Anapole moment measurement in Fr

Luis A. Orozco
Joint Quantum Institute, Department of Physics
University of Maryland

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Current members at UMD:

Adrian Perez Galvan (now at Cal Tech)
Dong Sheng
Jonathan Hood

FrPNC collaboration at TRIUMF: S. Aubin, J. A. Behr, V. Flambaum, E. Gómez, G. Gwinner (Spokesperson), K. P. Jackson, D. Melconian, L. A. Orozco, M. R. Pearson, G. D. Sprouse, Y. Zhao.

Institutions: College of William and Mary, TRIUMF, University of New South Wales, Universidad Autónoma de San Luis Potosí, University of Manitoba, Texas A&M, University of Maryland, Stony Brook.

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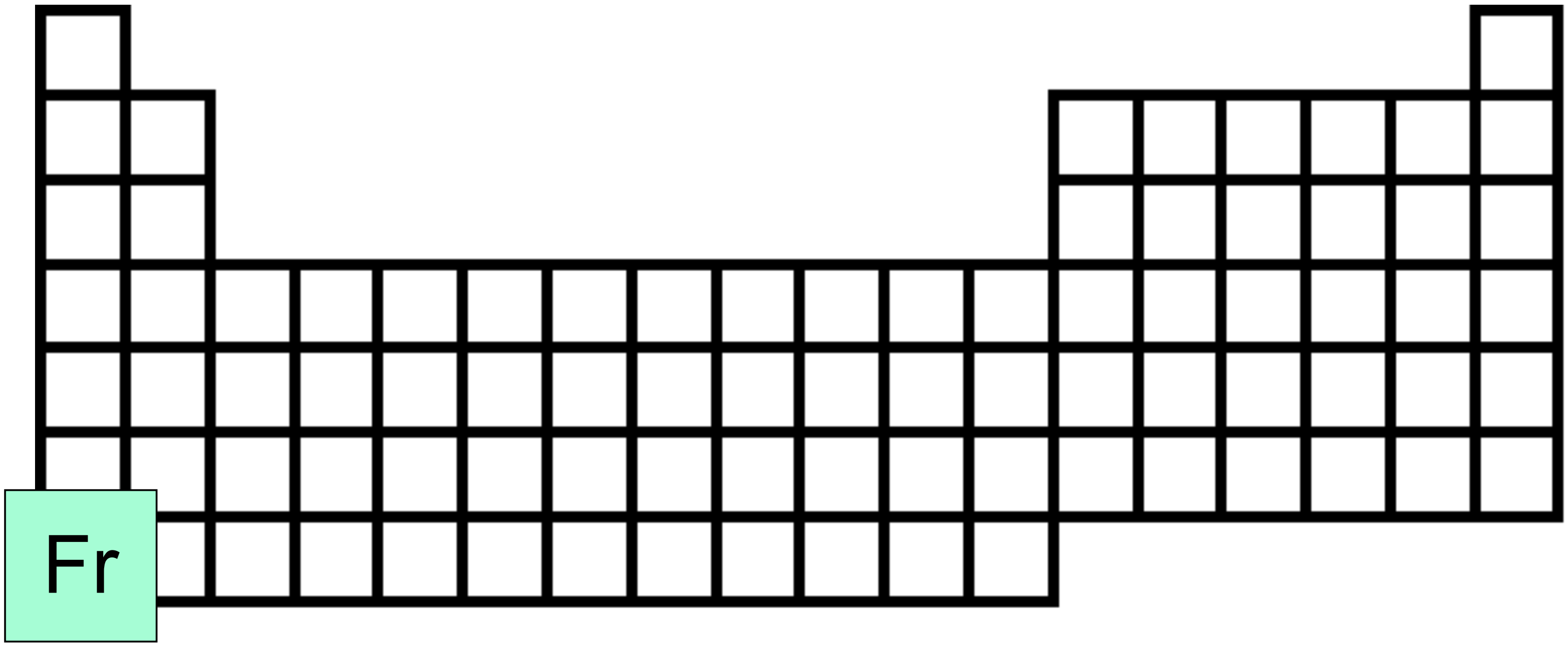
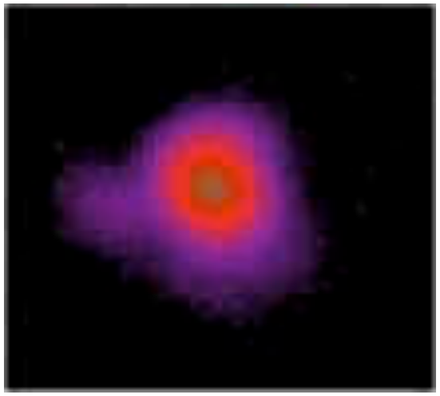


- Z=87; A=208-212 at Stony Brook; at Triumf also neutron rich ~221
- Radioactive (^{223}Fr,^{212}Fr: $\tau_{1/2}$≈20min; ^{210}Fr: $\tau_{1/2}$≈ 3min)

  ⇒ make our own, trap it

- Simple atomic structure, quantitatively understandable
- We want to use it to study the weak interaction through the signature of parity non-conservation.

A Brief History of Francium at Stony Brook



2,000 atom Fr MOT

1991-94: Construction of 1st production and trapping apparatus.

1995: Produced and Trapped Francium in a MOT.

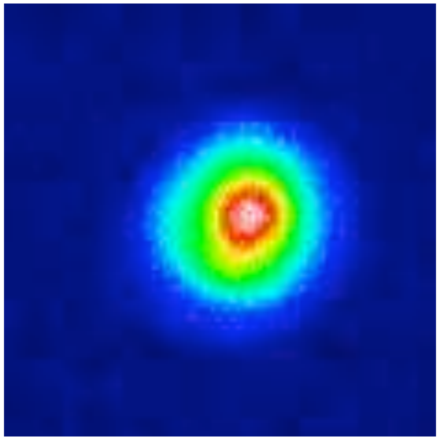
1996-2000: Laser spectroscopy of Francium ($8S_{1/2}$, $7P_{1/2}$,$7D_{5/2}$,$7D_{3/2}$, hyperfine anomaly).

2000-2002: High efficiency trap.

2003: Spectroscopy of $9S_{1/2}$ 8p levels,

2004: Study of 8s levels.

2007: Magnetic moment ^{210}Fr. (M. Safronova)



250,000 atom Fr MOT

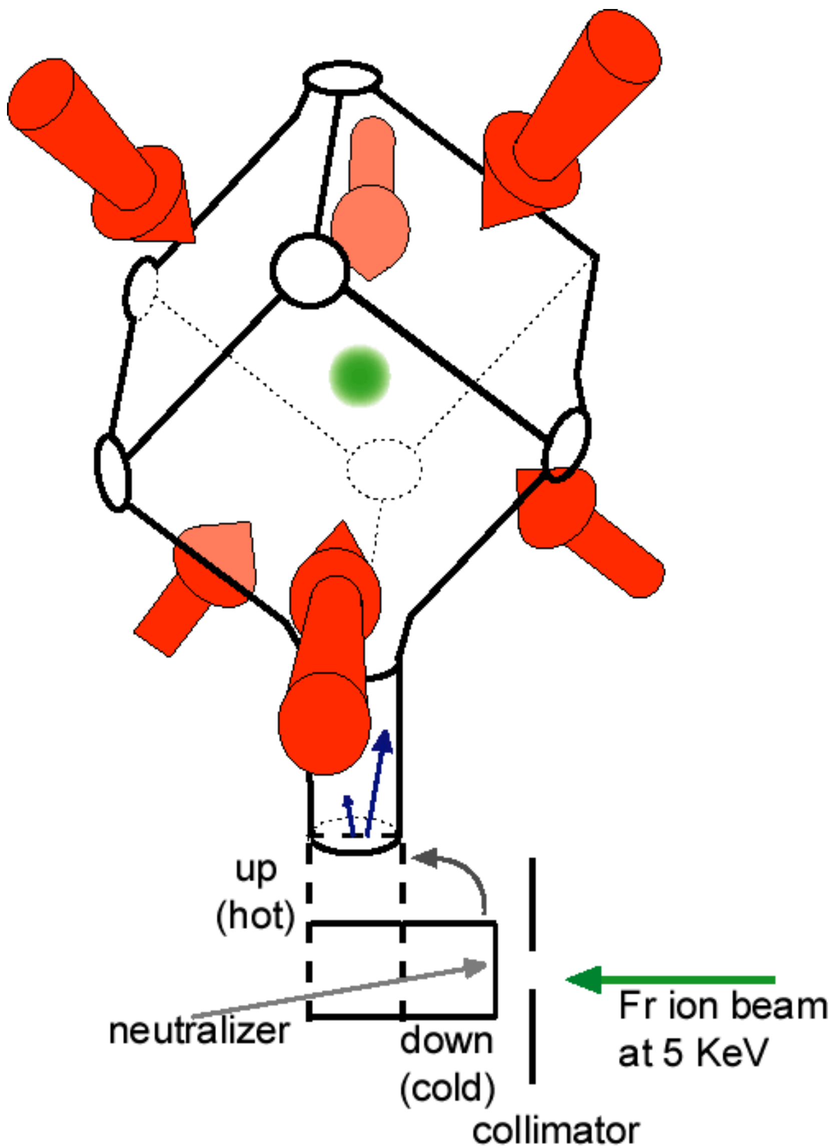
Second generation Design

Pulsed system (movable neutralizer, good vacuum, no holes).

Square cell (5 cm per side).

18 mW/cm^2 per beam at 718 nm.

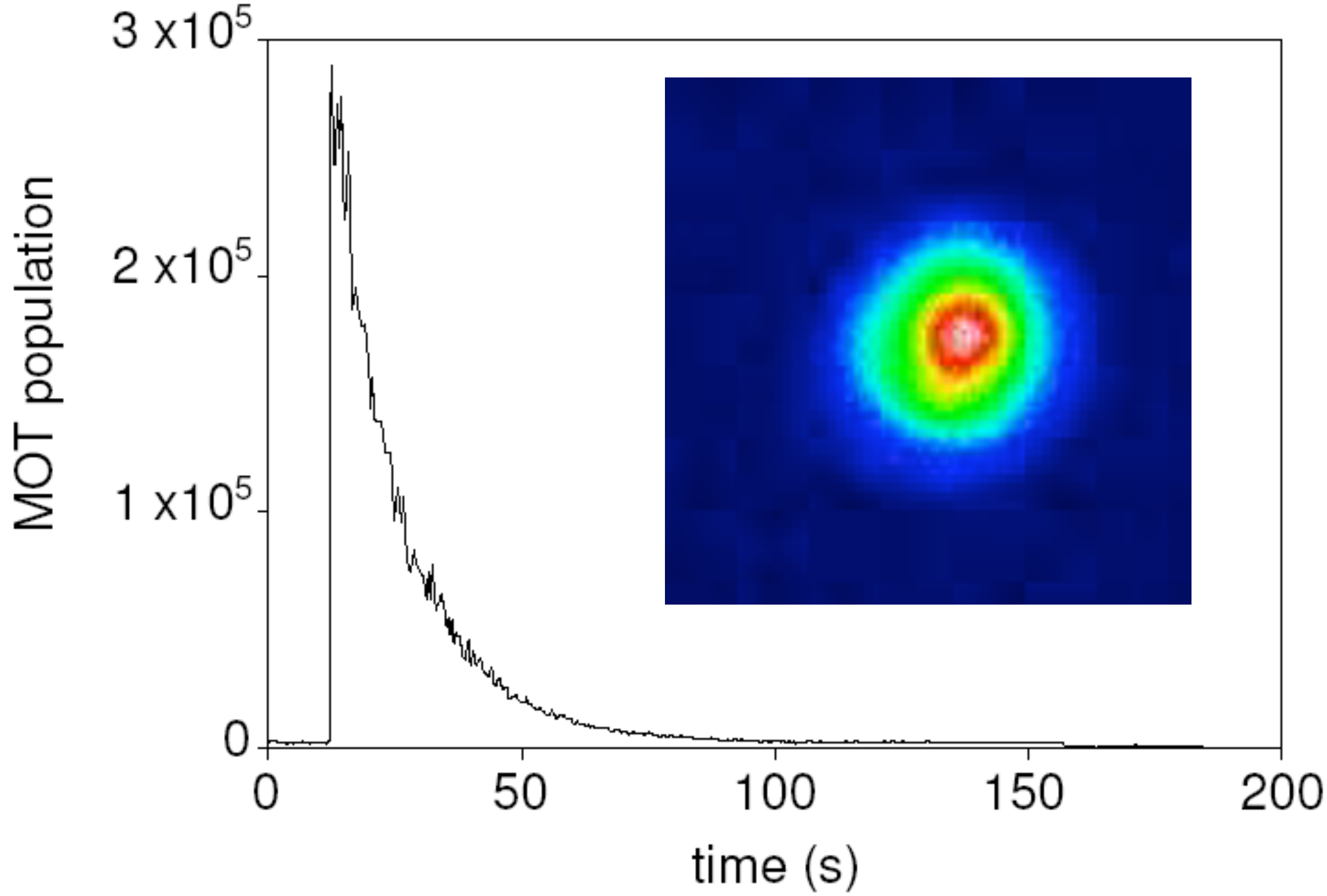
4 cm beams.



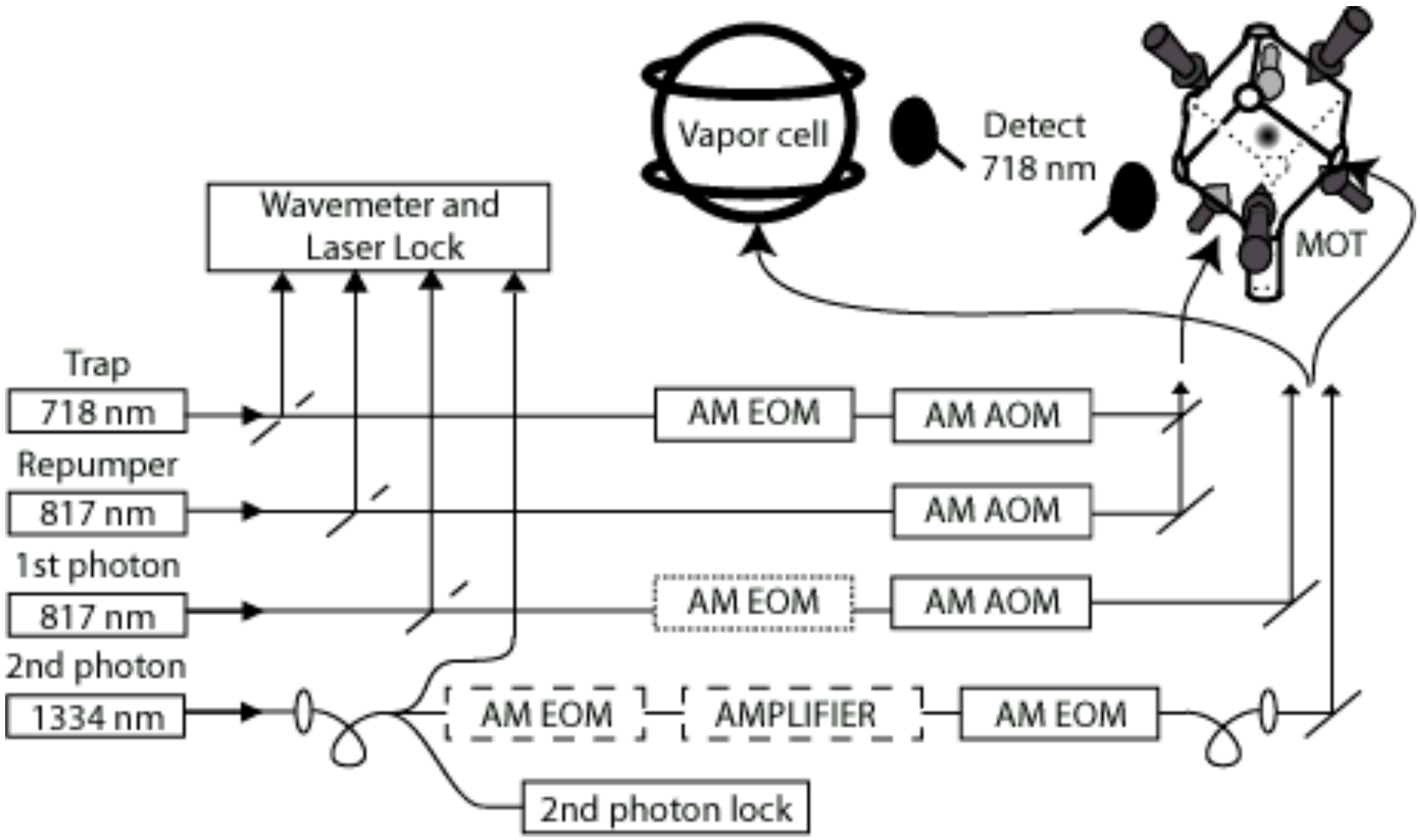
Second Generation Results

We have trapped over **350,000** ^{210}Fr atoms.

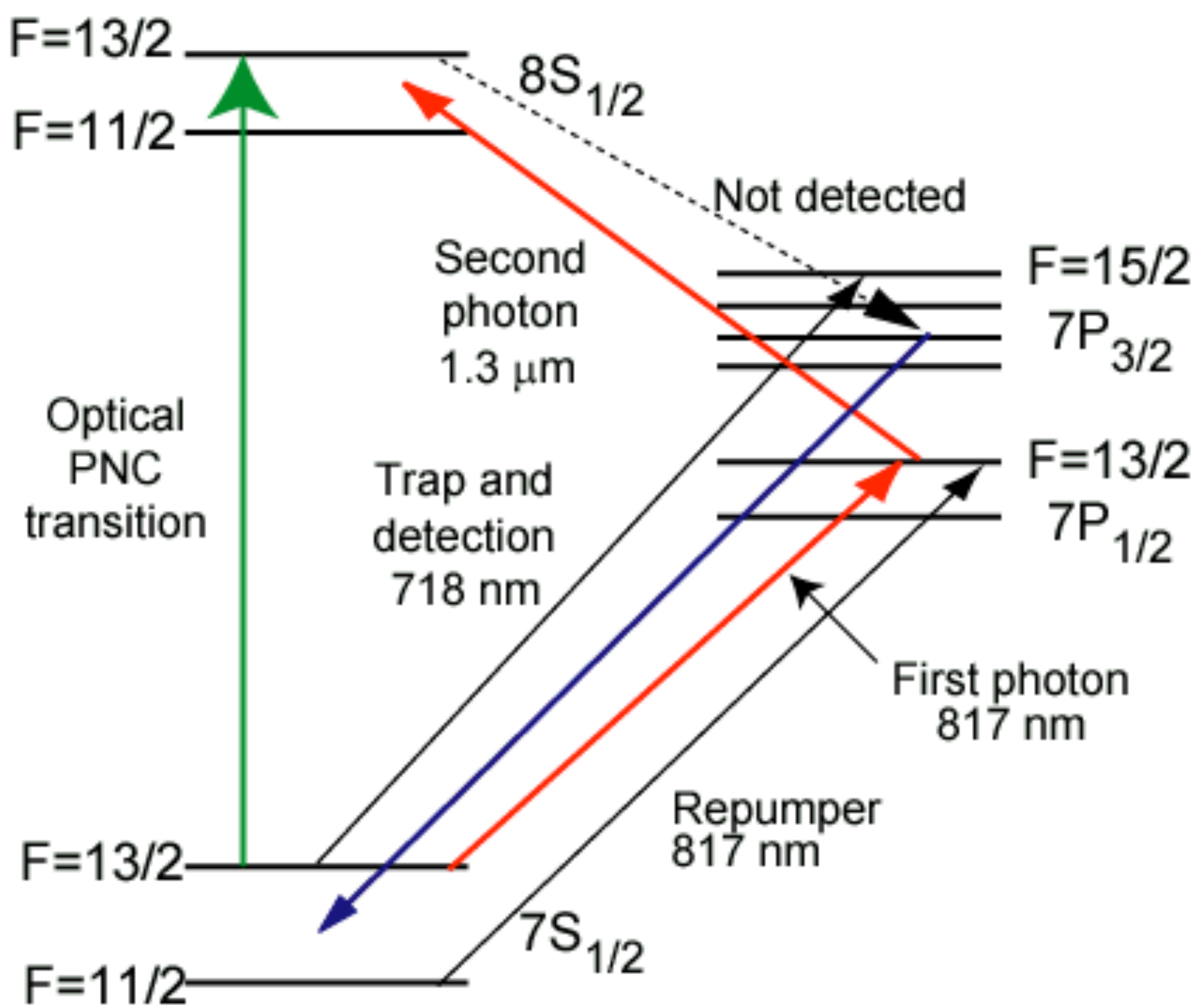
We have an overall efficiency of 1 %



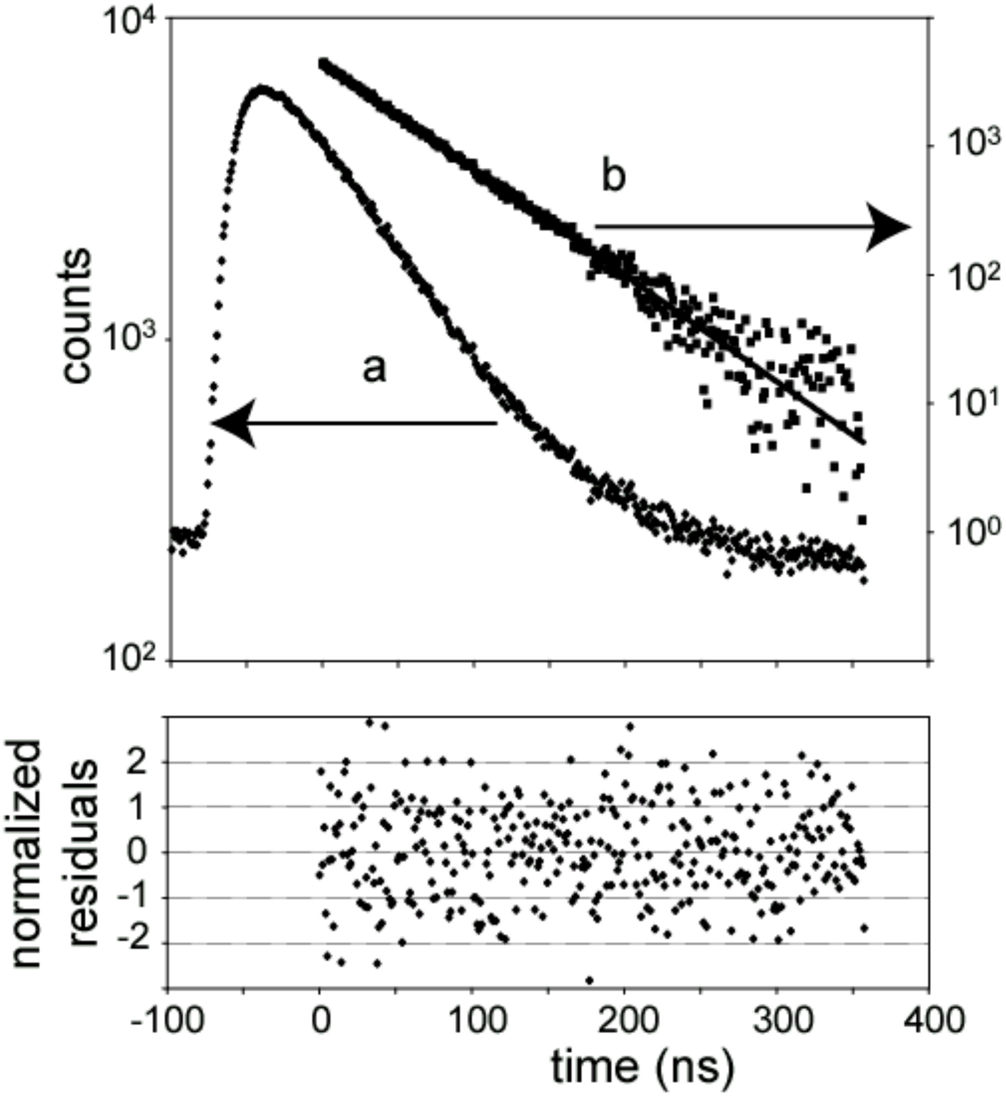
Experimental setup for 8s lifetime



Lifetime of the 8s level

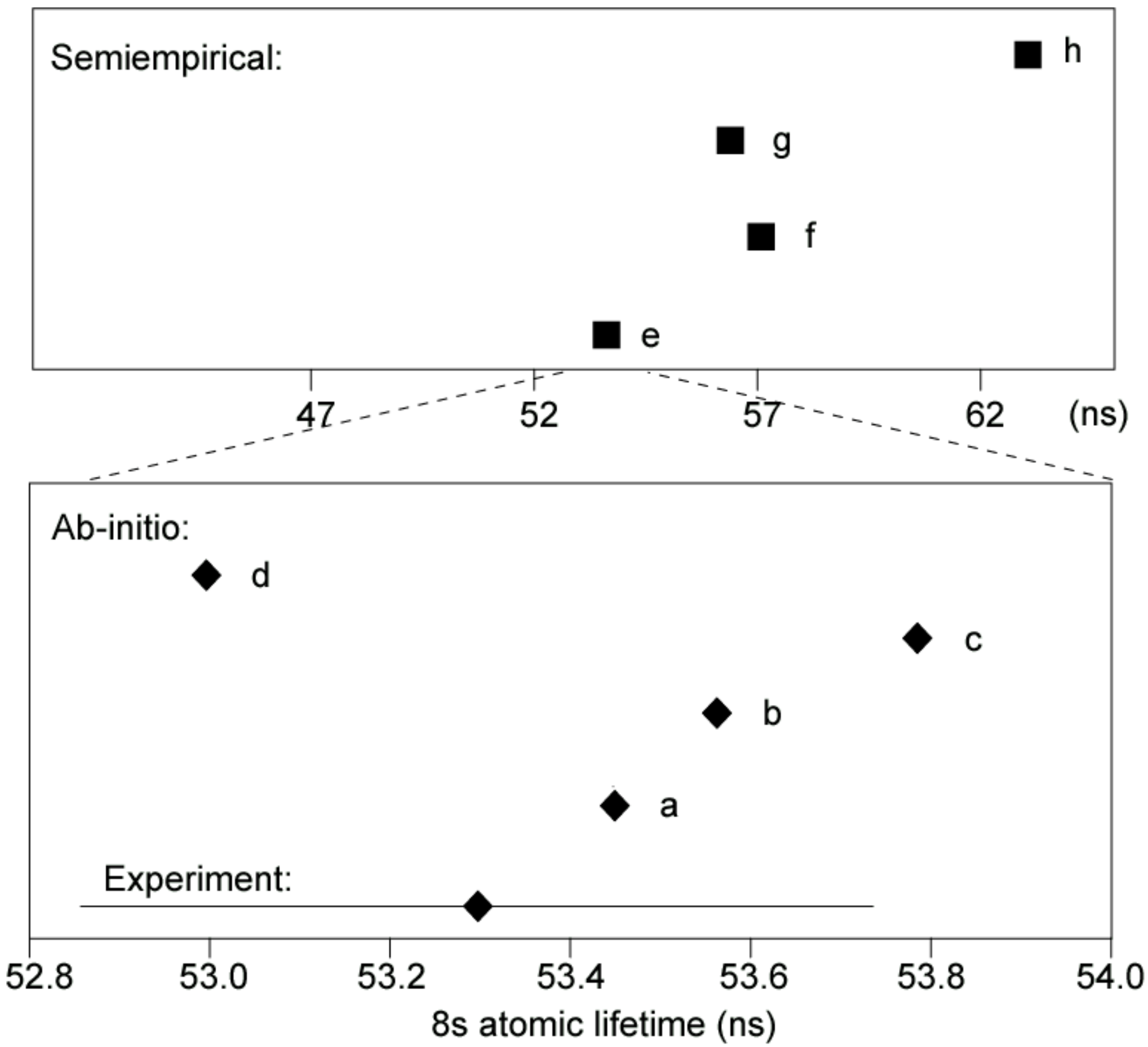


8s decay



Lifetime = 53.30 ± 0.44 ns

Comparison with theory



a) Safronova *et.al.*

b) Dzuba *et.al.*

c) Johnson *et.al.*

d) Dzuba *et.al.*

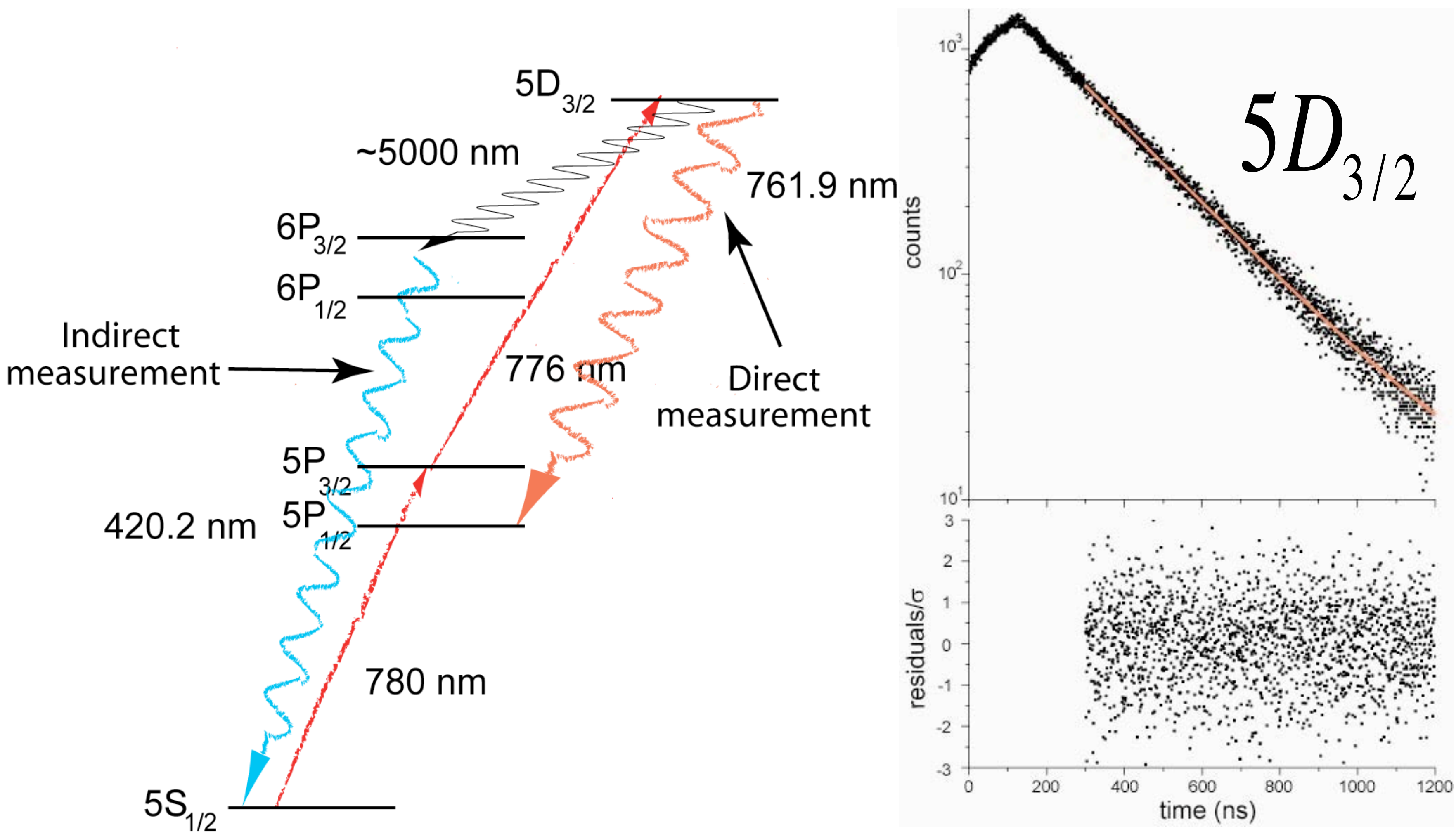
e) Marinescu *et.al.*

f) Theodosiou *et.al.*

g) Biemont *et.al.*

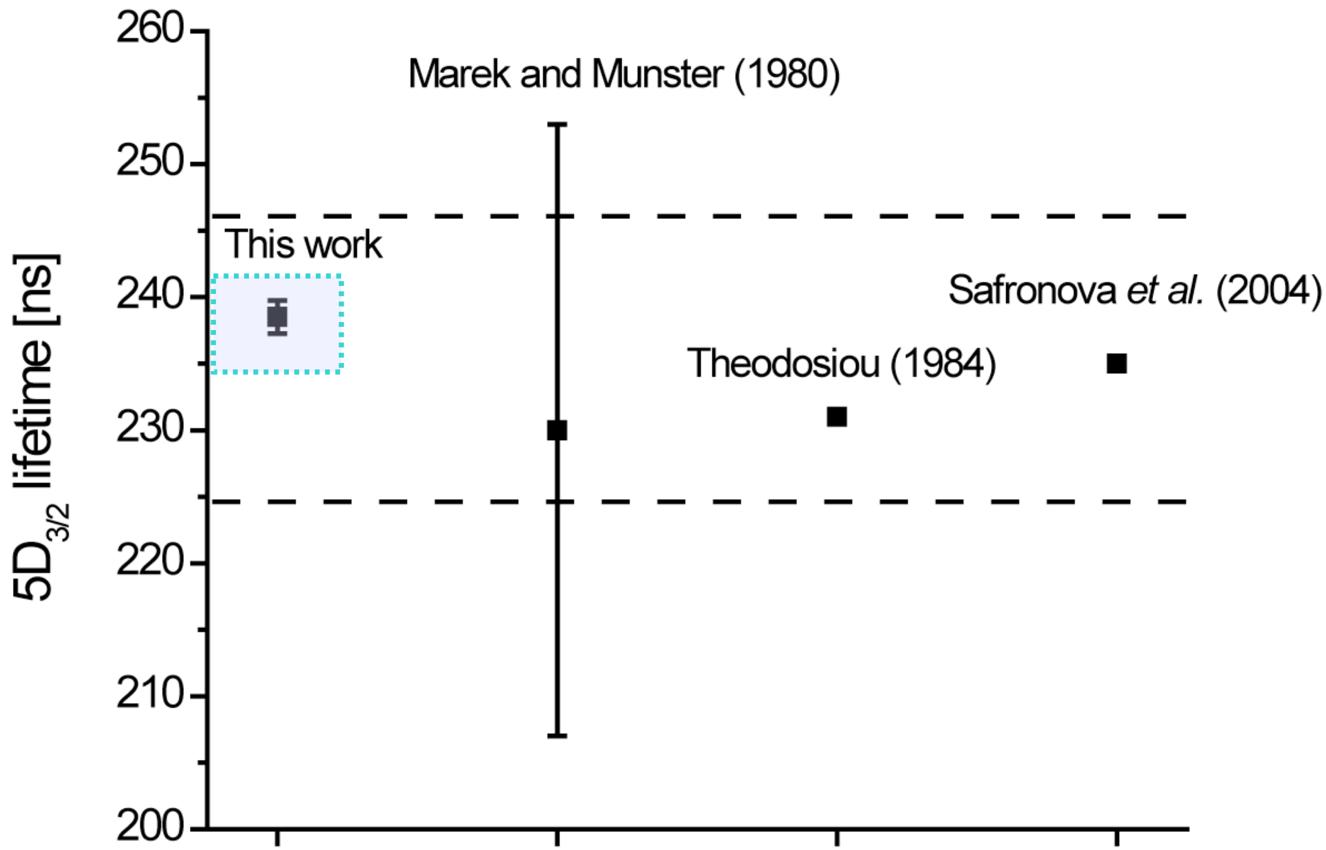
h) Van Wijngaarden *et.al.*

$5D_{3/2}$ state lifetime measurement in Rb



Comparison with previous results

$5D_{3/2}$



246.3 ± 1.6 ns

Anomalies

$$A_{\text{extended}} = A_{\text{point}} f_R (1 + \varepsilon_{BCRS})(1 + \varepsilon_{BW})$$

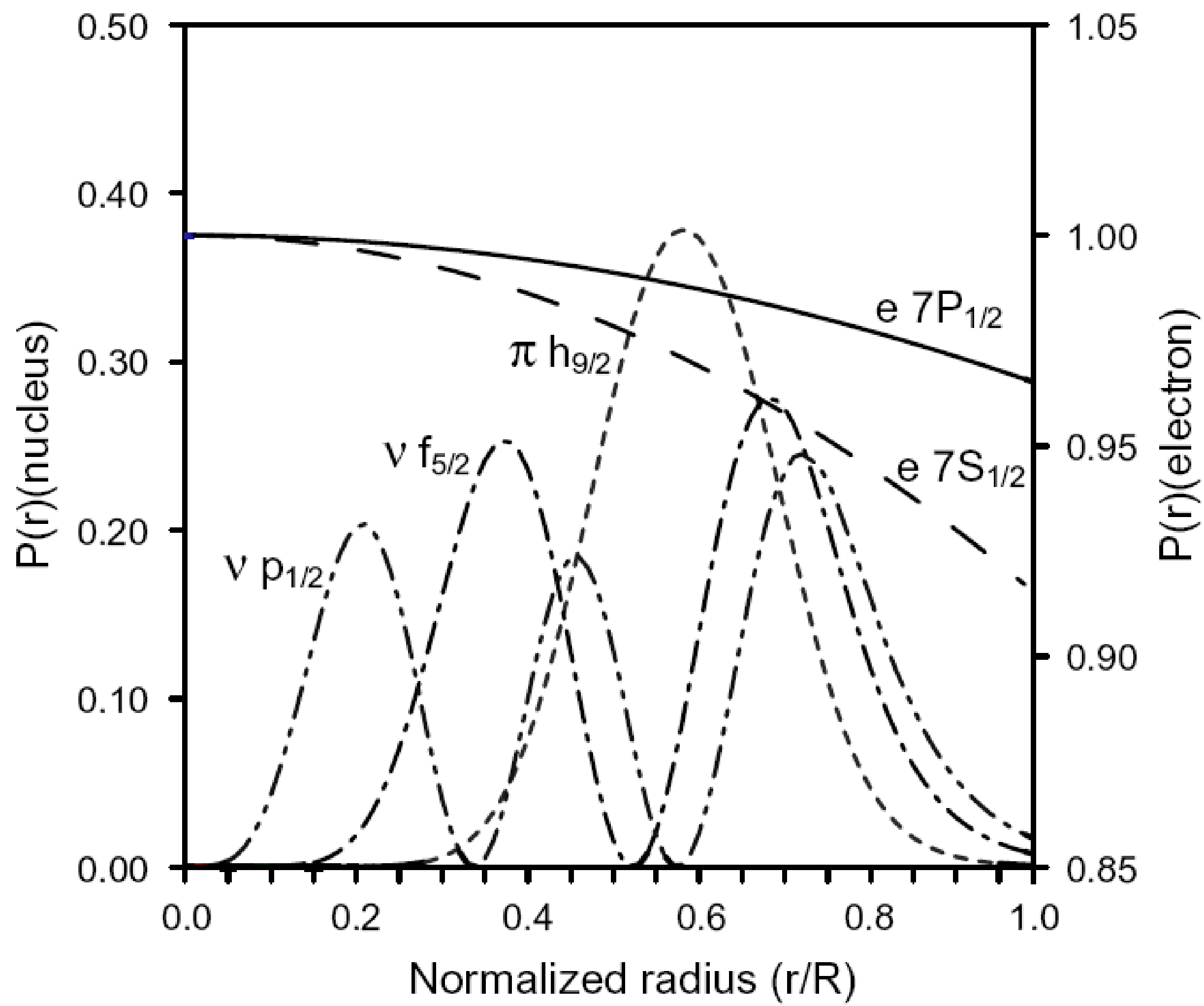
f_R = relativistic correction

ε_{BCRS} = Breit-Crawford-Rosenthal-Schawlow correction CHARGE

ε_{BW} = Bohr-Weisskopf correction MAGNETIZATION

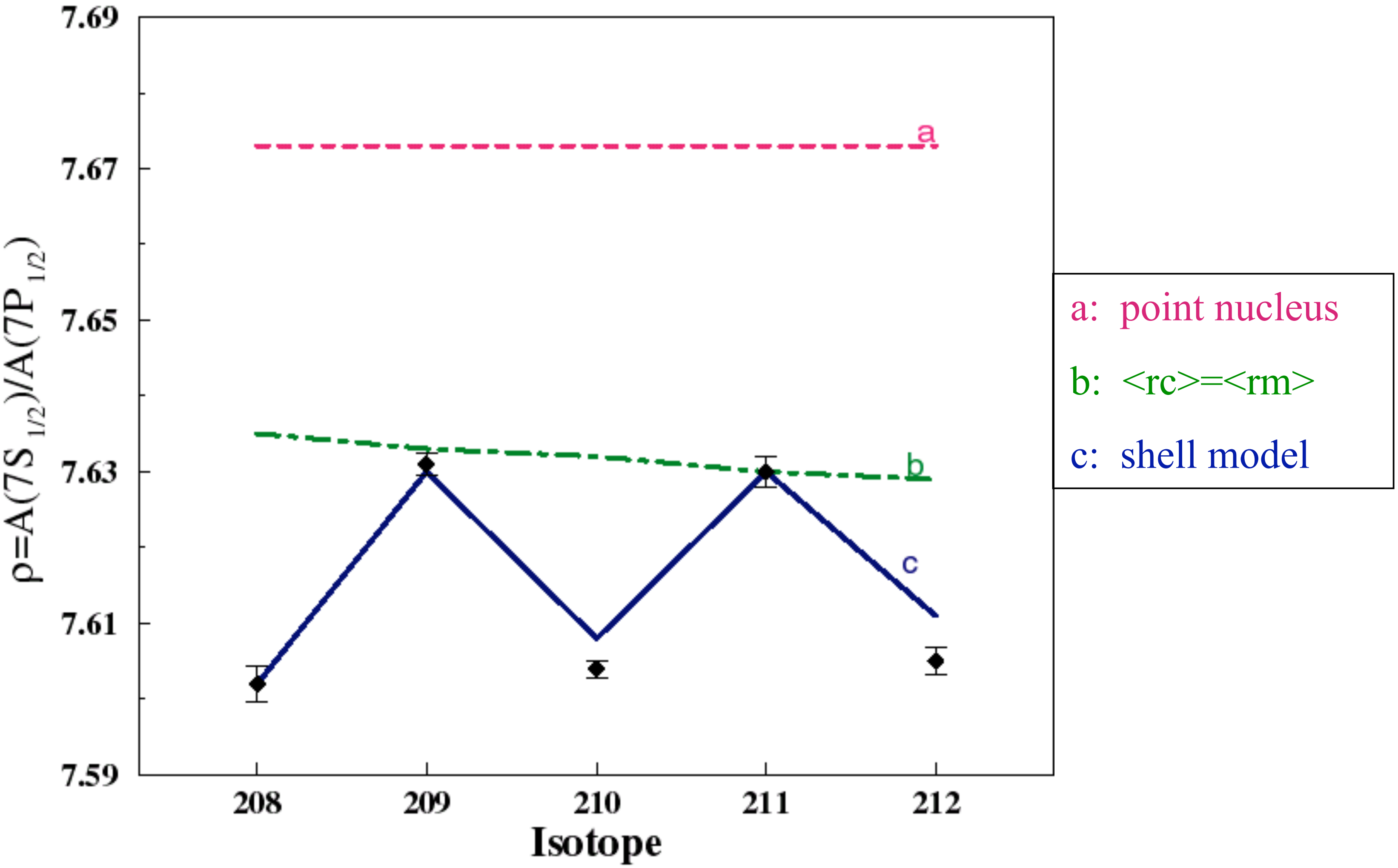
Amount of deviation from the point interaction for two isotopes

$$\frac{A^{85}_{extended} / g_I^{\,85}}{A^{87}_{extended} / g_I^{\,87}} = 1 + {}_{87}\delta_{85} = 1 + (\varepsilon^{85}_{BW} - \varepsilon^{87}_{BW})$$

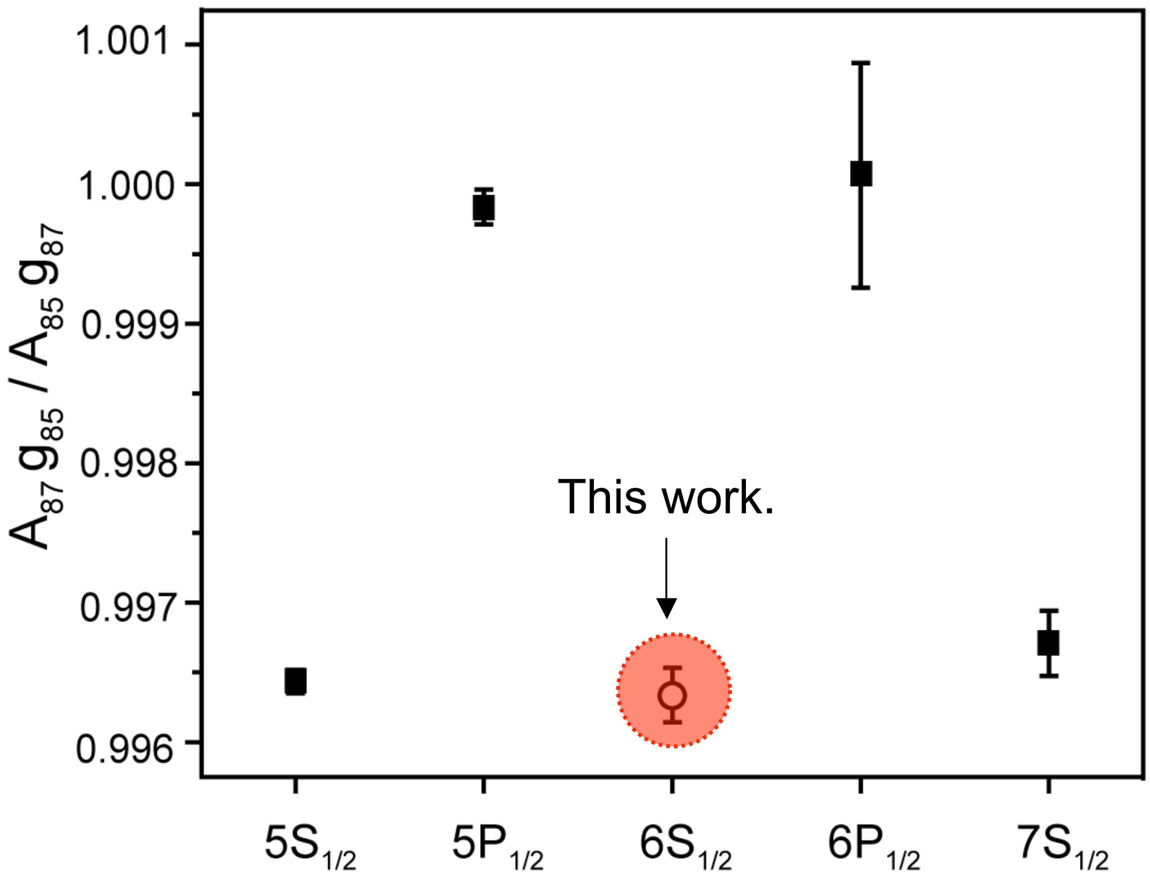


Nuclear structure calculations from Alex Brown

Hyperfine Anomaly



Rubidium Hyperfine anomaly in the excited state



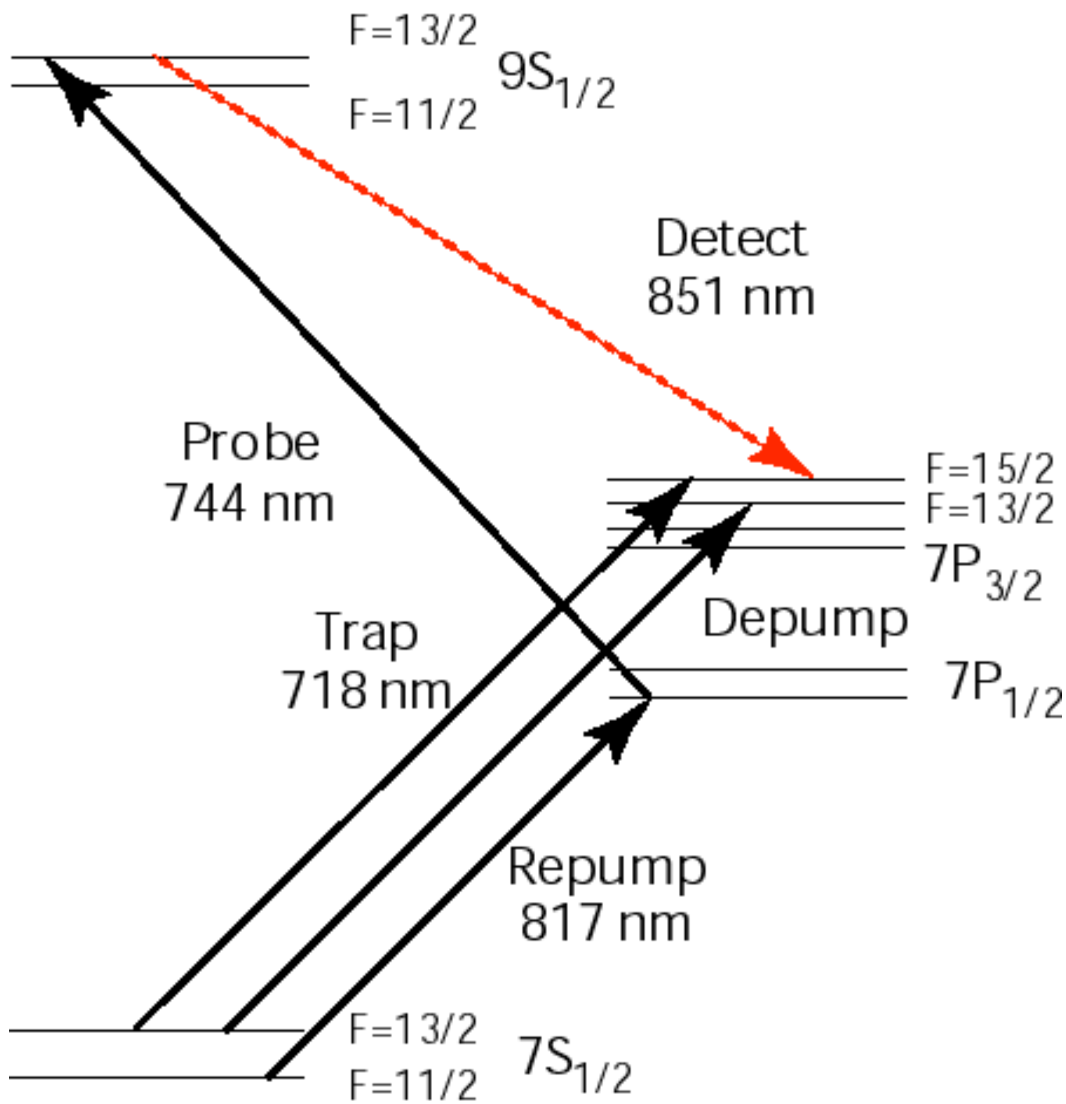
$5S_{1/2}$, $6P_{1/2}$: Rev. Mod. Phys. 49, 31 (1977).

$5P_{1/2}$: Appl. Phys. B: Photophys. Laser Chem. 53, 142 (1991).

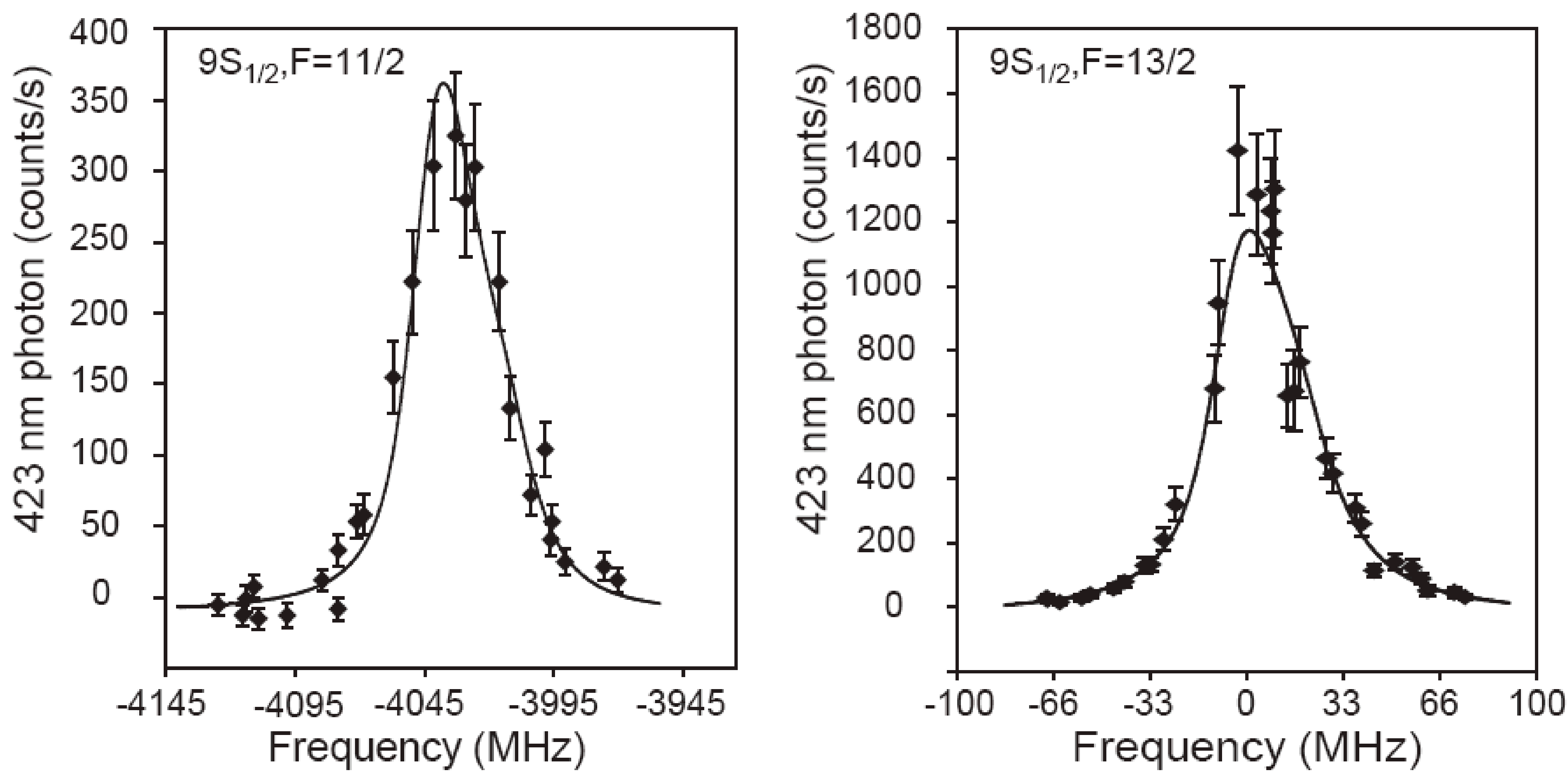
$7S_{1/2}$: Opt. Lett. 30, 842 (2005).

$${}_{87}\delta_{85} = -0.0036(2)$$

Spectroscopy of the 9S state



Hyperfine splitting of the 9S level: 4044.7(2.3)MHz, A= 622.25(36) MHz



Extraction of the magnetic moment for ^{210}Fr from a calculated hyperfine constant by the group of Marianna Safronova: 4.38(5) μ_N.

Fr	$7s$	$8s$	$9s$
DHF	4762	1220	501.2
SD	7750	1632	639.1
Final	7277	1584	624.8
Correlation(%)	34.6	22.9	19.8
Triple excitations (%)	-6.5	-3.1	-2.3
Experiment	7195.1(9)	1577.8(23)	622.32(30)
Reference	[27]	[28]	Present work
$\mu_{n\ exp}$	$4.35(5)\mu_N$	$4.38(5)\mu_N$	$4.38(5)\mu_N$

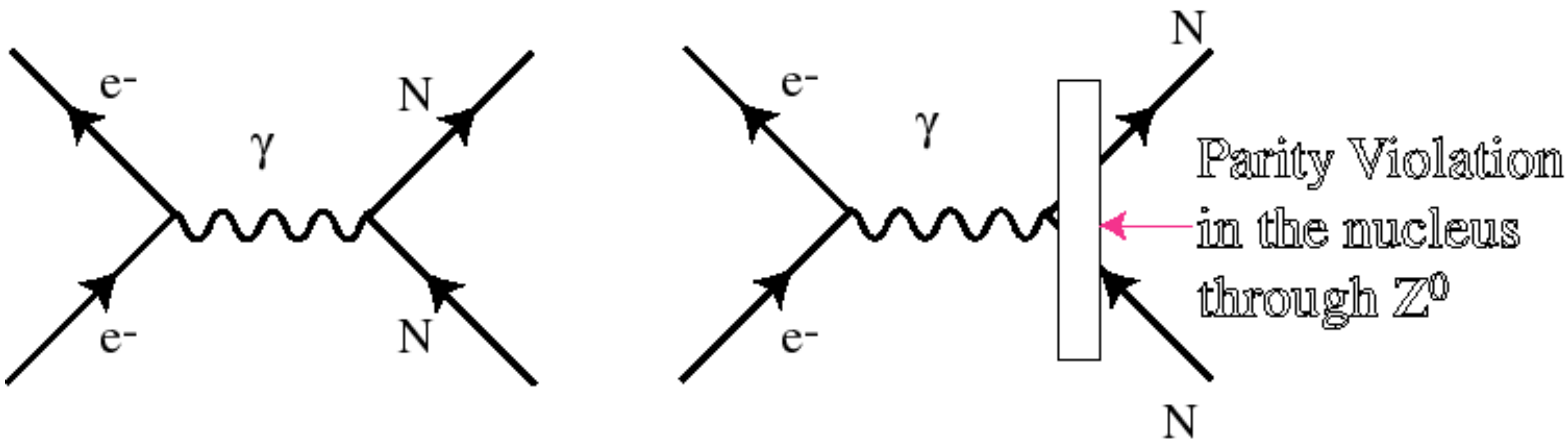
What we know about francium: (better than 1%)!

Table 5. ^{210}Fr trapping parameters.

Trapping energy ($7P_{3/2}$)	$13\,923.381 \pm 0.003\ \mathrm{cm}^{-1}$
Repumping energy ($7P_{1/2}$)	$12\,238.425 \pm 0.003\ \mathrm{cm}^{-1}$
I	6
$7S_{1/2}$ hyperfine splitting [39]	$46\,768.2 \pm 2.6$ MHz
$A(7S_{1/2})$ [39]	7195.1 ± 0.4 MHz
$A(7P_{3/2})$ [148]	78.0 ± 0.2 MHz
$B(7P_{3/2})$ [148]	51 ± 0.4 MHz
$A(7P_{1/2})$ [28]	946.3 ± 0.2 MHz
Linewidth $7P_{3/2}$ $\Gamma/2\pi$	7.57 MHz
Linewidth $7P_{1/2}$ $\Gamma/2\pi$	5.40 MHz
Doppler temperature limit ($7P_{3/2}$)	$T_D = 182\ \mu$K
Doppler velocity ($7P_{3/2}$)	$v_D = 8.4\ \mathrm{cm\,s}^{-1}$
Recoil temperature limit ($7P_{3/2}$)	$T_r = 176$ nK
Recoil velocity ($7P_{3/2}$)	$v_r = 2.6\ \mathrm{mm\,s}^{-1}$
$I_{sat}(7P_{3/2})$ (two-level atom)	$2.7\ \mathrm{mW\,cm}^{-2}$
Radioactive half-life	3.2 min
Emitted alpha energy	6.54 MeV

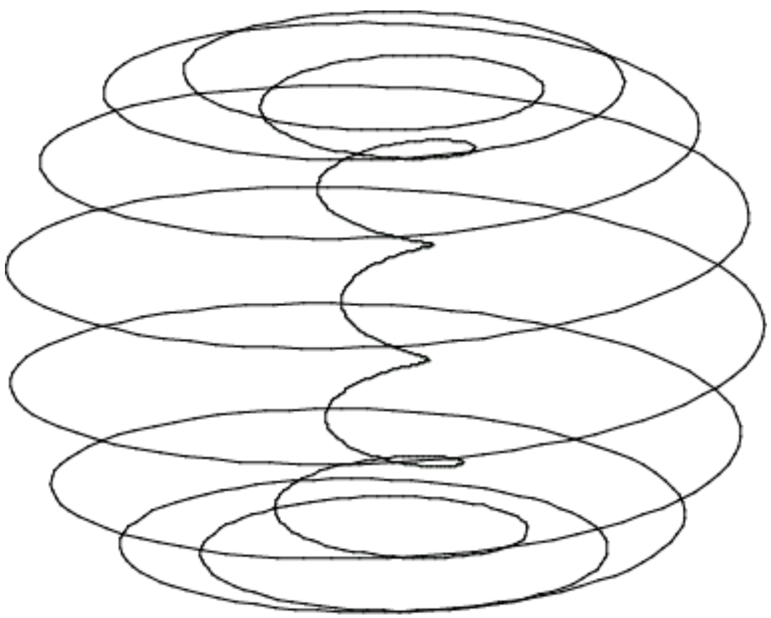
The Anapole Moment

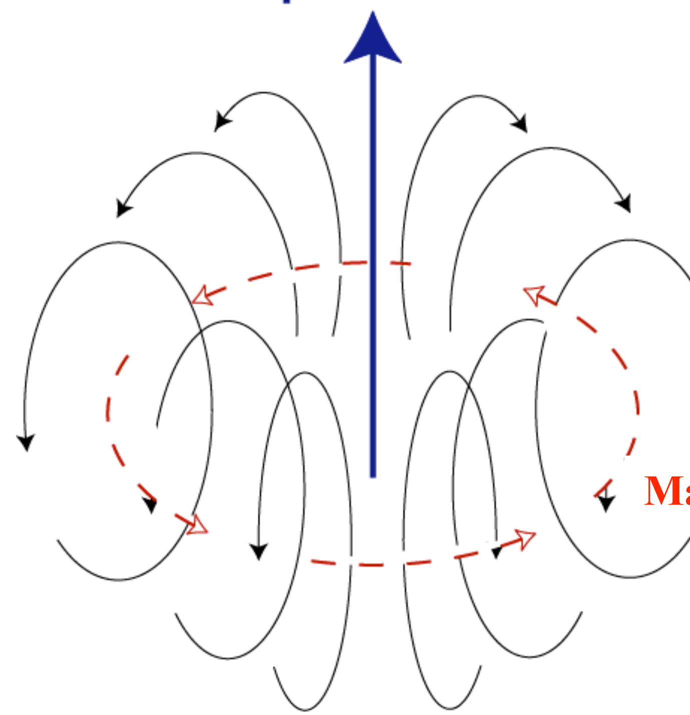
1958 Zel'dovich, Vaks
1980 Khriplovich, Flambaum, Shuskov
1995 Seattle experiment Thallium
1997 Boulder experiment Cesium



It can be thought as a "weak radiative correction". The nuclear wave function has parity violating components (V_e A_N). It has to be probed inside the nucleus by an electromagnetic interaction.

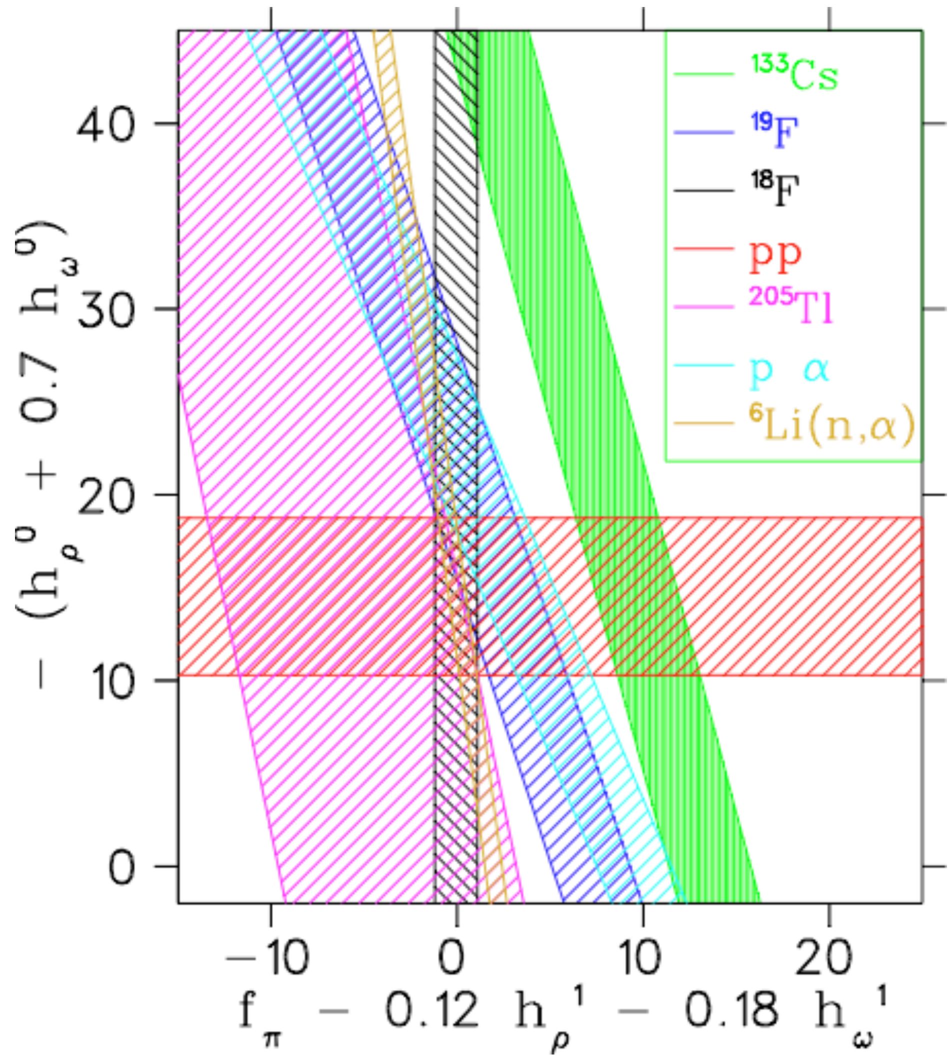
Chiral current



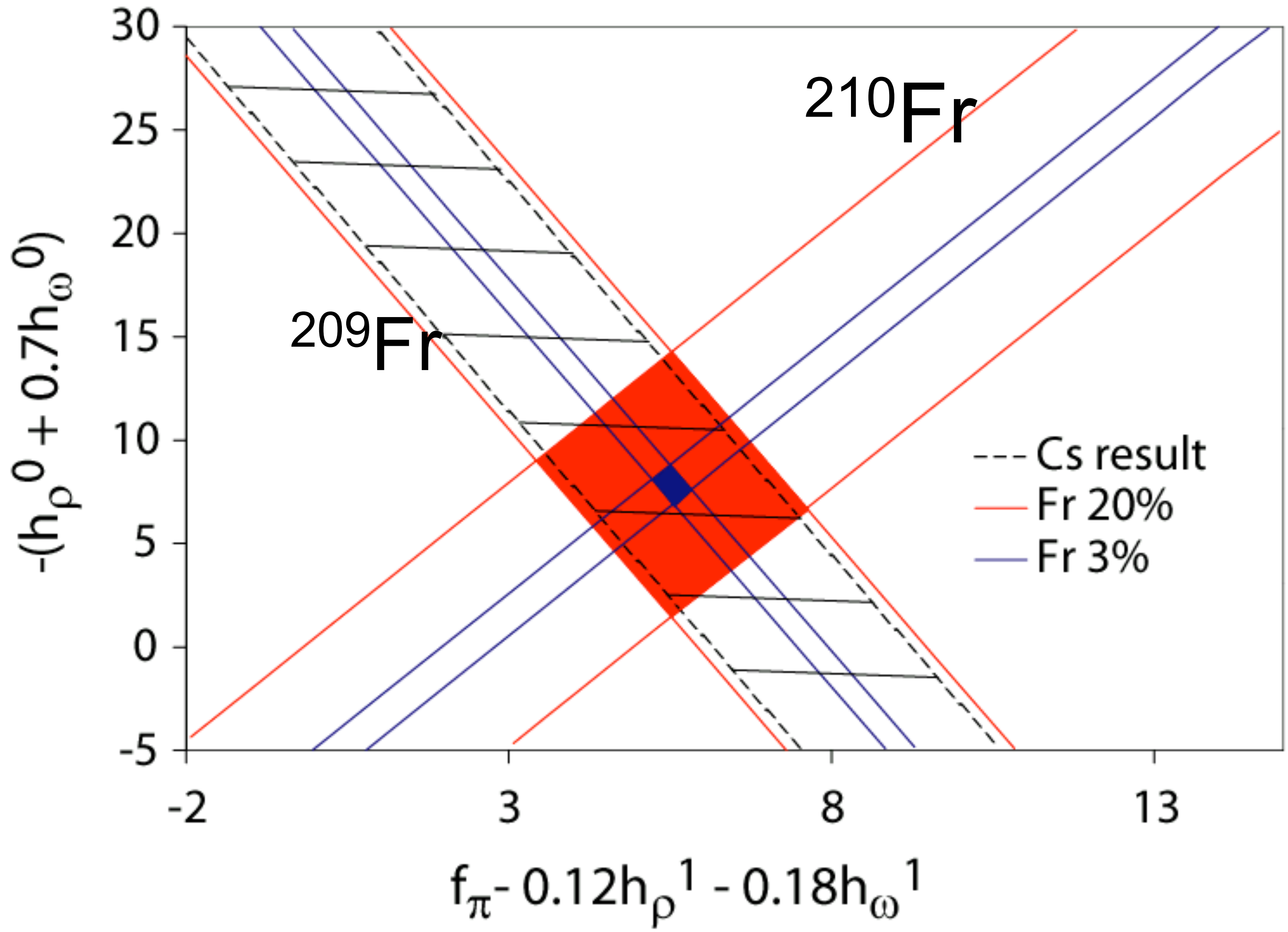


Anapole moment

$$\vec{a} = \int dr r^2 J(r)$$



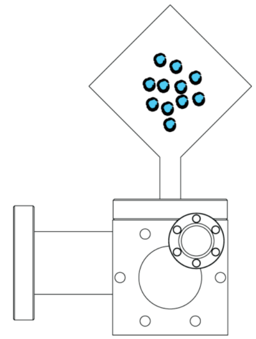
Constraints on the PNC meson couplings (10^7). The error bands are one standard deviation. The illustrated region contains all of the DDH "reasonable ranges" for the indicated parameters (Behr, based on Haxton and Wieman).



Constraints of couplings from measuring two francium isotopes.

Experimental scheme

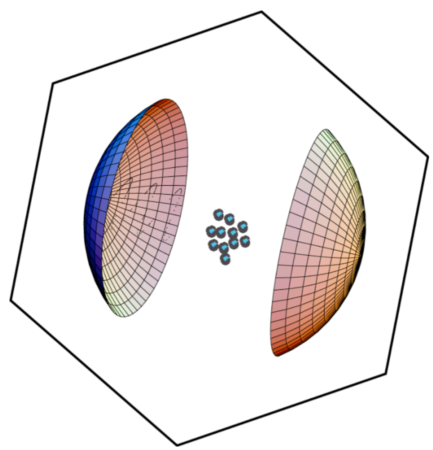
Transport of Fr^+



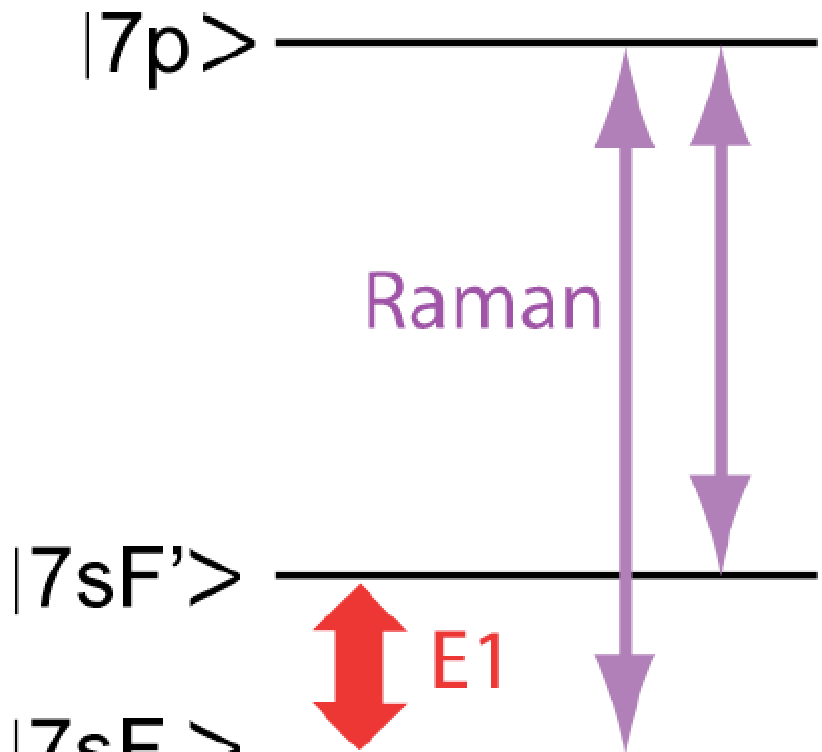
Neutralize, cool and trap neutral Fr in dry-film glass cell.

Long distance transfer to science chamber.

Requirements of science chamber:
- UHV (10^{-10} torr or better).
- Space for Fabry-Perot RF cavity.
- Sufficient viewports for laser probes.



Recapture.



Where:

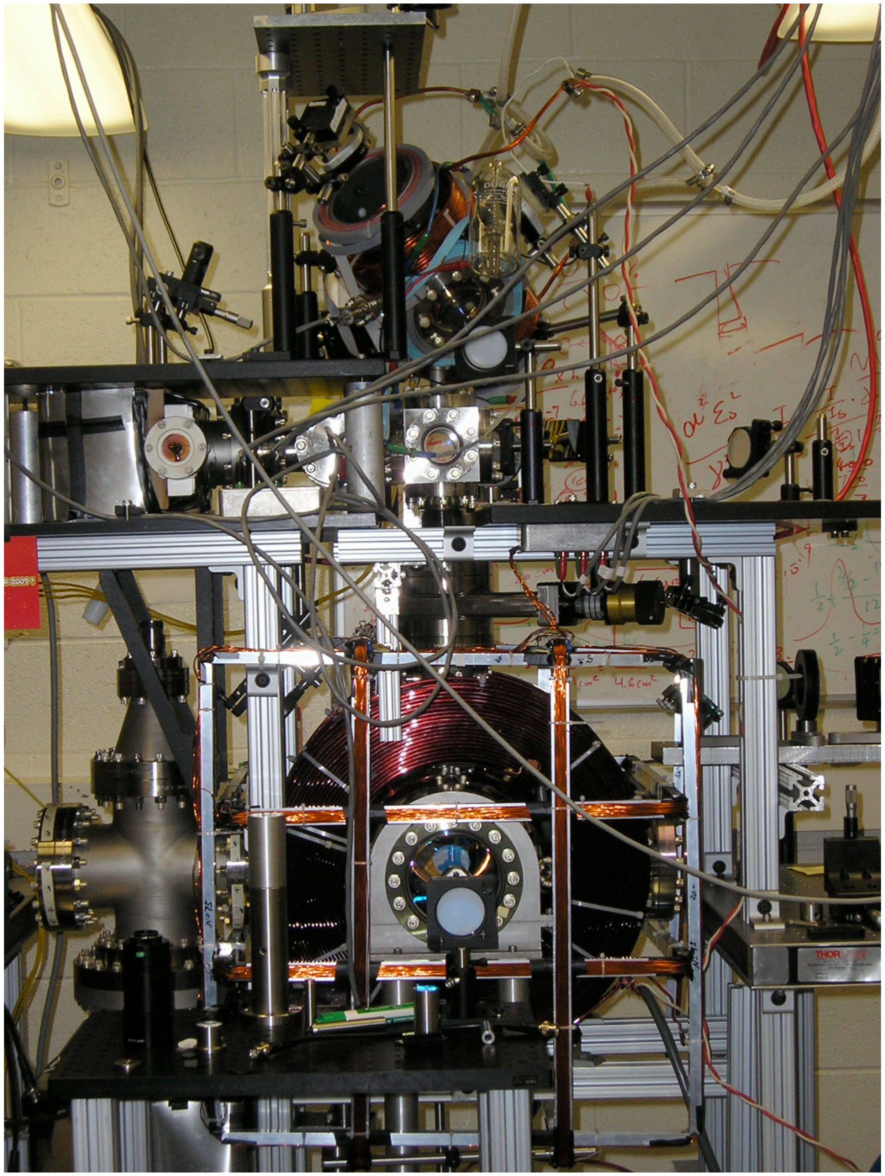
$$\overline{|sFm\rangle} = |sFm\rangle - i5.9\times 10^{-13} \times \kappa_a (F(F+1) - 25.5)\,|pFm\rangle$$

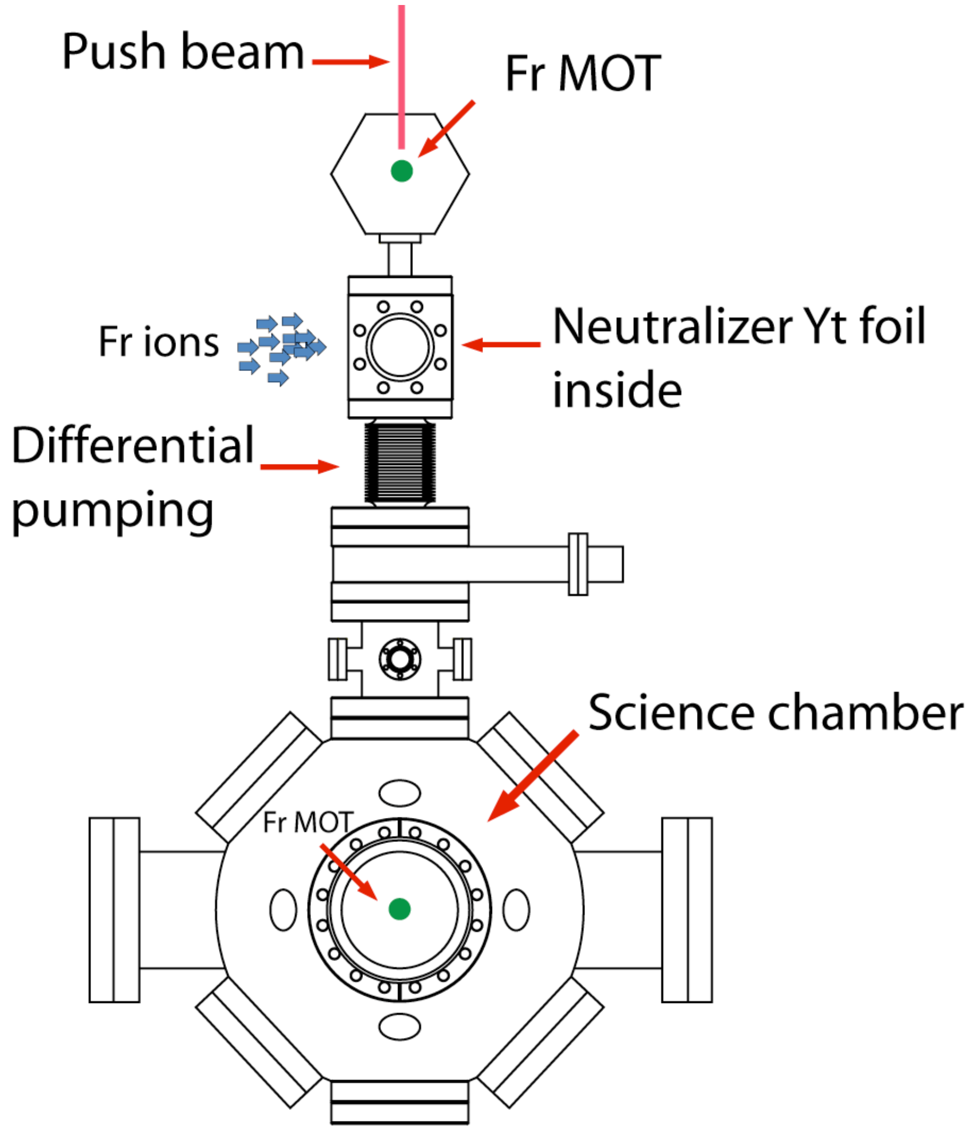
1. Define handedness of coordinate system ($iE_{RF} \times (E_{R1} \times E_{R2}) \cdot B_{DC}$).
2. Create superposition to interfere and enhance PV signal:

$$A_{total} = A_{R1} \pm A_{E1}^{PNC}$$

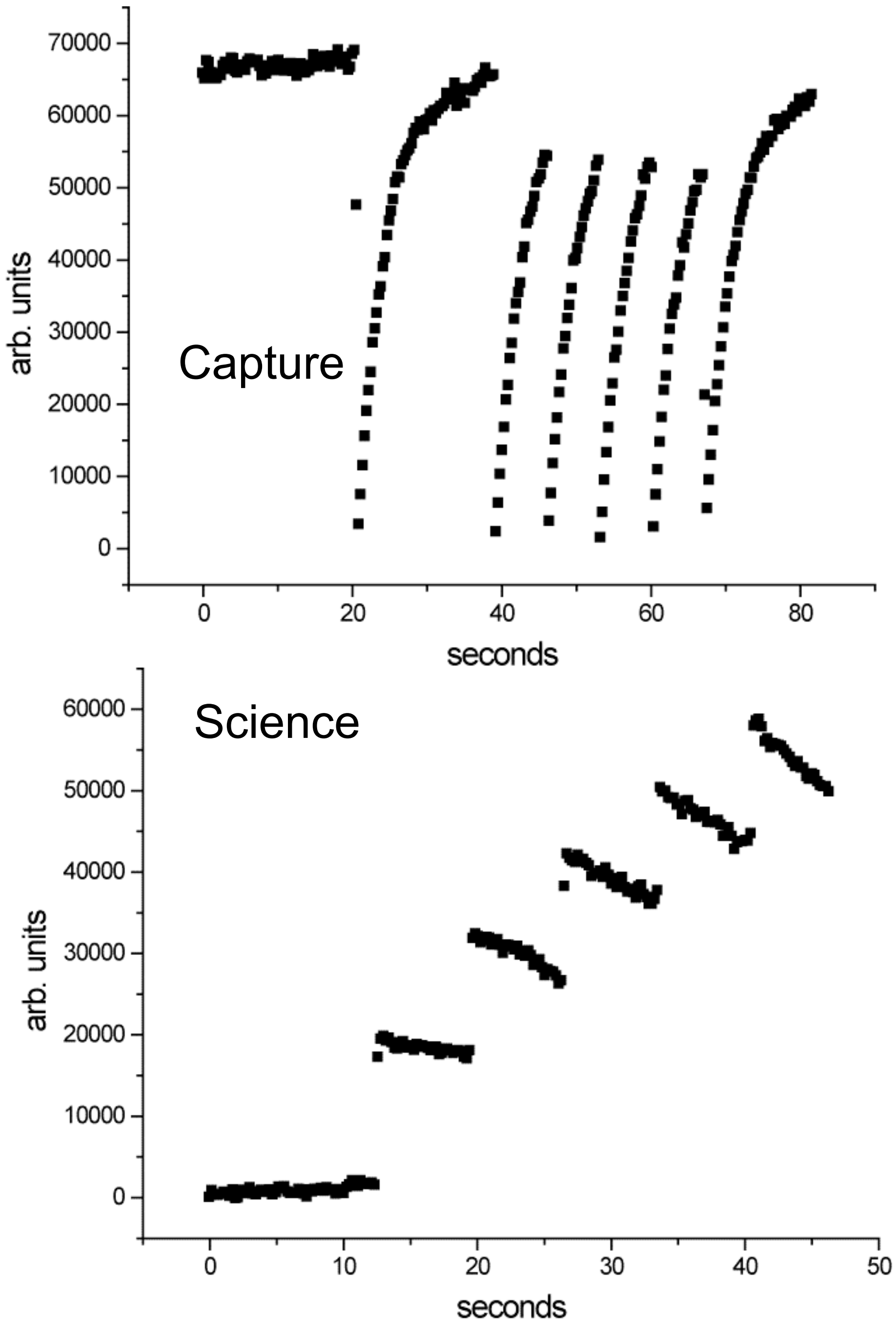
3. Measure rate of transition
4. Change handedness of coordinate system.
5. Repeat.

$$\frac{S}{N} \approx 2\frac{A_{E1}^{PNC}\,t}{\hbar}\sqrt{N}$$

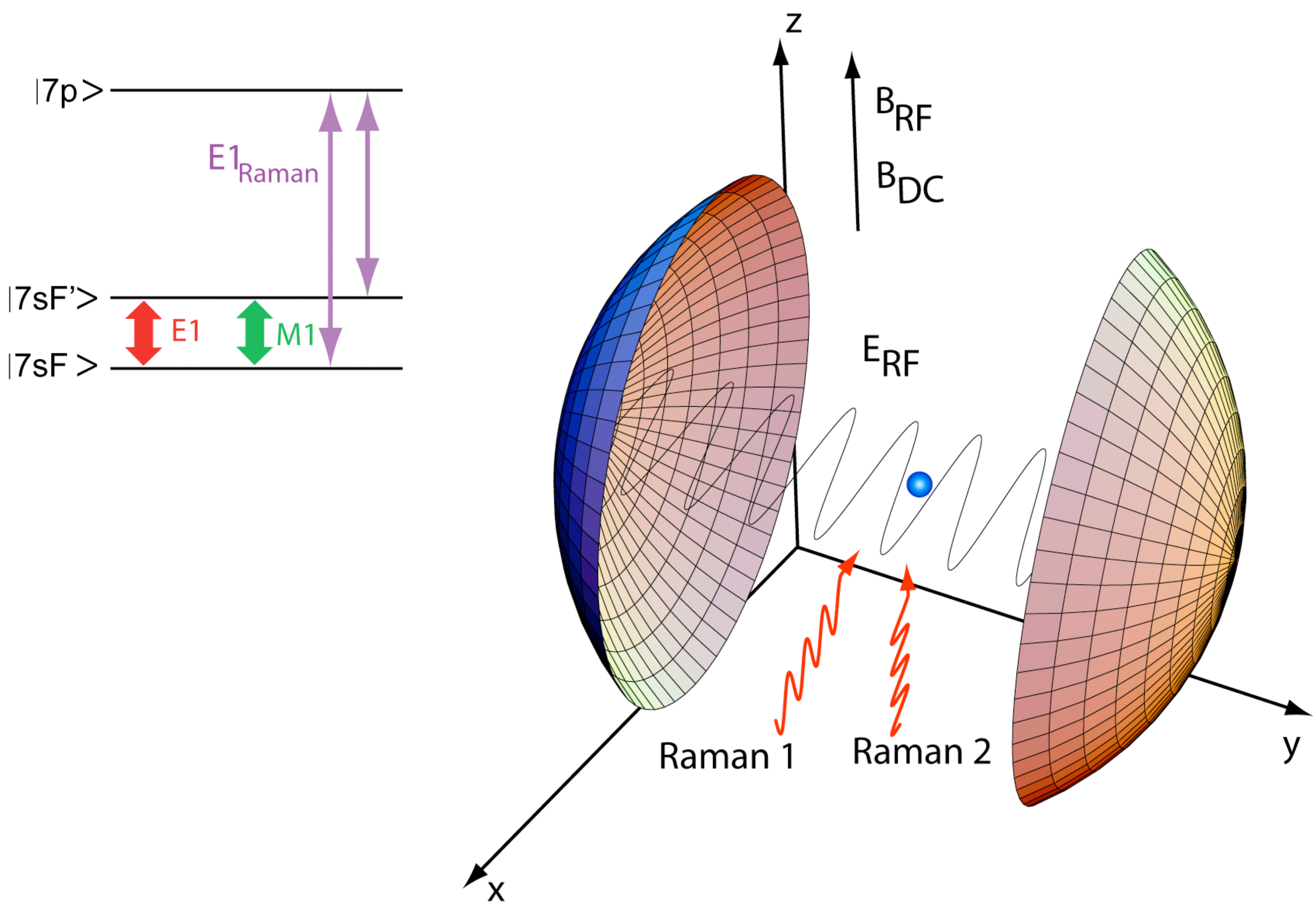




Push beam
Fr MOT
Fr ions
Neutralizer Yt foil inside
Differential pumping
Science chamber
Fr MOT

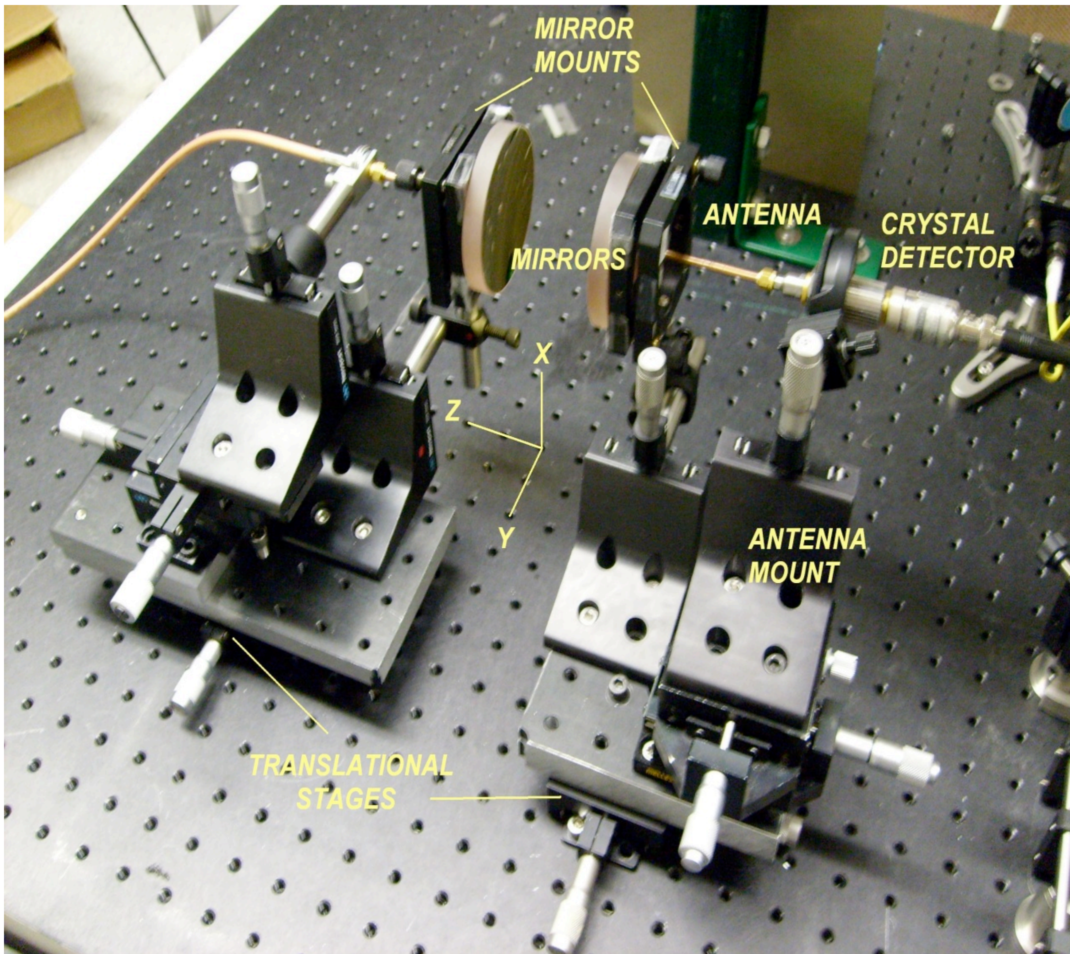


Captured atoms in lower MOT. Transferred efficiency > 50%. The change in MOT lifetime is due to collisions.



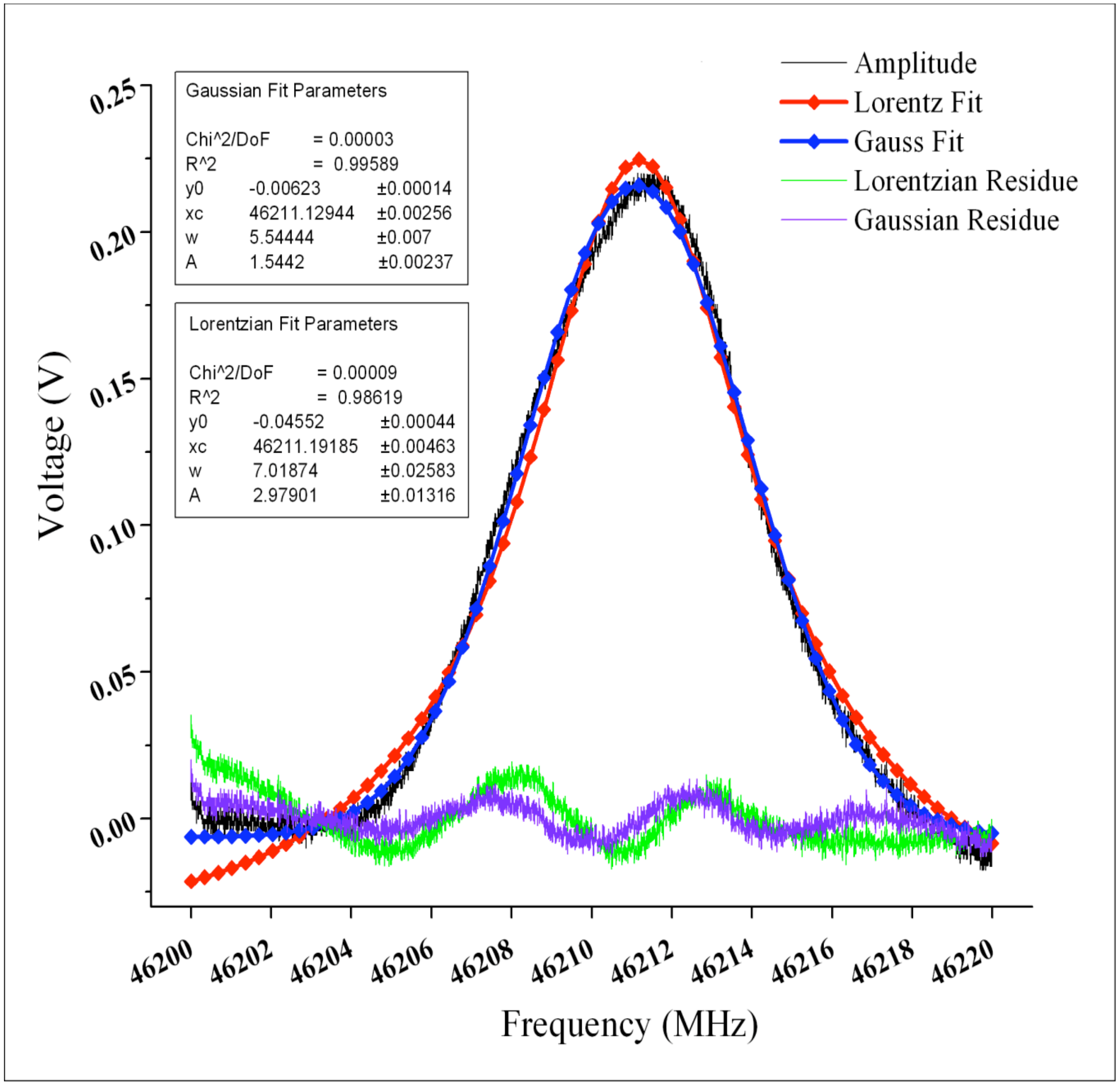
$$i(E_{RF} \times (E_{R1} \times E_{R2})) \cdot B_{DC}$$

RF Fabry-Perot cavity



- Gold plated glass mirrors with R=13.5 cm.
- Dipole antennas to couple power.

Mode properties of RF cavity

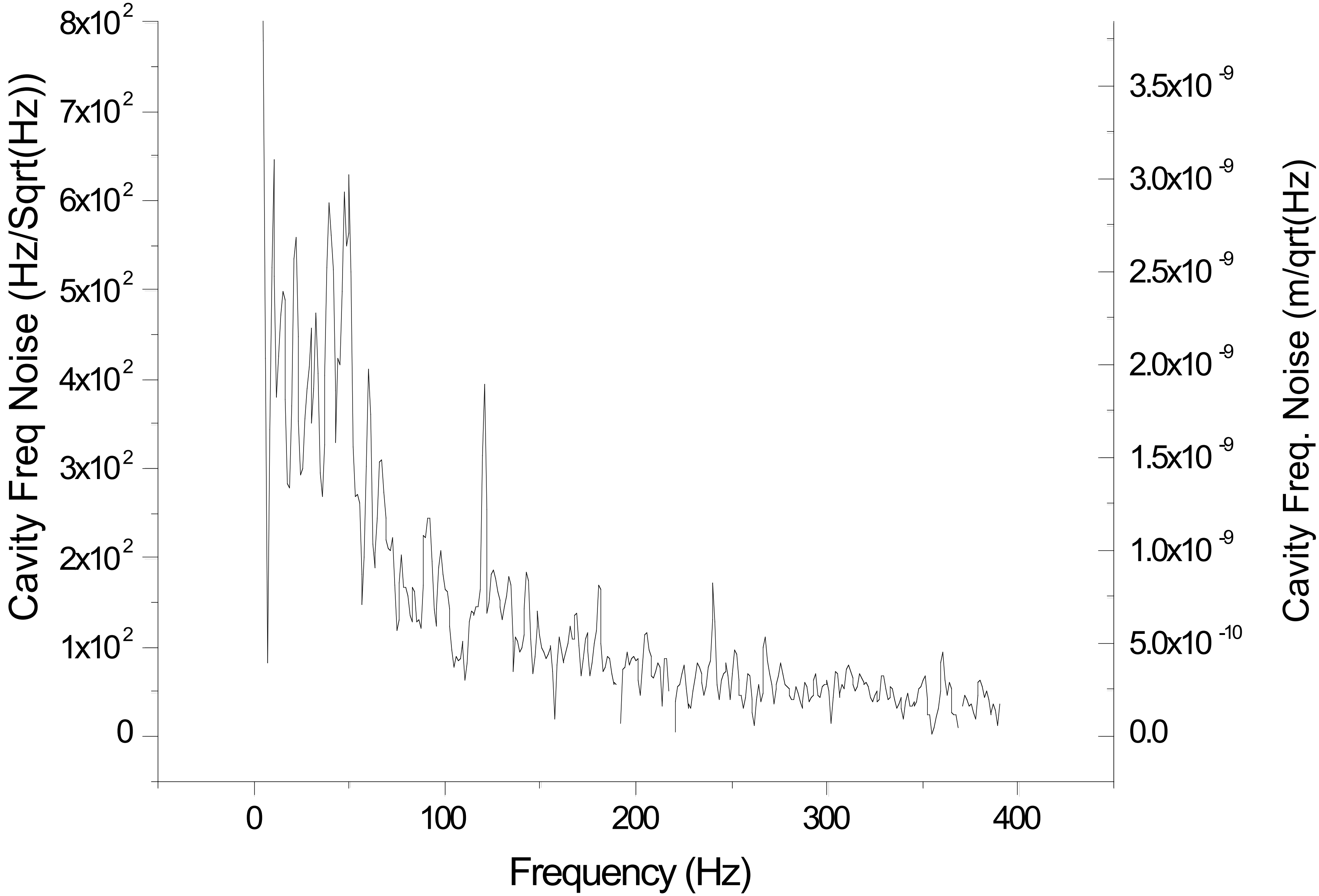


ν = 46. 211 GHz

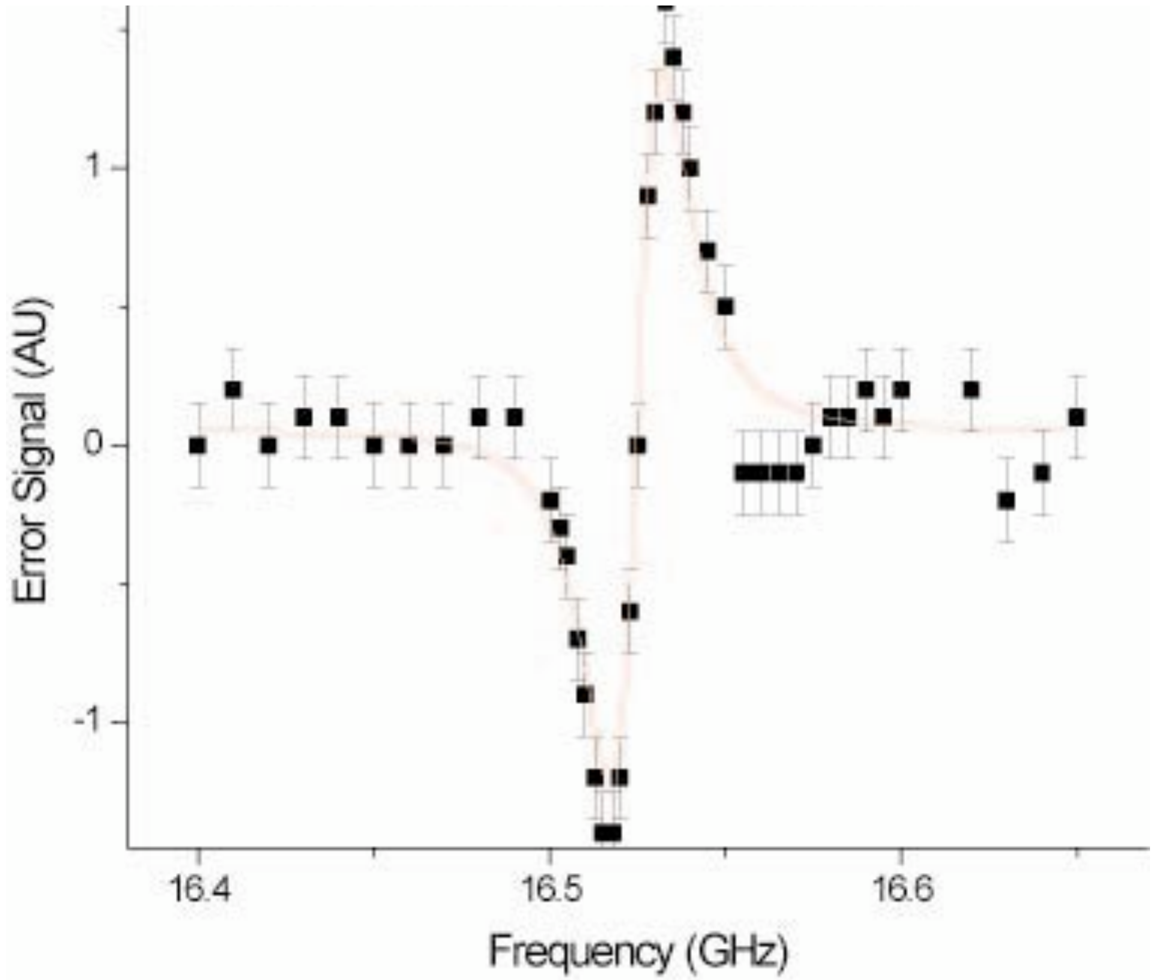
FWHM = 5.5 MHz

Q= 8335

Power Spectral Density of the microwave cavity length

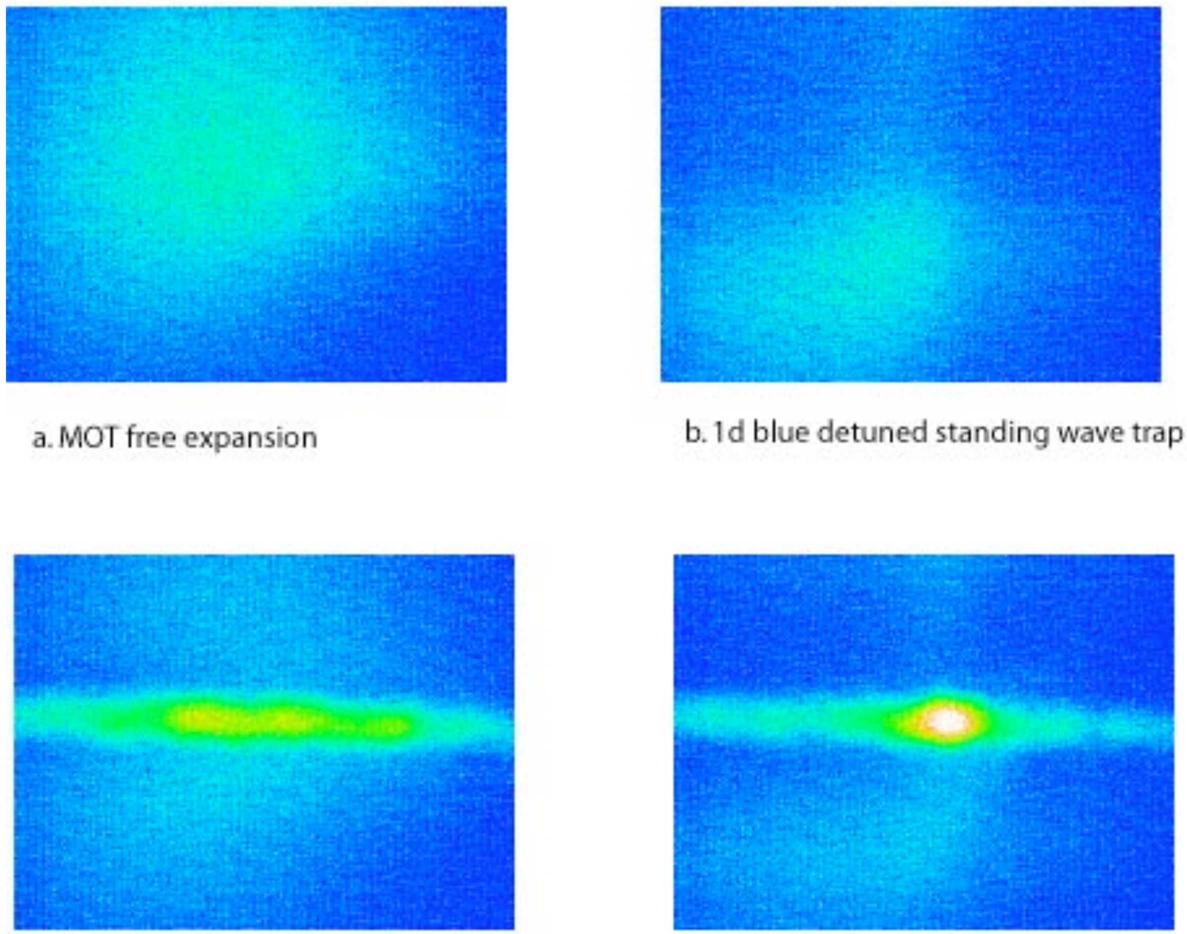


Error signal with Pound (Drever-Hall) method



Use two acousto-optical modulators to generate a dynamical hollow beam. Trap parameters 400 mW laser with 2.3 nm blue detuned from the ^{87}Rb D_2 line, 30 μm waist and 100 μm rotating diameter.

Fluorescence Image after 35ms expansion of the atoms



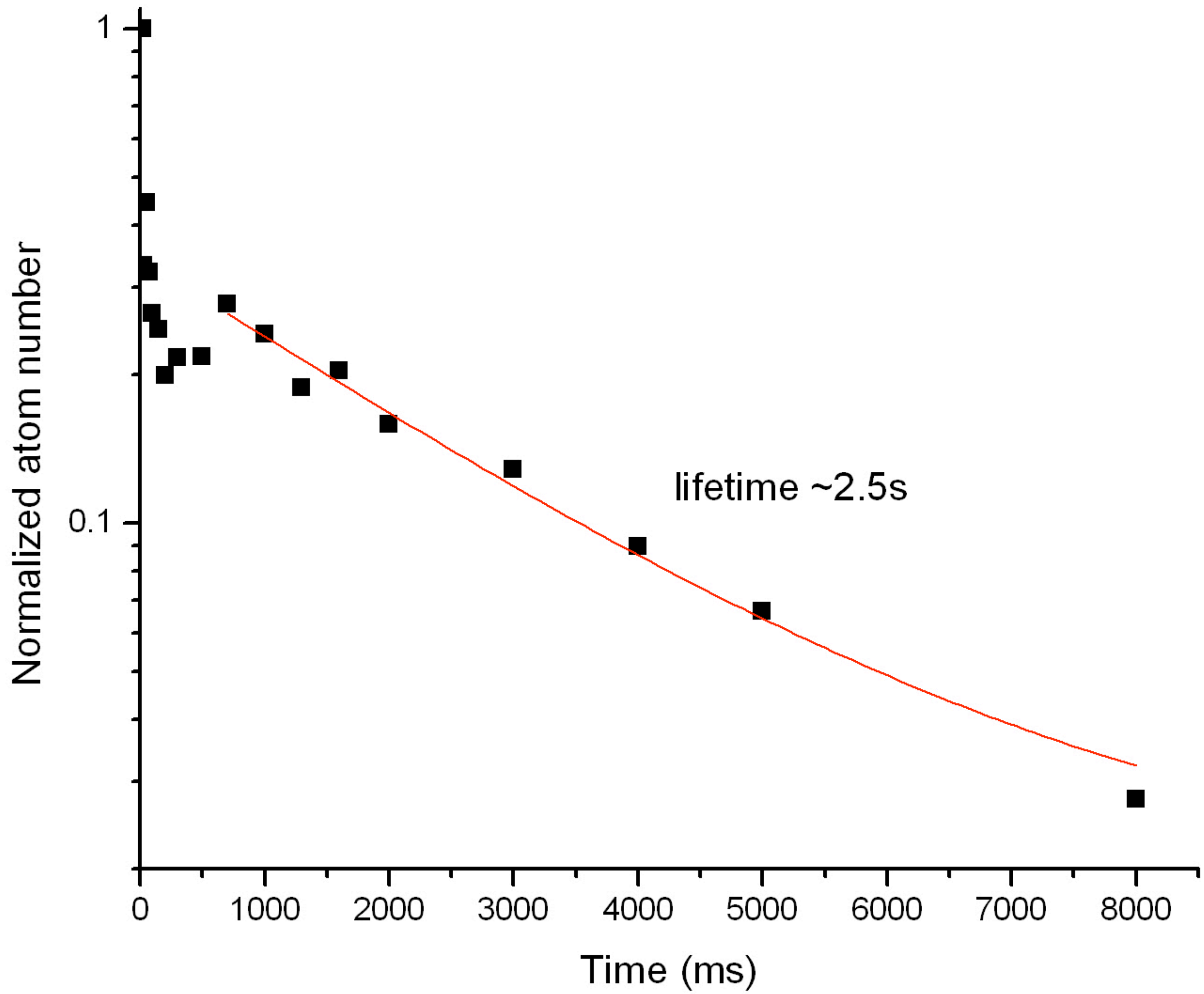
a. MOT free expansion

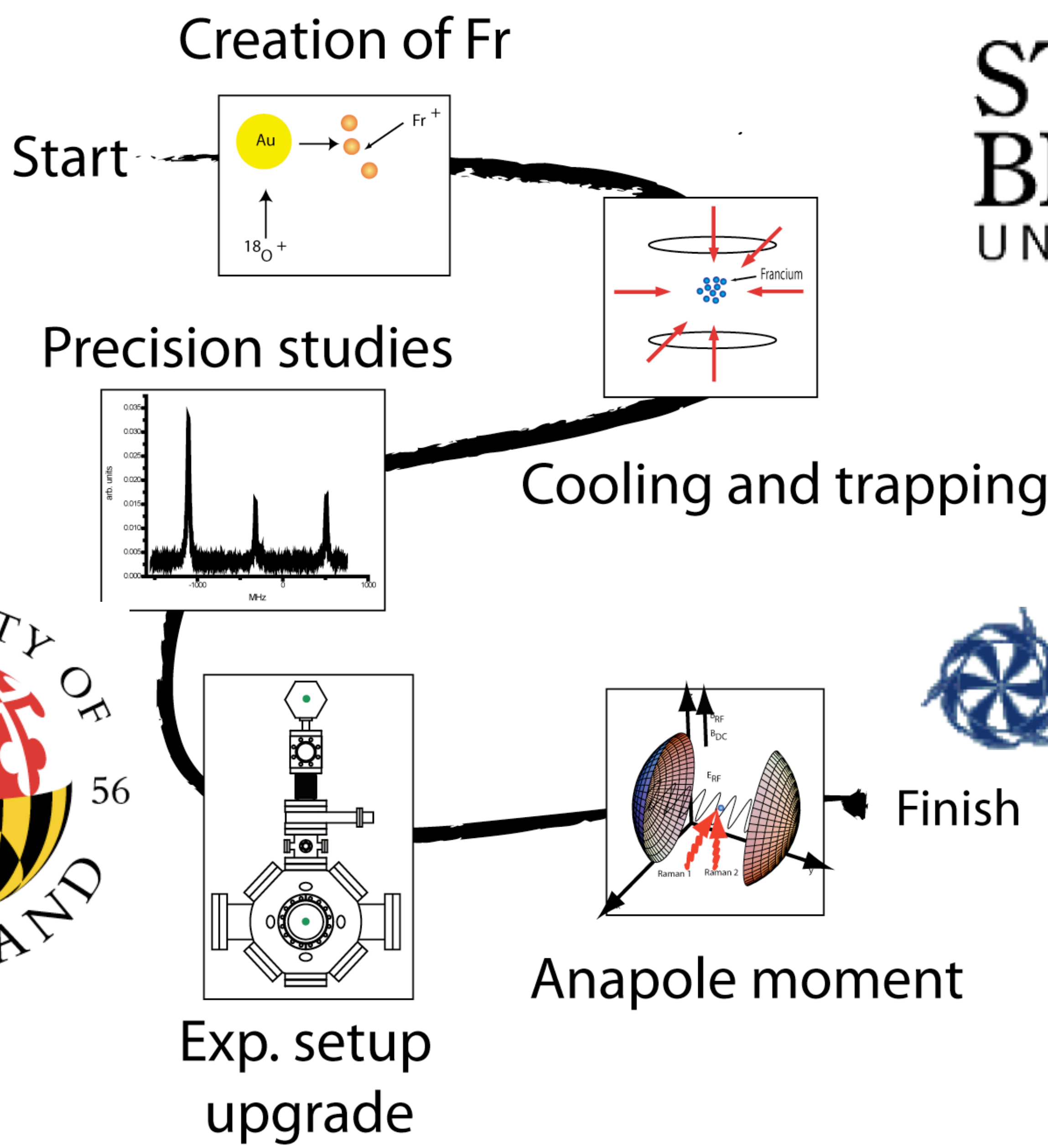
b. 1d blue detuned standing wave trap

c. Blue detuned rotating dipole trap

d. blue dipole trap + 1d blue detuned standing wave trap

Lifetime of atoms in the trap





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$$\frac{Signal}{Noise} = 2\Omega_{E1}\Delta t\sqrt{N} = 2$$

Number of atoms = $N \sim 10^4$

$\Omega_{E1} \sim 10$ mrad

Interaction time = $\Delta t \sim 1$s

Road Map for FrPNC

- Test system with Rb at UMD.

- The apparatus also works for Optical PNC

- Measurement of the anapole moment of a chain of Fr isotopes through the E1 forbidden hyperfine transition.

- Shot noise limited signal-to-noise better than 1 $(Hz)^{-1/2}$.

- Calculations of atomic and nuclear structure will allow the extraction of weak coupling constants in the presence of strong interactions.