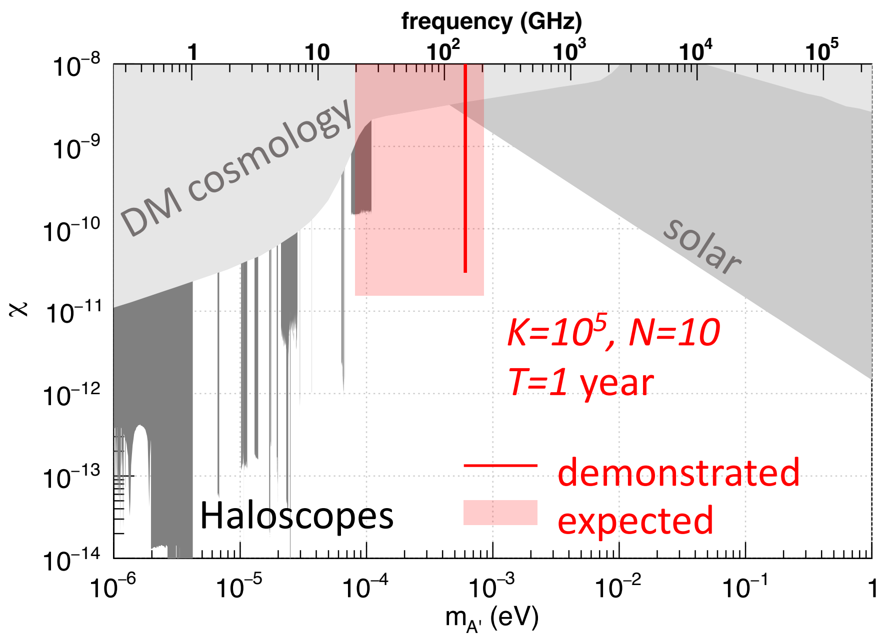


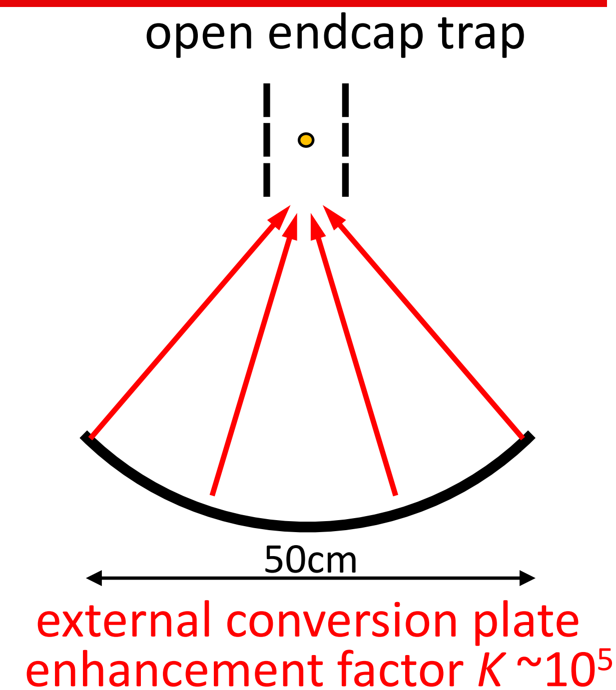


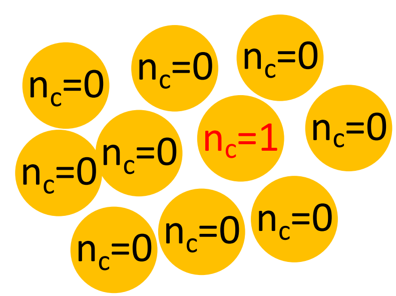
Future

Ideas

- ✓Using an open endcap trap
- ✓external focusing antenna
- ✓trap n_e=10 (or more) electrons and look for one cyc. excitation







Also designing an experiment for an axion can reach QCD axion at ~meV, but only $\Delta\omega/\omega$~10^{-6}

Why Measure ν_a, not ν_s?

$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_a}{\nu_c}$$

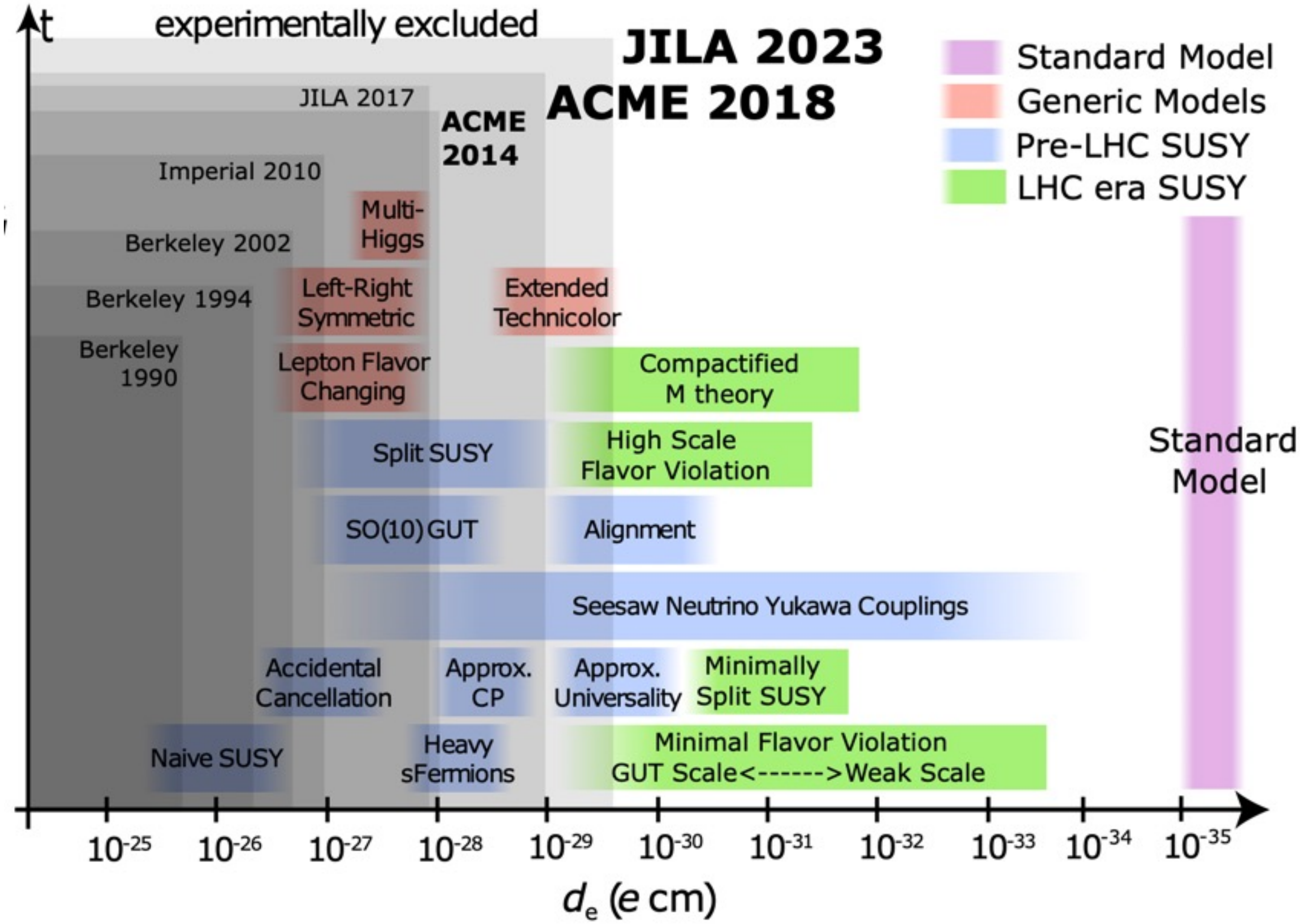
~1.001

~0.001

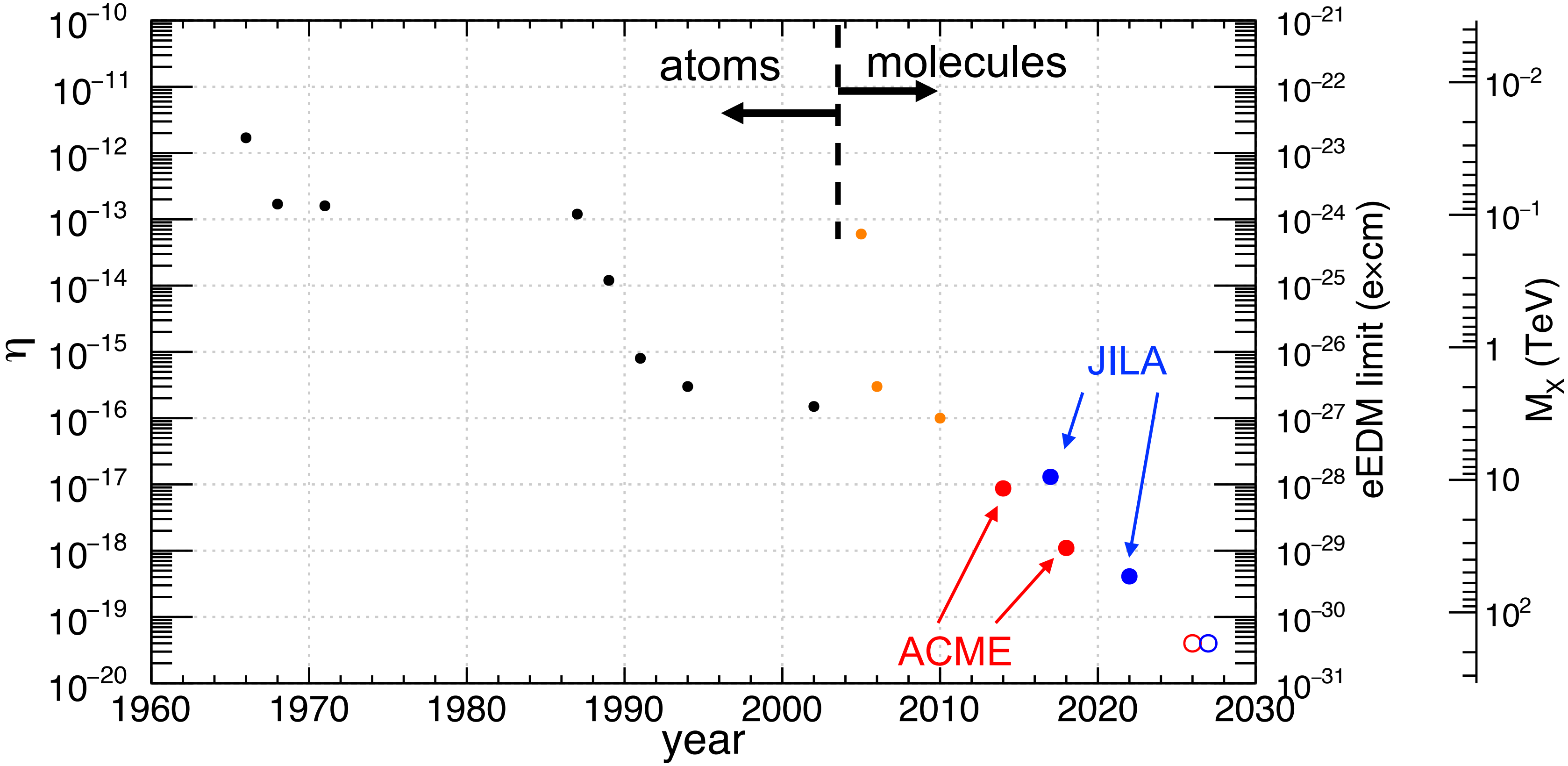
😣 measuring this at 10^{-13} precision

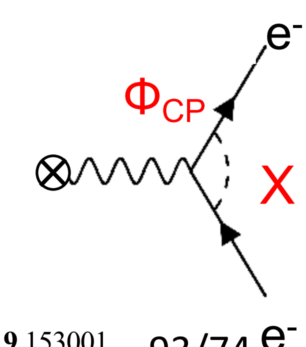
🤗 measuring this at 10^{-10} precision

Broad eEDM limit



electron EDM History





Science **343**, 269 (2014) Phys. Rev. Lett. **119** 153001
Nature **562**, 355 (2018) Science, **381**,46 (2023)

Molecule & Pear Nuclear = Best & Best

$$\delta\theta_{QCD} \propto \frac{1}{E\,A\,\tau\sqrt{\dot{N}}}$$

	^{199}Hg current best limit	^{229}ThF^{+} proposed
effective E field E	10 kV/cm	~ GV/cm
EDM size by θ_{QCD} (e×cm) A	$5\times10^{-20}\ \times\theta_{QCD}$	$2\times10^{-16}\ \times\theta_{QCD}$
spin precession time τ	150 s	10s - 1000s?
N of count per second $\dot{N}$	10^{12}	1 - 100?

$\times10^{5}$ molecule enhancement

$\times10^{3}$ pear-shape enhancement

$\mathcal{O}(1)$

research topic

ion trap

- can improve θ_{QCD} limit with 1 molecule, τ=10 seconds, and 1 week of measurement

One More Best: Magnetic Field Insensitivity

want to make this small

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \overrightarrow{d_e} \cdot \vec{E}$$

2.002…

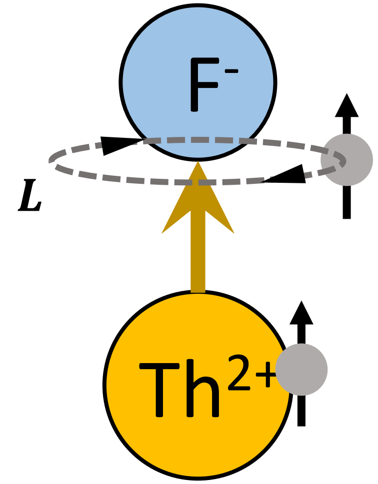
$$\mu = \frac{-e\hbar}{2m} (\boldsymbol{L} + g\,\boldsymbol{S})$$

choose a state with $\boldsymbol{L} = -\mathbf{2}$ and $\boldsymbol{S} = +\mathbf{1}$

→ >100 suppression of $\boldsymbol{\mu} \cdot \boldsymbol{B}$

Developed and successfully used in eEDM.
called ***<u>3Δ1</u>*** state

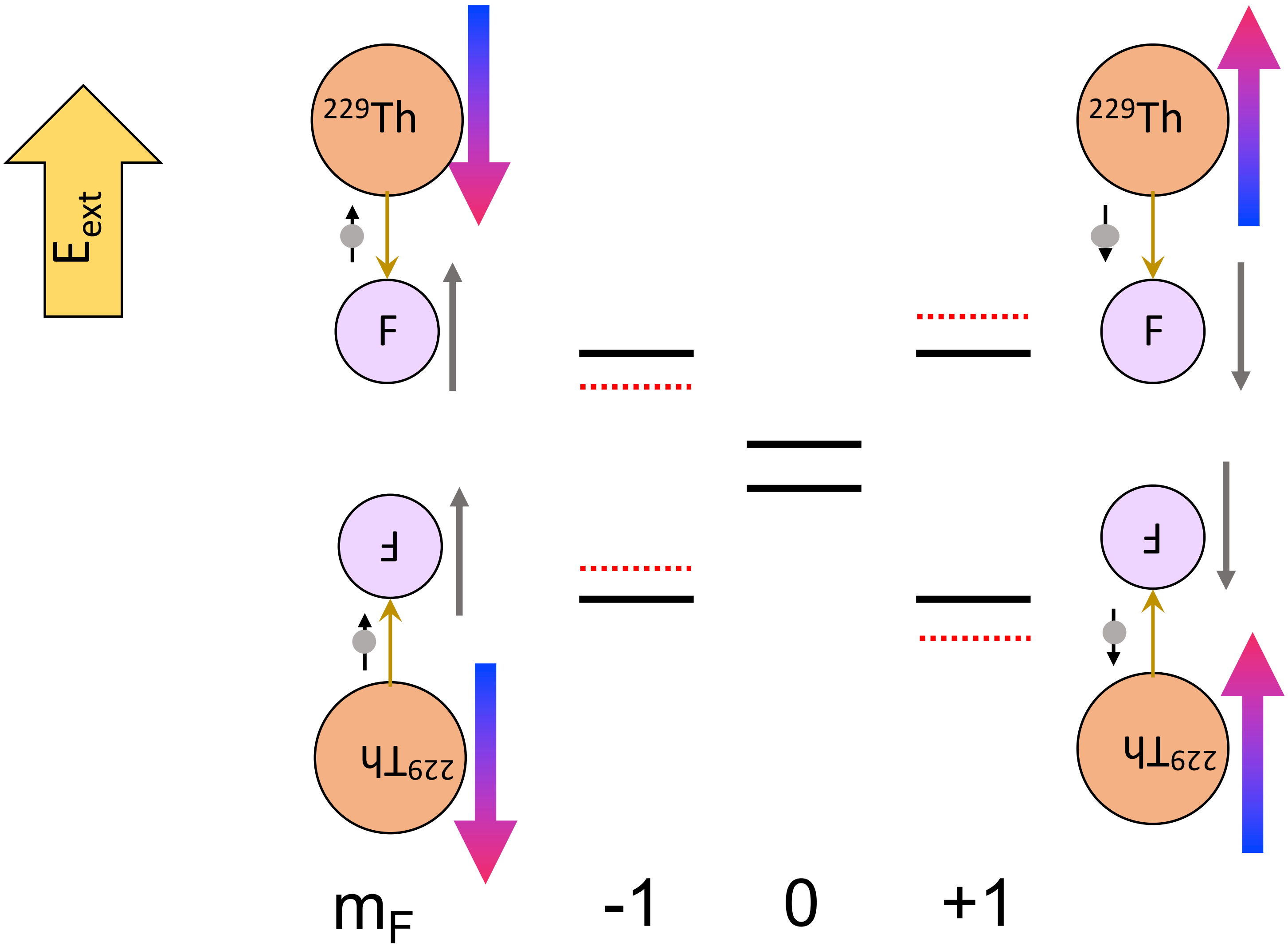
Only two known ground-state 3Δ1 molecules
ThF^+ and WC



E. R. Meyer, J. L. Bohn, and M. P. Deskevich, PRA **73**, 062108 (2006)
Leanhardt, Aaron E., et al. J. of Mol. Spec., **270** 1 (2011)
D. DeMille, et.al., AIP Conference Proceedings, **596,** 72 (2001)

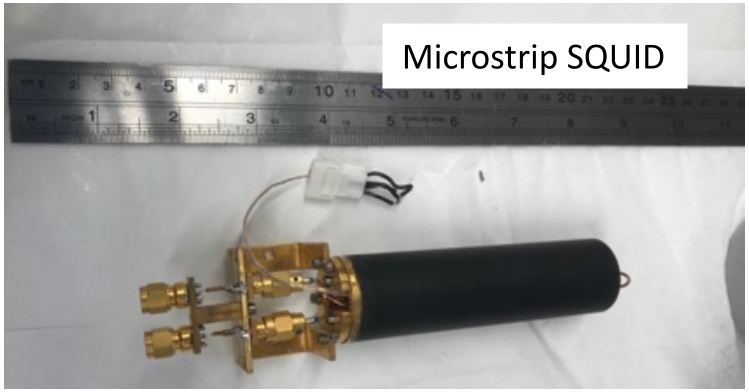
Possible States to Use

there are 72 states in $^3\Delta_1$: Use $F_1 = J + I_{Th} = 3/2$, $F = F_1 + I_F = 1$

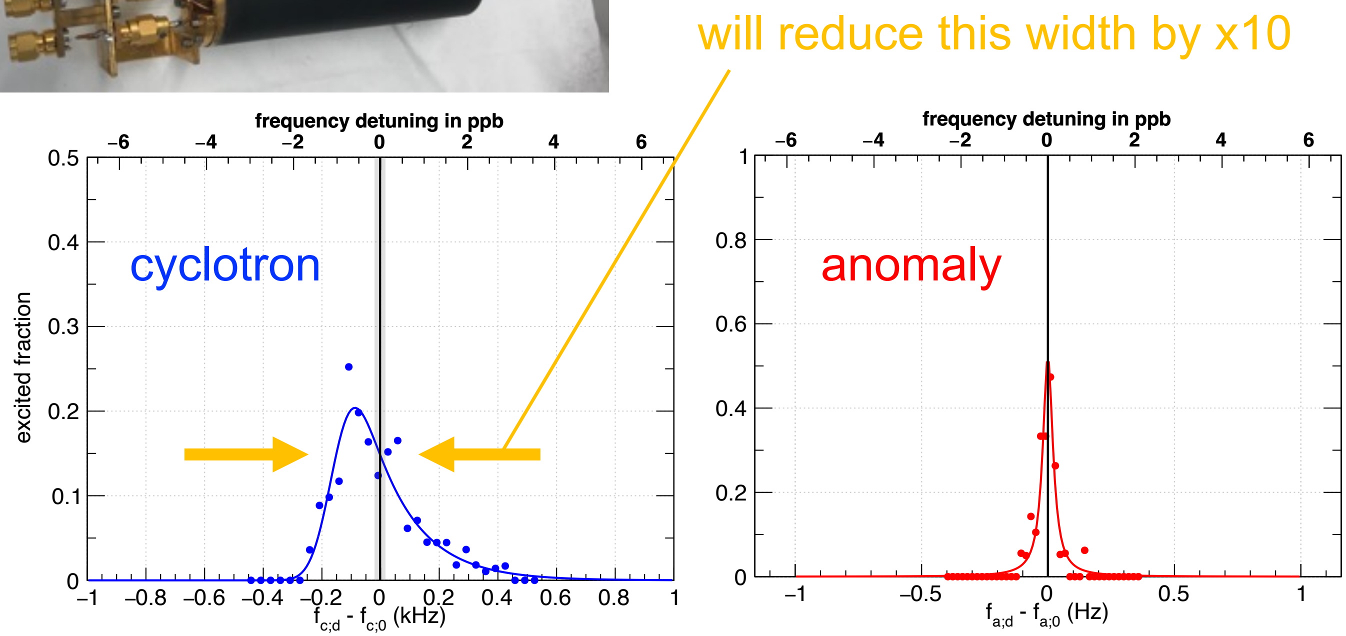


Toward muon g-2 sensitivity
Superconducting amplifier

- Reduce thermal linewidth by x10
- ongoing in the Gabrielse group



stat.	0.029×10^{-12}
sys. (temperature)	0.094×10^{-12}
sys. (microwave cavity)	0.090×10^{-12}



$^{229}ThF^+$ structure