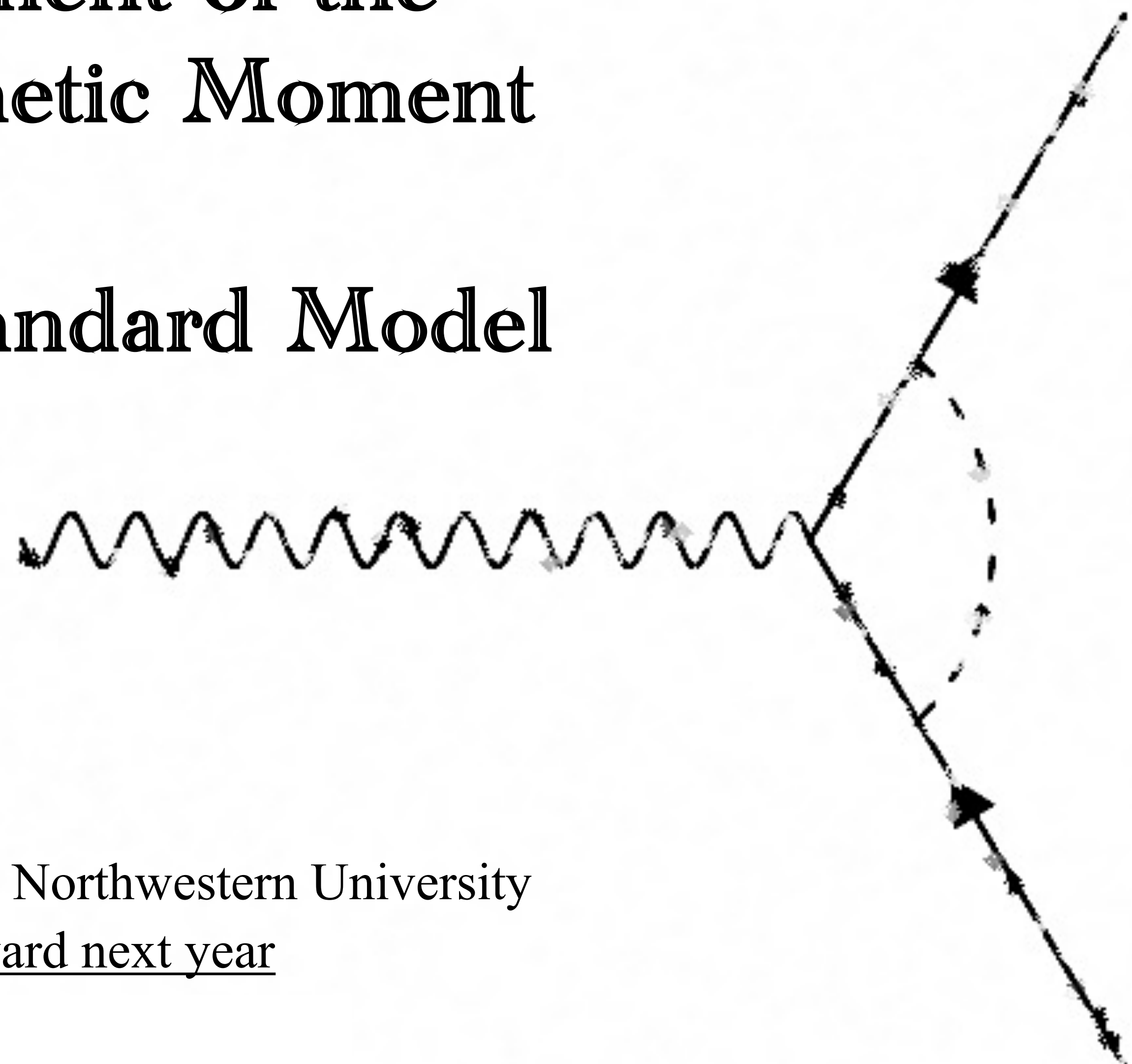
New Measurement of the Electron Magnetic Moment and Beyond the Standard Model



Xing Fan

Research Assistant Professor Northwestern University

<u>Starting a new group at Harvard next year</u>

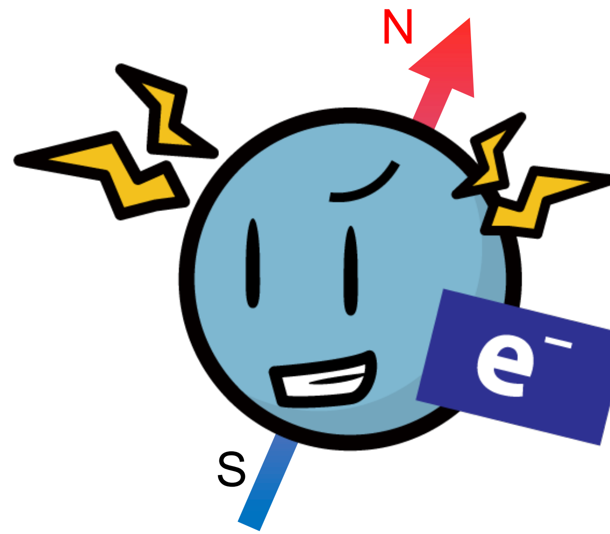
U.S. DEPARTMENT OF ENERGY

JOHN TEMPLETON FOUNDATION

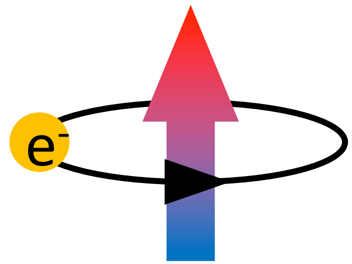
Masason Foundation

Electron's Magnetic Moment

- Magnetic moment of an orbiting charge



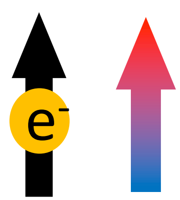
angular momentum ***L***



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

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

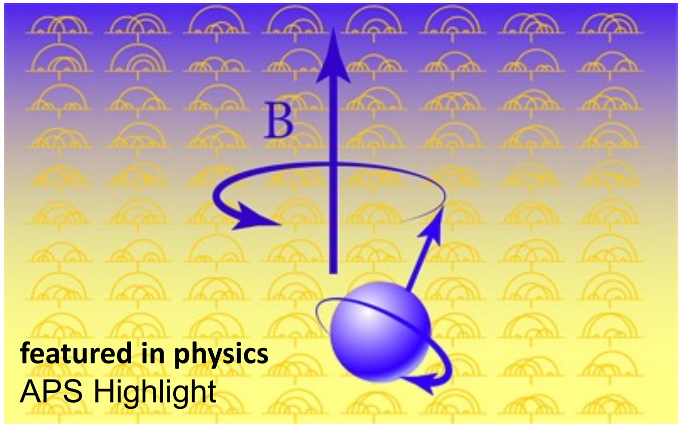
$\boldsymbol{S} = \frac{\hbar}{2}$



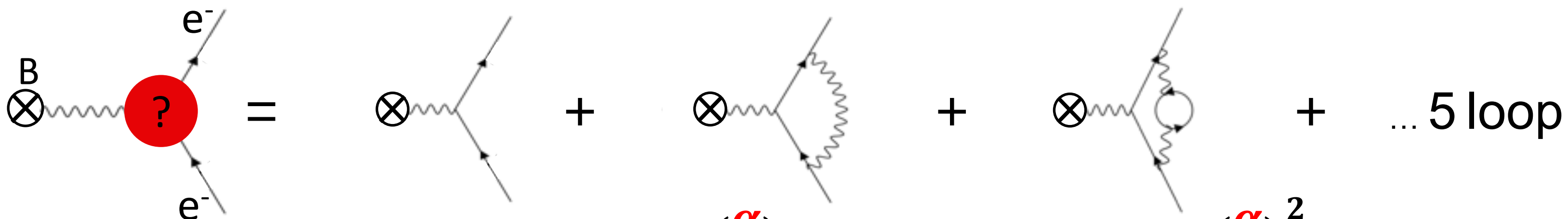
$$\boldsymbol{\mu} = \frac{-e}{2m} \times \frac{\hbar}{2} \; ? \times g$$

***g*= 2.002 319 304 360 ...**

SM g-factor

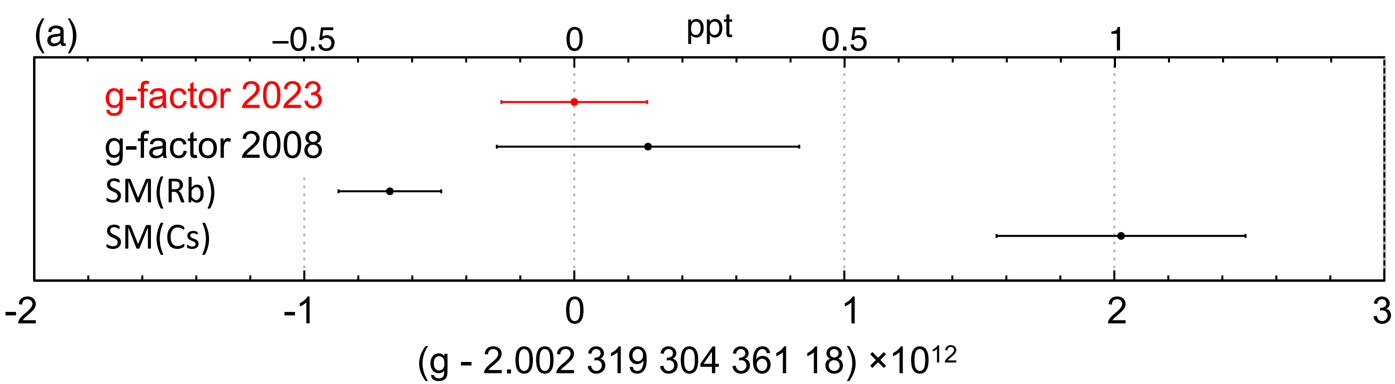


***g*(SM calc.) = 2.002 319 304 360 50 (18)**

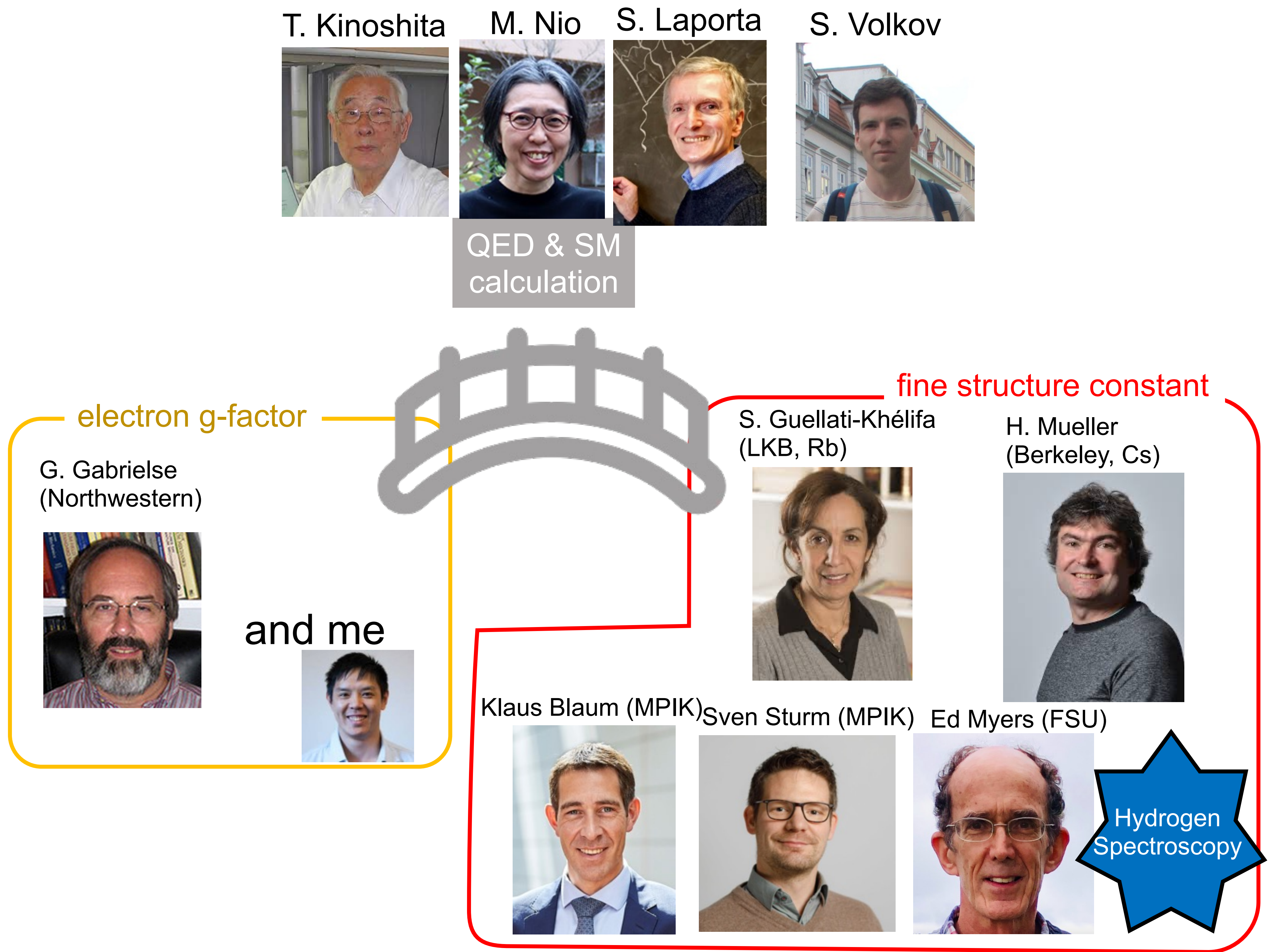


$$g = 2 + \left(\frac{\alpha}{\pi}\right) + -0.656\ldots\times\left(\frac{\alpha}{\pi}\right)^2 + \cdots$$

fine structure constant



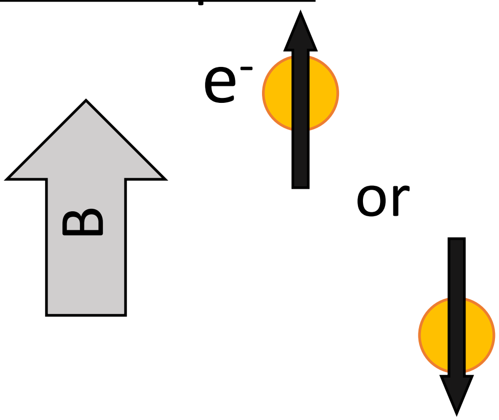
XF, et al, Phys. Rev. Lett. **130**, 071801 (2023)



T. Kinoshita
M. Nio
S. Laporta
S. Volkov
QED & SM calculation
electron g-factor
G. Gabrielse (Northwestern)
and me
fine structure constant
S. Guellati-Khélifa (LKB, Rb)
H. Mueller (Berkeley, Cs)
Klaus Blaum (MPIK)
Sven Sturm (MPIK)
Ed Myers (FSU)
Hydrogen Spectroscopy

Principle of *g*-factor measurement

<u>In free space</u>



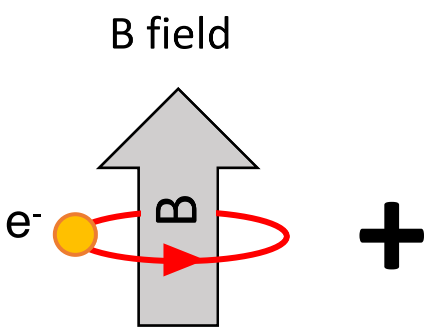
$$\Delta E_s = 2\mu \cdot B = \frac{g}{2} \times \frac{\hbar e B}{m}$$

spin precession
energy $h\nu_s$

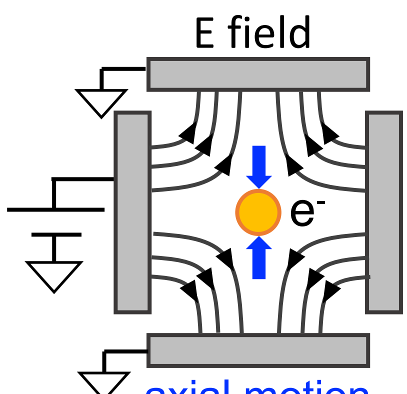
$$\frac{g}{2} = \frac{\nu_s}{\nu_c}$$

cyclotron motion
energy $h\nu_c$

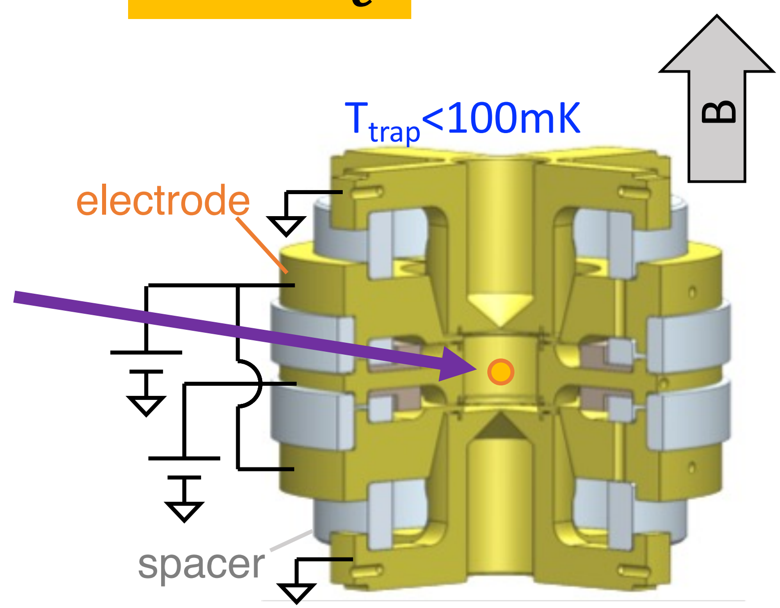
<u>In a Penning trap</u>



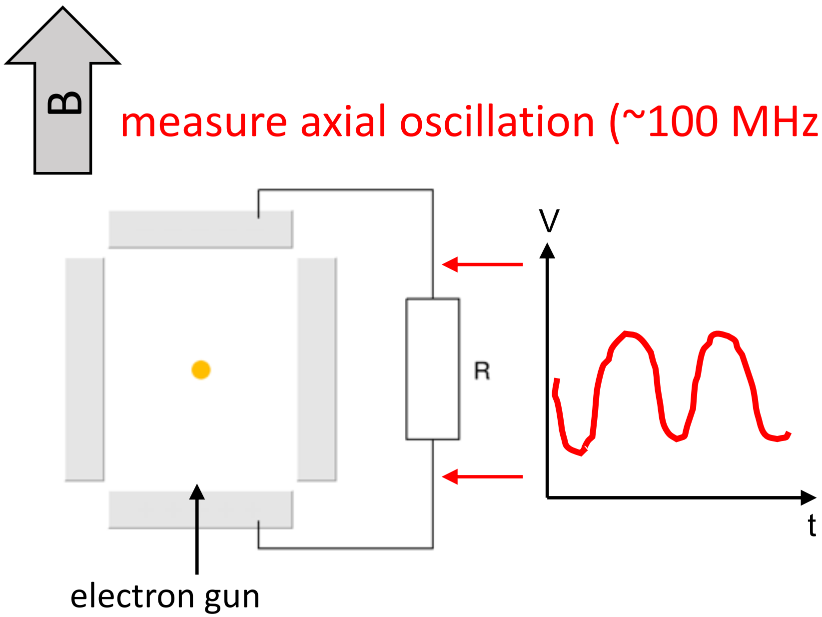
cyclotron motion
ν_c~150GHz

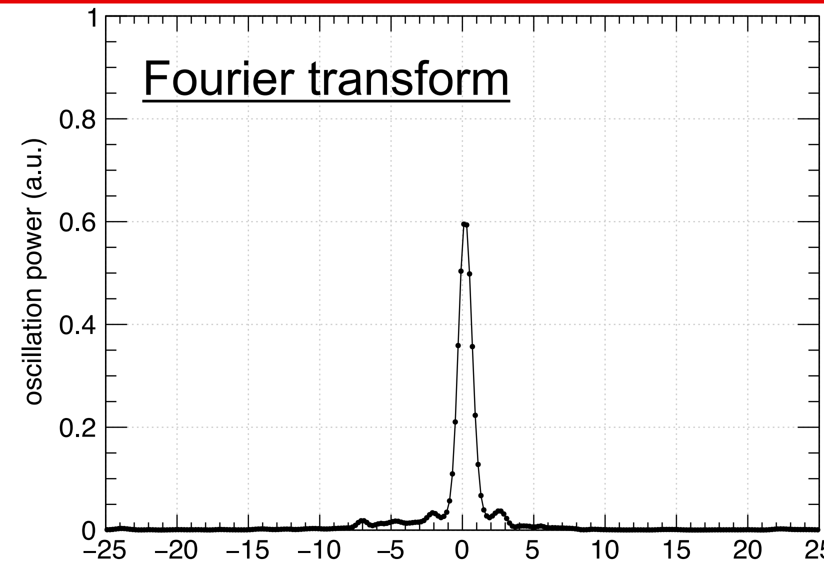


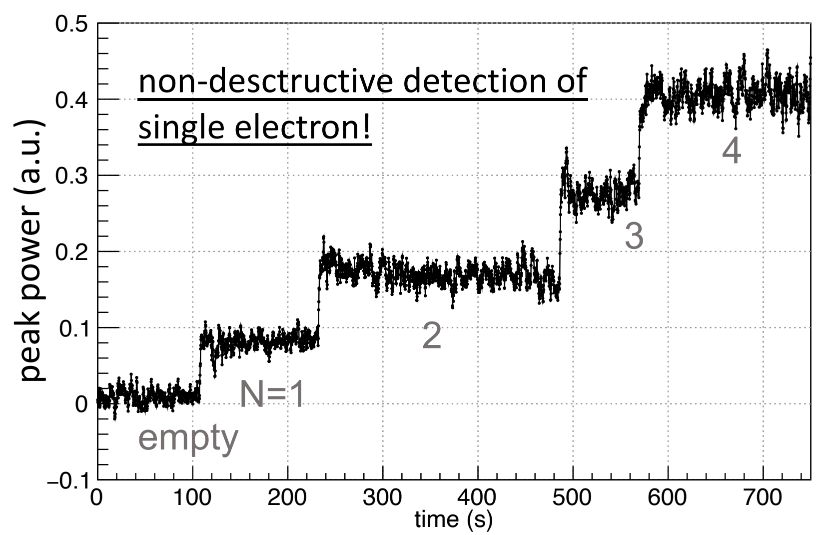
axial motion
ν_z~100MHz



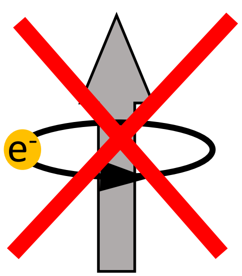
Electron Detection with Axial Motion







Quantum Picture of Cyclotron Motion = Penning Trap "Atom"



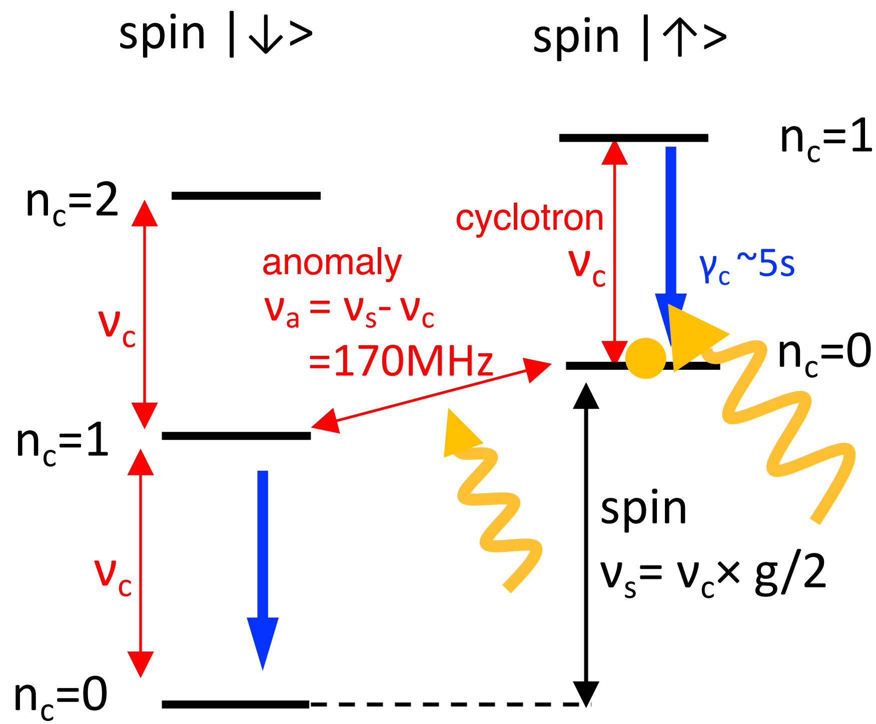
$\nu_c = 150$ GHz

$h\nu_c / k_B = 7.2$K

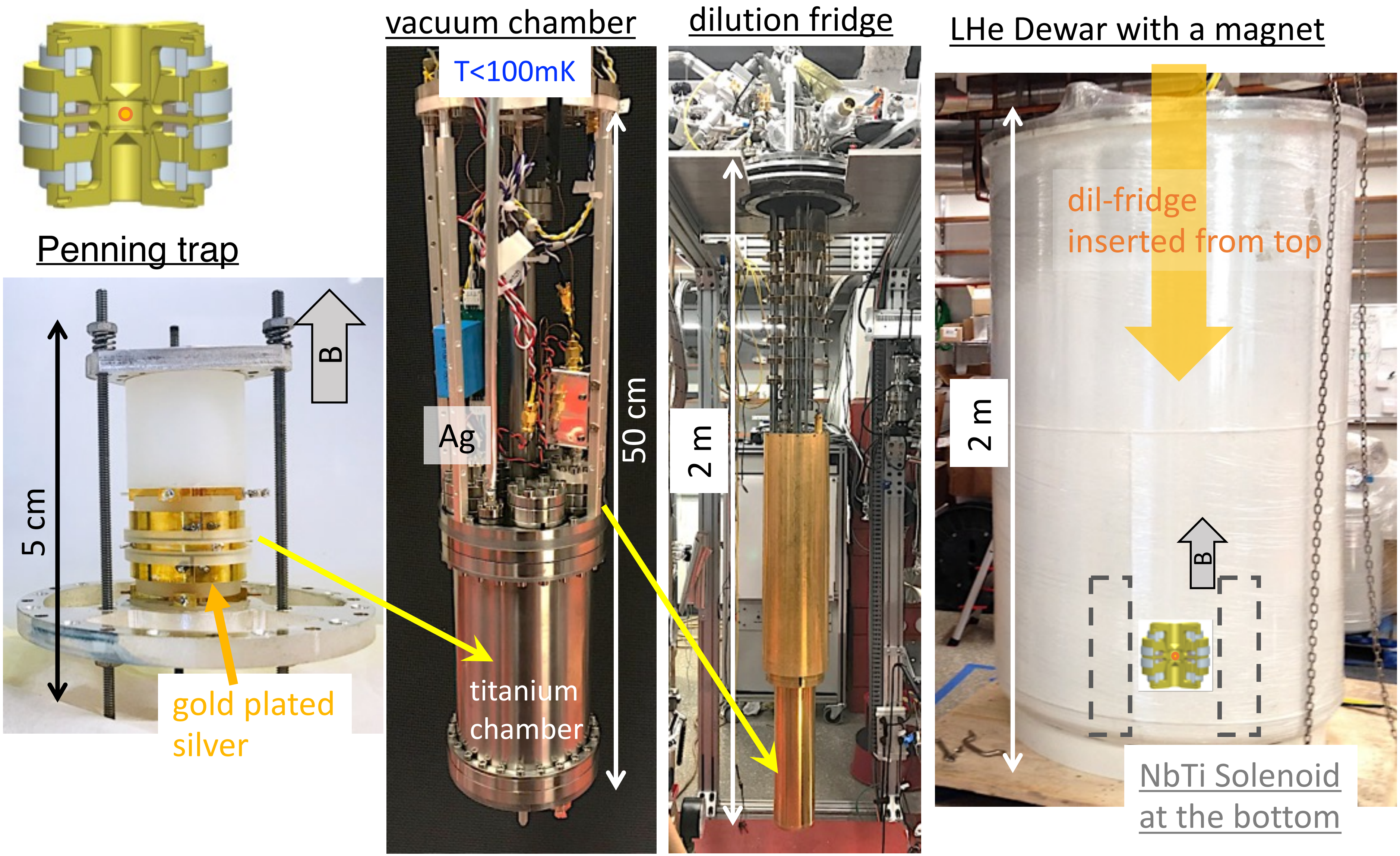
$T_{trap} = 100$mK

Quantized energy levels

(Landau levels)

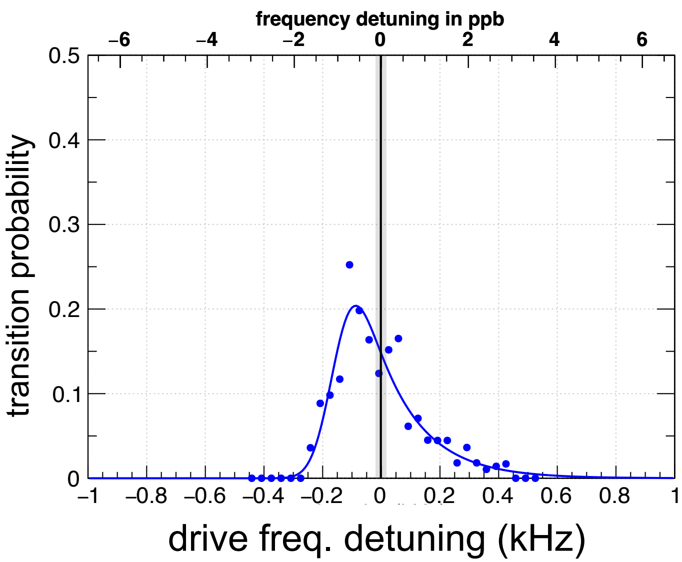


The New Apparatus

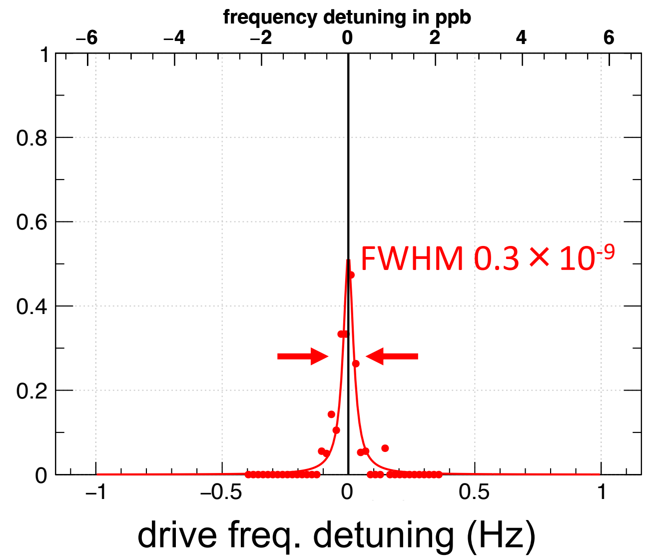


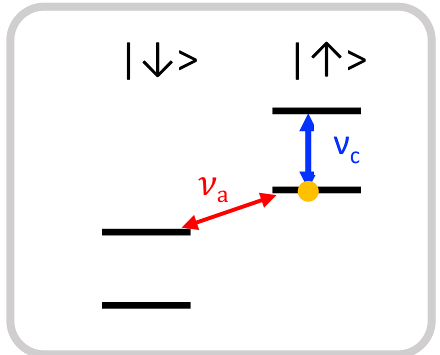
Spectroscopy
Transition Prob. vs Drive Freq

cyclotron



anomaly



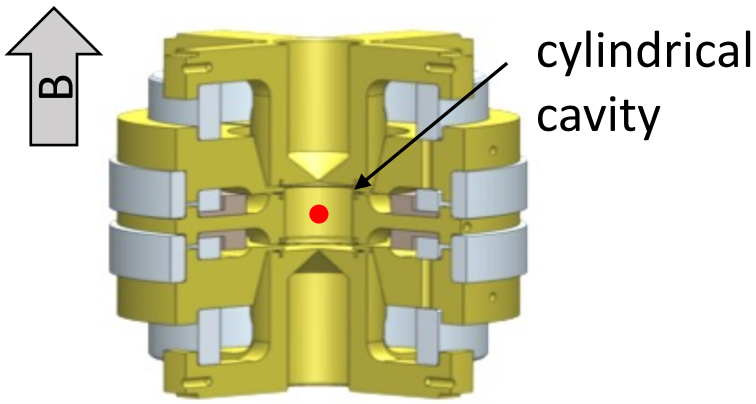


$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_a}{\nu_c}$$

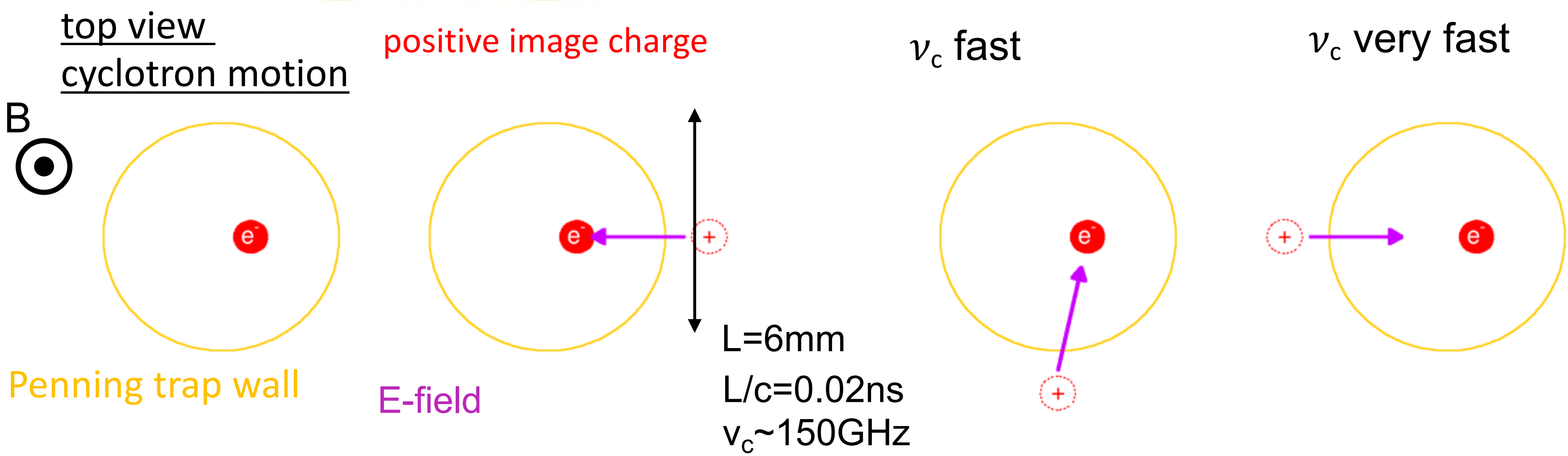
- Linewidth is dominated by axial temperature and fast 0.5ppb B field fluctuation

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

Image Charge Shift

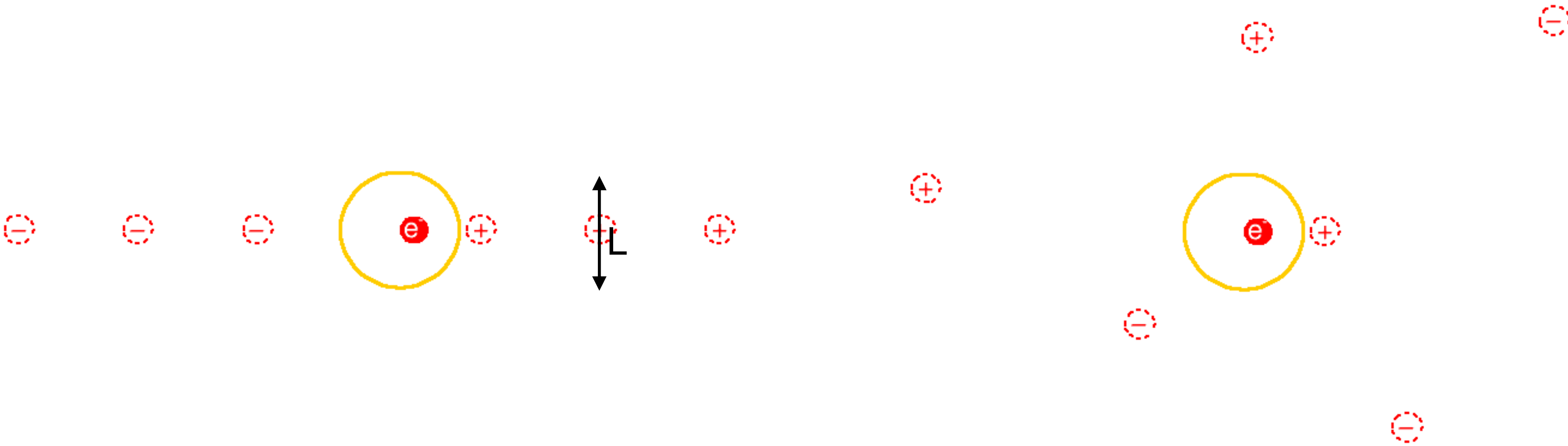


$$\frac{g}{2} = \frac{\nu_s}{\nu_c + \Delta\nu_c^{ICS}}$$



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

Image Charge of Image Charge…

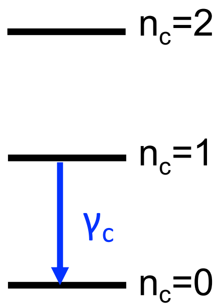


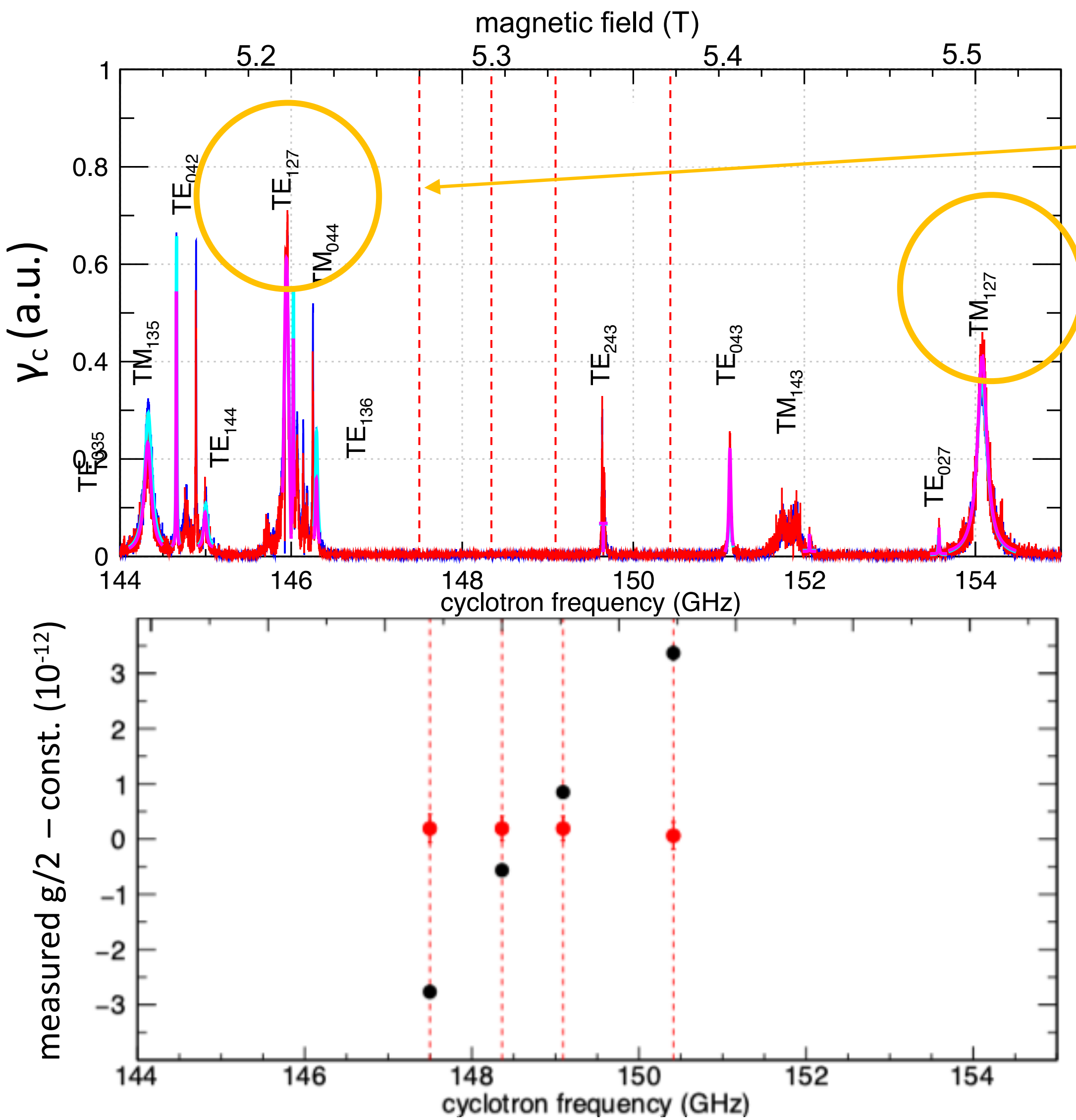
ν_c = c/2L × n
<u>large shift!</u>

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!

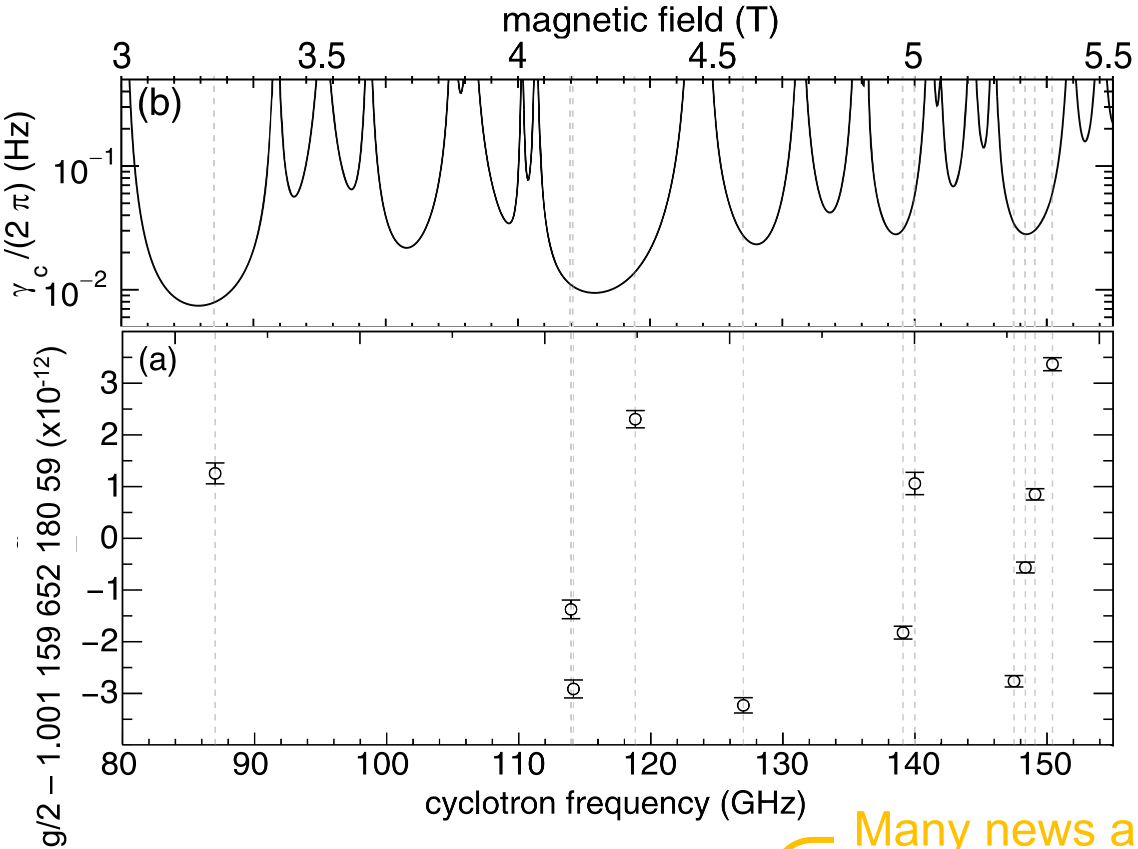




strongly coupled resonances

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

average 11 fields from 3 T to 5.5T

g = 2.002 319 304 361 18 (27)

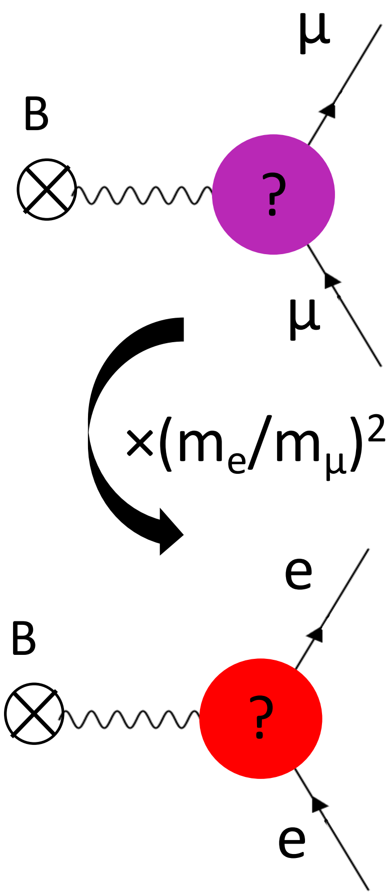
α^{-1} = 137.035 999 166 (15)

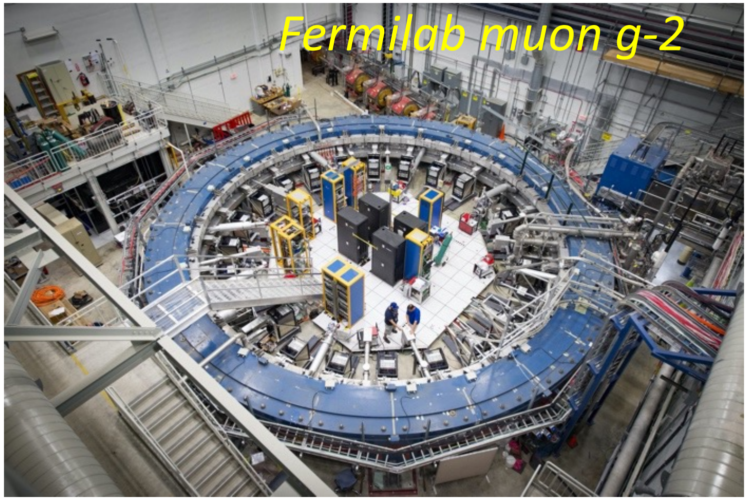
Many news articles

PHYS ORG · WIRED · ScienceNews INDEPENDENT JOURNALISM SINCE 1921 · nature RESEARCH HIGHLIGHT · NewScientist …etc

appears in 18 Wikipedia pages

Able to Check Muon g-2?





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

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

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

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

another factor of 2.2

and a better α measurement

Rb (Sorbonne), Cs(Berkeley), Sr? Yb?

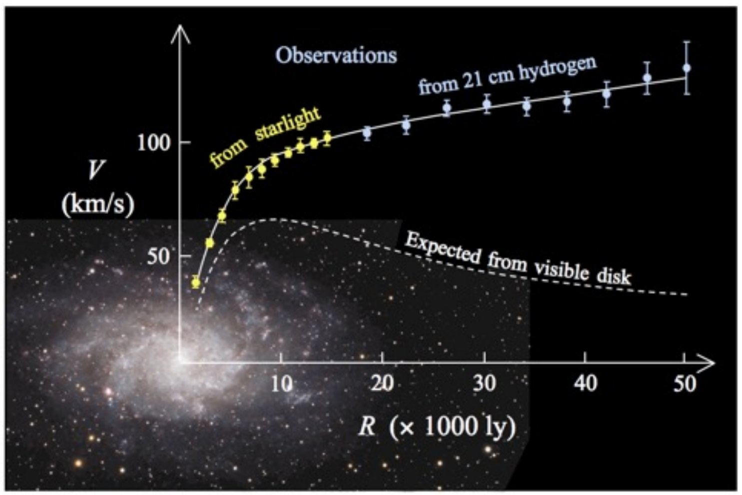
Applying electron g-factor Technique for other physics?

QCD Axion Search

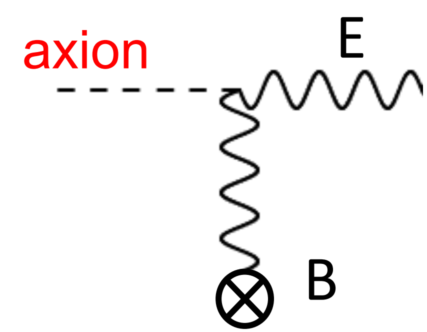
PHYSICAL REVIEW LETTERS **129,** 261801 (2022)

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]



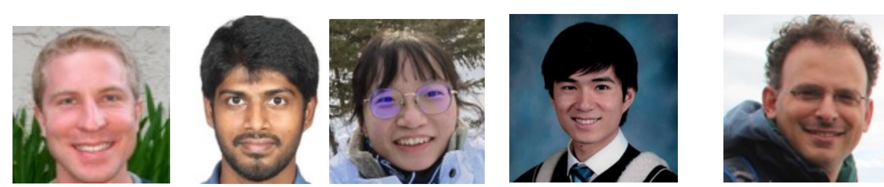
axion-photon coupling



theory collaborators

Stanford University
- Peter Graham
- Harikrishnan Ramani
- Samuel S. Y. Wong
- Yawen Xiao

Fermilab National Laboratory
- Roni Harnik

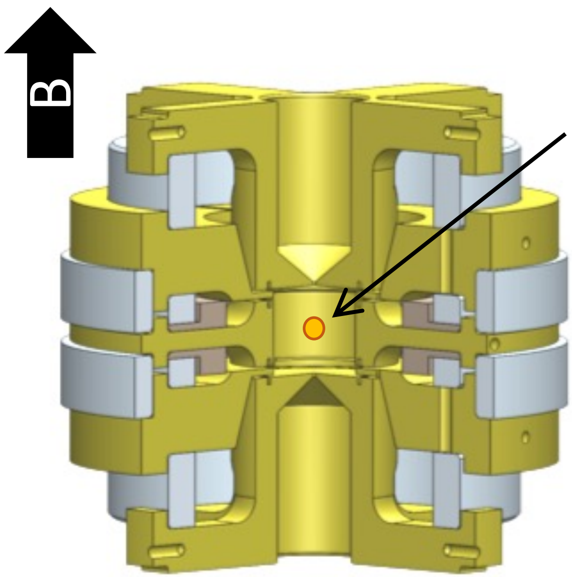


Stanford University

Fermilab

SQMS

Trapped-Electron Milli-eV Detector

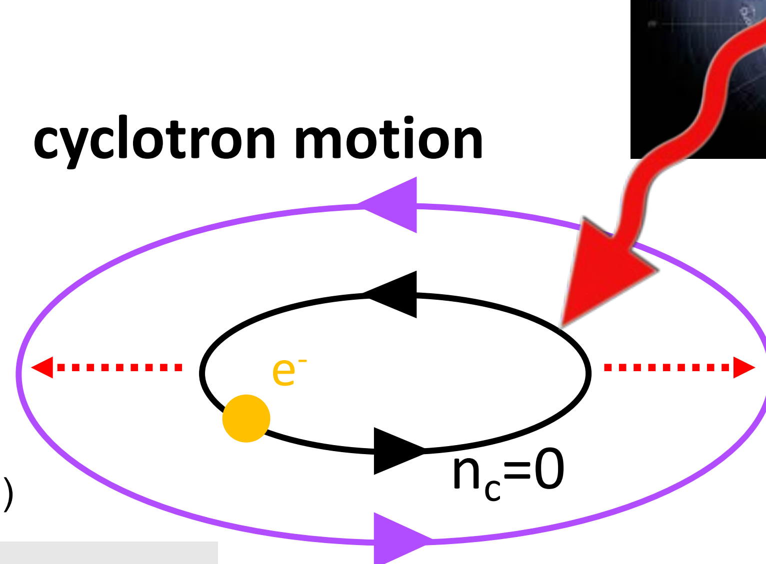


electron(s)
left at n_c=0

XF, et. al., Phys. Rev. Lett. **129**, 261801 (2022)

- challenging meV range (mm-wave)
- background free
- tunable 0.1-1 meV
- compatible with B field

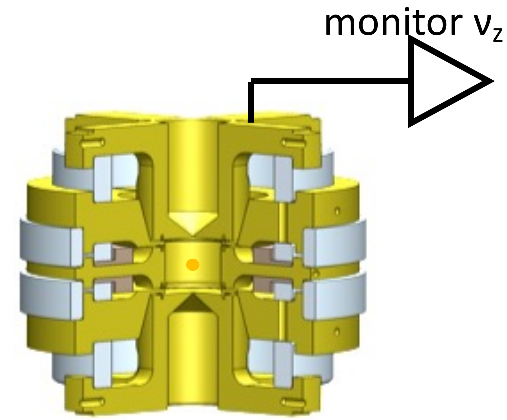
cyclotron motion



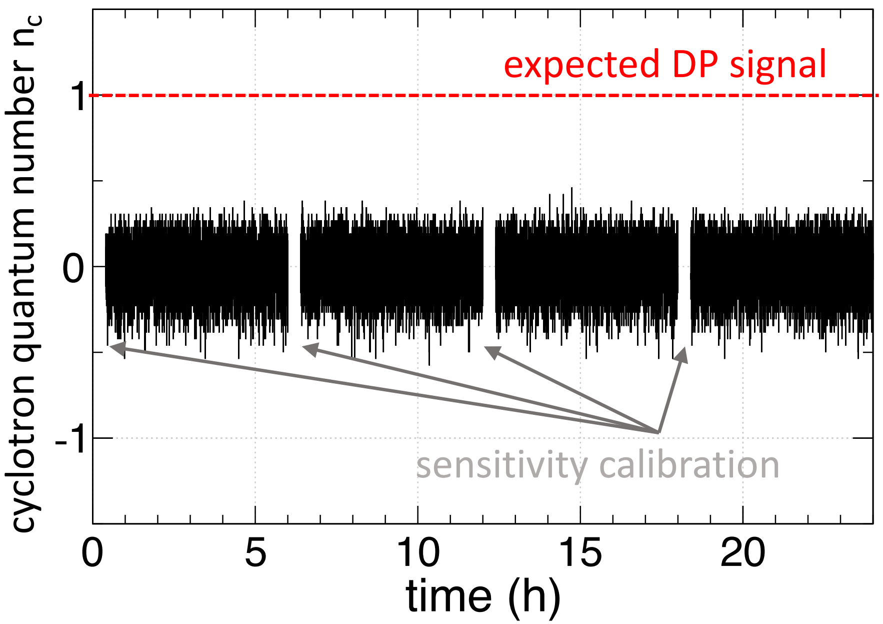
$$\omega_c = \frac{eB}{m}$$

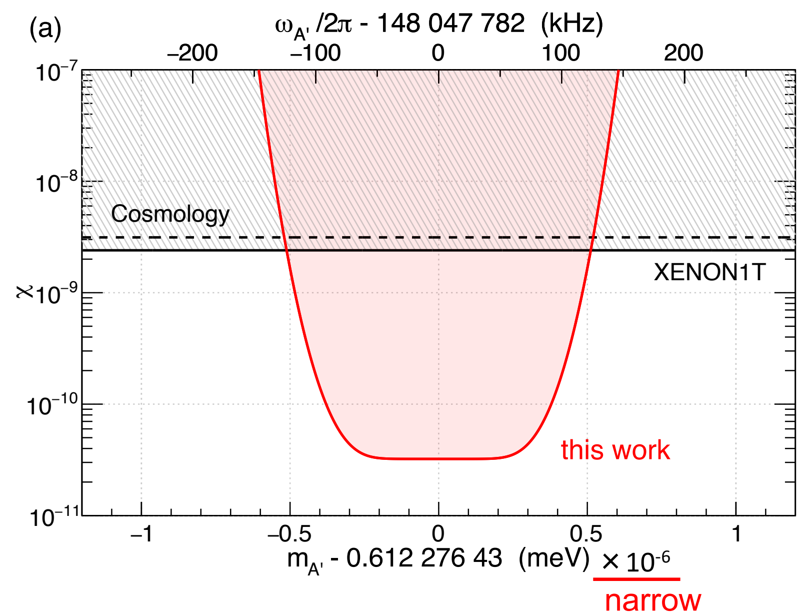
meV B-compatible
BG-free photon counter

Demonstration Search



just leave at n_c=0 and monitor n_c





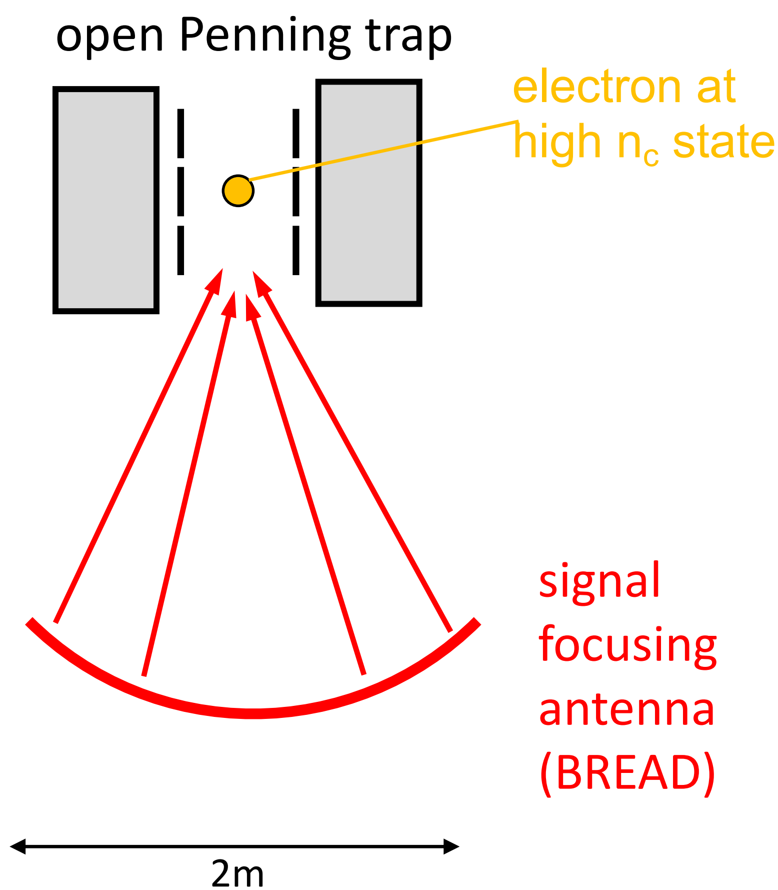
narrow because we used the g-factor setup
what if we construct a dedicated system?

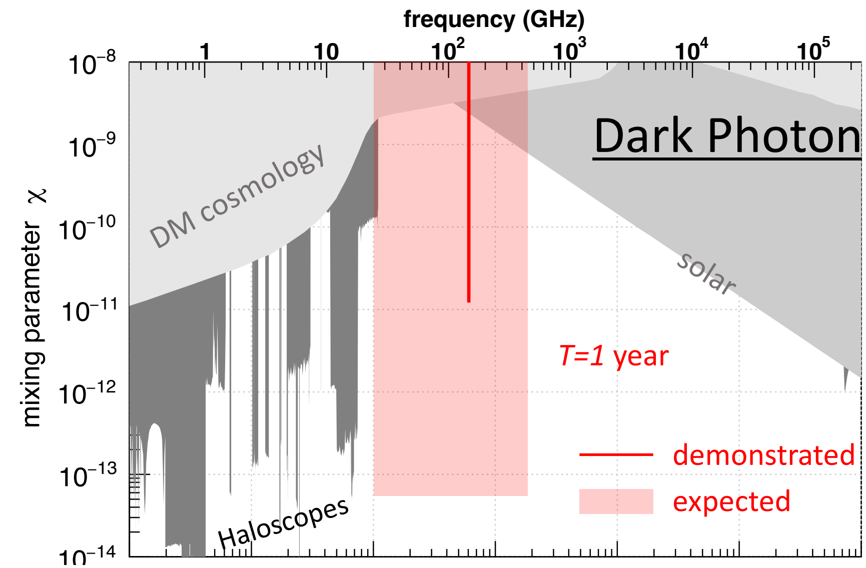
Ideas

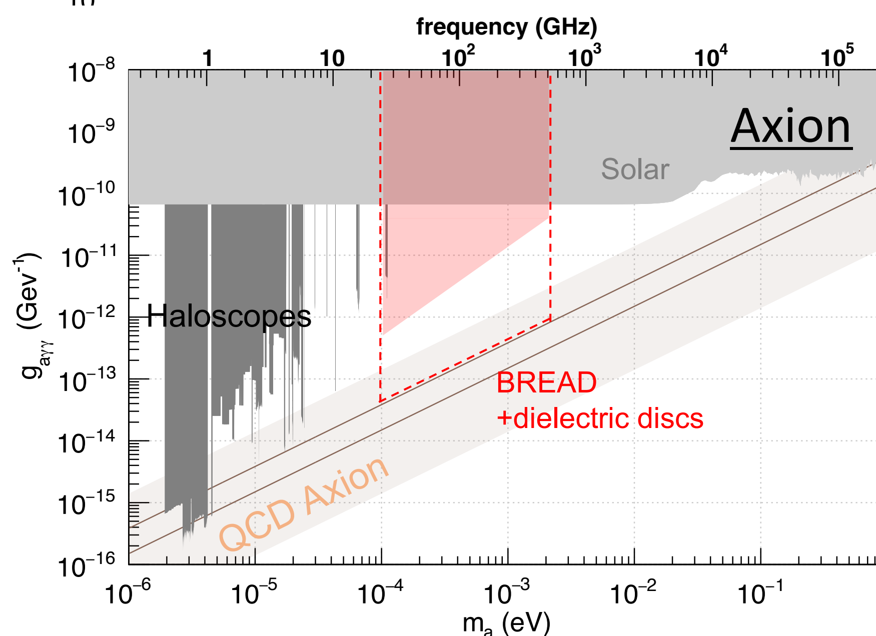
$$\text{sensitivity} \propto A \times n_c$$

conversion surface area (A)

electron's cyclotron quantum number (n_c)

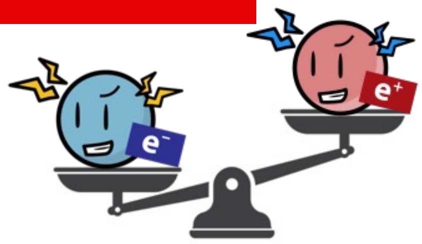






BREAD, PRL **128**, 131801 (2022)

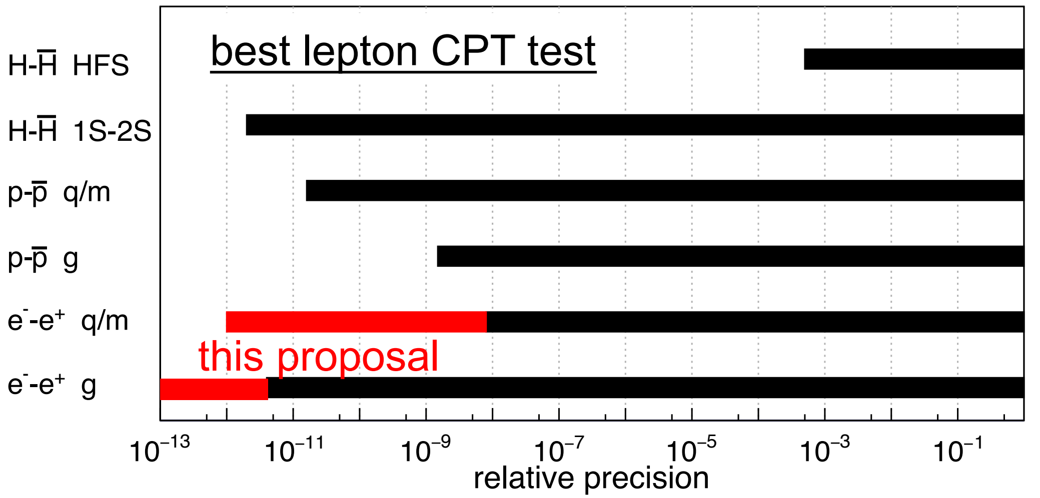
Positron's Measurement



- e^+ g-factor measurement
  - **x100 better than 1987's measurement**
  - most precise lepton CPT test

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

- m_{e+}/m_{e-} at 10^{-11} precision, **x10,000 better than 1981's measurement**
- co-trapping proton and positron
- anti-gravity test at $\delta(\bar{g}/g) \sim 0.03$ level



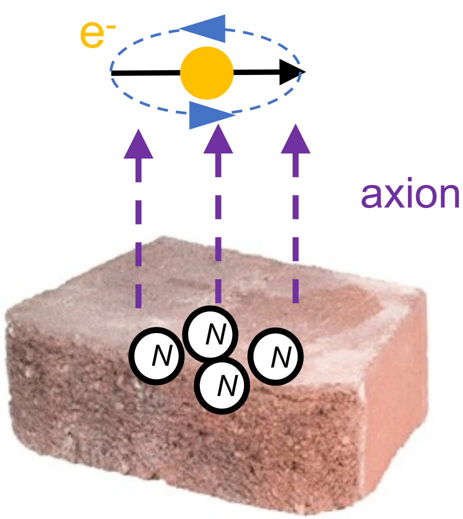
Earth-Sourced Axion-Nucleon-Electron Coupling

axion

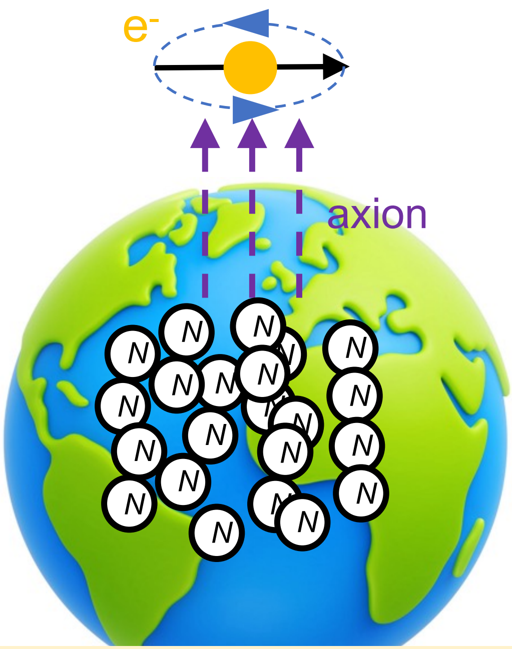
$$\mathcal{L} \supset g_s\phi\bar{N}N + c_\psi \frac{\partial_\mu\phi}{f_\phi}\bar{\psi}\gamma^\mu\gamma^5\psi,$$

nucleon fermion

causes spin rotation near heavy block



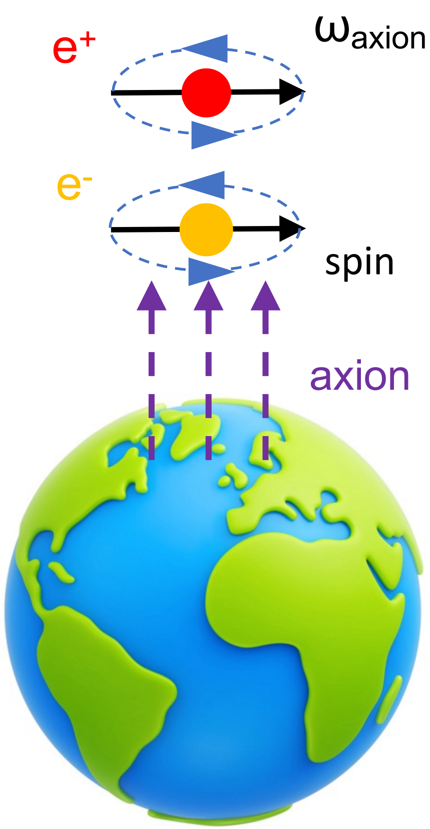
earth-source



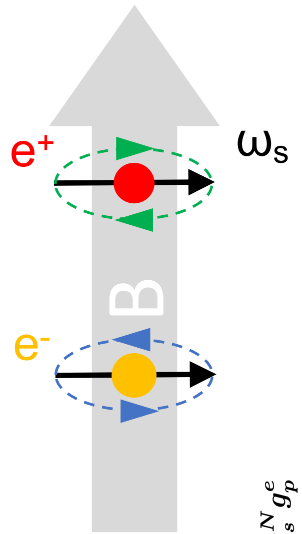
Prateek Agrawal, et. al., Phys. Rev. D 108, 015017

how to separate from static B?

Penning Trap
Particle anti-particle Switch



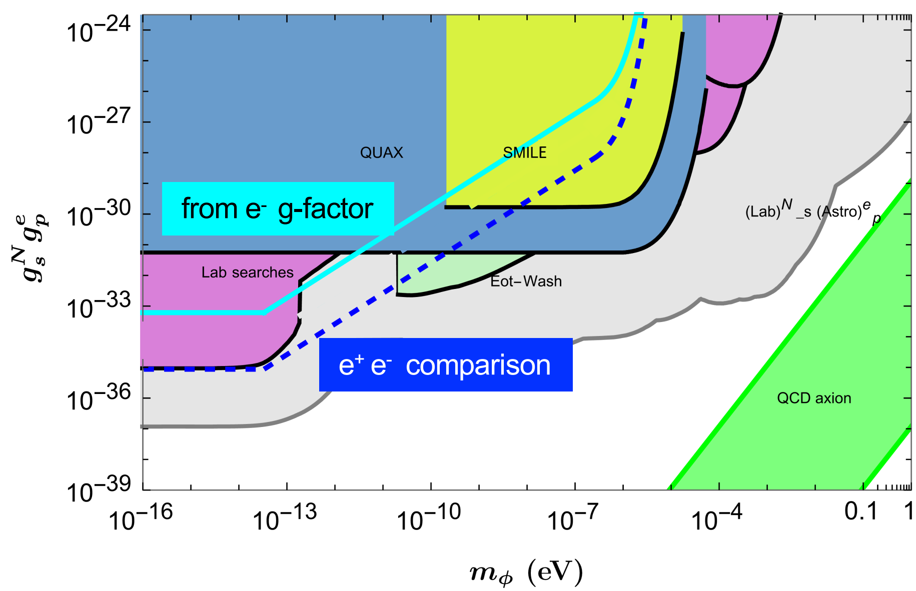
+



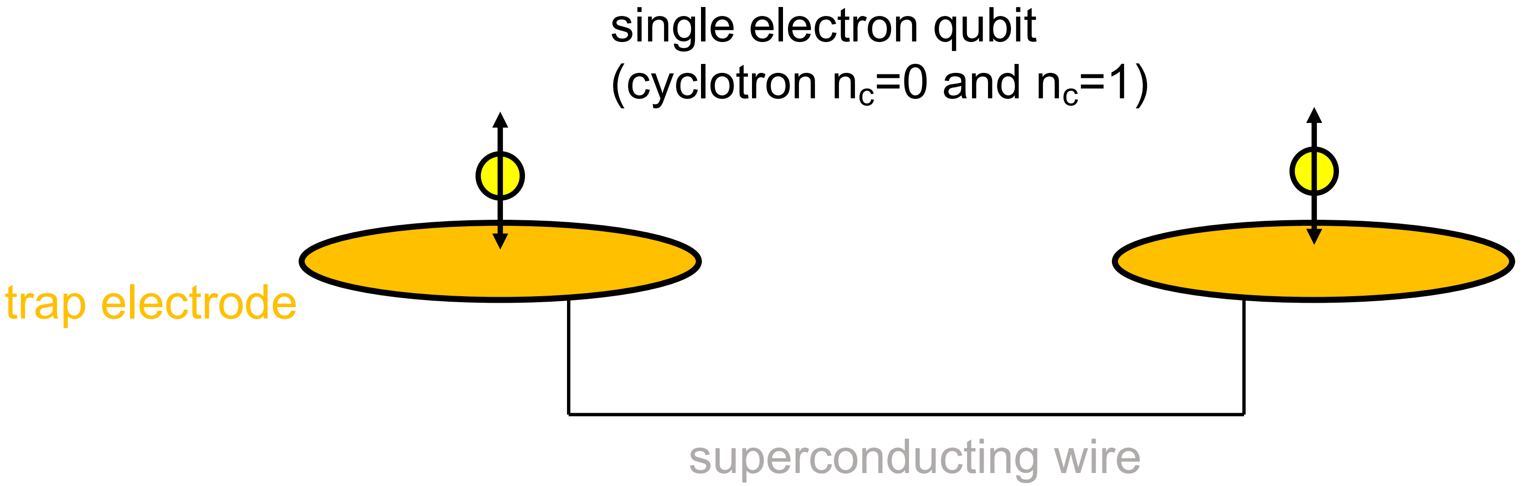
XF and Mario Reig, arxiv:2310.18797

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

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

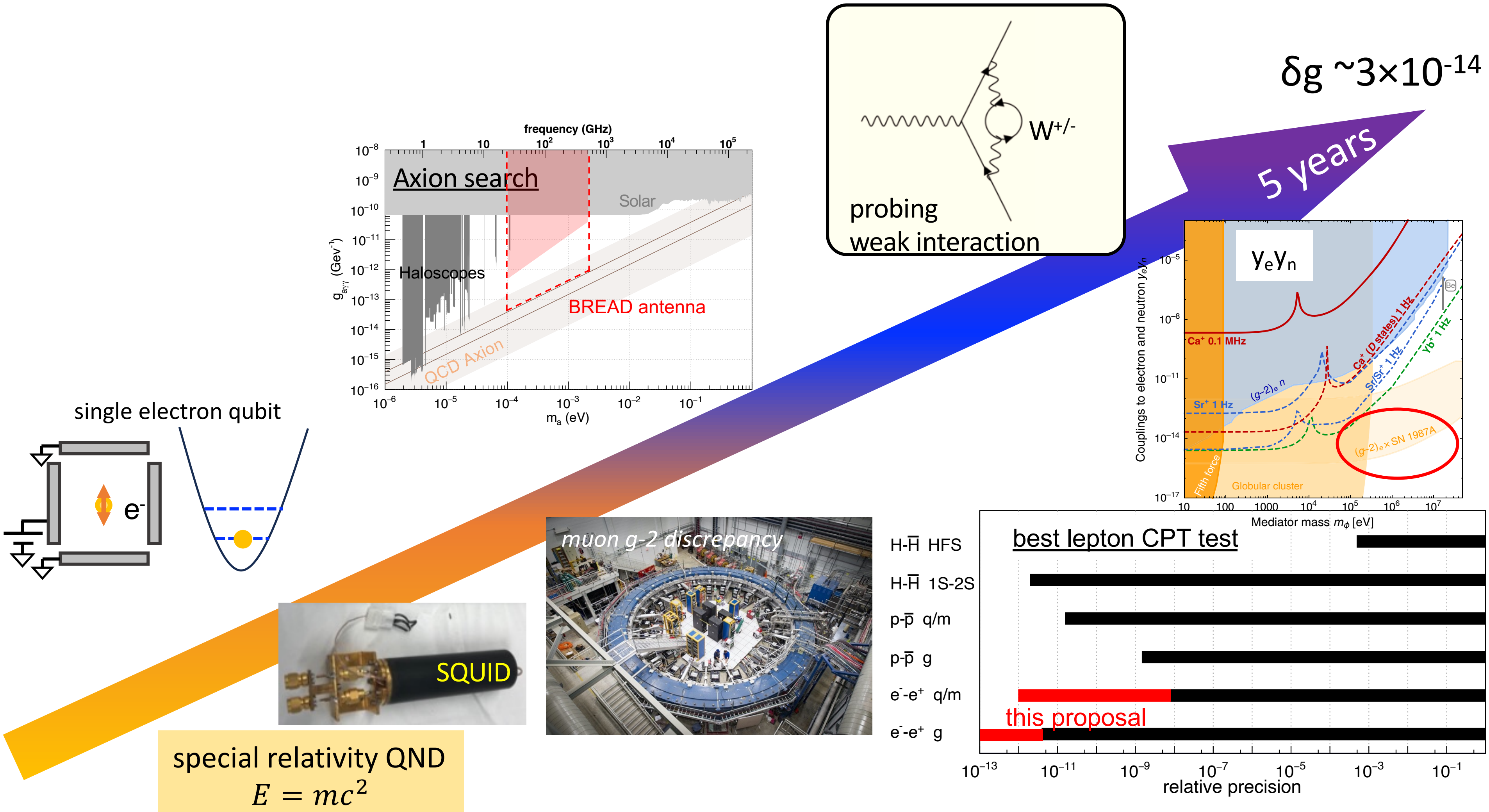


Electron Quantum Computing



- ~100,000 lighter than atoms → 10^3 faster qubit operation
- free space qubit → long coherence time expected (>ms)
- scalable with surface Penning trap

Expected Results



starting at Harvard 2025 July

Looking for Students/Postdocs!

xingfan@g.harvard.edu