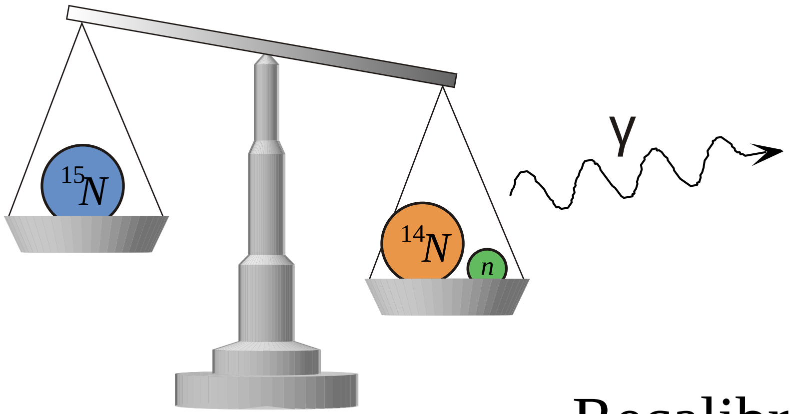
Interesting and Diverse Physics with Precision Mass Spectrometry

Have Done at $\frac{\Delta m}{m} \approx 10^{-10}$

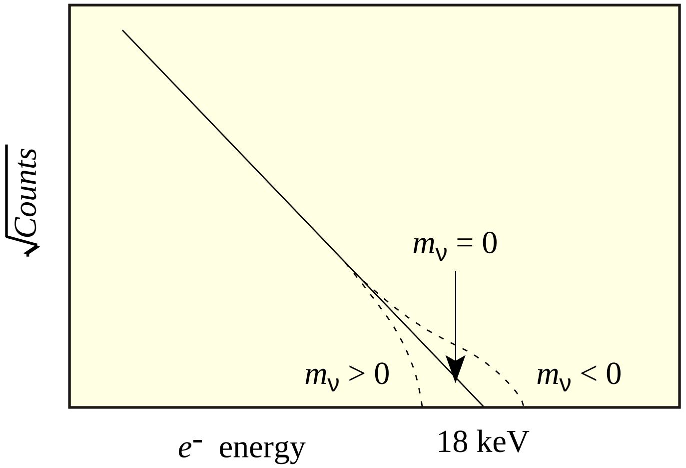
^{28}Si for atomic definition of the kilogram
to replace artifact standard



Recalibration of the γ-ray spectrum

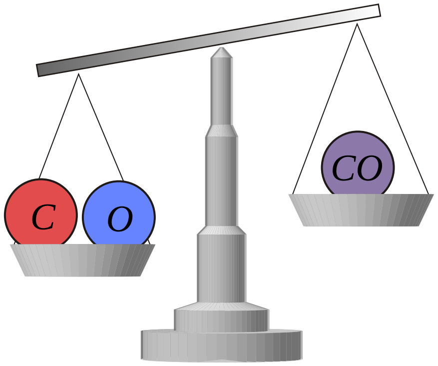
Can Do at $\frac{\Delta m}{m} \approx 10^{-11}$ to 10^{-12}

^{3}He, ^{3}H to Place Limits on the Electron Neutrino Rest Mass



^{32}S, ^{33}S for Precise Tests of $E=mc^2$

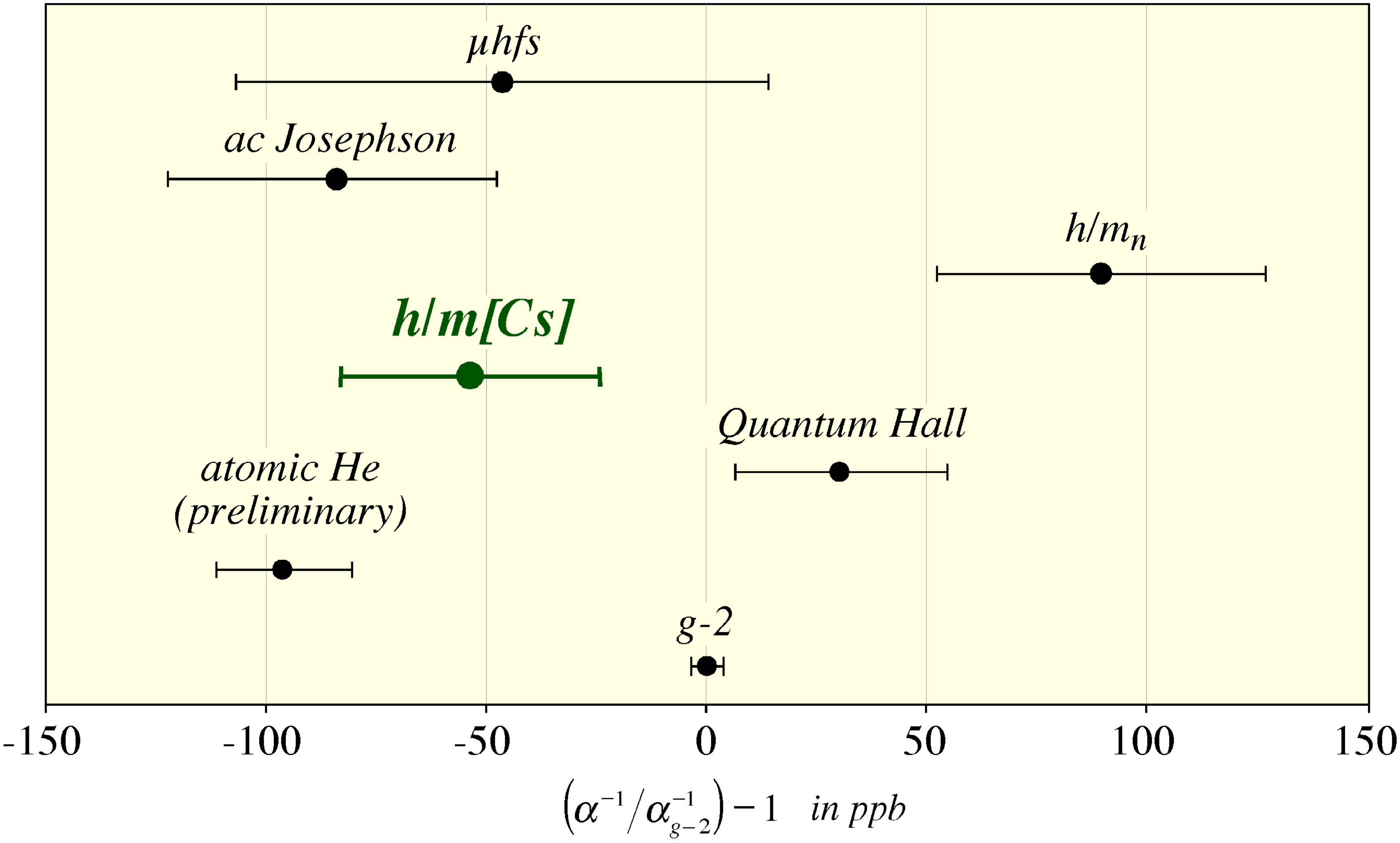
Weigh Chemical Binding Energies ?



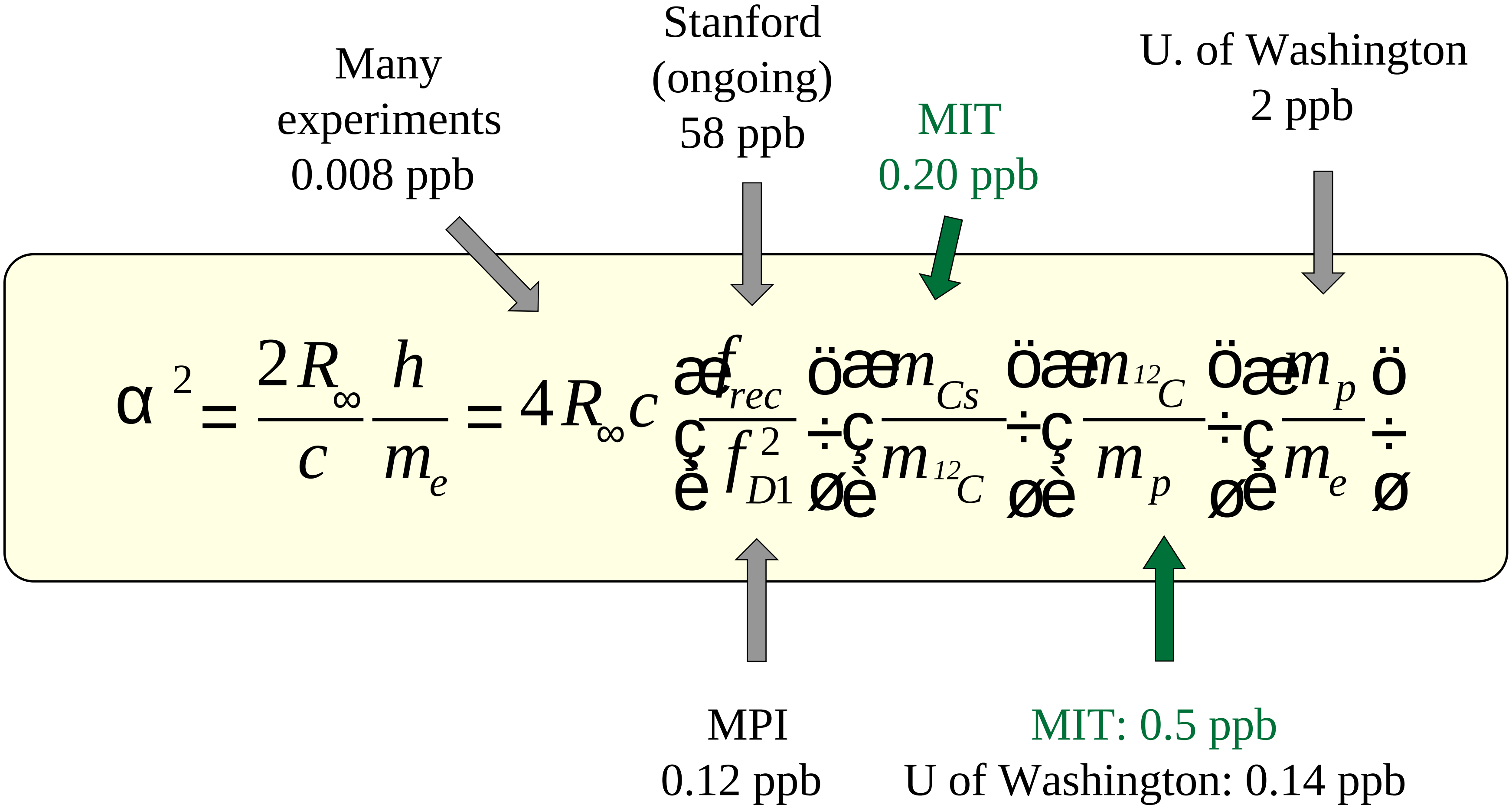
The Fine Structure Constant

$$\alpha = \mu_0 c \frac{e^2}{2h}$$

reference: $\alpha^{-1}_{g\text{-}2} = 137.035\,999\,6\,(5)$



New Determination of α



Many experiments
0.008 ppb

Stanford (ongoing)
58 ppb

MIT
0.20 ppb

U. of Washington
2 ppb

$$\alpha^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = 4R_\infty c\left(\frac{f_{rec}}{f_{D1}^2}\right)\left(\frac{m_{Cs}}{m_{^{12}C}}\right)\left(\frac{m_{^{12}C}}{m_p}\right)\left(\frac{m_p}{m_e}\right)$$

MPI
0.12 ppb

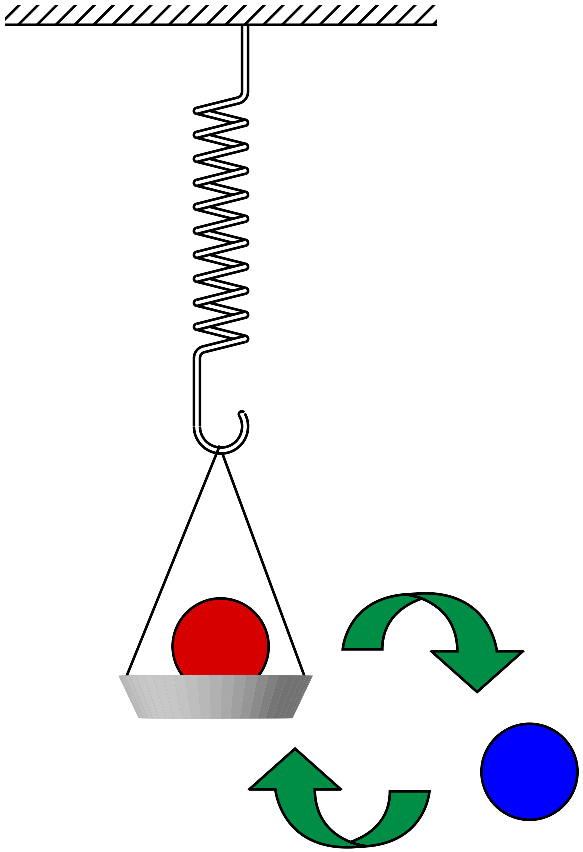
MIT: 0.5 ppb
U of Washington: 0.14 ppb

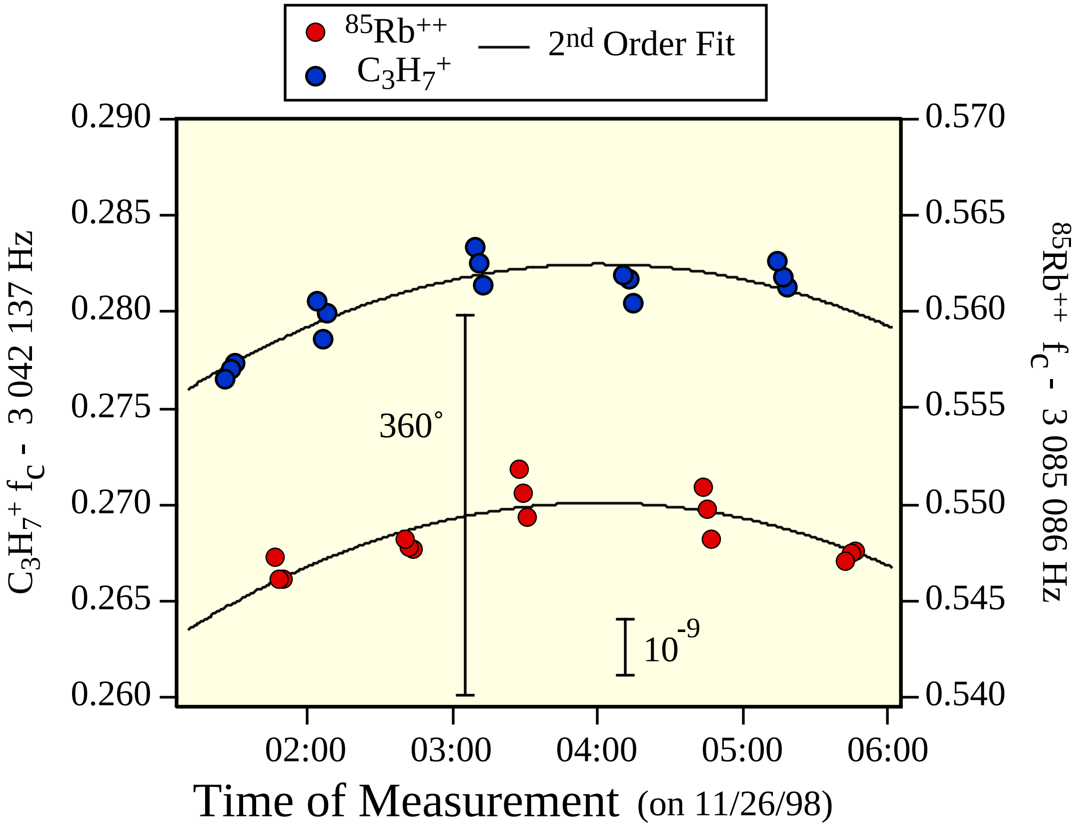
The MIT Mass Table

Atom	MIT Mass (u)	$\Delta m/m \times 10^{10}$	Previous accepted value	
			Factor of improvement in precision	Difference (in units of old error)
^{1}H	1.007 825 031 6 (5)	5.0	24	-0.28
n	1.008 664 916 4 (8)	8.1	17	-0.54
^{2}H	2.014 101 777 9 (5)	2.5	48	-0.05
^{13}C	13.003 354 838 1 (10)	0.8	17	0.71
^{14}N	14.003 074 004 0 (12)	0.9	22	0.08
^{15}N	15.000 108 897 7 (11)	0.7	36	-1.81
^{16}O	15.994 914 619 5 (21)	1.3	24	-0.21
^{20}Ne	19.992 440 175 4 (23)	1.2	957	2.08
^{23}Na	22.989 769 280 7 (28)	1.2	93	-1.46
^{28}Si	27.976 926 532 4 (20)	0.7	350	-0.81
^{40}Ar	39.962 383 122 0 (33)	0.8	424	-0.41
^{85}Rb	84.911 789 732 (14)	1.6	193	-0.99
^{87}Rb	86.909 180 520 (15)	1.7	187	-1.89
^{133}Cs	132.905 451 931 (27)	2.0	111	1.64

🟩 For a new determination of the fine structure constant α

Single Ion

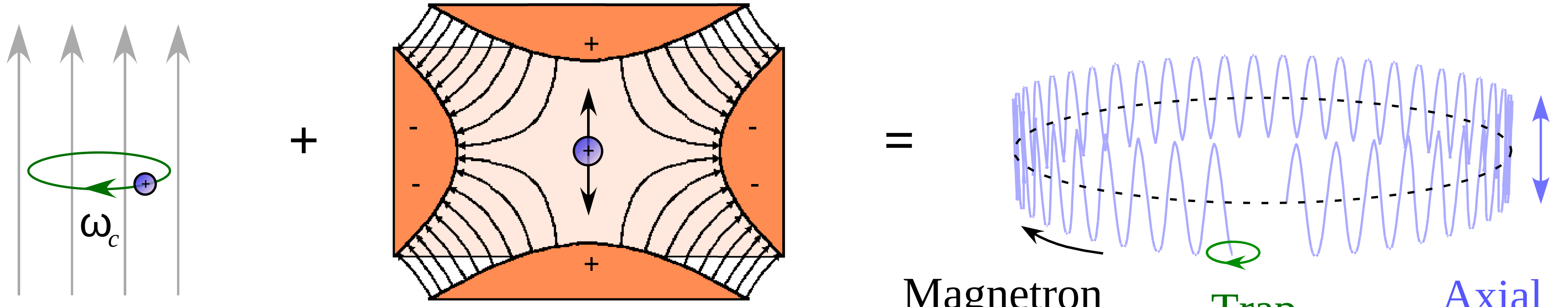




Magnetic field fluctuations limit precision to 10^{-10}

Ion Motion in a Penning Trap

Radial Confinement + Axial Confinement = New Normal Modes



8.5 Tesla Magnetic Field

Magnetron ~ 5 kHz

Trap Cyclotron ~ 5 MHz

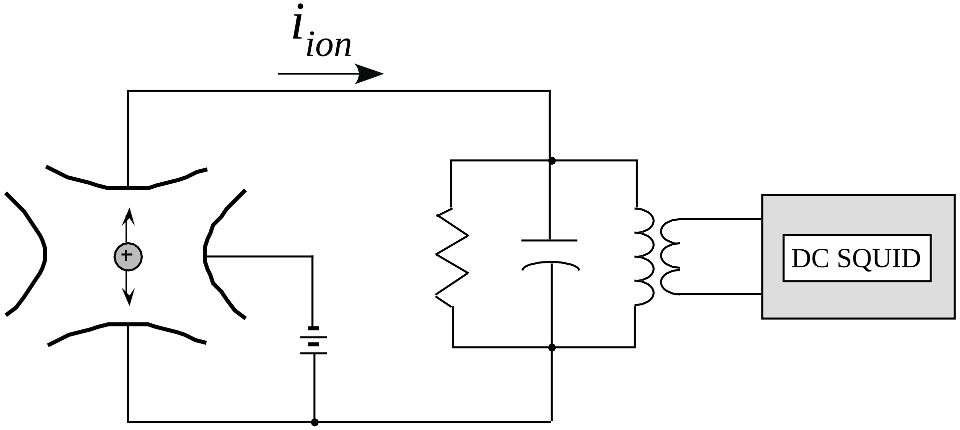
Axial ~ 200 kHz

SINGLE ions → Small Ion-Ion Perturbations

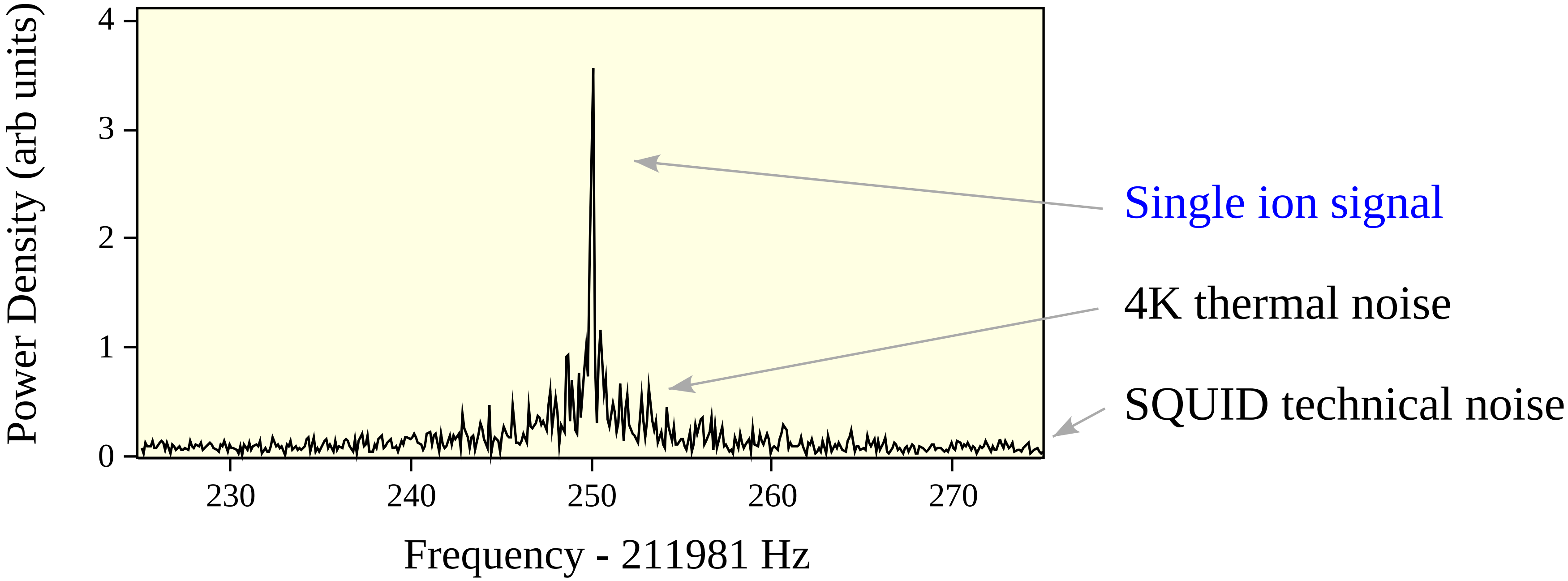
$$\omega_c = \frac{qB}{m} \rightarrow \frac{m_1}{m_2} = \frac{q_1 \omega_2}{q_2 \omega_1}$$

Detecting a Single Ion

A single ion
oscillating along z axis → current of 10^{-15} A induced in the endcap !



We use a superconducting resonant transformer (Q ~ 40 000) and a DC SQUID to detect this miniscule current.

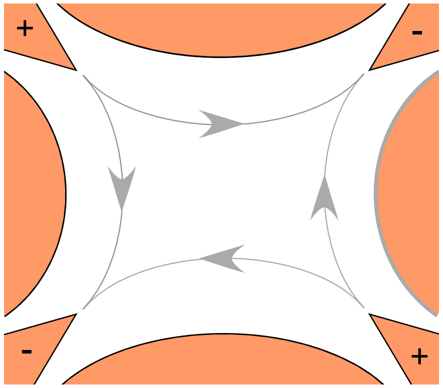


Single ion signal

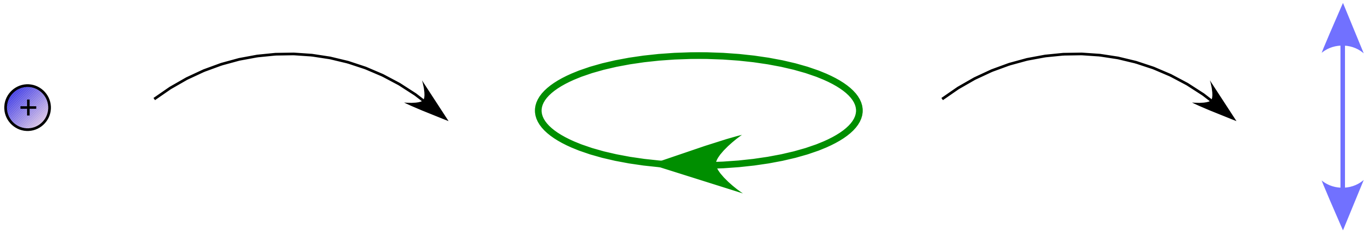
4K thermal noise

SQUID technical noise

Measuring the Cyclotron Frequency



Cool and detect the cyclotron mode by coupling to the damped and detected axial mode.



Cyclotron Drive

π-pulse
phase is preserved!

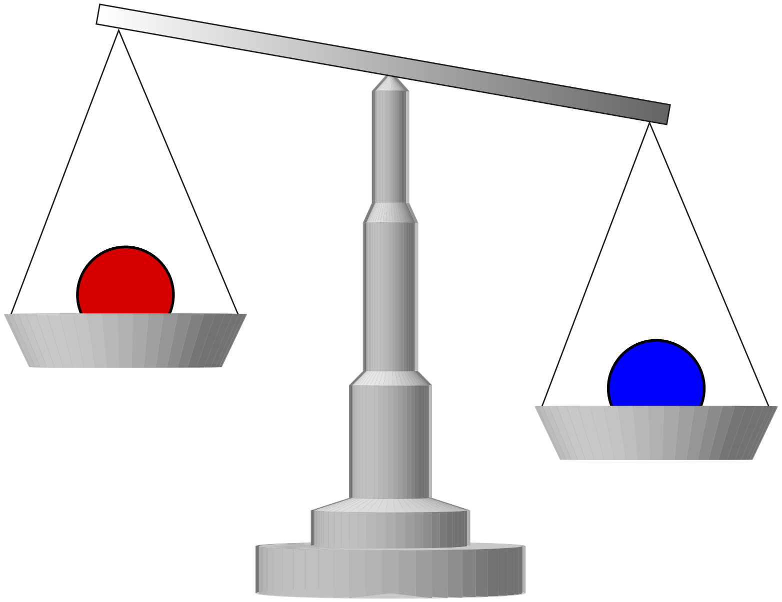
Cool ion

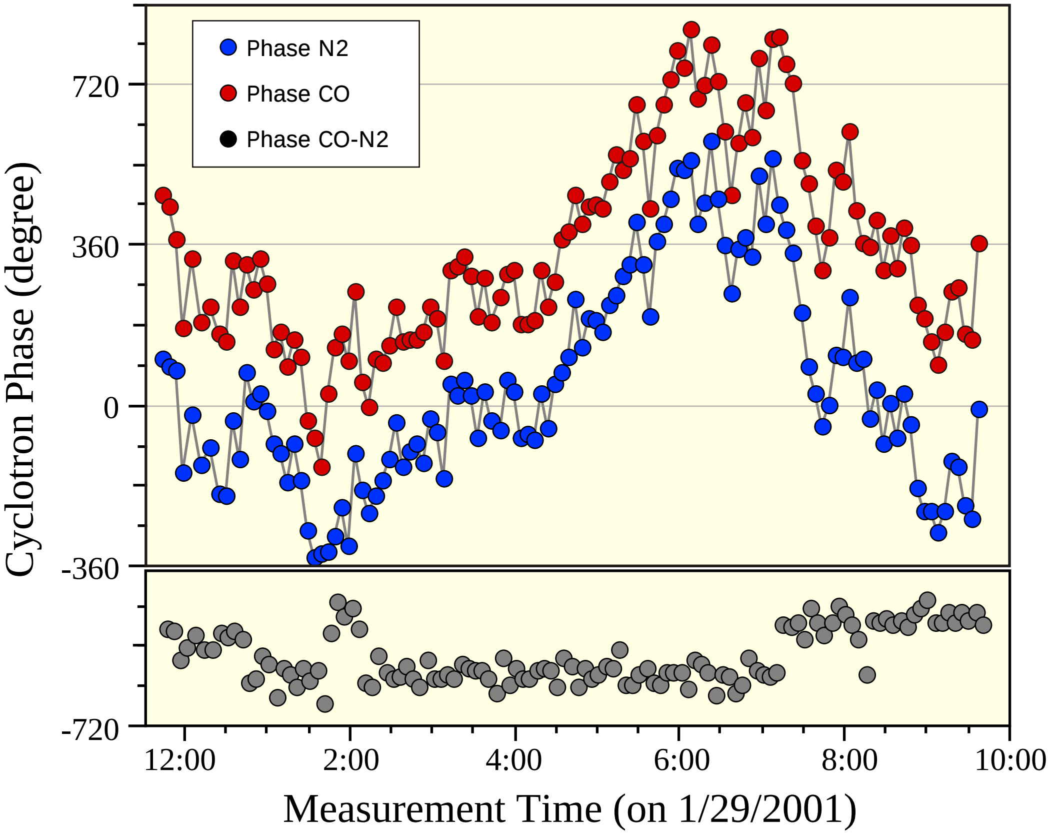
Wait for time T
(in the dark)

Detect Phase

50 s evolution time (T) yields a precision of 1 part in 10^{10}

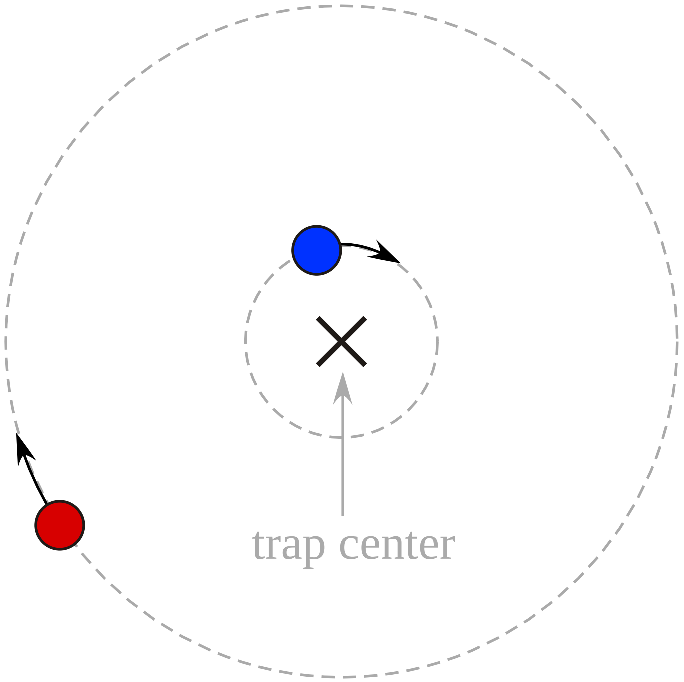
Two Ions

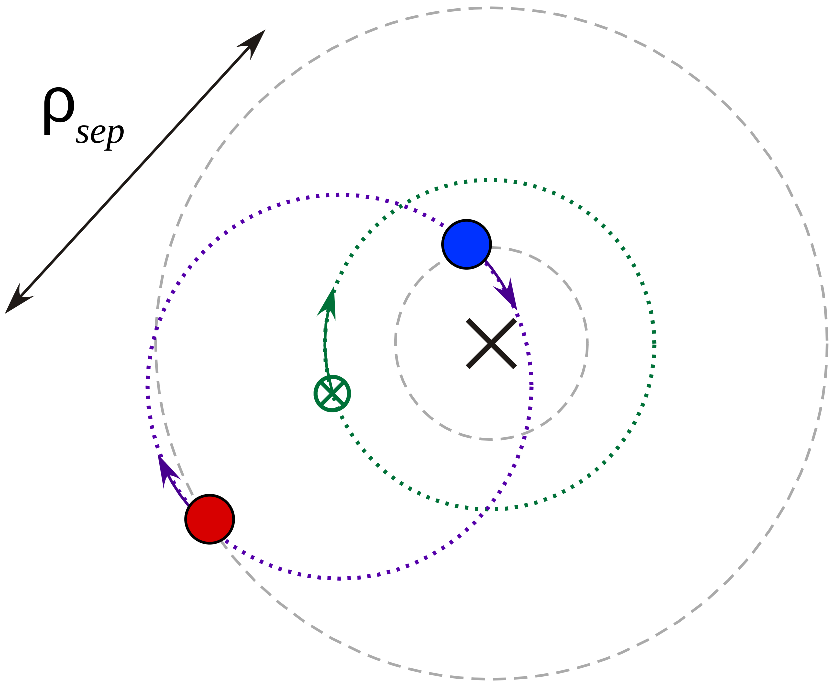




Precision of 10^{-10} in 3 minutes (during the day) !!

Magnetron Mode Locking





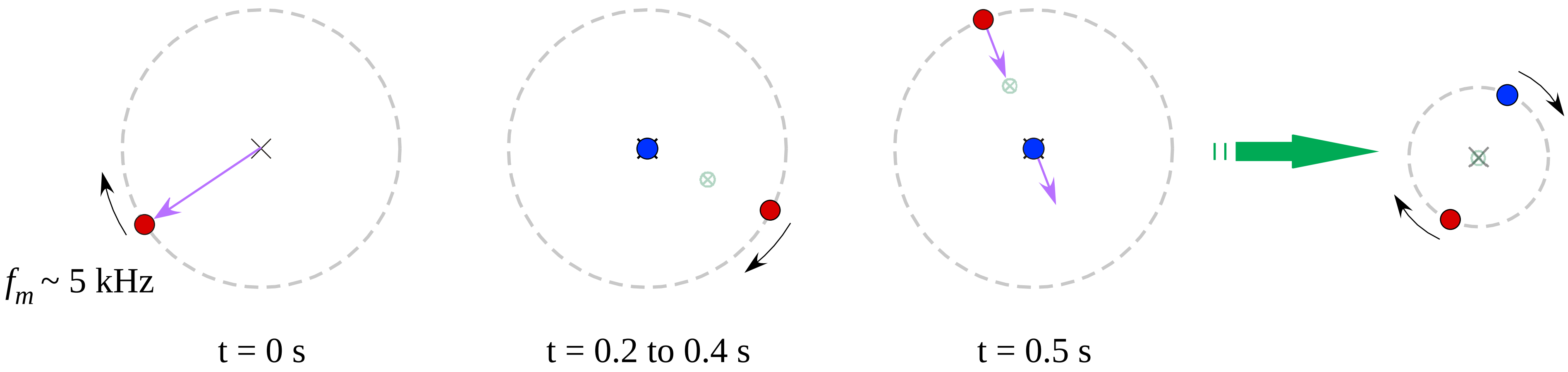
Independent Magnetron Modes + Small Ion-Ion Coupling =

New Normal Modes:
- Center of Mass (⊗)
- Separation

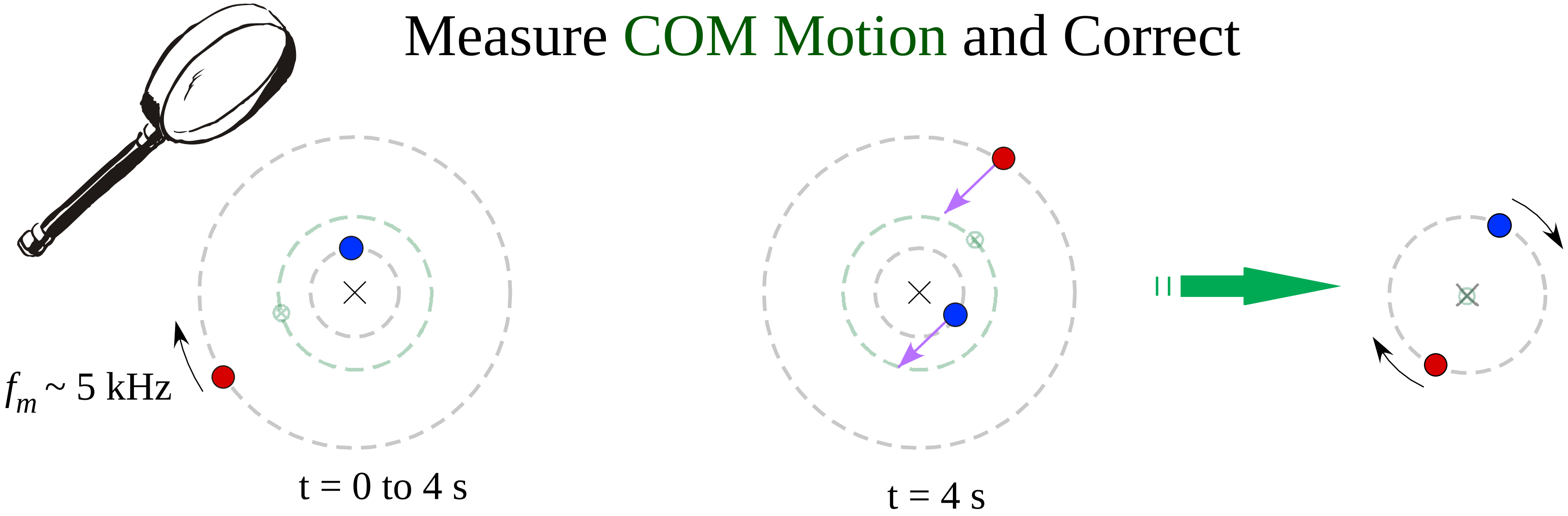
- ρ_{sep} is constant and ions sample the same B field
- At $\rho_{sep} \sim 1\ mm$ predict ion-ion perturbations $< 2 \times 10^{-12}$

Controlling the Ions Orbit

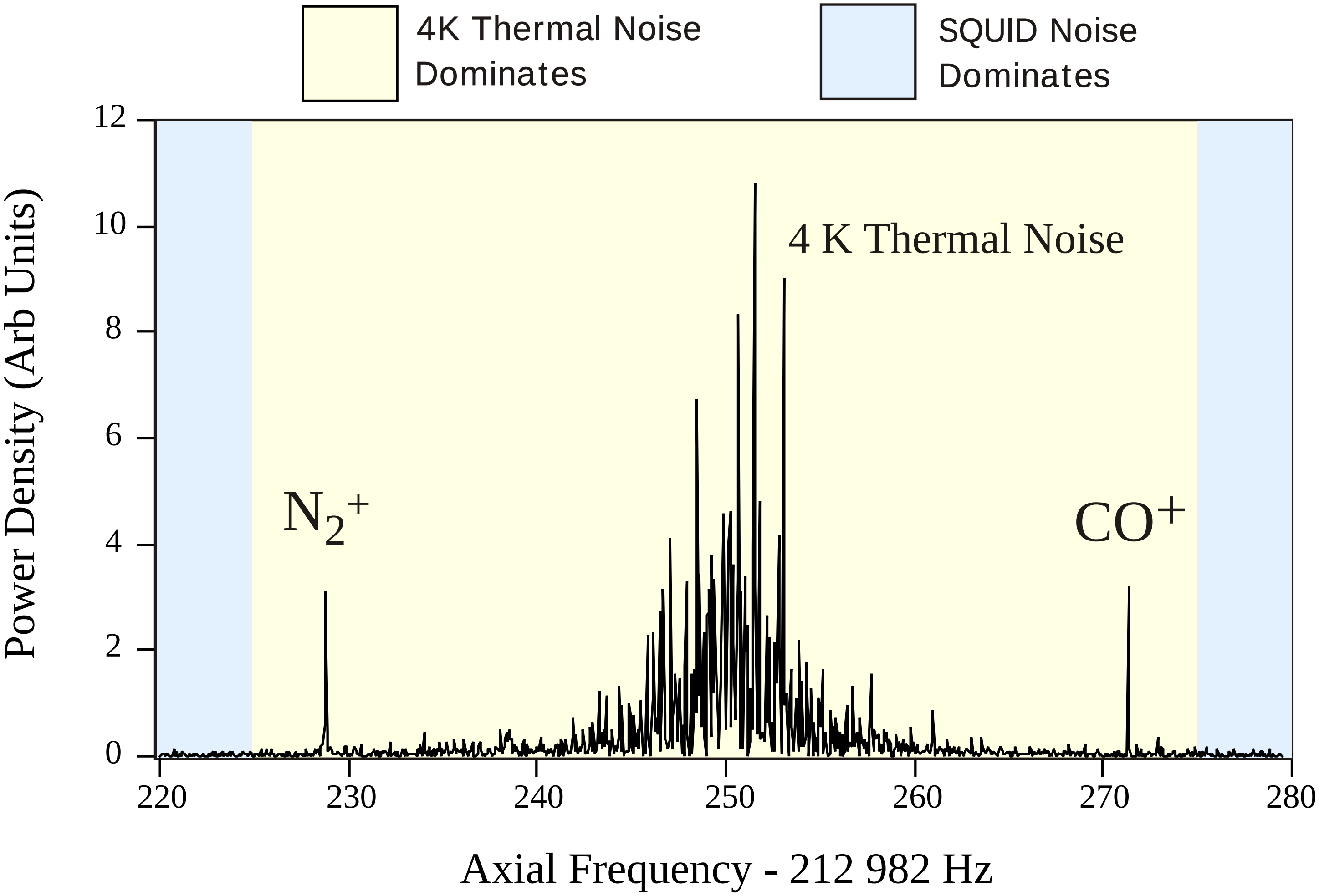
Set Center of Mass Motion, Make 2nd Ion, and Quickly Zero



Measure COM Motion and Correct



Two Ion Signal

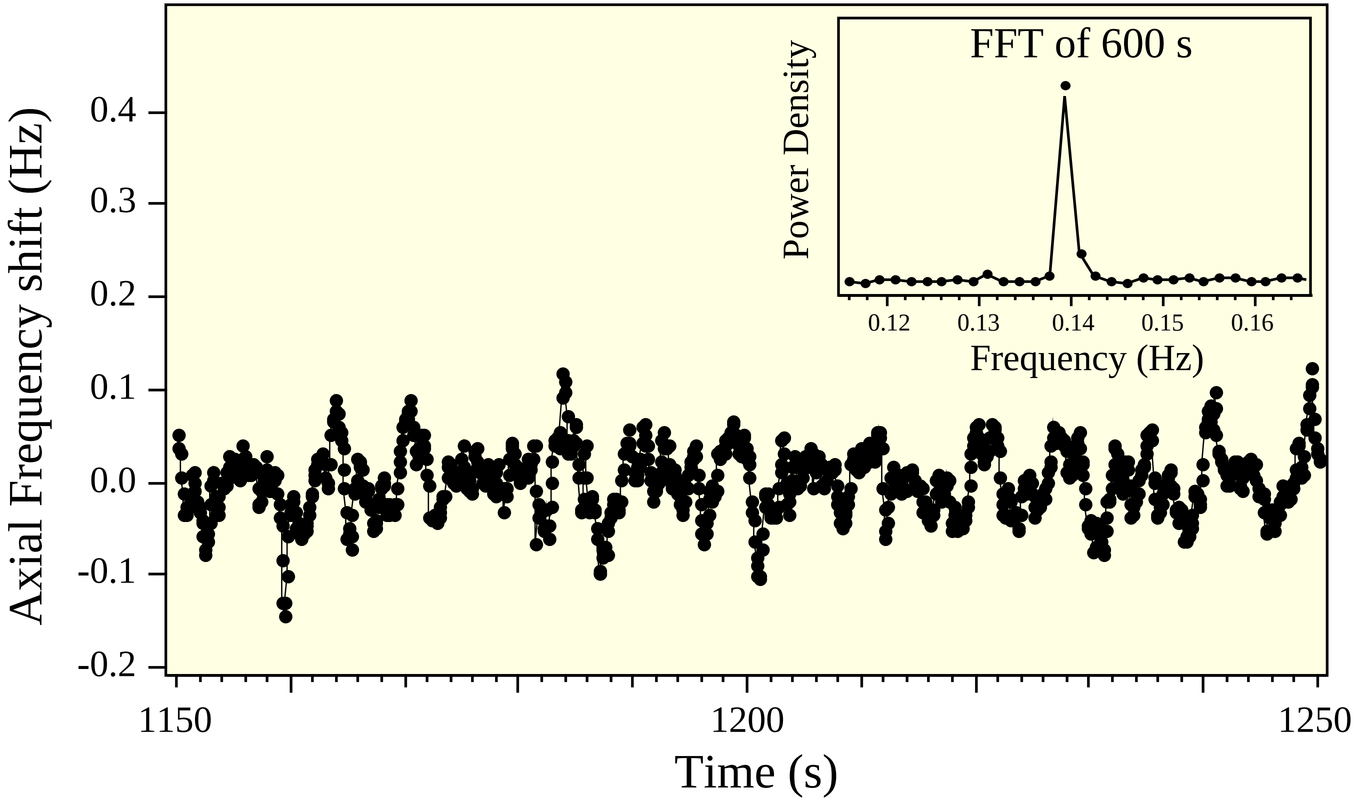


Typical Axial Signals from ions after 240 sec of Cyclotron Phase Accumulation

Watching the Motion of the Ions

Electrostatic anharmonicities → f_z is a function of radius

Axial frequency of CO^+ in the presence of $N2^+$

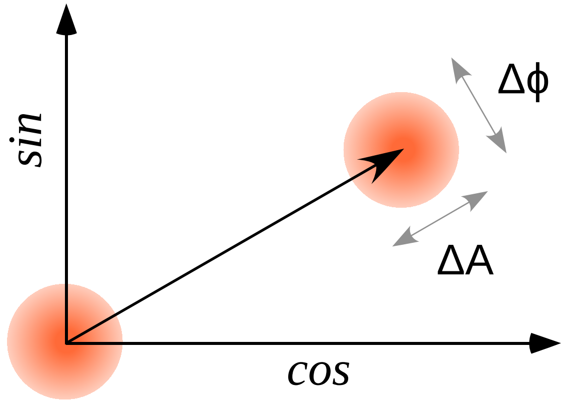


Magnetron radius of each ion is oscillating with a period ~ 7 s

(calculated period for ρ_{sep} ~ 700 µm)

Effect of Finite Temperature (4K)

Problem:



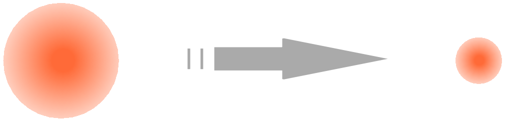
Δϕ cyclotron phase noise

ΔA cyclotron frequency variation (~ 5 x 10^{-11}) due to magnetic field inhomogeneity and special relativity:

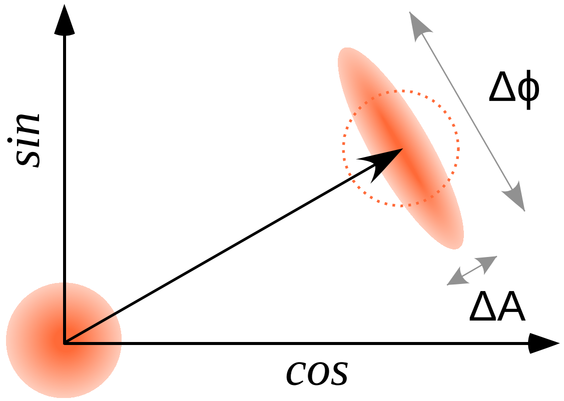
$$\omega_c = \frac{qB}{\gamma\, m} \quad \text{and} \quad v = \omega_c A$$

Solutions:

- Cool the ion (see below)



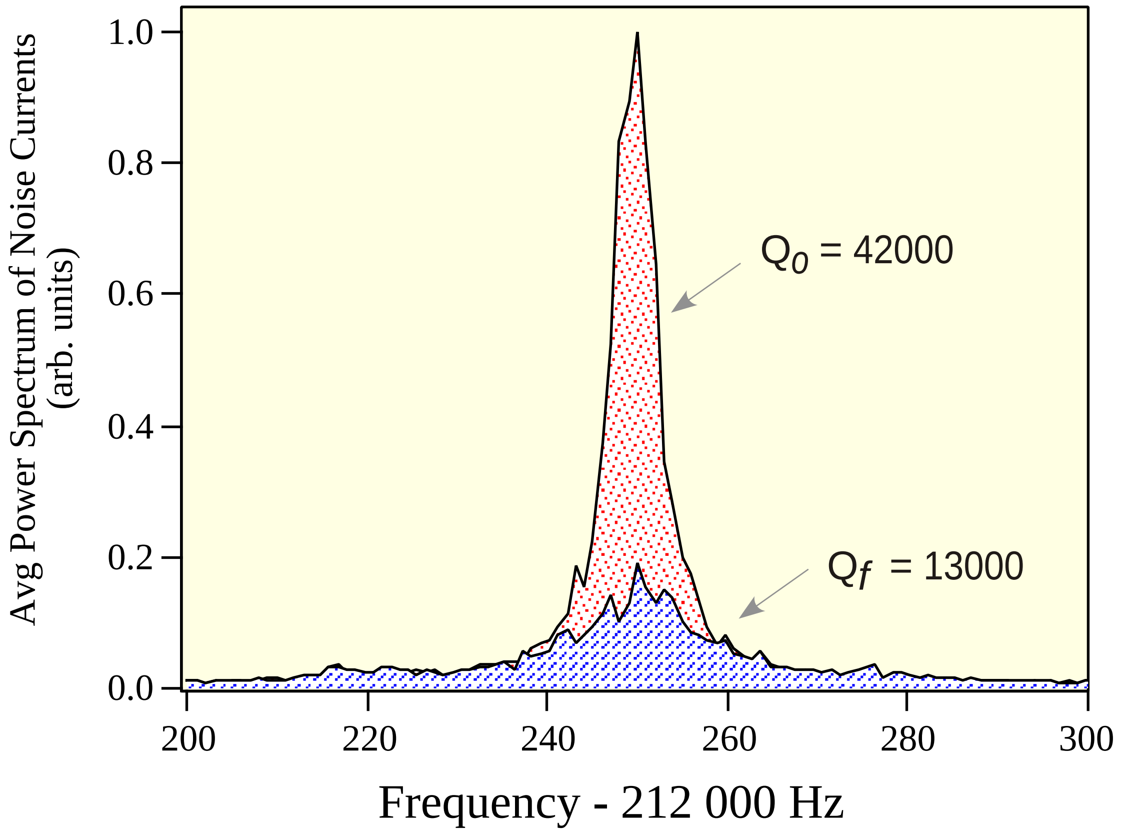
- Classical Squeezed States



“Squeeze” the noise to reduce the amplitude fluctuations by a factor of 2 below the thermal limit.

Electronic Refrigeration

Use feedback to reduce thermal noise currents in the detector



In this data, the temperature of the resonant transformer is reduced by a factor of 3.

The ion’s axial motion comes to equilibrium with this subthermal detector.

➡ Observed factor of ~ 2 reduction in phase noise.