Measuring the electron and positron magnetic moments to test the Standard Model's most precise prediction

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Prof. Gerald Gabrielse

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- Ronald Alexander (new student)
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- many undergrads and visitors

2008 and earlier
- David Hanneke
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- Brian D'Urso
- Steve Peil
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- Joseph Tan
- Maarten Jansen
- Kamal Abdullah
- Ramon van Handel
- many undergrads and visitors

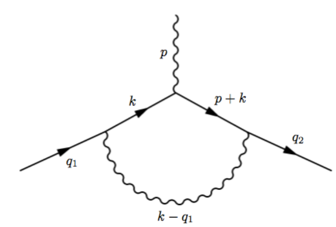
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. "High efficiency positron accumulation for high-precision magnetic moment experiments." *Rev. Sci. Instrum*. 86, 053301 (2015)

Positrons trapped
Expected precision e+ and e- improvement
- Design for better B field stability
- Cavity assisted sideband cooling
- Correlated measurement

Introduction to precision e⁺/e⁻ magnetic dipole moment measurements

$$\vec{\mu} = \mp \frac{g}{2} \mu_B \frac{\vec{S}}{\hbar/2} \qquad\qquad \mu_B = \frac{e\hbar}{2m}$$

g/2 = 1/2	Classical particle with equal charge/mass distribution
g/2 = 1	Dirac point particle
g/2 = 1.001 159 …	Dirac point particle plus Standard Model vacuum



$$\frac{g}{2}(electron) = \frac{\mu}{\mu_B}(electron) = 1.001\ 159\ 652\ 180\ 73\ (28)\ [.28\ \ ppt]$$

D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett.* **100**, 120801 (2008)

Electron magnetic moment is the most precisely measured fundamental property of an elementary particle!

One motivation: testing the Standard Model by testing CPT symmetry

- **C**harge Conjugation: $e^- \rightarrow e^+$
- **P**arity Transformation: $\vec{x} \rightarrow -\vec{x}$
- **T**ime Reversal: $t \rightarrow -t$

- CPT Theorem: CPT is an exact symmetry for any local, Lorentz invariant quantum field theory (which includes the Standard Model)

G. Lüders, Ann. Phys. **2**, 1 (1957)

- CPT symmetry violation indicates beyond-the-Standard-Model physics

Positron/electron g comparison is best test of CPT symmetry in a lepton system

Standard Model predicts e+, e- magnetic moments should be same magnitude.

$$\frac{g}{2}(electron) = 1.001\ 159\ 652\ 180\ 73\ (28)\ [.28\ \ ppt]$$

D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett.* **100**, 120801 (2008)

$$\frac{g}{2}(positron) = 1.001\ 159\ 652\ 1879\ (4.3)\ [4.3\ \ ppt]$$

R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, *Phys. Rev. Lett.* **59**. 26 (1987)

Best measurement of positron *g*-value is only 4.3 ppt.

$$\frac{g(e^-)}{g(e^+)} = 1 + (0.5 \pm 2.1) \times 10^{-12}$$

Can be improved by 15x with positron measurement at current electron precision level!

Solution: new and improved apparatus with positron loading capability is built and trapping positrons!

Standard Model predicts *g* from *α*

$$\frac{g}{2} = \frac{\mu}{\mu_B}$$

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

$$+ a_{\mu,\tau} + a_{hadronic} + a_{weak}$$

Standard Model test requires an independent α

$$\frac{g}{2} = \frac{\mu}{\mu_B} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 \cdot \quad + a_{\mu,\tau} + a_{hadronic} + a_{weak}$$

$$\alpha \equiv \frac{1}{4\pi\varepsilon_0}\frac{e^2}{hc} \qquad R_\infty \equiv \frac{1}{(4\pi\varepsilon_0)^2}\frac{e^4 m_e c}{2h^3c^2} \qquad \frac{h}{M_{Rb}} = 2c^2\frac{f_{recoil}}{(f)^2}$$

atom recoil velocity from 1000 photons

R. Bouchendira, P. Cladé, S. Guellati-Khélifa, F. Nez, and F. Biraben, Phys. Rev. Lett. **106**, 080801 (2011)

$$\alpha = \frac{2R_\infty}{c}\frac{h}{M_{Rb}}\frac{M_{Cs}}{M_p}\frac{M_p}{m_e}$$

Haensch, …

Myers, …
Pritchard, …
Van Dyck, …

Quint, Blaum, …

Comparing our g to g from independent α tests Standard Model's most precise prediction

$$\frac{g}{2} = \frac{\mu}{\mu_B} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 \cdot \quad + a_{\mu,\tau} + a_{hadronic} + a_{weak}$$

Predicted: $\frac{g}{2} = 1.001\ 159\ 652\ 181\ 64\ \ (76)$

- R. Bouchendira, P. Cladé, S. Guellati-Khélifa, F. Nez, and F. Biraben, Phys. Rev. Lett. **106**, 080801 (2011).
- T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, arXiv:1412.8284v2 (2015).

Measured: $\frac{g}{2} = 1.001\ 159\ 652\ 180\ \ 73\ (28)$

- D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett.* **100**, 120801 (2008).

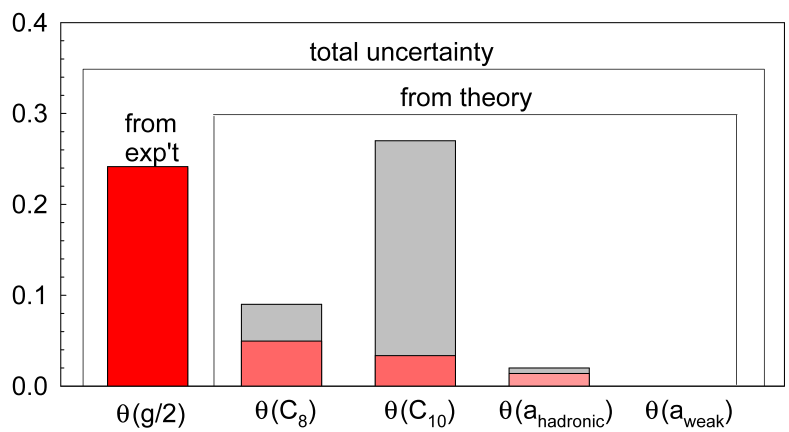
Sets a bound on electron substructure or new physics beyond the standard model

Standard Model gives the most accurate fine structure constant from *g*

$$\frac{g}{2} = \frac{\mu}{\mu_B} = 1 + \underbrace{C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3}_{\text{Calculated analytically}} + \underbrace{C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5}_{\text{Calculated numerically}} \cdot \; + a_{\mu,\tau} + a_{hadronic} + a_{weak}$$

$$\alpha^{-1} = 137.035\ 999\ 157\ (33)(4)\ [0.24\ \text{ppb, exp.}][0.03\ \text{ppb, th.}]$$
$$= 137.035\ 999\ 157\ (33)\ [0.24\ \text{ppb}]$$

Sources of uncertainty in α determination from g



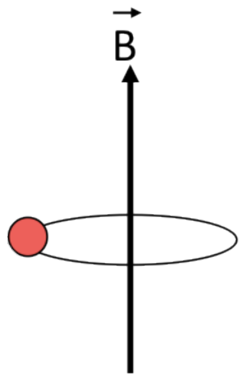
Experimental determination of g/2 now the primary source of uncertainty →

improved g/2 = improved α

D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008)
T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, , Phys. Rev. D **91**, 033006 (2015)

Measuring g as a frequency ratio

- g in free space (in a magnetic field):

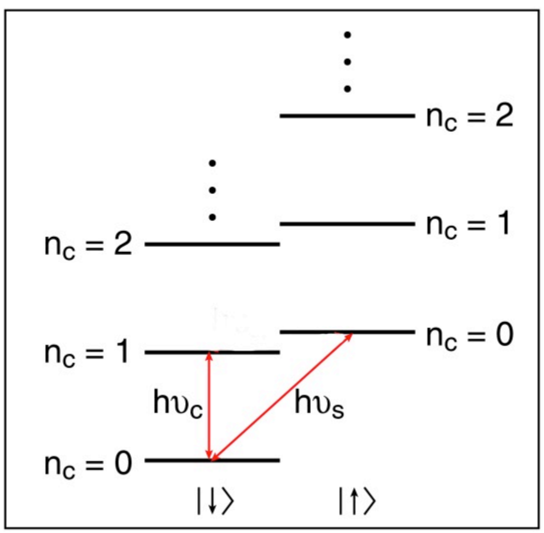


Cyclotron frequency: $\nu_c = \dfrac{eB}{2\pi m}$

Spin frequency: $\nu_s = \nu_c \dfrac{g}{2}$

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

Nice experimental feature: the magnetic field cancels out



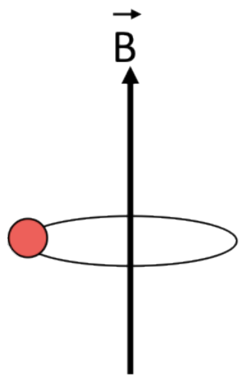
g/2 = 1.001 159 652 180 73…

Dirac point particle plus Standard Model vacuum

Louisell, W. H., Pidd, R. W., & Crane, H. R., *Physical Review*, *94*(1), 7 (1954).
D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett.* **100**, 120801 (2008).

Measuring g-2 as a frequency ratio

- g in free space (in a magnetic field):



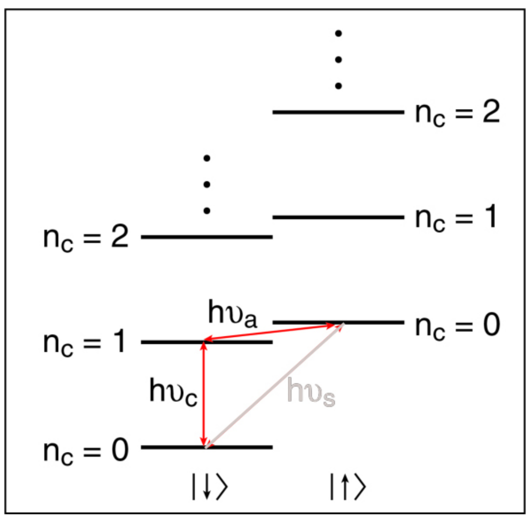
$$\nu_c = \frac{eB}{2\pi m}$$

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

Define anomaly frequency:

$$\nu_a = \nu_s - \nu_c$$

$$\Rightarrow \boxed{\begin{aligned} \frac{g}{2} = \frac{\nu_s}{\nu_c} &= 1 + \frac{\nu_s - \nu_c}{\nu_c} \\ &= 1 + \frac{\nu_a}{\nu_c} \end{aligned}}$$



$g/2$ = 1.001 159 652 180 73...

Dirac point particle plus Standard Model vacuum

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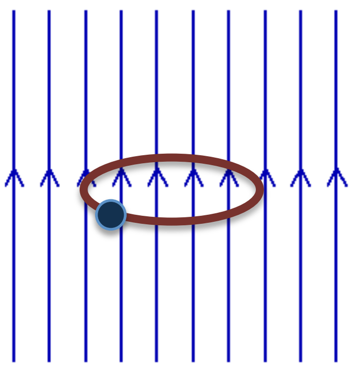
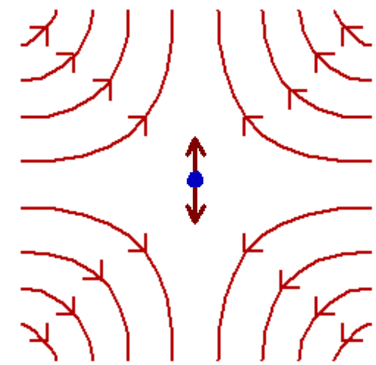
g in a Penning trap

B field

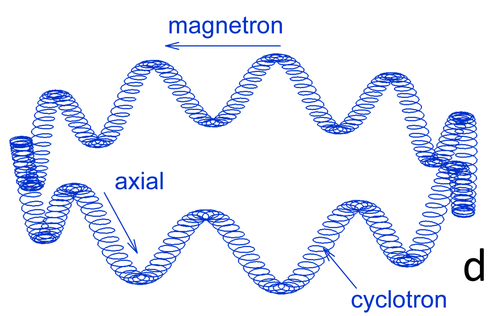


Magnetic field from 6T superconducting magnet provides radial confinement and causes cyclotron motion (150 GHz)

Quadrupole **E** field



Quadrupole E field from silver cylindrical trap electrodes provides axial confinement and causes axial oscillation (200 MHz)



Also causes magnetron motion (ExB drift at 137 kHz)

And shifts cyclotron and anomaly frequencies (well-understood, correctable)

$$\bar{\nu}_c \gg \bar{\nu}_z \gg \bar{\nu}_m$$

$$\frac{g}{2} = 1 + \frac{\nu_a}{\nu_c} = 1 + \frac{\nu_a' - \frac{2\nu_z^2}{\nu_c'}}{\nu_c' + \frac{2\nu_z^2}{\nu_c'}}$$

Brown-Gabrielse invariance theorem

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

Special relativistic shift requires knowledge of exact cyclotron/spin state

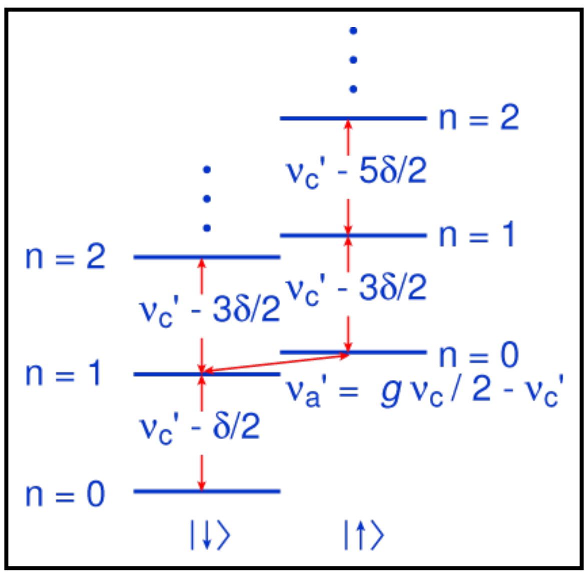
Special relativistic shift to cyclotron frequency matters at our precision level:

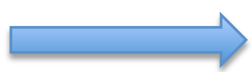
$$\Delta\nu_c = -\delta(n = 1 + m_s)$$

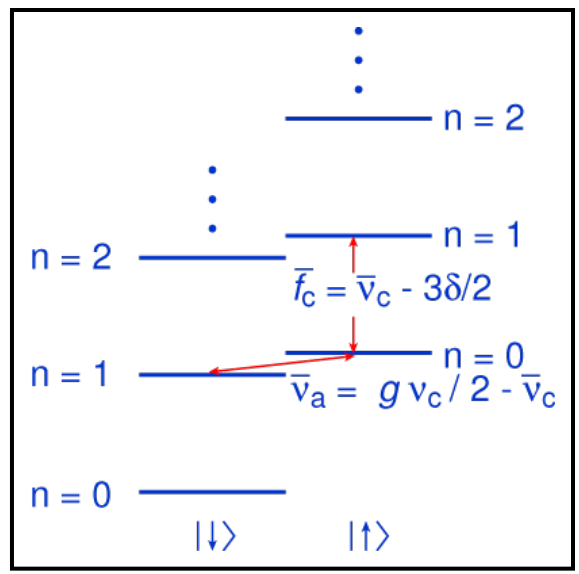
$$\frac{\delta}{\nu_c} = \frac{h\nu_c}{mc^2} \approx 10^{-9}$$

Solution: drive exactly the same transition every time

- 6 T magnetic field to give ~7 K cyclotron level spacing
- Dilution refrigerator with T=100 mK to stay in ground state
- Excite and detect single cyclotron or anomaly transitions
- Special relativistic shift can be calculated from measured frequencies

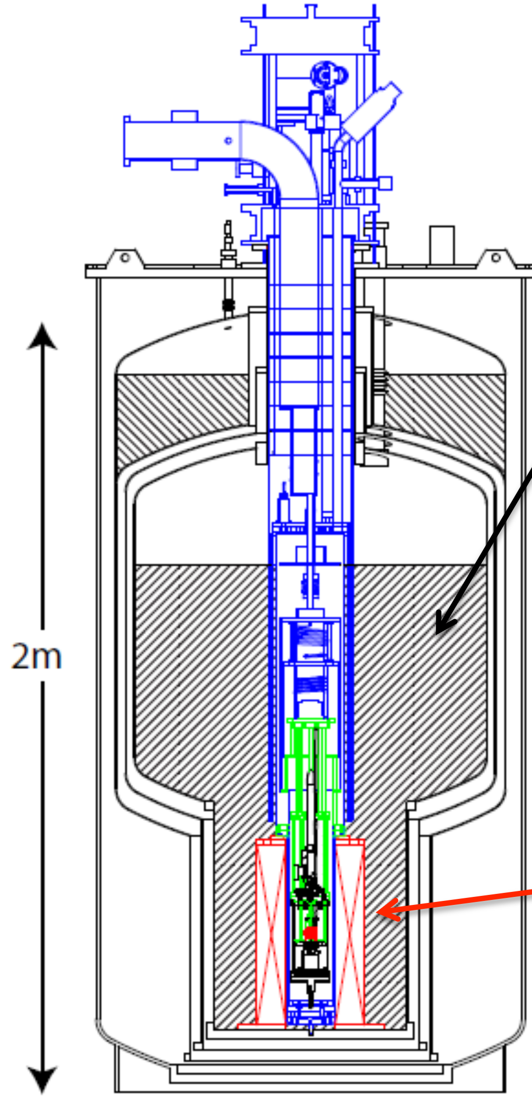






L.S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

The new apparatus

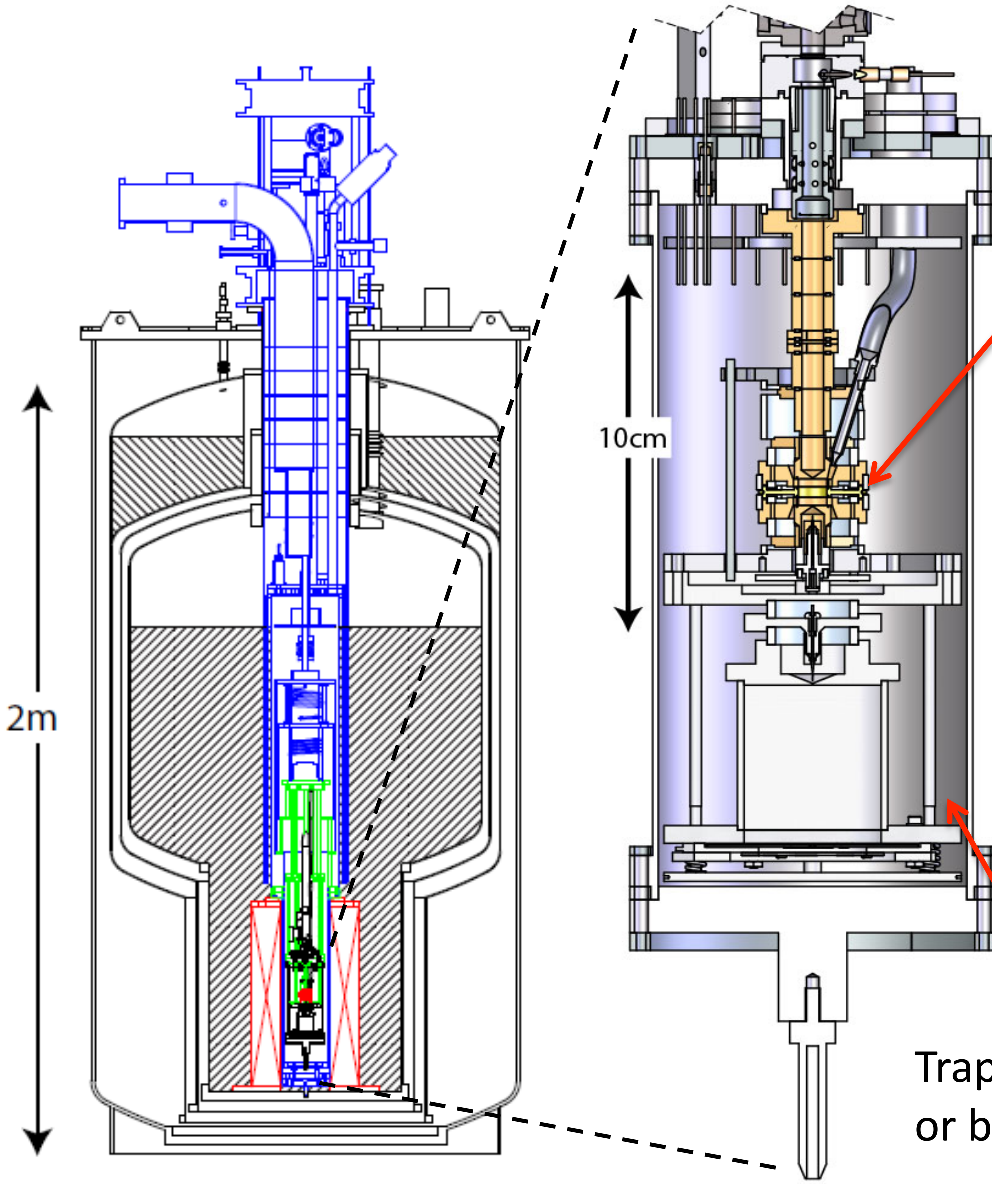


500 L He dewar

Magnetic field:
6 T superconducting solenoid

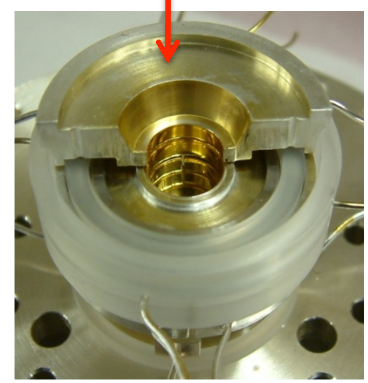
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

The new apparatus



Electric field:

- New trap
- Cylindrical silver electrodes
- V ~ 100 V



← 2.5 cm →

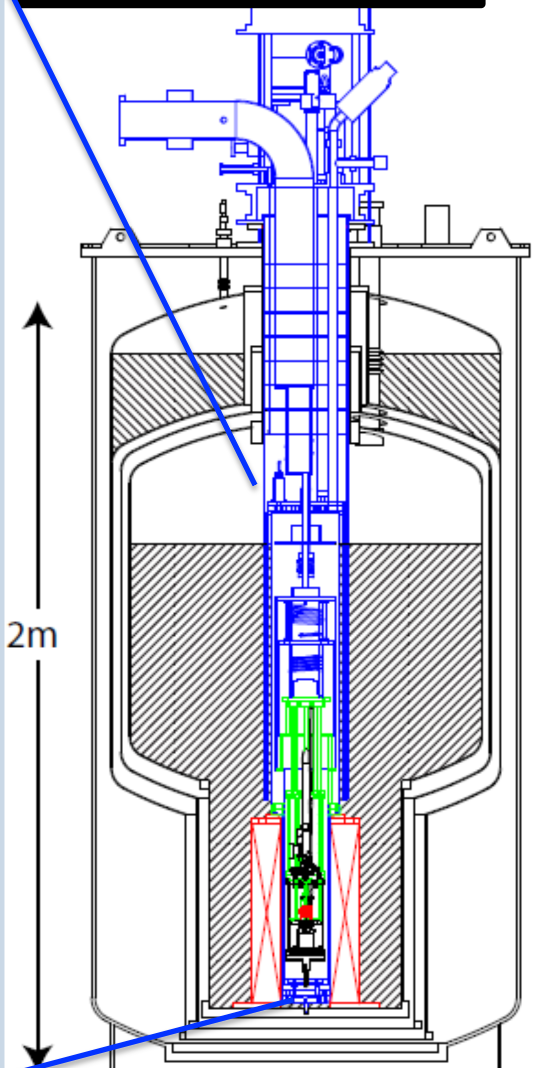
Trap vacuum of 5e-17 torr or better

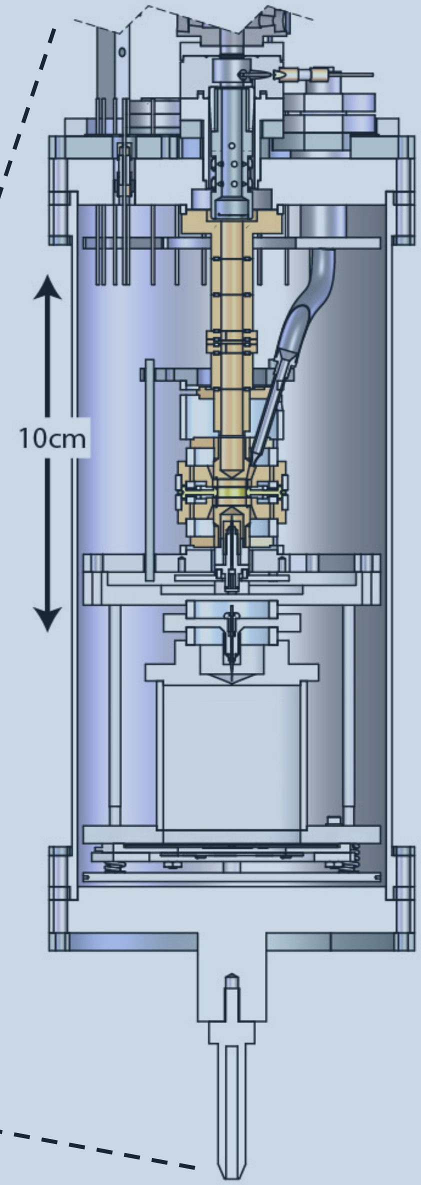
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

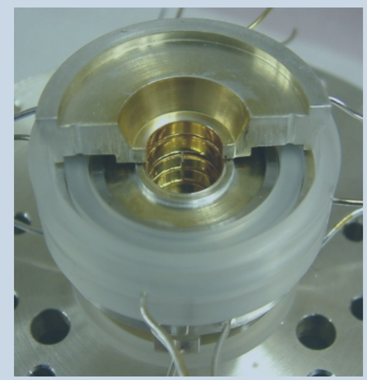
The new apparatus

Dilution refrigerator:

- T = 100 mK







← 2.5 cm →

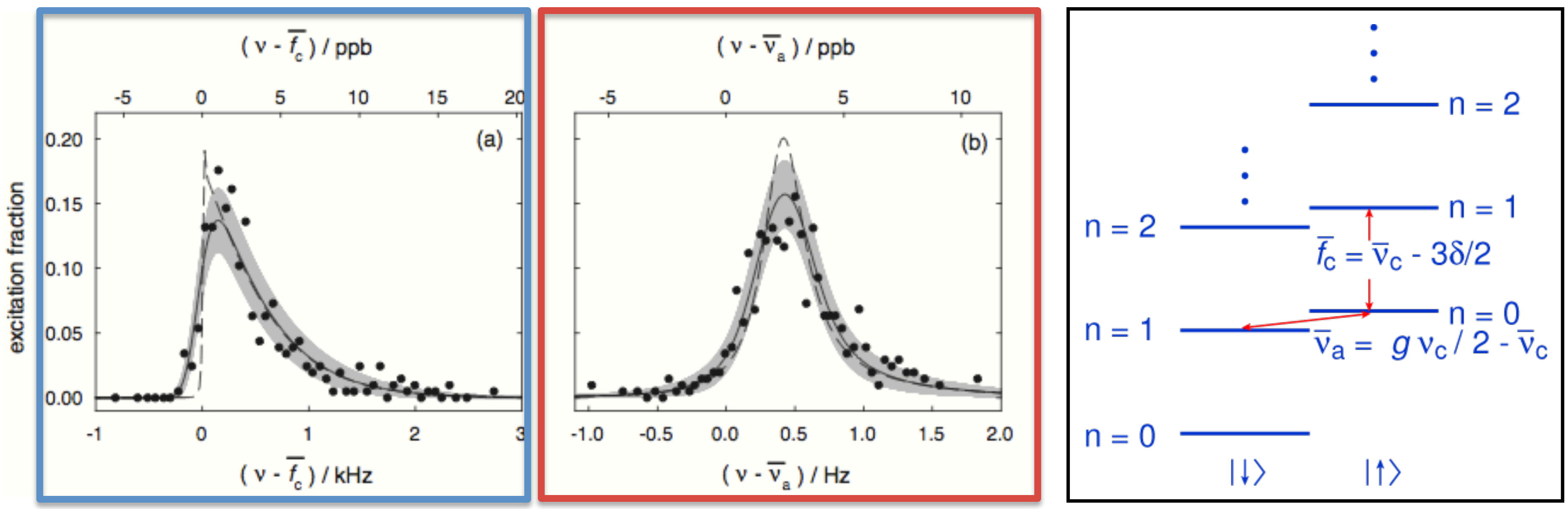
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Ingredients of a g/2 measurement

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

$$= 1 + \frac{\nu_a}{\nu_c}$$

- Measure cyclotron frequency
- Measure anomaly frequency

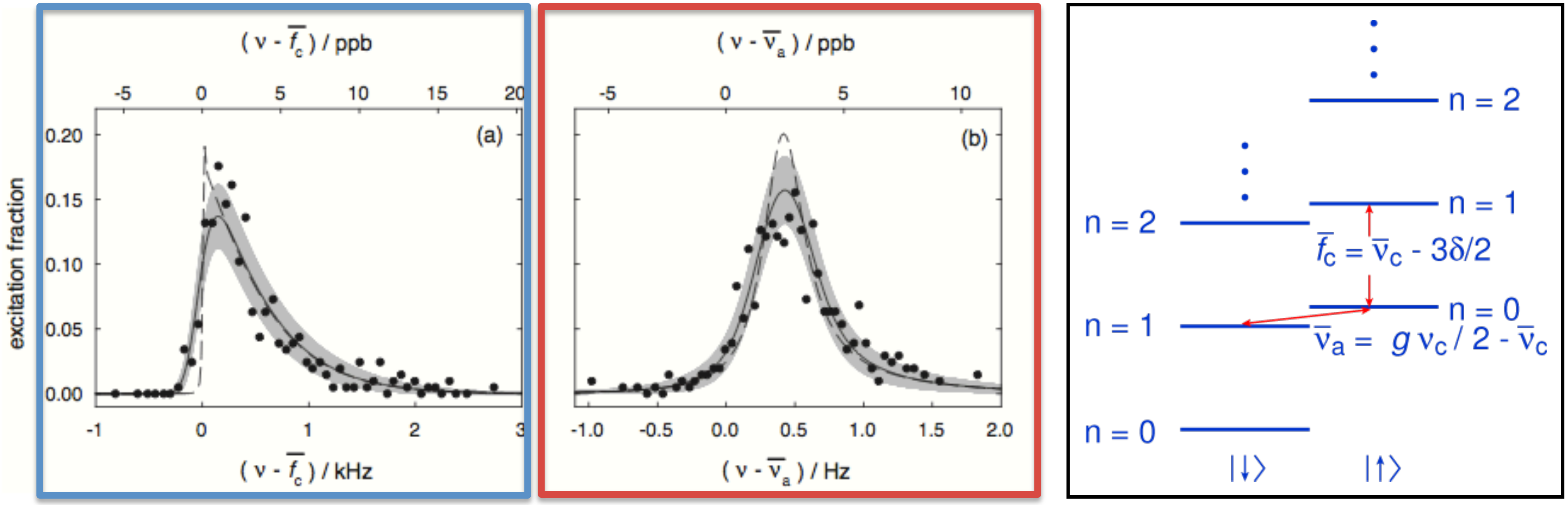


D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

Ingredients of a g/2 measurement

$$\frac{g}{2} \approx 1 + \frac{\bar{\nu}_a - \dfrac{\bar{\nu}_z^2}{2\bar{f}_c}}{\bar{f}_c + \dfrac{3\delta}{2} + \dfrac{\bar{\nu}_z^2}{2\bar{f}_c}} + \frac{\Delta\omega}{\omega}$$

- Measure cyclotron frequency
- Measure anomaly frequency
- Measure axial frequency (less precision needed)
- Calculate special relativistic shift (δ)
- Calculate $\Delta\omega/\omega$ from measured cavity mode couplings



D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

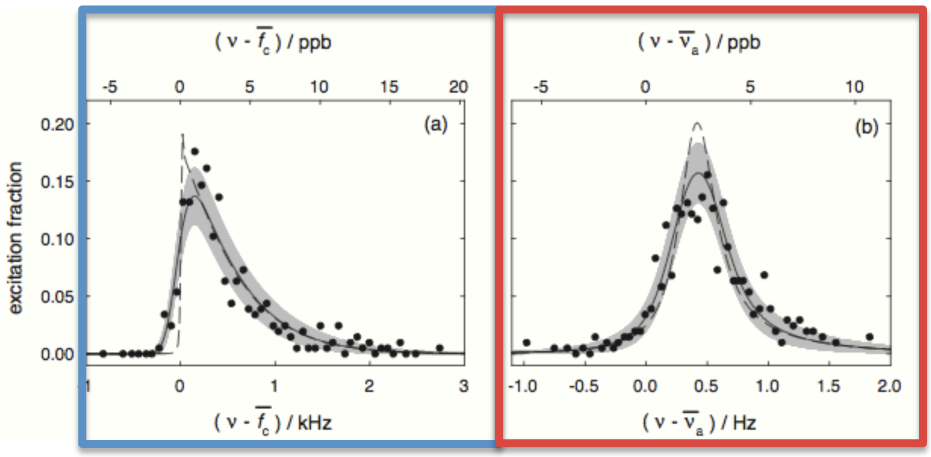
Cyclotron/anomaly lineshapes dominate uncertainty

$$\frac{g}{2} \approx 1 + \frac{\bar{\nu}_a - \frac{\bar{\nu}_z^2}{2\bar{f}_c}}{\bar{f}_c + \frac{3\delta}{2} + \frac{\bar{\nu}_z^2}{2\bar{f}_c}} + \frac{\Delta\omega}{\omega}$$

g/2 = 1.001 159 652 180 73 (28) [0.28 ppt]

Uncertainties for *g* in parts-per-trillion.

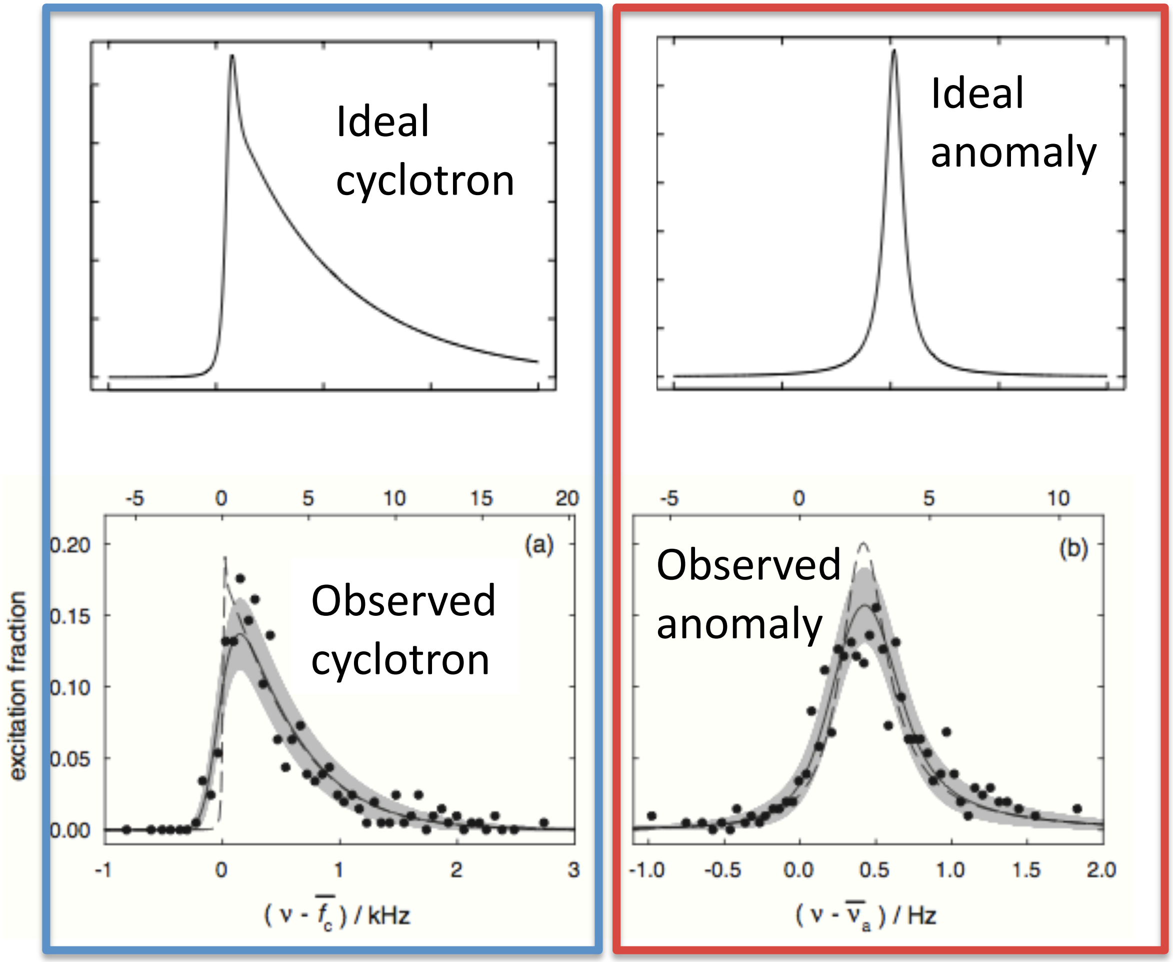
ν_c / GHz =	147.5	149.2	150.3	151.3
Statistics	0.39	0.17	0.17	0.24
Cavity shift	0.13	0.06	0.07	0.28
Uncorrelated lineshape model	0.56	0.00	0.15	0.30
Correlated lineshape model	0.24	0.24	0.24	0.24
Total	**0.73**	**0.30**	**0.34**	**0.53**



D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

Cyclotron/anomaly lineshapes dominate uncertainty

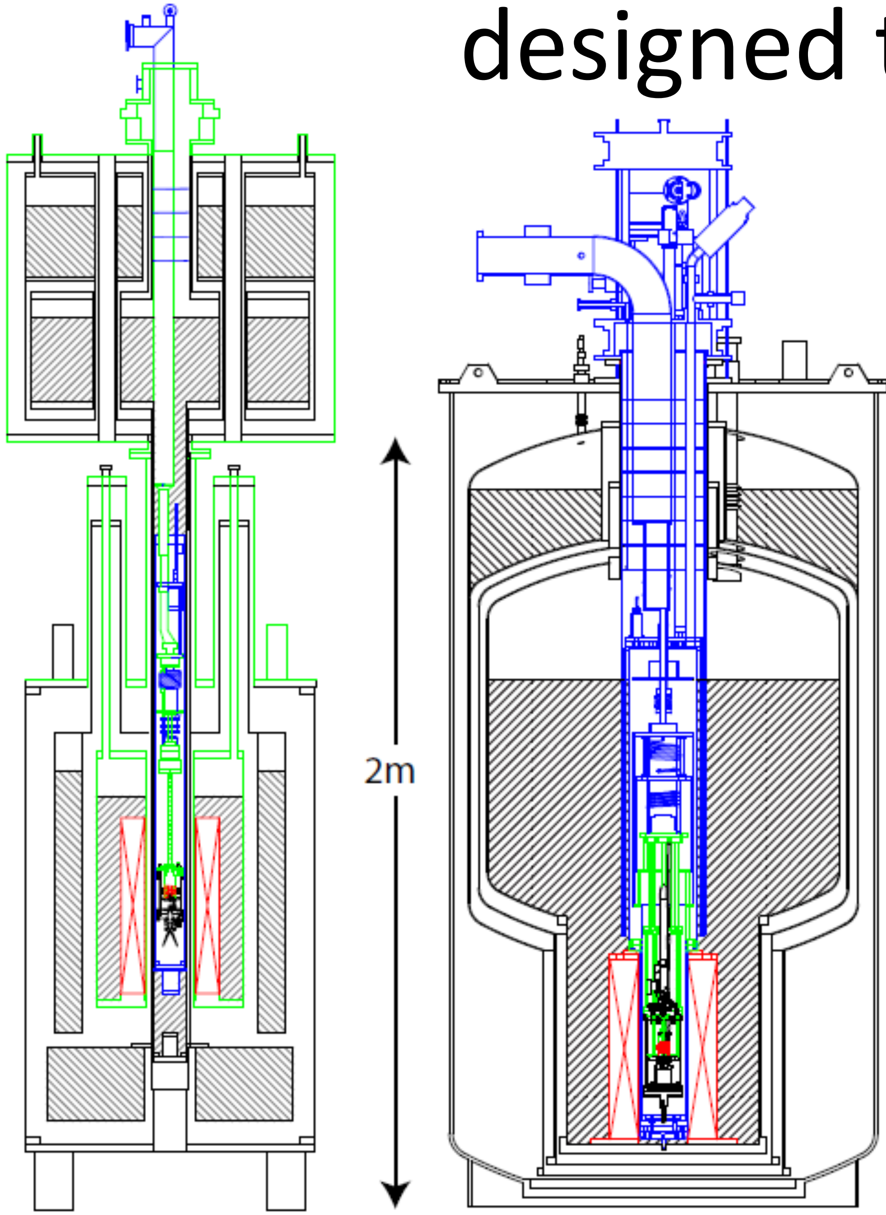
Excitation fractions vs. frequency



- Blurring could be caused by B-field noise or instability, e.g. from trap electrodes moving with respect to magnet
- Lineshape blurring limits linesplitting to about 1 part in 10
- Better design and new methods possible in new apparatus should yield cleaner, narrower cyclotron and anomaly lines

D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Part of the solution: new apparatus is designed to be extremely stable

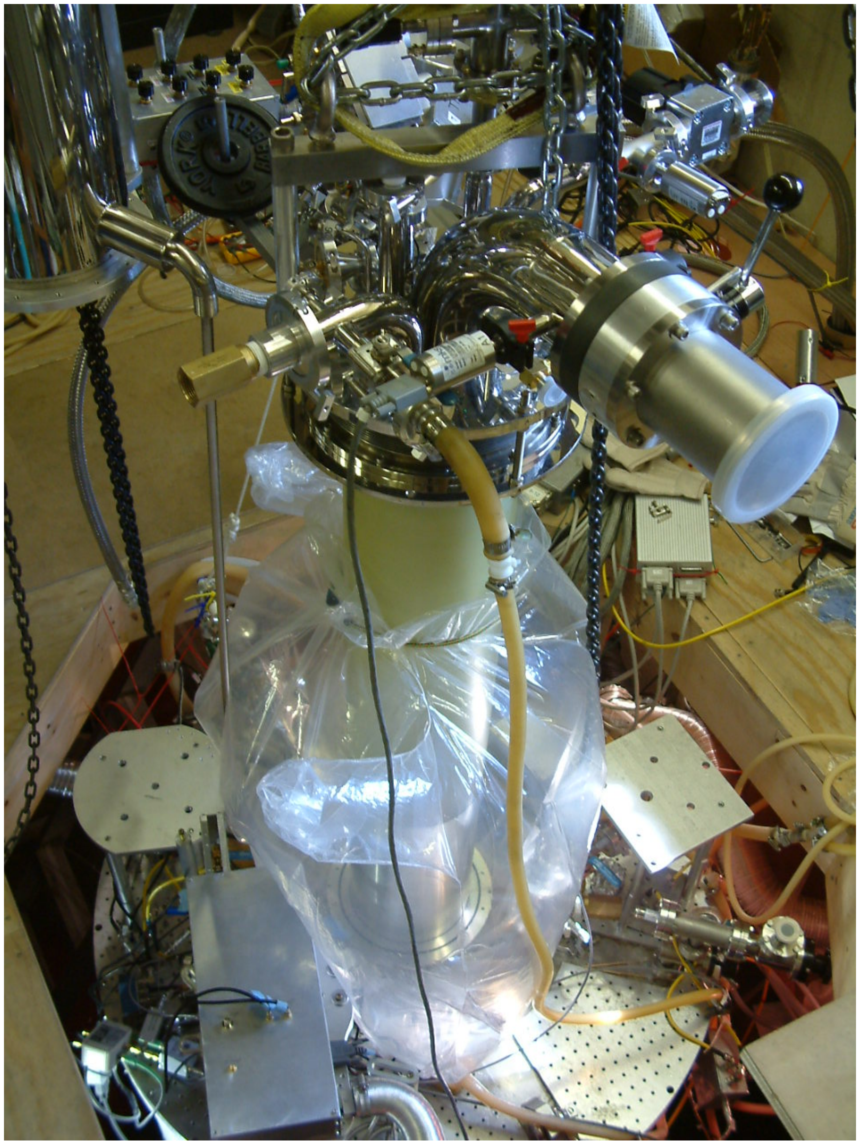


Improvements to reduce possible sources of lineshape blurring include:

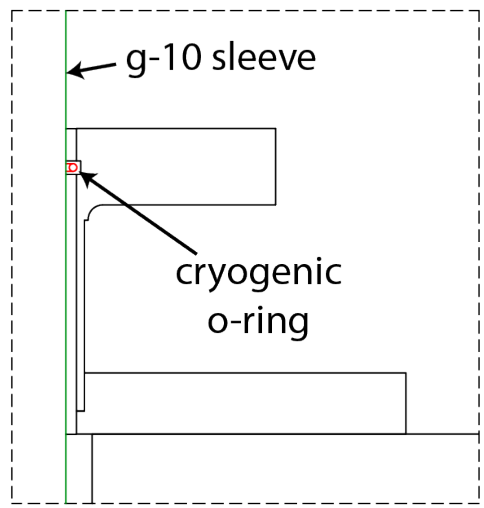
- Better mechanical support structure and alignment reduces susceptibility to vibration-induced noise
- Very low magnetic field drift
- Better magnetic field shielding (self-shielding solenoid)
- Improved helium hold time
- More fridge cooling power for stabler temperature
- More room for electronics– positron loading trap

S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

With stability come practical challenges

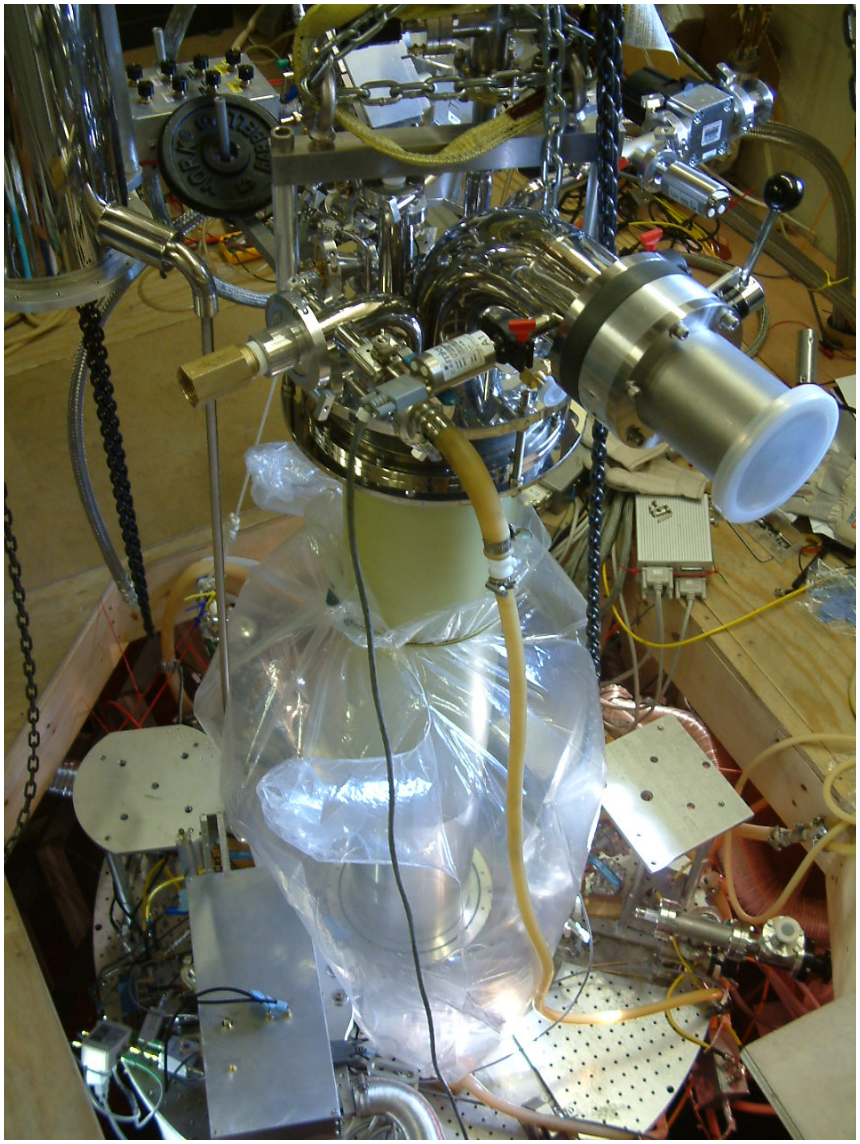


- Need to lower warm apparatus straight into a liquid helium dewar without quenching the magnet
  - 4-5 hour cooling time
  - Sliding seal plus glove bag to avoid paramagnetic oxygen ice



S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

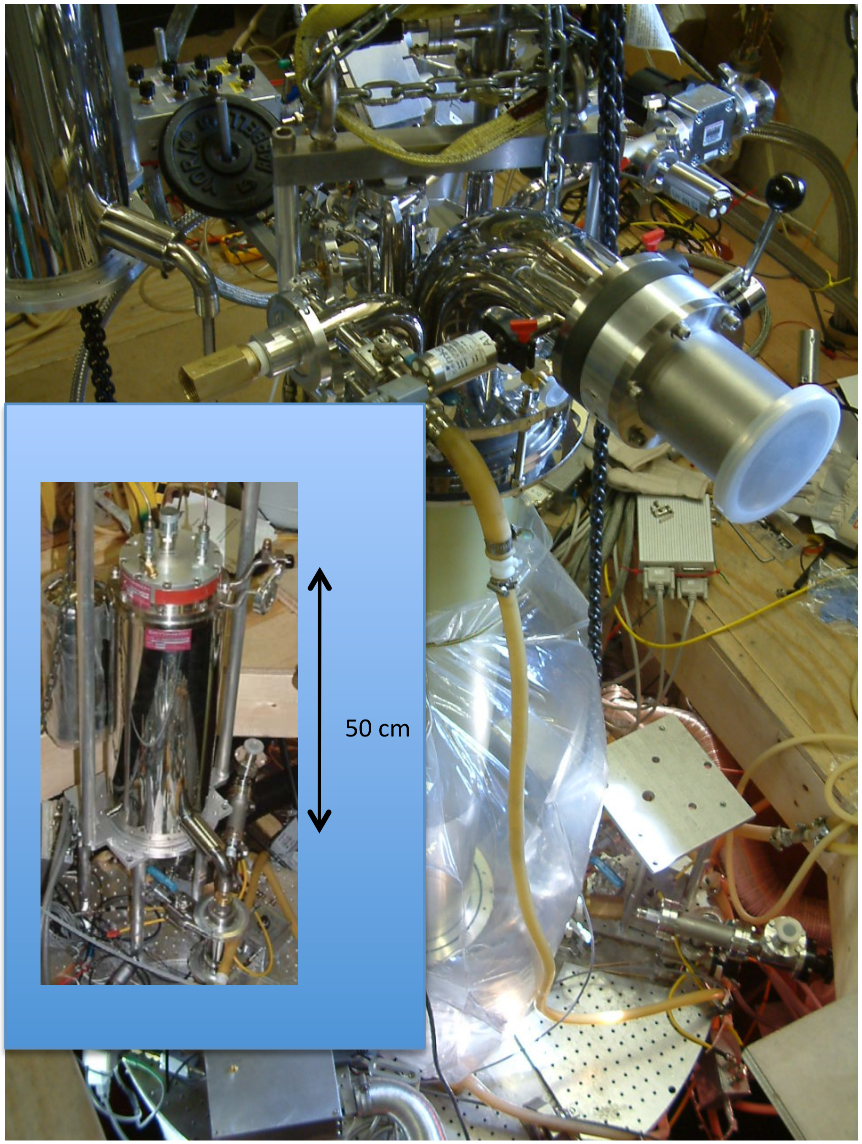
With stability come practical challenges

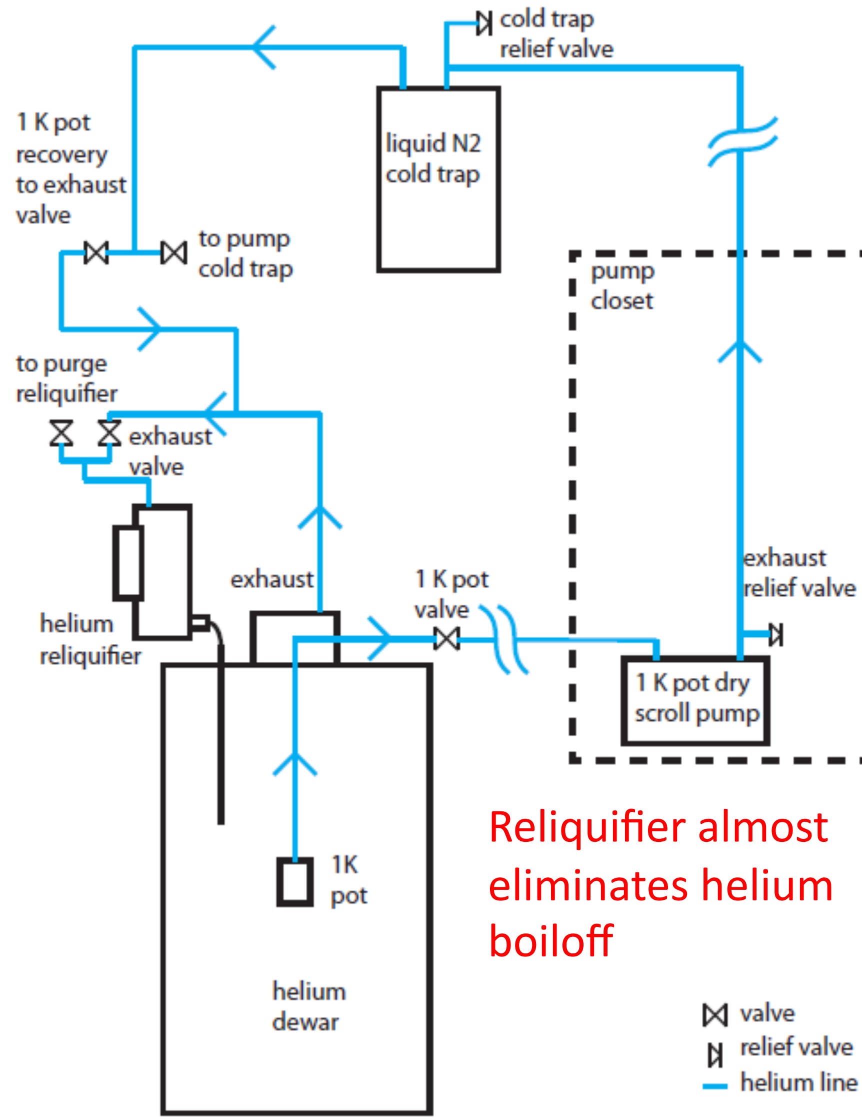


- Need to lower warm apparatus straight into a liquid helium Dewar without quenching the magnet
  - 4-5 hour cooling time
  - Sliding seal plus glove bag to avoid paramagnetic oxygen ice
- Helium for new large Dewar is expensive, so need efficient recovery
  - Added helium reliquifier

S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

With stability come practical challenges

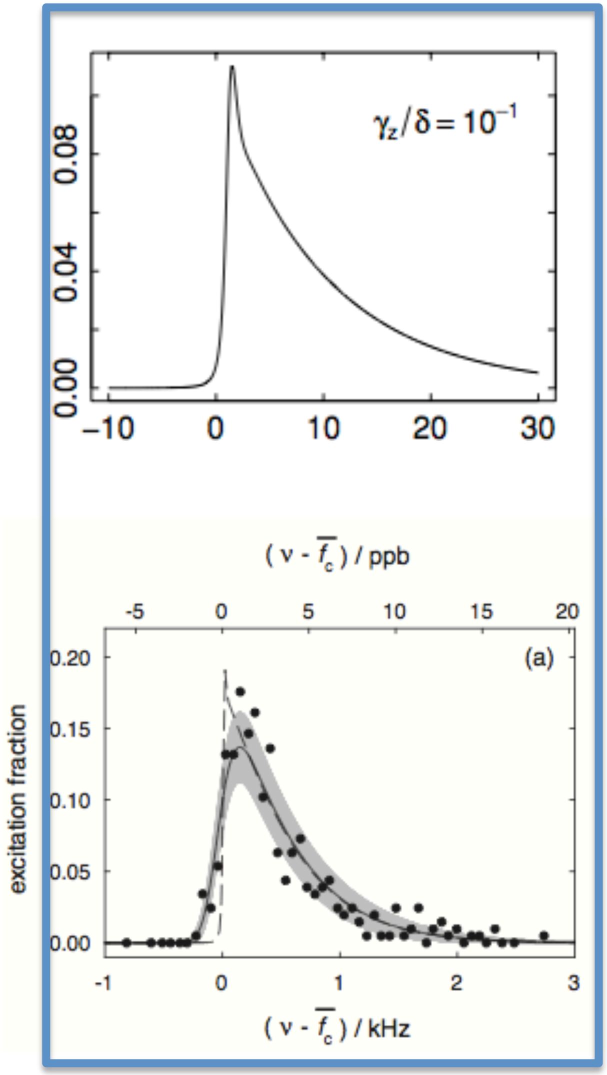


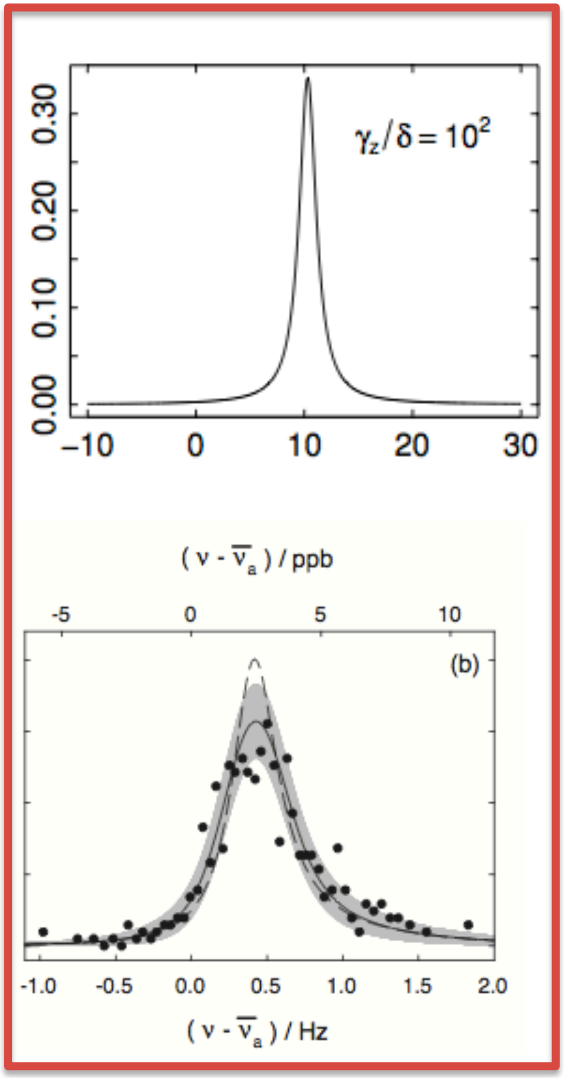


Reliquifier almost eliminates helium boiloff

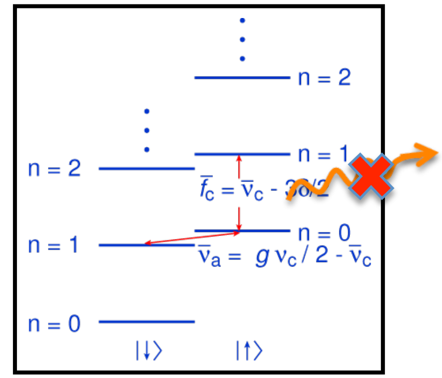
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Besides improving magnetic field stability, what can we do?





- More details about linewidth and detection…



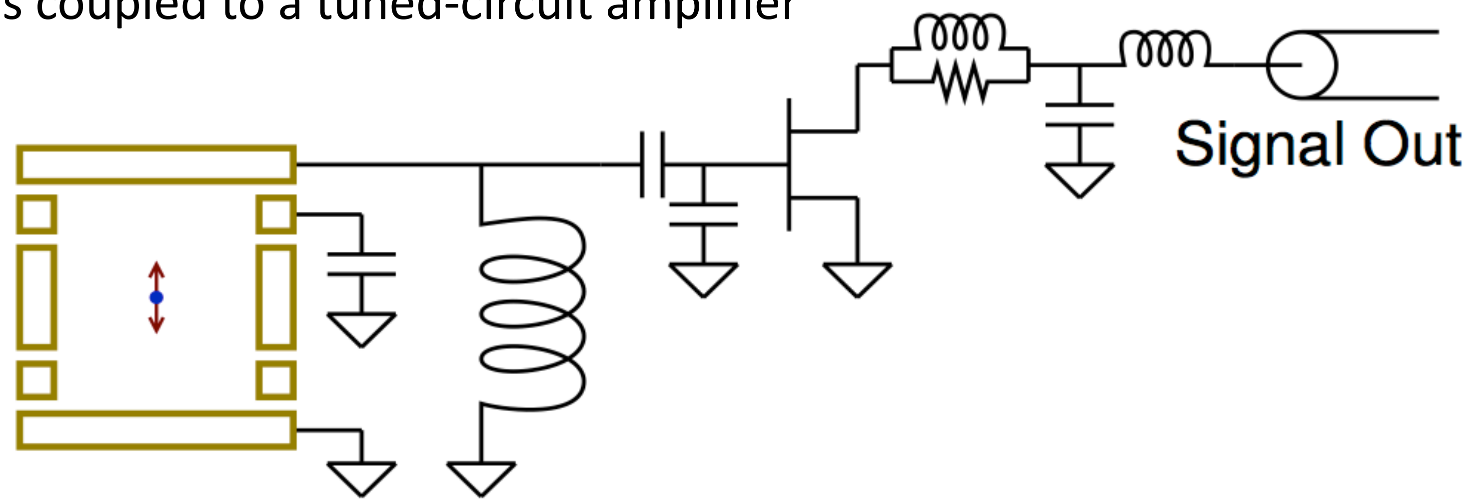
- Don't detect single 150 GHz photon from single cyclotron jump
- Instead, couple to 200 MHz axial motion and detect that

D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

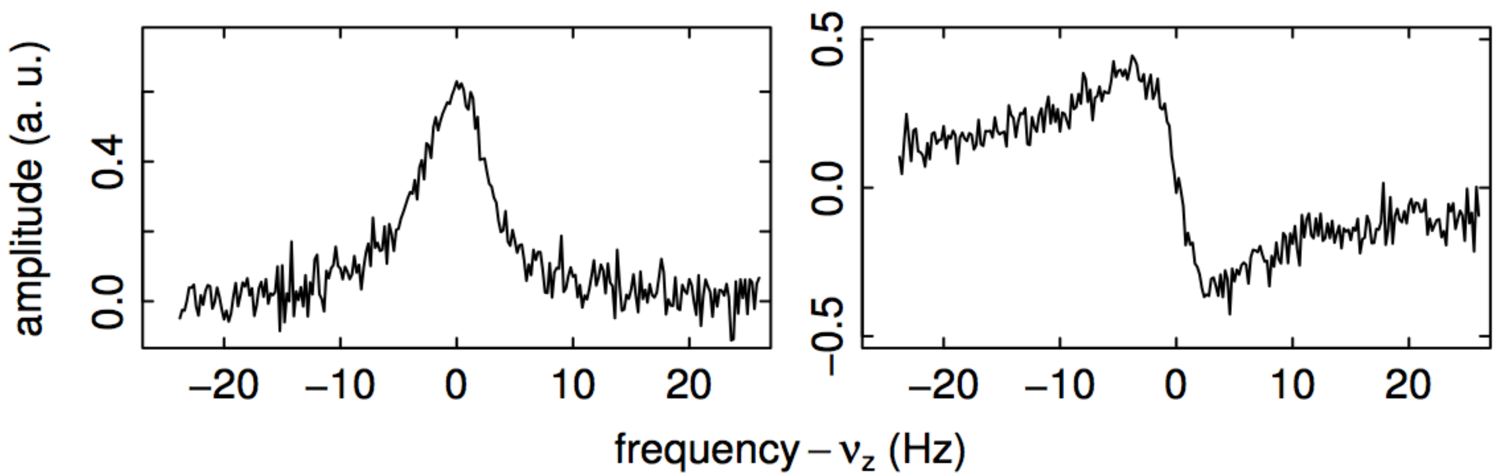
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum.* 86, 053301 (2015)

Detection of single-particle axial motion

- Particle is coupled to a tuned-circuit amplifier



- Axial motion is driven to increase signal

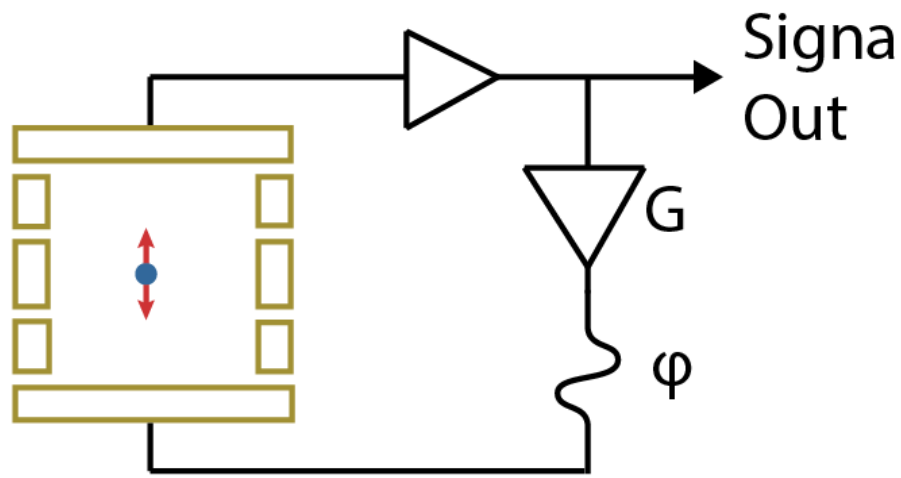


L.S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

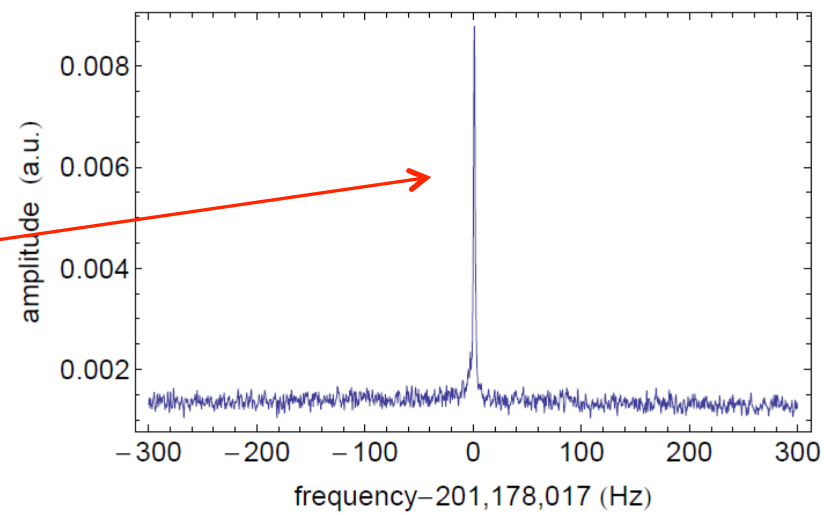
The single-particle self-excited oscillator

- Need large stable signal to quickly read axial frequency without ambiguity
- Set feedback gain to exactly cancel damping from amp
- Adjust the gain in real time to maintain a stable amplitude

$$m\left(\ddot{z} + (1-G)\gamma_z \dot{z} + \omega_z^2 z\right) = 0$$



SEO signal from a single electron in the new apparatus

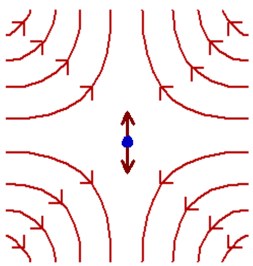


B. D’Urso, R. Van Handel, B. Odom, D. Hanneke, and G. Gabrielse, *Phys. Rev. Lett.* **94**, 113002 (2005).

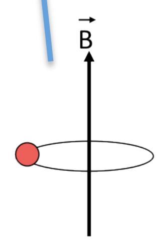
Spin and cyclotron state detection via coupling to axial motion

Axial motion:

$$H_{z0} + H'_z = \left(\frac{1}{2} m\omega_{z0}^2 - \mu_{s,c} B_2\right) z^2$$



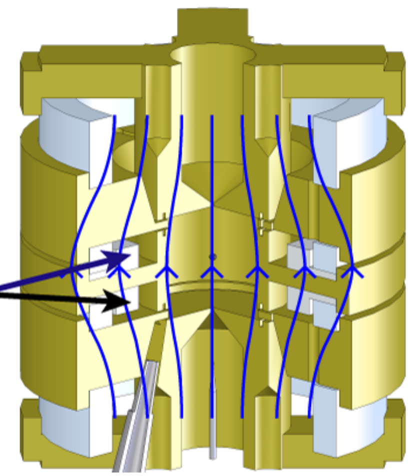
Electrostatic quadrupole



cyclotron and spin state (magnetic moment)

magnetic bottle

nickel rings



Change in cyclotron or spin state causes measurable shift in axial frequency:

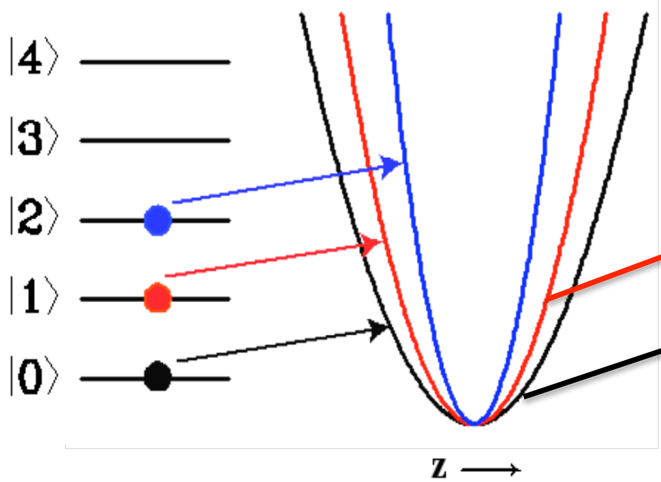
$$\frac{\Delta\nu_z}{\nu_z} \approx 7\times 10^{-9}\left(n + \frac{1}{2} + \frac{g}{2} m_s\right)$$

L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

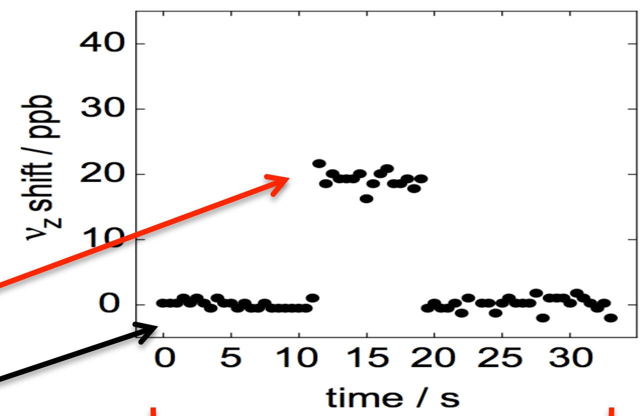
Spin and cyclotron state detection via coupling to axial motion

Cyclotron state

Axial potential



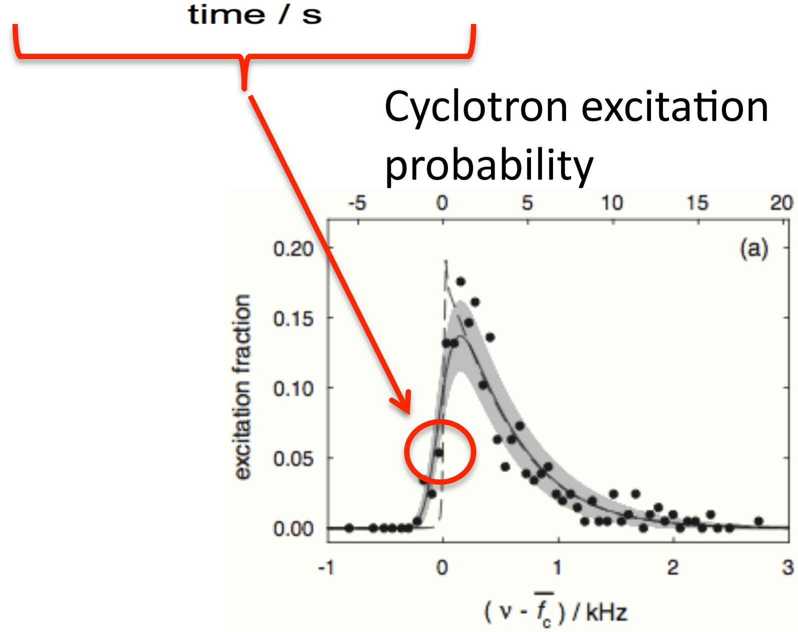
Axial frequency



Use self-excited oscillator to monitor axial frequency and detect transitions

Change in cyclotron or spin state causes measurable shift in axial frequency

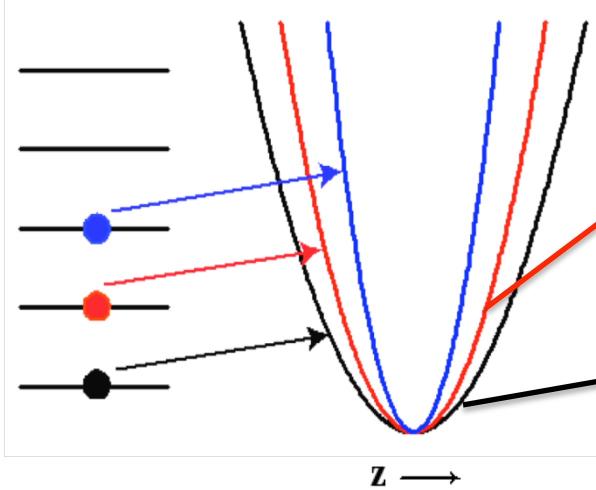
Cyclotron excitation probability



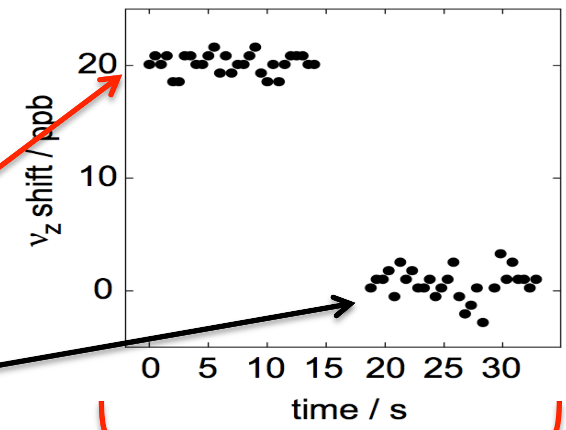
L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

Spin and cyclotron state detection via coupling to axial motion

Axial potential



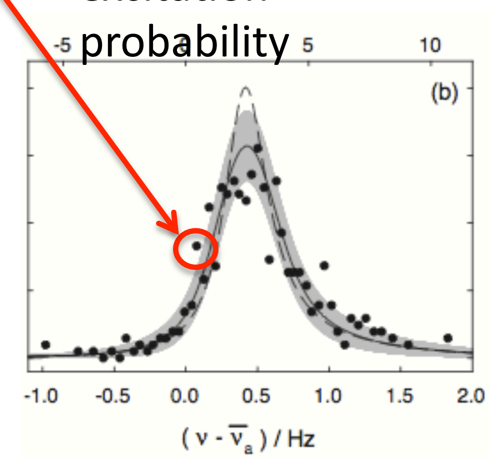
Axial frequency



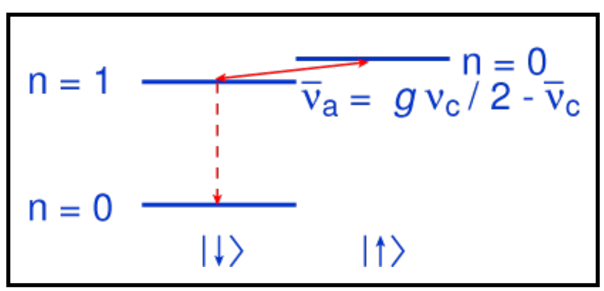
Use self-excited oscillator to monitor axial frequency and detect transitions

Change in cyclotron or spin state causes measurable shift in axial frequency

Anomaly excitation probability

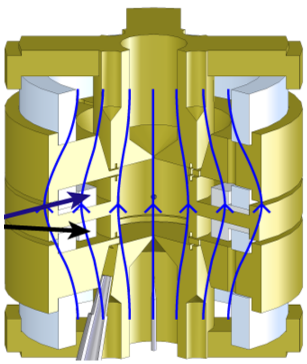


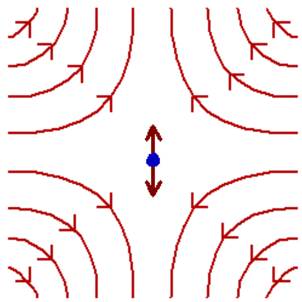
Similar for anomaly transition:

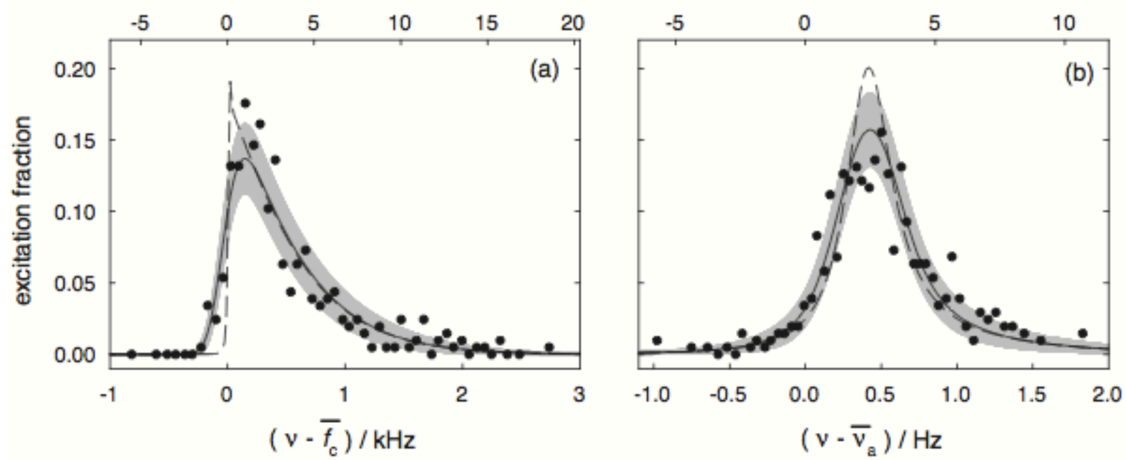


L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

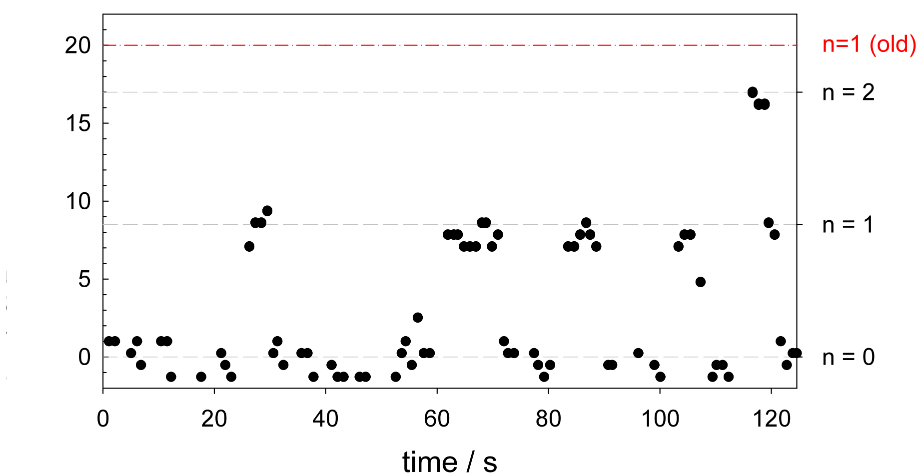
But this coupling to axial motion broadens cyclotron and anomaly lines







Shifts to axial frequency in old and new traps



New apparatus:

smaller magnetic bottle

→ reduced coupling strength

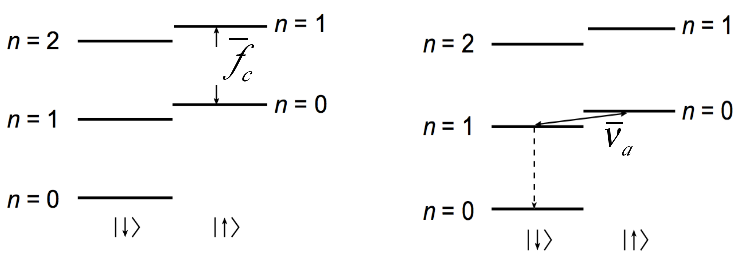
→ expected narrower lines

L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)
B. D'Urso *et al.*, Phys. Rev. Lett. **94**, 113002 (2005)
D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008.
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum.* 86, 053301 (2015)

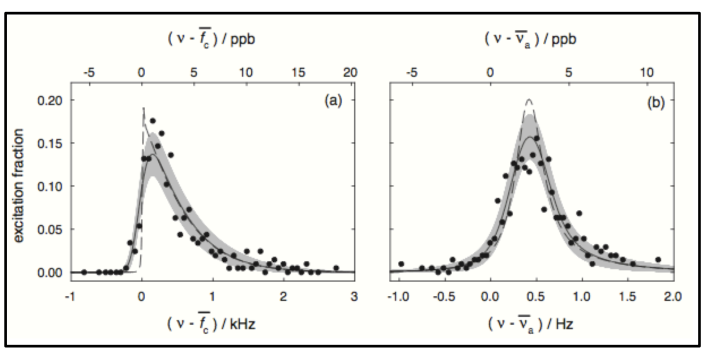
New technique for defeating magnetic field drifts: Correlated Measurement

2008 Protocol

- Cyclotron attempts followed by anomaly attempts

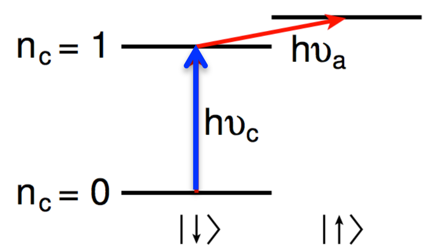


- Combine data, adjust for field drift, fit both lines to extract g/2

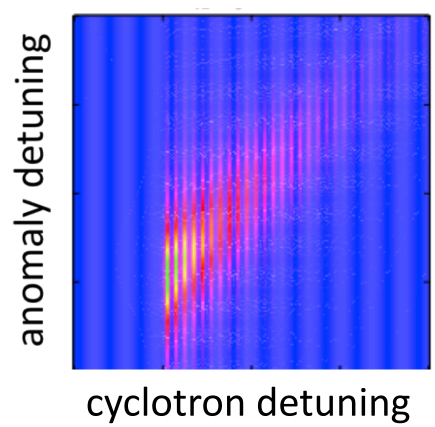


New Protocol

- Apply cyclotron and anomaly drives simultaneously

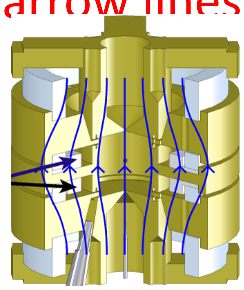


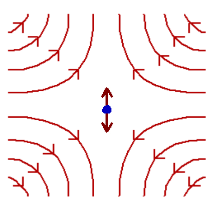
- Generate 2-D correlated lineshape, extract g/2



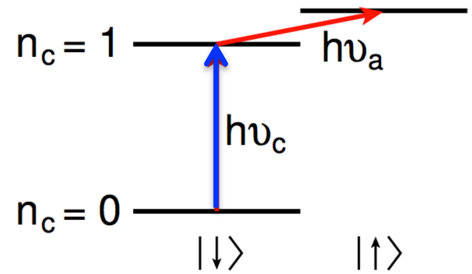
Advantages of the Correlated Measurement protocol

- Eliminates magnetic field drifts between a given anomaly and cyclotron data point
- In low-axial-damping limit, system stays in single axial state during a measurement, creating discrete peaks
- Combined with cooling to axial ground state, successive attempts see same very small range of fields from magnetic bottle distortion, which makes for very narrow lines

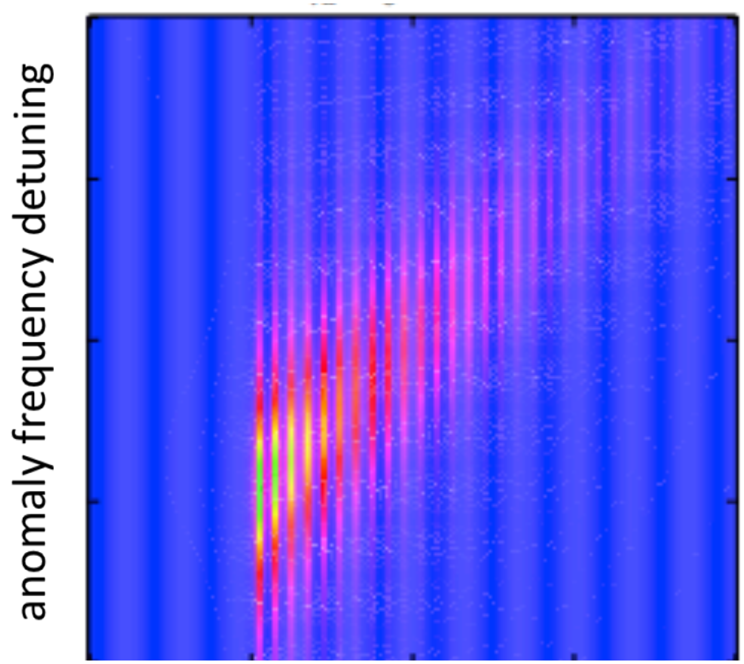




$$\frac{g}{2} = 1 + \frac{\nu_a}{\nu_c}$$



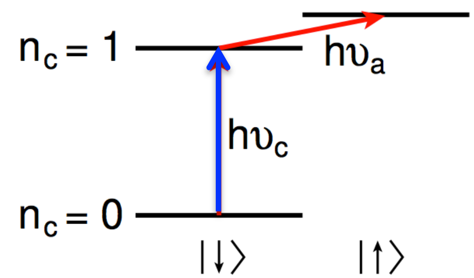
Excitation probability for drive frequency pairs

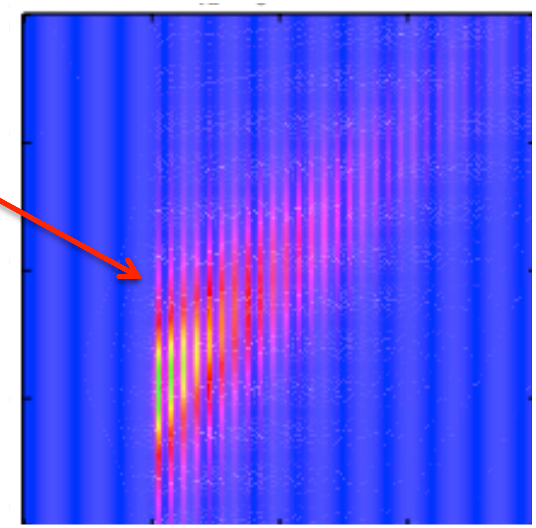


L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)
B. D'Urso, Ph.D. thesis, Harvard University (2003)

Technical challenges of the Correlated Measurement protocol

- Lower transition success rate, so statistics could be an issue
  - Both cyclotron and anomaly drive attempts must be successful to get an excitation
  - Much narrower lines, and must still know B-field well enough to drive transitions
- Need to be in low axial damping limit to see discrete quantum states, so must develop a method of decoupling particle from amplifier. Development of cryogenic low-loss high-B-field-tolerant RF switch is ongoing
- For maximum benefit, need to cool to axial ground state with cavity-assisted axial sideband cooling



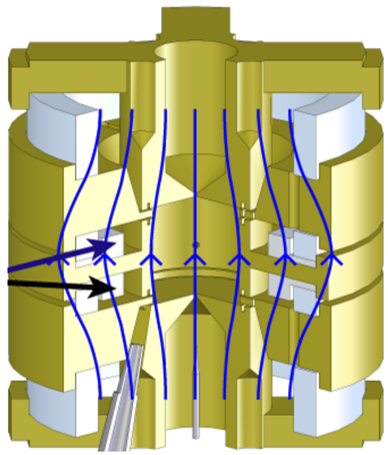


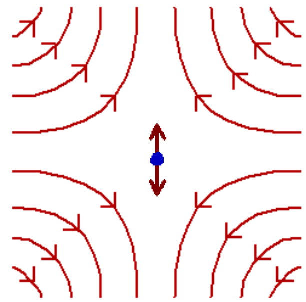
Next technique in development!

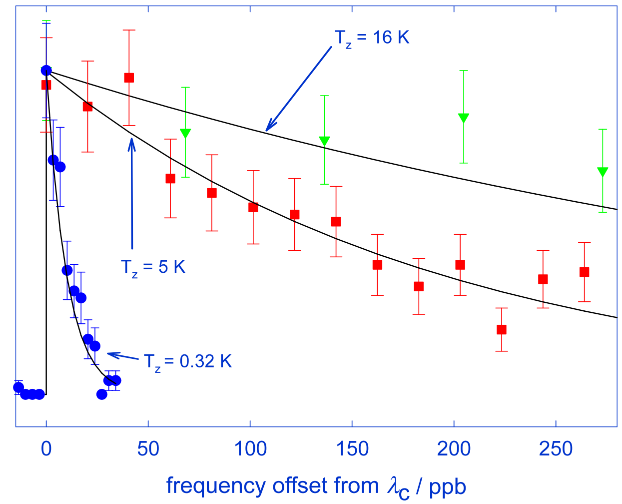
L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)
B. D'Urso, Ph.D. thesis, Harvard University (2003)

Axial-cyclotron sideband cooling

Want to reduce axial state to reduce spread of magnetic fields particle sees during an axial oscillation:



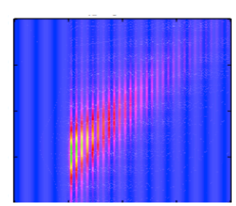




- Decouple axial motion from amp => no thermalization to 100 mK
- Apply a drive at $\bar{\omega}_C - \bar{\omega}_z$ to drive sideband transition that decreases axial state and increases cyclotron state
- Cyclotron decays via synchrotron radiation
- Cooling limit: $$T_z = \frac{\omega_z}{\omega_c'} T_c \approx 1 \times 10^{-4} K$$

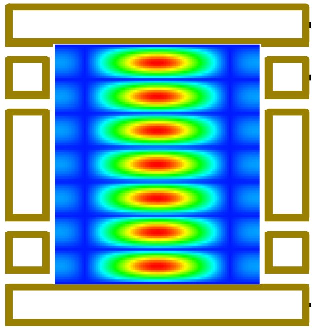
Compare: axial state spacing is about 10 mK

- Good enough to get to axial ground state for correlated measurement

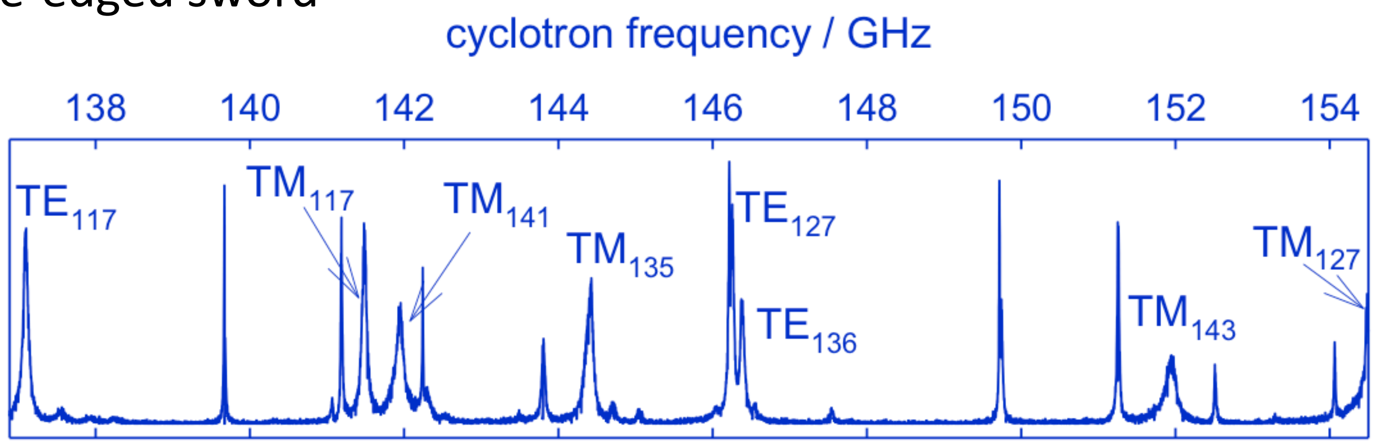


L. S. Brown, G. Gabrielse, K. Helmerson, and J. Tan, Phys. Rev. Lett. **51**, 44-47 (1985)
D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

Penning trap as microwave cavity



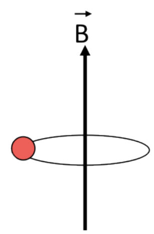
- Walls of the cylindrical electrodes form a resonant microwave cavity near electron's cyclotron frequency
- Changing B field changes cyclotron frequency, brings particle into and out of resonance with modes
- Particle's interaction with mode fields affects cyclotron lifetime, cyclotron frequency, and our ability to couple microwaves into cavity
- Double-edged sword

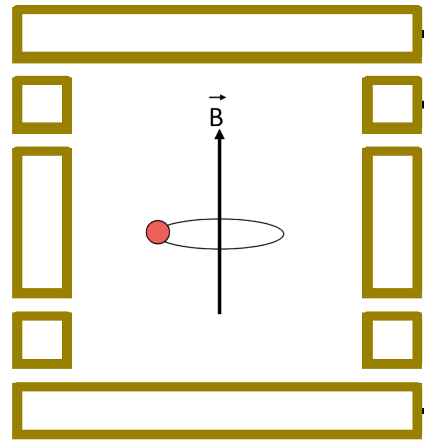


L. S. Brown, G. Gabrielse, K. Helmerson, and J. Tan, Phys. Rev. Lett. **51**, 44-47 (1985)
D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

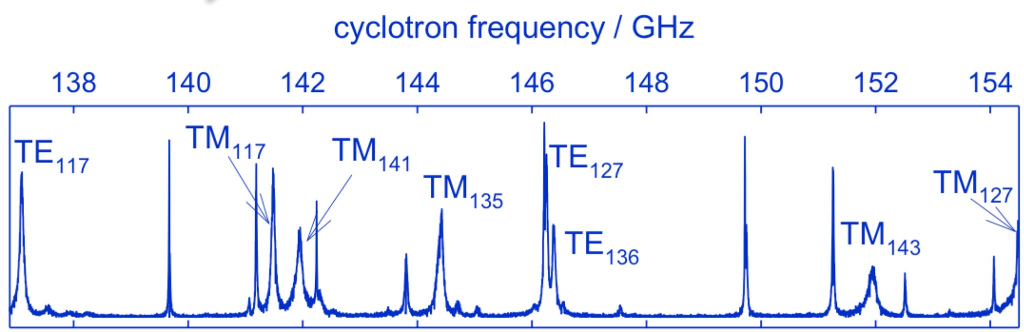
Cavity inhibits spontaneous emission

- Free space cyclotron lifetime is 89 msec

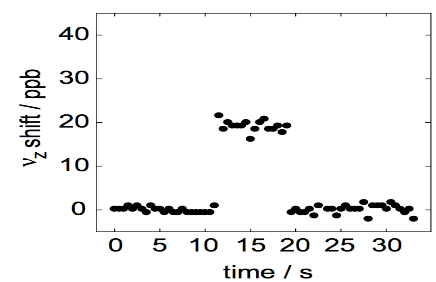




- Lifetime in cavity can be as high at 16 sec far from from strong cyclotron coupling modes
- Inhibited by factor of 180!

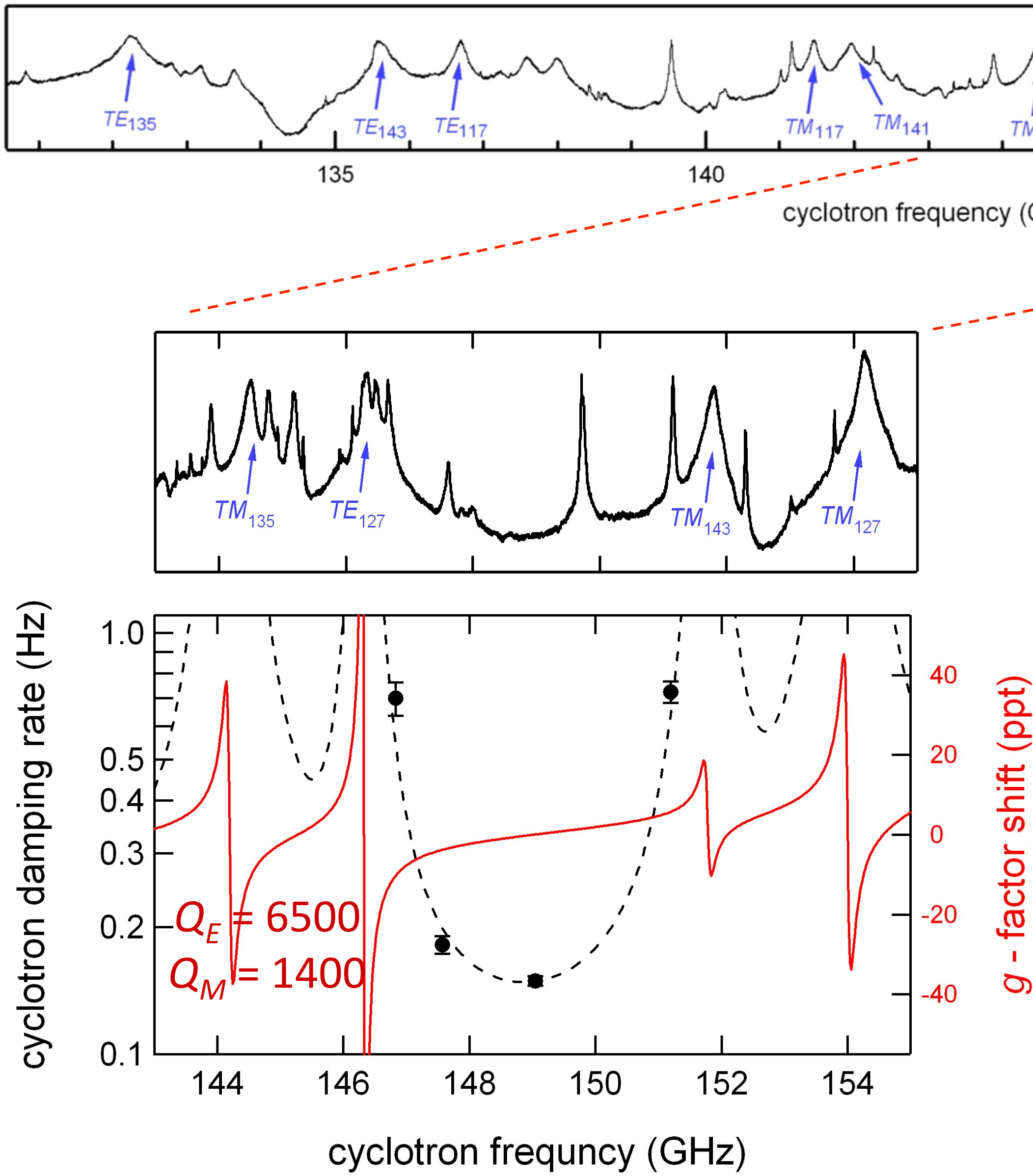


- Need some inhibition to have time to average self-excited oscillator to detect axial frequency shifts that indicate transitions



L. S. Brown, G. Gabrielse, K. Helmerson, and J. Tan, Phys. Rev. Lett. **51**, 44-47 (1985)
D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

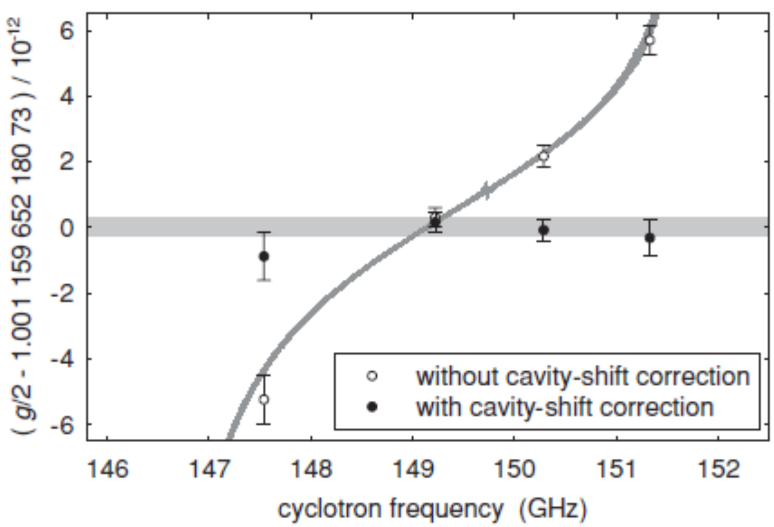
Strong coupling modes affect cyclotron frequency as well as lifetime



- These cavity modes alter cyclotron frequency to shift measured g factor
- For 2008 measurement, cyclotron lifetimes at each magnetic field value were measured to correct for g-factor shifts

L.Brown and G.Gabrielse, *Phys.Rev.A* **25**, 2423 (1982)

Cavity shifts do not limit g-2 uncertainty at current level

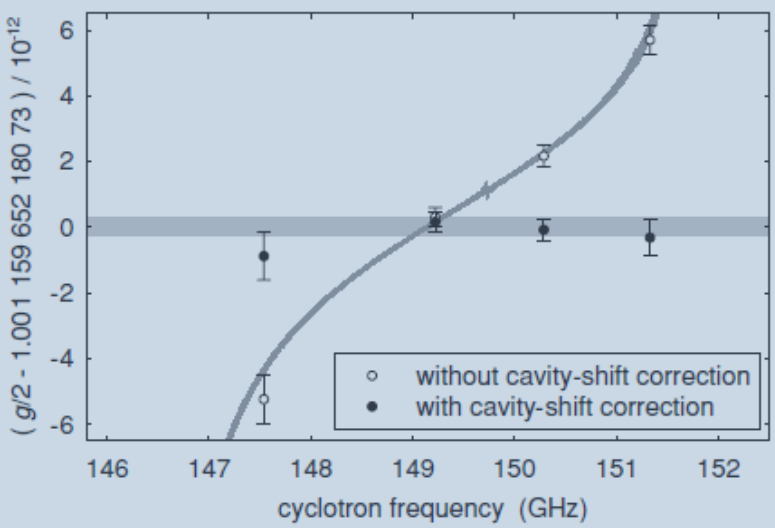


Uncertainties for 2008 *g* in parts-per-trillion.

ν_c / GHz =	147.5	149.2	150.3	151.3
Statistics	0.39	0.17	0.17	0.24
Cavity shift	0.13	0.06	0.07	0.28
Uncorrelated lineshape model	0.56	0.00	0.15	0.30
Correlated lineshape model	0.24	0.24	0.24	0.24
Total	**0.73**	**0.30**	**0.34**	**0.53**

D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

Cavity shifts no longer limit g-2 uncertainty



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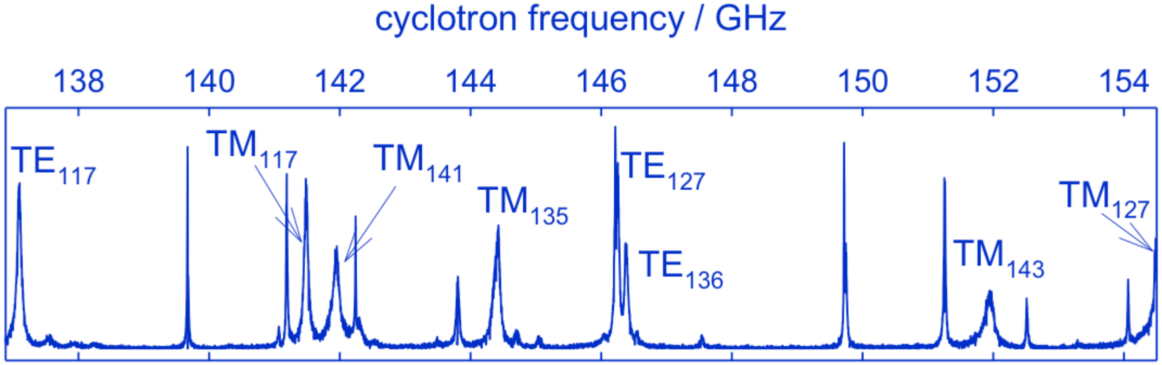
Total	**0.73**	**0.30**	**0.34**	**0.53**

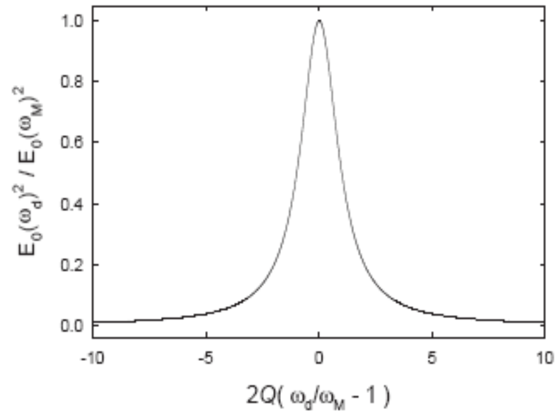
But other cavity modes can also actively help us cool axial motion!

D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)

Cavity assistance in axial sideband cooling

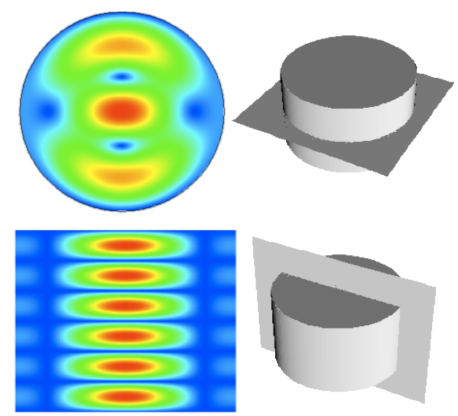


Power coupling efficiency:



- Need to drive on a "cooling mode" with correct geometry for these sideband transitions:
  - E field like $z\hat{\rho}$ or $\rho\hat{z}$
- If far from cooling mode, almost all microwave power is reflected
- On cooling mode, good power transmission and order-x10 geometrical enhancement of E field
- But also need to stay away from strong coupling modes that shift g factors and reduce cyclotron lifetime!

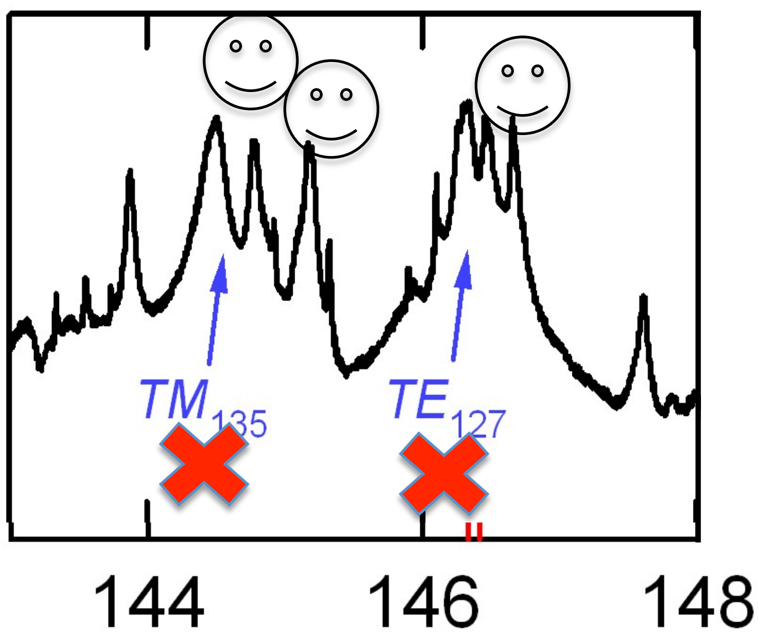
Transverse E-field on cross sections of a cooling mode in the trap



D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, Phys Rev **A** 83, 052122 (2011)

Cavity mode structure of the 2008 trap prevented cavity-assisted axial sideband cooling

- 2008 trap: all cooling modes were too close to strong cyclotron coupling modes, so none could be used at g-measurement locations

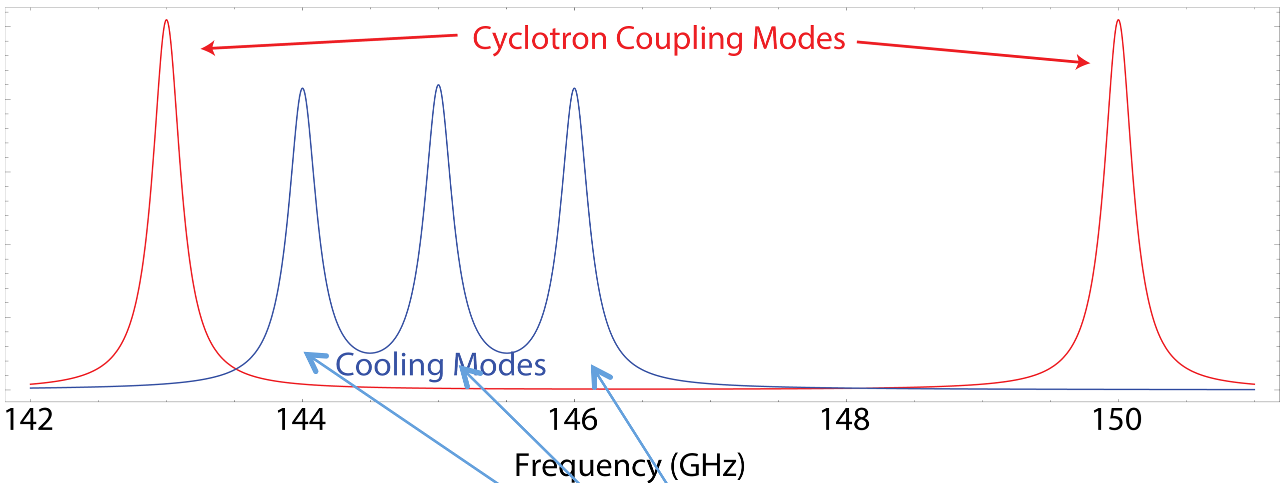


cyclotron frequency

D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, Phys Rev **A** 83, 052122 (2011).

Cavity mode structure of the new trap will enable cavity-assisted axial sideband cooling

- 2008 trap: all cooling modes were too close to strong cyclotron coupling modes, so none could be used at g-measurement locations
- Relative frequencies of modes depend of trap geometry



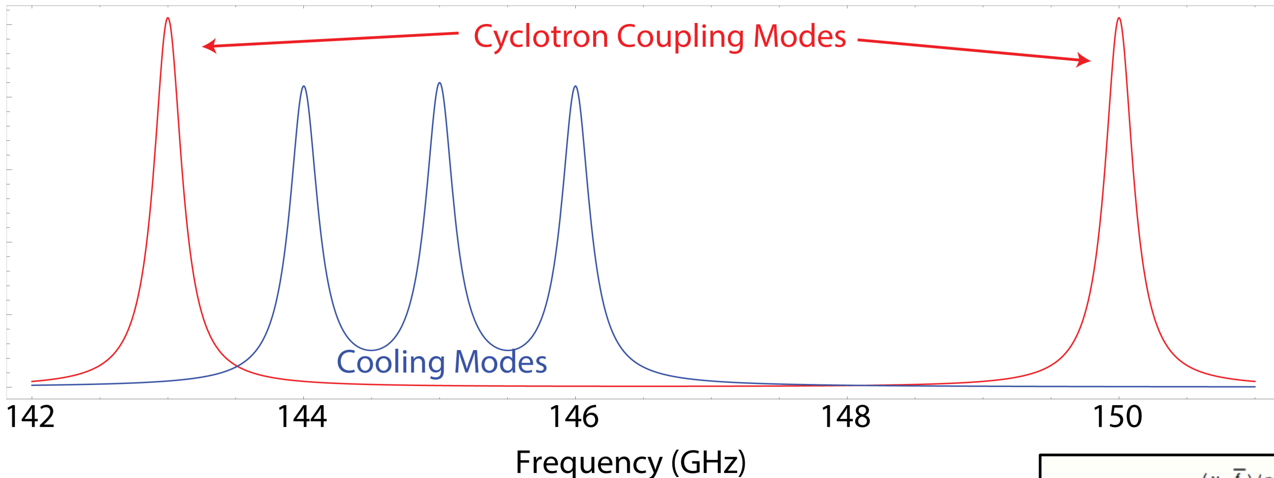
Strong cyclotron damping modes: cause short lifetime and cavity shift, so must be avoided

Cooling modes: enable axial-cyclotron sideband cooling

New trap: designed to have usable cooling modes that should make axial cooling possible!

New apparatus in S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Cavity mode structure of the new trap will enable cavity-assisted axial sideband cooling



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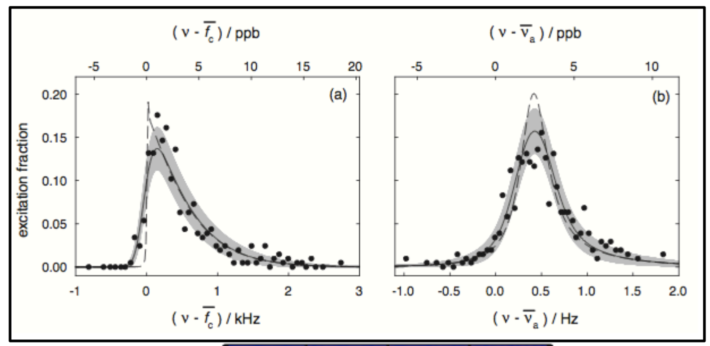
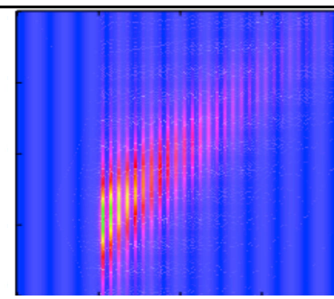
Cooling modes: enable axial-cyclotron sideband cooling





- Any cooling: expected to narrow cyclotron and anomaly lines, with either measurement protocol

- Full cooling to ground state: maximum benefit of correlated measurement protocol

New apparatus in S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Another frontier: better statistics

- Rate-limiting step: wait several lifetimes for cyclotron decay after anomaly transition attempt (or correlated transition attempt)
- To speed this step, sweep down with adiabatic fast passage or π-pulse

Uncertainties for *g* in parts-per-trillion.

ν_c / GHz =	147.5	149.2	150.3	151.3
Statistics	0.39	0.17	0.17	0.24
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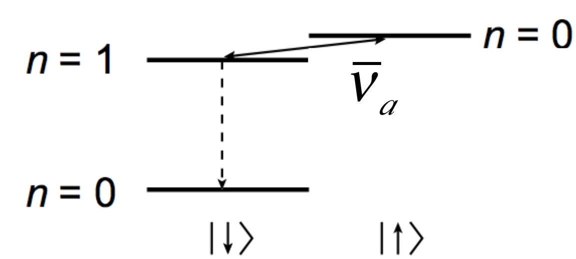
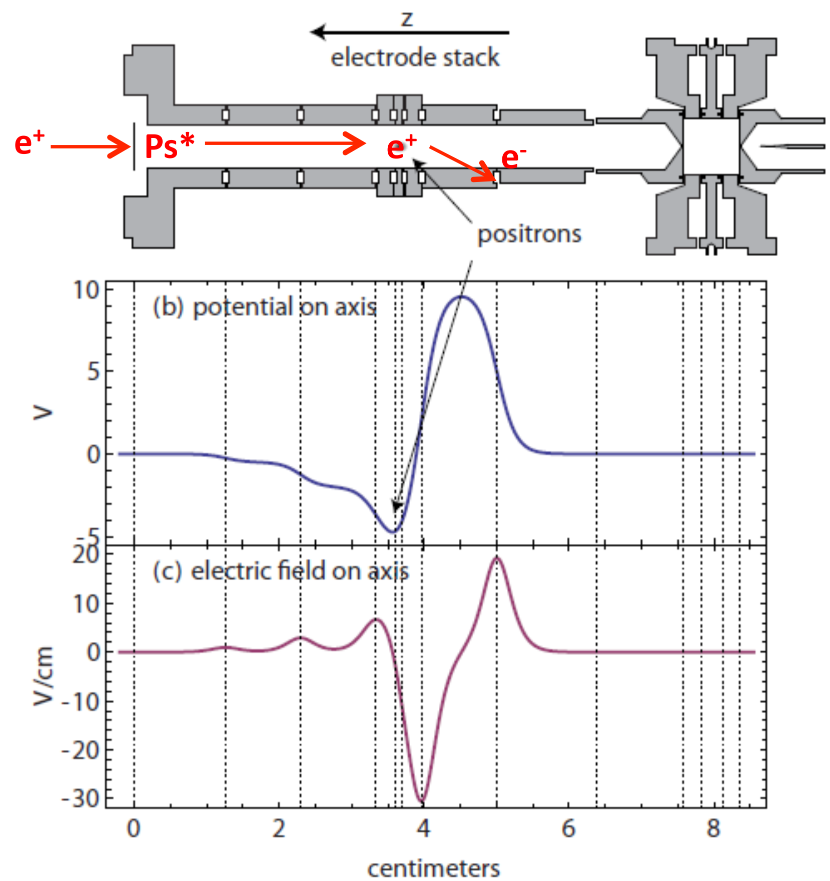


D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev Lett. **100**, 120801 (2008)
D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, Phys Rev **A** 83, 052122 (2011)

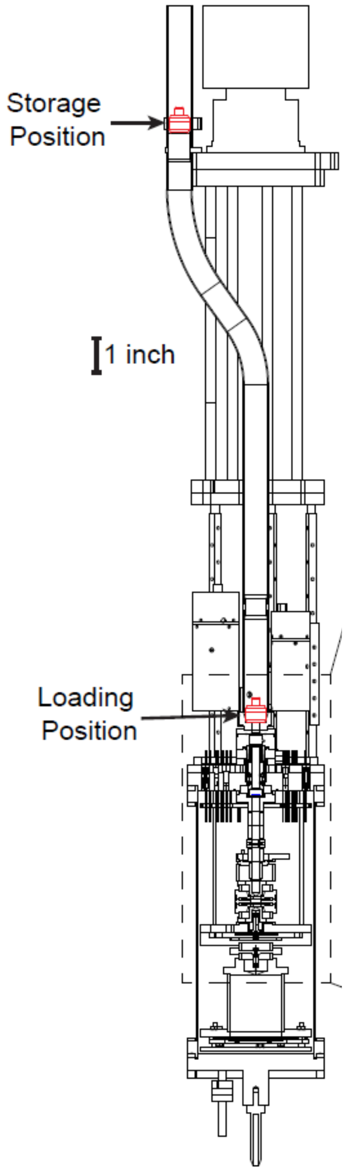
Positron loading mechanism

- Positrons come from beta decay of ^{22}Na
- Positrons pass through single crystal tungsten moderator → form loosely bound positronium
- Electric field in trap strips away electron and leaves positron trapped



J. Estrada, T. Roach, J. N. Tan, P. Yesley, and G. Gabrielse, Phys. Rev. Lett. 84, 859 (2000).

Positron loading demonstrated in new apparatus with small retractable source



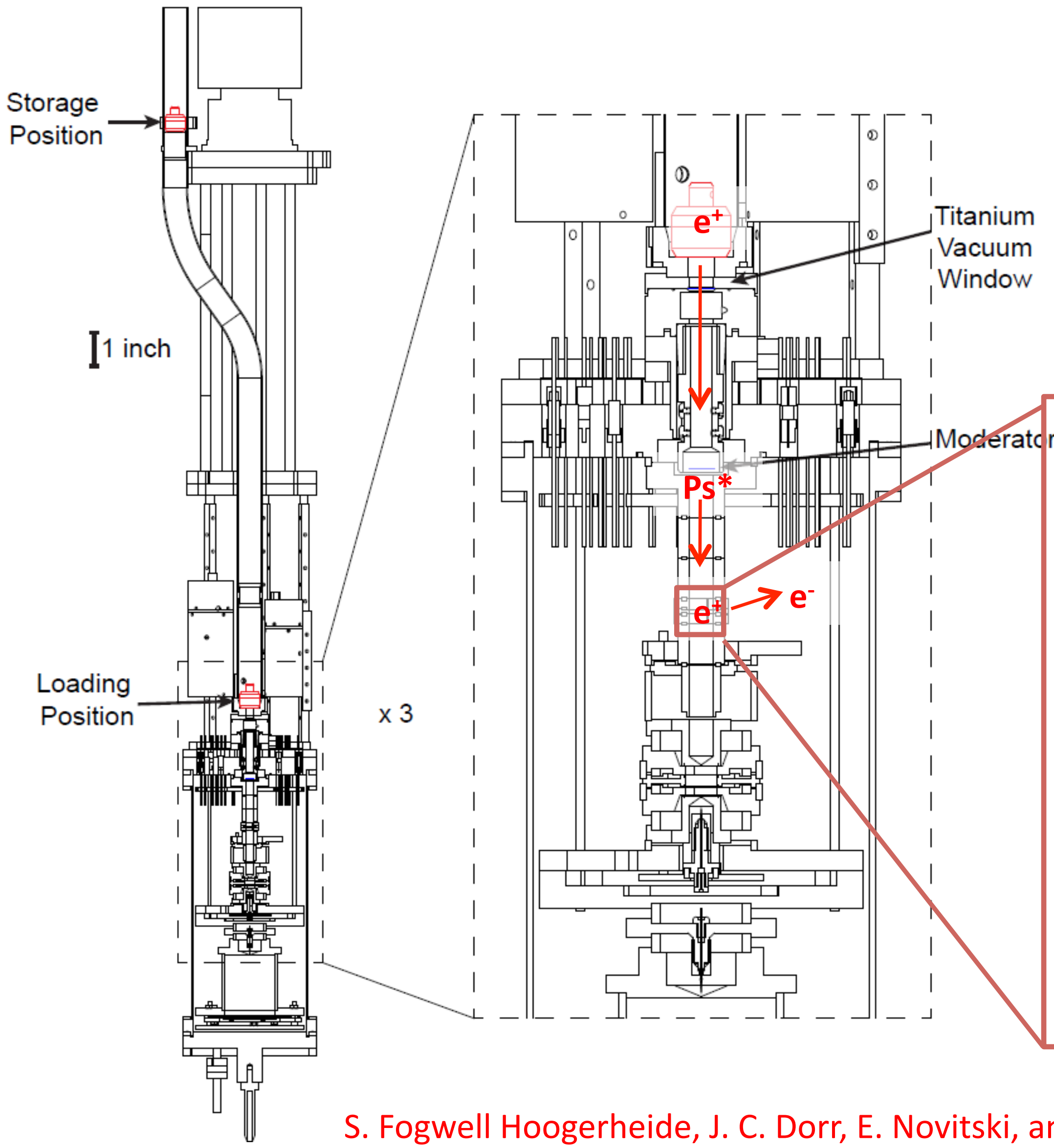
- Method was developed for accumulating millions of positrons with large ~ mCi radioactive sources (a safety headache)

- Relatively tiny 6.5 uCi source requires no shielding

- Source is retractable to preserve pristine environment for measurement
  - Required wider dilution refrigerator
  - Design challenges at 100 mK: 0.8 mm hole from 300 K to 100 mK would cause 200 uW of heating

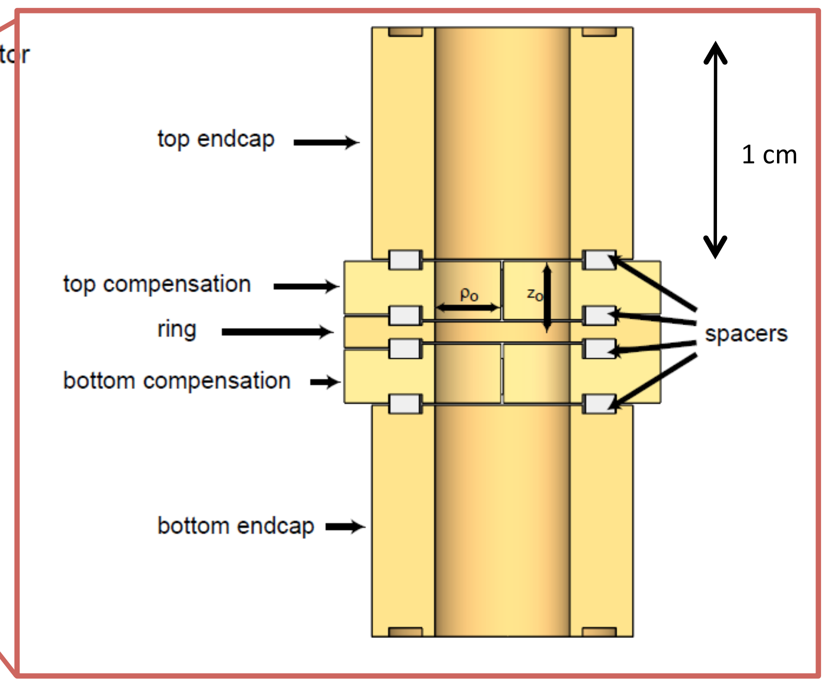
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Additional Penning trap to catch positrons from source



- Precision trap is closed-endcap (0.25 mm holes)

- Built new open-encap trap and detection electronics for e+ loading



S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

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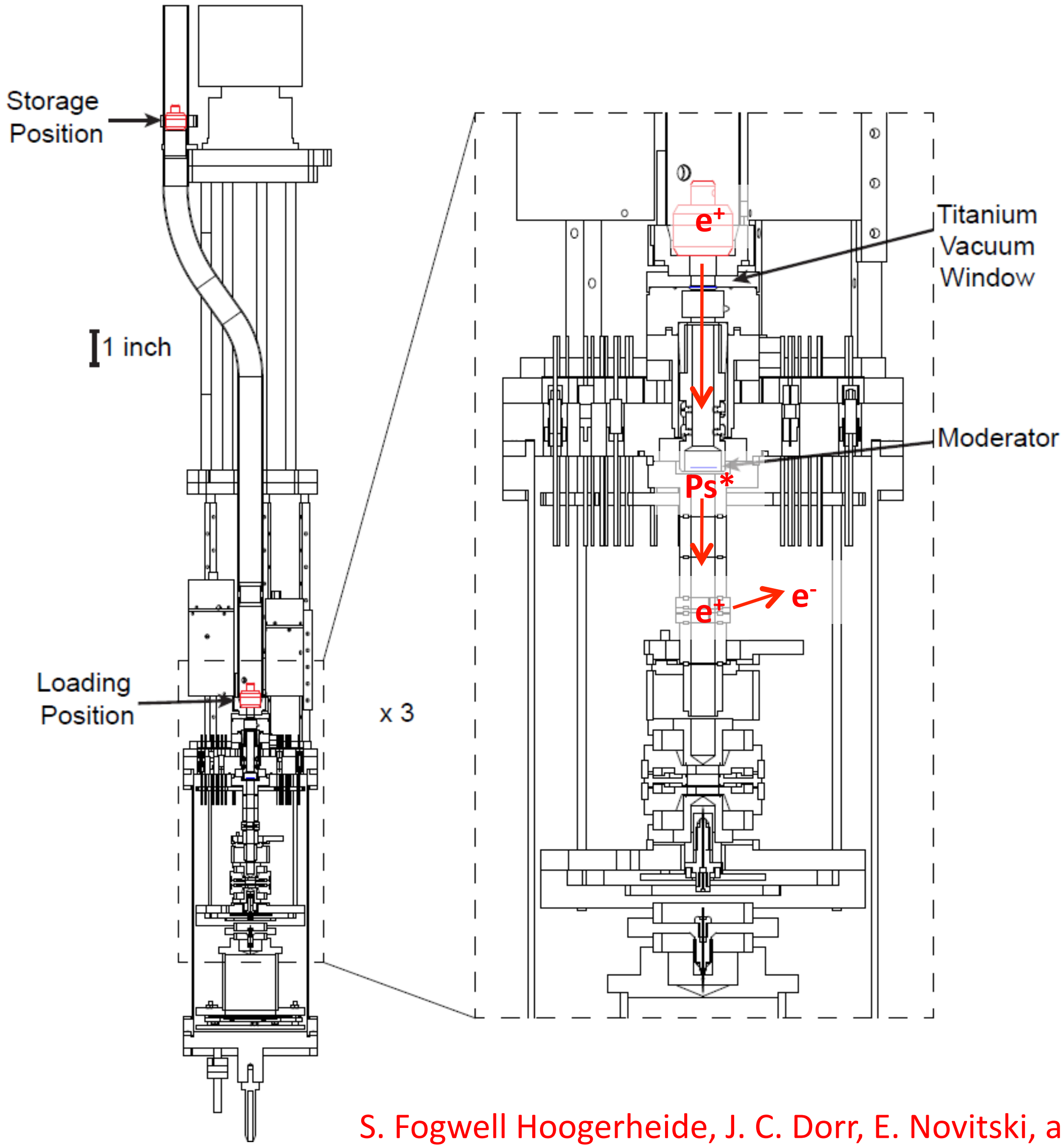
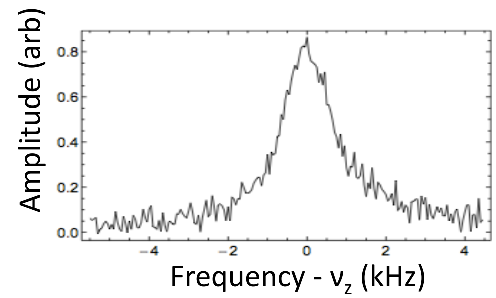




- Demonstrated higher positron loading rate than 1987 UW positron measurement with 75x smaller source (6.5 μC)
- Next step: pulsed transfer to precision trap

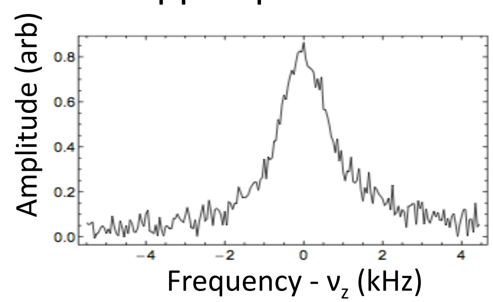
S. Fogwell Hoogerheide, J. C. Dorr, E. Novitski, and G. Gabrielse. *Rev. Sci. Instrum*. 86, 053301 (2015)

Status and outlook

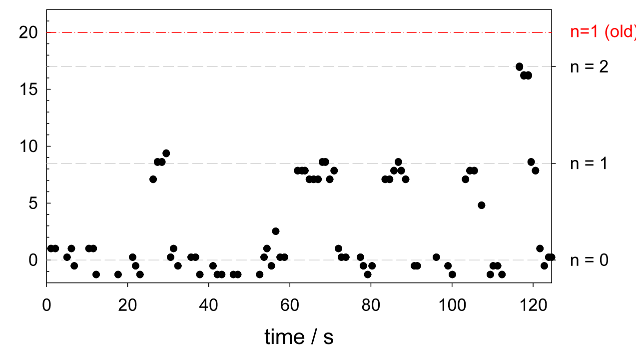
Improvements that have already been implemented

- New apparatus with positrons, improved stability, smaller magnetic bottle, better cavity mode structure, and more…

Driven axial response from trapped positrons

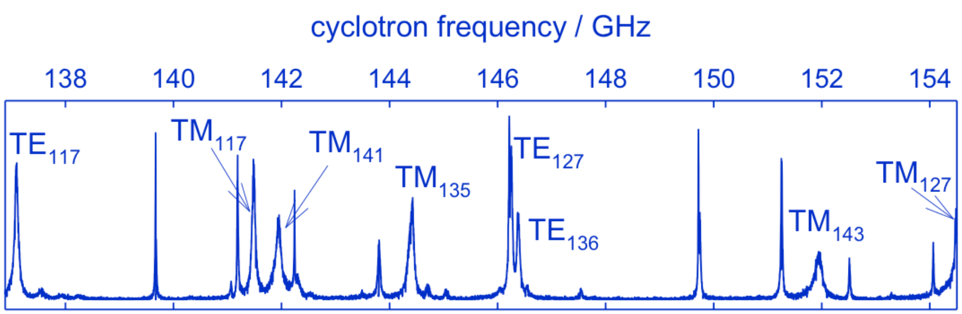


Smaller jumps



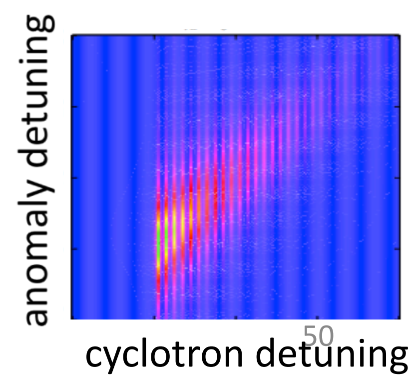
Remaining basic preparation

- Transfer positrons from loading trap into precision trap to prepare for positron measurement
- Characterize apparatus (cavity mode structure, systematic checks, etc)



New techniques in development

- Cavity-assisted axial sideband cooling
- Correlated measurement



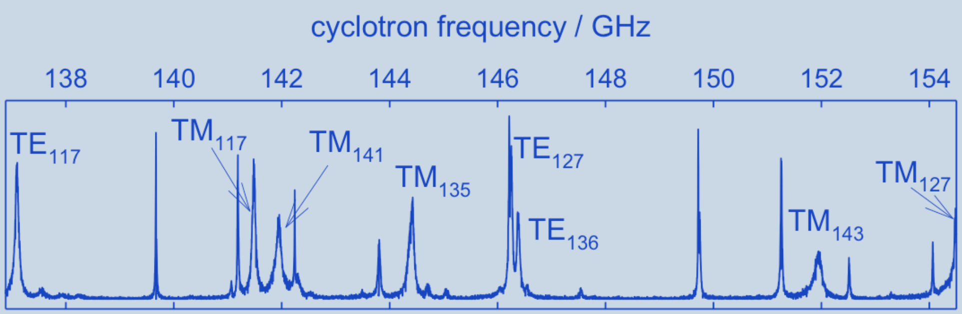
Status and outlook

Improvements that have already been implemented

New apparatus to enable improved tests of the Standard Model via new measurements of positron and electron g-2 at greater precision than the 2008 electron measurement

Remaining basic preparation

- Transfer positrons from loading trap into precision trap to prepare for positron measurement
- Characterize apparatus (cavity mode structure, systematic checks, etc)



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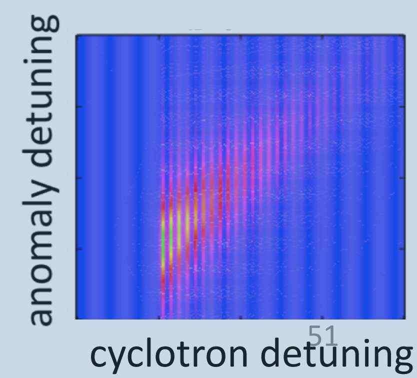

Thank you