

Future measurement of electron $g-2$

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Northwestern
University

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Move to Northwestern



Electron magnetic moment

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

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

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

$$\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

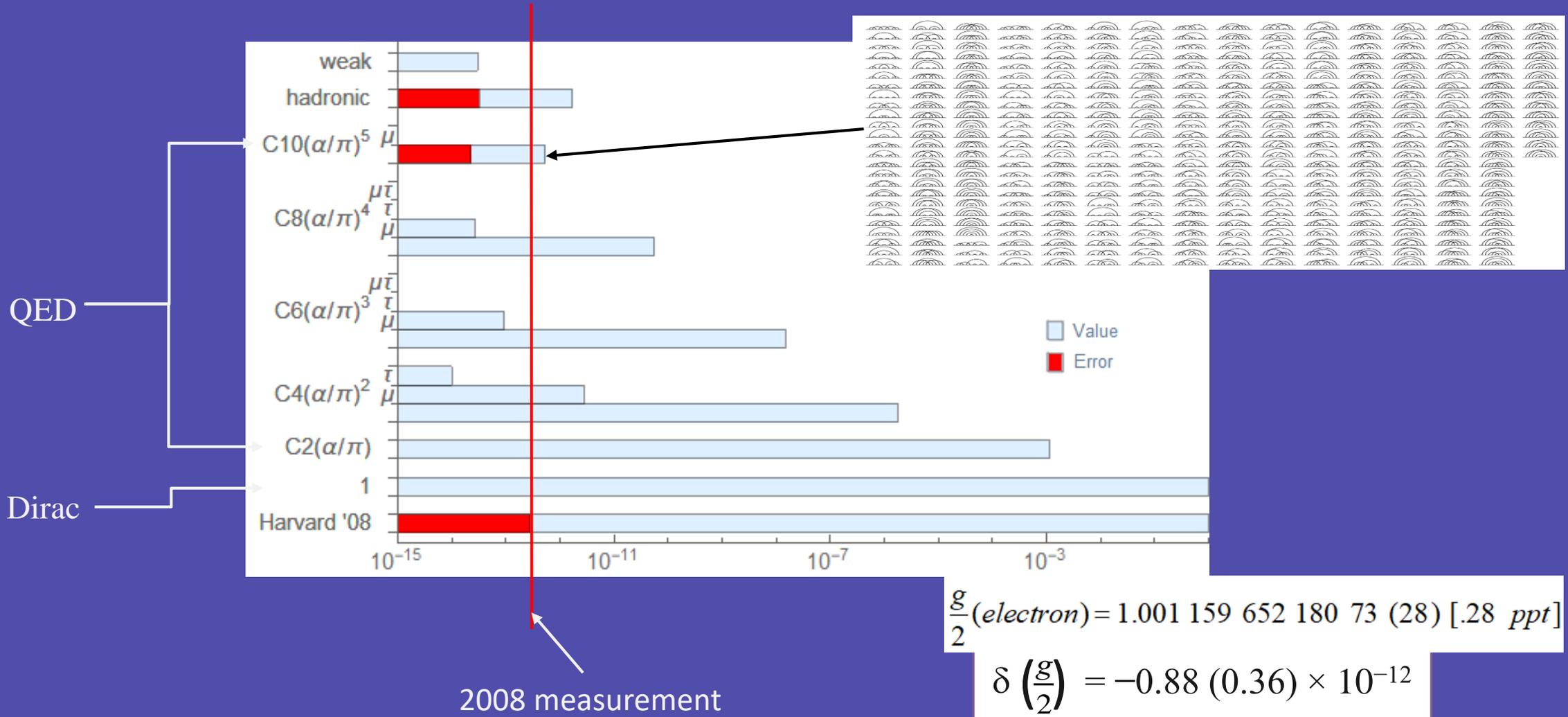
Electron magnetic moment

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

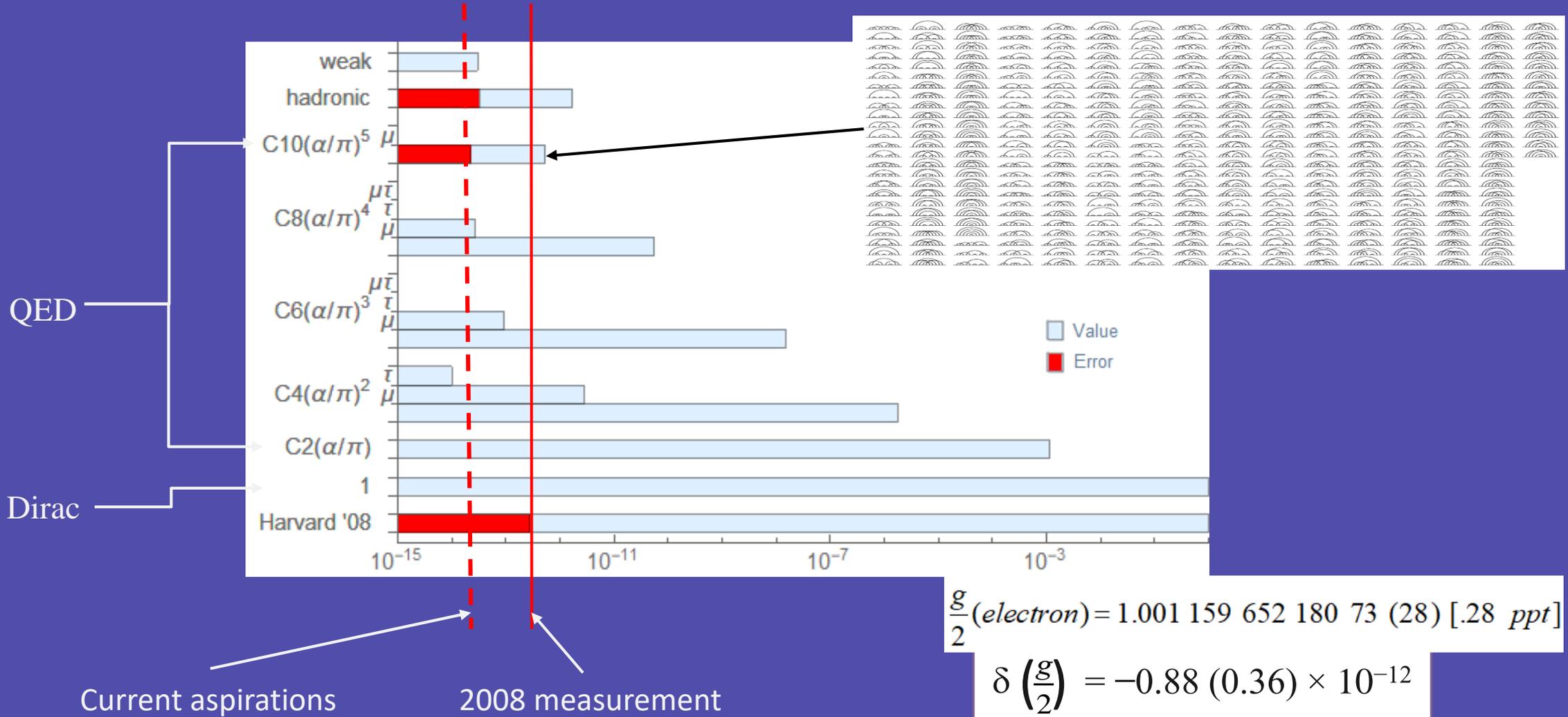
$$+ a_{hadronic} + a_{weak}$$

QED	$C_2 = 0.5,$ $C_4 = -0.328\,478\,444\,002\,62\,(25),$ $C_6 = 1.181\,234\,016\,818\,3\,(79),$ $C_8 = -1.911\,321\,391\,8\,(12),$ $C_{10} = 6.73\,(16),$	<p>essentially exact</p> <p>Kinoshita, Nio, ...</p>
Hadronic	$a_e^{hadronic} = 1.693\,(11) \times 10^{-12},$	
Weak	$a_{weak} = 0.03053\,(23) \times 10^{-12}$	

Previous measurements



Previous measurements



g-factor measurement

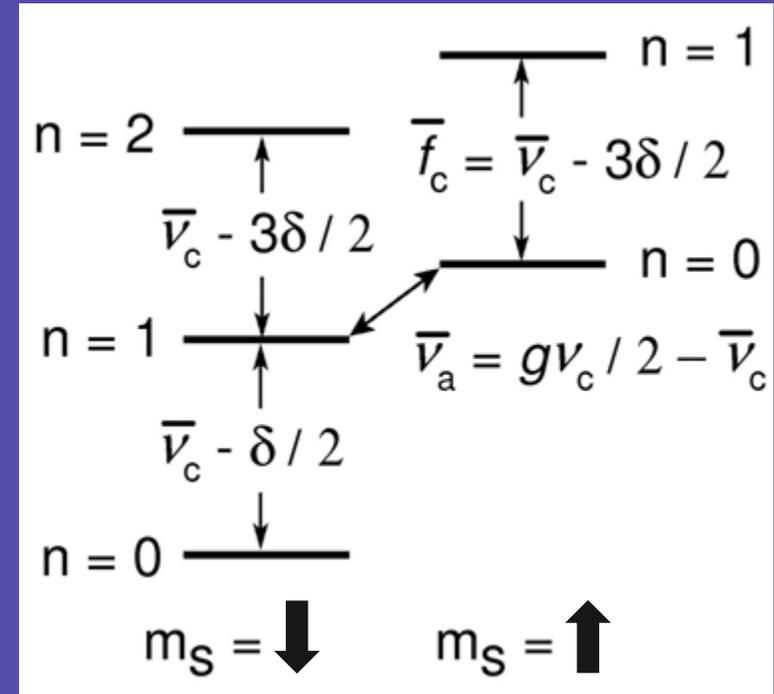
Spin flip energy:

$$\hbar \omega_s = -\vec{\mu} \cdot \vec{B} = -2\mu B$$

Cyclotron energy:

$$\hbar \omega_c = \hbar \frac{eB}{m} = 2\mu_B B$$

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



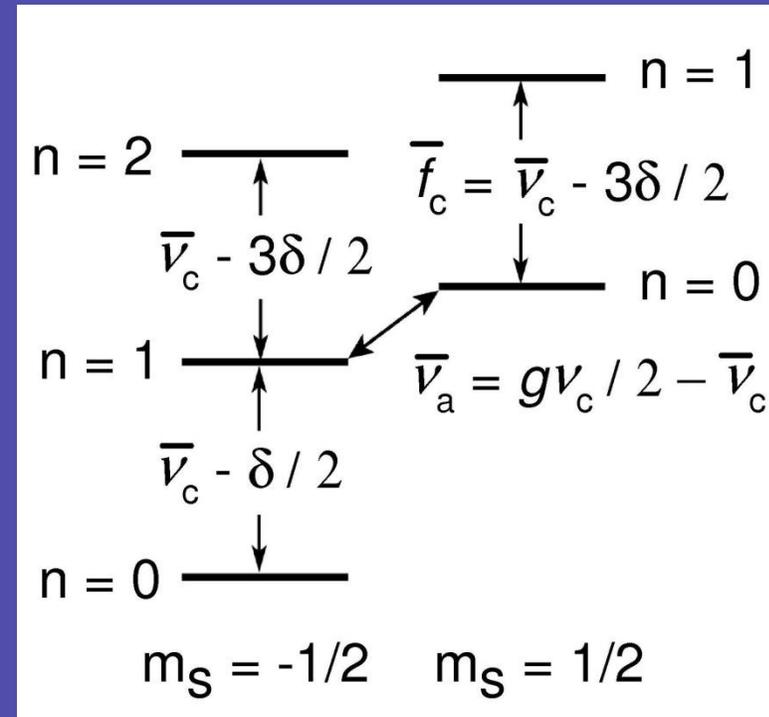
Real measurement

- one electron in a Penning trap
- lowest cyclotron and spin states

$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = \frac{\bar{\nu}_c + (\nu_s - \bar{\nu}_c)}{\nu_c} = \frac{\bar{\nu}_c + \bar{\nu}_a}{\nu_c}$$

$$\frac{g}{2} = \frac{\mu}{\mu_B} = \frac{\omega_s}{\omega_c} \rightarrow \frac{g}{2} \approx 1 + \frac{\bar{\nu}_a - \frac{\bar{\nu}_z^2}{2f_c}}{f_c + \frac{3\delta}{2} + \frac{\bar{\nu}_z^2}{2f_c}}$$

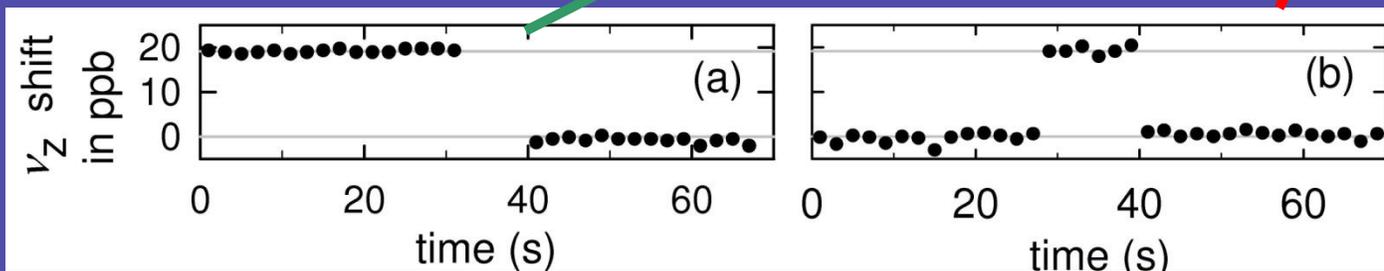
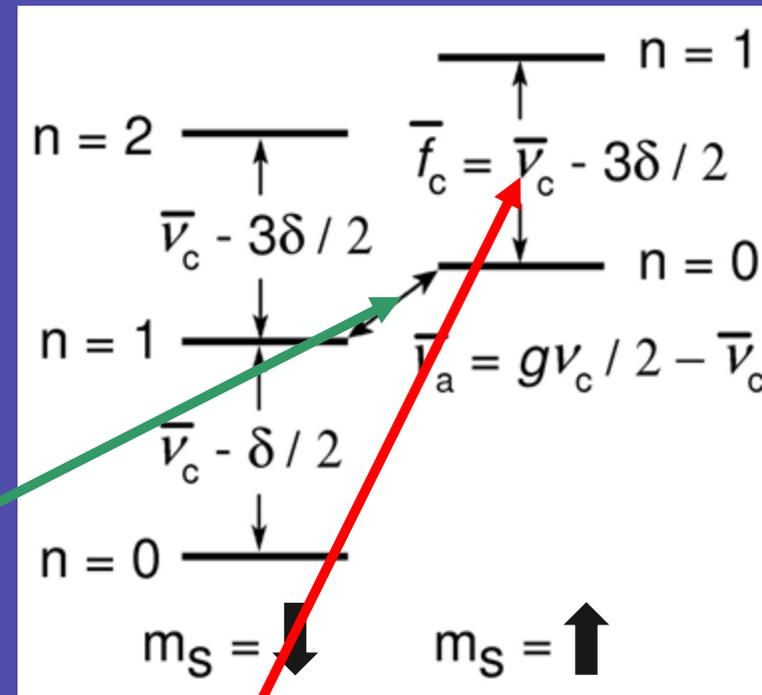
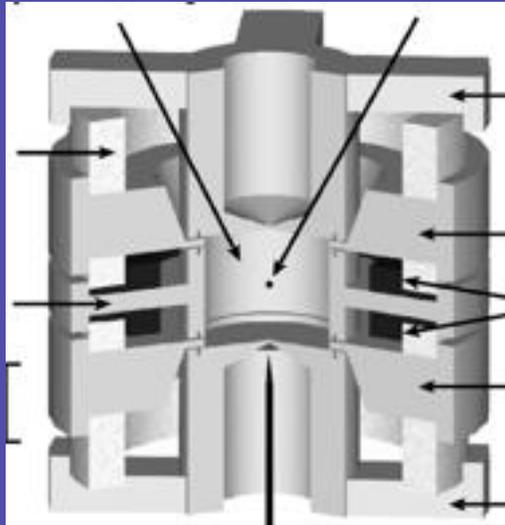
To deduce $g \rightarrow$ measure only three eigenfrequencies of the imperfect trap



expansion for $\bar{\nu}_c > \bar{\nu}_z > \bar{\nu}_m > \delta$

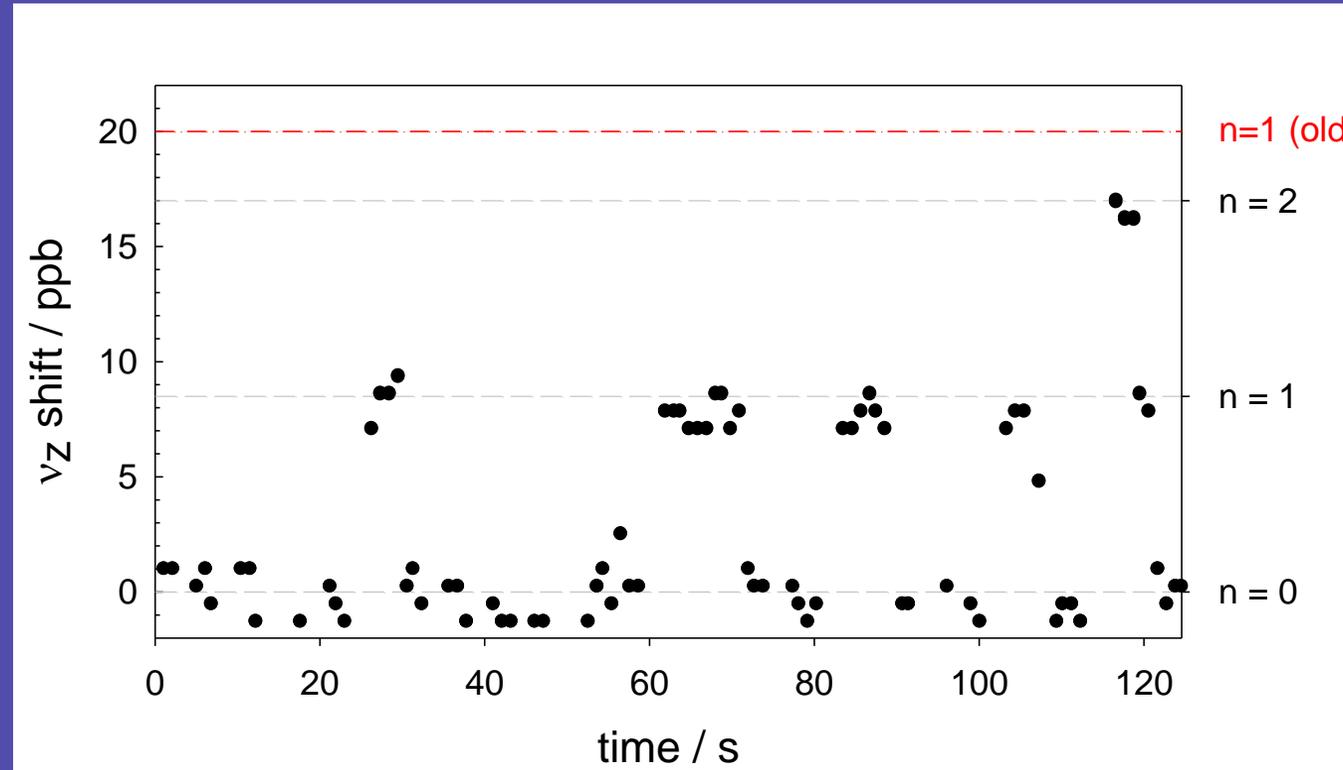
g-factor measurement

- one electron in a Penning trap
- lowest cyclotron and spin states



$$\frac{\mu}{\mu_B} = -\frac{\omega_s}{\omega_c}$$

Smaller magnetic bottle



Quantum limited detection?

Currently lumped LC resonator with FET amplifier

Use of high frequency (~ 200 MHz) SQUID detector

Low field with cancellation coils

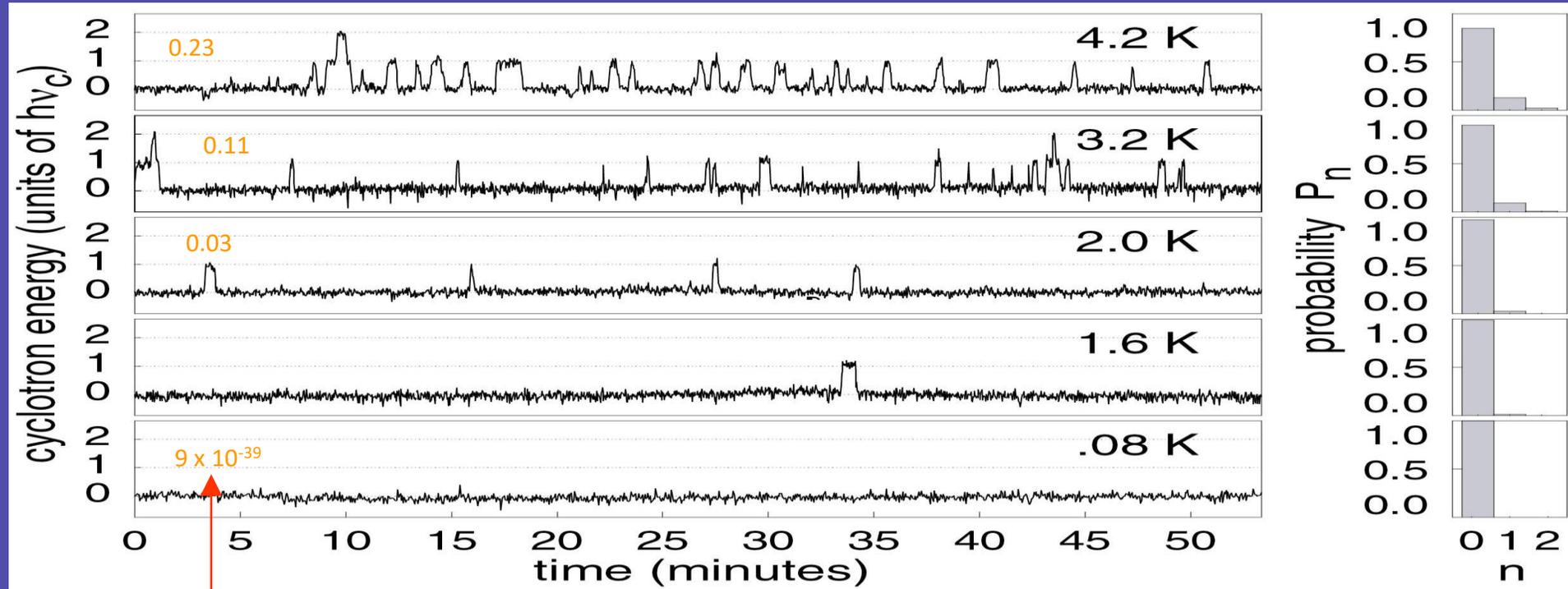
New super conducting magnet with bucking coils

Lower heat dissipation

Cooler particle motion

Electron in cyclotron ground state

Quantum Non-Demolition



average number
of blackbody
photons in the
cavity

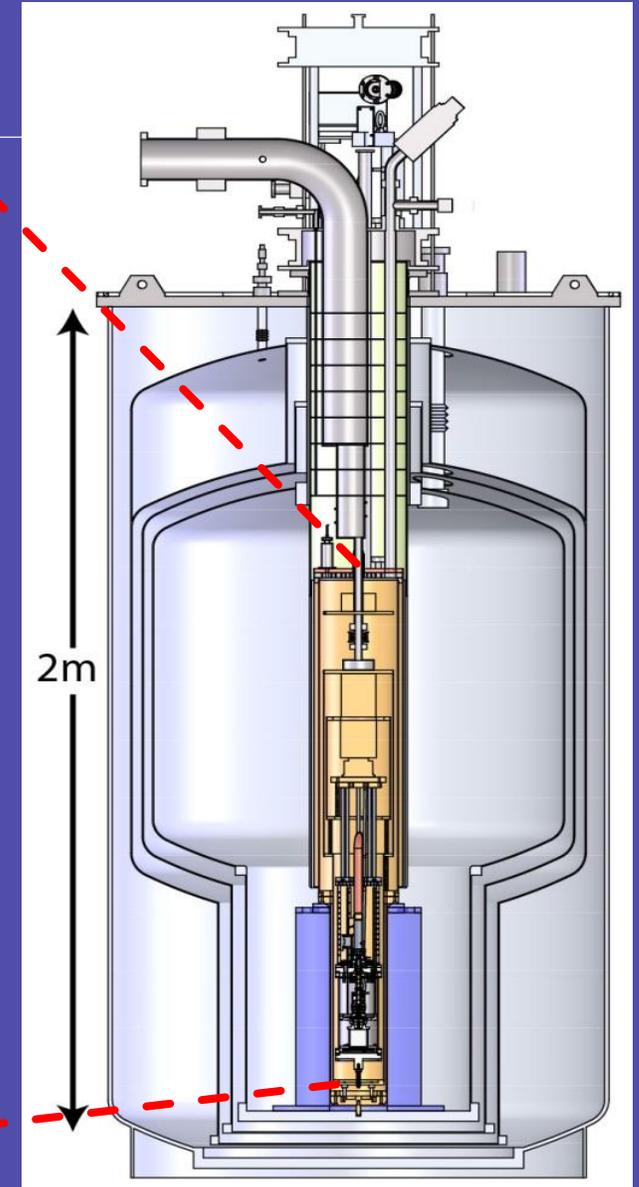
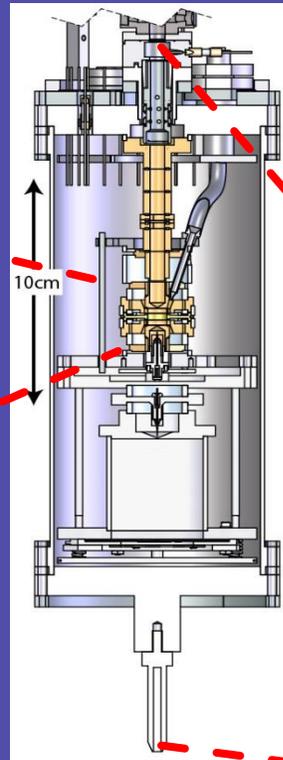
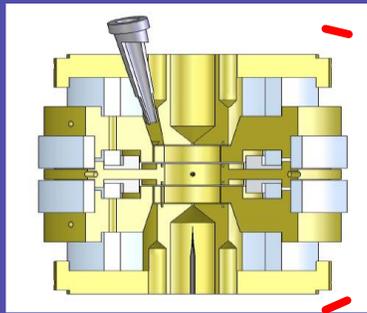
On a short time scale

→ in one Fock state or another

Averaged over hours

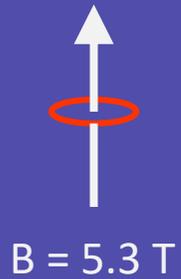
→ in a thermal state

Apparatus



Cavity-inhibited spontaneous emission

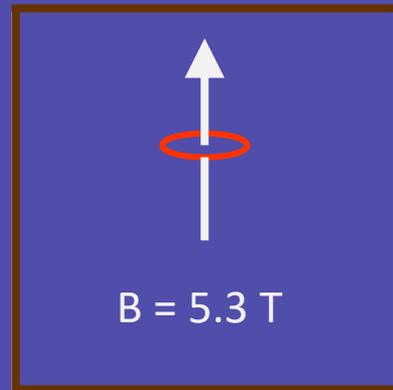
Free Space



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

Purcell
Kleppner
Gabielse and Dehmelt

Within
Trap Cavity

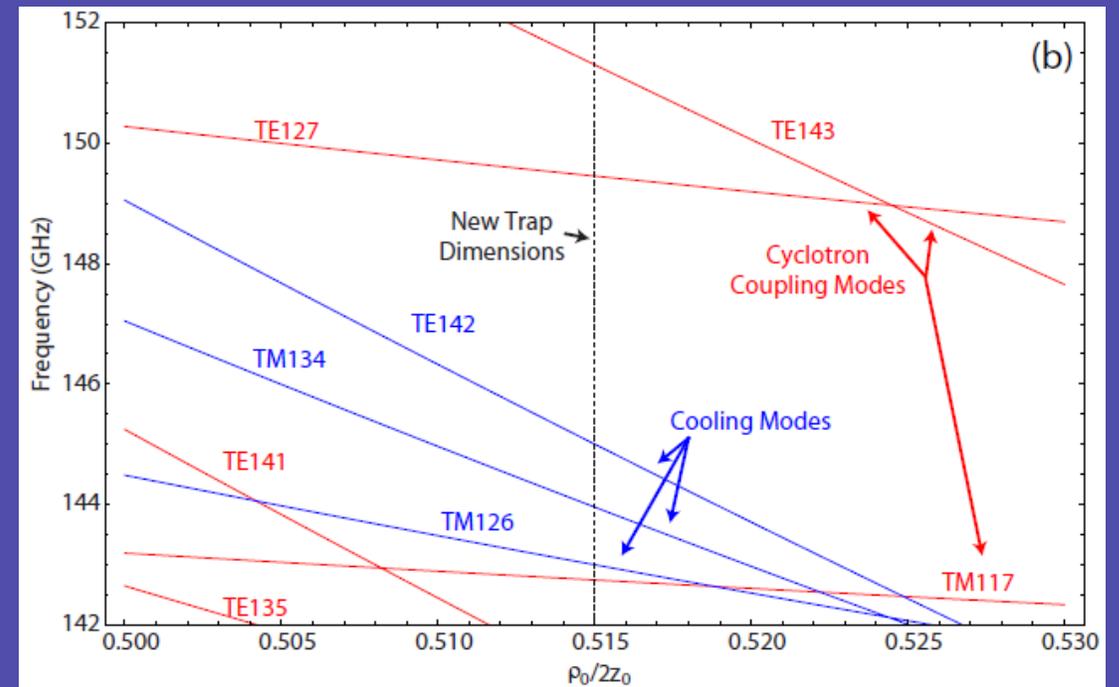
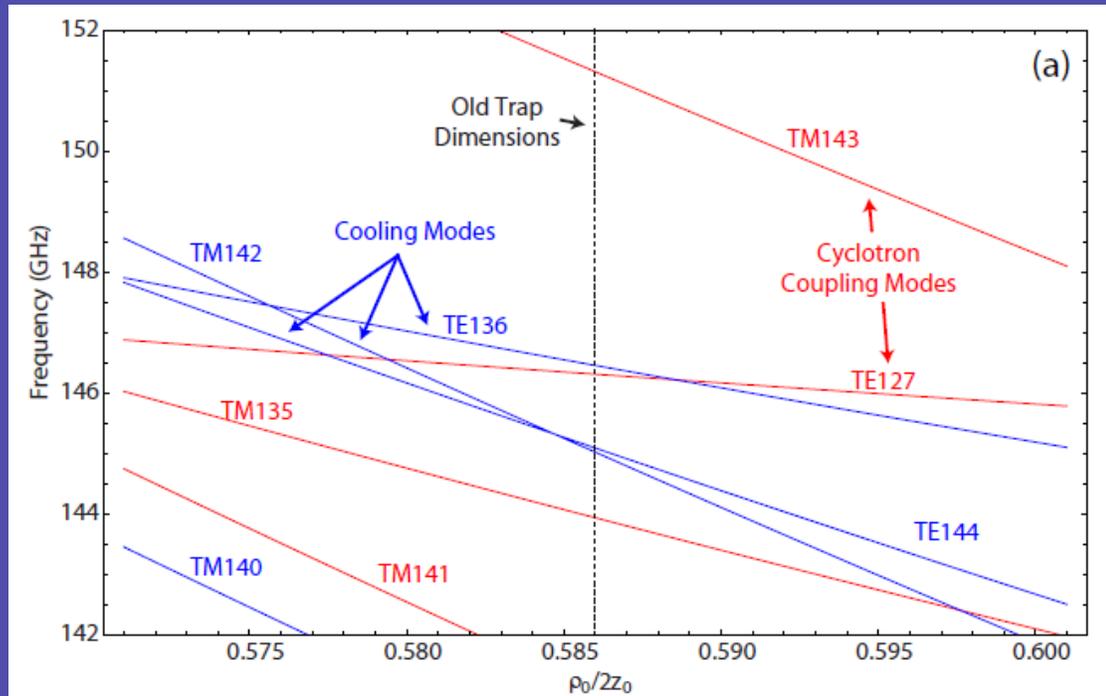


$$\gamma = \frac{1}{16 \text{ sec}}$$

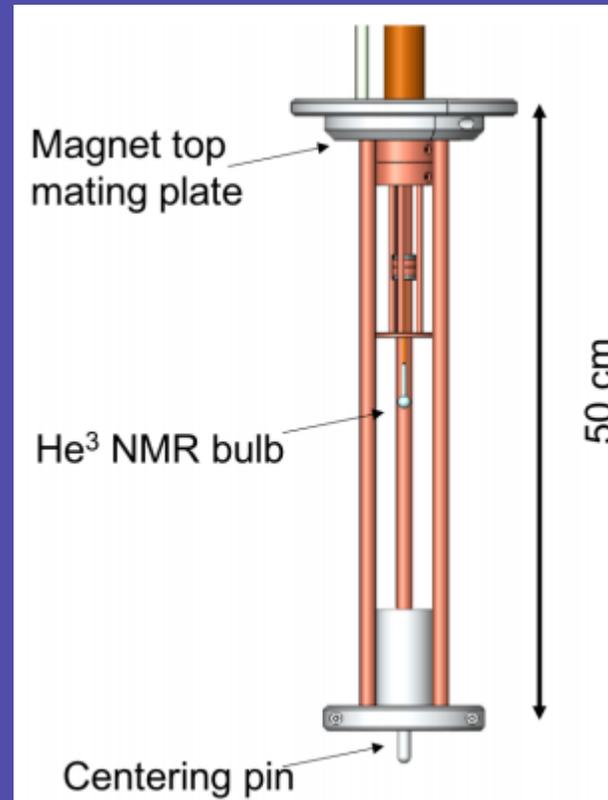
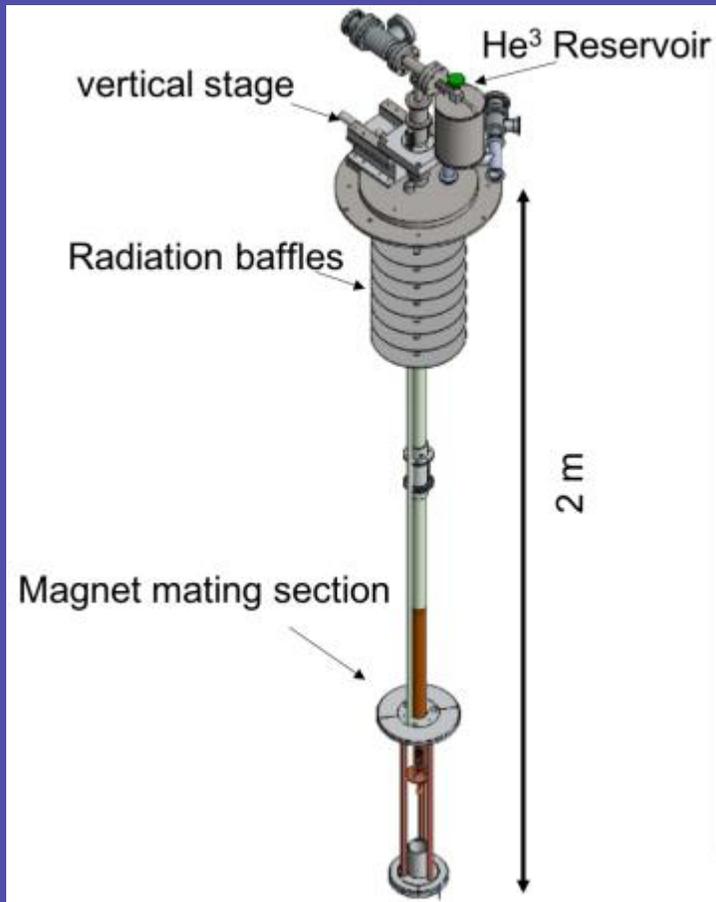
Inhibited
By 210

Inhibition gives the averaging time needed
to resolve a one-quantum transition

Cavity modes



Magnetic field measurement



Helium – 3 NMR probe

$T_1 = 360 (30) \text{ s}$

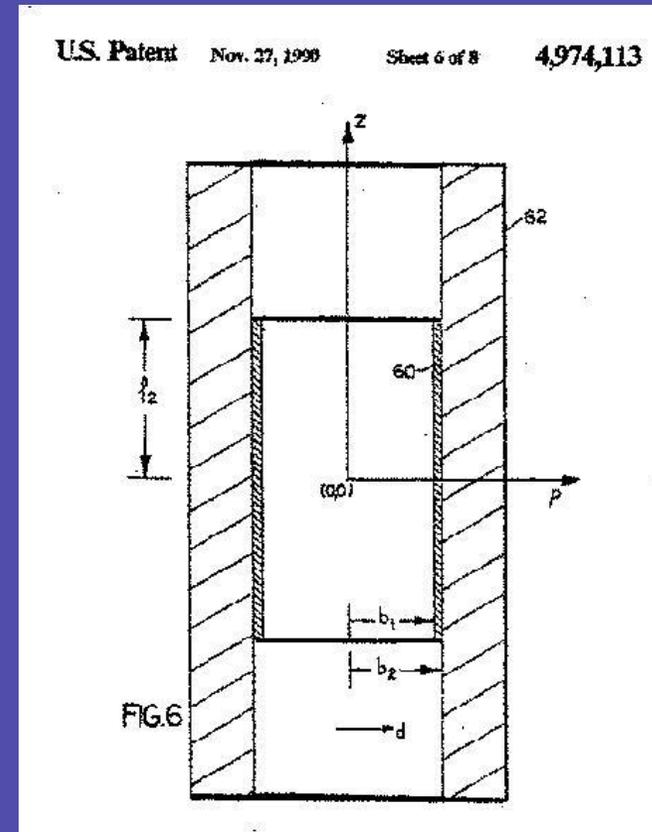
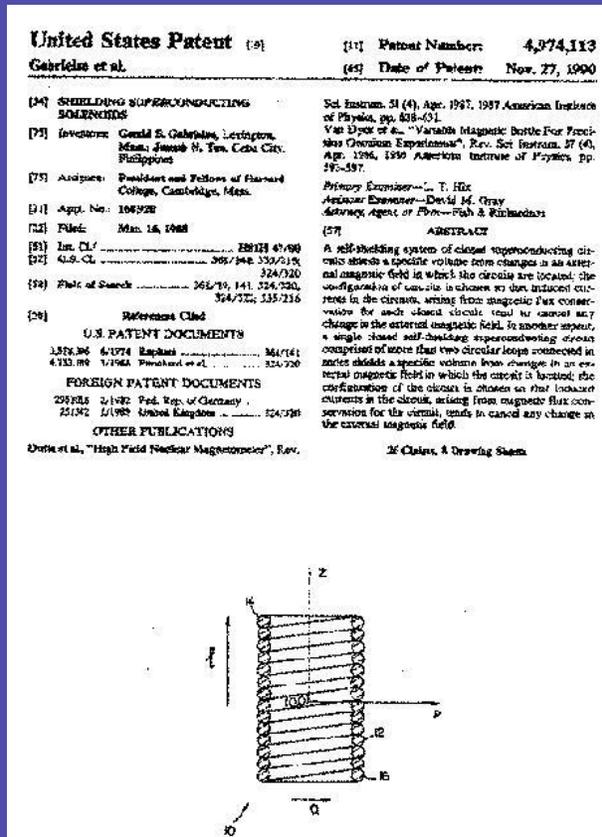
$T_2 = 2.7 (0.2) \text{ s}$

Homogeneity $\leq 50 \text{ ppb}$

Drift rate $0.20 (0.02) \text{ ppb/h}$

Self-shielding solenoid

Flux conservation \rightarrow Field conservation
 Reduces field fluctuations by about a factor > 1000

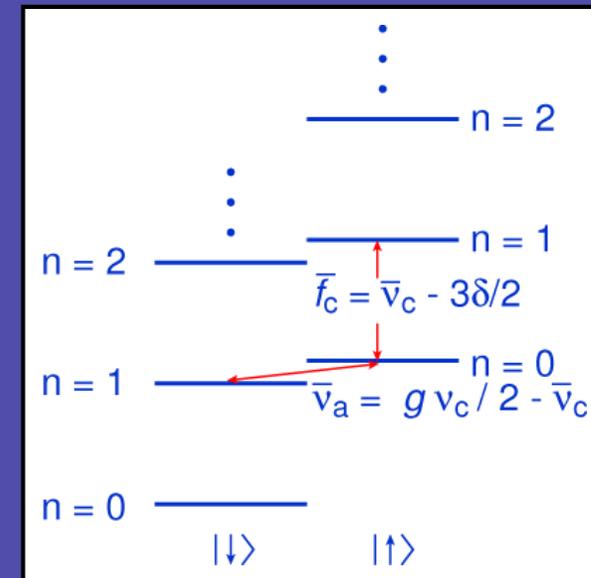
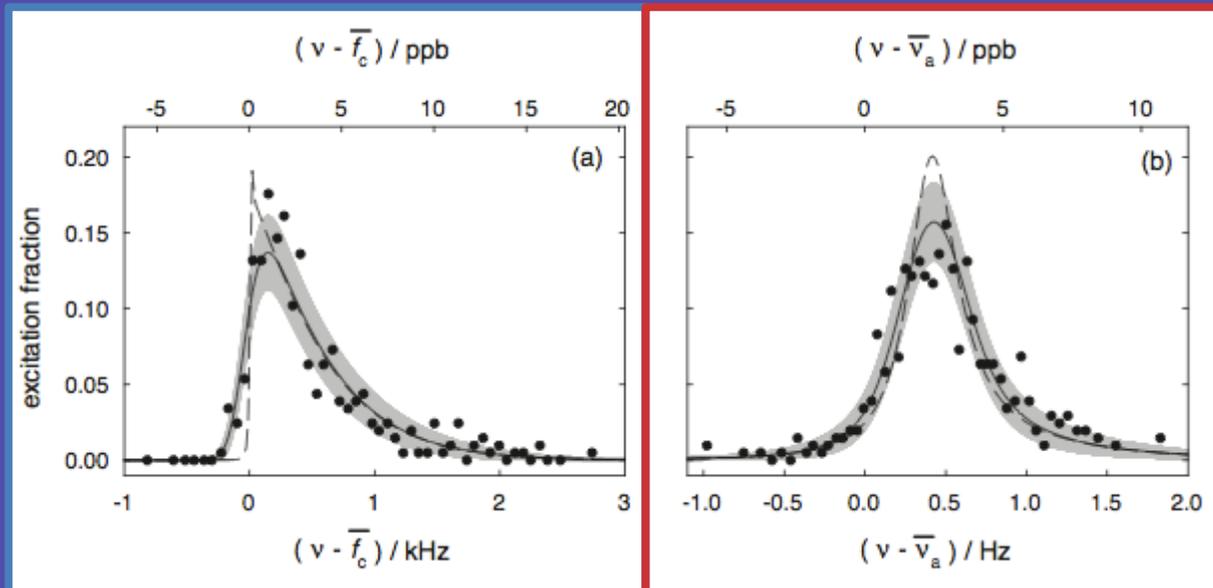


What are our sources of uncertainty?

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

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

2008 data:



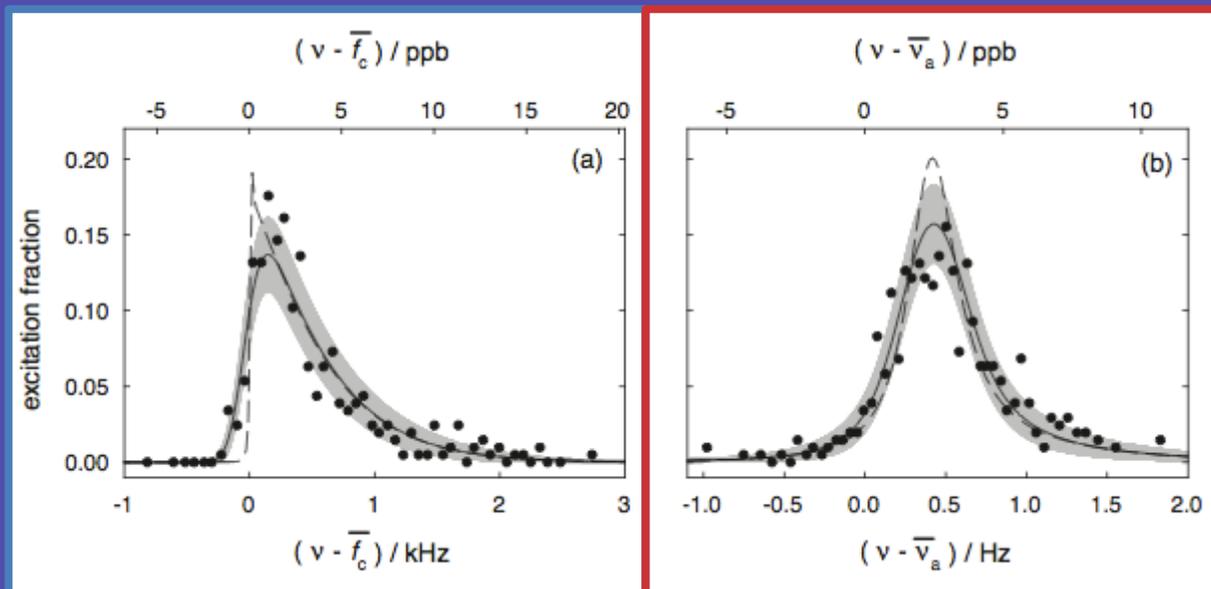
Blurring in cyclotron/anomaly lineshapes

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

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

Uncertainties for $g/2$ in parts-per-trillion.

2008 data:



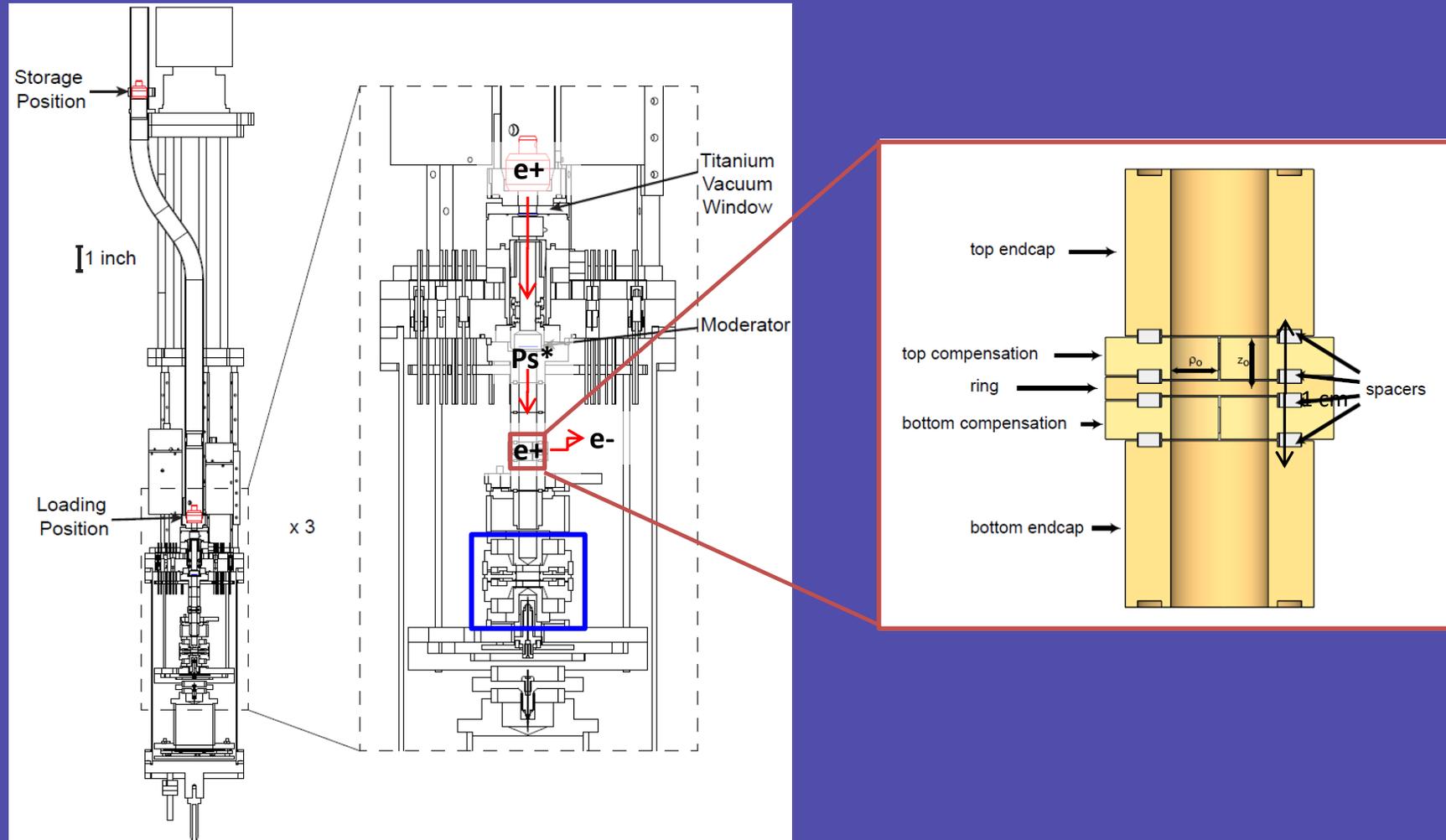
$\nu_c / \text{GHz} =$	147.5	149.2	150.3	151.3
Statistics	0.39	0.17	0.17	0.24
Cavity shift	0.13	0.06	0.07	0.28
Uncorrelated lineshape model	0.56	0.00	0.15	0.30
Correlated lineshape model	0.24	0.24	0.24	0.24
Total	0.73	0.30	0.34	0.53

CPT test

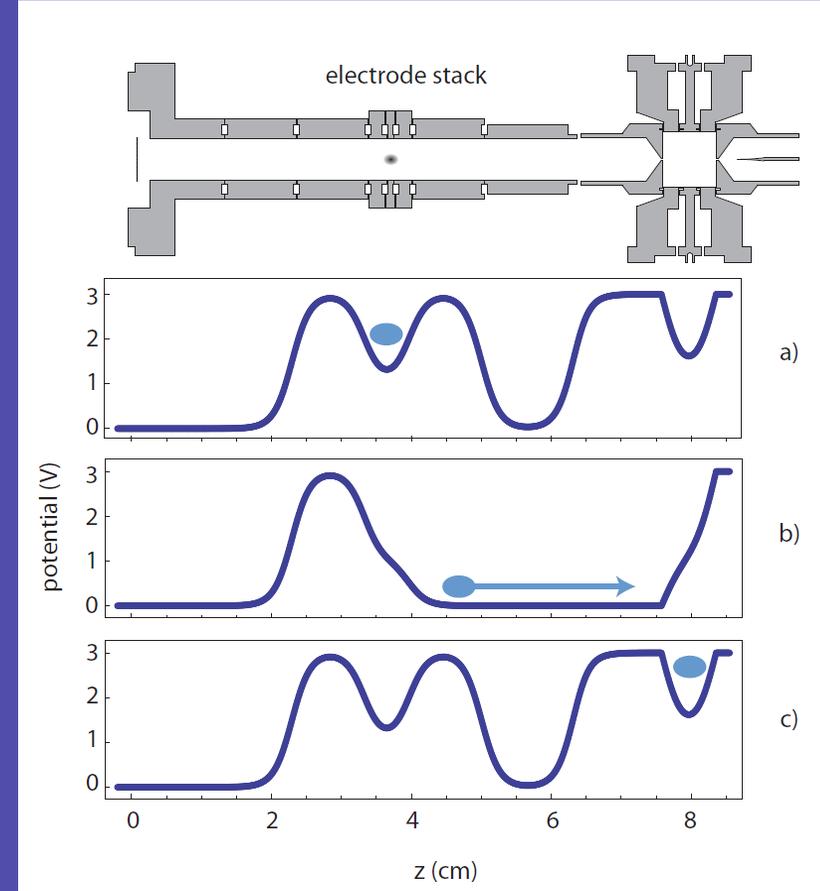
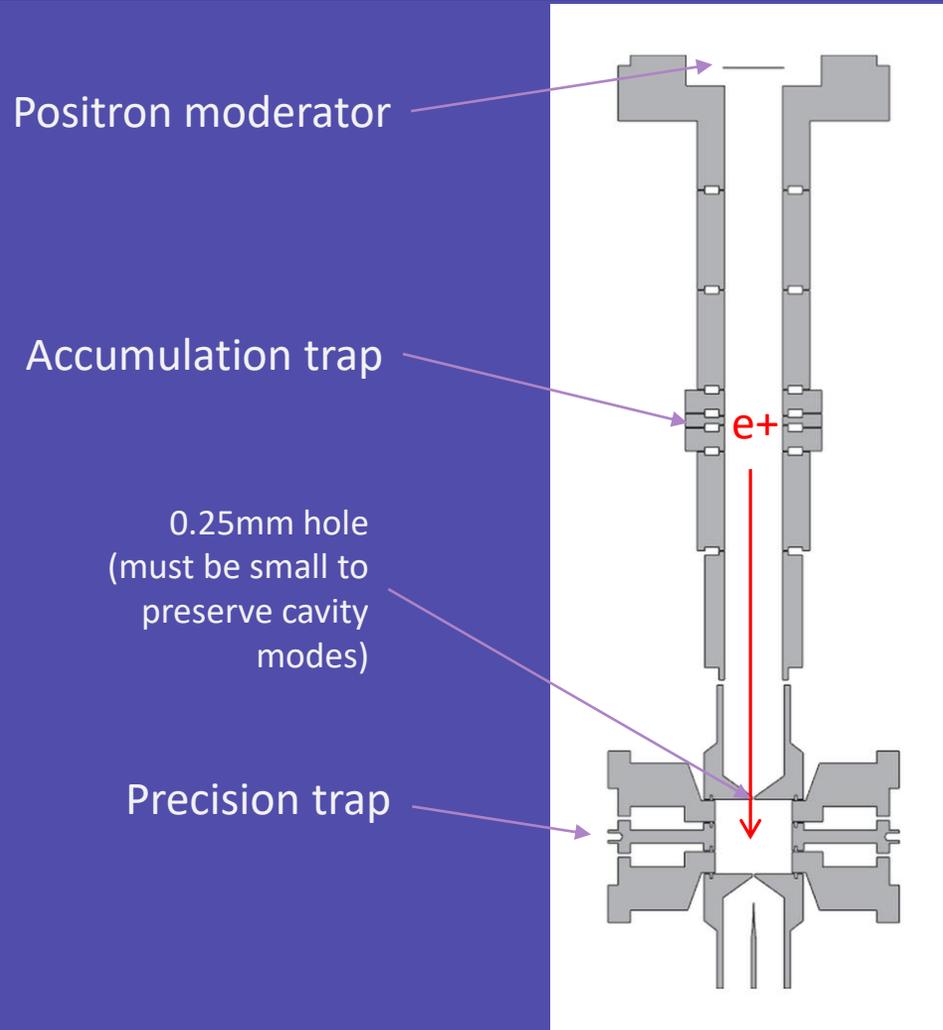
$$\frac{g}{2}(electron) = 1.001\,159\,652\,180\,73\,(28) [0.28\ ppt]$$
$$\frac{g}{2}(positron) = 1.001\,159\,652\,1879\,(4.3) [4.3\ ppt]$$

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

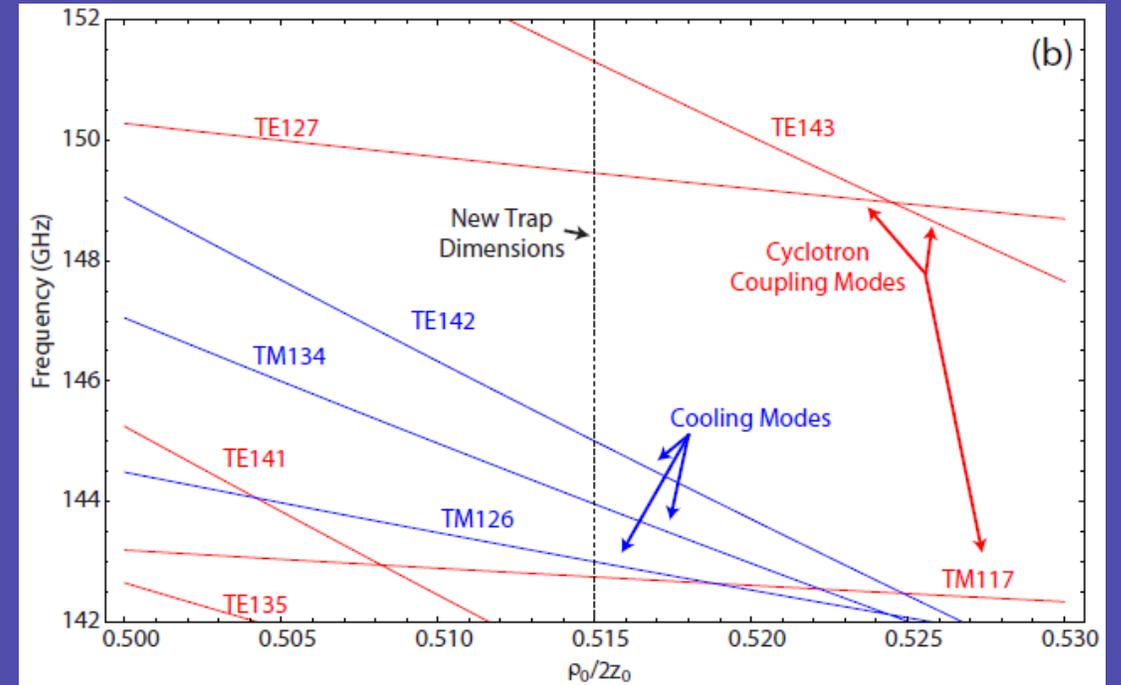
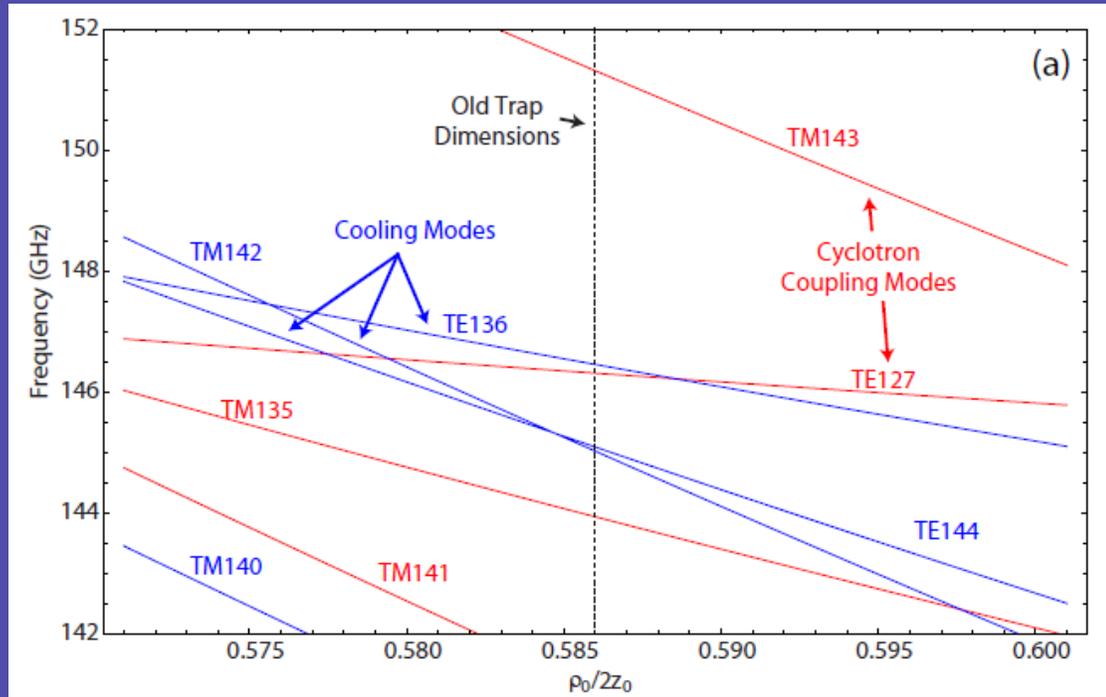
Loading positrons



Transfer

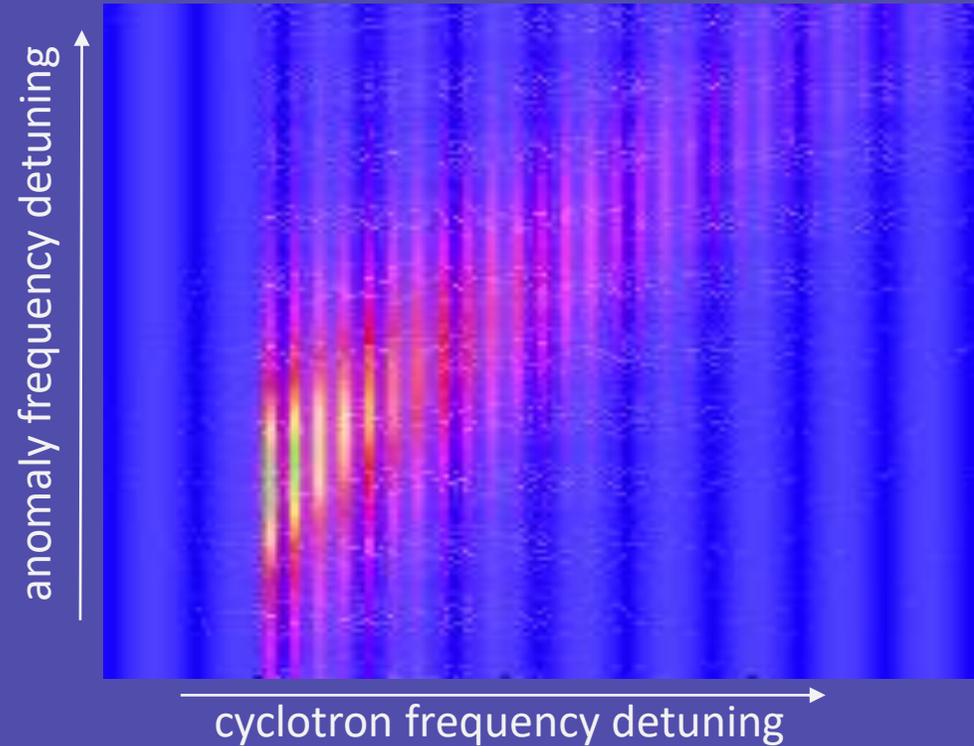
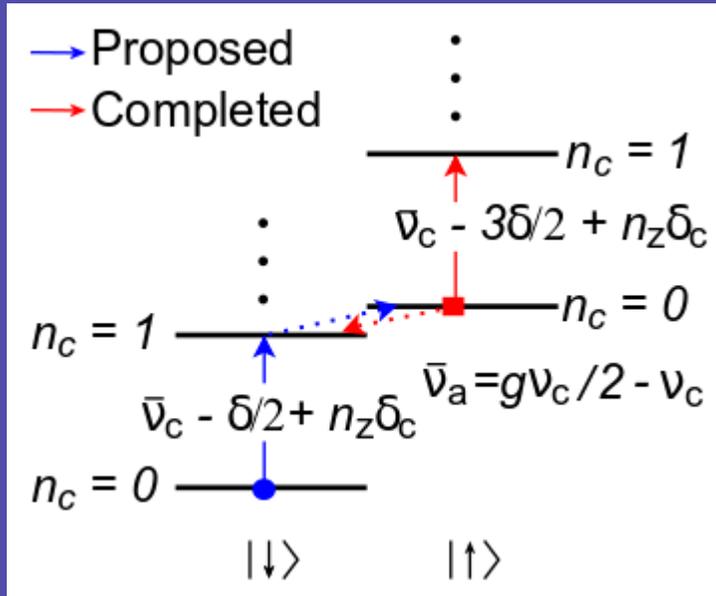


Cavity-assisted axial sideband cooling



Simultaneous measurement

Excitation probability for drive frequency pairs



Measurements underway

Measuring the positron magnetic moment

- Loaded positrons from a “student source”
- Goal: the best lepton CPT test by a factor of 20 to 200

Measuring the electron magnetic moment 10 times more precisely

- By simultaneously driving cyclotron and spin transition determine the moment to 3 parts in 10^{14}
- Will start probing weak interaction effects
- Determine the fine structure constant ten times more precisely

Acknowledgements



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Current apparatus

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Bastiaan phair
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Xing Fan
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2008 and earlier

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Ching-hua Tseng
Joseph Tan
Maarten Jansen
Kamal Abdullah
Ramon van Handel
many undergrads and visitors

Previous measurements

