What we know about Francium

Institute of Theoretical Physics
Chinese Academy of Sciences
Beijing, China
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Luis A. Orozco
www.jqi.umd.edu

UNIVERSITY OF MARYLAND

Joint Quantum Institute

NIST

FrPNC Collaboration (Winter 2017)

Seth Aubin; College of William and Mary, USA.
John A. Behr, Matt R. Pearson, Alexander Gorolov, Mukut R. Kalita; TRIUMF, Canada.
Victor V. Flambaum; University of New South Wales, Australia.
Eduardo Gómez; Universidad Autónoma de San Luis Potosí, México.
Gerald Gwinner SPOEKESPERSON A. DeHart; University of Manitoba, Canada.
Luis A. Orozco; University of Maryland, USA.
Yanting Zhao; Shanxi University, Taijuan, China.

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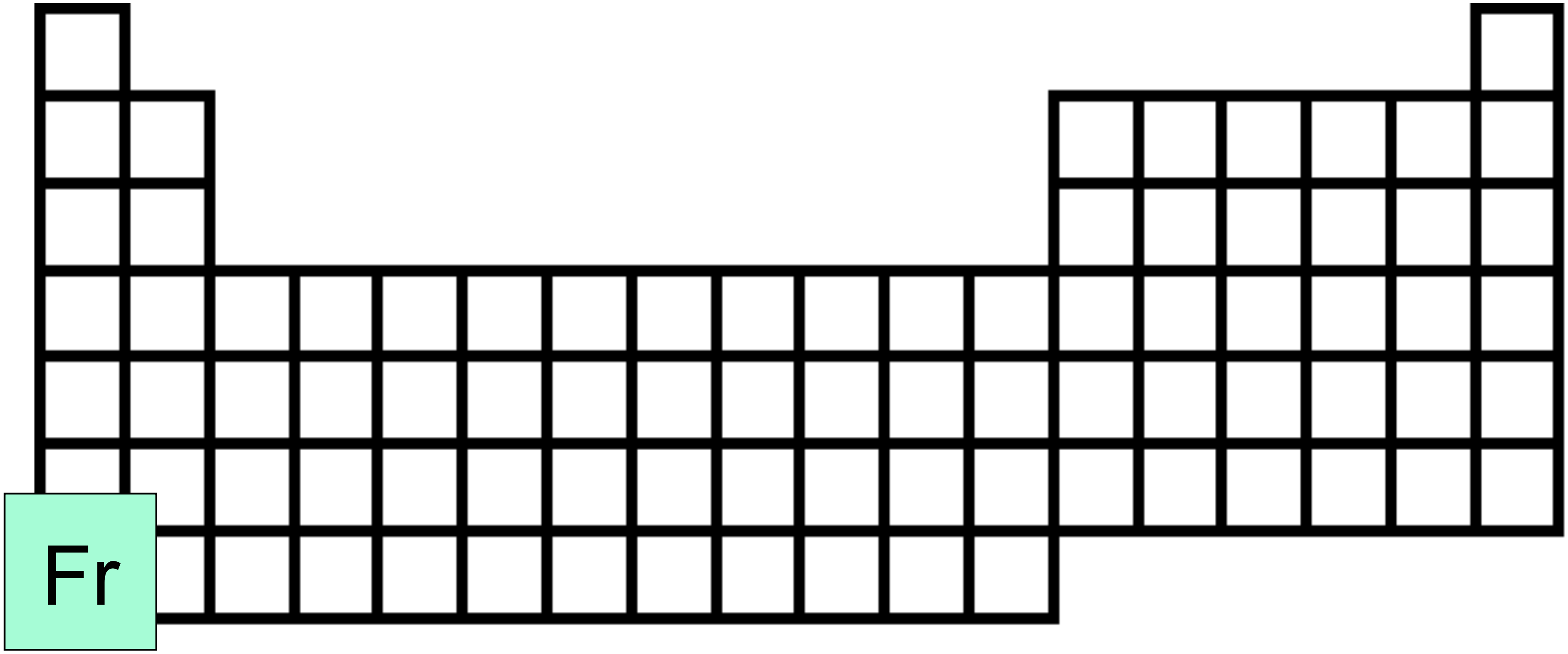
Discovery as a product of actinium decay 1939

$$^{227}_{89}\mathrm{Ac} \rightarrow {}^{223}_{87}\mathrm{Fr} + {}^{4}_{2}\alpha$$

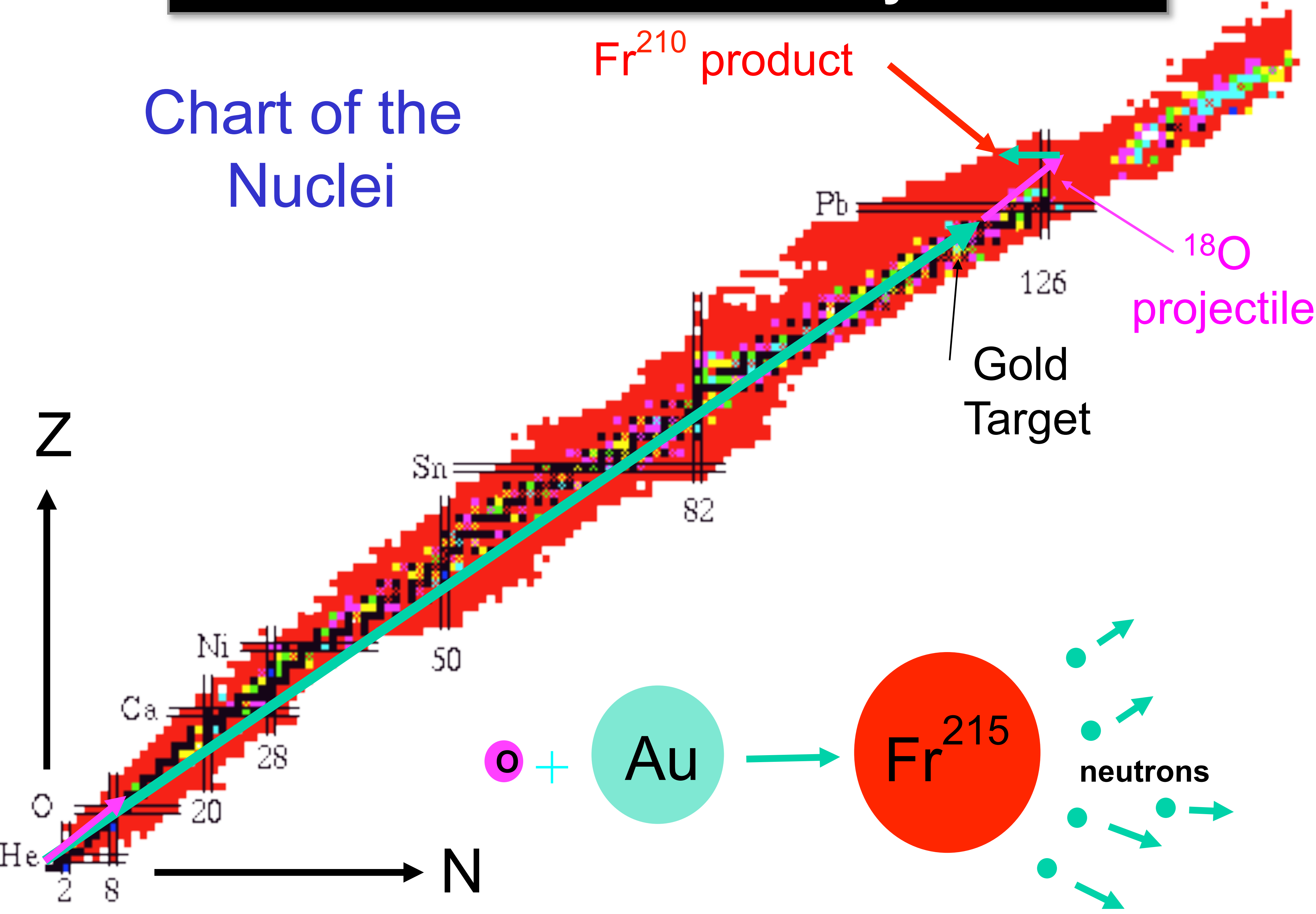
Actinium - Francium Alpha Particle

Margarite Perey, first row left, Radium Institute, Paris~1939



- $Z=87$; $A=206$-213 and neutron rich 221 (TRIUMF)
- Radioactive (^{212}Fr: $\tau_{1/2}=20$min; ^{209}Fr: $\tau_{1/2}=1$ min)
- Make it and trap it.
- Simple atomic structure, quantitatively understandable
- We want to use it as a laboratory to study the weak interaction through the signature of parity non-conservation.

How did we make Fr at Stony Brook ?

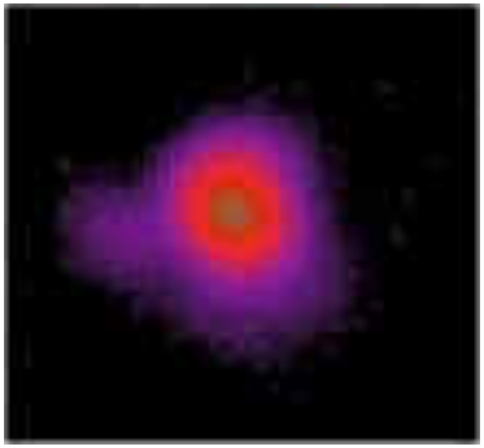


A Brief History of Francium at Stony Brook

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

1995: Produced and Trapped Francium in a MOT.

1996-2000: Laser spectroscopy of Francium.



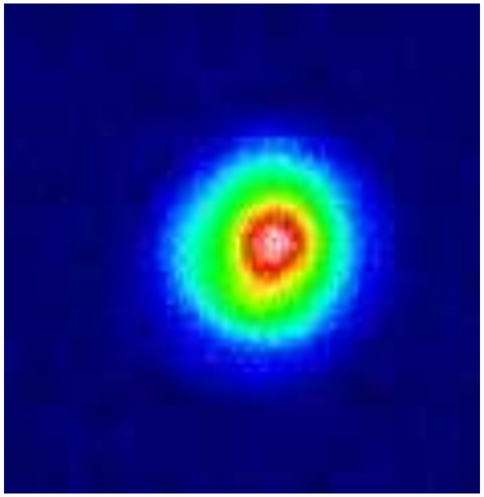
2,000 atoms
Fr MOT

2000-2002: High efficiency trap.

2003: Spectroscopy.

2004: Lifetime of 8S level.

2007: Magnetic moment ^{210}Fr .



250,000 atoms
Fr MOT

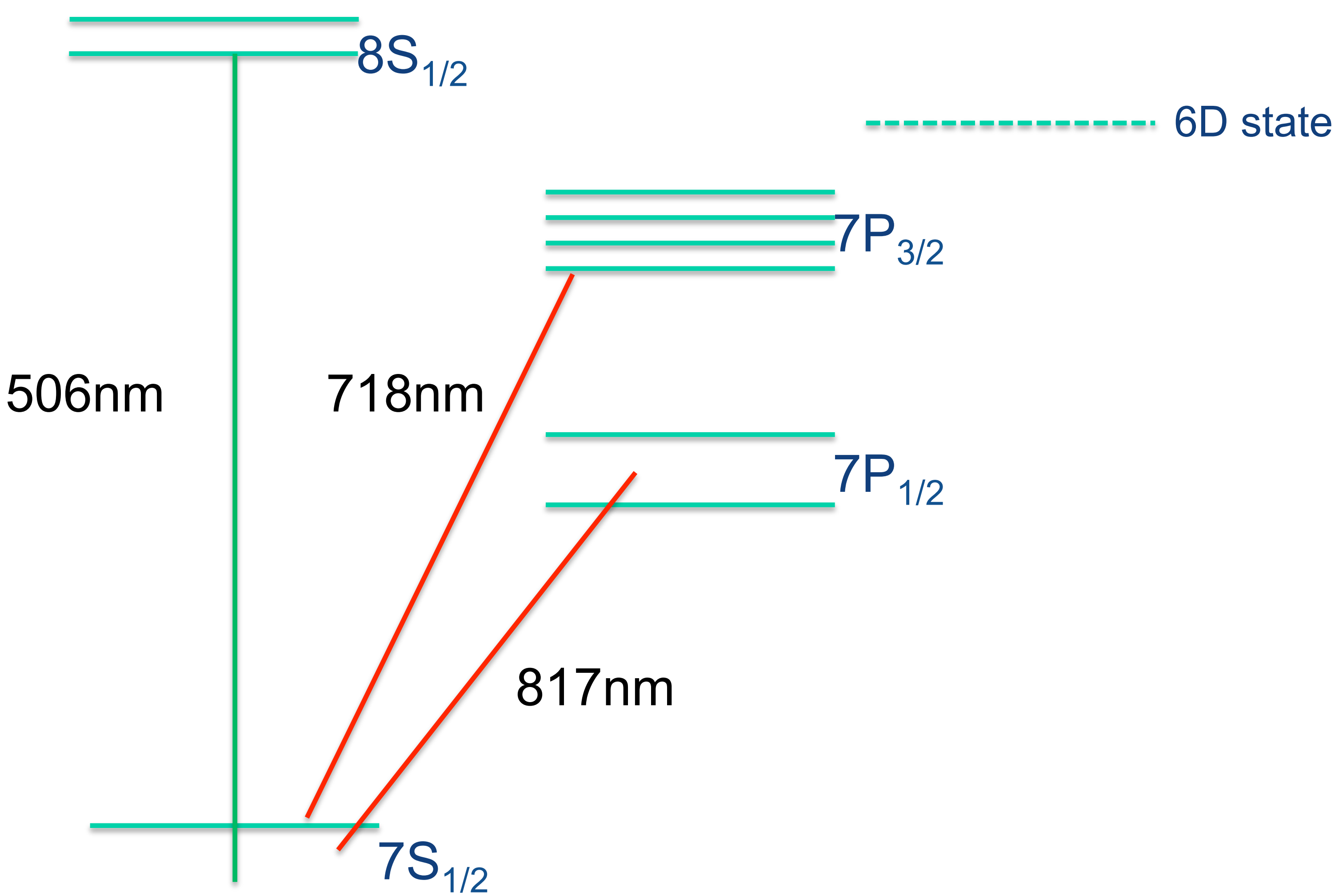
Spectroscopy studies of francium

Ideal cold sample of trapped atoms (no Doppler broadening)

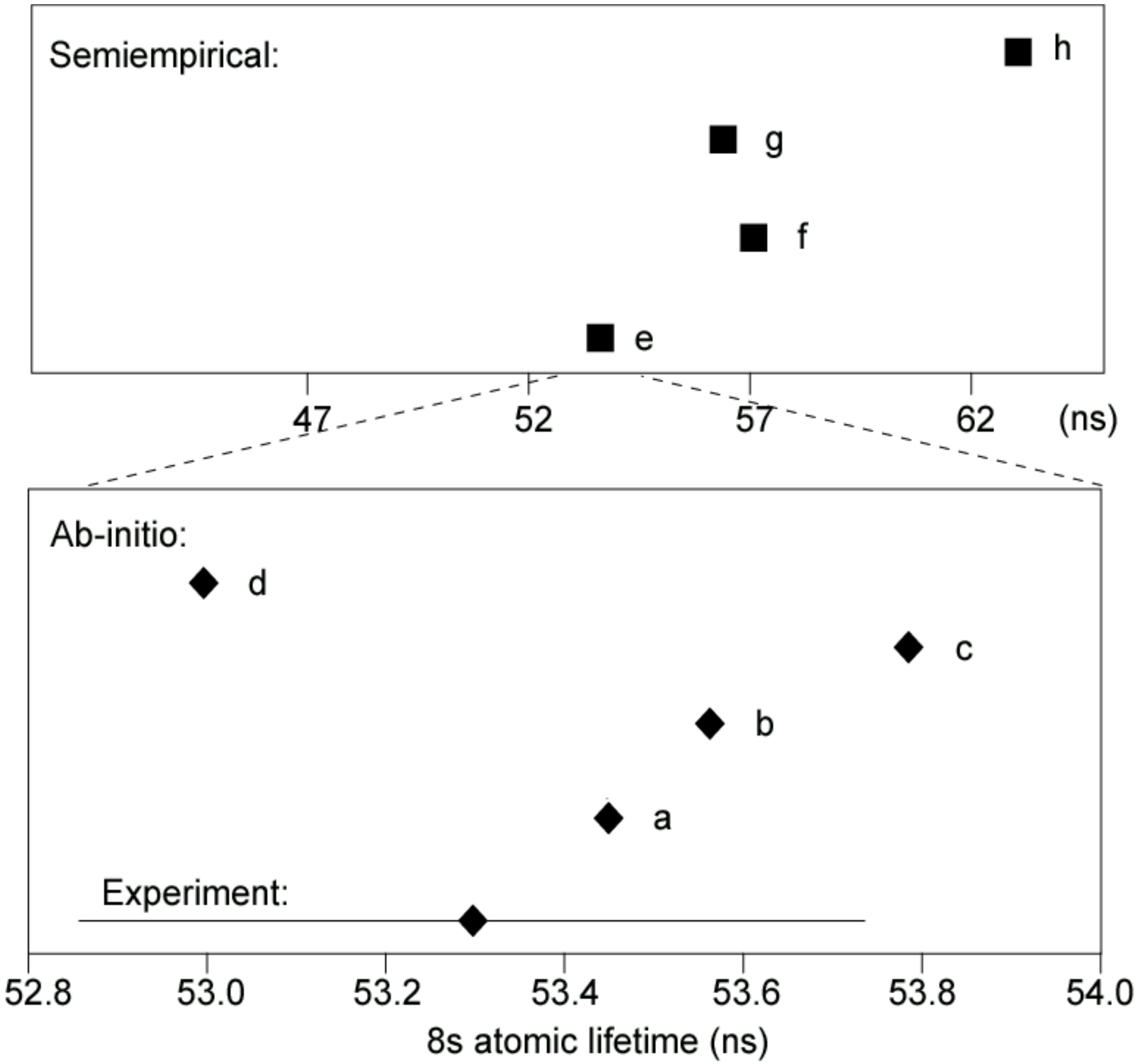
Energy levels
Excited state lifetimes (transition matrix elements)
Hyperfine splittings (wavefunctions at the nucleus)

Quantitative comparisons to *ab initio* calculations.
Nuclear structure studies (nuclear magnetization).

Francium Atomic Energy Levels



8s atomic lifetime measurement and theory



a) Safronova *et.al.*

b) Dzuba *et.al.*

c) Johnson *et.al.*

d) Dzuba *et.al.*

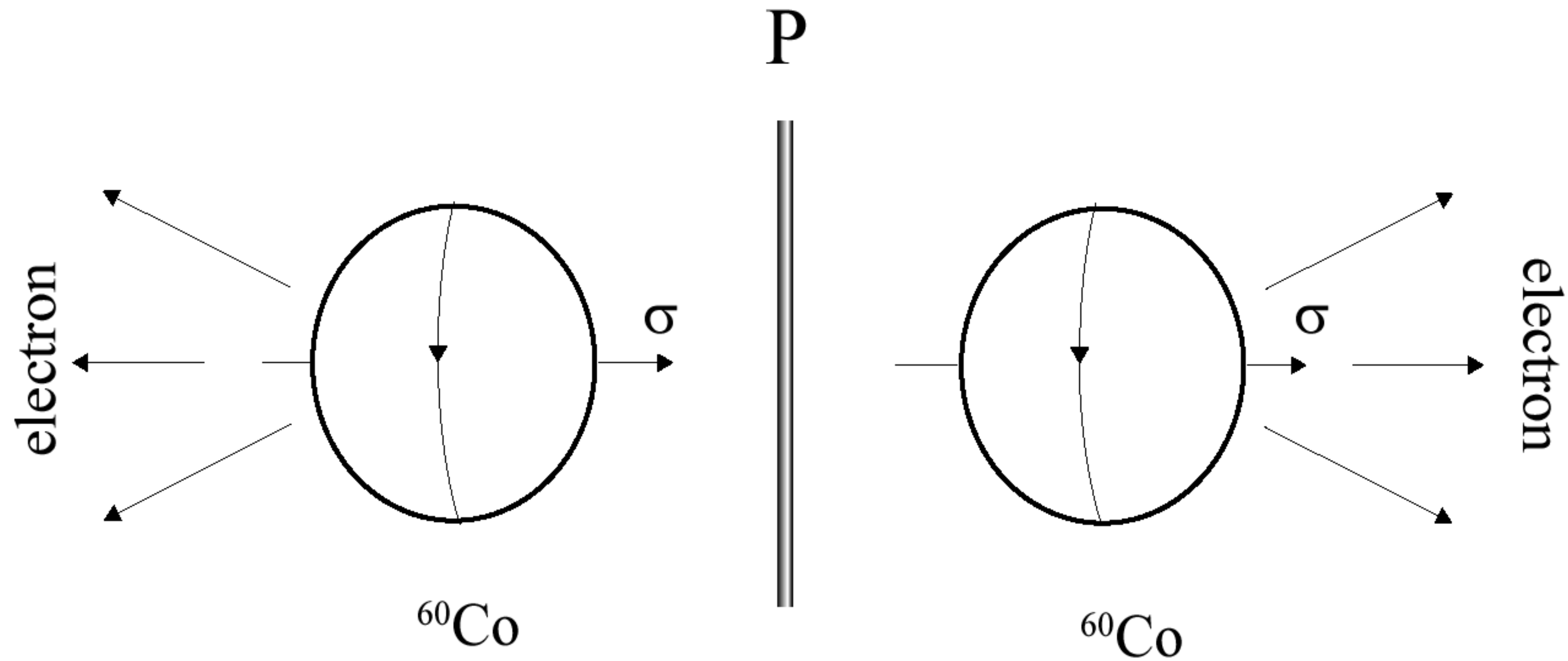
e) Marinescu *et.al.*

f) Theodosiou *et.al.*

g) Biemont *et.al.*

h) Van Wijngaarden *et.al.*

Nature (the weak interaction) lacks P symmetry.
1950 Purcell and Ramsey say it should be tested.
1956 T. D. Lee and C. N Yang point to the weak interaction.
1957 Three experiments show that the weak interaction violates P: Wu, Lederman and Telegdi lead the three efforts.
The Columbia-NBS experiment by Wu, Ambler, Hayward, Hoppes and Hudson studied β decay of cobalt (σ• p).



Weak interaction in atomic physics

Coulomb, spin-orbit, etc.

$$H_{atomic} = H_0 + H_{PV}$$

Parity violating. (1958 Zel'dovich)

The new Hamiltonian induces a perturbation on the eigenstates:

$$|\varphi_0\rangle \rightarrow |\Psi\rangle = |\varphi_0\rangle + \sum_n \frac{\langle \varphi_n | H_{PV} | \varphi_0 \rangle}{E_0 - E_n} |\varphi_n\rangle$$

The ground state of alkali: $|\Psi\rangle = |nS_{1/2}\rangle + \delta\, |nP_{1/2}\rangle + \ldots$

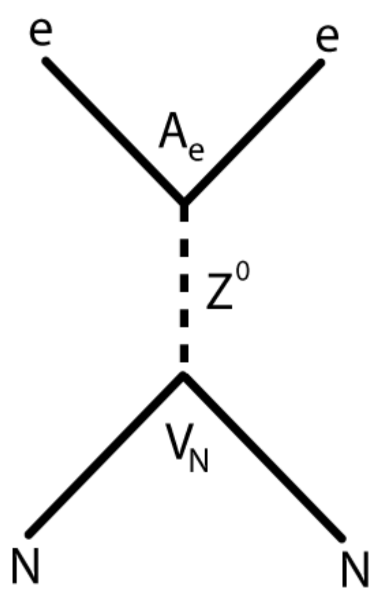
Forbidden transitions (*e.g.* E1 between same S states) become allowed

$$A \propto \langle \Psi | r | \Psi \rangle \neq 0$$

$$H_{PV} = \frac{G_F}{\sqrt{2}}(\kappa_{1i}\gamma_5 - \kappa_{nsd,i}\sigma_n \cdot \alpha)\delta(\mathbf{r})$$

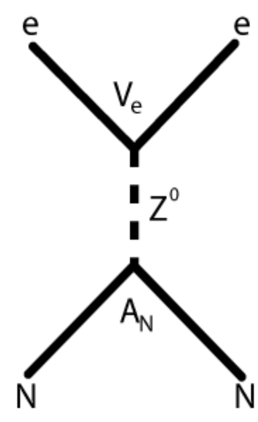
H_{PV}^{NSI}

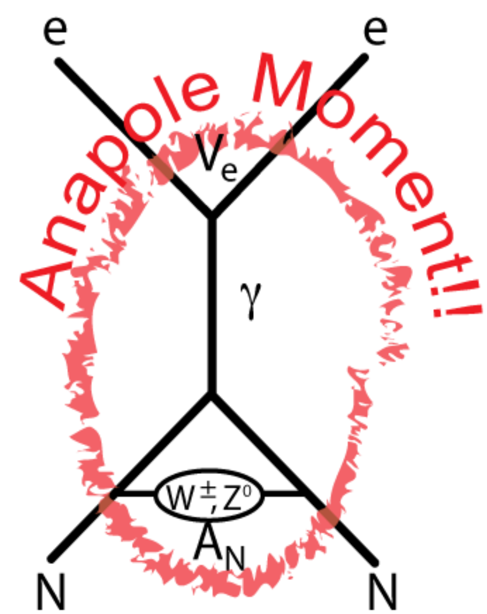
Nuclear spin independent Interaction:
- Coherent over all nucleons.
- Measurement increases as Z^3, from Q_{weak}, |S> and |P>

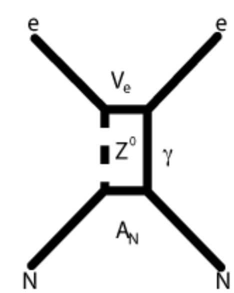


H_{PV}^{NSD}

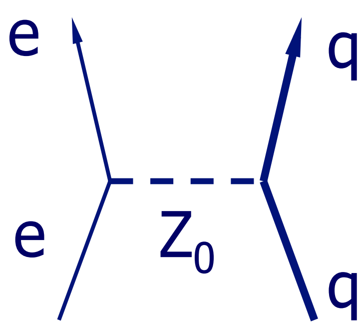
Nuclear spin dependent interaction:
- Only from valence nucleons.
- Measurement increases as $Z^{8/3}$
- Main contribution from anapole moment for heavy nuclei.







How to extract weak charge Q_w from Cs experiment?



Electron-quark parity violating interaction (exchange of virtual Z_0 boson)

$$H_W = \frac{G_F}{\sqrt{2}} \left(\bar{e}\gamma_\mu \gamma_5 e \right) \left\{ C_{1u} \bar{u}\gamma^\mu u + C_{1d} \bar{d}\gamma^\mu d \right\} + \ldots$$

Neutron density function

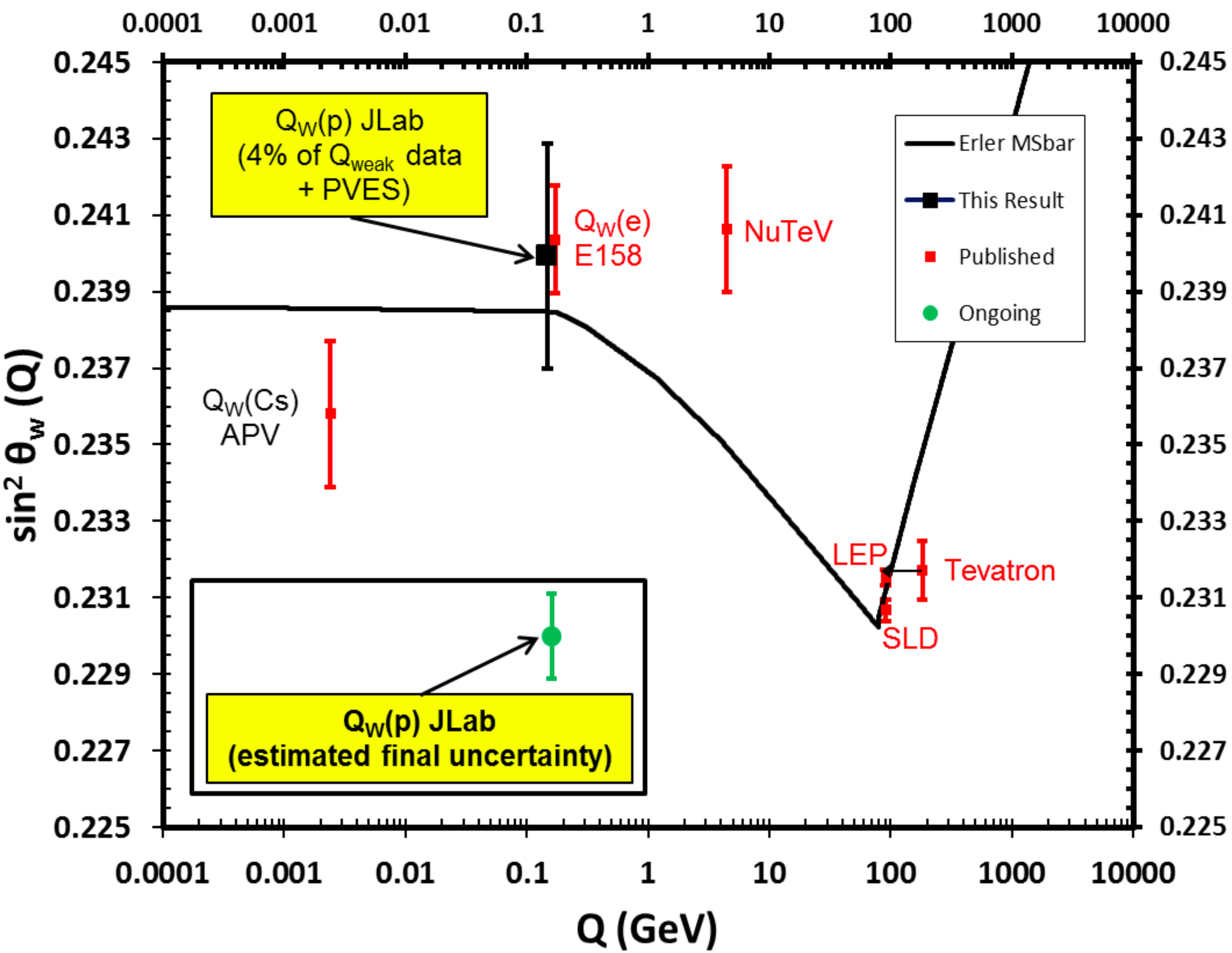
Electronic sector: $H^{(1)}_{PNC} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(r)$

Extraction of weak the charge:

Theoretical calculation of PNC amplitude

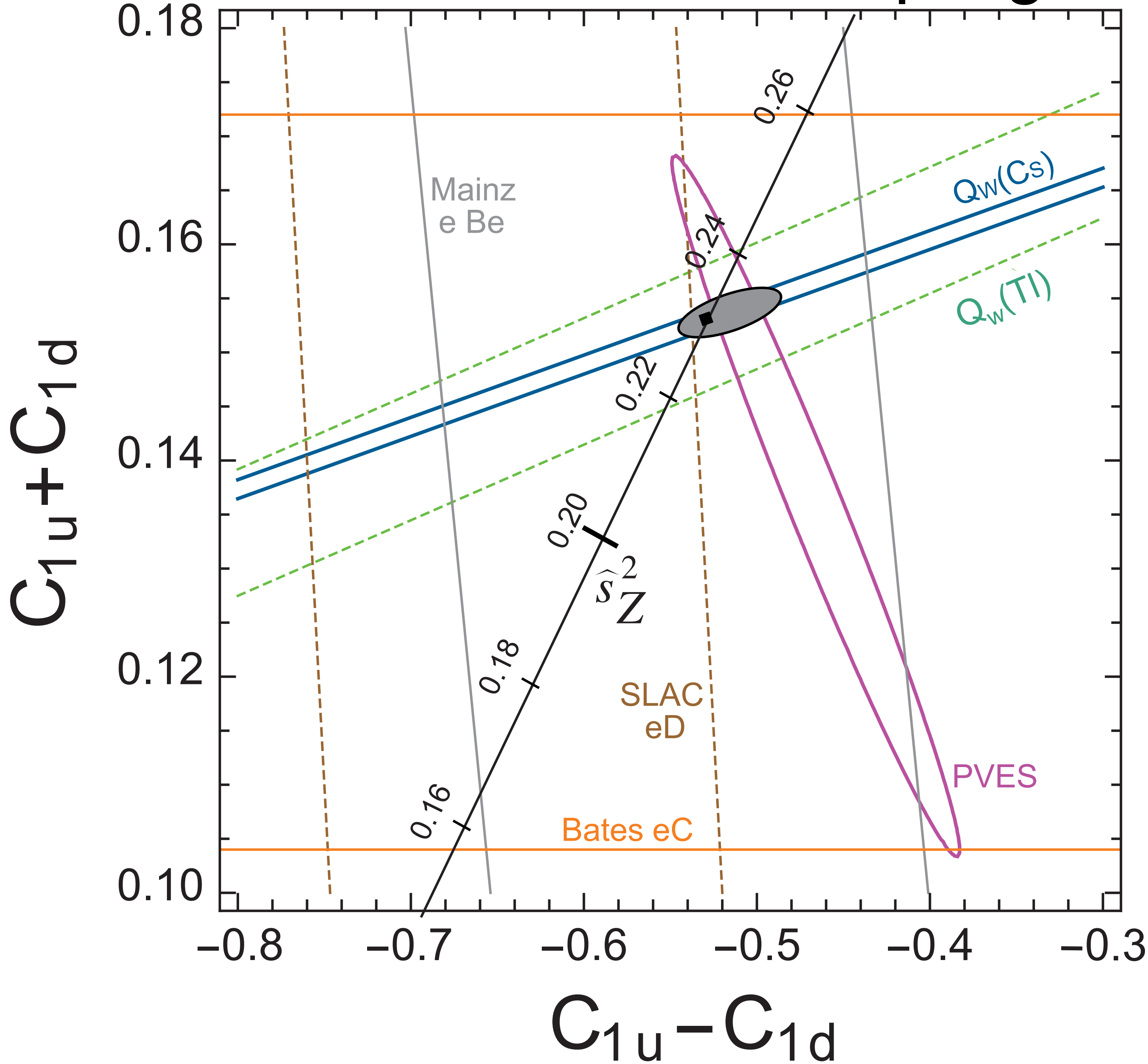
Measured value → $E_{PNC} = E^{theory}_{PNC} Q_W^{\text{inferred}}$

Safranova



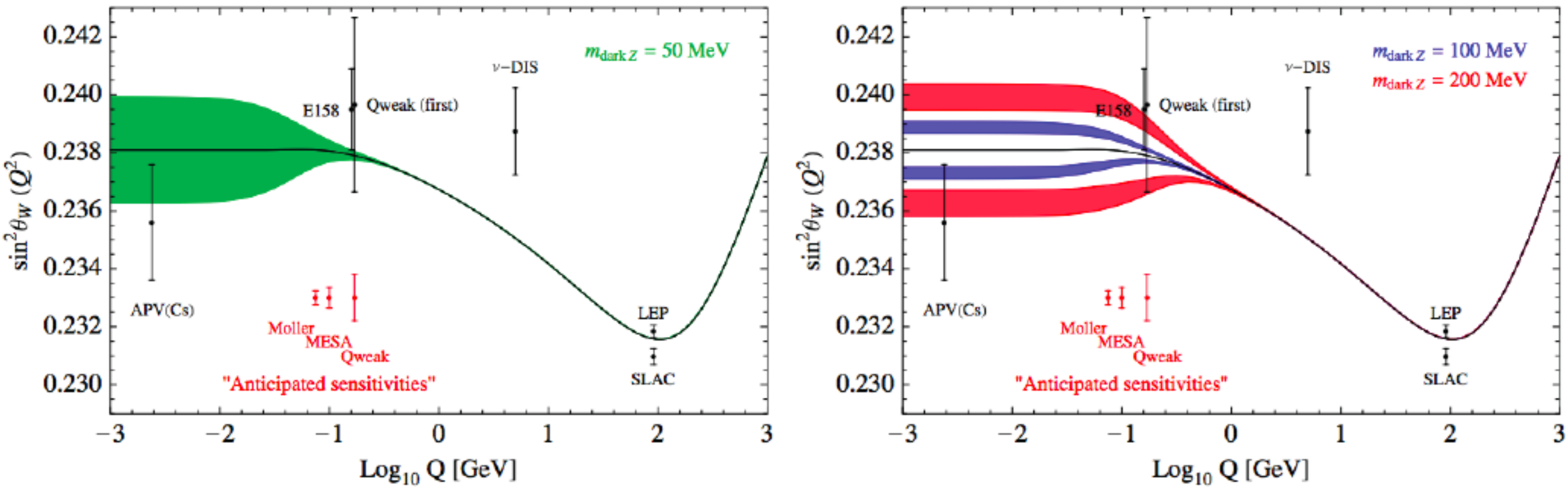
Q_W(p) JLab
(4% of Q_weak data
+ PVES)
Q_W(e)
E158
NuTeV
Q_W(Cs)
APV
LEP
Tevatron
SLD
Erler MSbar
This Result
Published
Ongoing
Q_W(p) JLab
(estimated final uncertainty)
sin² θ_w (Q)
Q (GeV)
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
0.245
0.243
0.241
0.239
0.237
0.235
0.233
0.231
0.229
0.227
0.225

Constraints on couplings



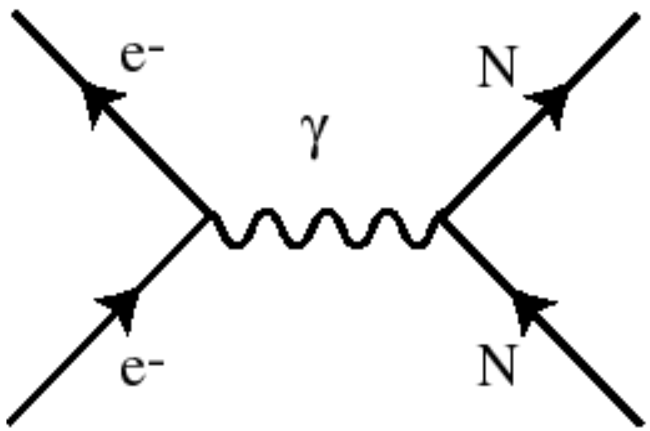
PDG 2013

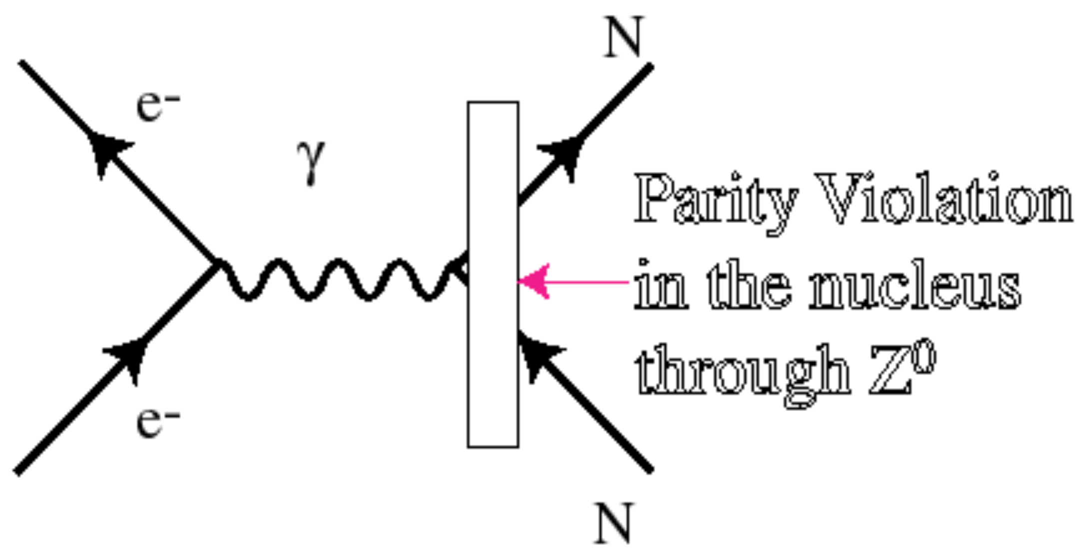
Parity violation from dark bosons (Davoudiasl PRD 89, 095006 (2014)



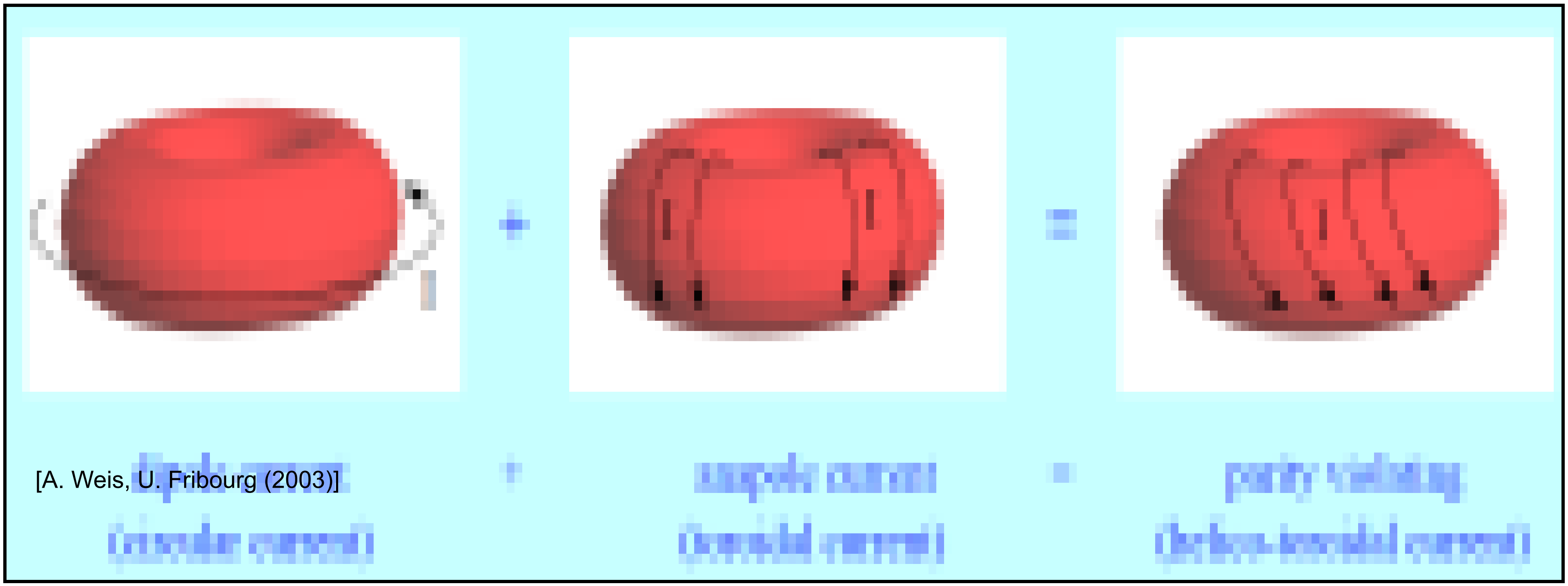
The Anapole Moment History

1958 Zel'dovich, Vaks
1980 Khriplovich, Flambaum
1984 Khriplovich, Flambaum, Shuskov
1995 Fortson (Seattle) bound from an experiment Thallium
1997 Wieman (Boulder) 15% measurement from an experiment in one isotope of Cesium





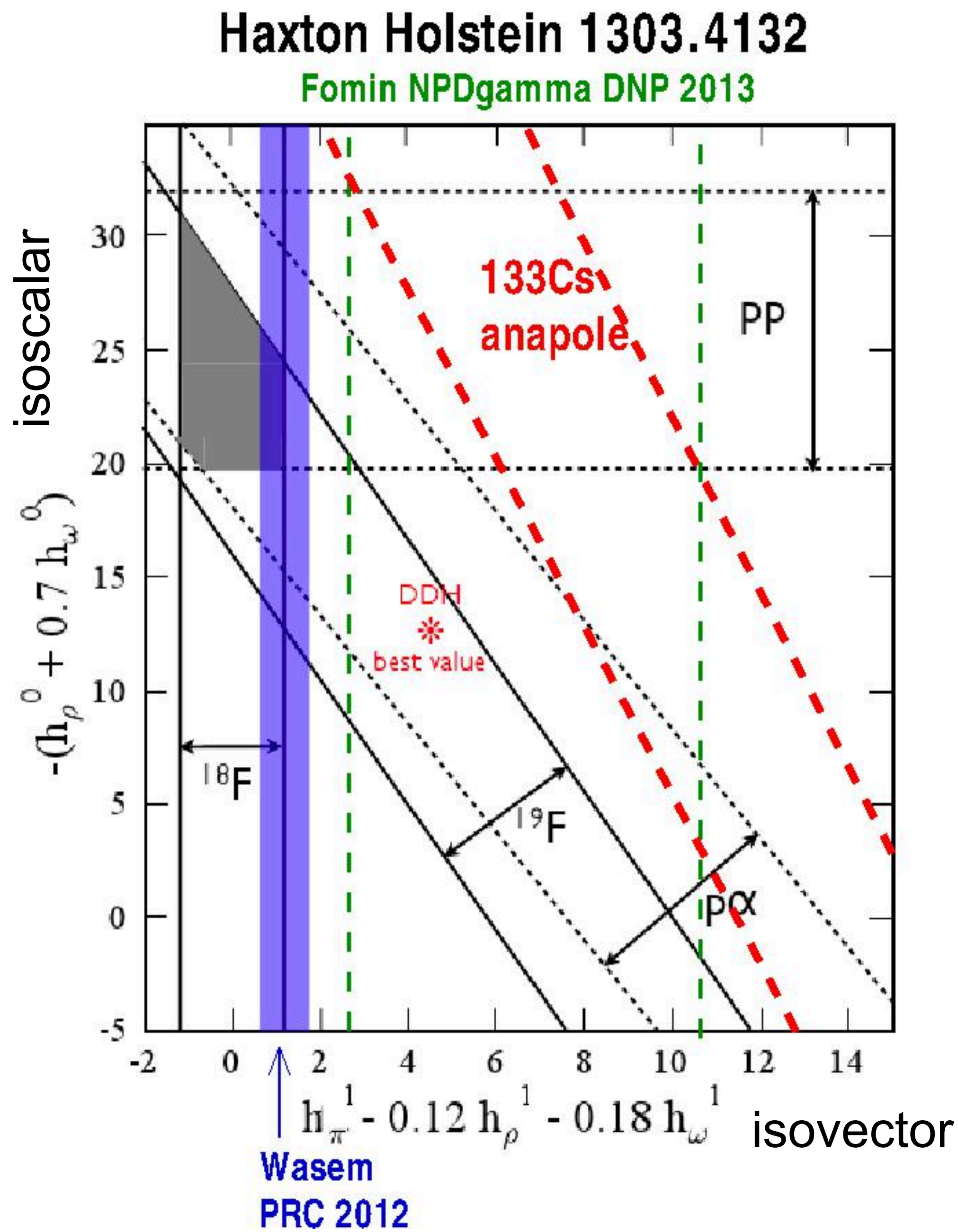
The anapole moment is:
Electromagnetic moment produced by a toroidal current. Time-reversal conserving.
Localized moment, contact interaction.


[A. Weis, U. Fribourg (2003)]

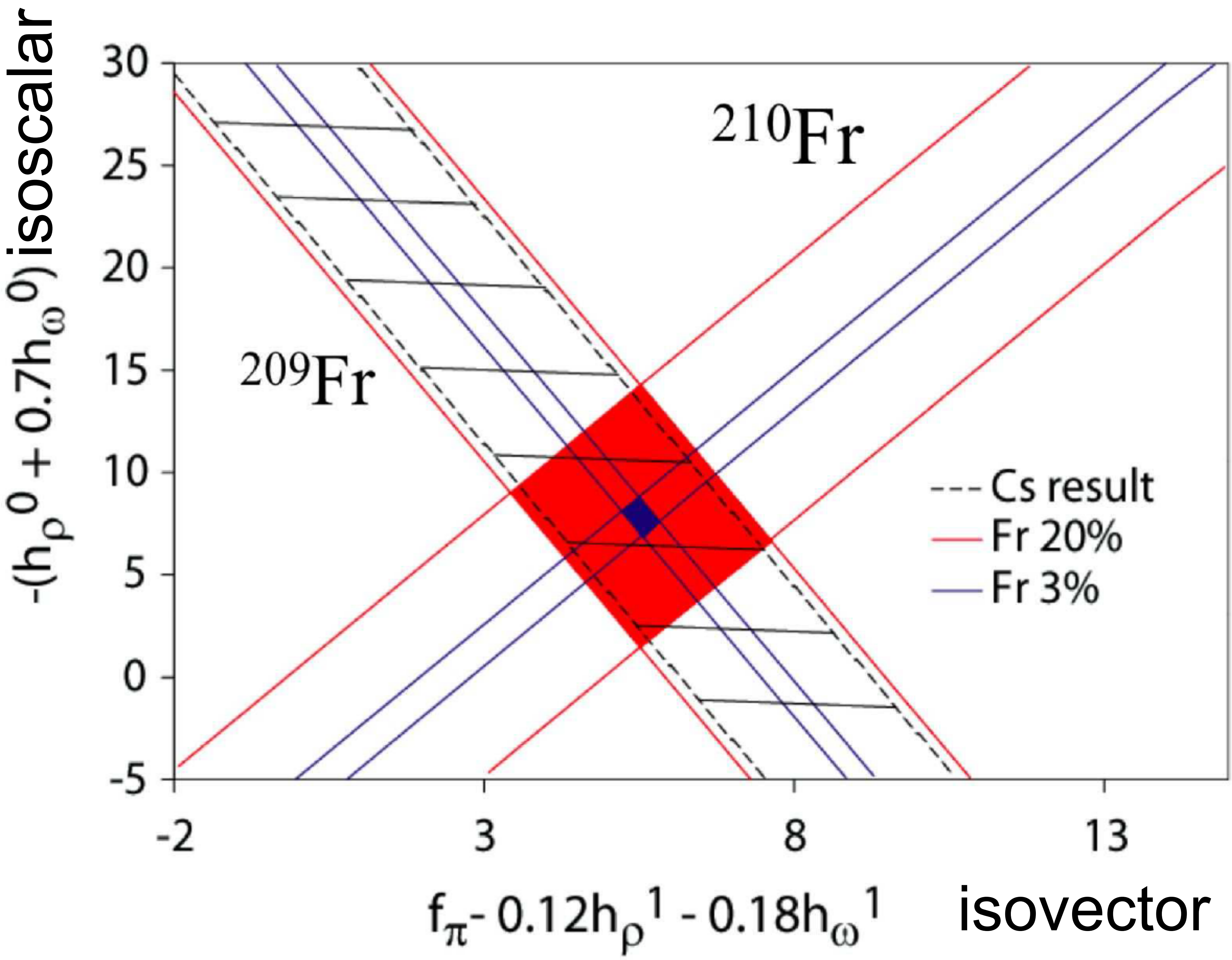
Anapole moment

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

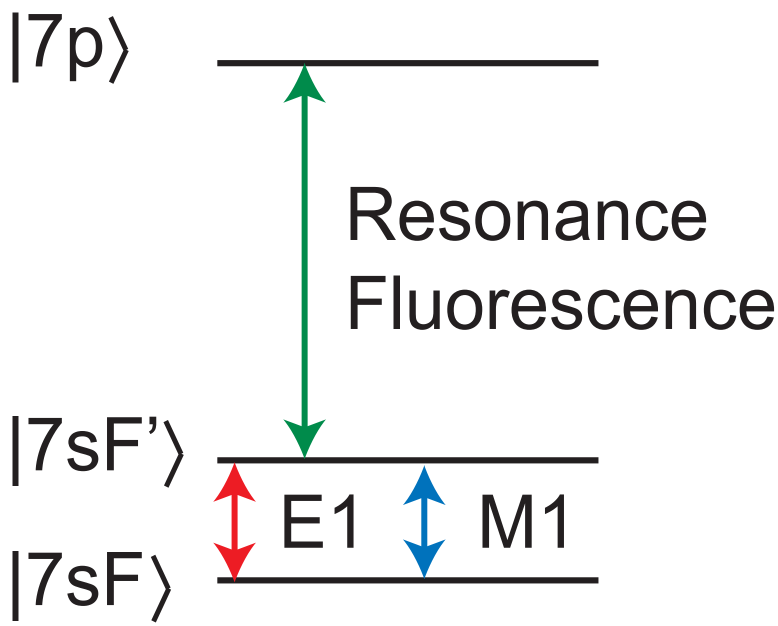
Does weak N-N interaction change in heavy nuclei?



The dream in francium



Method



Expected signal with 450 V/m

$$A_{E1}/\hbar = 0.01\, rad/s$$

1.- Define handedness of the apparatus by the coordinate system

$$(iE_{RF} \times B_{M1} \cdot B_{DC})$$

2.- Create superposition to interfere and enhance PNC signal:

$$A_{total} = A_{M1}^{PC} \pm A_{E1}^{PNC}$$

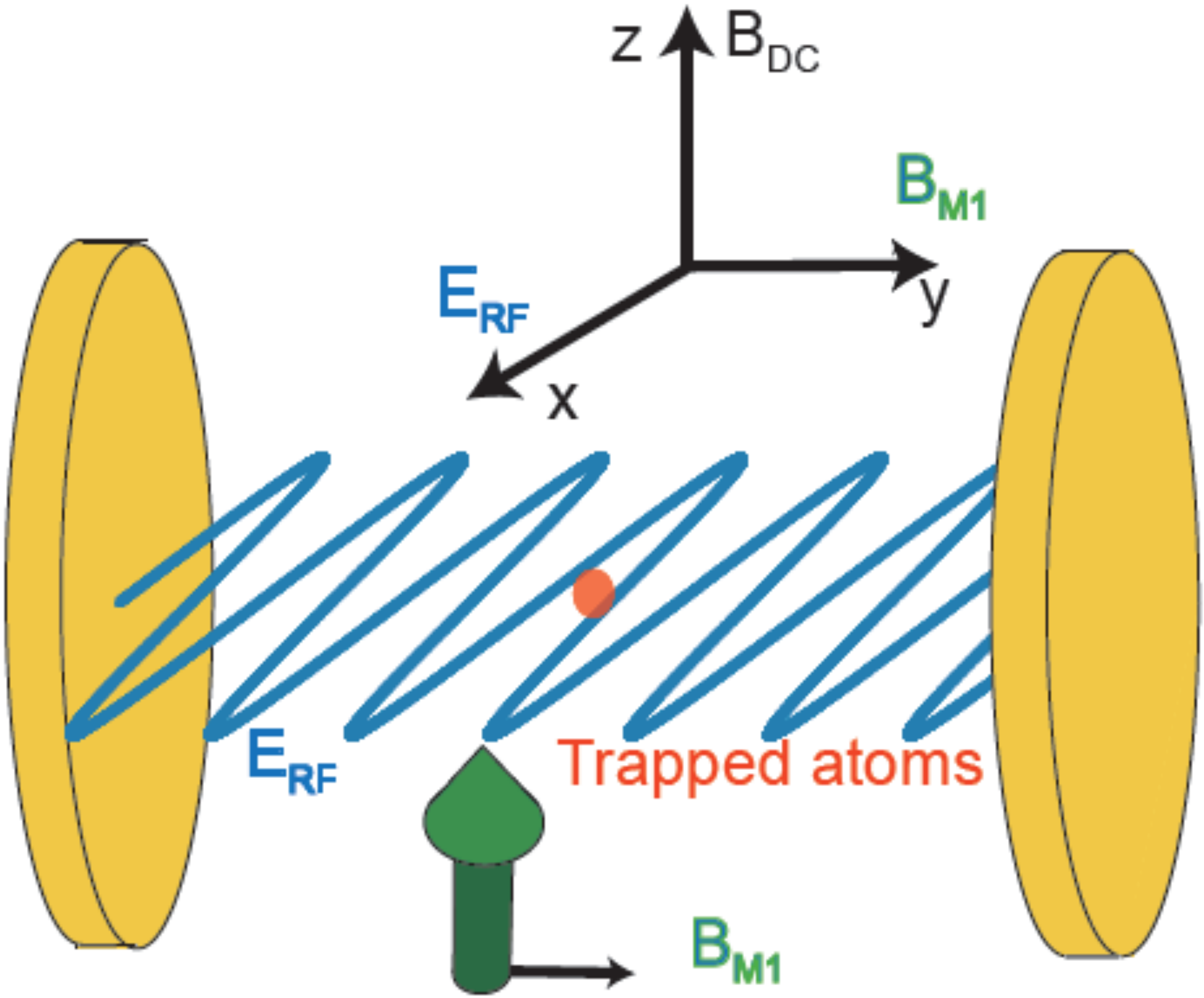
3.- Measure rate of transition through resonance fluorescence.

$$Rate \propto \left|A_{total}\right|^2$$

4.- Change handedness of apparatus

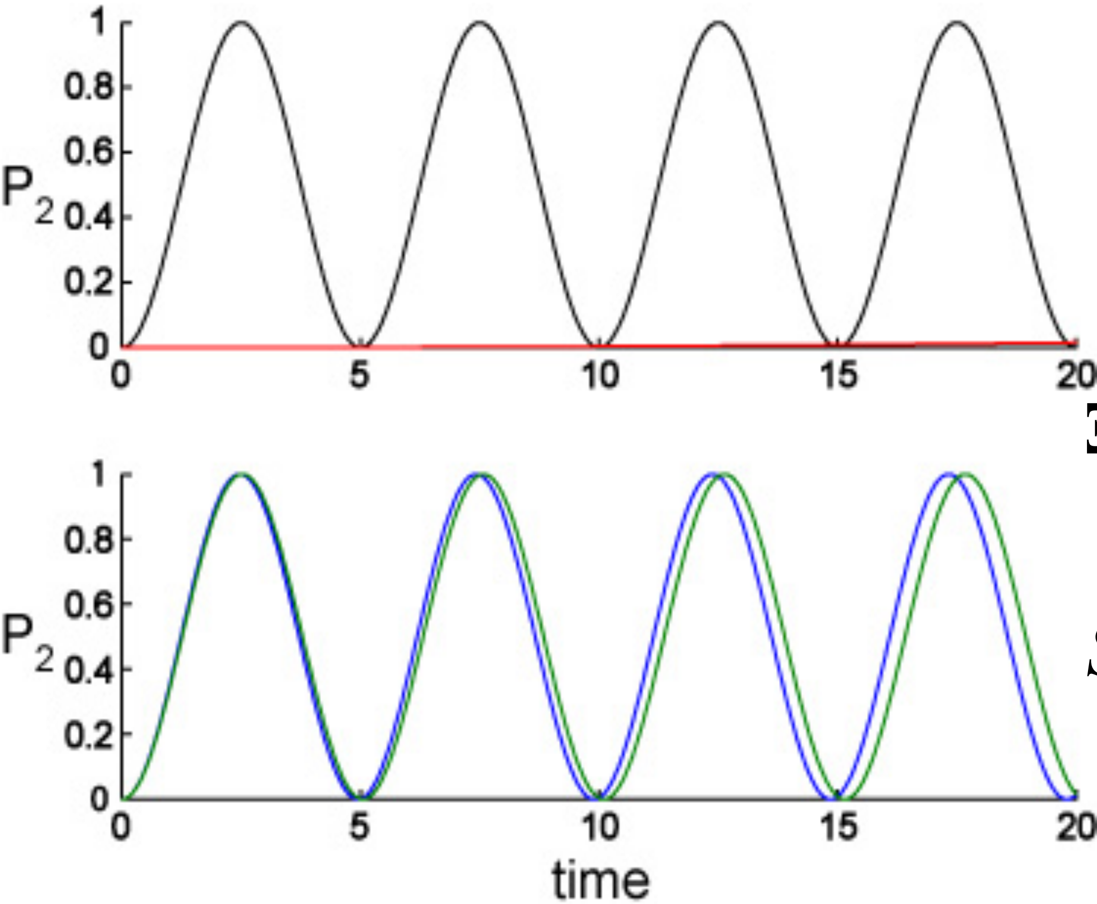
$$Signal \propto \left|A_{total}^{+}\right|^2 - \left|A_{total}^{-}\right|^2$$

5.- Repeat.



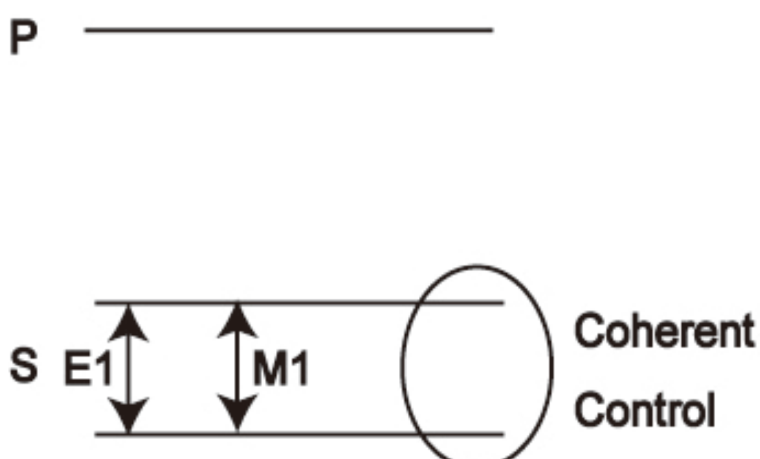
z
B_DC
B_M1
E_RF
y
x
E_RF
Trapped atoms
B_M1

Principle of the measurement



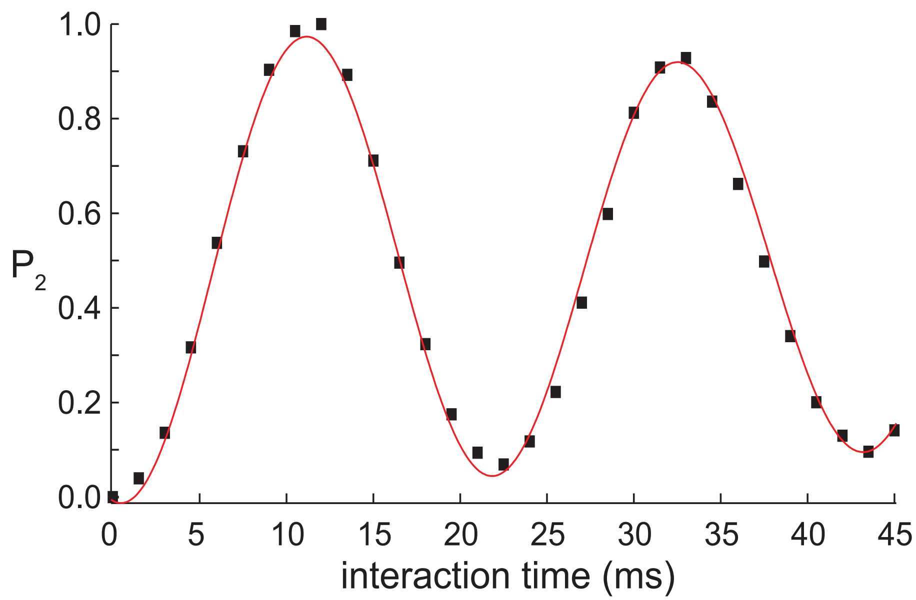
$$\Xi_{\pm} = N \sin^2\left(\frac{(A_{M1} \pm A_{E1})t_c}{2\hbar}\right)$$

$$S = \Xi_{+} - \Xi_{-} \cong N \sin\left(\frac{A_{M1}t_c}{2\hbar}\right)\left(\frac{A_{E1}t_c}{2\hbar}\right)$$

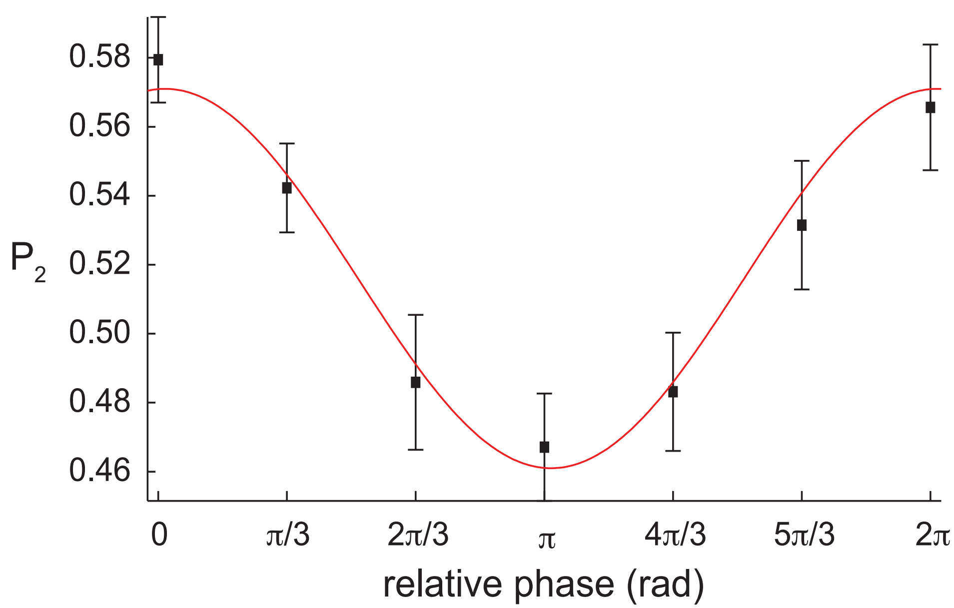


Control phase of different interactions
Ground state hyperfine splitting
Fr ~46 GHz, Z=87
Rb ~6.834 GHz, Z=37

Oscillations and sensitivity test



M1 Rabi oscillations (50 Hz) with 10^5 Rb atoms in blue detuned (20 nm) dipole trap.



At 37.5 ms, add a second microwave source with 10^4 attenuation, change of the phase.

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

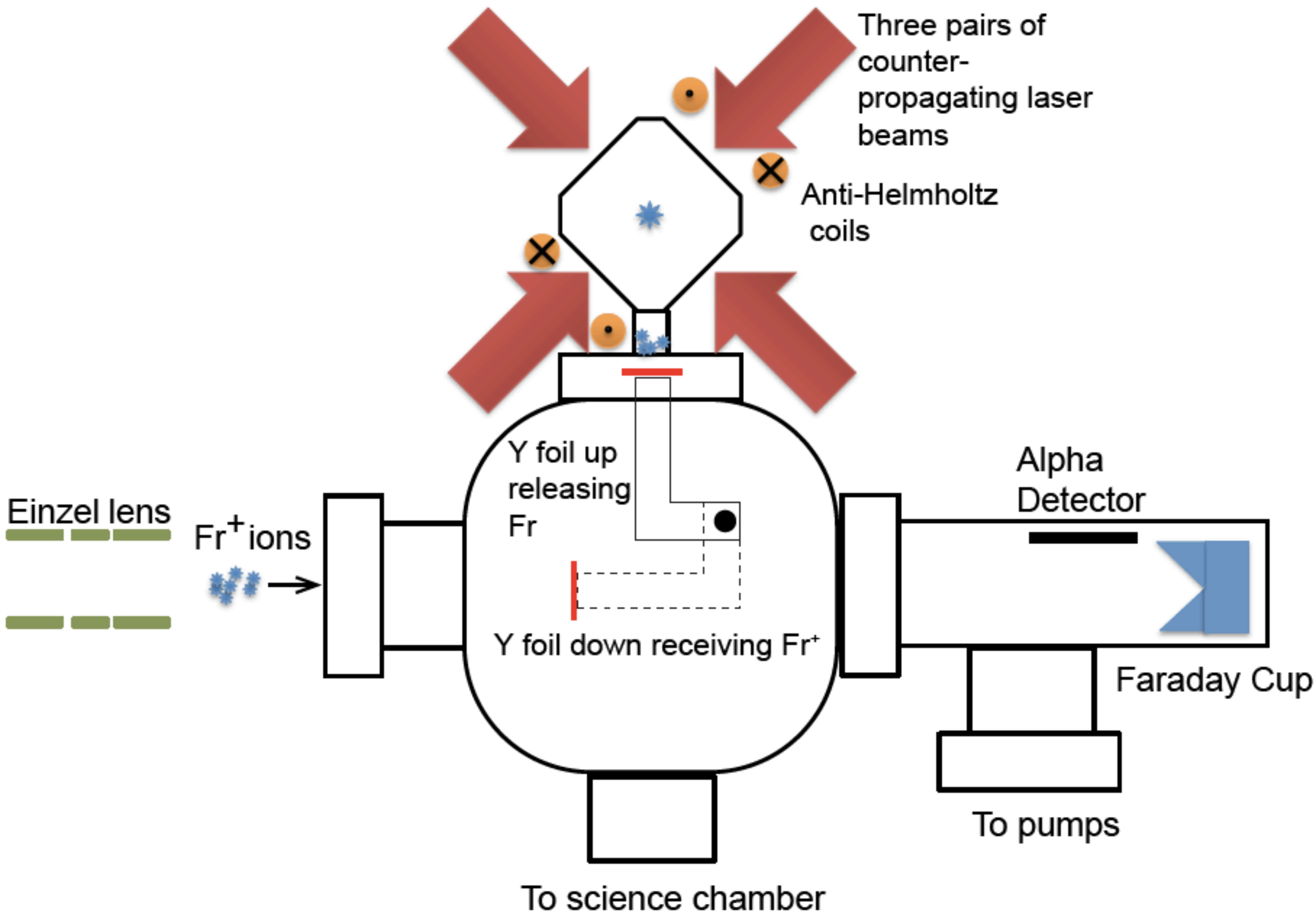
Number of atoms = $N \sim 10^6$

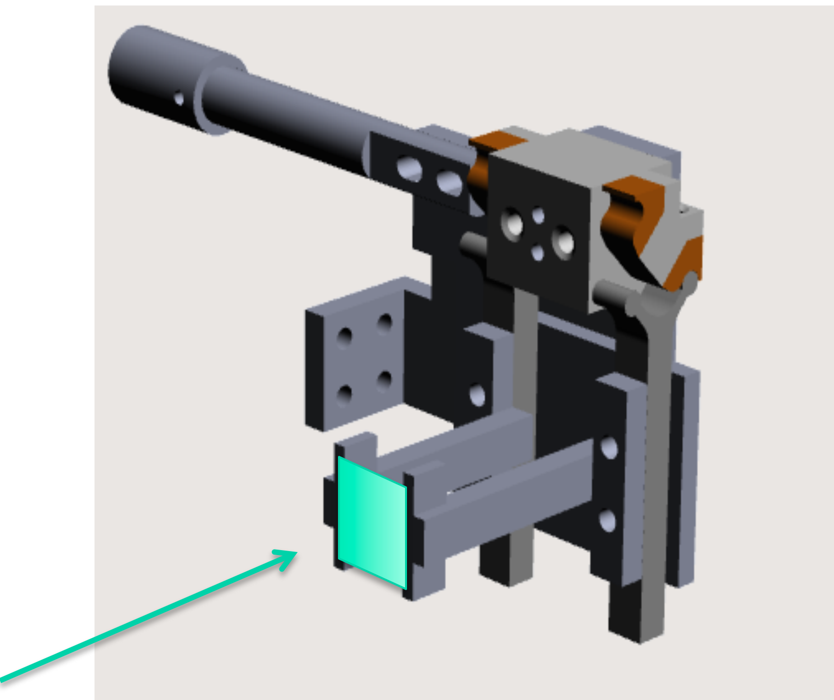
Ω_{E1} ~ 10 mrad

Interaction time = Δt ~ 0.1s

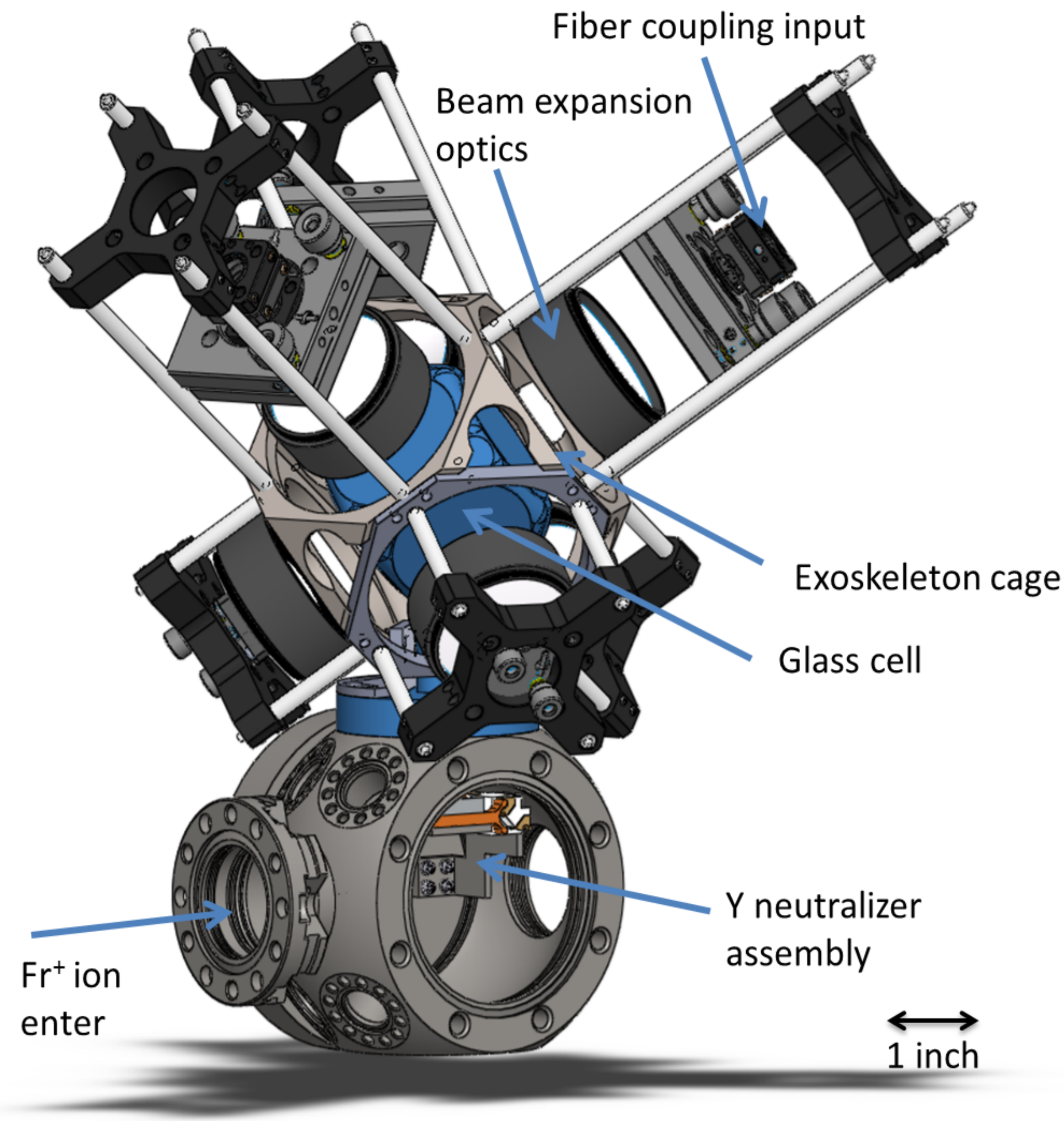
ISAC I hall at TRIUMF, Francium Trapping Facility

High efficiency capture MOT



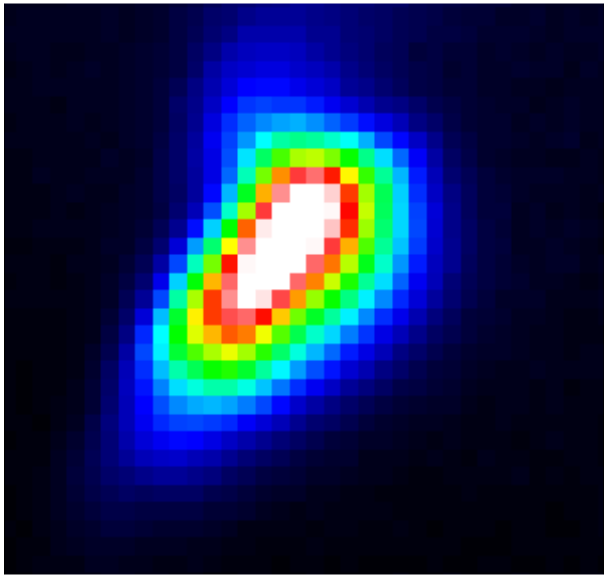


Fr beam onto Y of Zr foil



Commissioning of Apparatus:

- Trapped atoms: ~ 2.5×10^5 to 2.5×10^6
- Efficiency ~ 1% now higher.
- Trap lifetimes ~ 20s



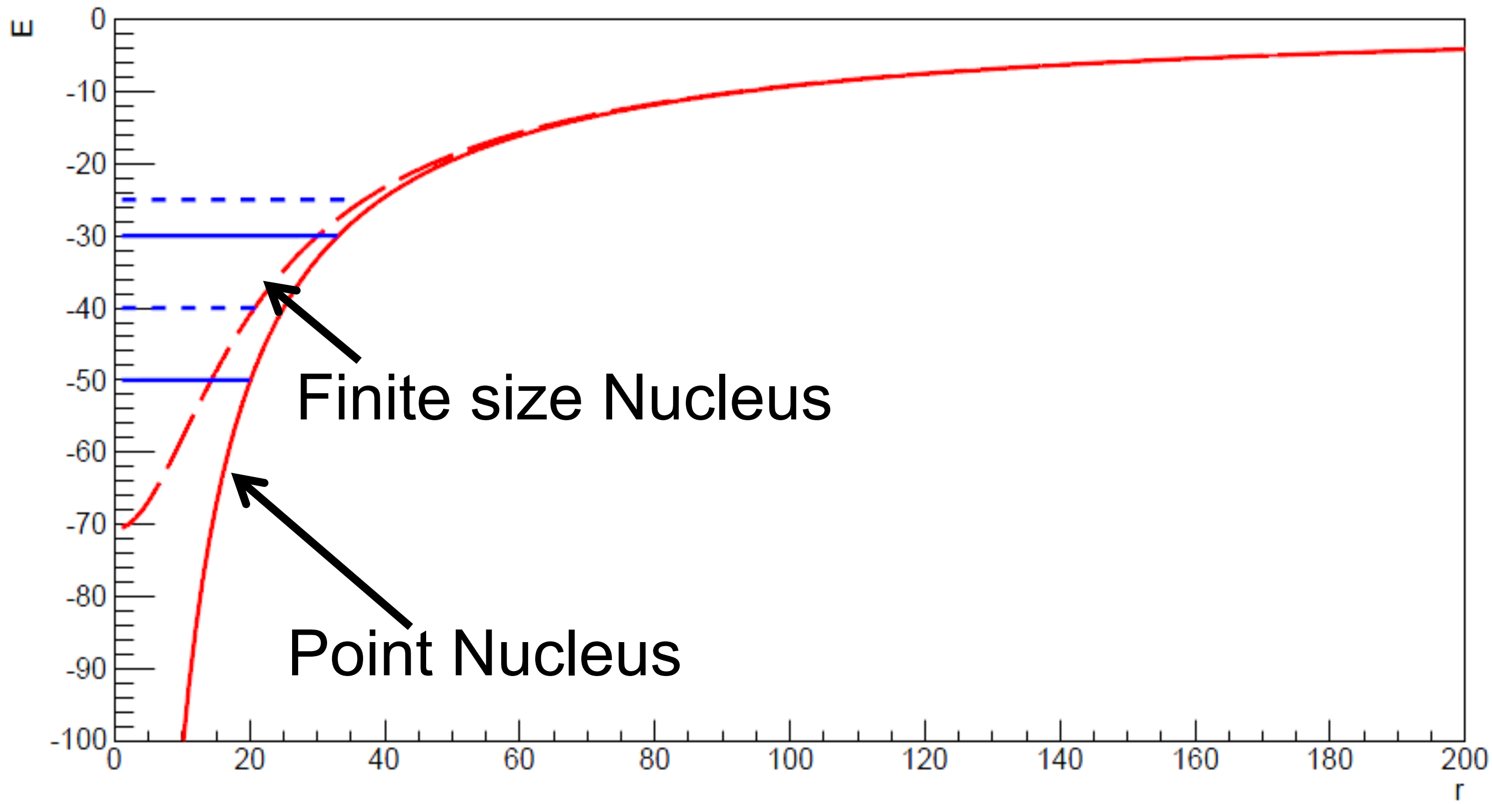
Isotope Shift

Mass Shift

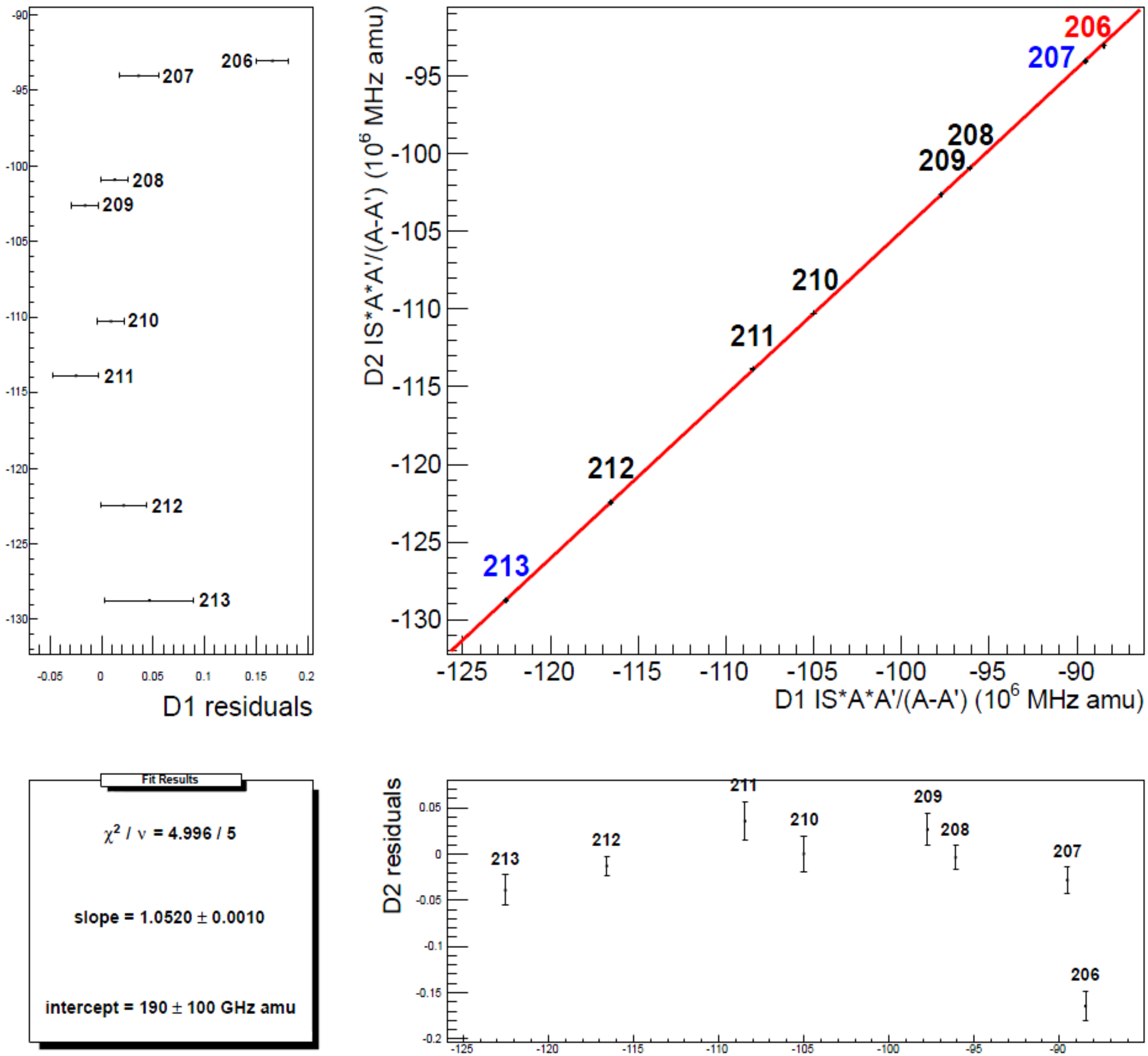
Field Shift

Reduced mass (easy)

Electronic correlations (difficult)



King plot



D1 residuals
D2 IS*A*A'/(A-A') (10^6 MHz amu)
D1 IS*A*A'/(A-A') (10^6 MHz amu)
D2 residuals
206
207
208
209
210
211
212
213
Fit Results
χ² / ν = 4.996 / 5
slope = 1.0520 ± 0.0010
intercept = 190 ± 100 GHz amu

Results

$$\frac{F_{D2}}{F_{D1}} = 1.052\ (1)$$

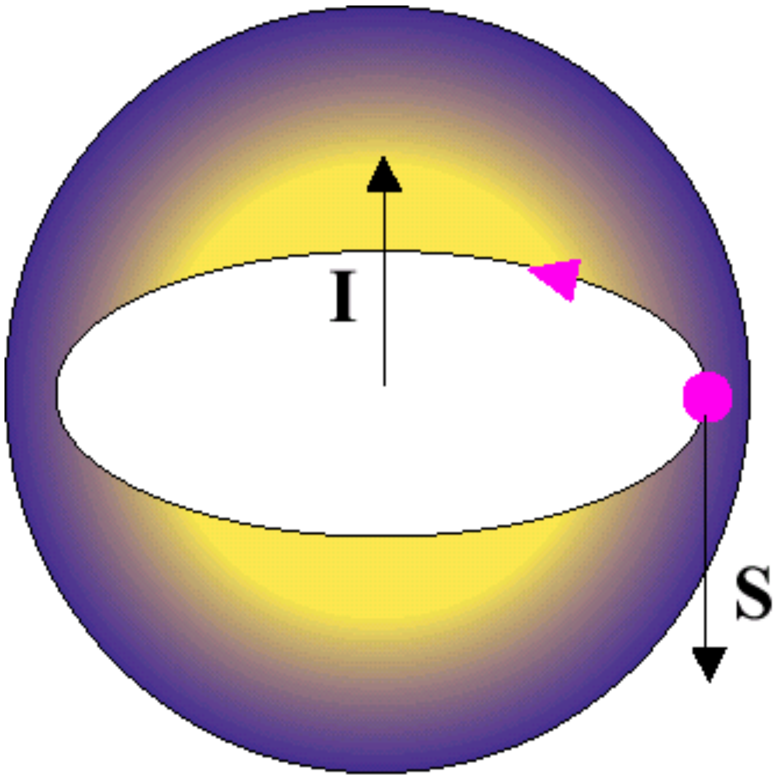
$$S_{D2} - S_{D1}\frac{F_{D2}}{F_{D1}} = 190\ (100)\ \text{GHz amu}$$

Method	$7S_{1/2}$	$7P_{1/2}$	$7P_{3/2}$	F_{D2}/F_{D1}
BO(Σ^{∞})	-20463	-693	303	1.0504
SD + E3	-20188	-640	361	1.0512
M-P	-20782	-696	245	1.0468

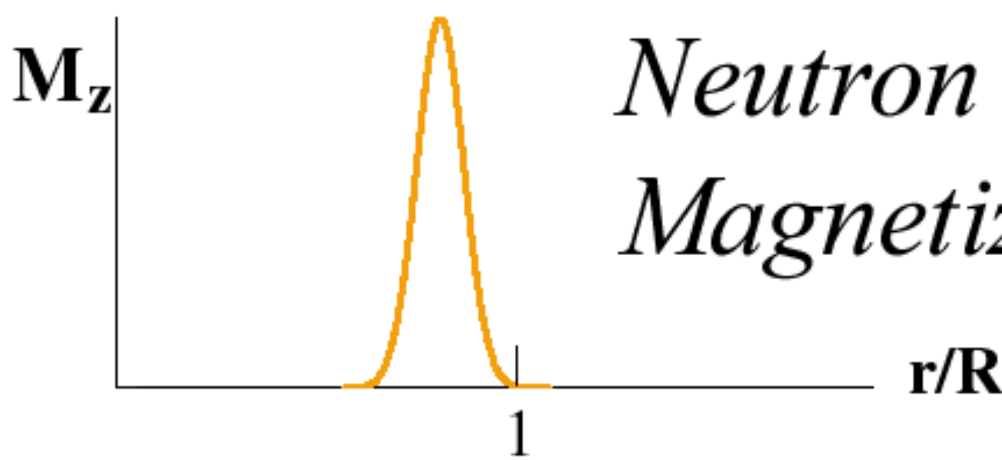
Dzuba, Johnson and Safronova, *Phys. Rev. A* **72**, 022503 (2005)

Mårtensson-Pendrill, *Mol. Phys.* **98**, 1201 (2000)

Nuclear Magnetization



Unpaired Neutron $2f_{5/2}$



Neutron Magnetization

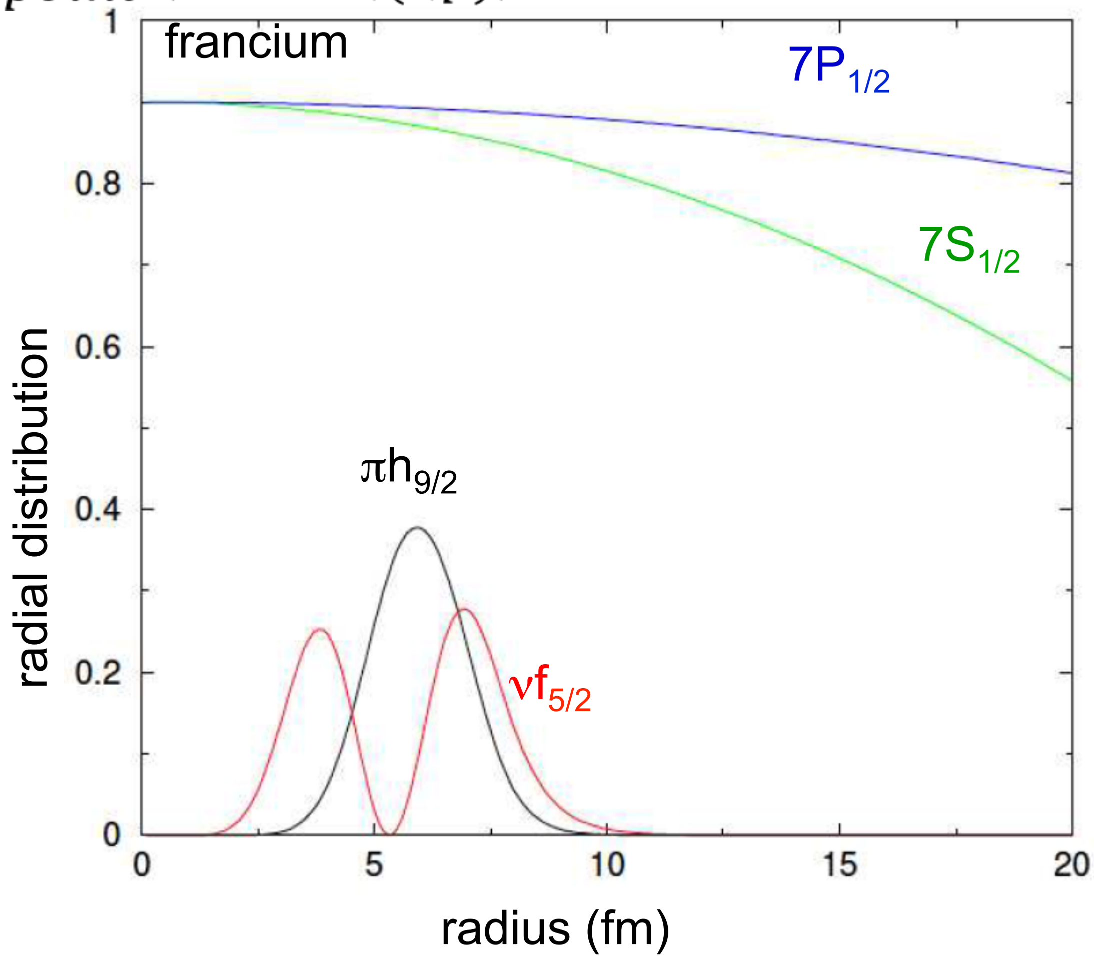
Hyperfine Interaction: Interaction of electron with the magnetic moment of nucleus.

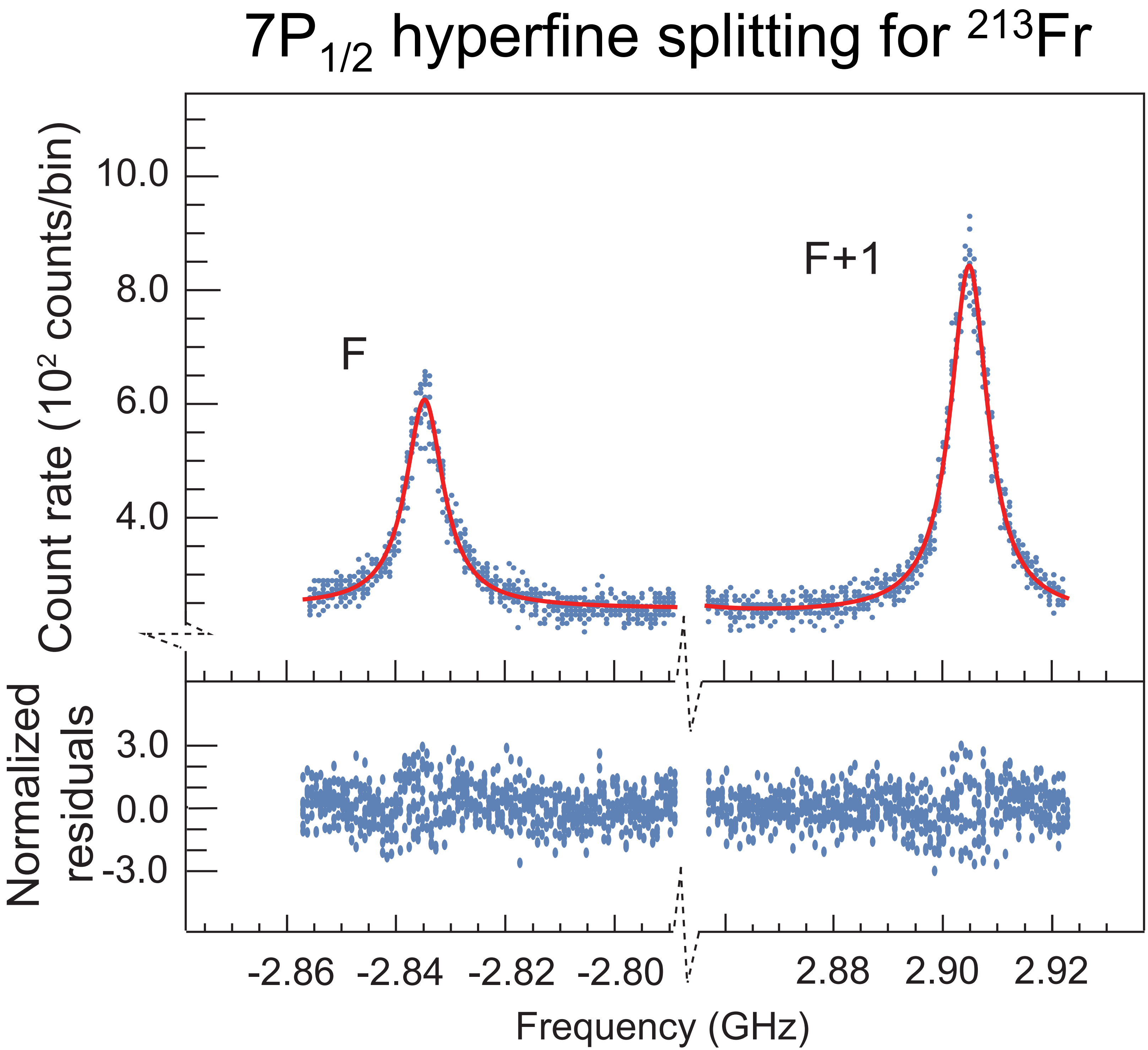
Hyperfine Anomaly: ε quantifies the effect of the finite size of the nucleus.

$A_{S,P}$ [ρ]= hyperfine coefficient
∝ hyperfine splitting

$$W_{hyper} = h\, A_{S,P}[\rho]\, \vec{I} \cdot \vec{J}$$
$$= W_{point}^{S,P}\left(1 + \epsilon_{N,(s,p)}\right)$$

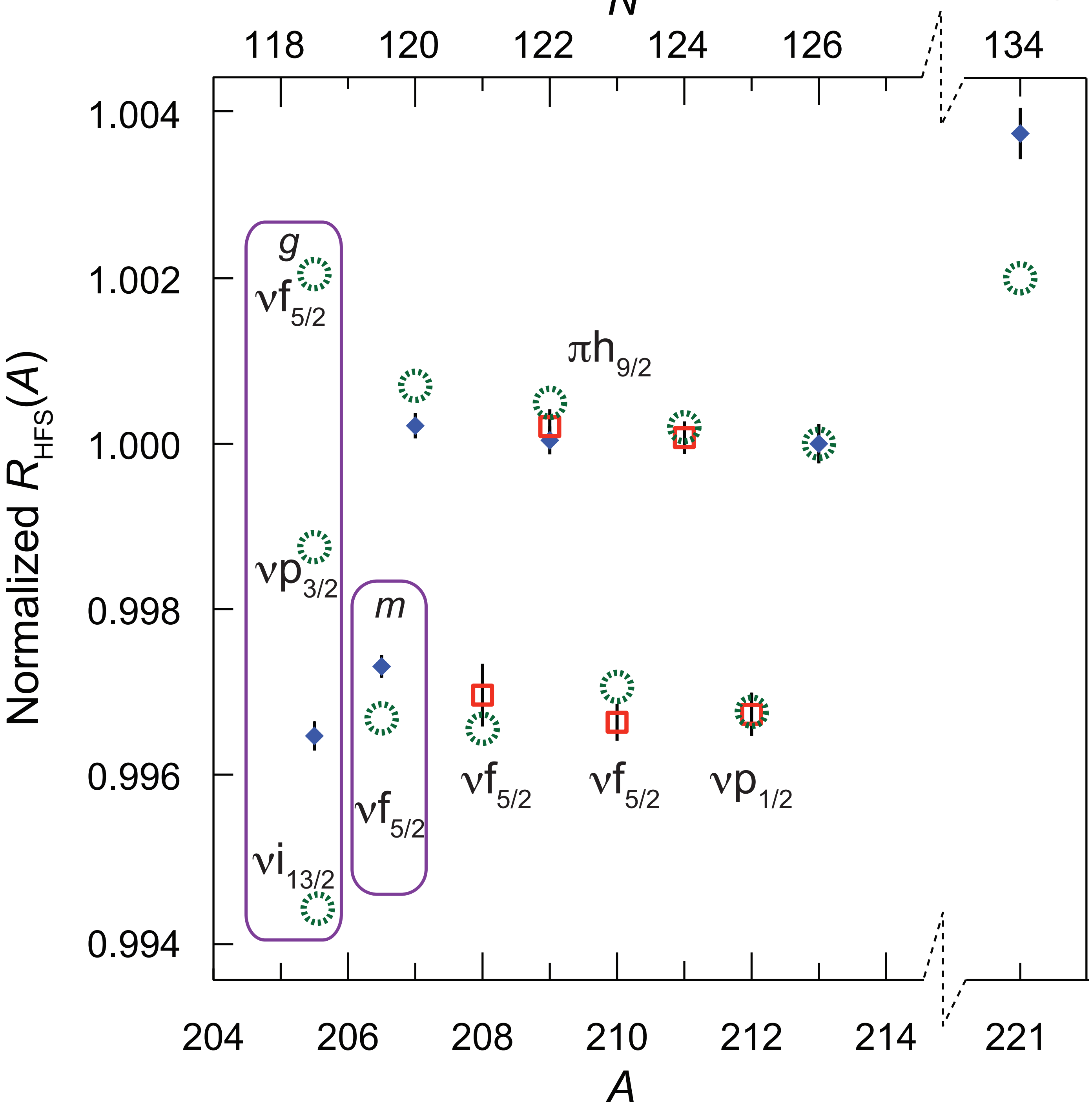
ρ=nuclear magnetization distribution





7P1/2 hyperfine splitting for 213Fr
Count rate (10² counts/bin)
10.0
8.0
6.0
4.0
F
F+1
Normalized residuals
3.0
0.0
-3.0
-2.86
-2.84
-2.82
-2.80
2.88
2.90
2.92
Frequency (GHz)

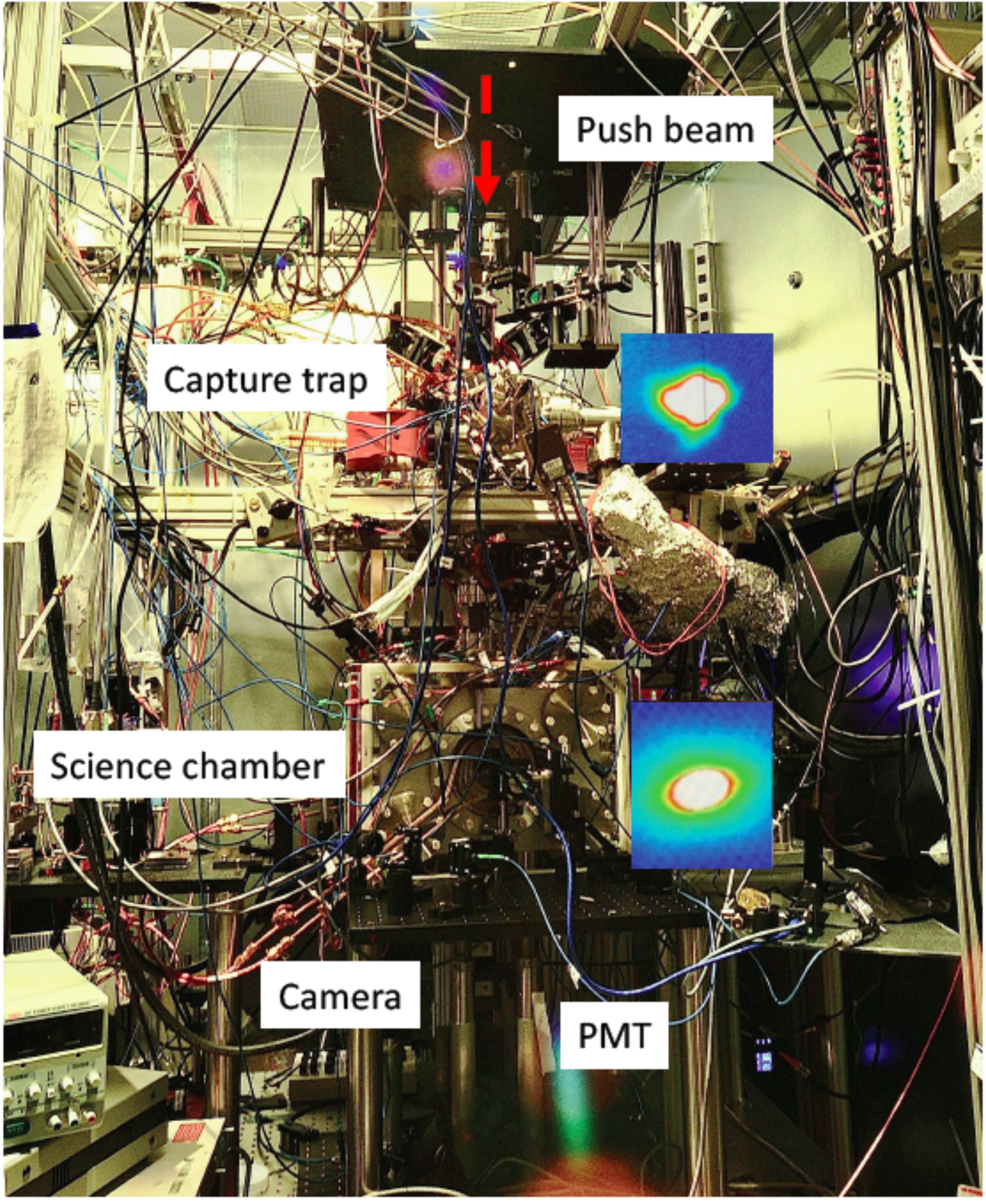
HF Anomaly

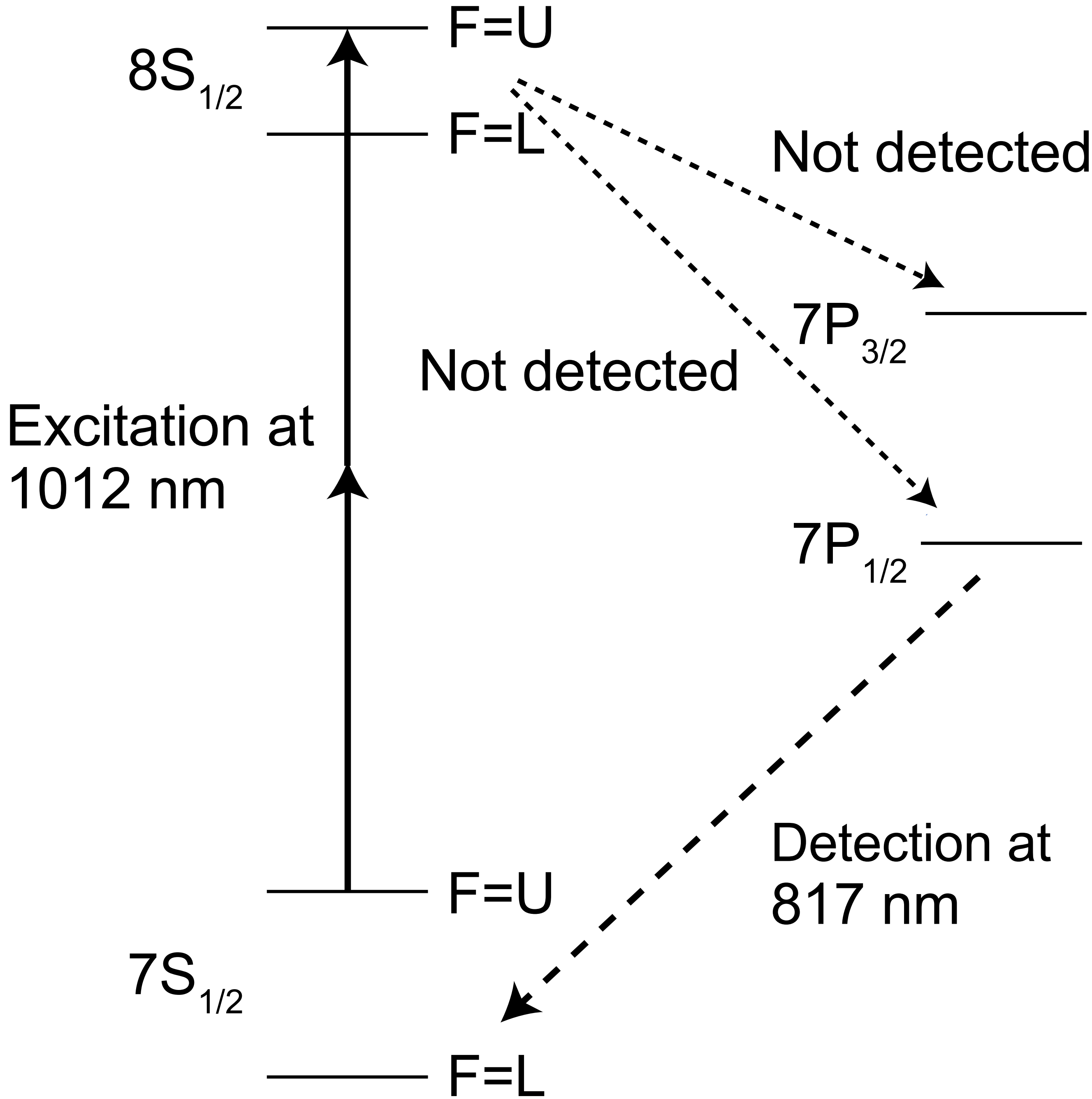


Green: Nuclear Structure Theory

Blue and Red: Measurements

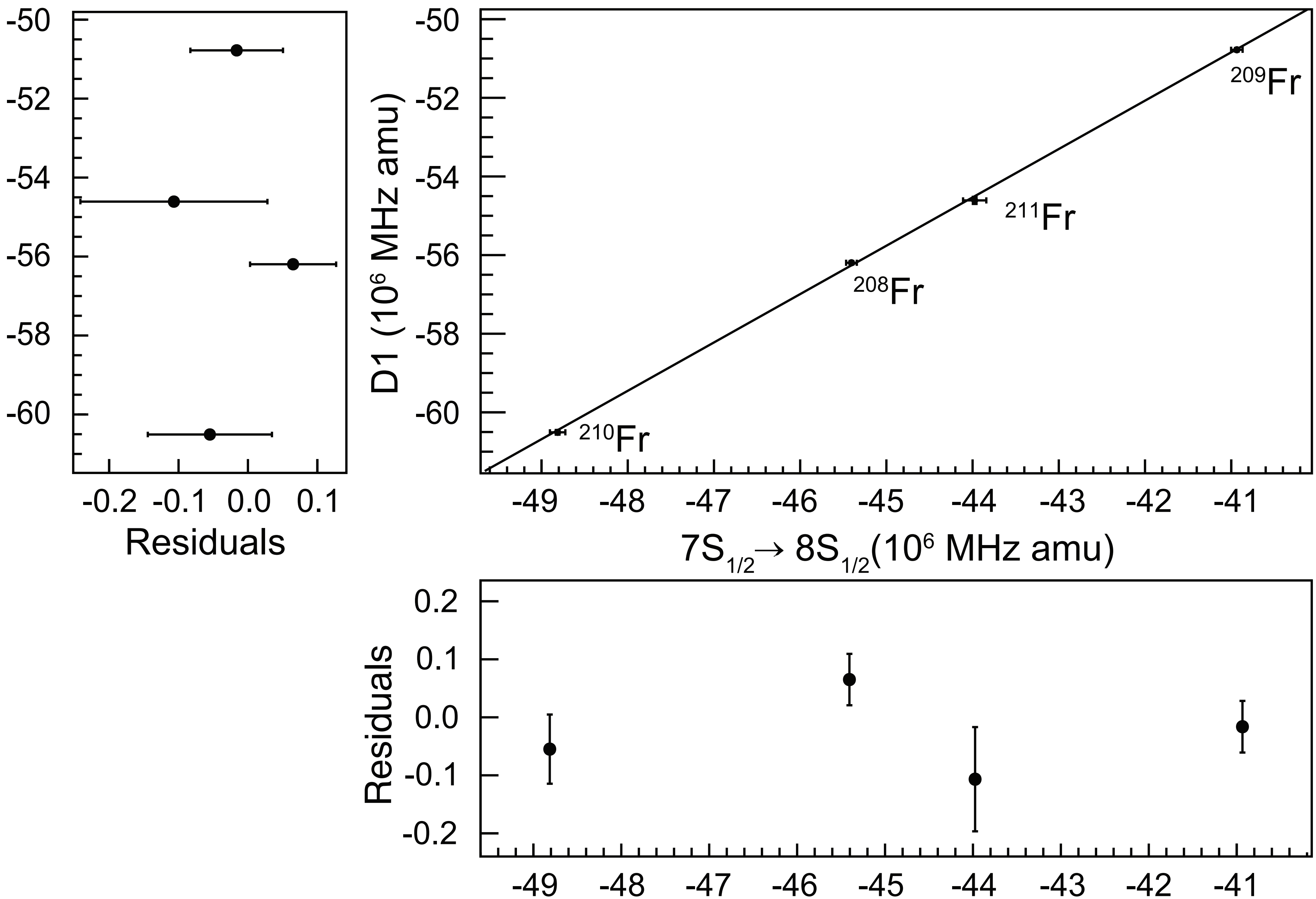
Two isomers for 206 *g* and *m*


Push beam
Capture trap
Science chamber
Camera
PMT



F=U
8S1/2
F=L
Not detected
7P3/2
Not detected
Excitation at
1012 nm
7P1/2
Detection at
817 nm
F=U
7S1/2
F=L

King plot two-photon vs D1 shifts relative to ^{213}Fr



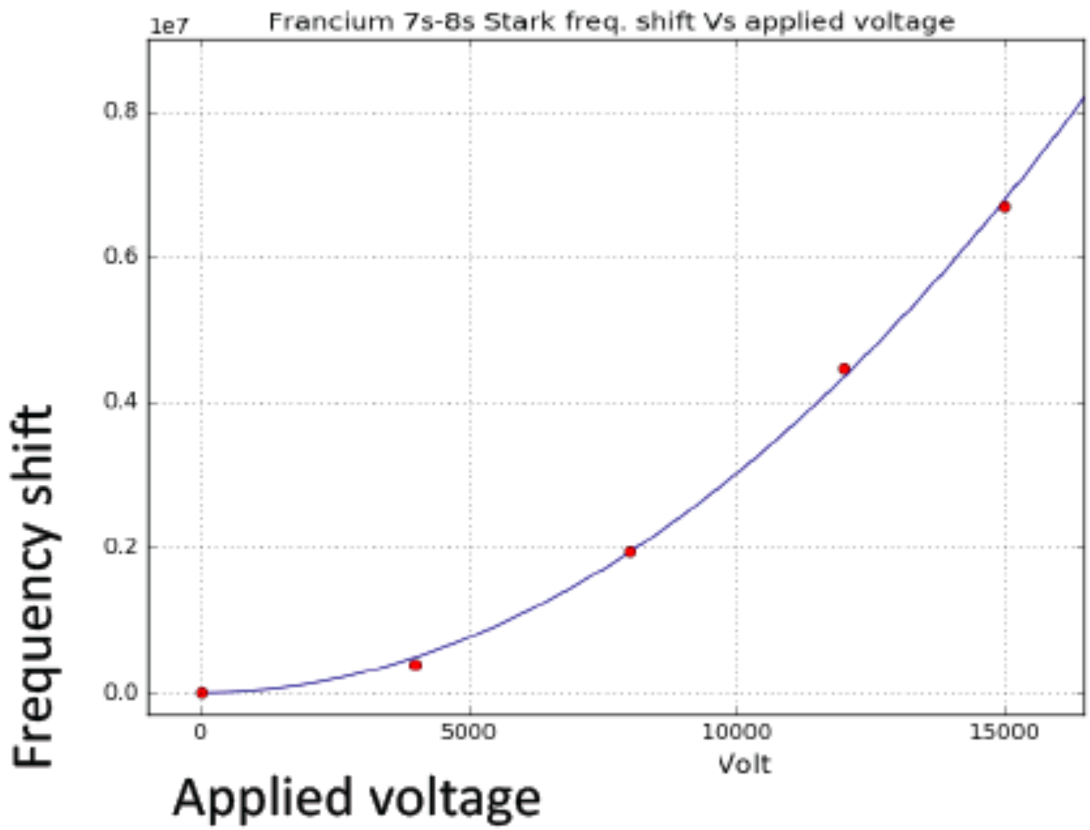
Comparison of the slope from the King plot

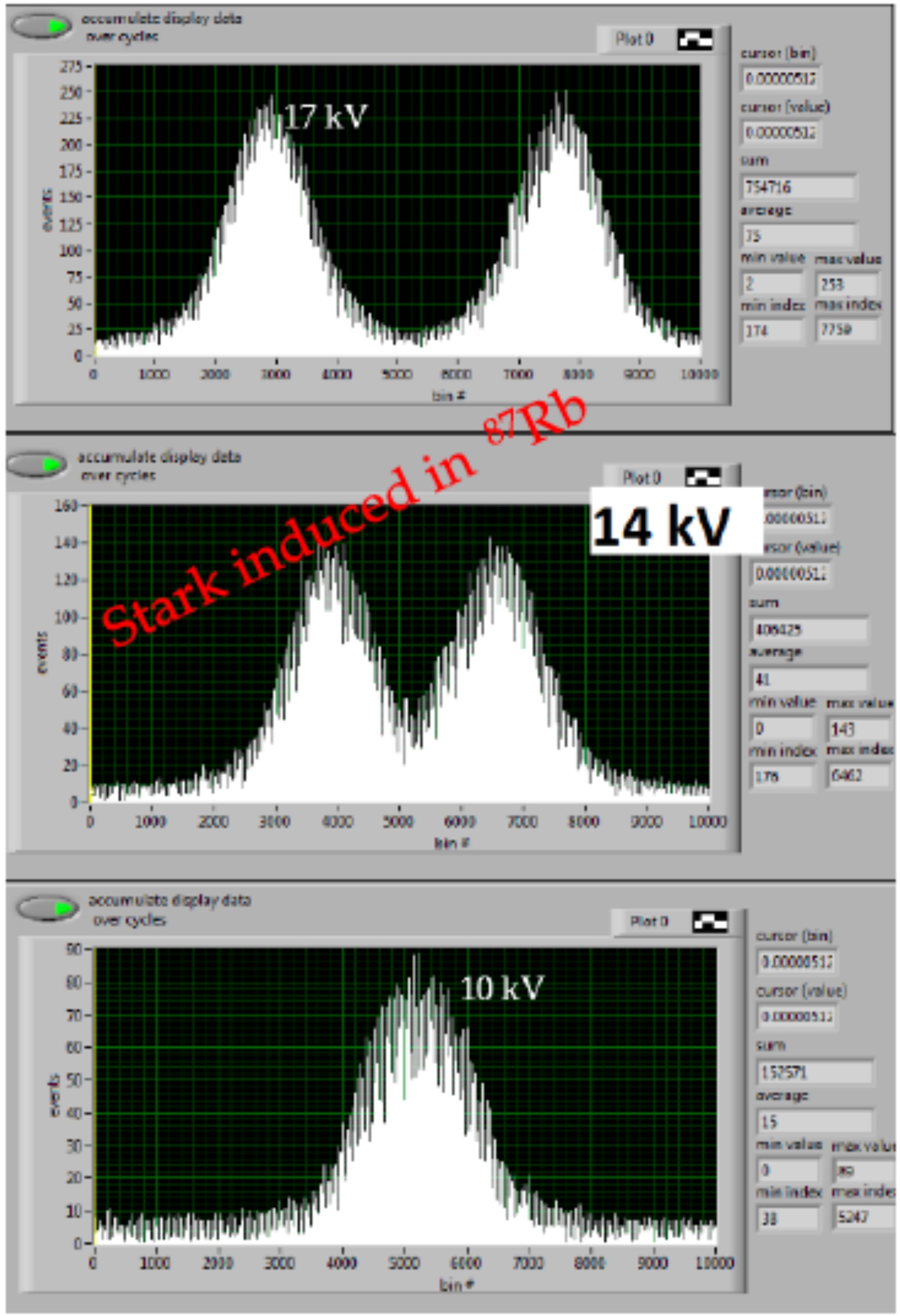
Experiment: 1.230 ± 0.019
Theory: 1.234 ± 0.010

Next step
DC Stark Shift for the 7S to 8S transition in Fr.
We have the results in Rb

Progress so far

- DC Stark shift of the 7s-8s transition.
- Electrodes with holes

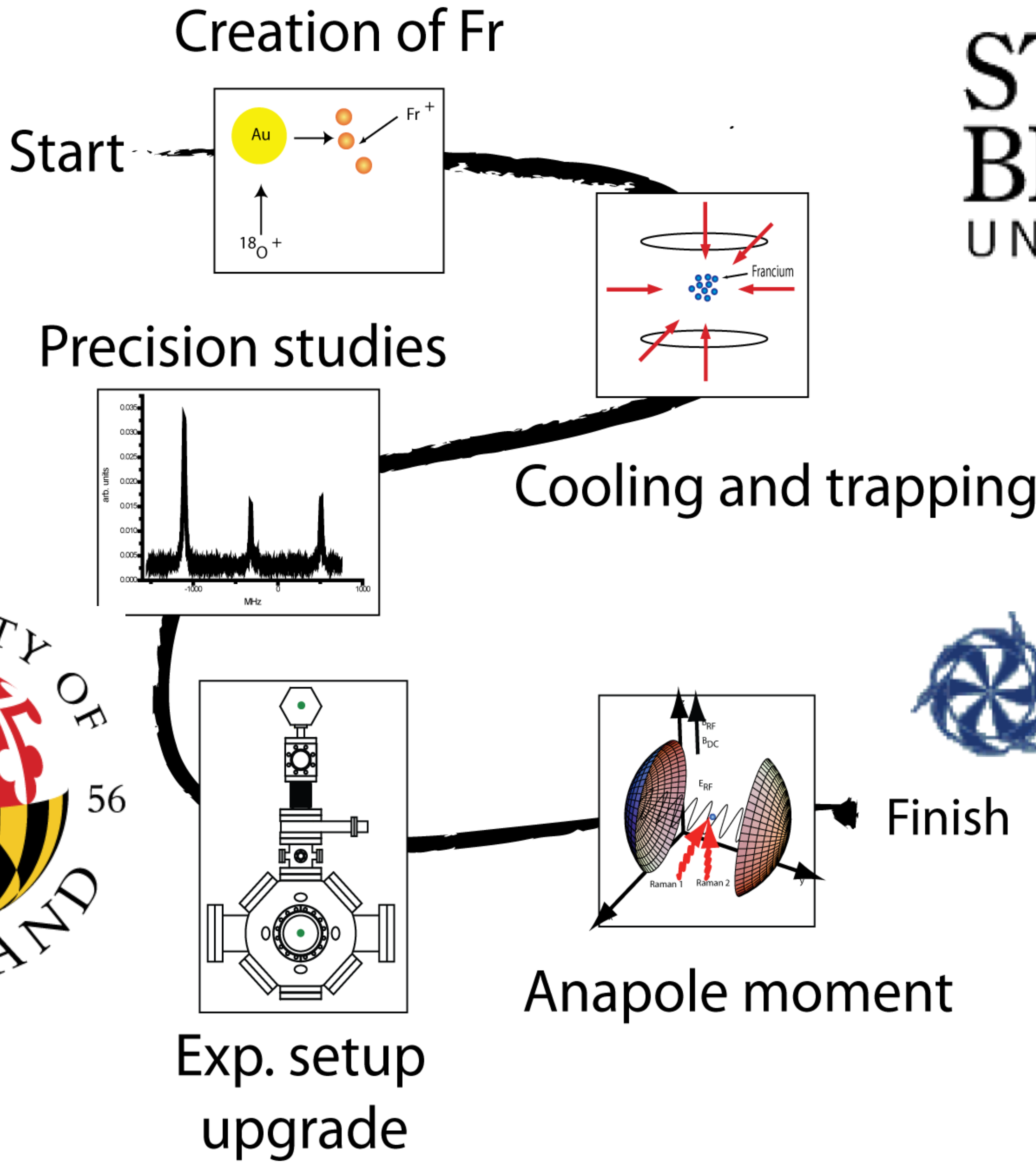



17 kV
Stark induced in ^{87}Rb
14 kV
10 kV
accumulate display data over cycles
Plot 0
events
bin #
cursor (bin)
cursor (value)
sum
average
min value
max value
min index
max index

- Isotope shifts of $^{206,207,213}Fr$ with respect to ^{209}Fr measured to within a few MHz in two transitions. Changes in the charge radius.

- $7P_{1/2}$ splitting measured for $^{206,207,209,213,\ 221}Fr$ to a few kHz for the Hyperfine anomaly. Changes in the magnetization radius.

- DC Startk shift observed, but now need to measure it in controlled environment



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THANKS!