Top

Left side

TEST

Right side

bottom

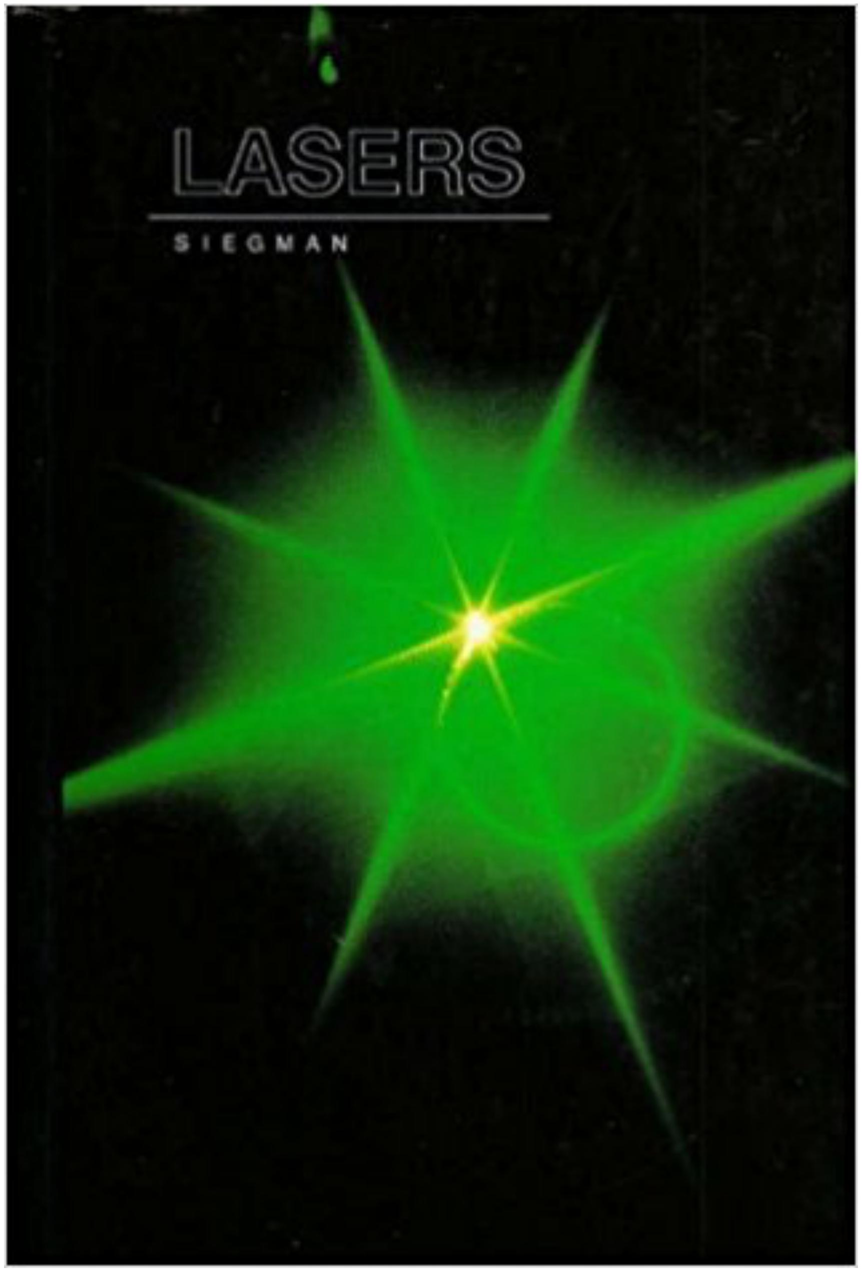
Laser applications to the study of atomic quantum structure.

2017 OSA Siegman International
School on Lasers, Lecture 5
CIO, León, México, August 2017
Luis A. Orozco
www.jqi.umd.edu

UNIVERSITY OF MARYLAND 18 56

jqi | PHYSICS FRONTIER CENTER
JOINT QUANTUM INSTITUTE

NIST



Anthony E Siegman
(1931-2011)

Course:

1st lecture: Introduction to the interaction of light with atoms, (nanofibers).

2nd lecture: Atom-light interaction of a two level atom (nanofibers at low intensity).

3rd lecture: Atom-light interaction of a two level atom (QO, cavity QED).

4th lecture: Different types of laser traps for atoms, (nanofibers, cavity QED, and spectroscopy).

5th lecture: Torsional modes of nanofibers. Weak interaction studies with Fr, a proposal.

Mechanical modes in nanofibers.


3 2012
Sylvain
Jonathan
Jeff


5 2013
Jeff, Krysten Peter Uchenna Pablo, Jonathan, Davi

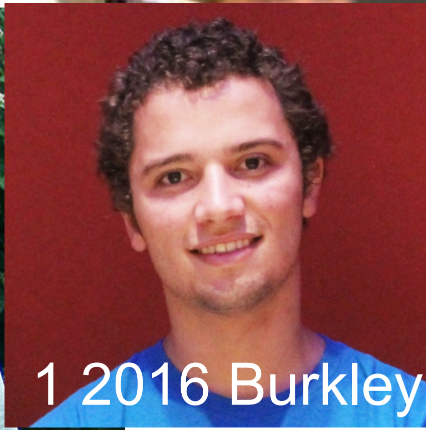
THE TEAM


Christiane

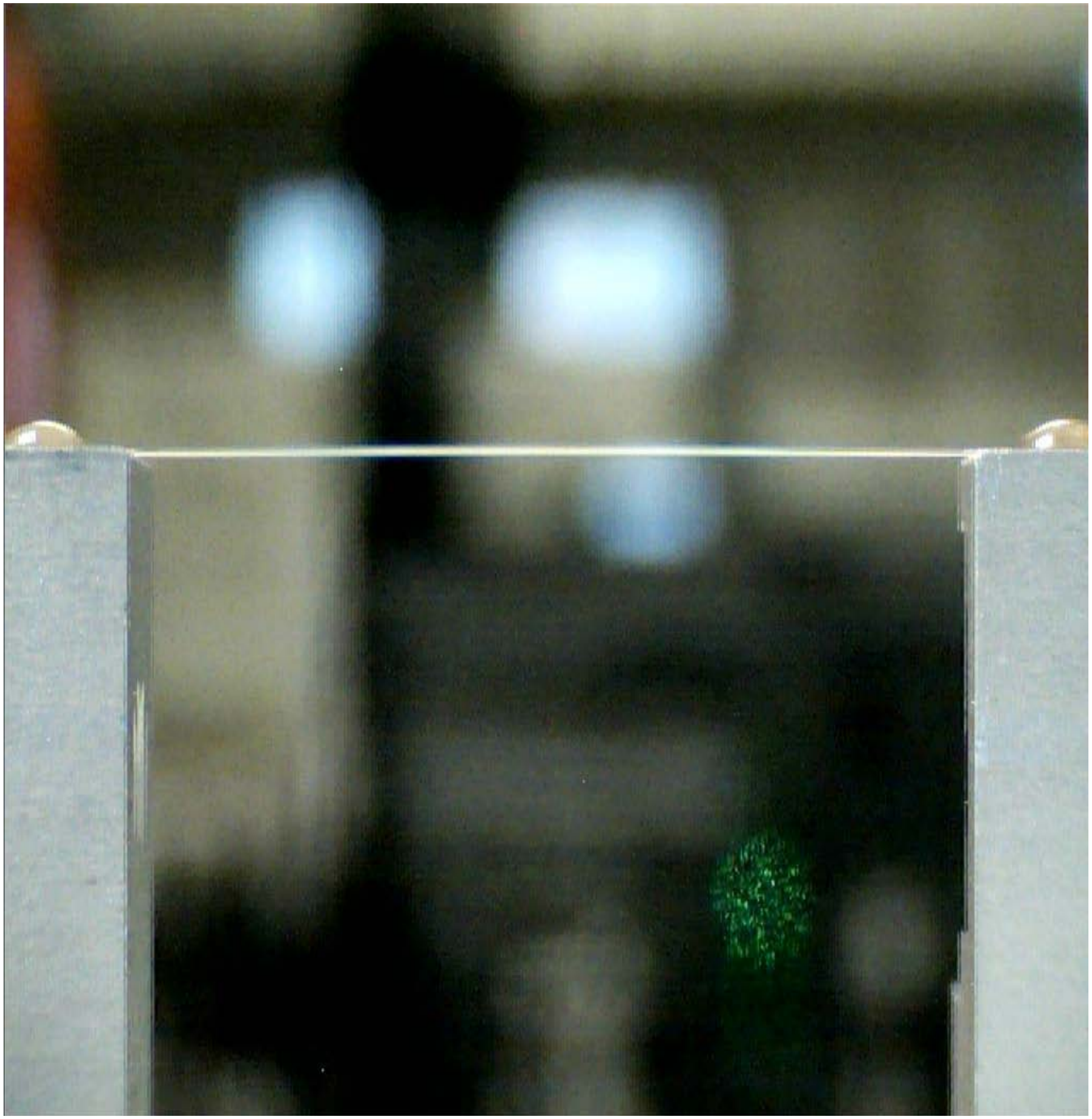

10 2014
Xavier


9 2015
Adnan


6 2015
Alan
Eliot
Jeff
Pablo

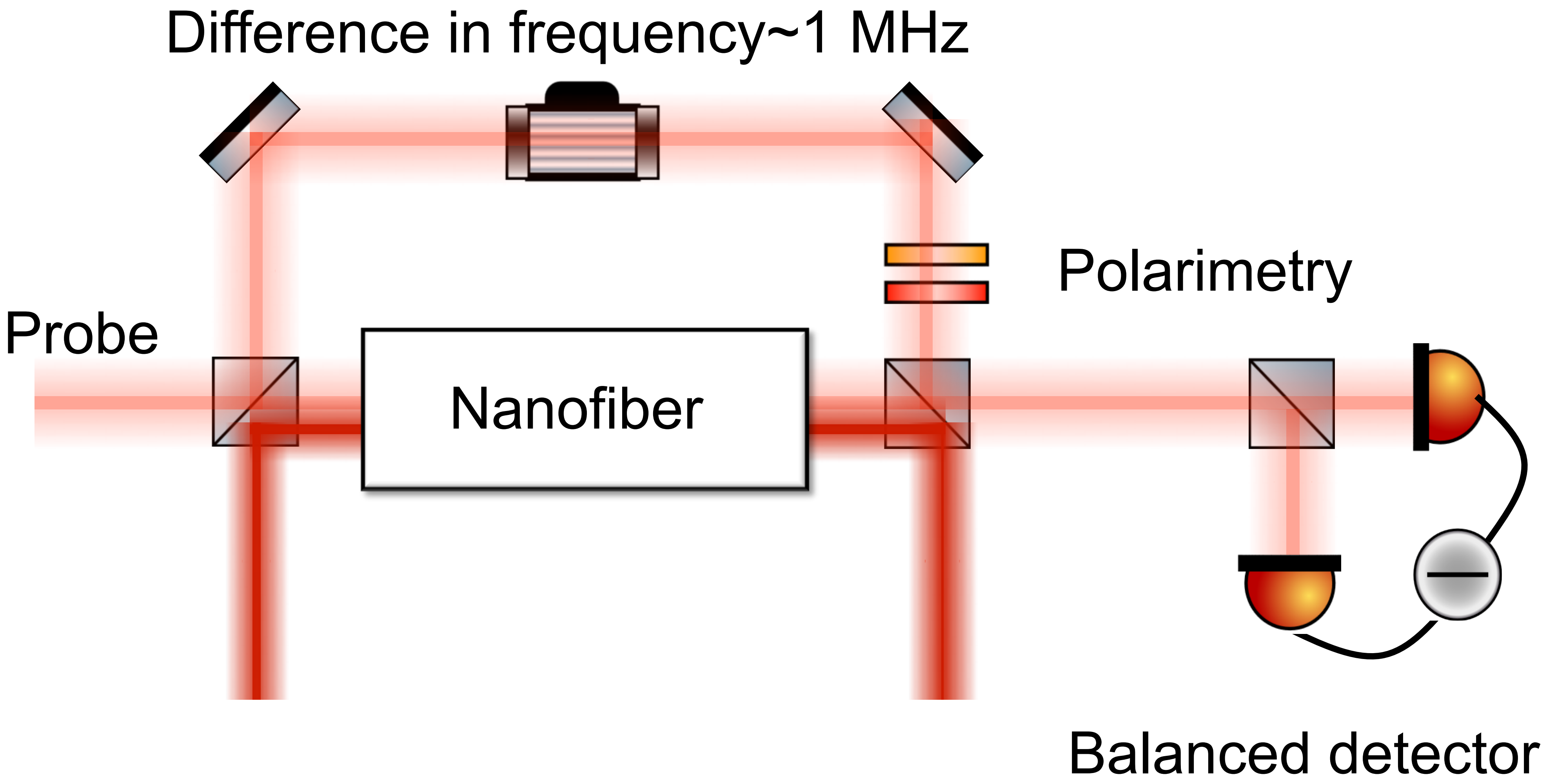

1 2016 Burkley

Mechanical modes



- Torsional modes
- Violin modes (vibrational)

Detection with heterodyne polarimetry.


Difference in frequency~1 MHz

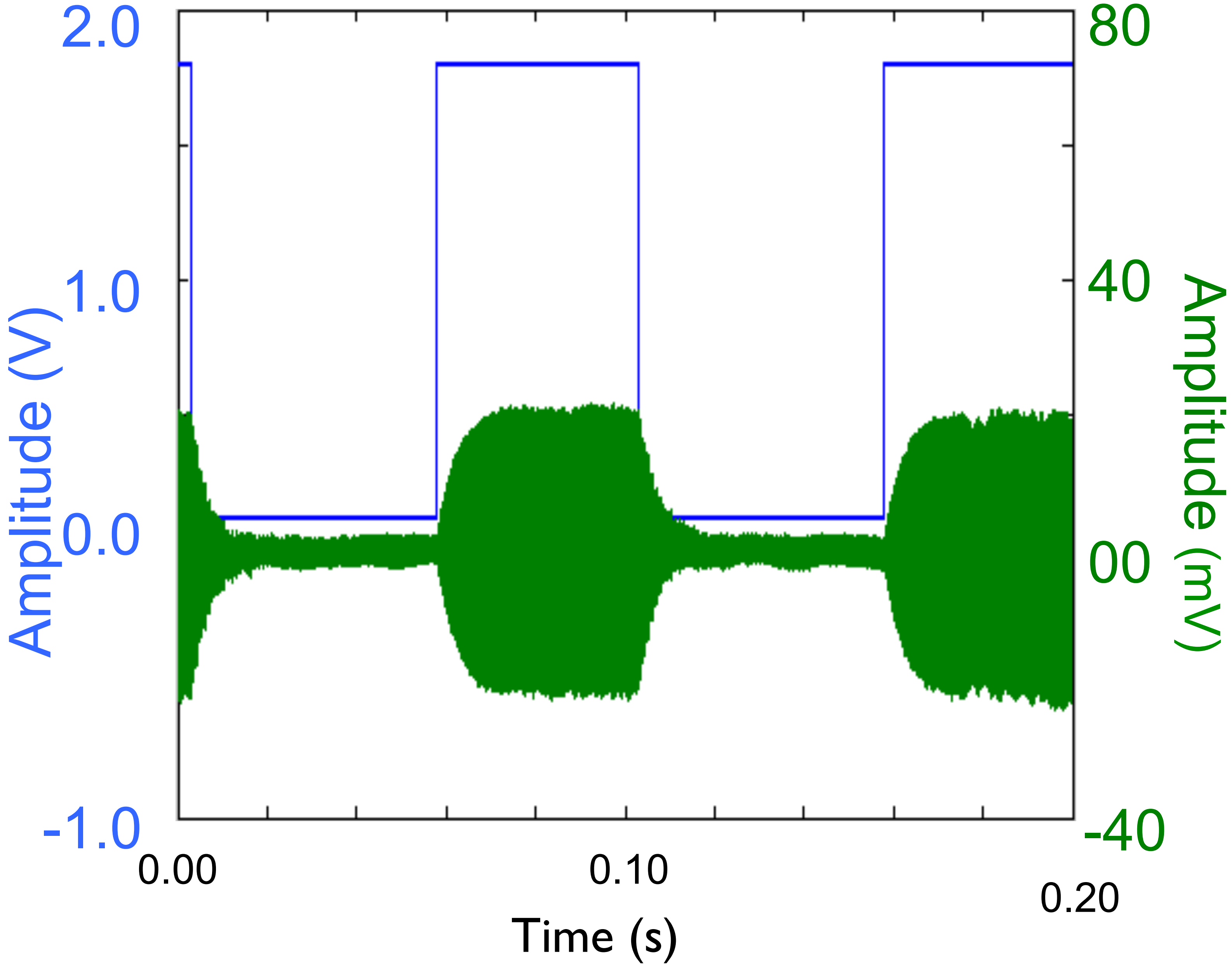
Polarimetry

Probe

Nanofiber

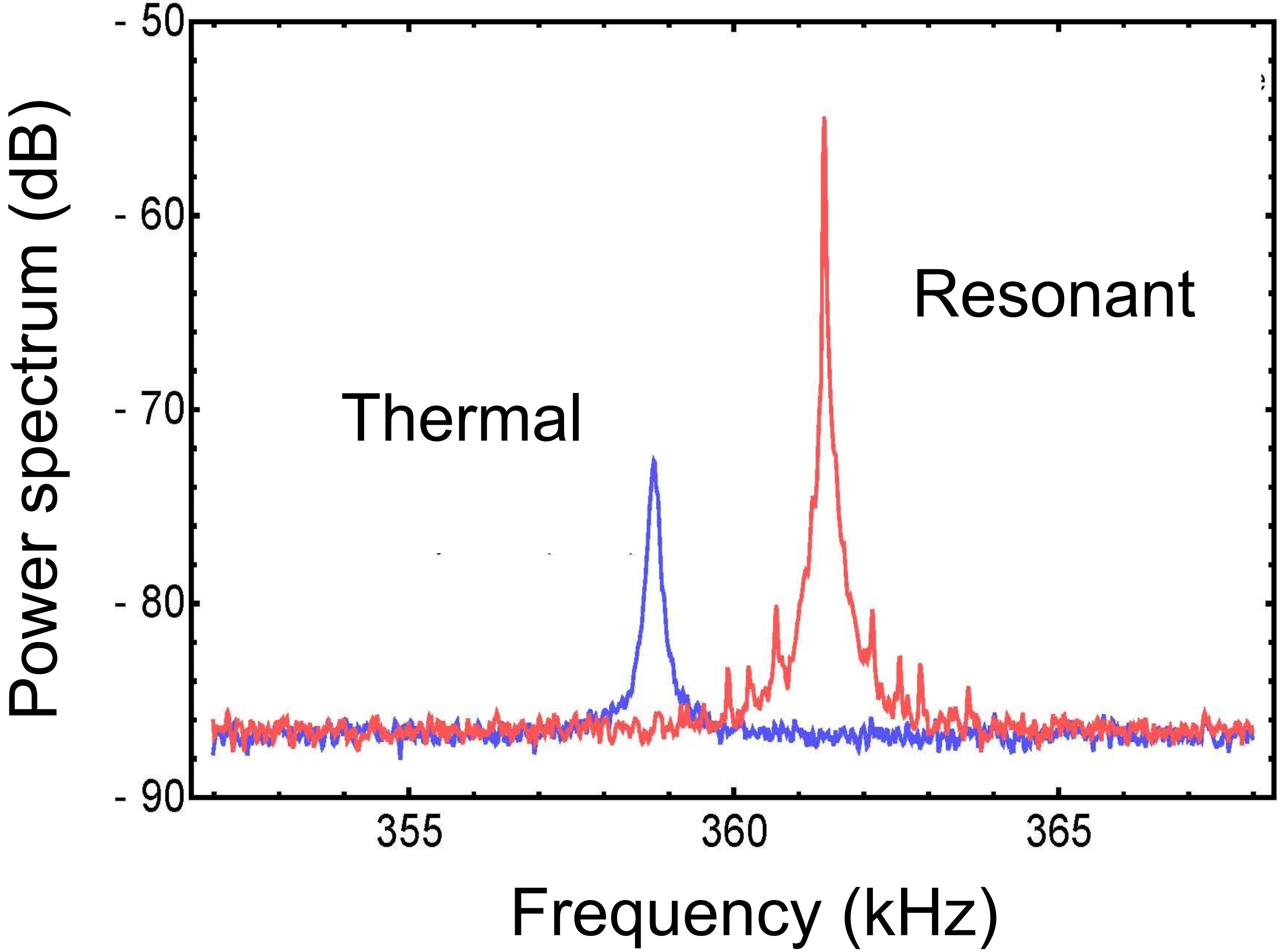
Balanced detector

Excitation

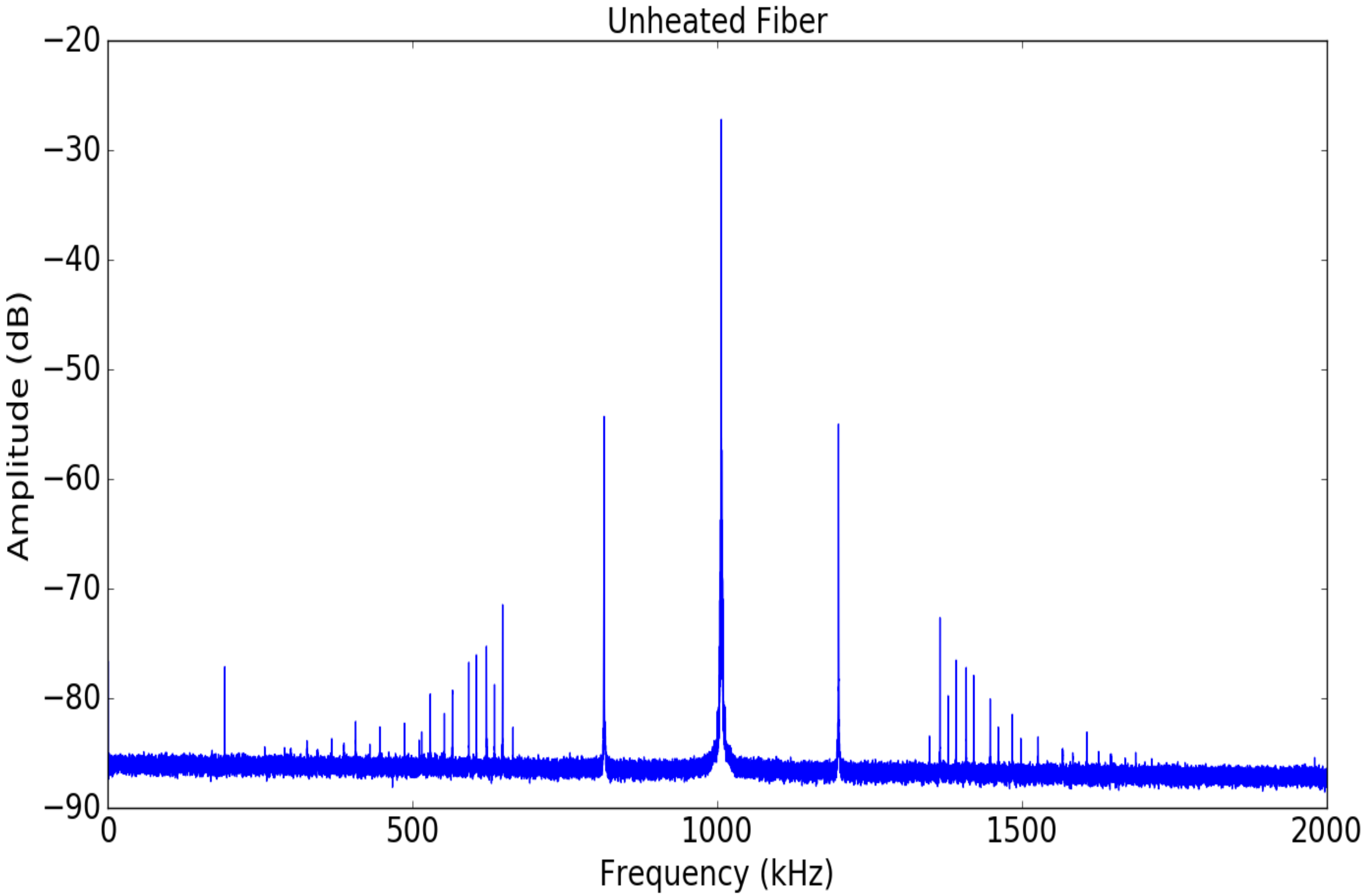


2.0
1.0
0.0
-1.0
Amplitude (V)
80
40
00
-40
Amplitude (mV)
0.00
0.10
0.20
Time (s)

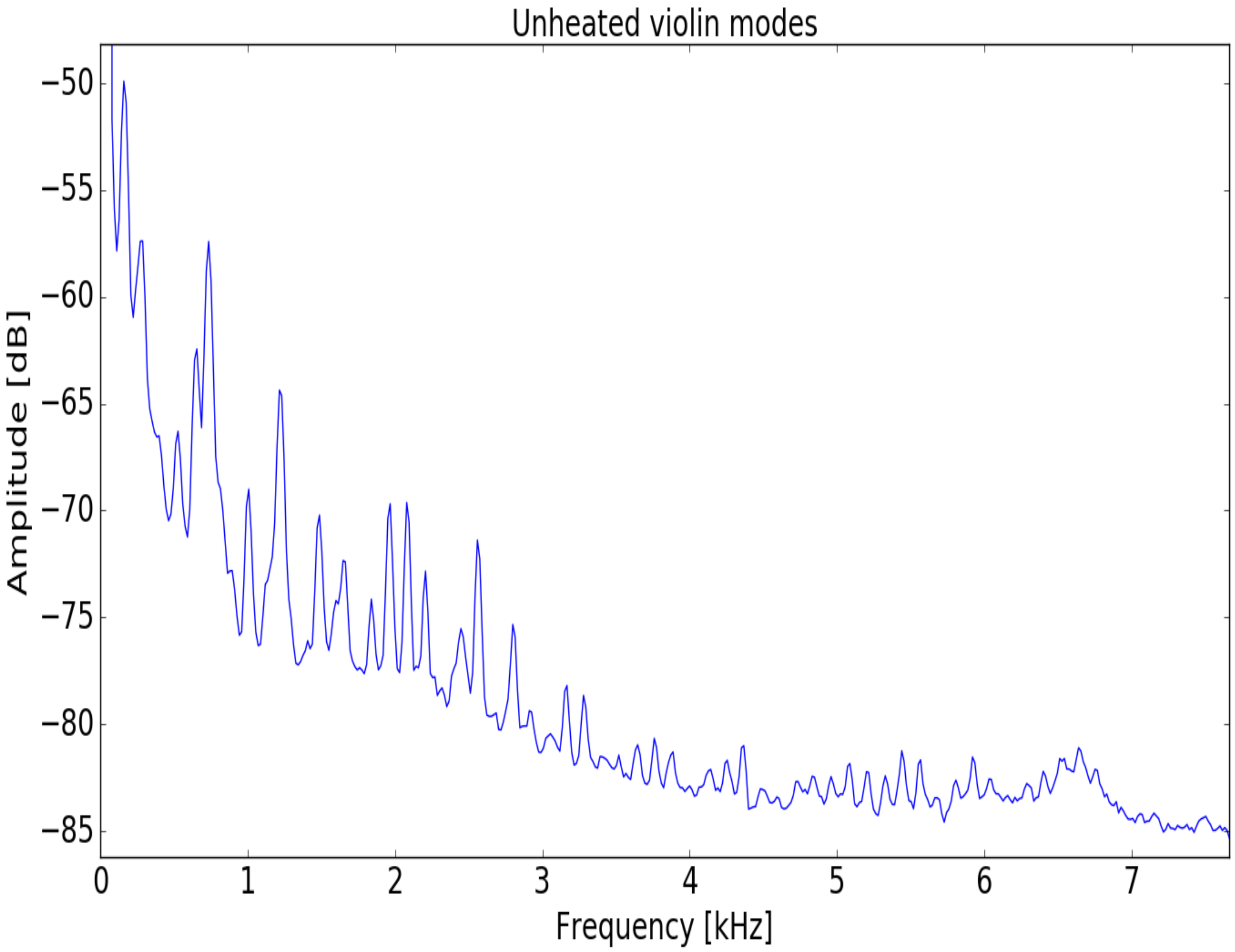
Compareson of two methods of excitation



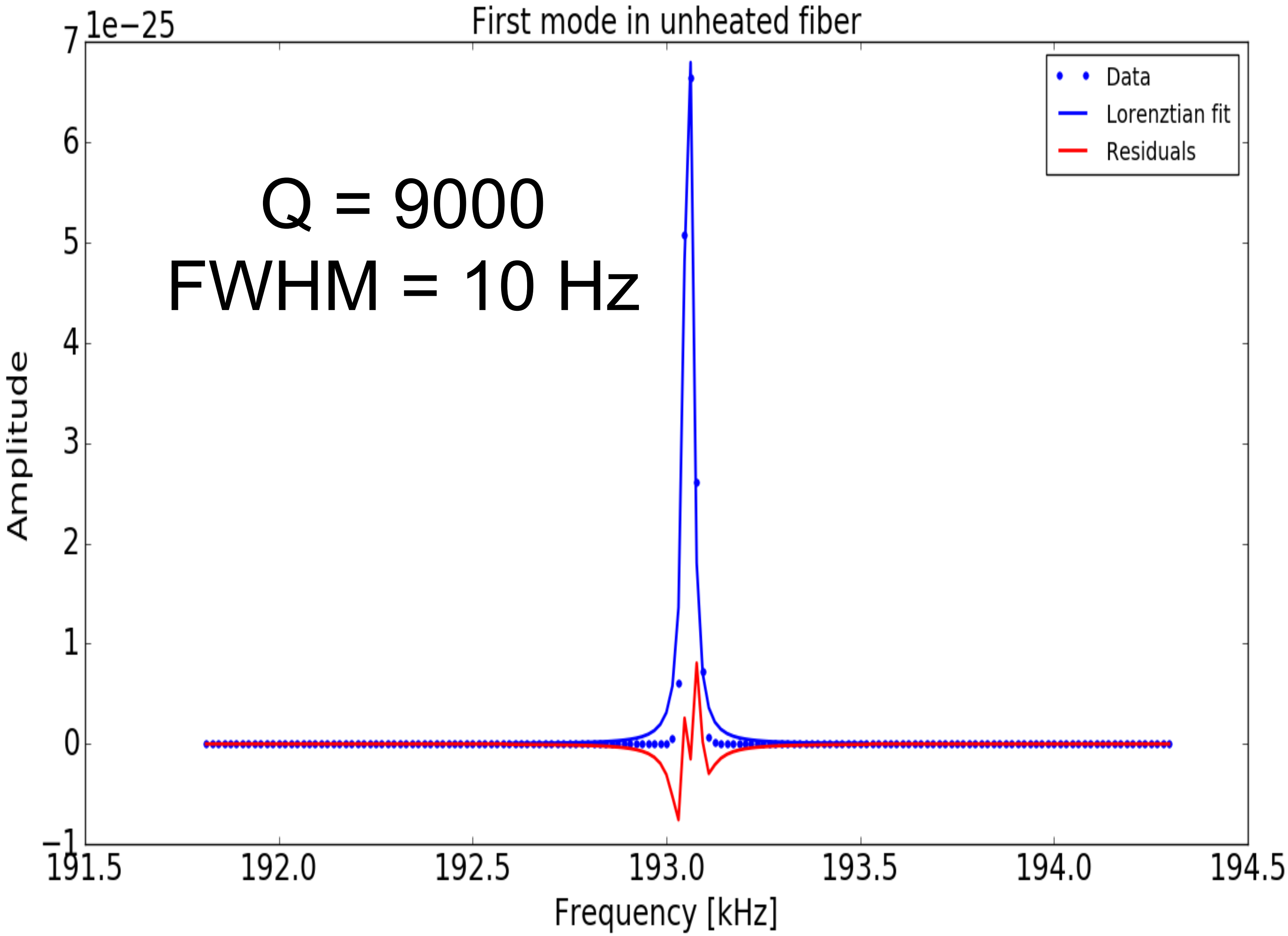
FFT


Unheated Fiber
Amplitude (dB)
−20
−30
−40
−50
−60
−70
−80
−90
0
500
1000
1500
2000
Frequency (kHz)

Violin modes



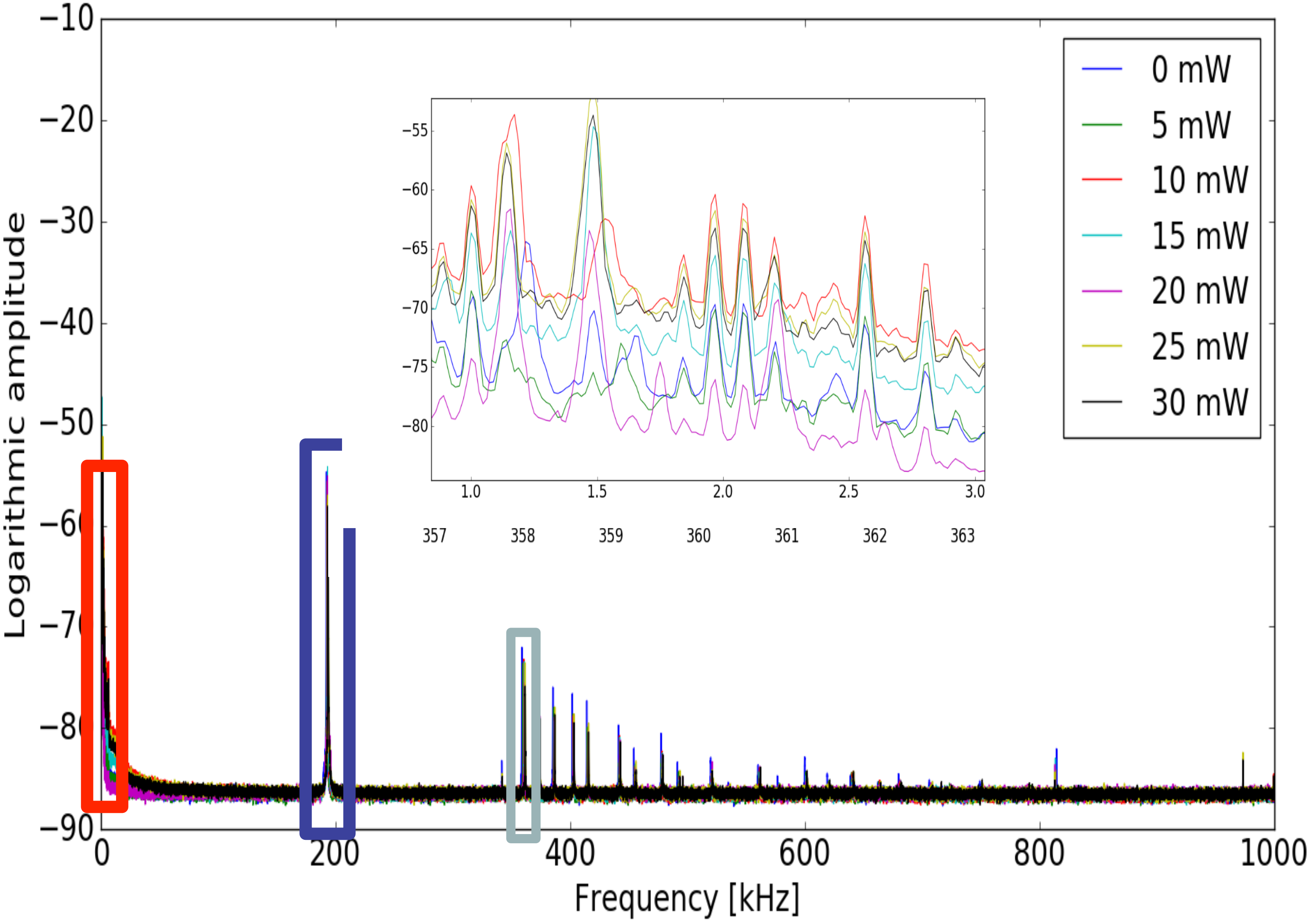
First torsional mode



Q = 9000

FWHM = 10 Hz

Modes in the heated nanofiber



Problem:
The frequency of the first torsional mode is very near to the trapping frequency and heats the atoms.

For dipole traps:
Spontaneous emission ~ $1/\delta^2$
Trap potential ~ $1/\delta$

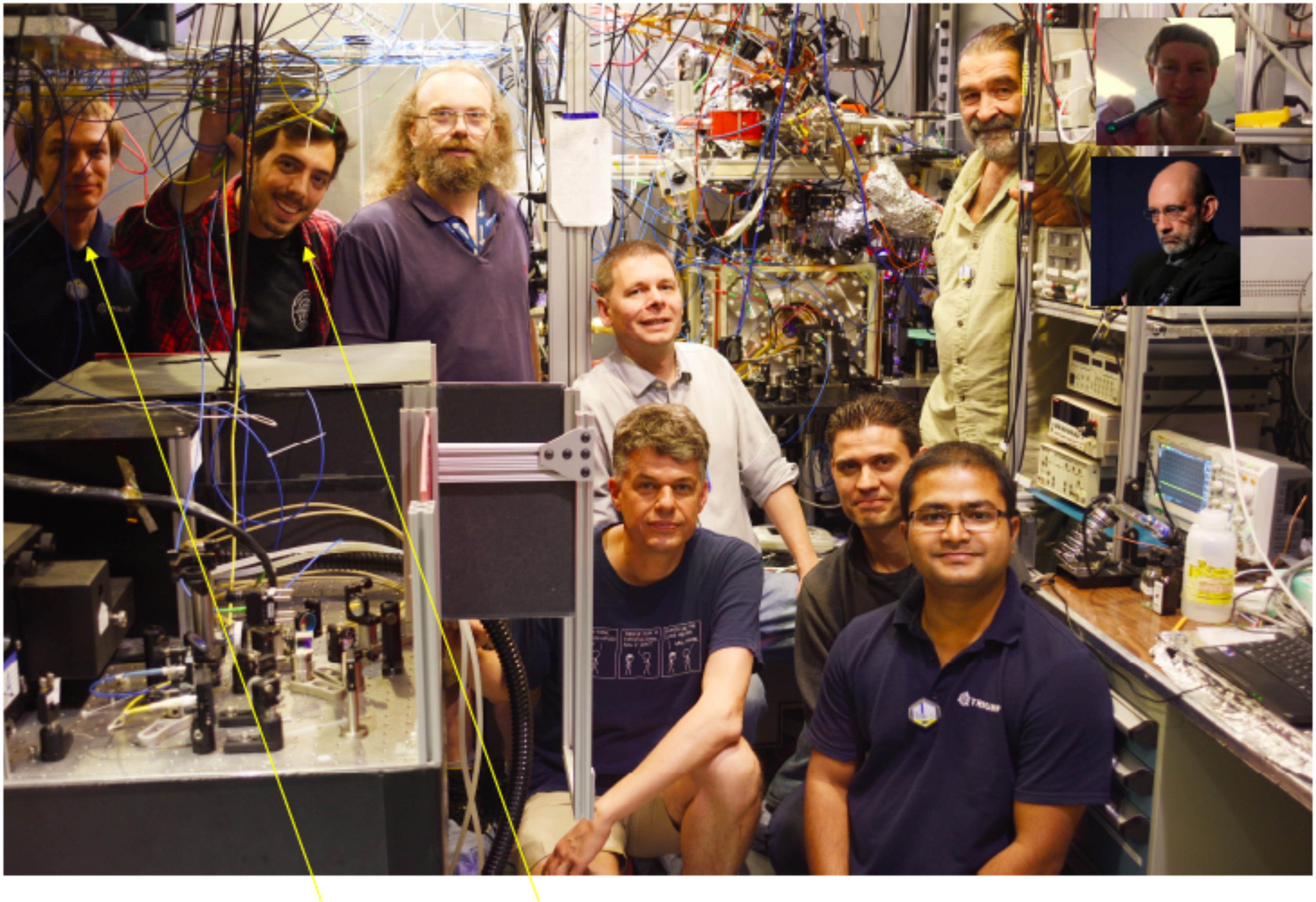
2. Weak interaction

Bibliography Lesson 5:

J. Zhang,M. Tandecki, R. Collister, S. Aubin, J. A. Behr, E. Gomez, G. Gwinner, L. A. Orozco, M. R. Pearson, and G. D. Sprouse, "Hyperfine Anomalies in Fr: Boundaries of the Spherical Single Particle Model" Phys. Rev. Lett.**115**, 042501 (2015).

E. Gomez, L. A. Orozco, and G. D. Sprouse "Spectroscopy with trapped francium: advances and perspectives for weak interaction studies," Rep. Prog. Phys **69**, 79, (2006).

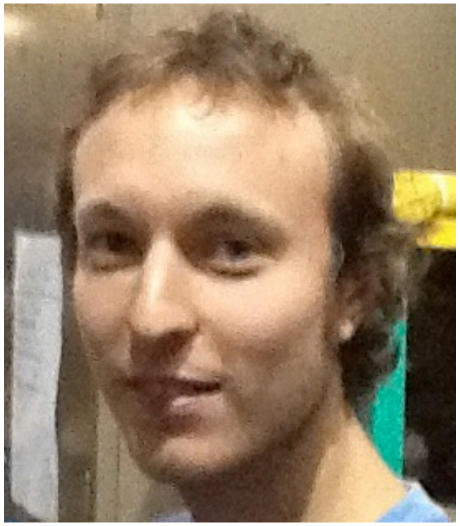
Current members (August 2016)



From Left to right: Michael Kossin, Austin deHart, Matt Pearson, Seth Aubin, Gerald Gwinner, Eduardo Gomez, Mukut Kalita, Alexandre Gorelov, John Behr, Luis Orozco.
Not in the picture: Andrew Senchuk and our theory colleagues : Marianna Safronova, Vladimir Dzuba, Victor Flambaum.

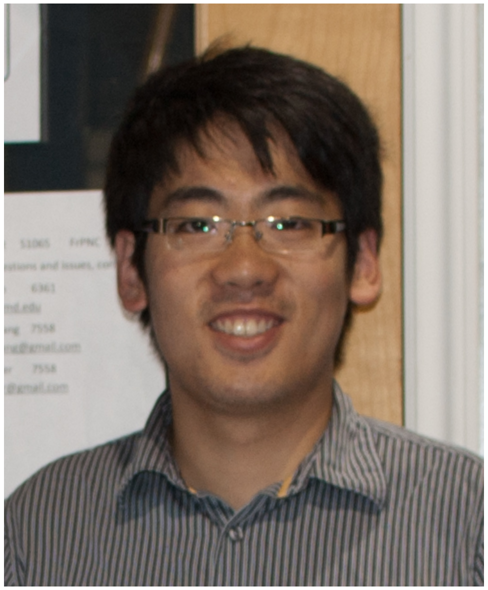
Former members

TRIUMF



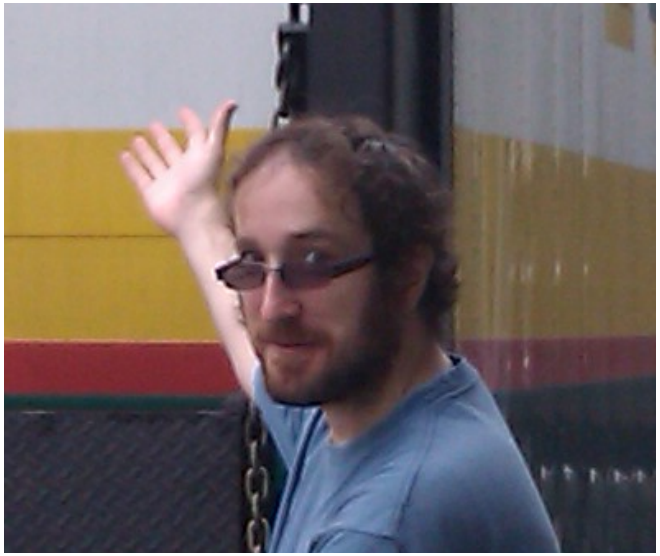
Michael Tandecki

University of Maryland



Jiehang Zhang

University of Manitoba



Robert Collister

The weak interaction

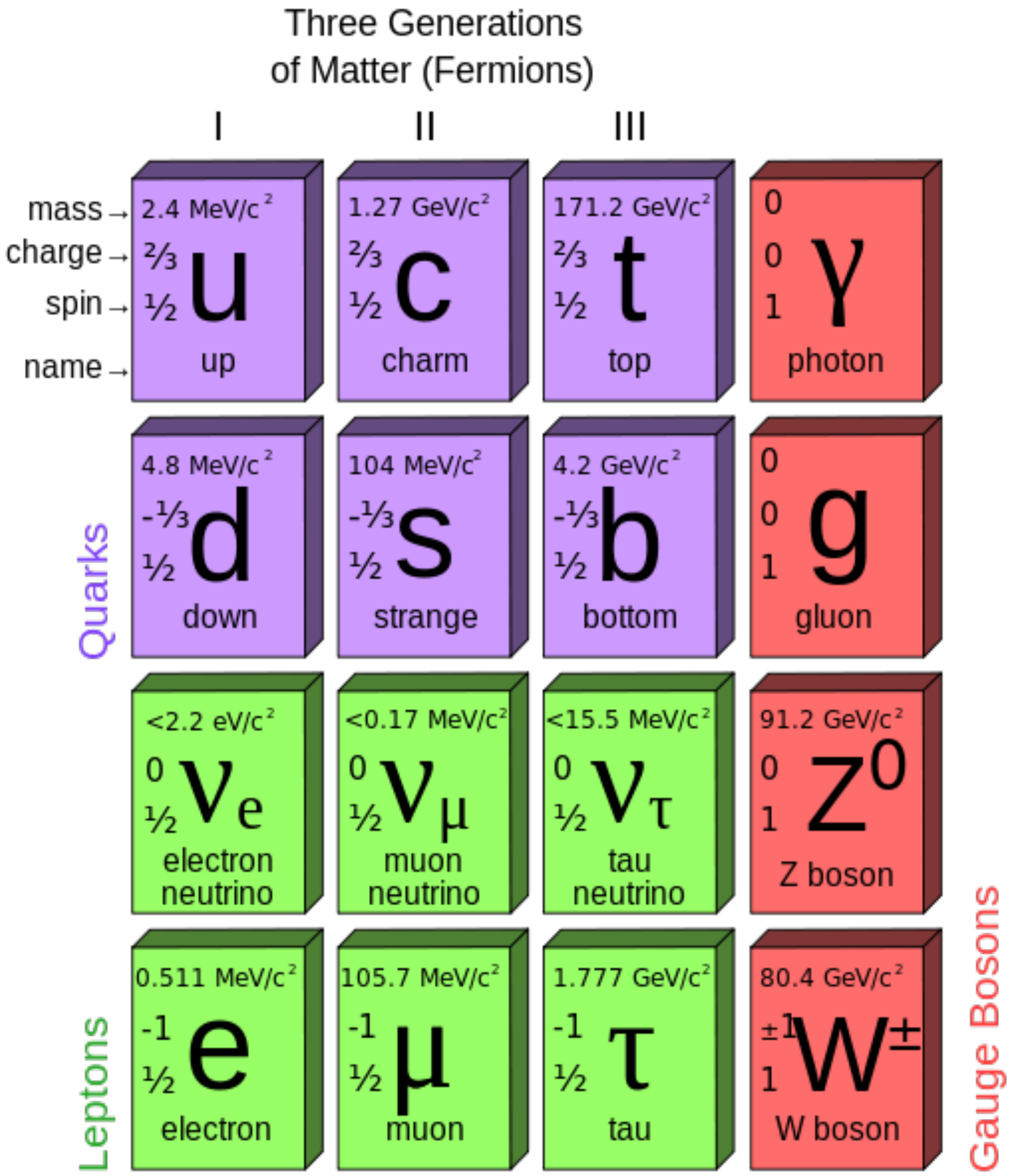
One of the four interactions: E&M, weak, strong, gravity. It is responsible for beta decay and the beginning of the solar cycle.

Beta electrons come out from some substances (Bequerel discovered radioactivity in 1896, Rutherford identified the classes alpha, beta and gamma). Now we know a neutron becomes a proton, ejecting an electron (beta) and an antineutrino.

The sun fuses hydrogen and produces helium, however hydrogen has just one proton and does not have neutrons. Helium has two neutrons and two protons. Where do the neutrons come from?

Since the time of Laplace the source of energy of the sun was a big question, they realized that even if it was pure coal it would not last.

The solution came with the weak interaction.



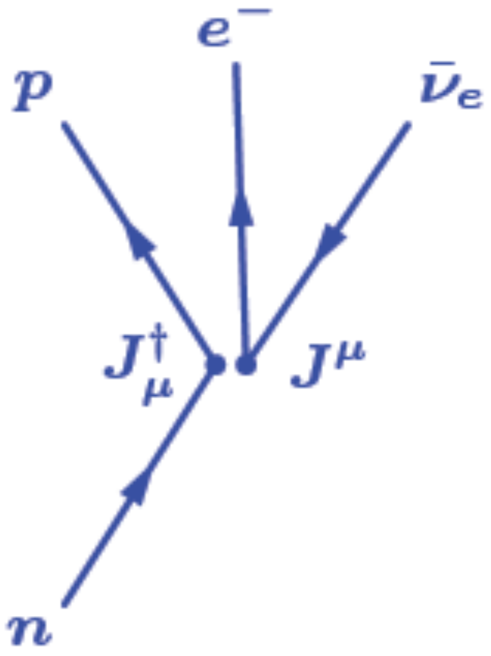
Three Generations
of Matter (Fermions)

mass →
charge →
spin →
name →

	I	II	III		
Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	Gauge Bosons
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson	
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^{\pm}$ W boson	

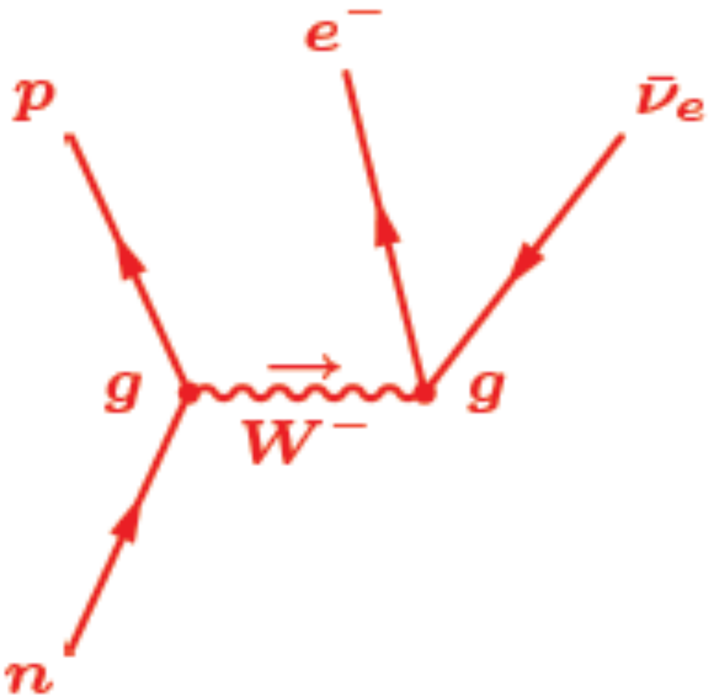
The weak interaction is the only one that changes the flavors of fundamental particles: a down quark becomes an up quark and a consequence the neutron becomes a proton.

Fermi Theory



Current-Current point (zero range) interaction inspired by E&M

Yukawa, Schwinger, Standard Model



Current-Current with an intermediate vector boson interaction

The carriers of the weak interaction are W^+, W^-, and Z^0. They are heavy (about an atom of Rubidium) so the particles have to be very close. Distances smaller than the size of a nucleus 10^{-15} m.

It violates parity completely (the neutrinos are lefties) and also CP partially.

Neutrinos continue to give us big surprises they have mass, they change flavor.

The New York Times | http://nyti.ms/1tLA32H

MAGAZINE

My Great-Great-Aunt Discovered Francium. And It Killed Her.

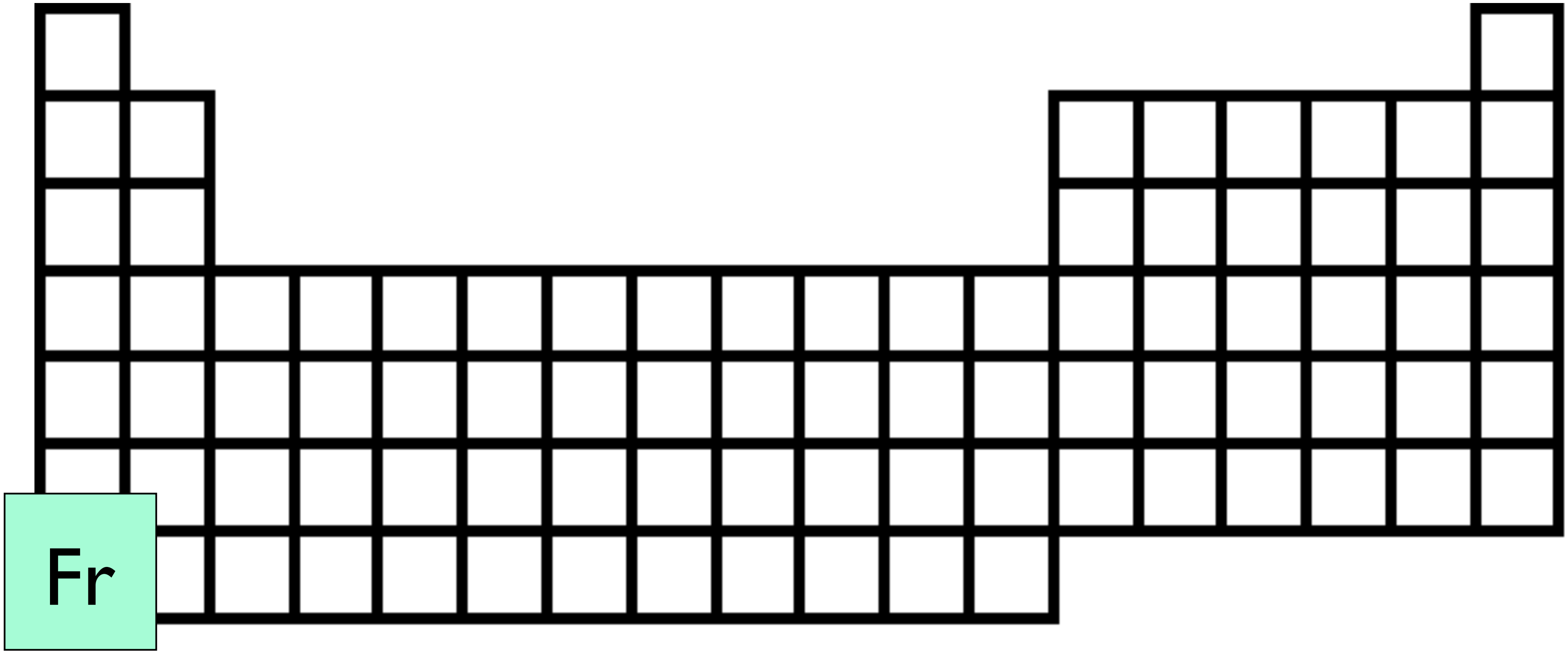
By VERONIQUE GREENWOOD DEC. 3, 2014

Orozco and his colleagues make francium because they think it is a perfect candidate to help understand the force behind beta decay. It has a heavy nucleus, which means there are many opportunities for particles to interact. It can be easily trapped, which is not true of other elements they might use. And it also emits and absorbs light at similar frequencies, which is useful for the experimenters. Someday, Orozco hopes, as the years pass and data are added to the compendium of human knowledge, francium will help researchers better understand the structure of matter.

But it won’t help cure cancer. When I bring up Marguerite Perey’s ambitions for her discovery, Orozco replies: “Oh! No.” He sounds surprised at the idea.

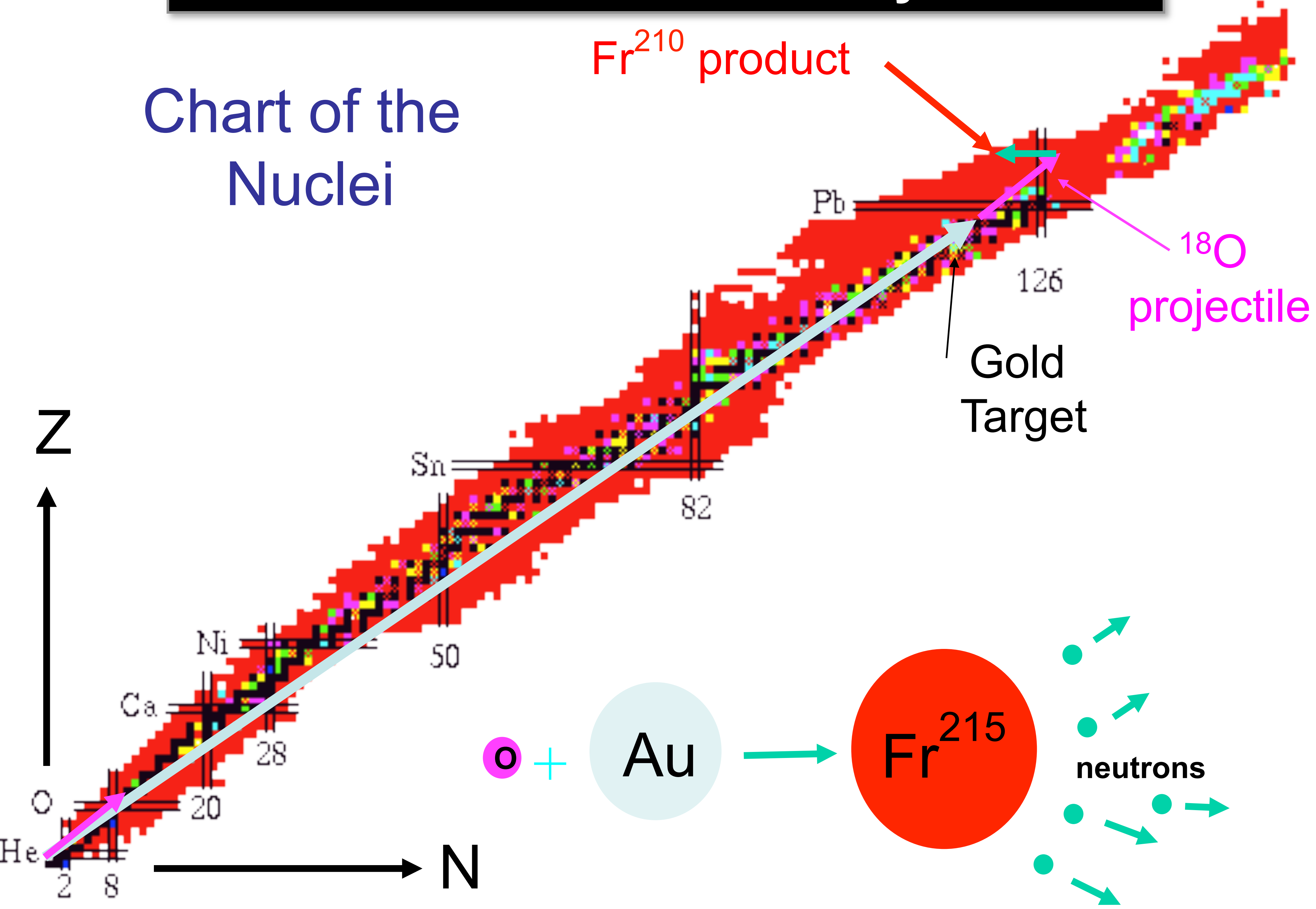
Marguerite Perey the discoverer of Francium

Courtesy of the Curie Institute, Paris



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

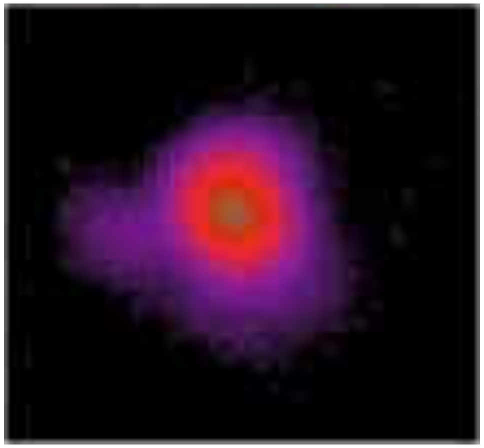
1996-2000: Laser spectroscopy of Francium ($8S_{1/2}$, $7P_{1/2}$,$7D_{5/2}$,$7D_{3/2}$, hyperfine anomaly).

2000-2002: High efficiency trap.

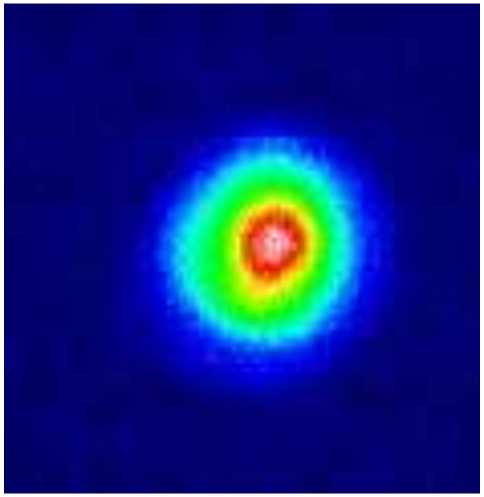
2003: Spectroscopy of $9S_{1/2}$,$8P_{1/2}$,$8P_{3/2}$ levels,

2004: Lifetime of 8S level.

2007: Magnetic moment ^{210}Fr based on $9S_{1/2}$.



2,000 atoms
Fr MOT



250,000 atoms
Fr MOT

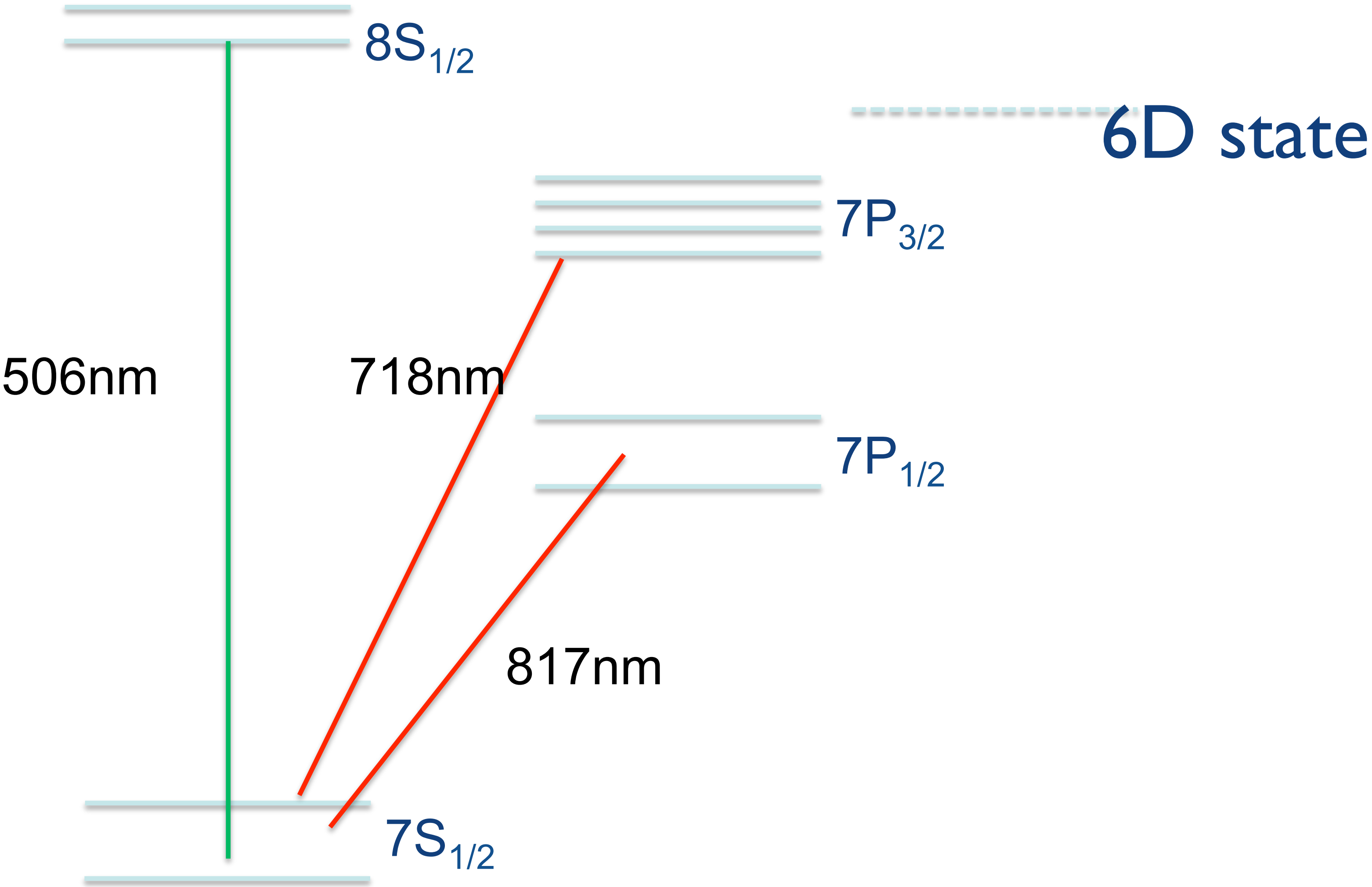
Spectroscopy studies of francium

Ideal cold sample of trapped atoms (no Doppler broadening)

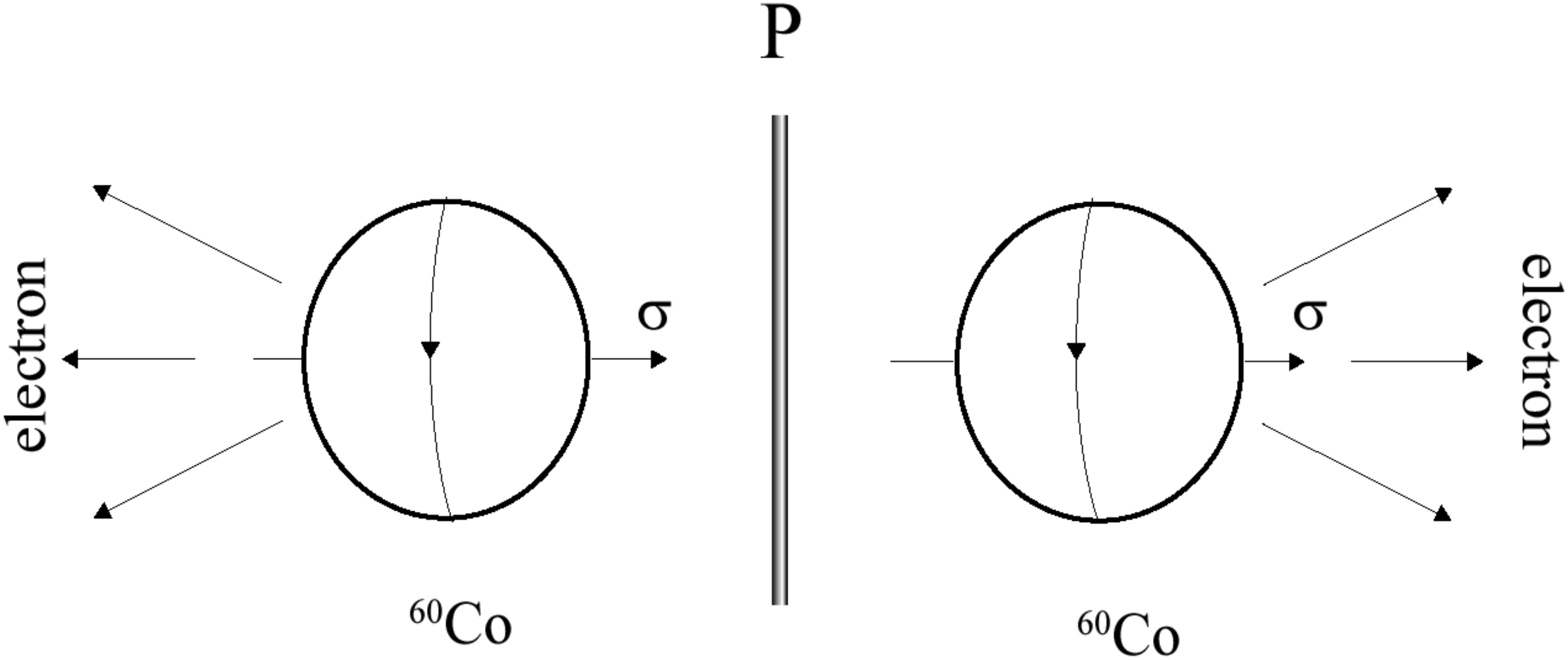
Energy levels
Excited state lifetimes (wavefunctions away from the nucleus)
Hyperfine splittings (wavefunctions at the nucleus)

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

Francium Atomic Energy Levels



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:

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

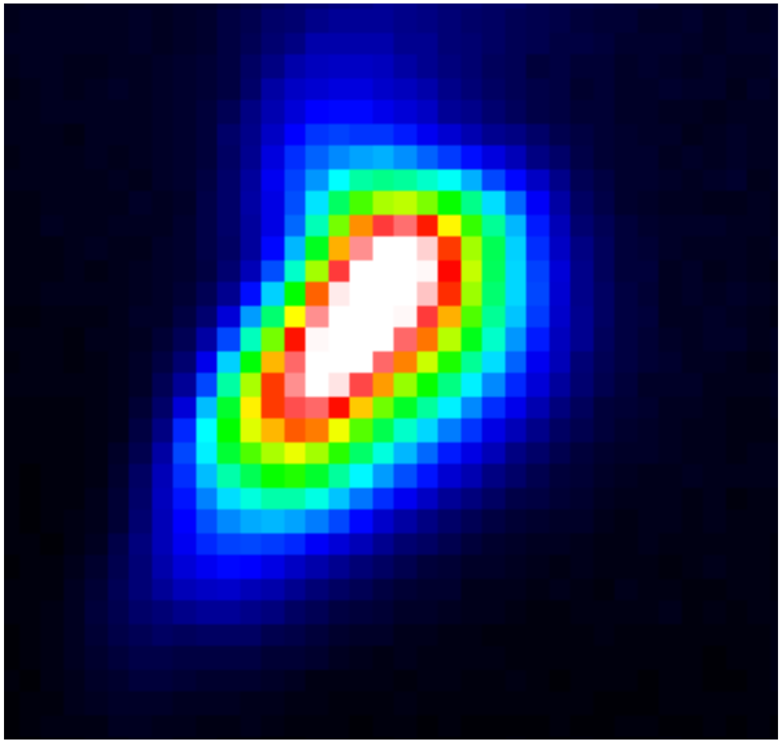
The ground state of alkali: $|\Psi\rangle = |nS_{1/2}\rangle + \delta\, |nP_{1/2}\rangle + \ldots$

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

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

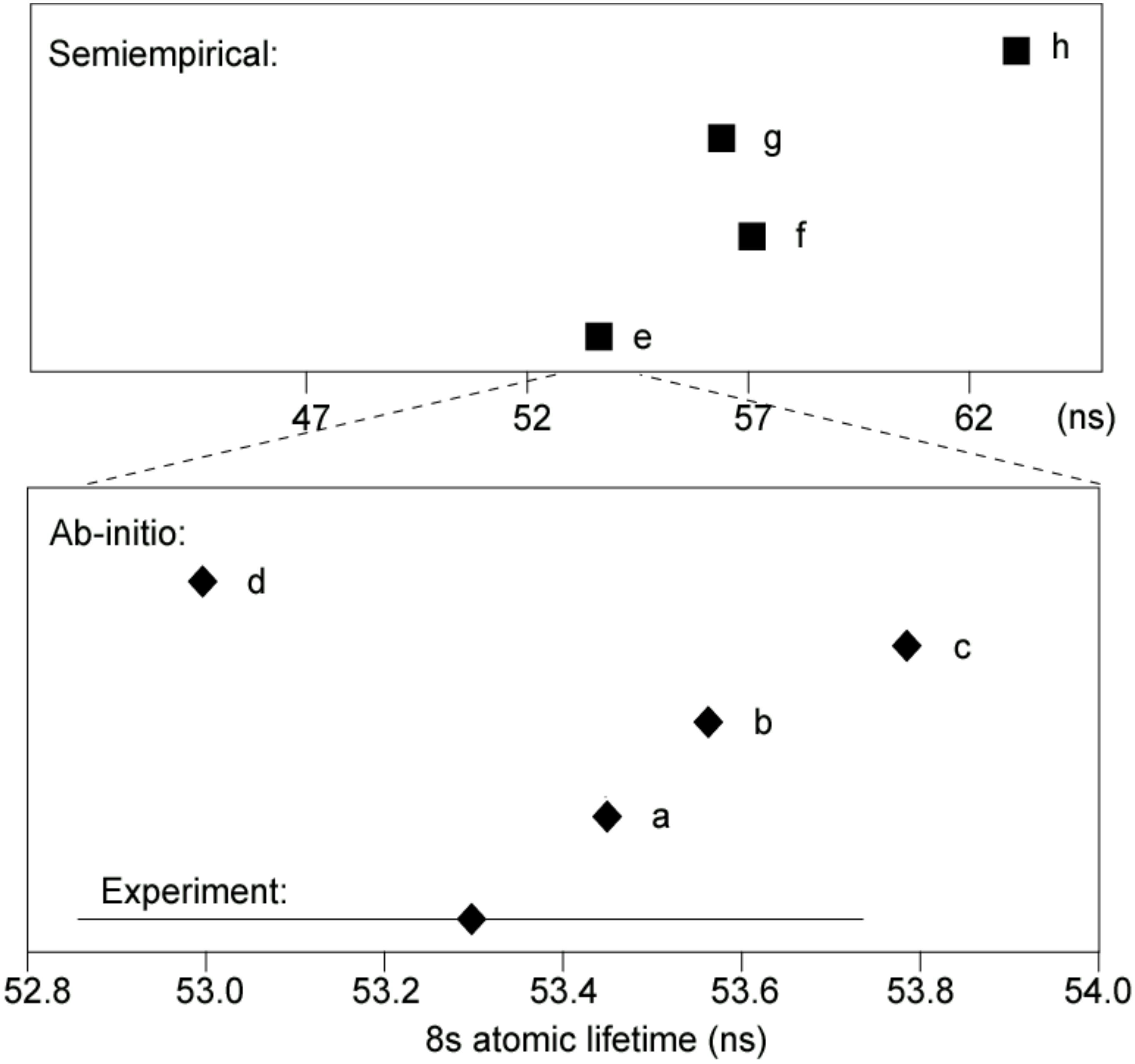
Commissioning of Capture: Sep., Dec. 2012

Trapped atoms: > 2.5 $\times 10^{6}$)
Efficiency ~ 0.5%



Trap lifetimes ~ 20s
Isotopes trapped 206, 207, 209, 213, 221.
Radioactive lifetime ($\tau_{1/2}$ = 50.5 s for ^{209}Fr)

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.*

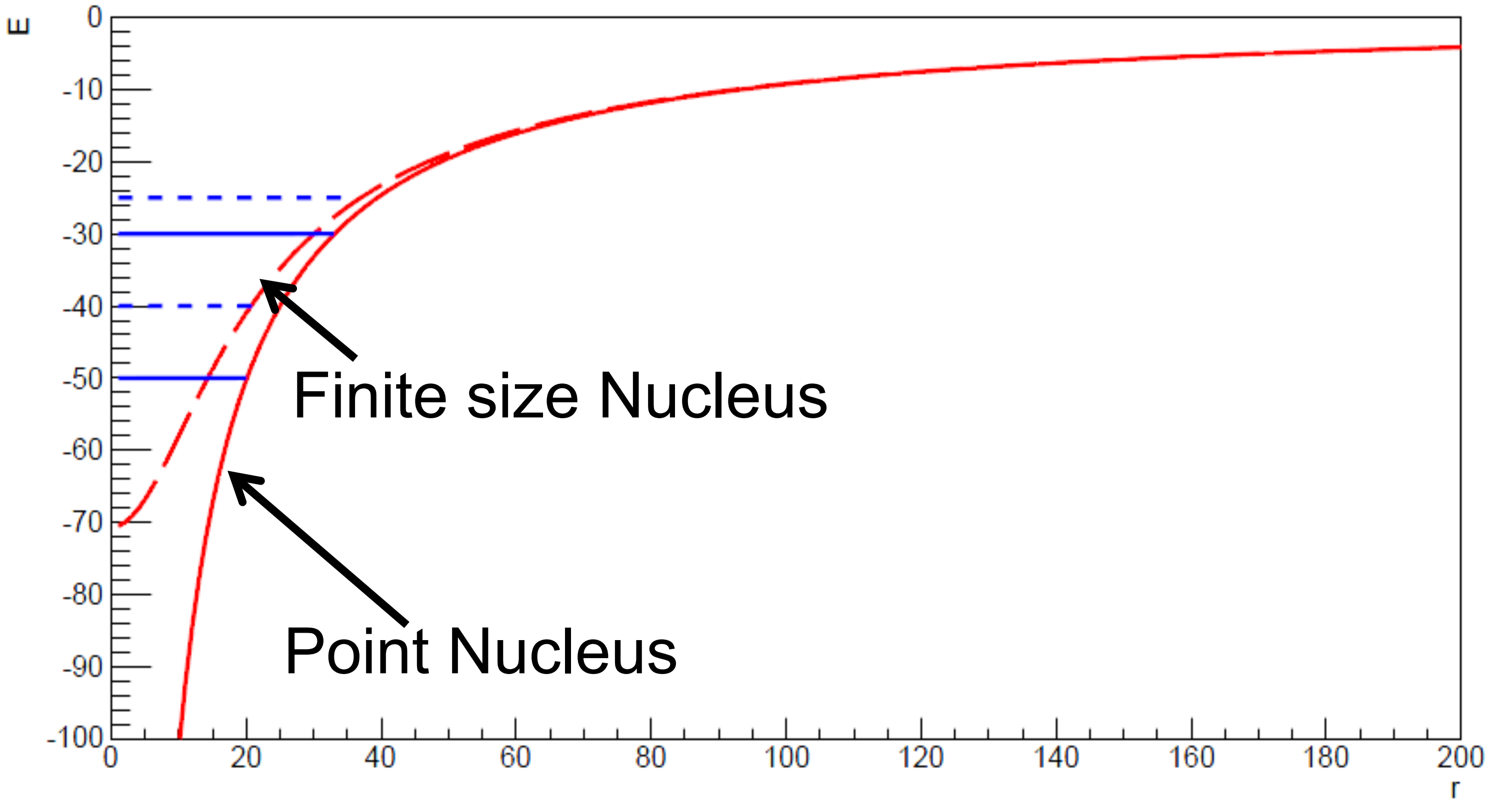
f) Theodosiou *et.al.*

g) Biemont *et.al.*

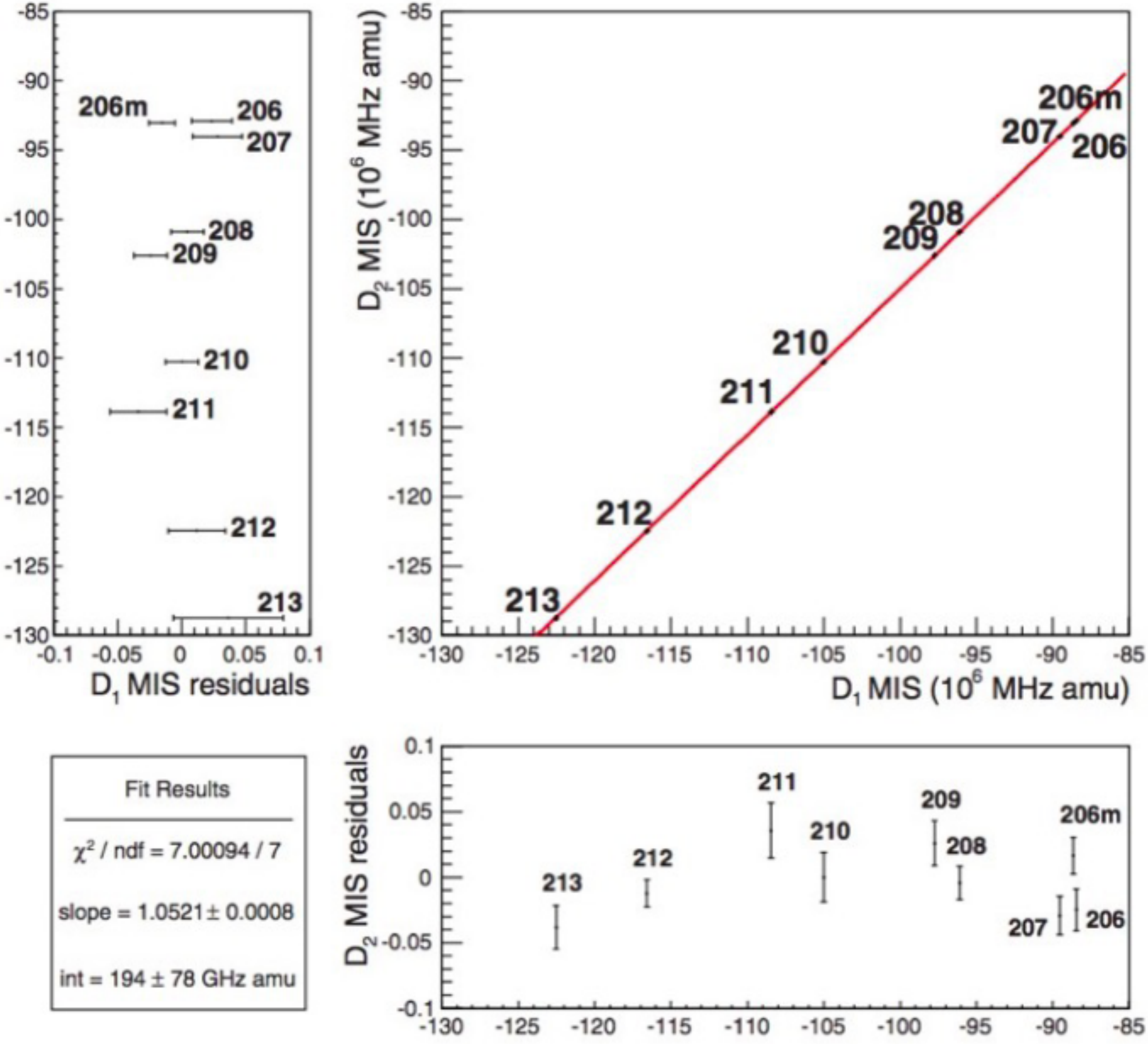
h) Van Wijngaarden *et.al.*

Isotope Shift

- Mass Shift
  - Reduced mass
  - Electronic correlations
- Field Shift



King Plot with the Isotope Shift for Fr on the D1 and D2 lines.



Fit Results

χ^2 / ndf = 7.00094 / 7

slope = 1.0521 ± 0.0008

int = 194 ± 78 GHz amu

Isotope shift comparison to theory

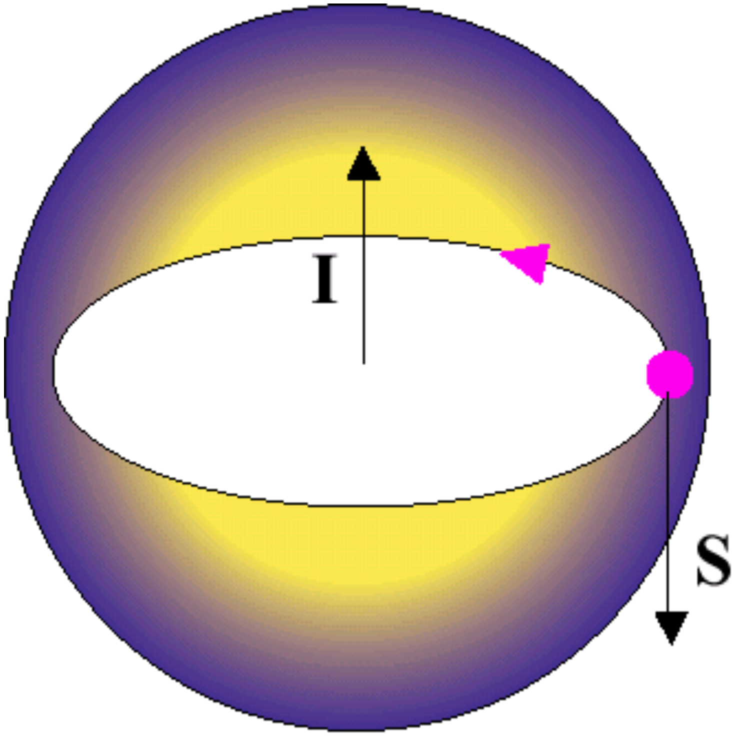
$$\frac{F_{D2}}{F_{D1}} = 1.052\,(1)$$

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

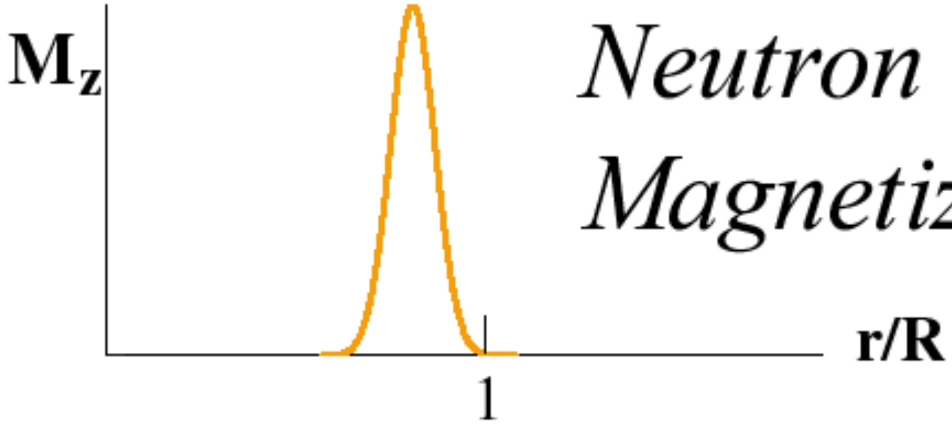
Method	$7S_{1/2}$	$7P_{1/2}$	$7P_{3/2}$	F_{D2}/F_{D1}
BO(Σ^{∞})	-20463	-693	303	1.0504
SD + E3	-20188	-640	361	1.0512
M-P	-20782	-696	245	1.0468

Dzuba, Johnson and Safronova, *Phys. Rev. A* **72**, 022503 (2005)
Mårtensson-Pendrill, *Mol. Phys.* **98**, 1201 (2000)

Neutron Distribution



Unpaired Neutron $2f_{5/2}$



Neutron Magnetization

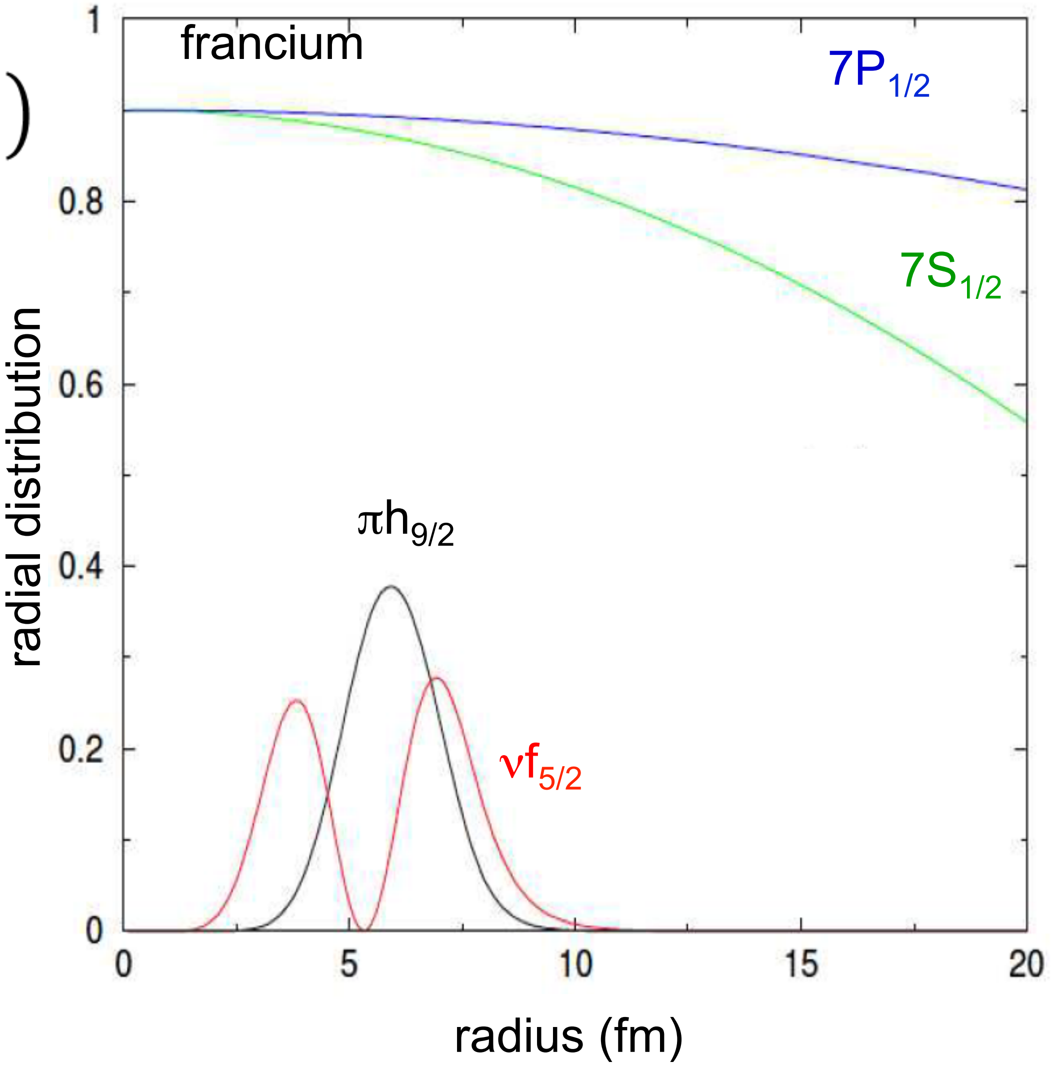
Hyperfine Interaction: Interaction of electron with the magnetic moment of nucleus.

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

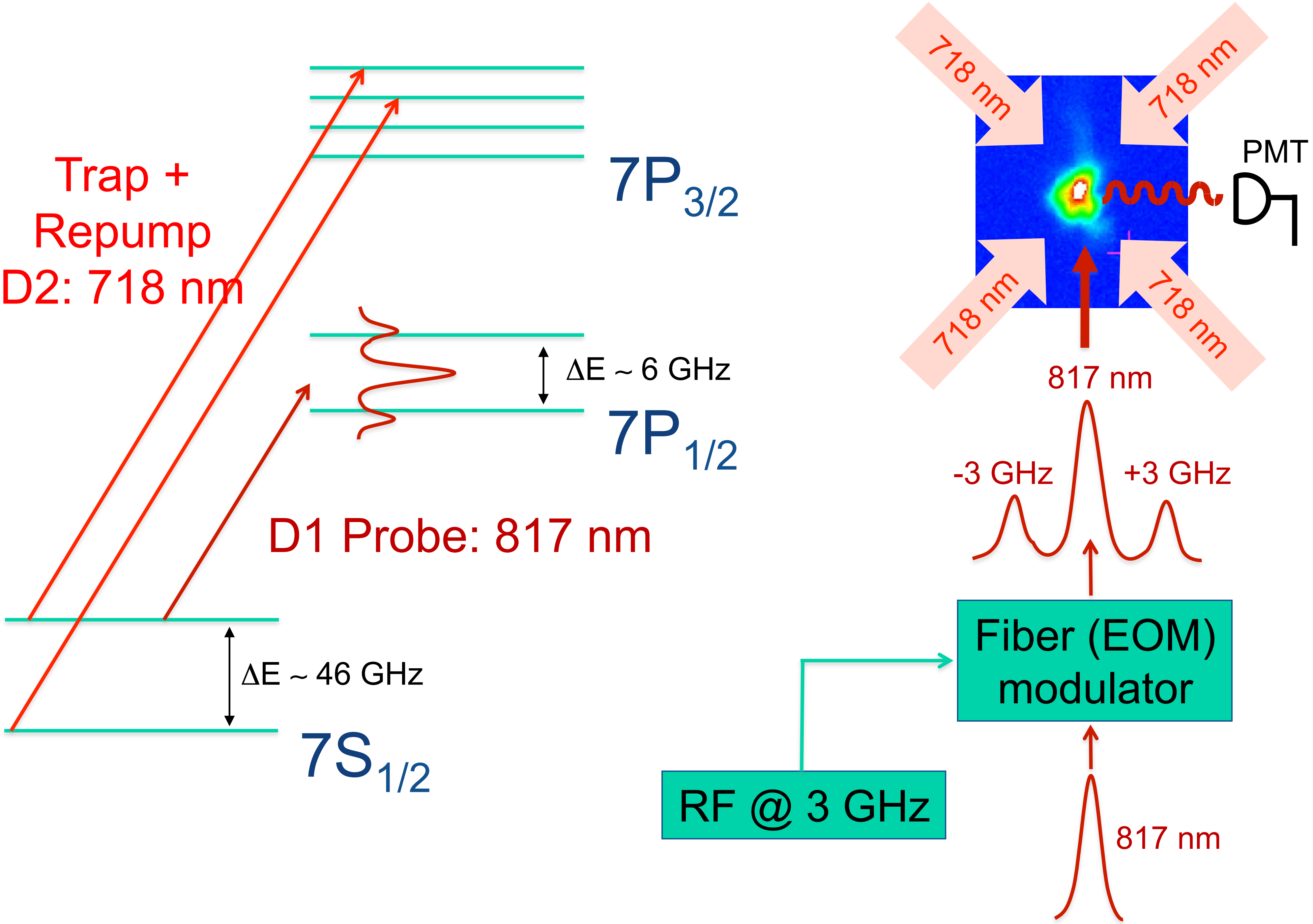
$$
\begin{aligned}
W_{hyper} &= h\, A_{S,P}[\rho]\, \vec{I}\cdot\vec{J} \\
&= W^{S,P}_{point}\left(1+\epsilon_{N,(s,p)}\right)
\end{aligned}
$$

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

ρ=nuclear magnetization distribution



Measurement of the $7P_{1/2}$ hyperfine splitting



Trap +
Repump
D2: 718 nm

$7P_{3/2}$

$\Delta E \sim 6$ GHz

$7P_{1/2}$

D1 Probe: 817 nm

$\Delta E \sim 46$ GHz

$7S_{1/2}$

718 nm

718 nm

718 nm

718 nm

PMT

817 nm

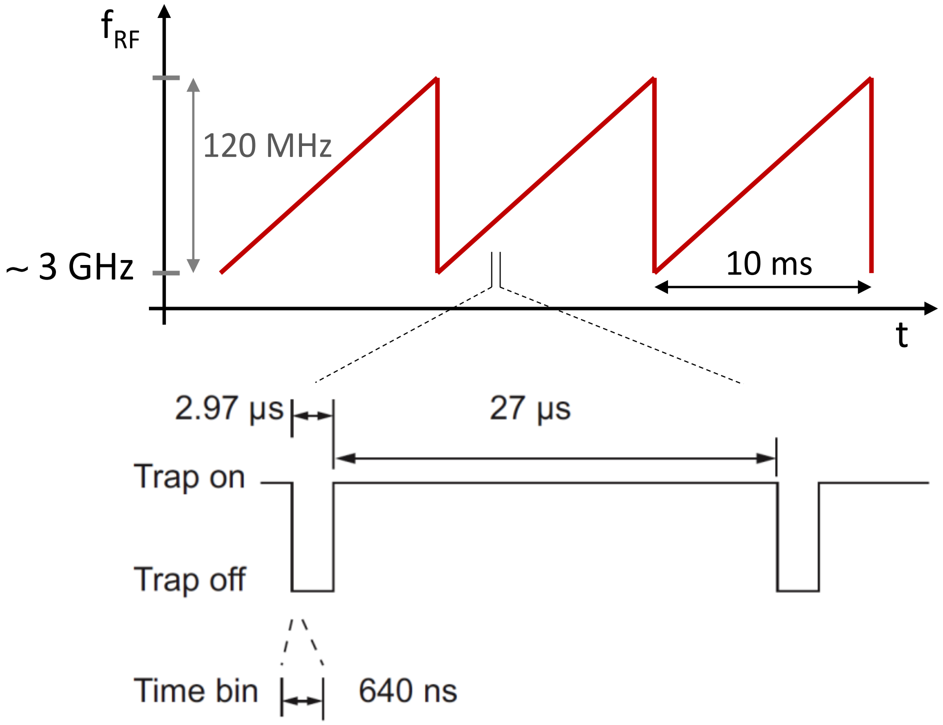
-3 GHz

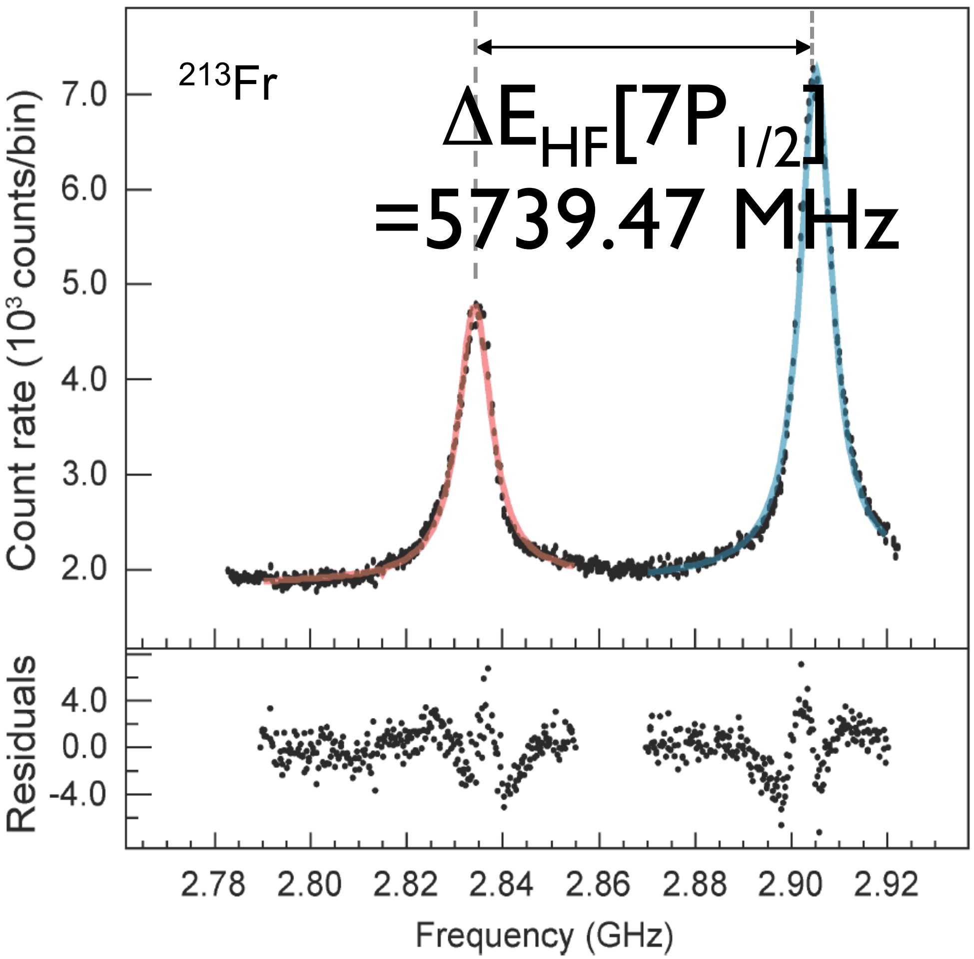
+3 GHz

Fiber (EOM) modulator

RF @ 3 GHz

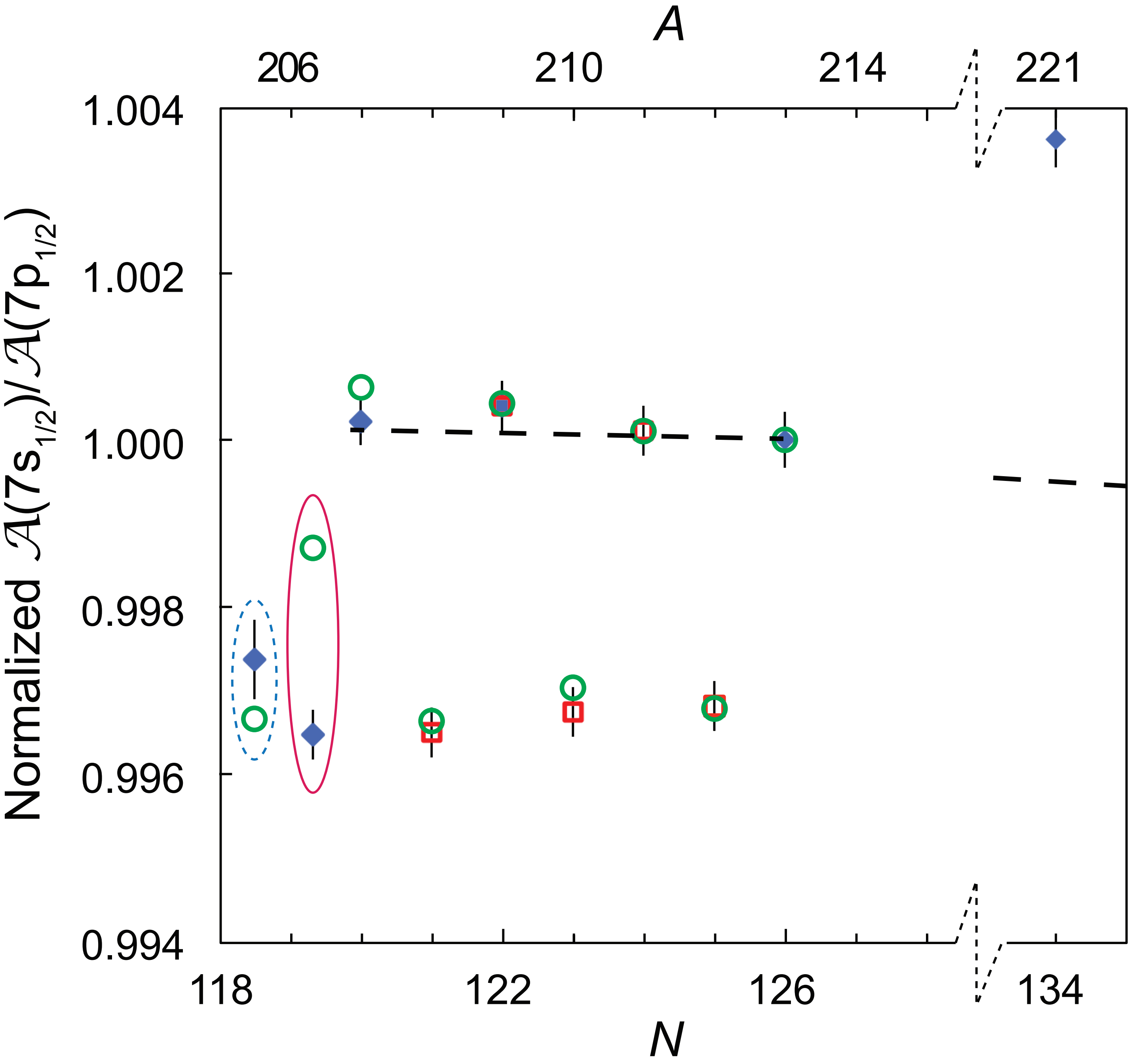
817 nm





$\Delta E_{HF}[7P_{1/2}]$
=5739.47 MHz

HF Anomaly results

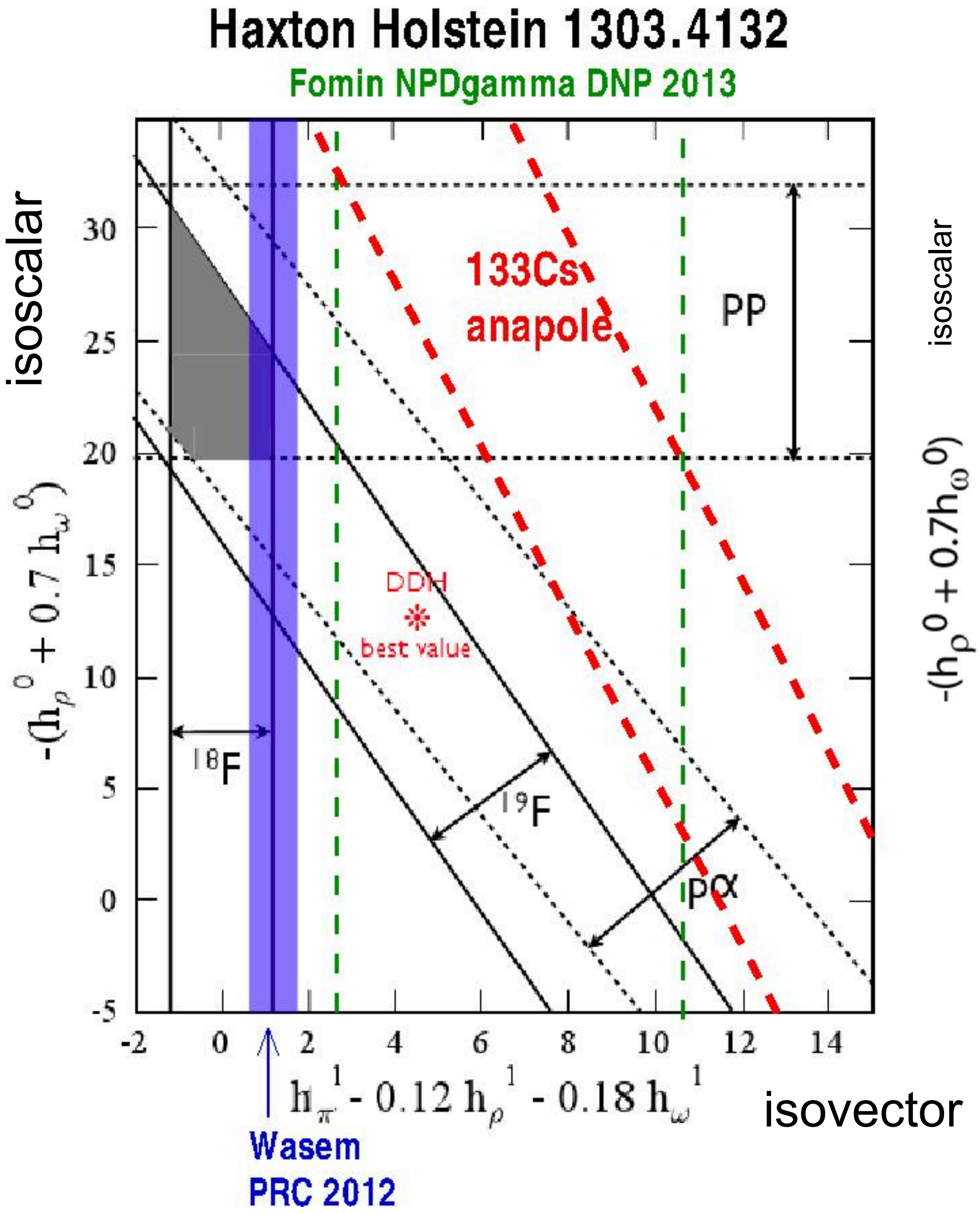


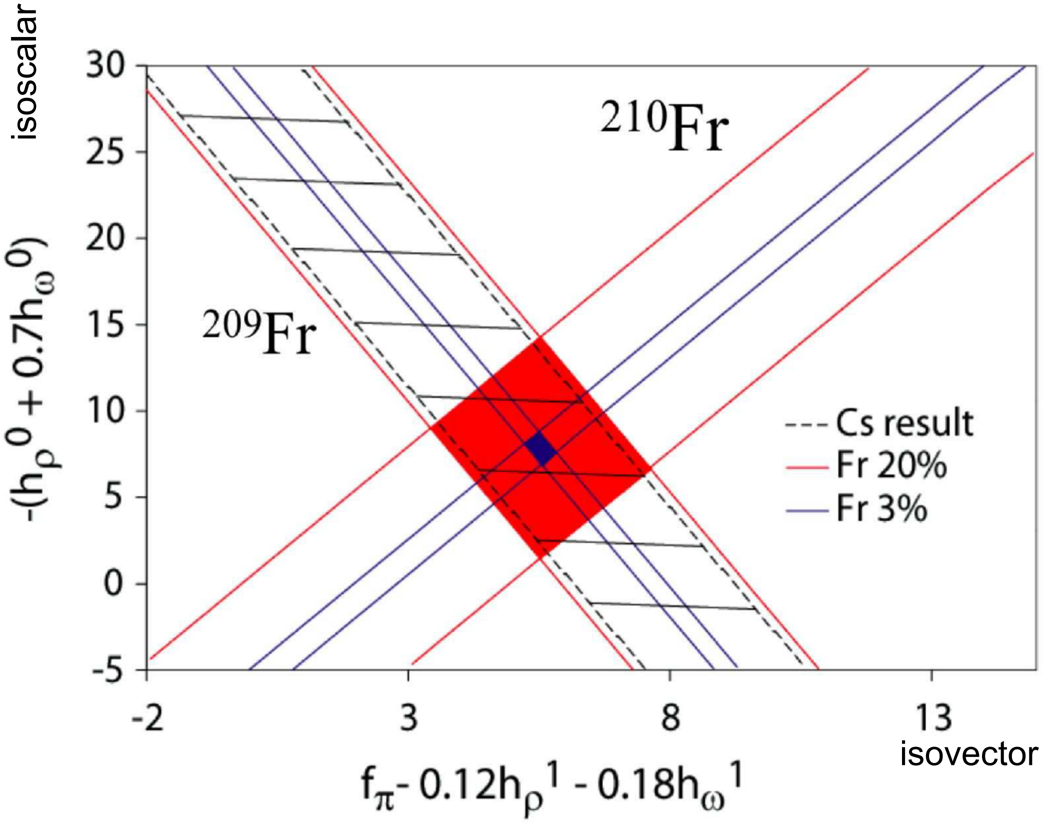
Dashed: Magnetic Radius equal to Charge Radius

Green: Nuclear Structure Theory

Blue and Red: Measurements

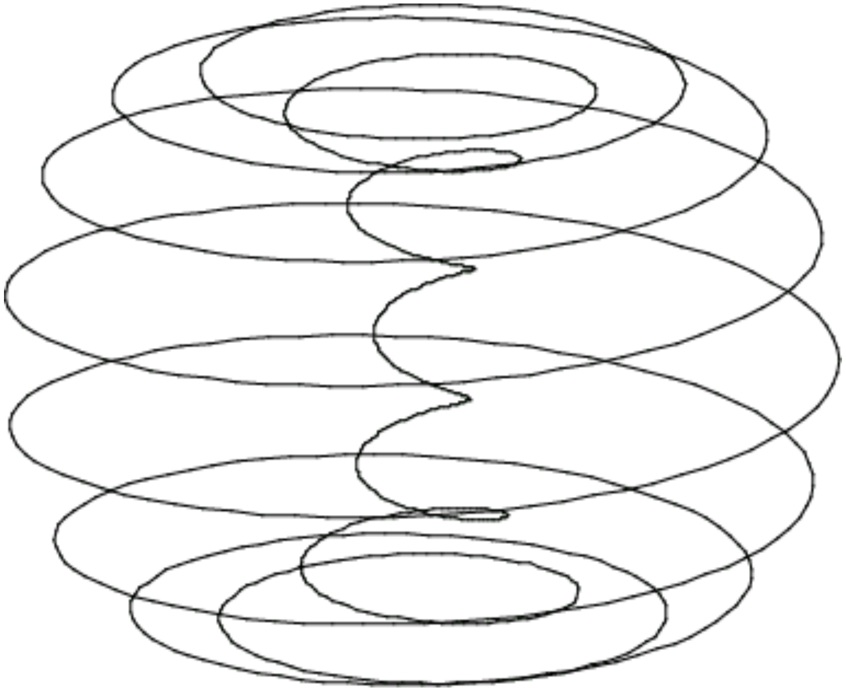
Measurements (statistics) to 30 KHz





Does weak N-N interaction change in heavy nuclei?

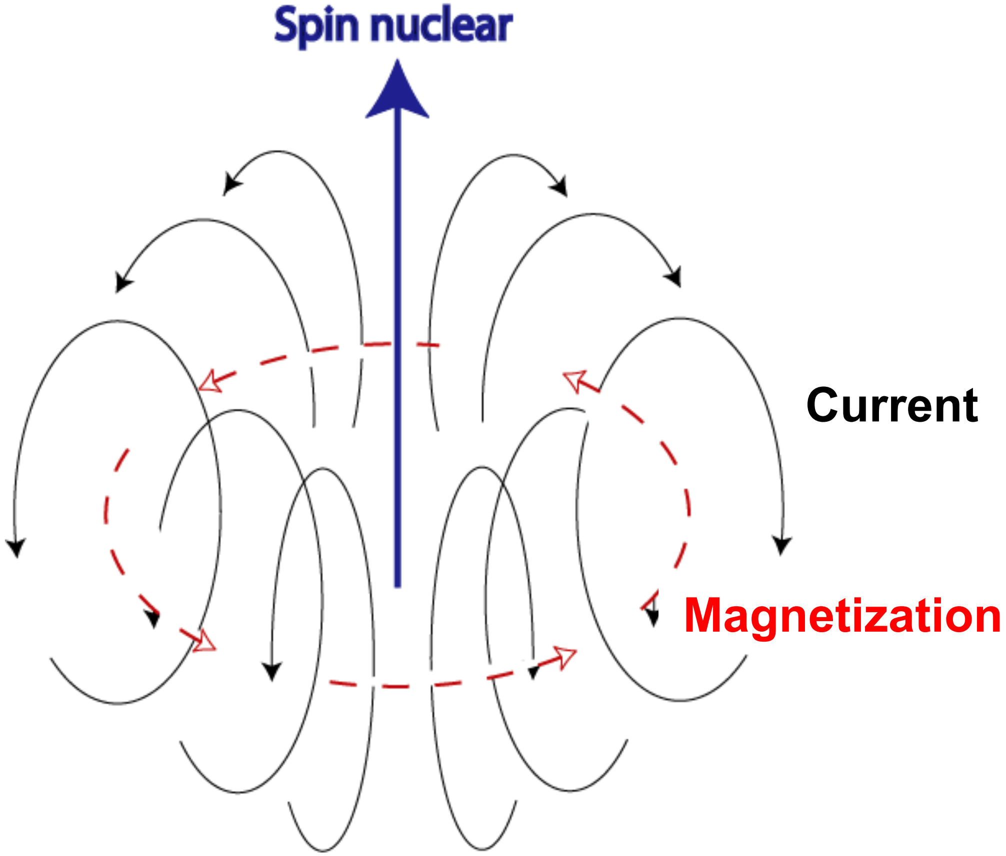
Chiral current



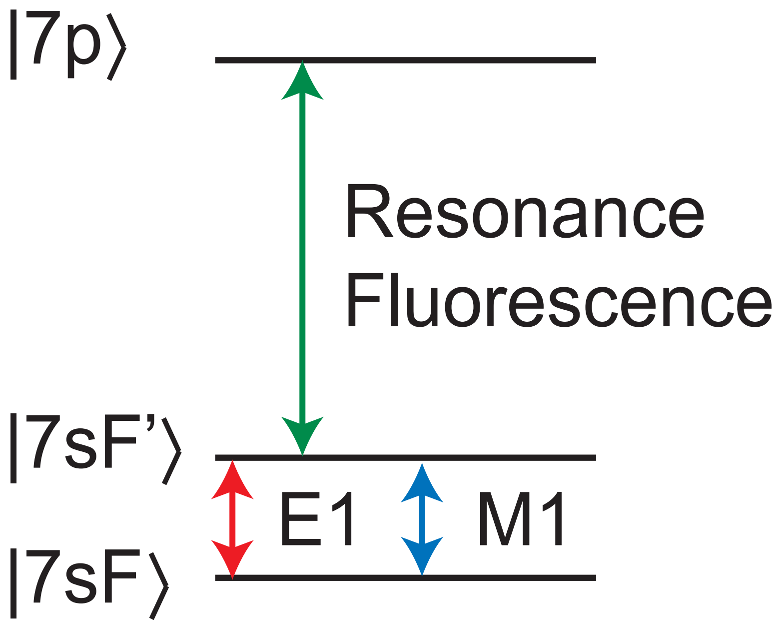
Anapole moment

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

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



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:

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

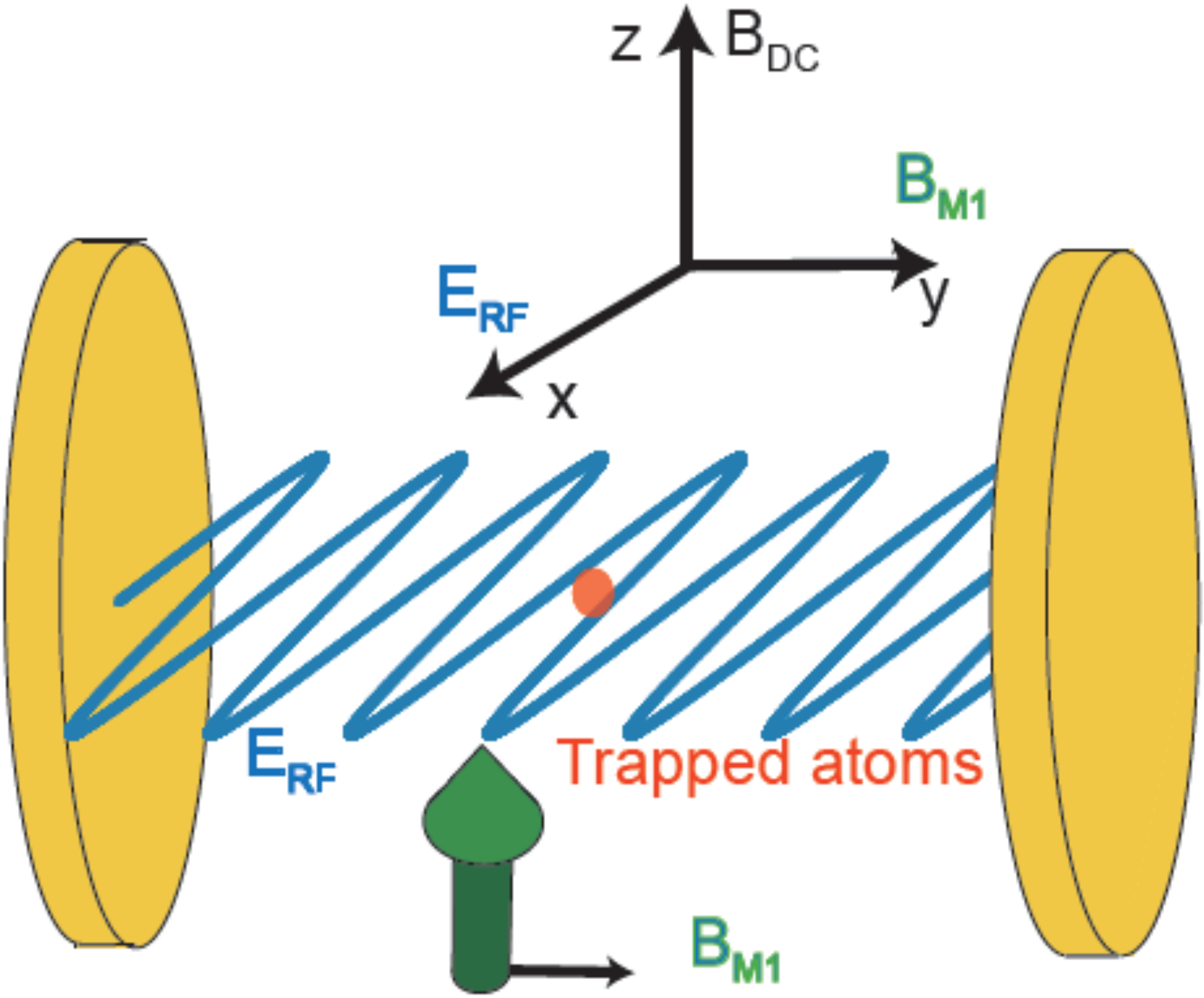
3.- Measure rate of transition through resonance fluorescence.

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

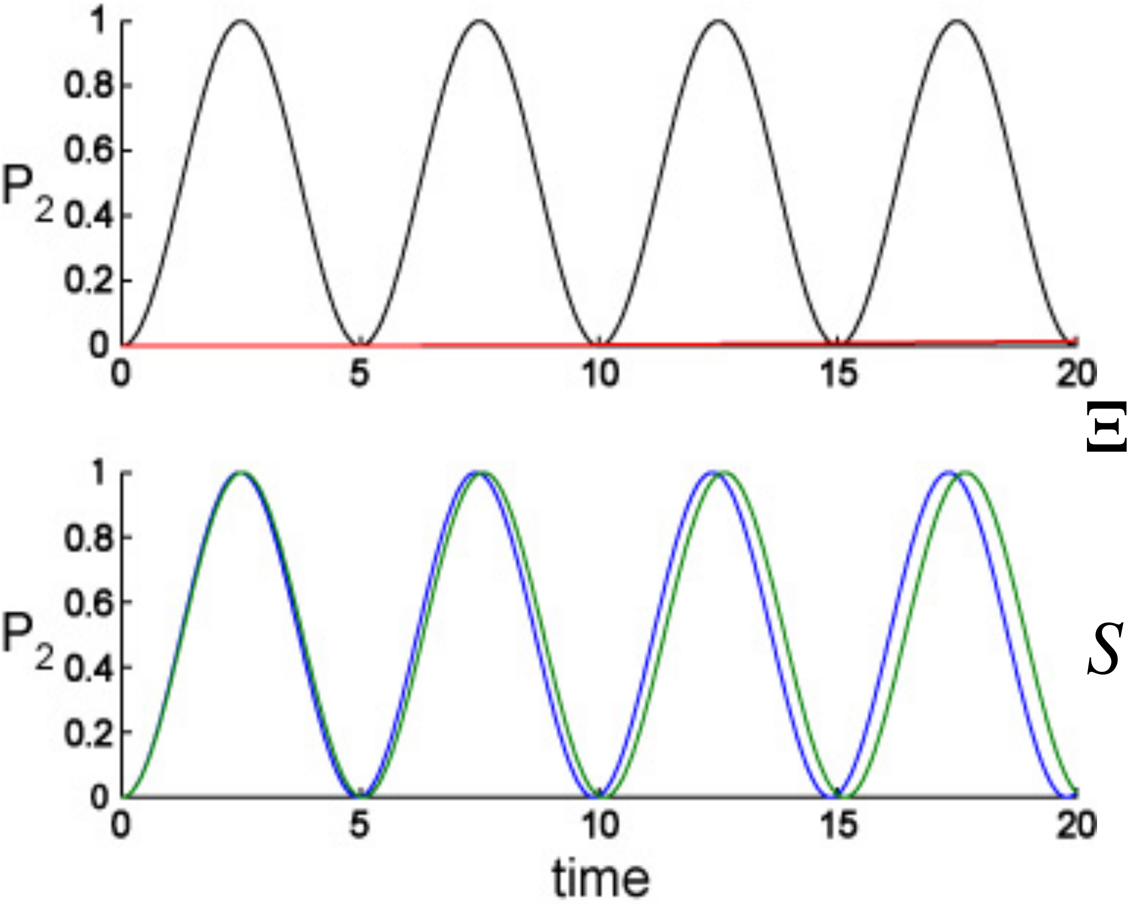
4.- Change handedness of apparatus

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

5.- Repeat.

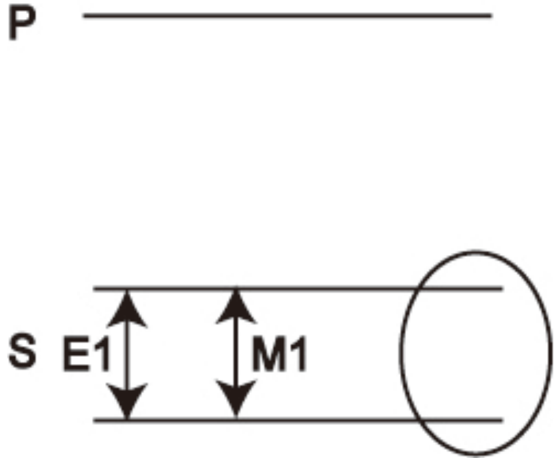

z
B_DC
B_M1
E_RF
y
x
E_RF
Trapped atoms
B_M1

Principle of the measurement



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

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



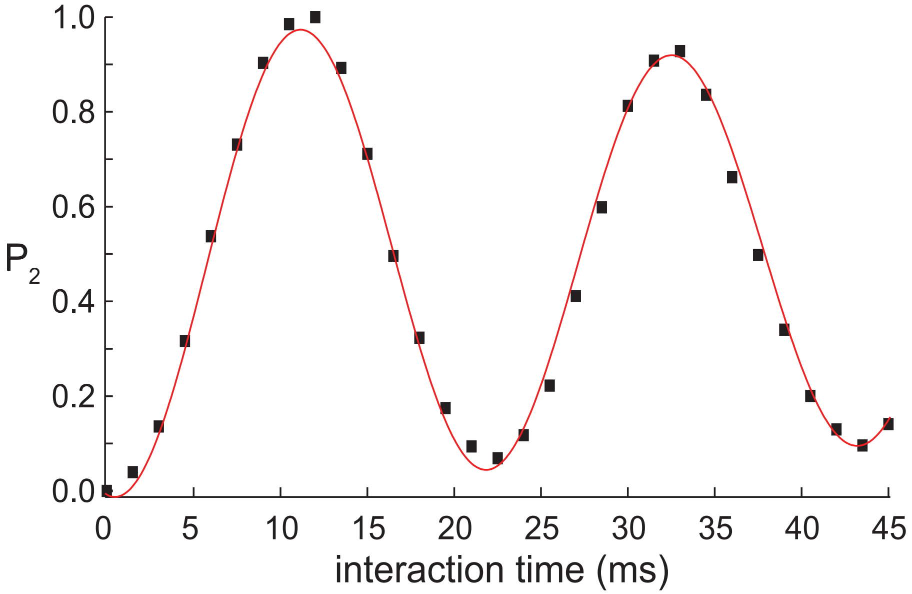
Control phase of different interactions

Ground state hyperfine splitting

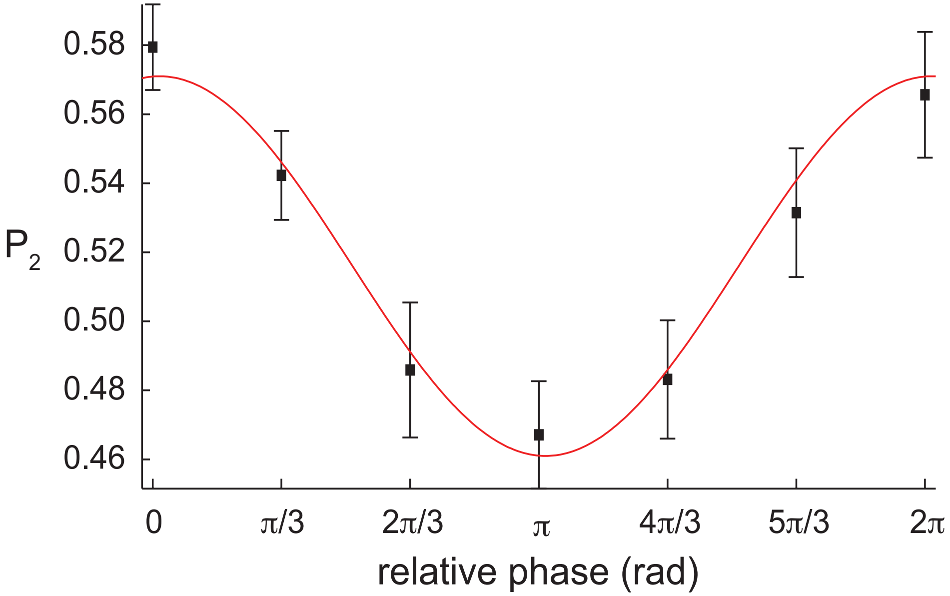
Fr ~46 GHz, Z=87

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. Decoherence time 180 ms.



While sitting at 37.5 ms, add a second microwave source with 10^4 attenuation, change of the phase and see the signal increase and decrease.

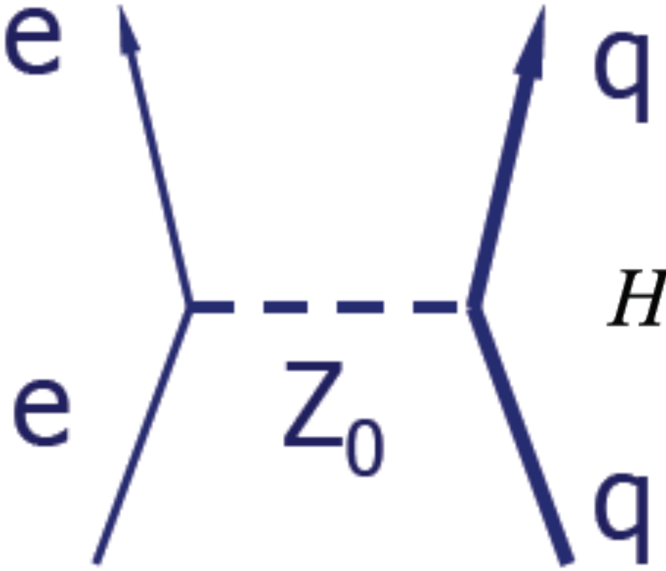
$$\frac{Signal}{Noise} = 2\Omega_{E1}\Delta t\sqrt{N} = 2$$

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

Ω_{E1} ~ 10 mrad

Interaction time = $\Delta\tau$ ~ 0.1s

How to extract Q_w, the weak charge, from an experiment with Fr due to the virtual exchange between an electron and a quark through a Z^0

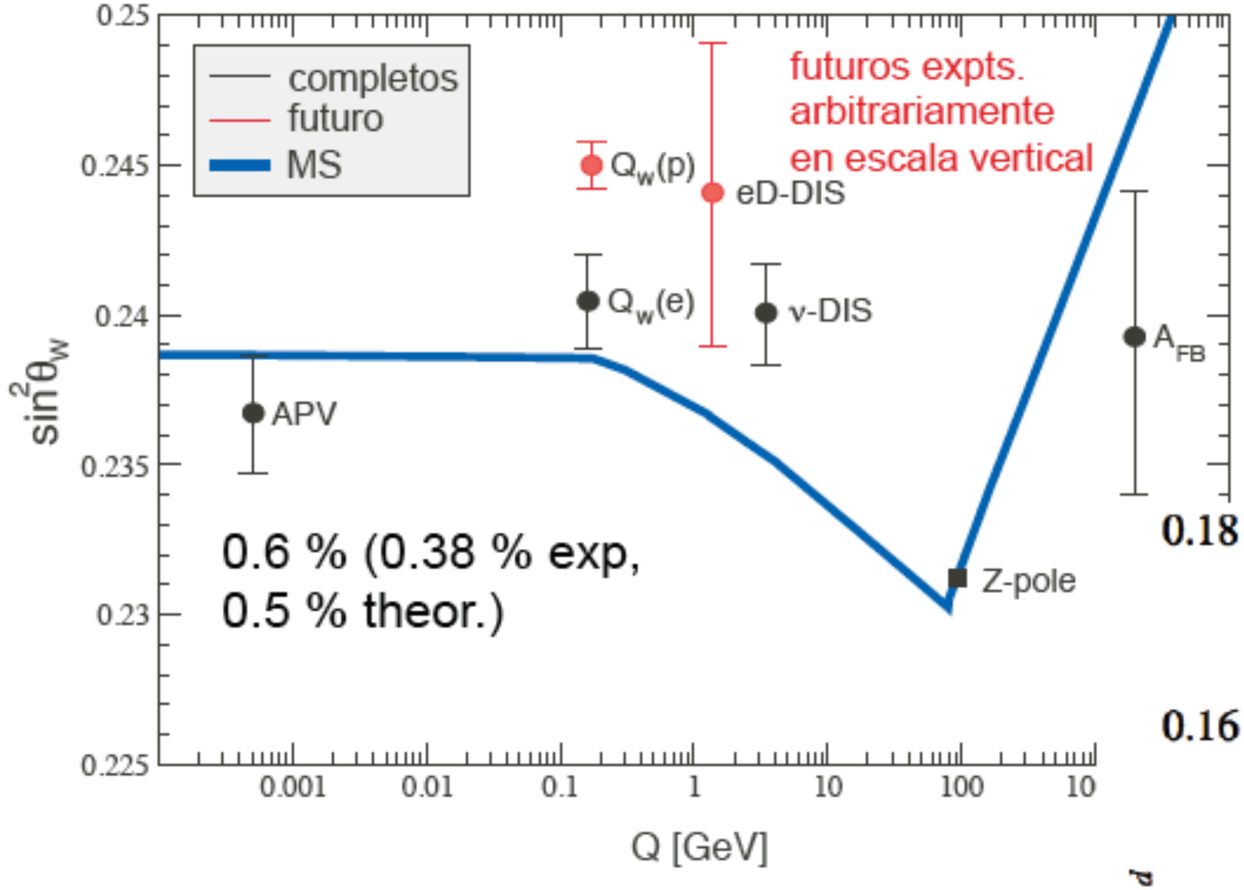


$$H_W = \frac{G_F}{\sqrt{2}}\left(\bar{e}\gamma_\mu\gamma_5 e\right)\left\{C_{1u}\bar{u}\gamma^\mu u + C_{1d}\bar{d}\gamma^\mu d\right\} + \ldots$$

Density of Neutrons

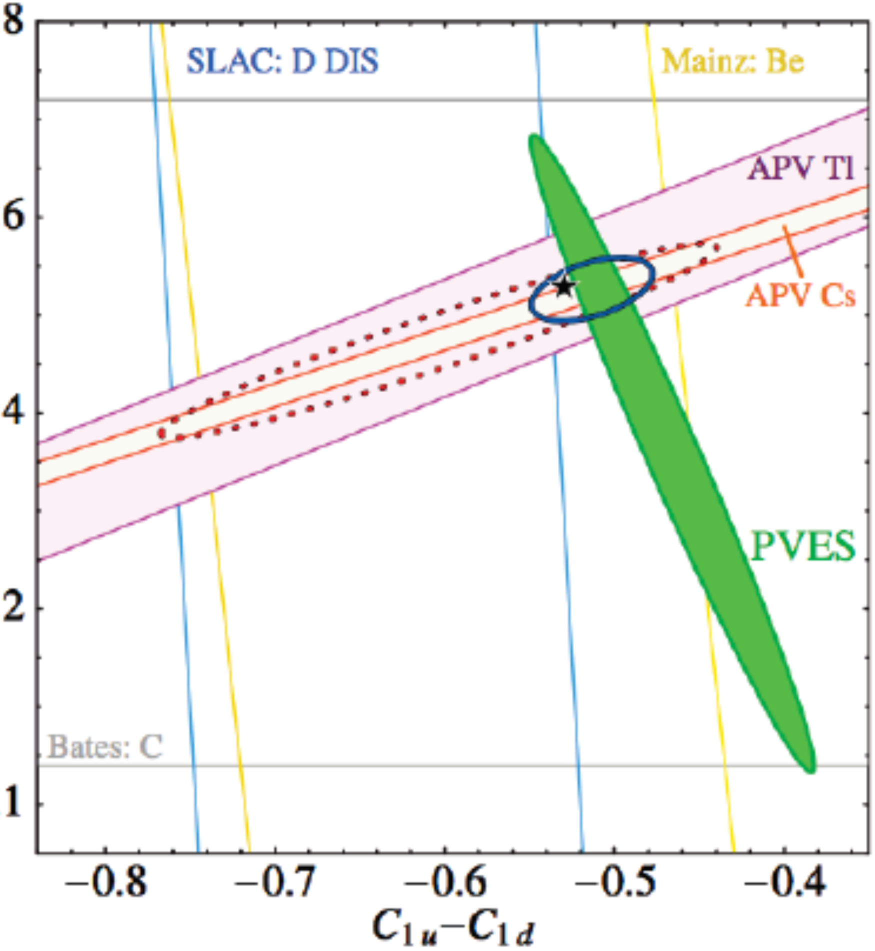
$$H^{(1)}_{PNC} = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(r)$$

Weimberg angle



0.6 % (0.38 % exp, 0.5 % theor.)

Q_{weak} proportional to $C_{1u} + C_{1d}$



PV from electron scatering gives $C_{1u} - C_{1d}$

APNC provides an orthogonal bound

Gracias