“Laser Studies of Basic Atoms and Nuclei – an Olympics of Precision”

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Outline

- Motivation
- Comments on Precision in Physics
- Helium Fine Structure
- Isotope Shifts and Nuclear Size
- Laser Frequency Doubling
- Summary and Conclusions

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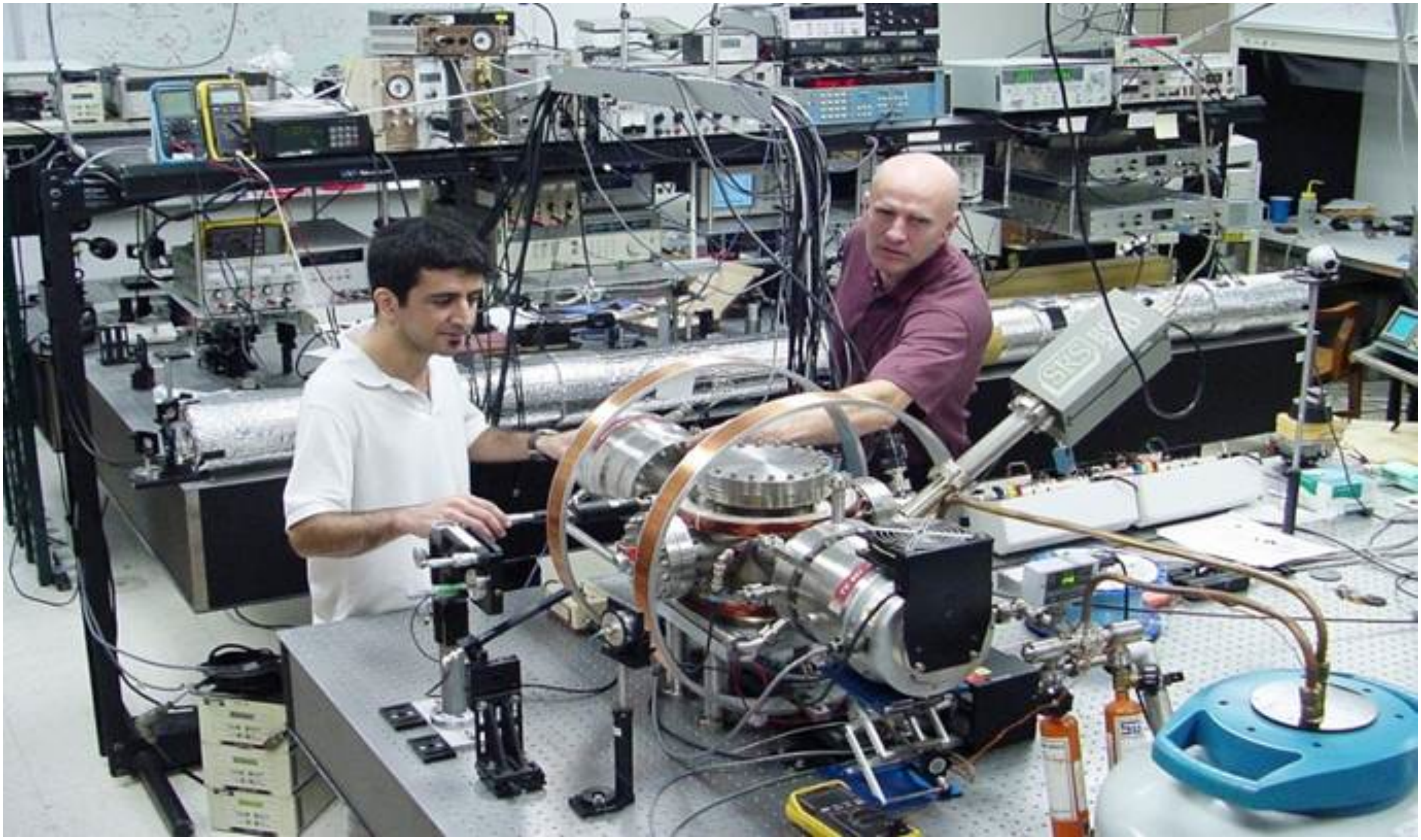
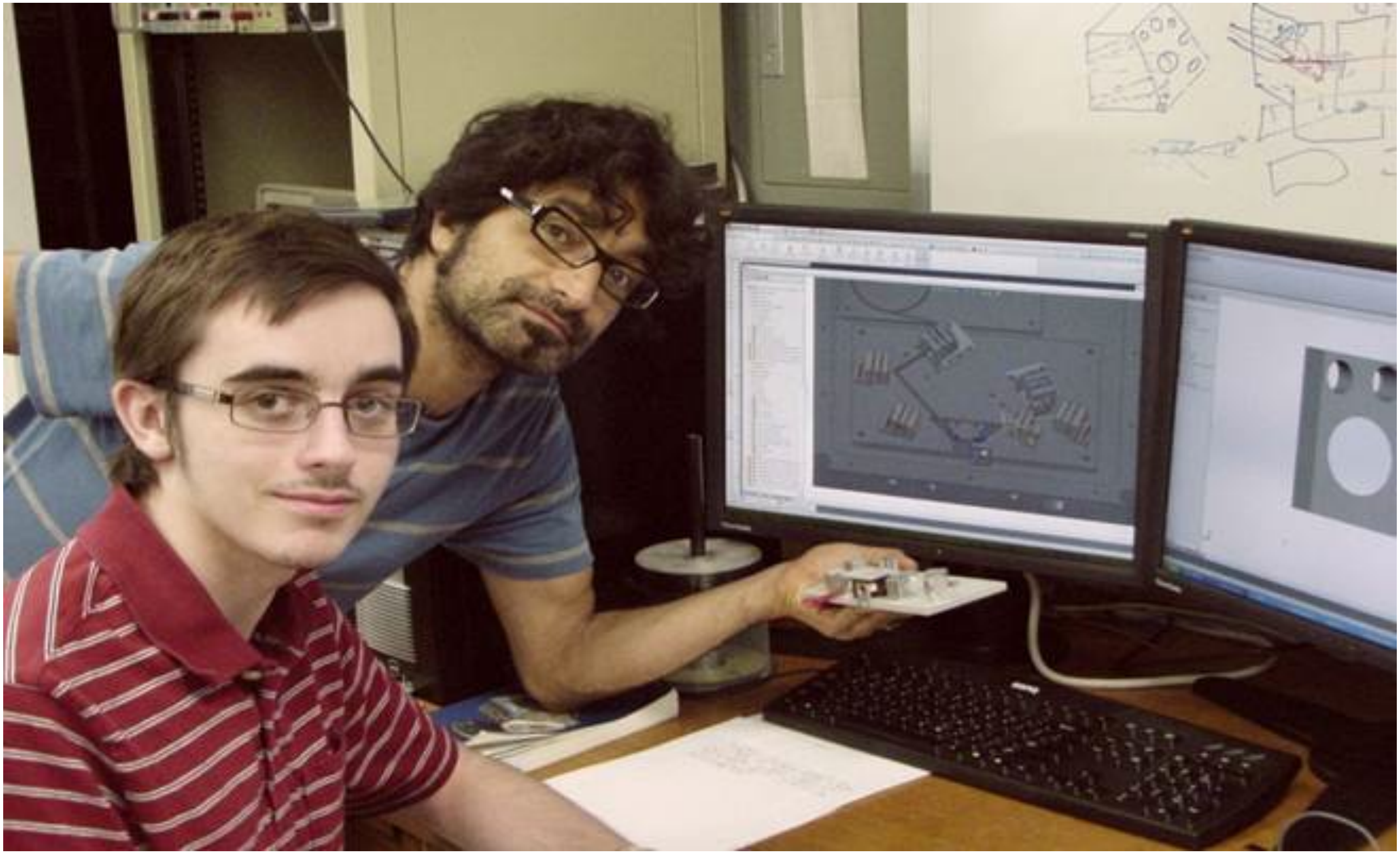
- People – training or human resource development


SKS


Fujikura


Trouble Shoot
Slicer TM Assembly



Custom machinist

Motivation – nontechnical

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Precision in theory and experiment

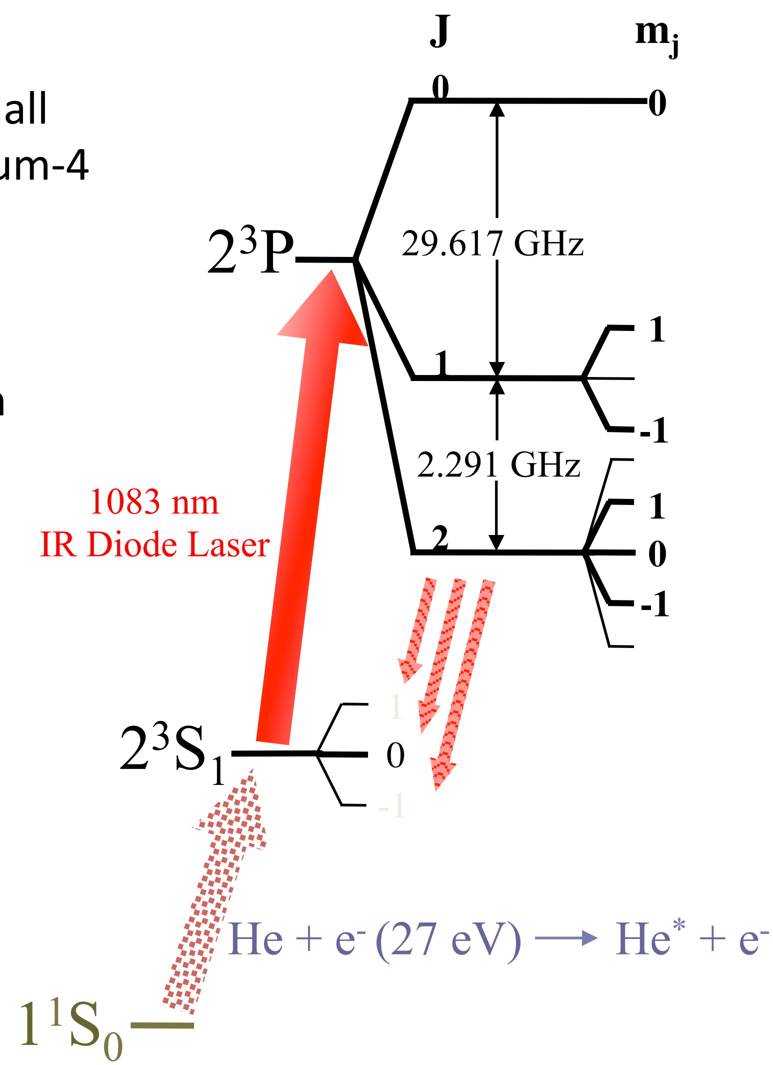
- Precision in experiment but no theory - application to standards
- Precision in theory but no experiment
- Precision based on theoretical assumption and experimental null measurement – powerful technique ($q_e = q_p$, $m_{in} = m_g$, parity, edm)
- Precision calculation and measurement – ppm, ppb, ppt – sensitive to any deviations
- A few “simple” systems that provide the tests – in electromagnetic systems these are primarily simple atoms, i.e. hydrogen and helium like.

Introduction to Helium Spectroscopy

Measurements conducted of the large and small fine structure splittings in the 2^3P level of helium-4

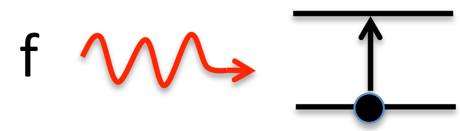
Technique involves a metastable atomic beam excited by a 1083nm diode laser

Implement new technologies and refine techniques for use in high precision laser spectroscopy



Basic Methodology

- $\Delta E = h\, f,$



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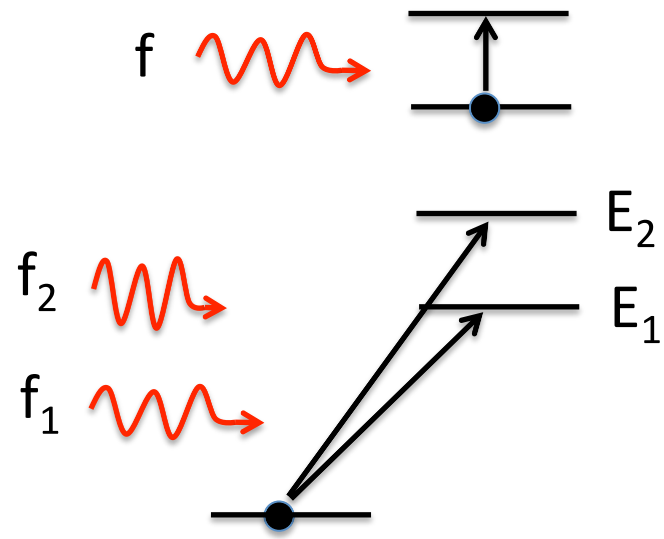

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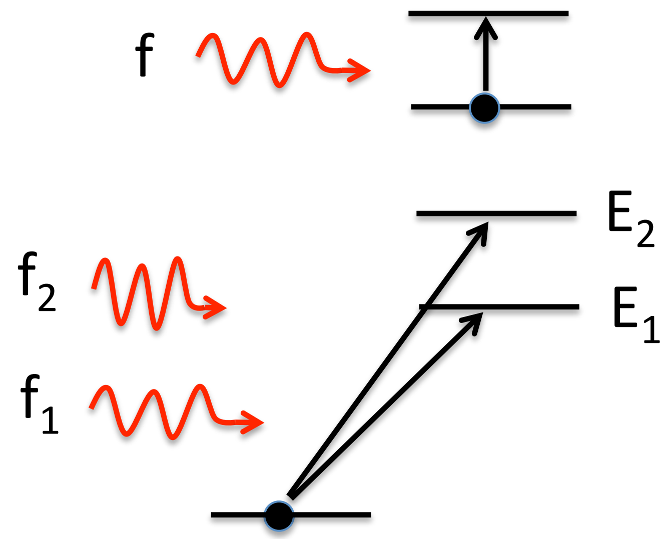

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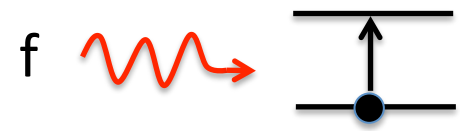

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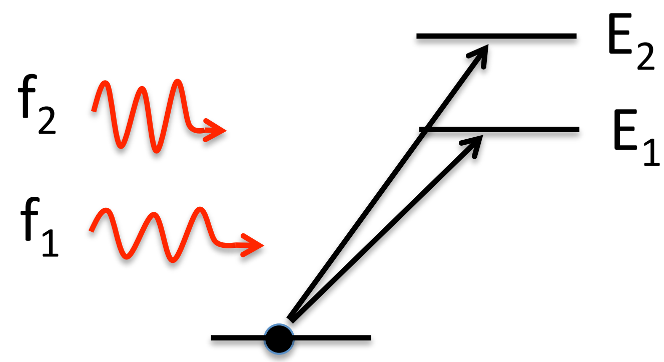


- Multiple splittings – which method?
- Stable states, systematic check
- Isotope shift

Theoretical Framework

- Basic He-4 Structure – Coulomb interaction and variational calculation
- Effective Operators – fine structure with perturbation theory
- Transition Probabilities – external time dependent field
- Magnetic Field Dependencies
- He-3 Hyperfine Structure
- $E = mc^2(1+c_2\alpha^2+c_4\alpha^4+c_5\alpha^5+c_6\alpha^6+\ldots)$
- α = fine structure constant, $\alpha = e^2/\hbar c$
- Big picture – Nucleus and electrons interacting through the electromagnetic field, i.e. emission and absorption of photons described by Feynman diagrams, demonstration?

Basic He-4 Structure

The basic structure of the helium atom can be understood by identifying the quantum numbers that describe the system.

Spin-Spin Interaction

Helium consists of 2 electrons, which are spin-½ particles. Thus, the total spin angular momentum of the system is

$$S = |s_1 - s_2|, \ldots, s_1 + s_2 \quad \text{with} \quad m_s = -S, \ldots, +S$$

So, $S = 0$ *with* $m_s = 0$ and $S = 1$ *with* $m_s = -1, 0, +1$

These are the Singlets and Triplets respectively that arise from the large electron-electron coulomb interaction.

Spin-Orbit Interaction (Fine Structure Splitting)

For the purposes of this experiment, the total angular momentum of the system will be limited to L = 0 and L = 1 for the 2^3S and the 2^3P states respectively. Thus,

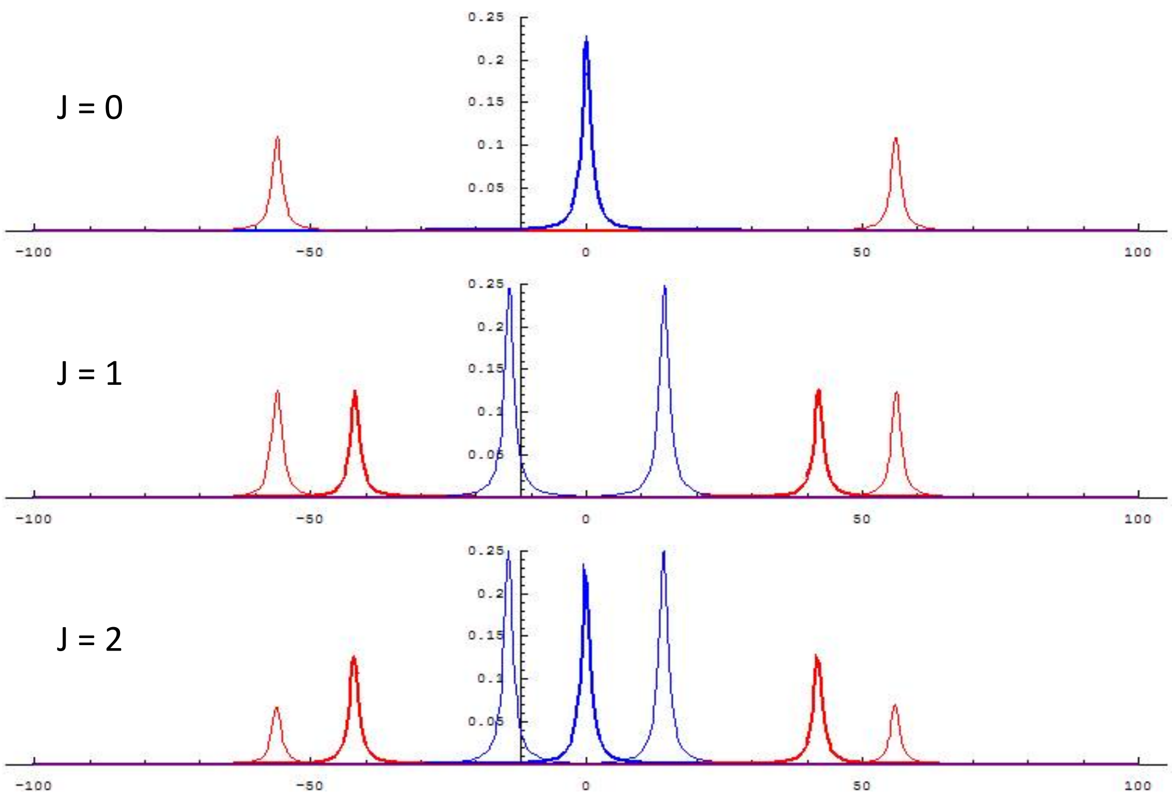
$$J = |S - L|, \ldots, S + L \quad \text{with} \quad m_j = -J, \ldots, +J$$

The total angular momentum for the 2^3P levels are

$J = 0, 1$ ***and*** 2 with the corresponding m_j

Transition Probabilities

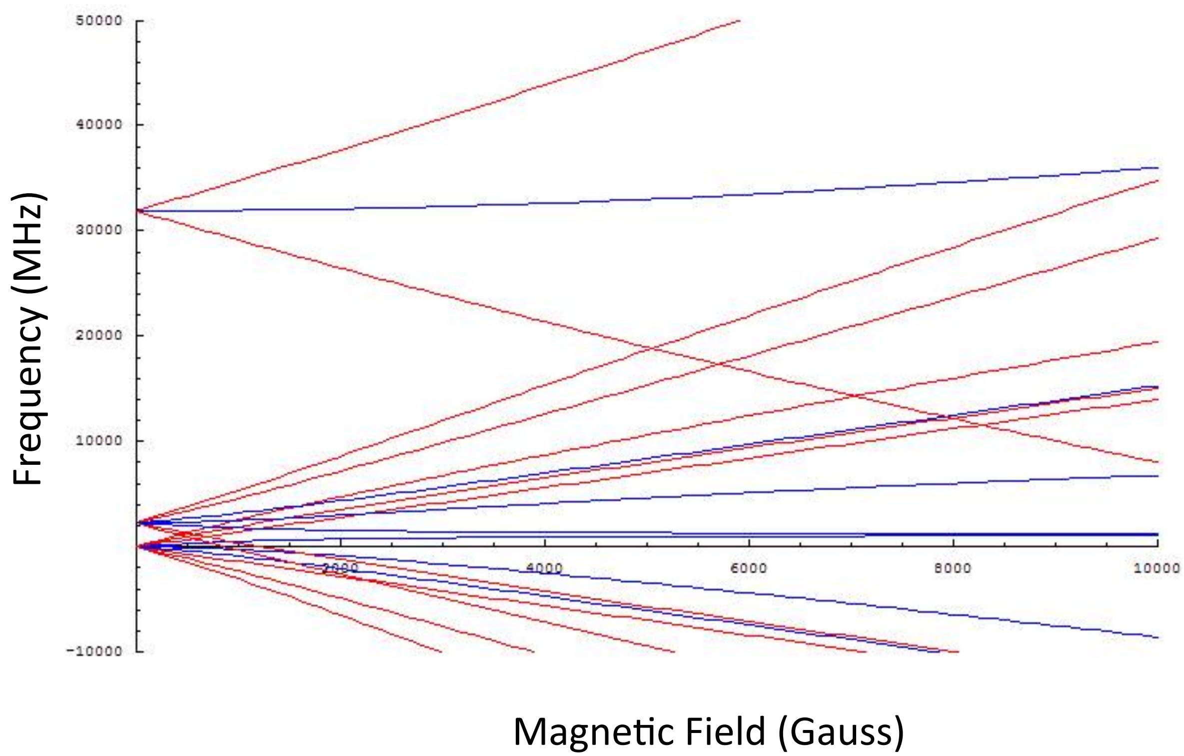
Relative Signal Strength



Magnetic Field Dependencies

The magnetic field dependence of the states is found by determining the energy eigenvalues for a range of magnetic field values. This is used not only to predict where the transitions are in a magnetic field, but also to extrapolate to zero field during the data analysis.

Relative Transition Frequency vs. Magnetic Field



He-3 Hyperfine Structure

A very valuable consistency check is possible by measuring the Helium-3 hyperfine structure. Although a much more complicated system, the 2^3S hyperfine splitting is know to a very high precision.

Unlike He-4, the nuclear spin quantum number (*I*) of He-3 is equal to ½. Adding in this angular momentum introduces the hyperfine splitting.

2^3S Metastable States

F = S – I,…,S + I = 1 - ½,…,1 + ½

F = 1/2 and F = 3/2

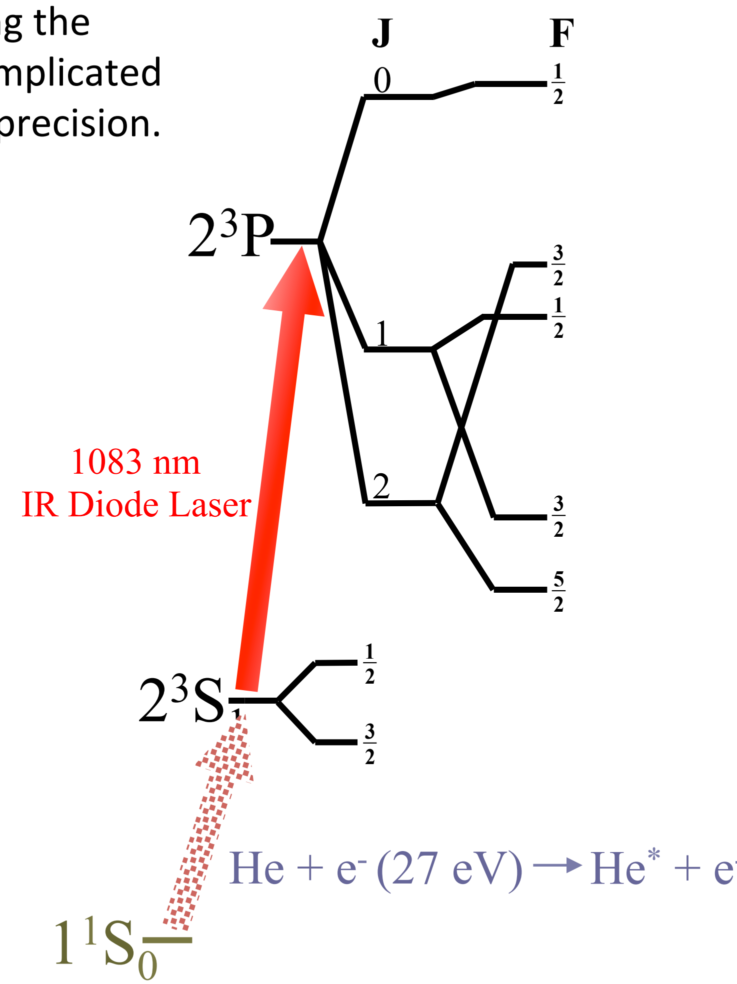
2^3P States

F = J – I,…,J + I

J = 0, F = 1/2

J = 1, F = 1/2 and F = 3/2

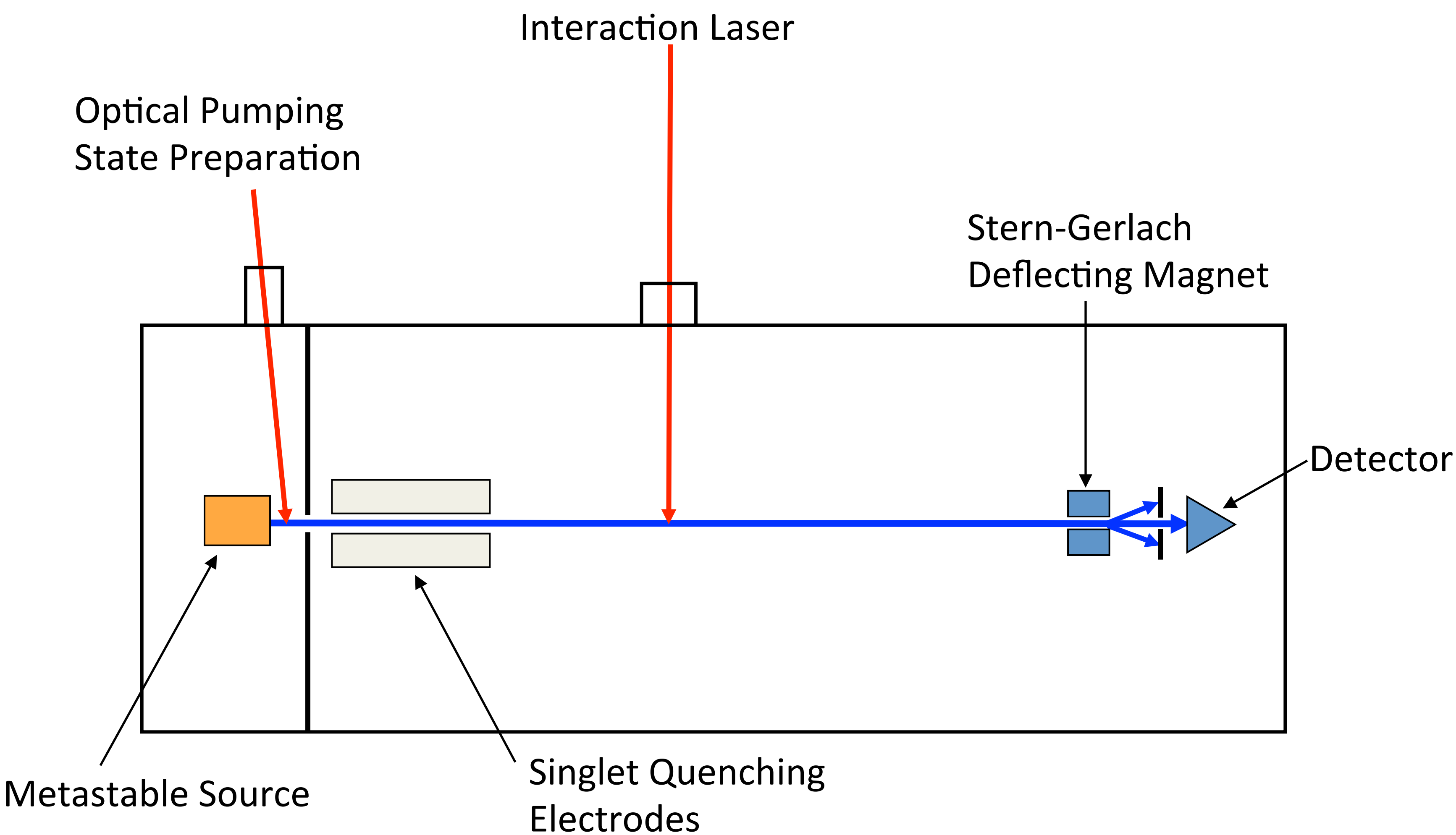
J = 2, F = 3/2 and F = 5/2



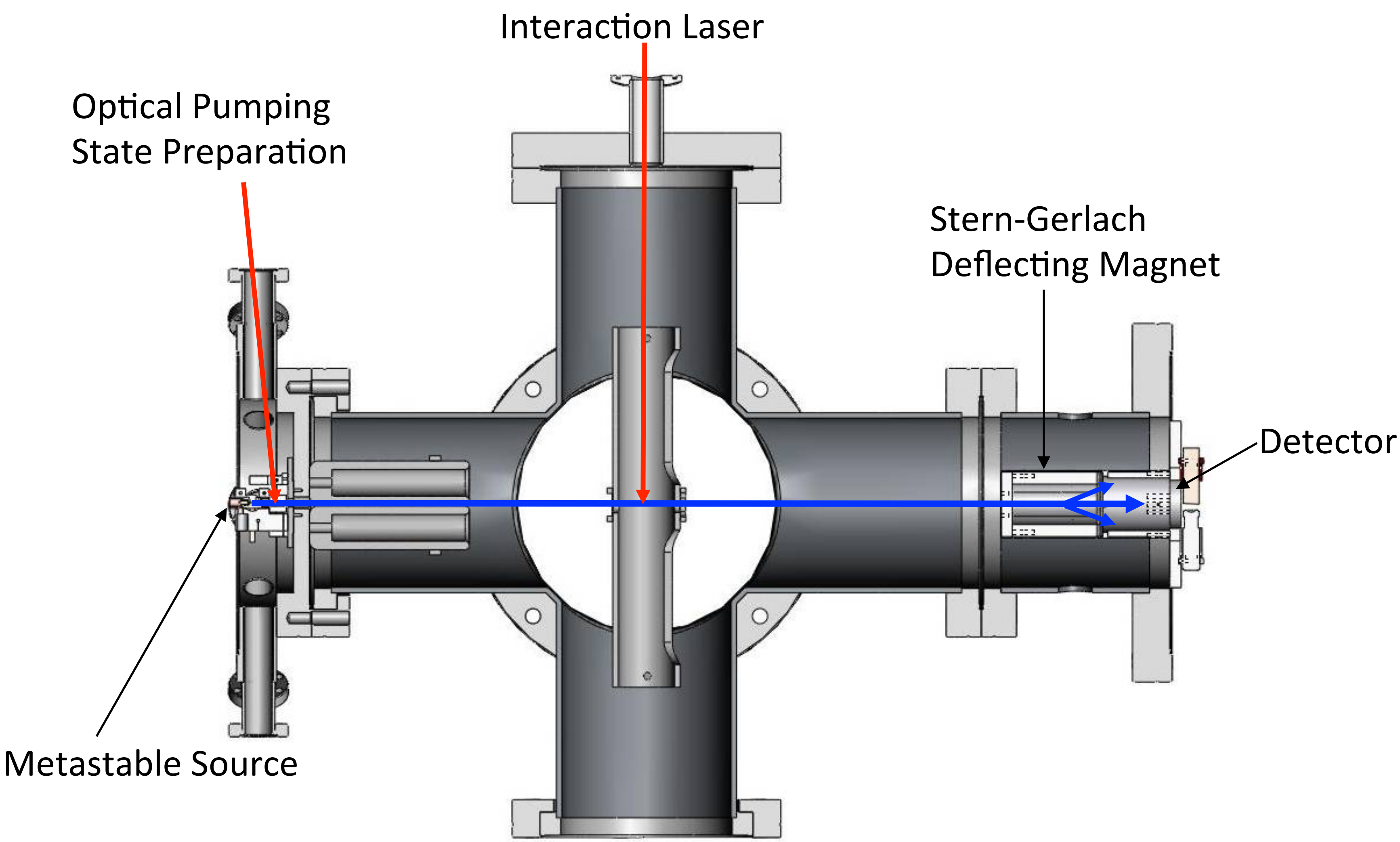
Experimental Setup

- Overview
- Metastable Source
- Optical Pumping
- Singlet Quenching
- Interaction Laser
- Signal Detection

Overview


Interaction Laser
Optical Pumping
State Preparation
Stern-Gerlach
Deflecting Magnet
Detector
Metastable Source
Singlet Quenching
Electrodes

Overview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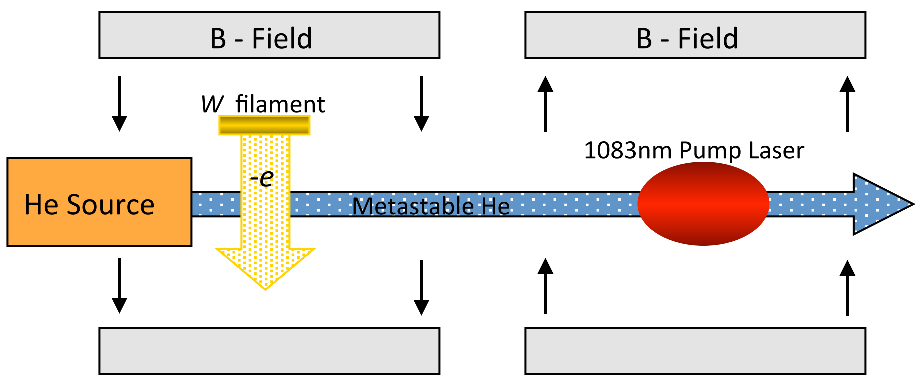
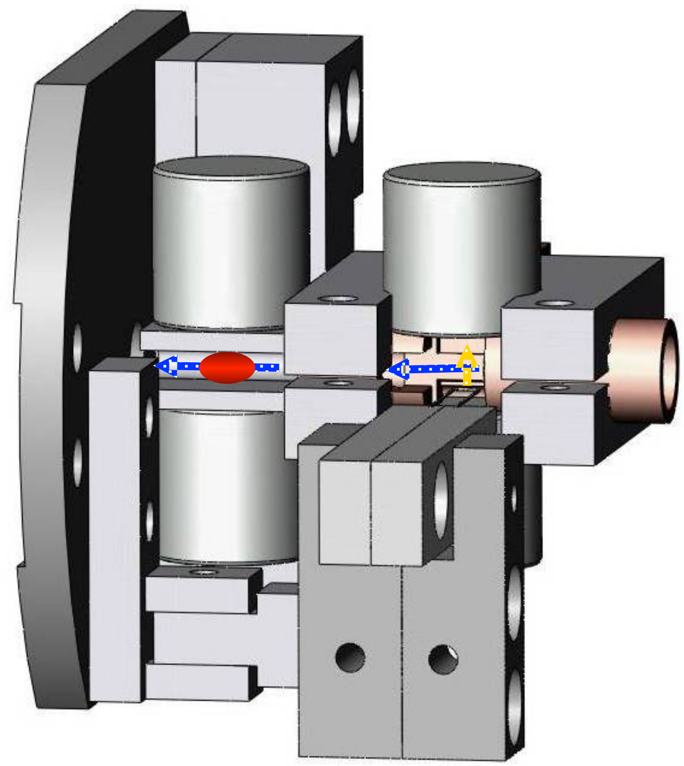
Metastable Source

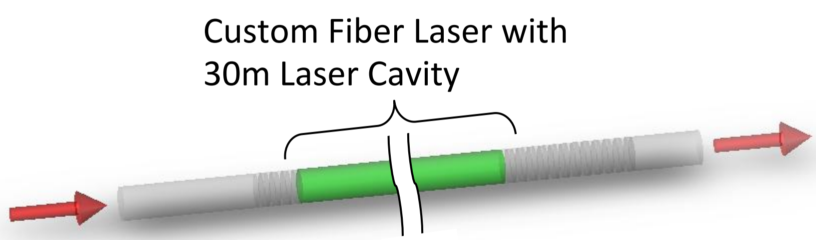
The metastable beam is generated by bombarding the helium atoms with electrons boiled off a hot cathode tungsten filament.

Peak electron energy for 2^3S metastable creation is ~40 eV.





Optical Pumping

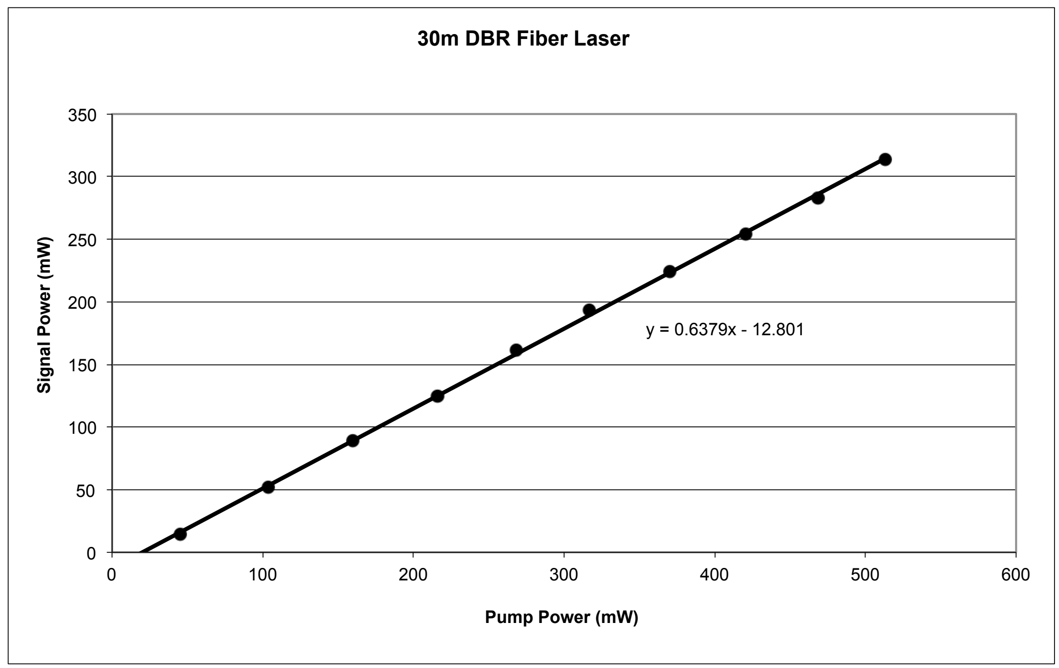


A custom designed and built fiber laser is used to pump out the 0 state metastable atoms into the ±1 states.

Fiber laser width is ~1 GHz

Pumping occurs in a large magnetic field (~0.4 T) to isolate transitions

0 state depopulation is better than 1000:1



Singlet Quenching

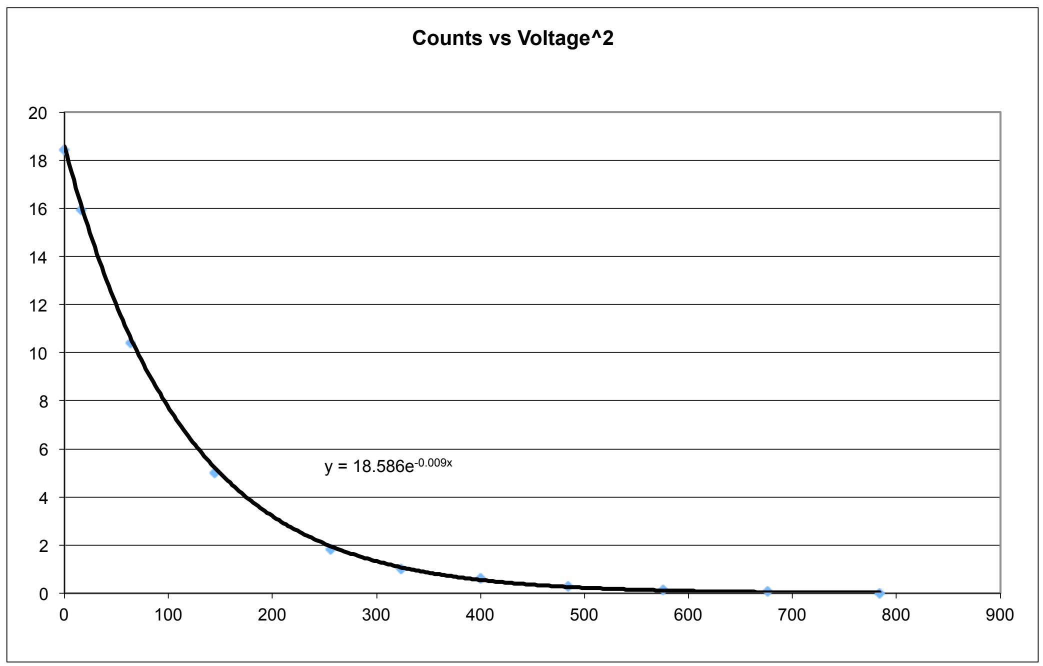
Singlets are removed from the atomic beam using a large electric field. The fall off is exponential with respect to the electric field squared, and thus the voltage applied to the electrodes squared.

Counts (C) can be expressed in terms of the voltage (V) as

$$C = C_0 e^{-(\frac{V}{V_c})^2}$$

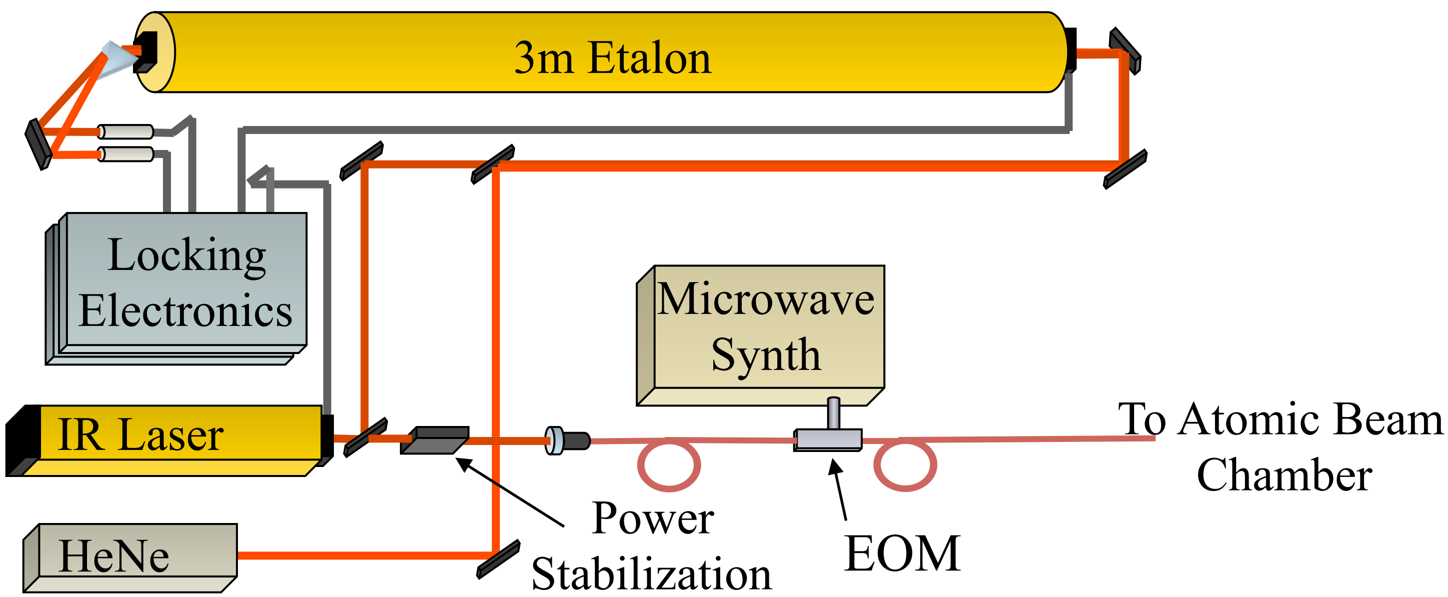
The characteristic voltage V_c = 10.6 kV

Quenching of 10000:1 at V = ~28 kV



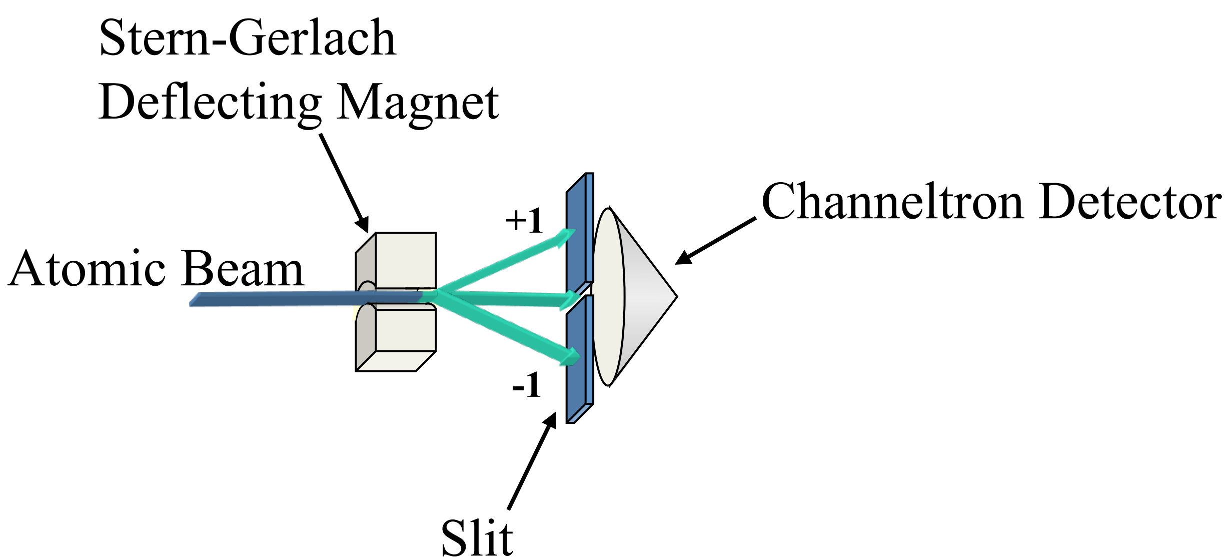
Interaction Laser

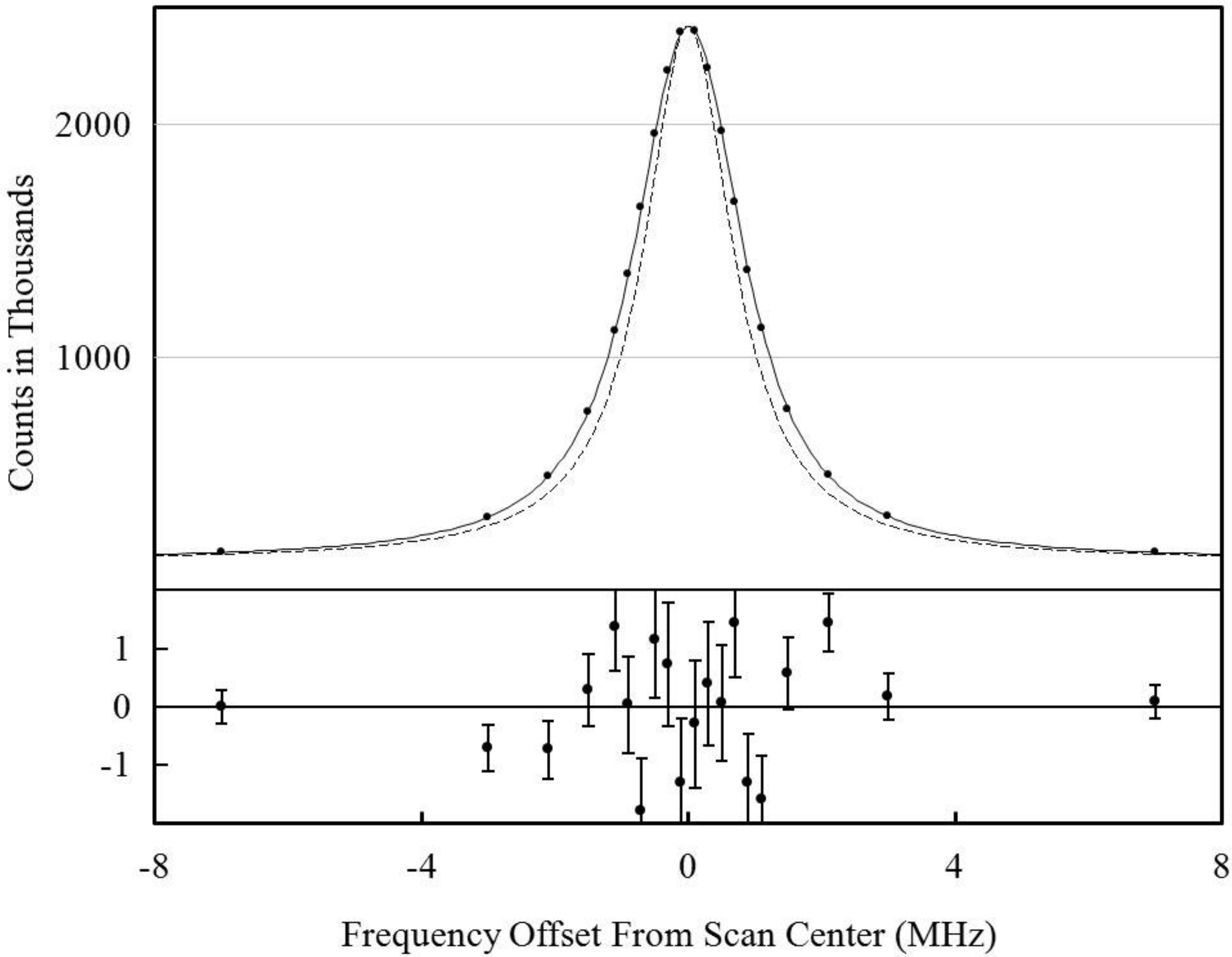
The interaction laser is a frequency and power stabilized 1083 nm diode laser. An electro-optic modulator is used to create tunable sidebands to excite the transitions.



Signal Detection

A channeltron detector is used to detect 0 state metastable atoms populated by the interaction laser. The ±1 states are deflect out of the atomic beam using a Stern-Gerlach deflecting magnet.





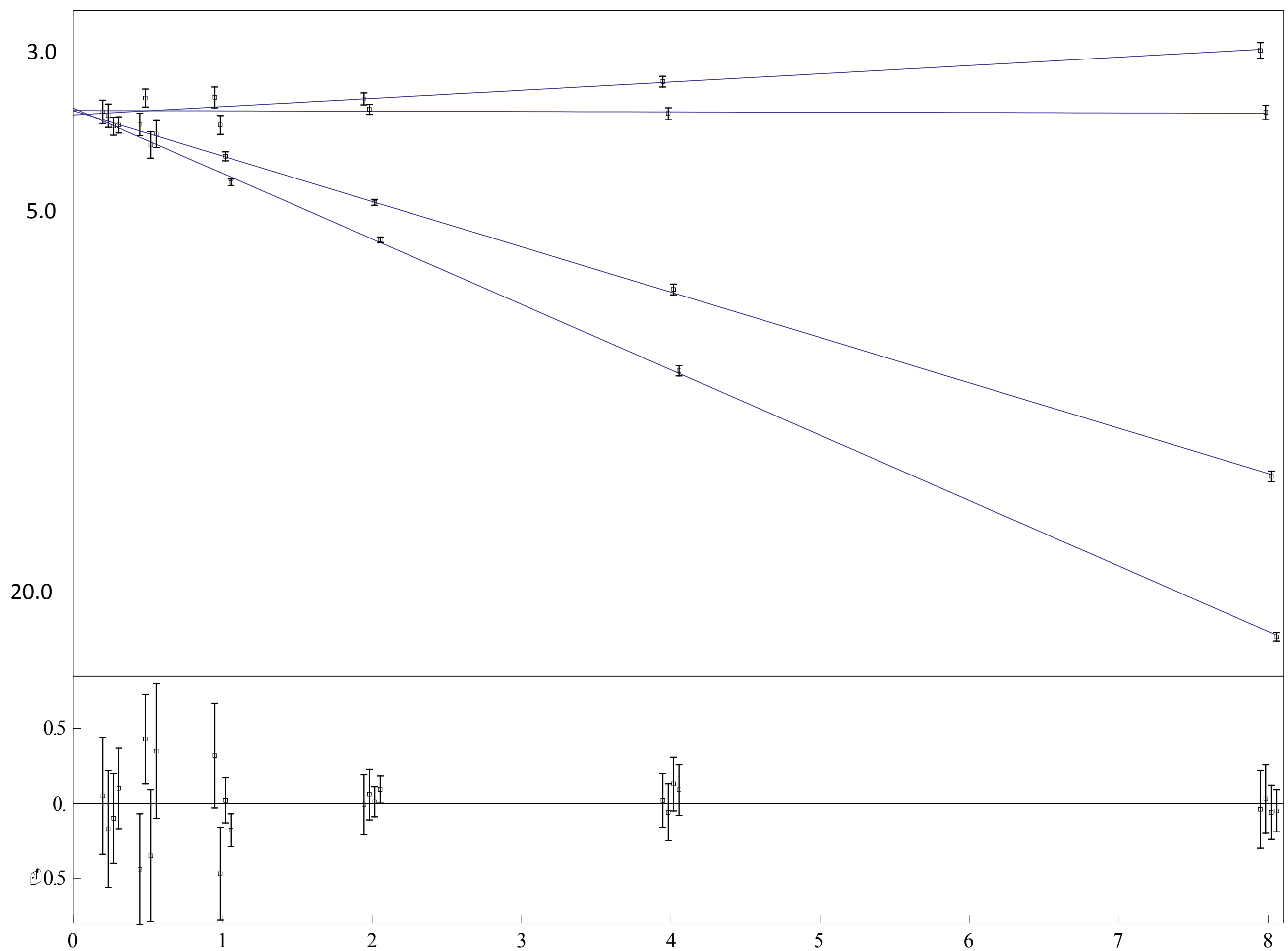
Counts in Thousands
2000
1000
1
0
-1
-8
-4
0
4
8
Frequency Offset From Scan Center (MHz)

How to determine error?

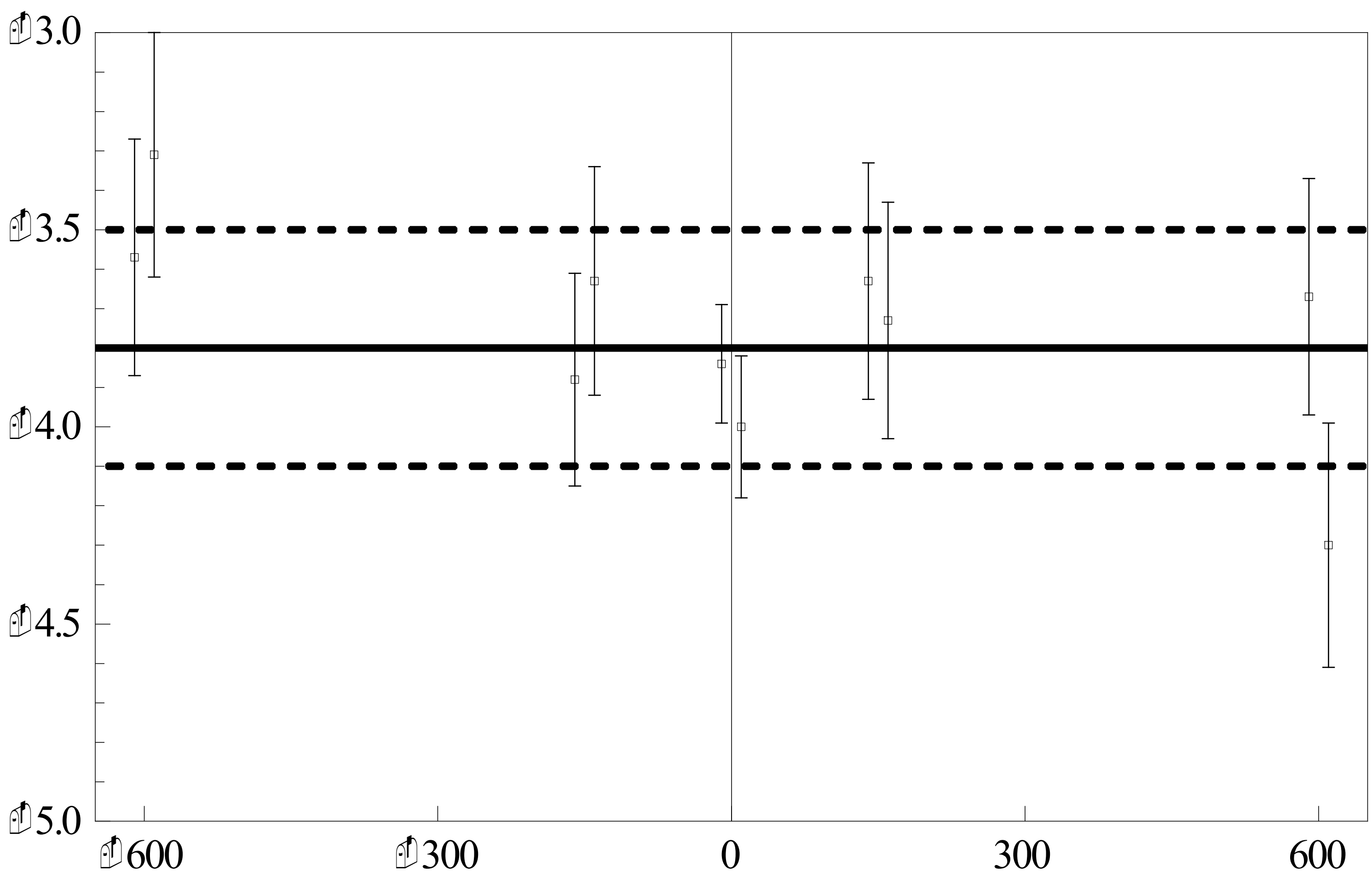
How to determine error?

- Method (1): Think very hard.

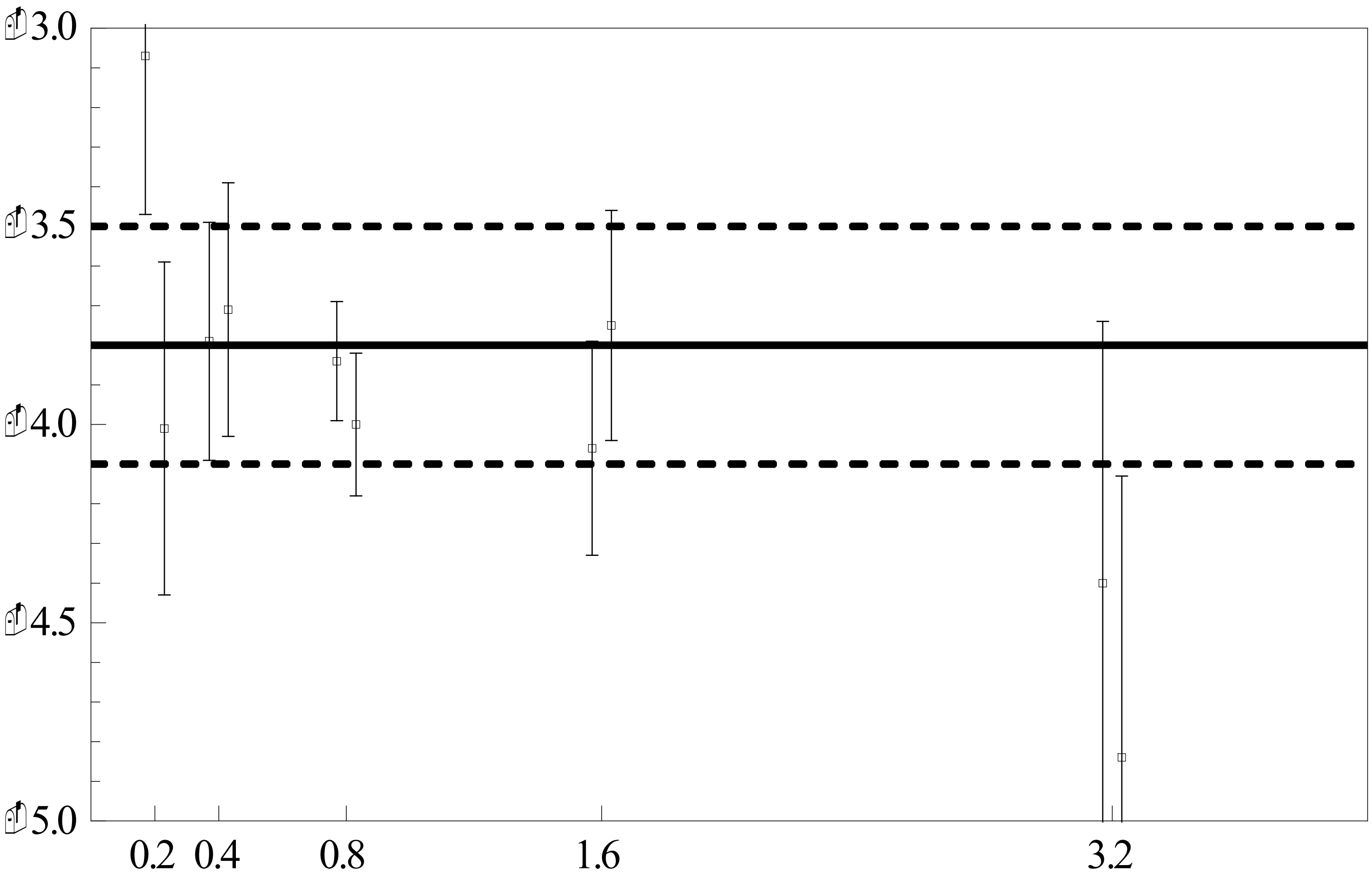
J02 splitting vs intensity



J02 splitting vs alignment



J02 splitting vs step size



J02 splitting vs B field

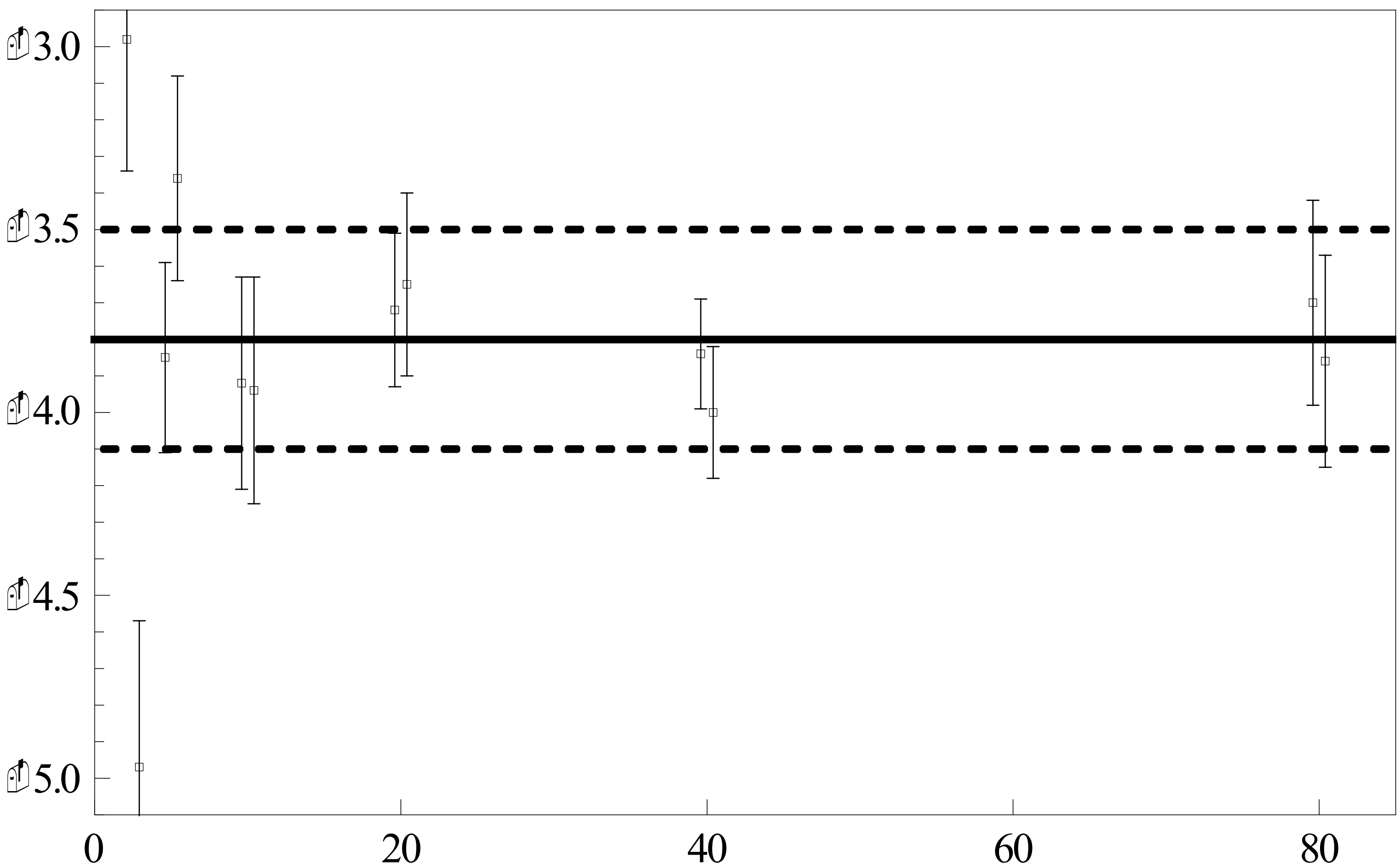


TABLE I. Uncertainty budget (kHz, 1 standard deviation).

Source	J=0 to J=2 fine structure interval
Laser Power	< 0.1
1st Order Doppler	< 0.1
B field	< 0.1
Line Shape	0.2
Other	0.1
Total (rms sum)	0.3

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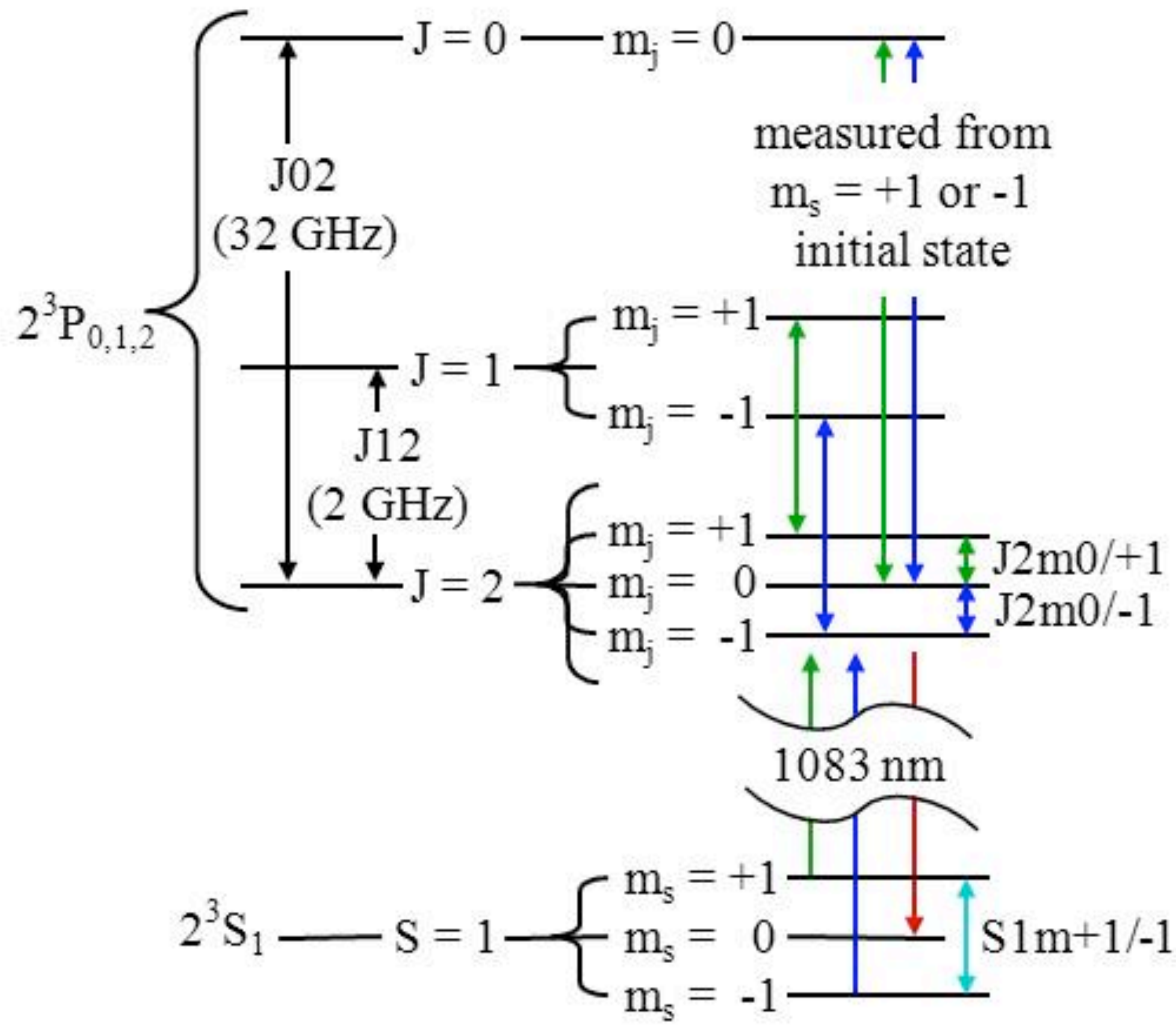
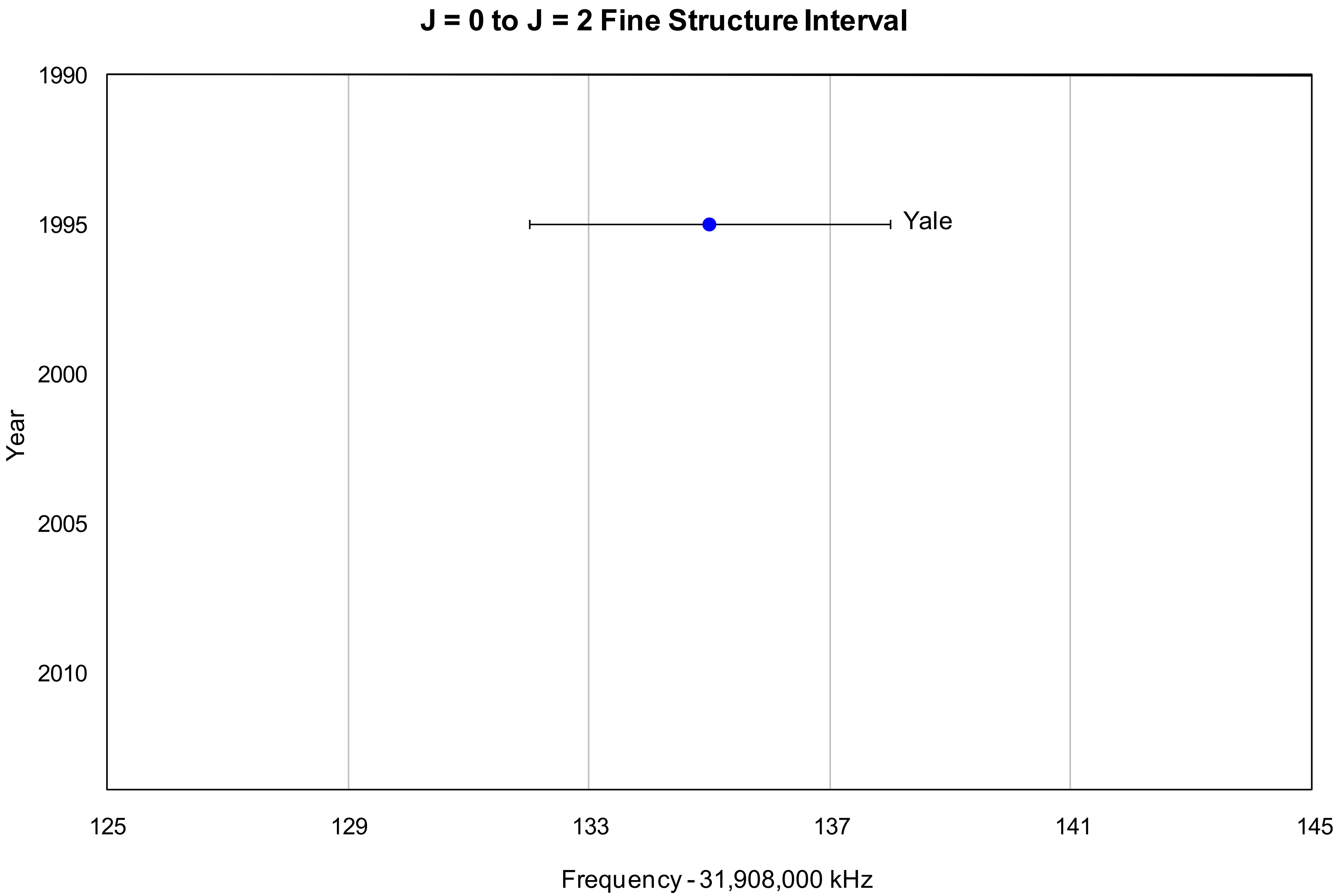
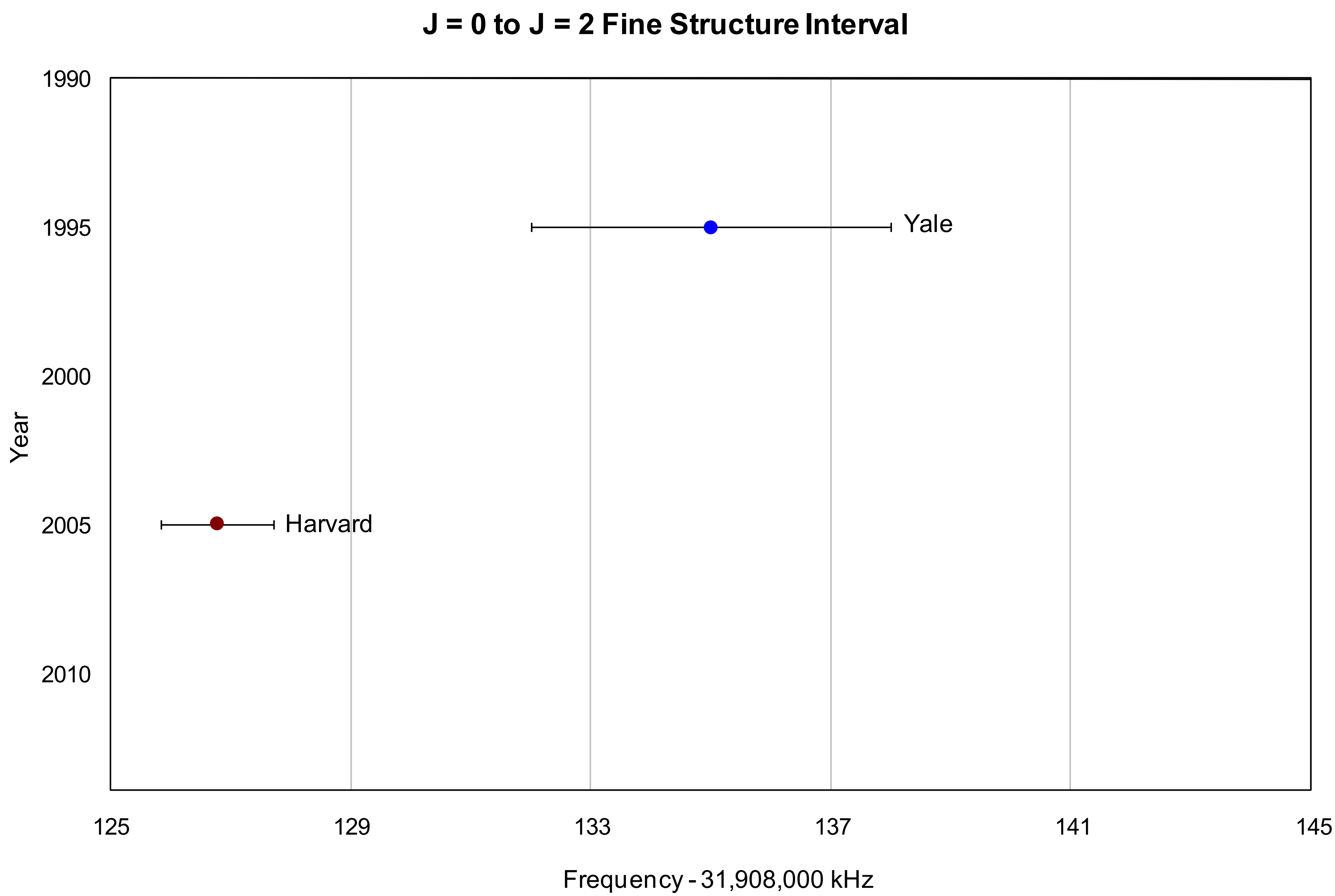
Is there a calibration method available for our technique?

Consistency Checks





J = 0 to J = 2 Fine Structure Interval
1990
1995
2000
2005
2010
Year
Yale
125
129
133
137
141
145
Frequency - 31,908,000 kHz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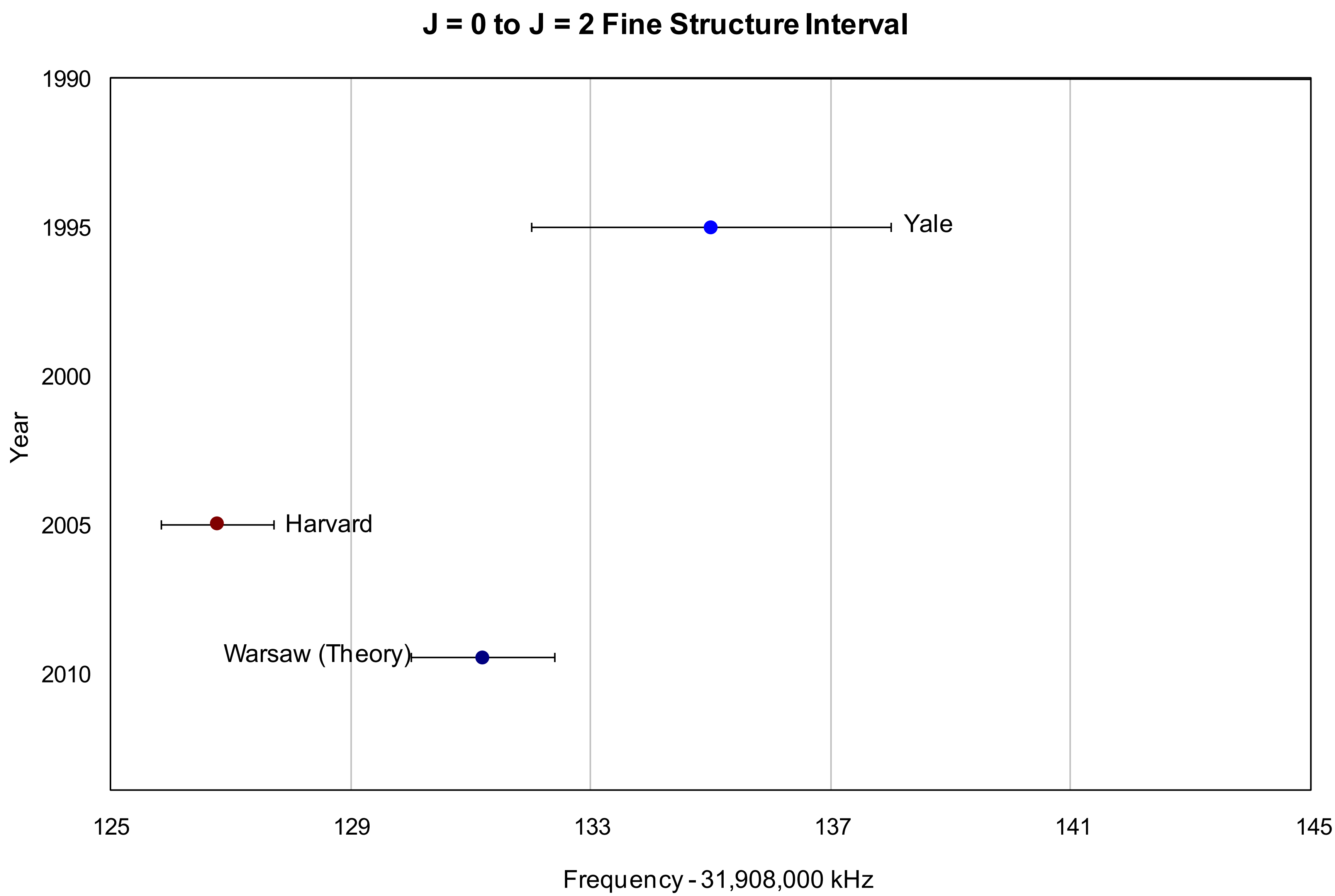

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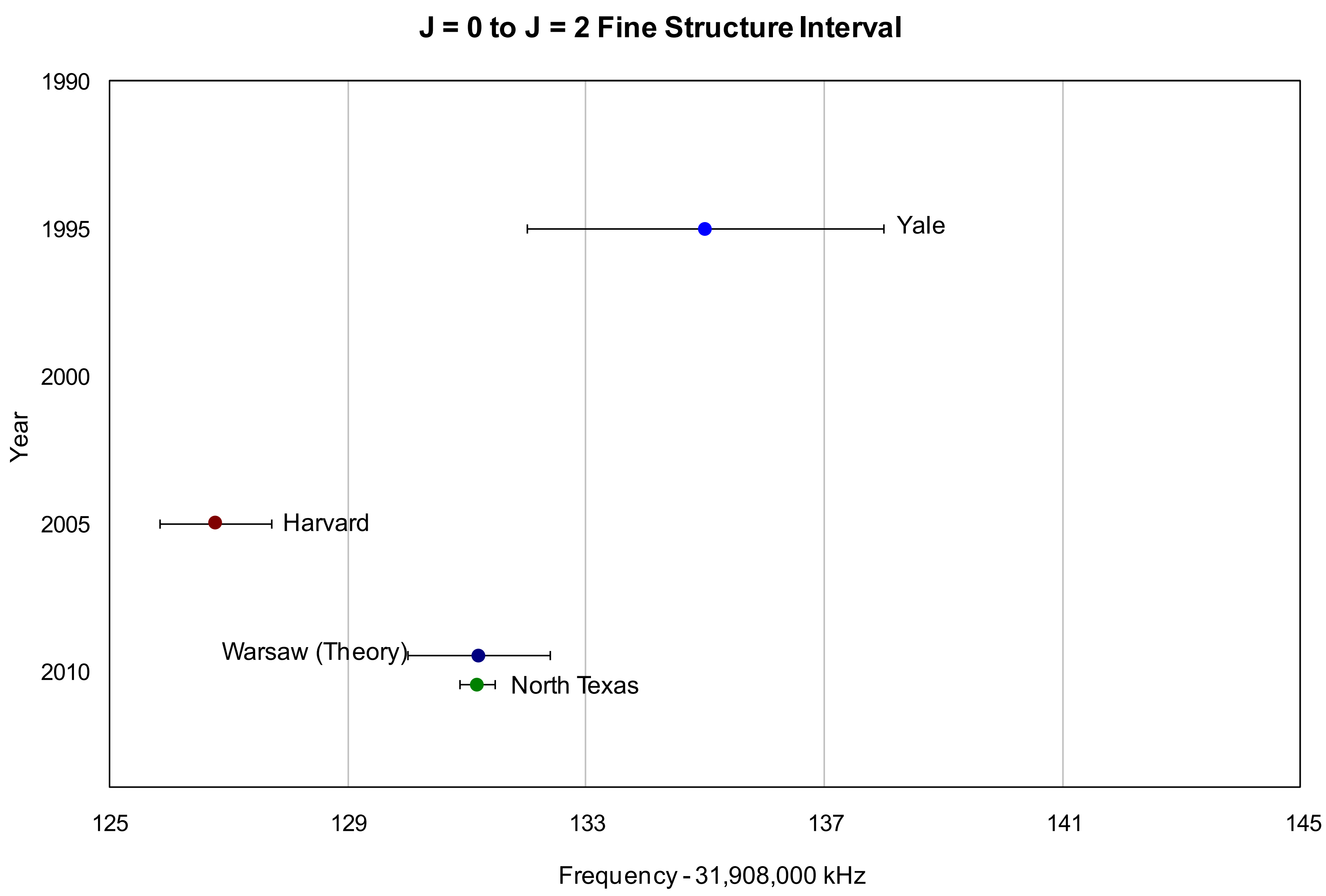
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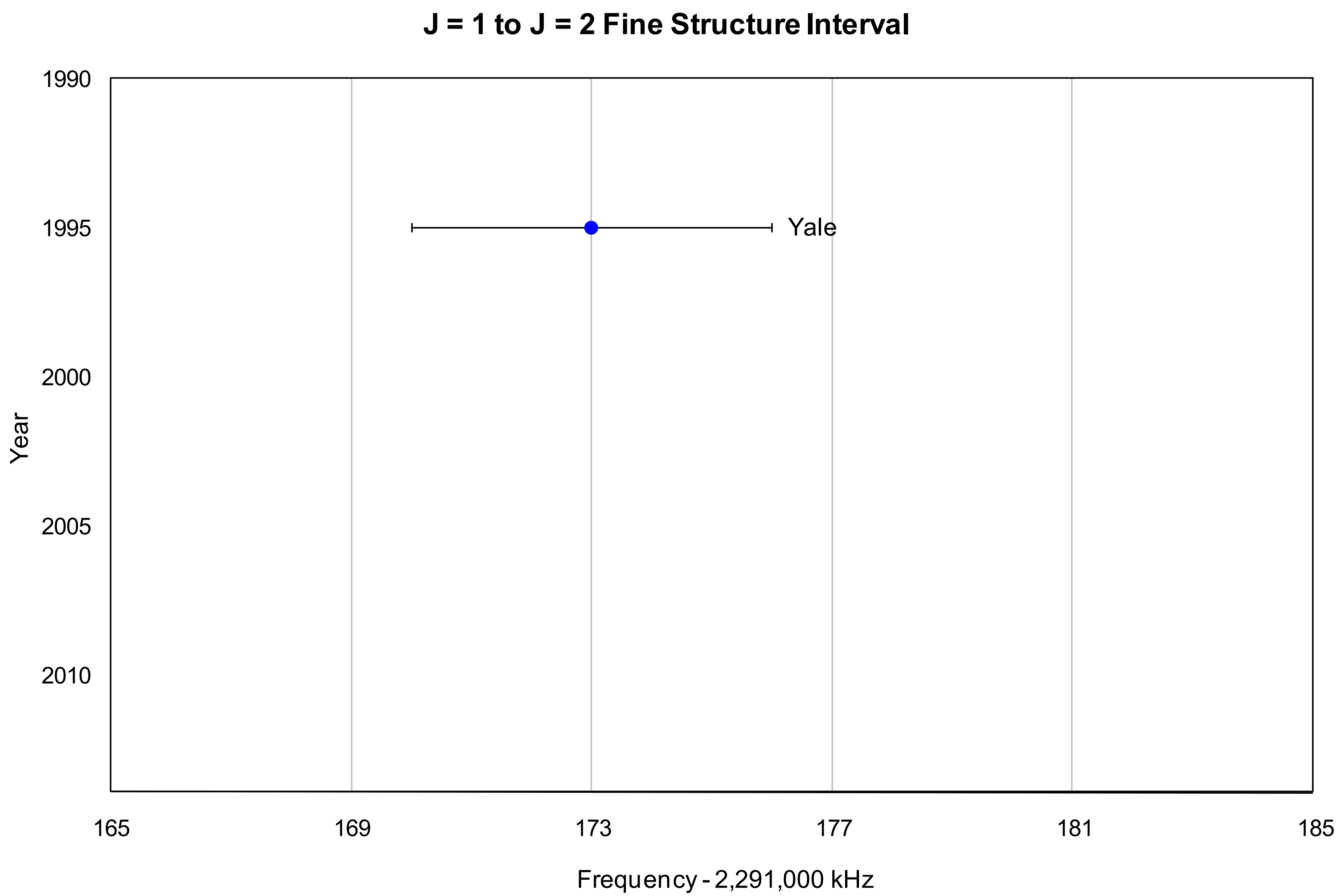
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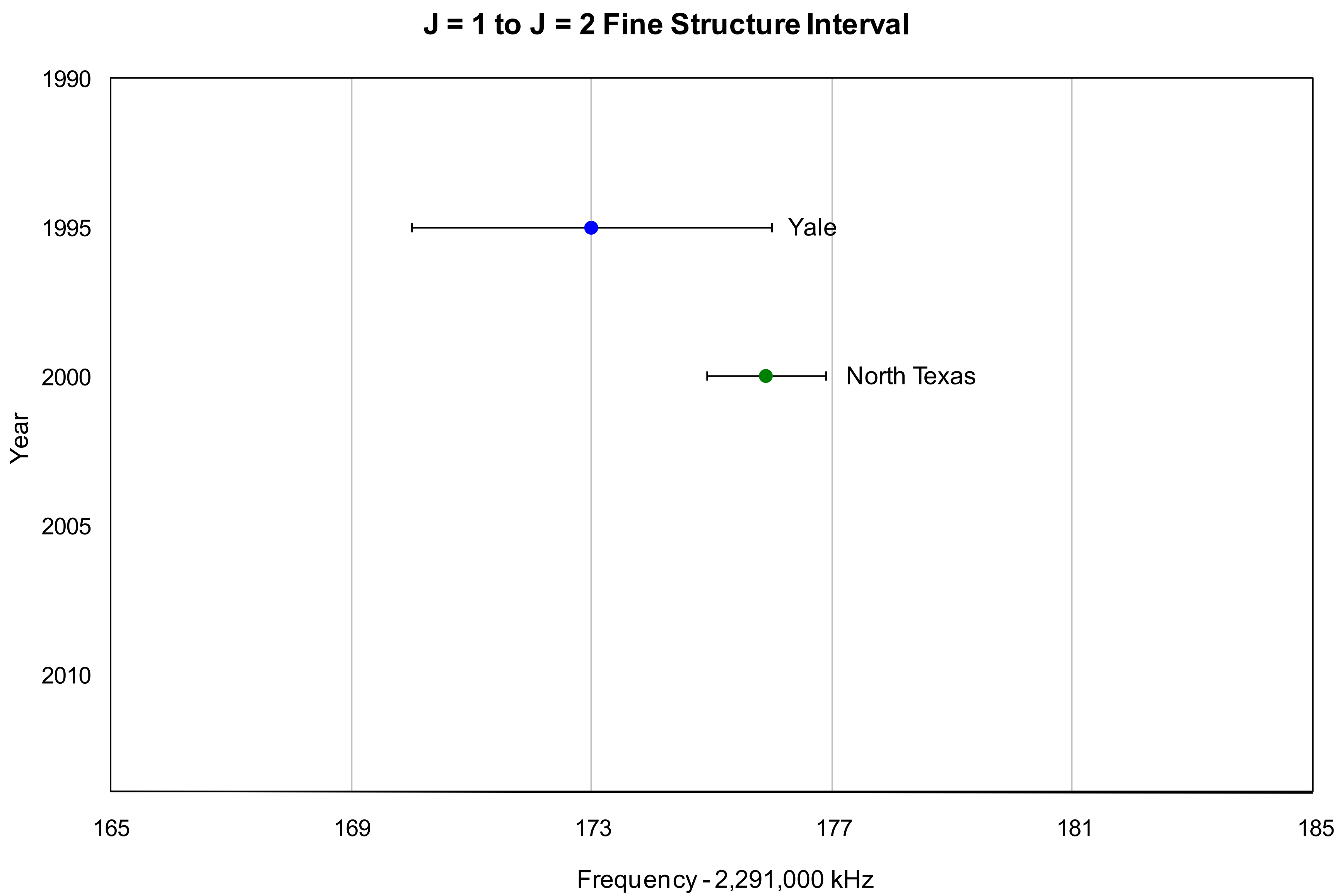
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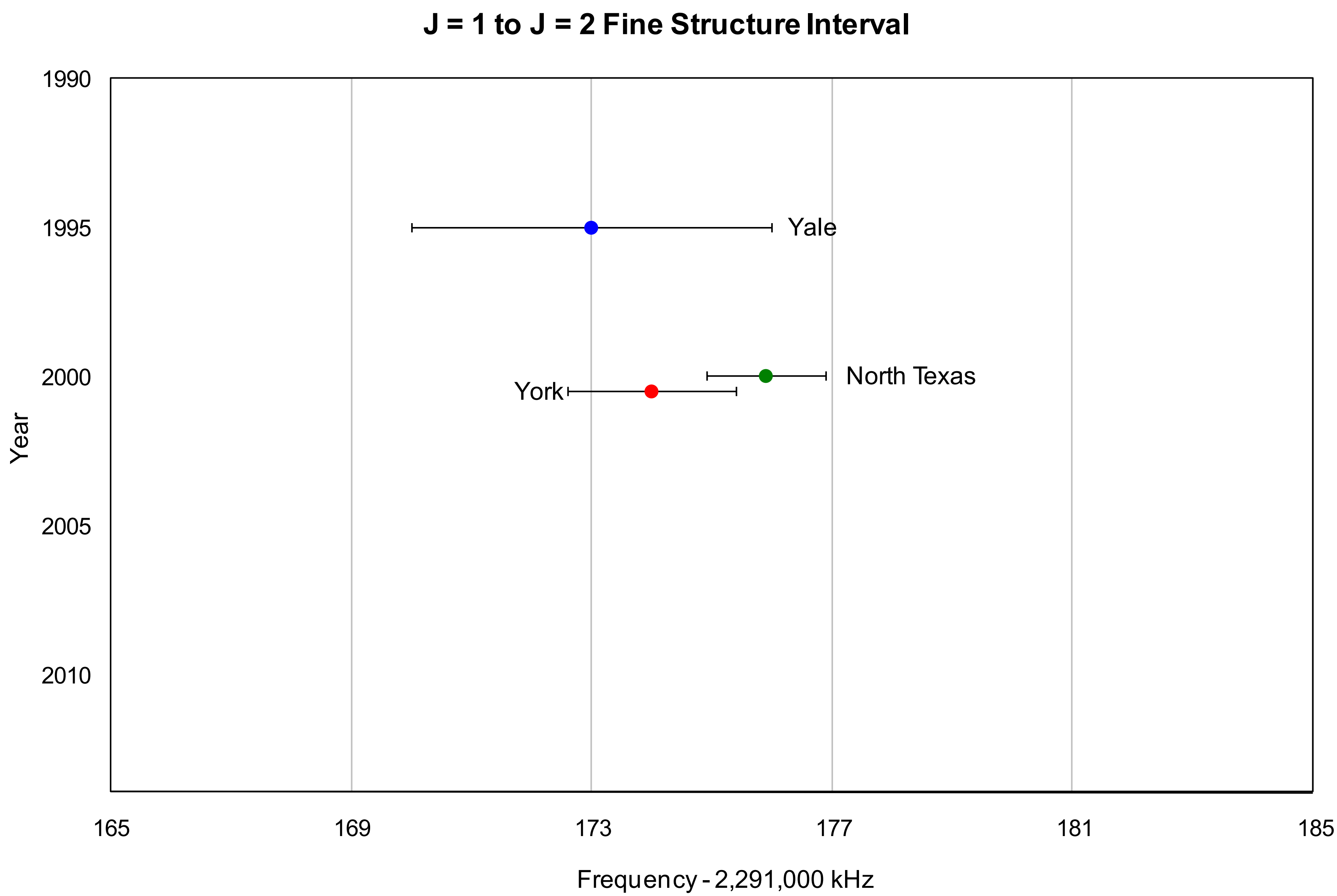
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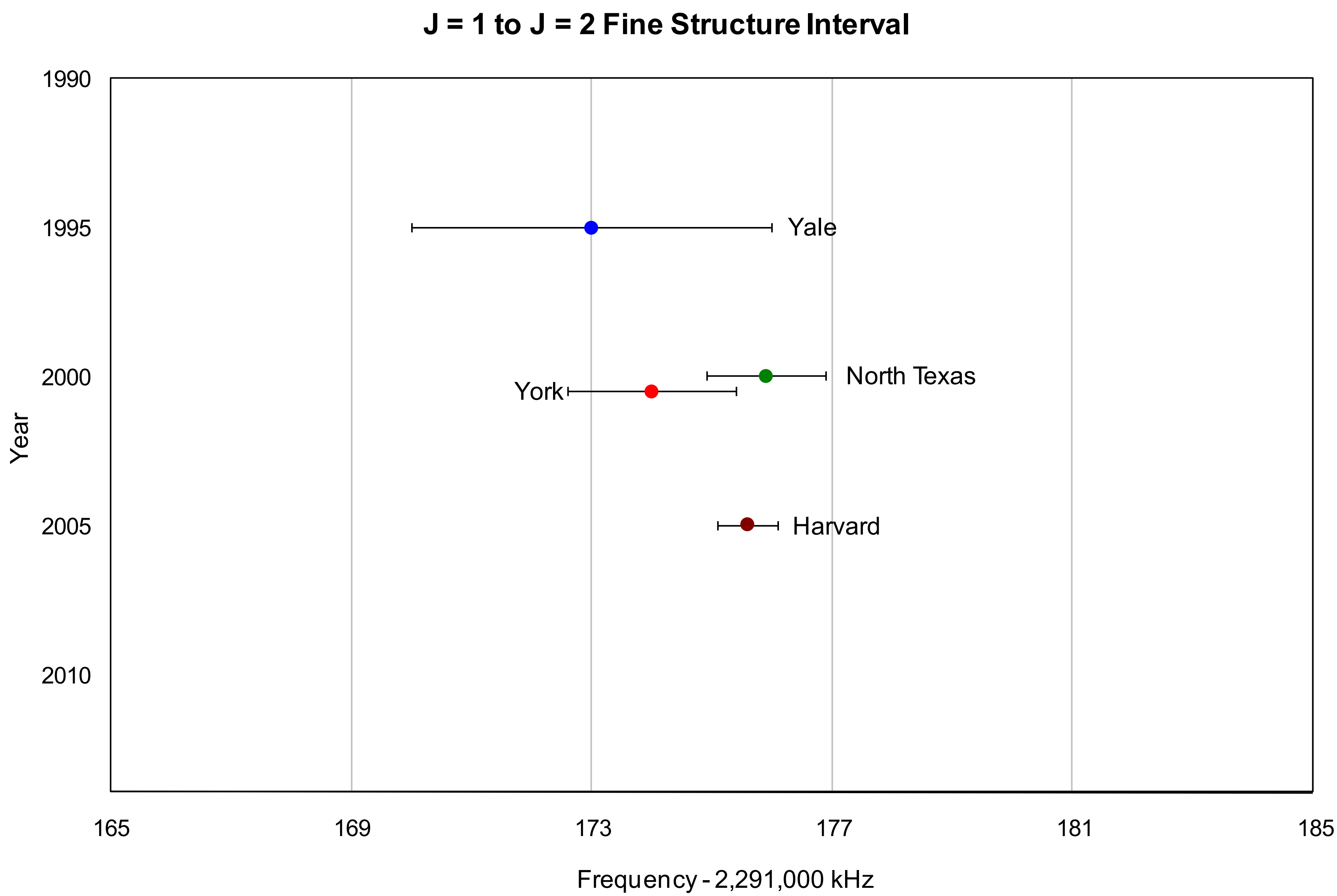
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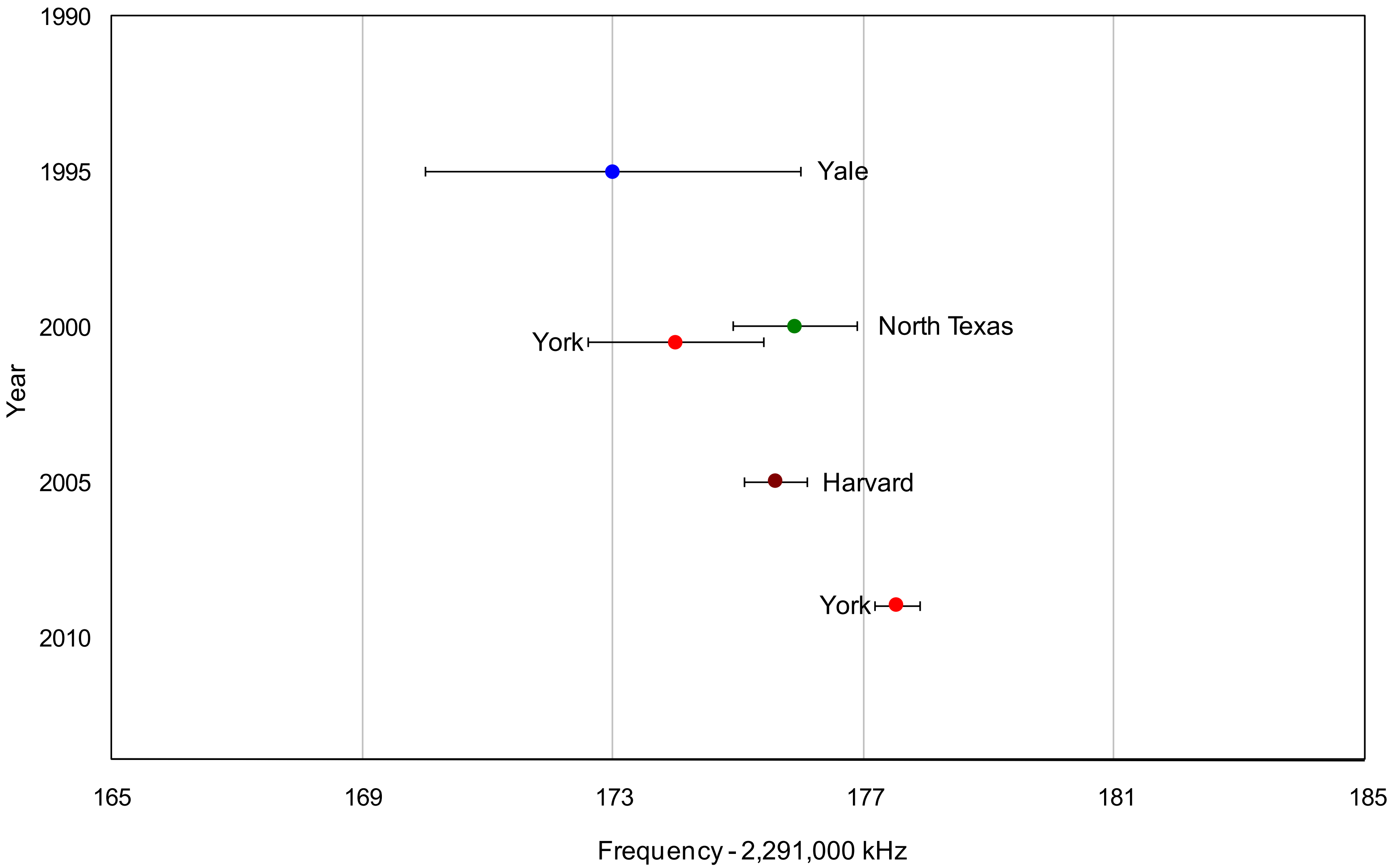

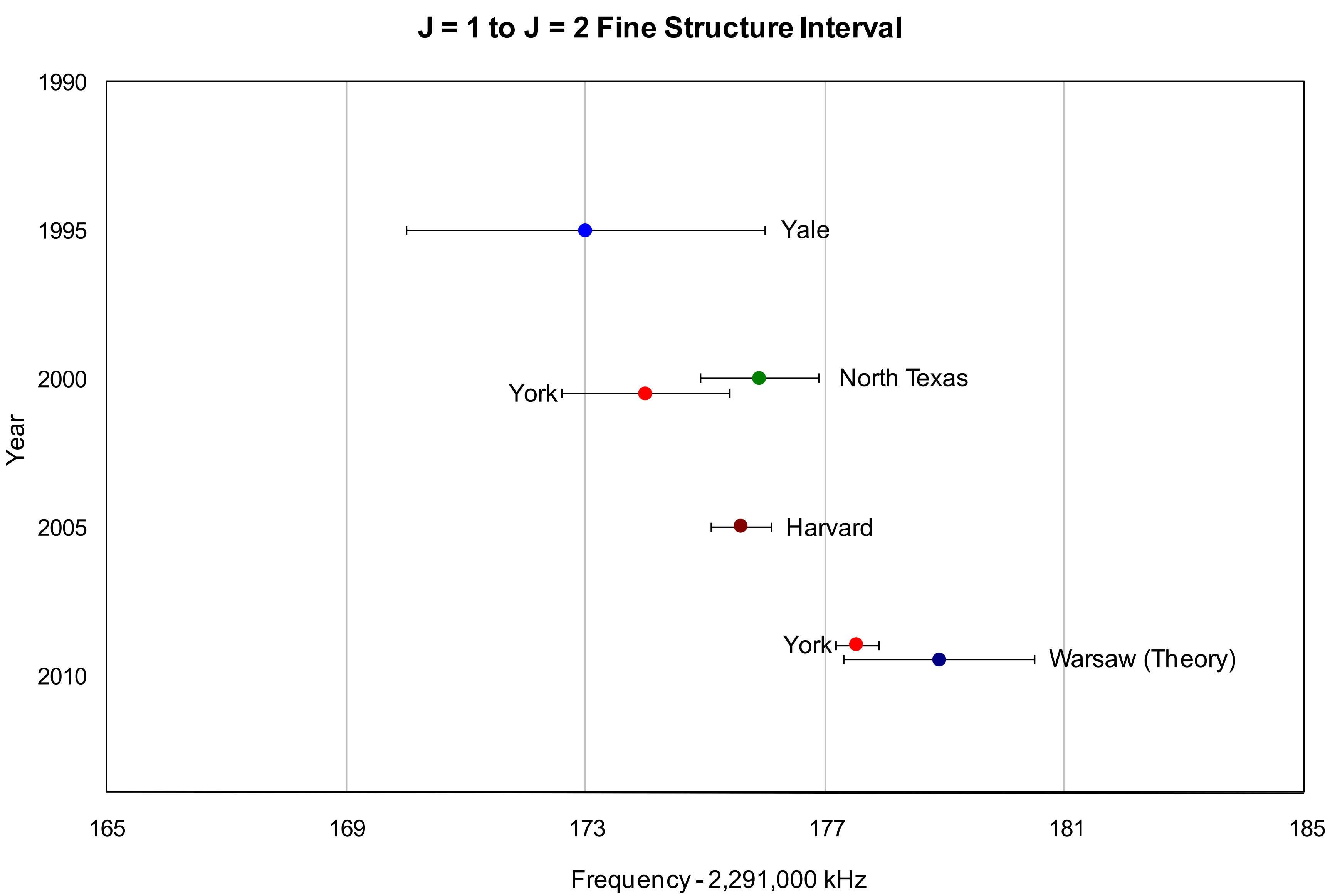
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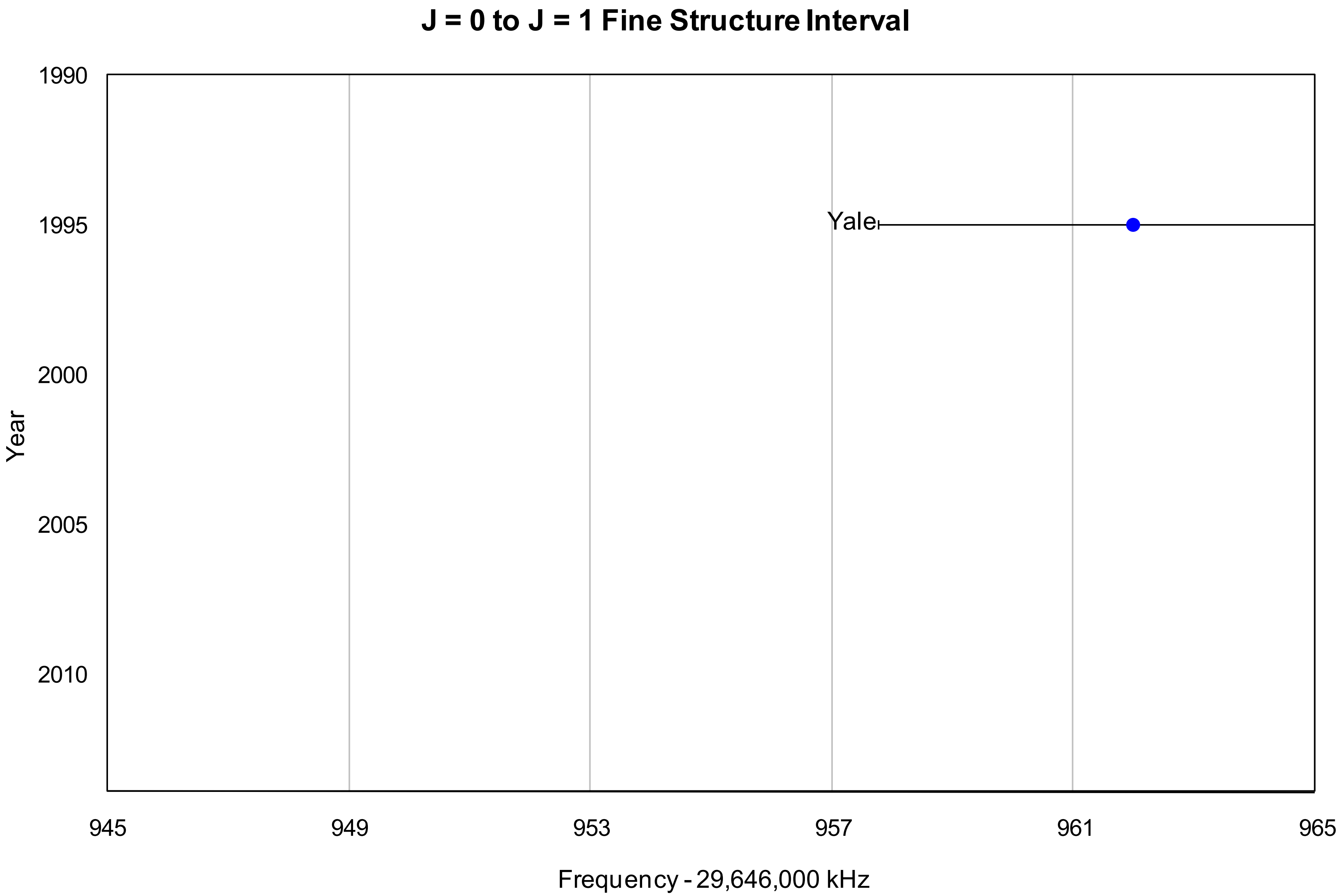

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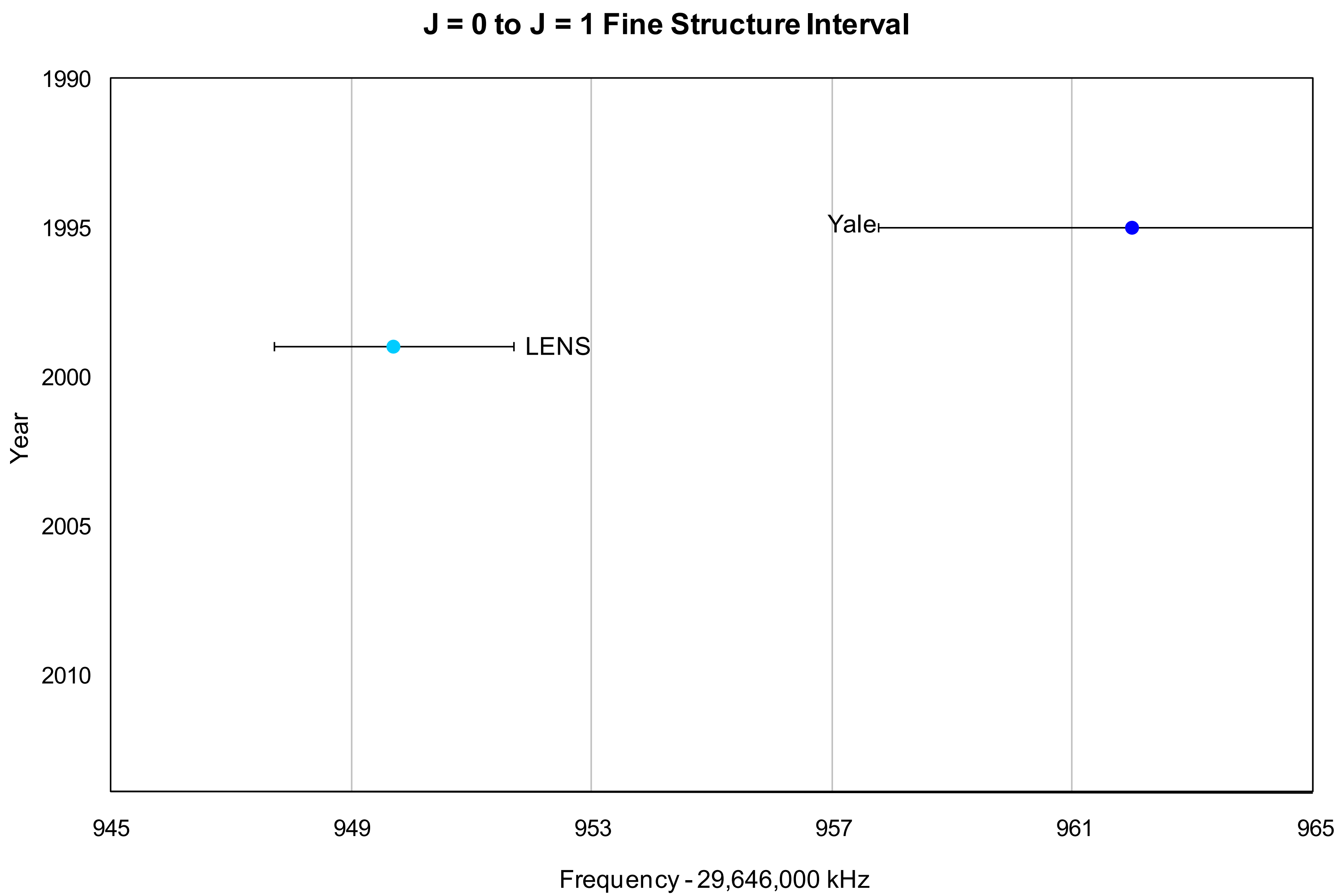
2010
Year
Yale
945
949
953
957
961
965
Frequency - 29,646,000 kHz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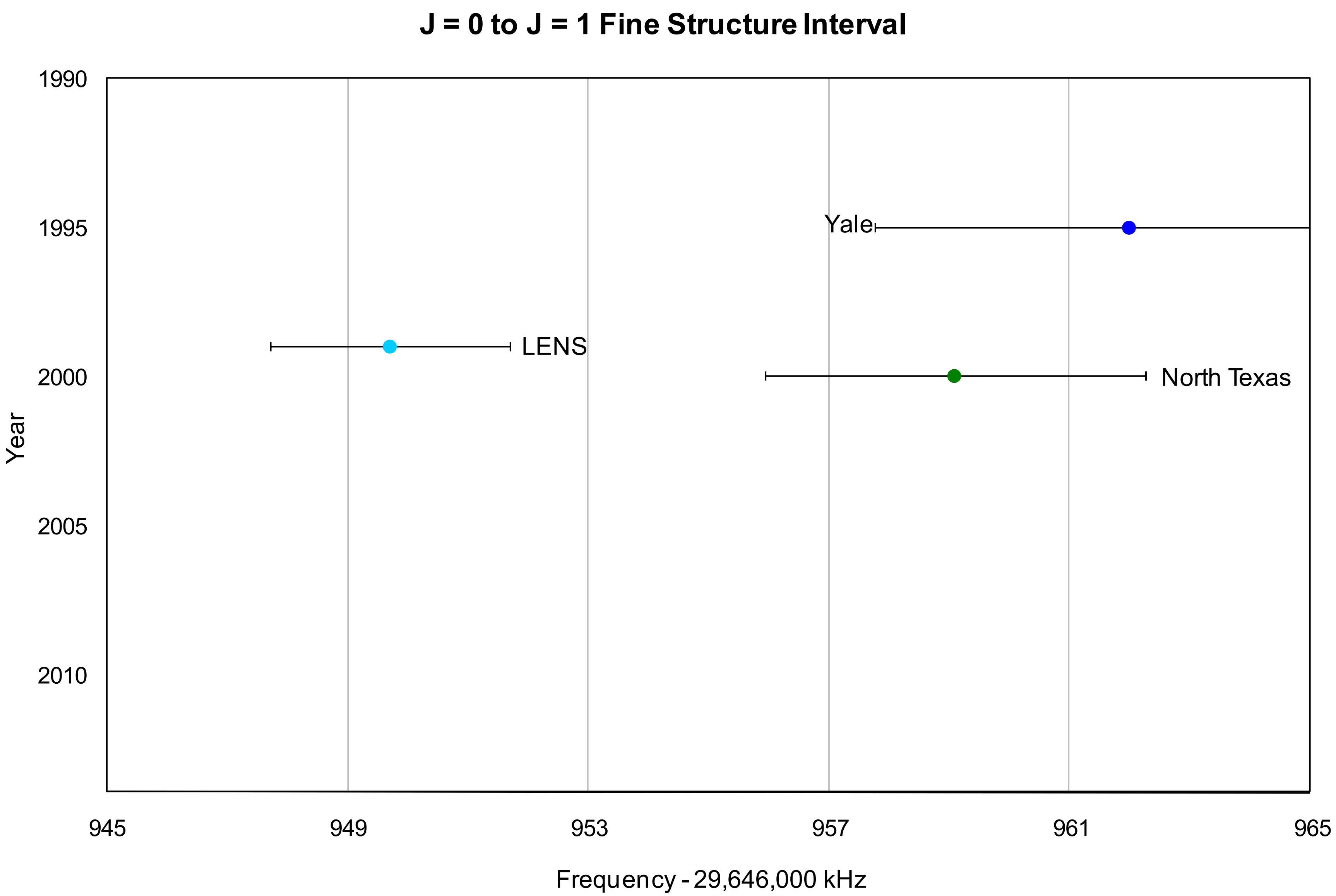
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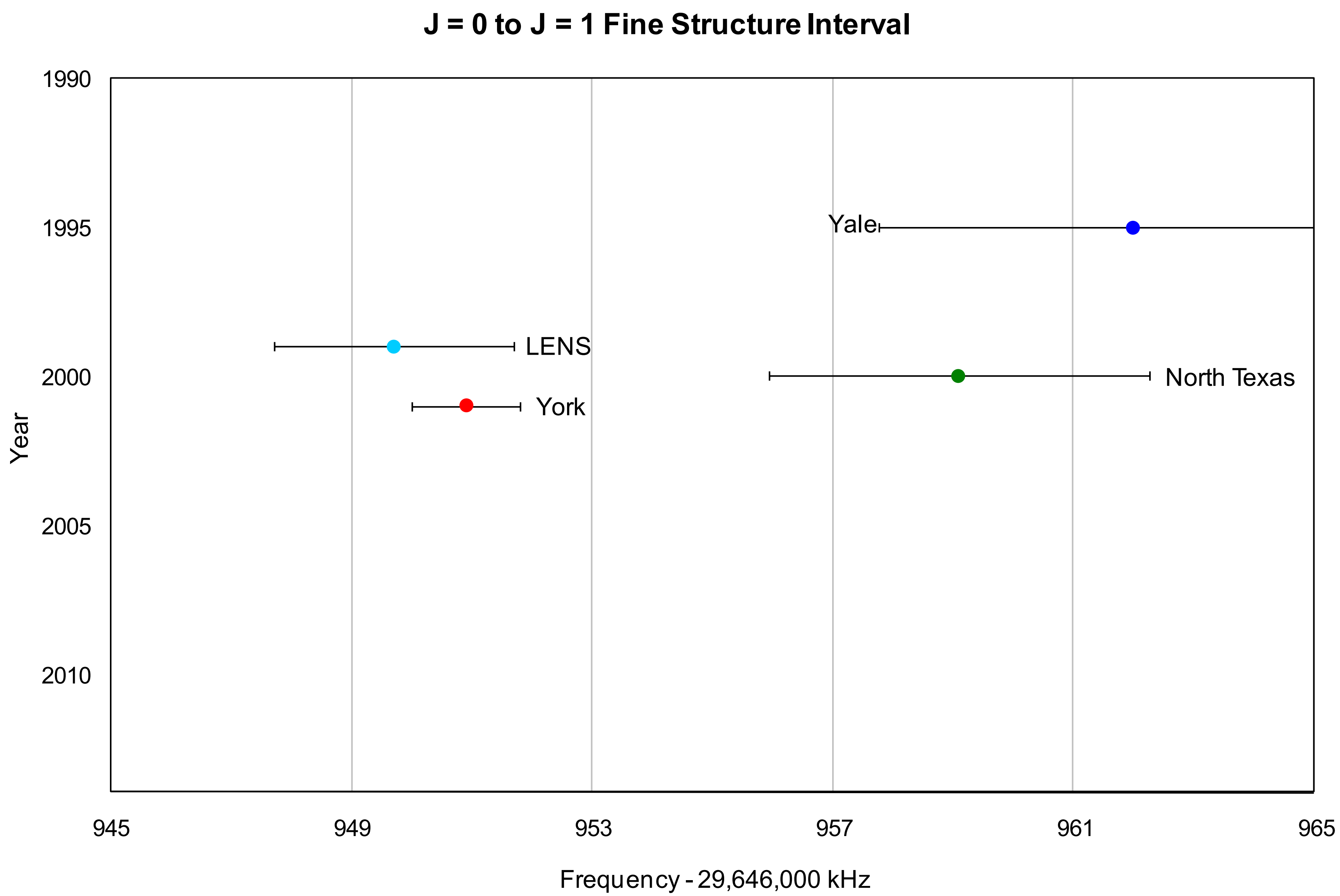

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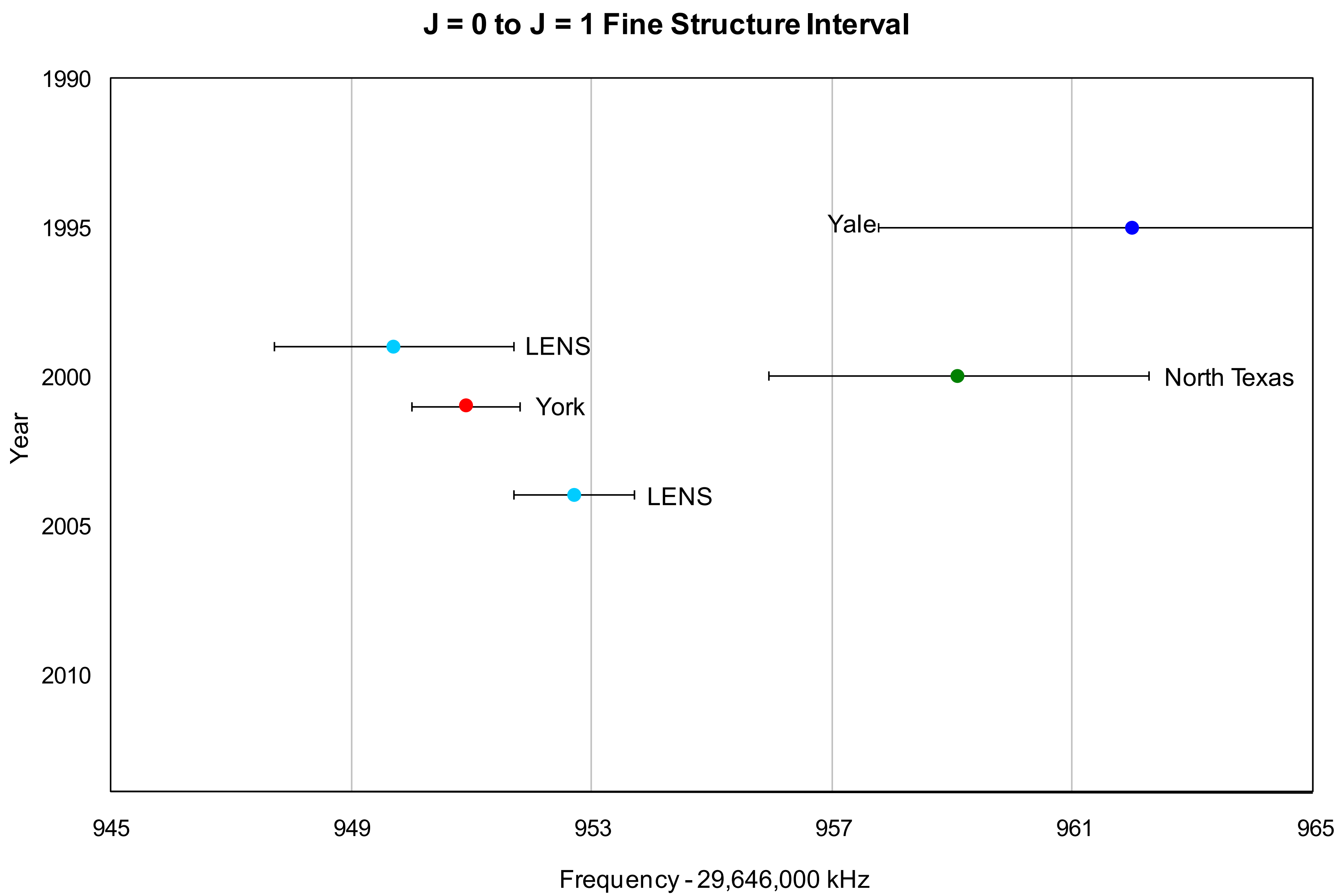

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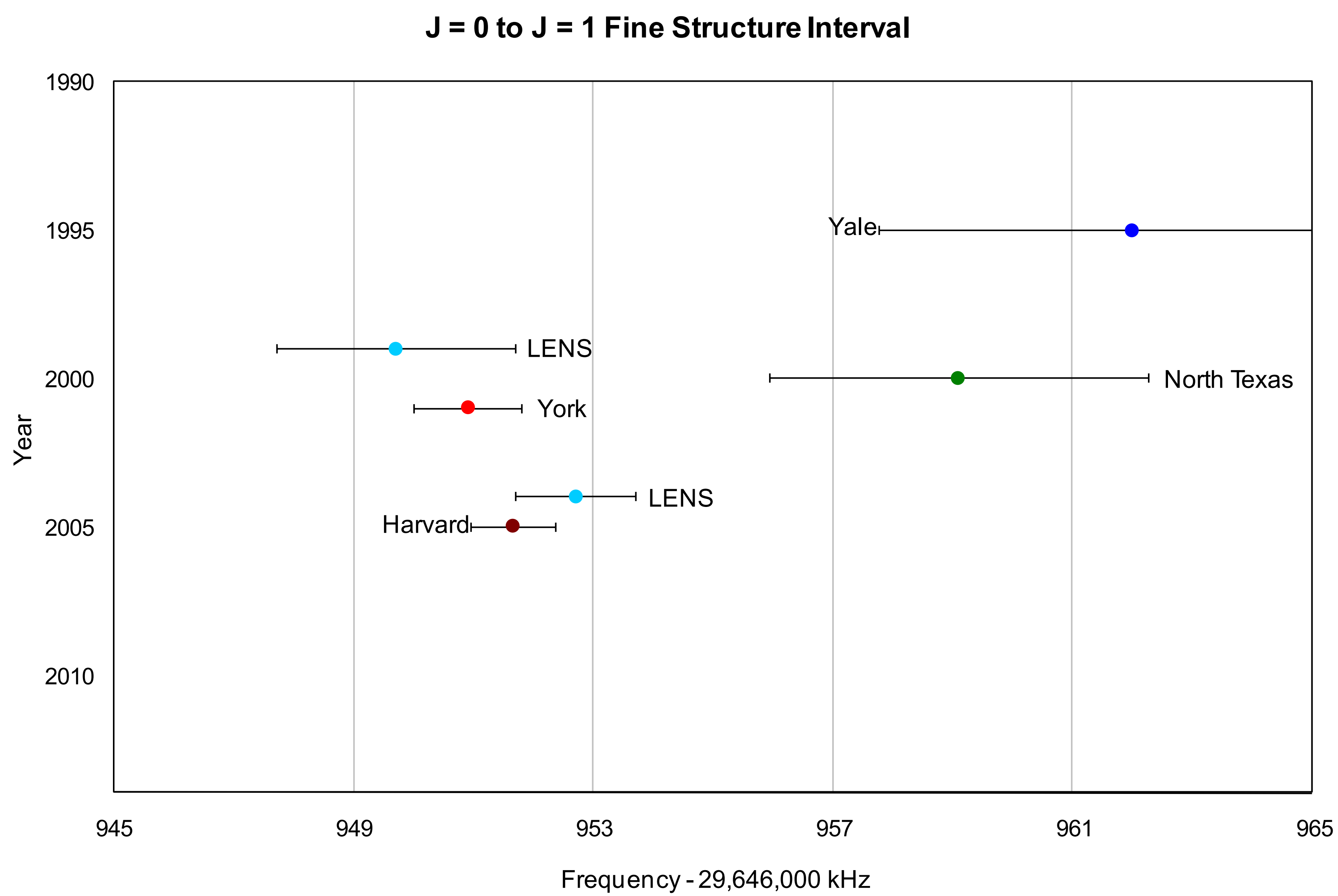
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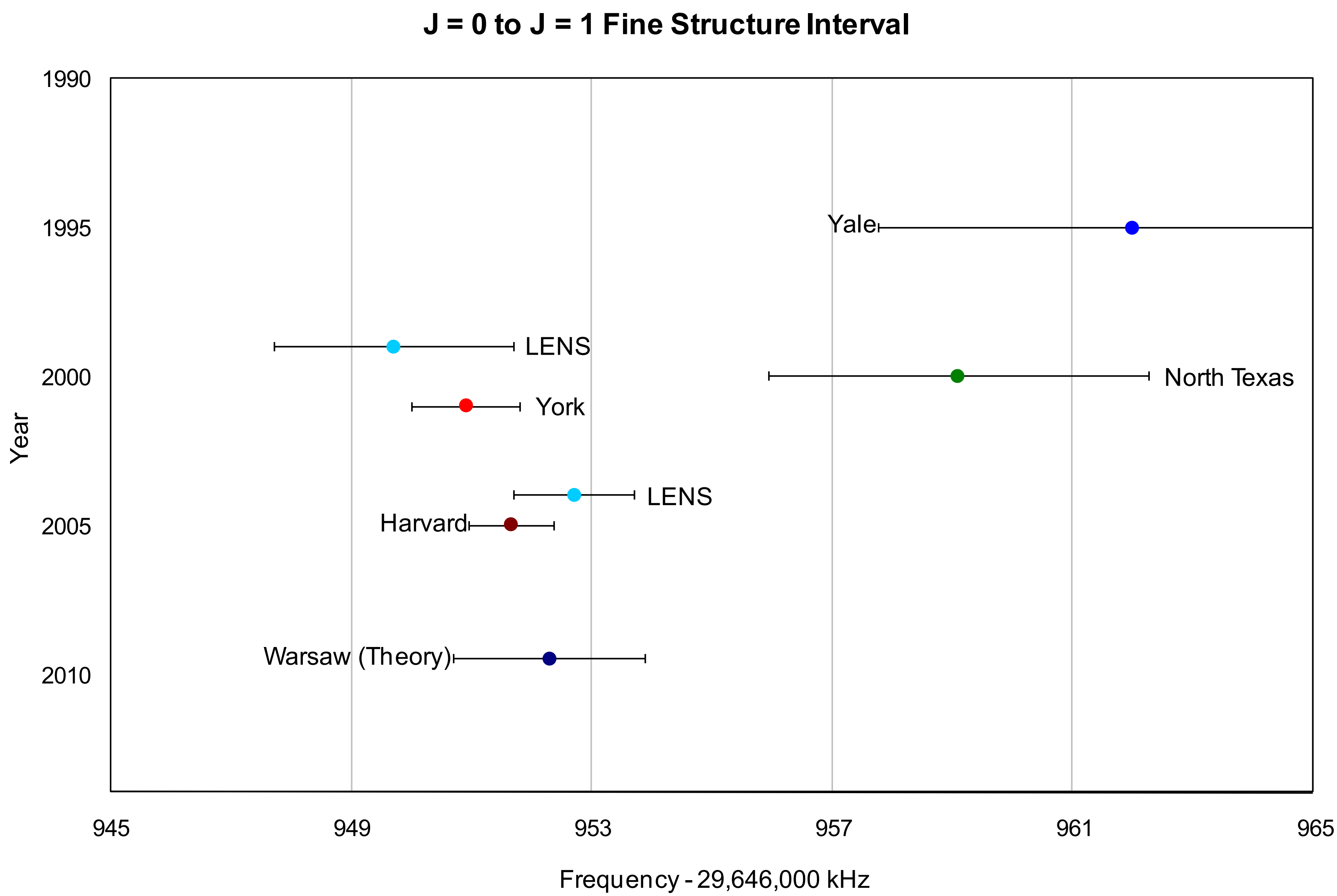
North Texas
York
LENS
Harvard
945
949
953
957
961
965
Frequency - 29,646,000 kHz



J = 0 to J = 1 Fine Structure Interval
1990
1995
2000
2005
2010
Year
Yale
LENS
North Texas
York
LENS
Harvard
Warsaw (Theory)
945
949
953
957
961
965
Frequency - 29,646,000 kHz

How to determine error?

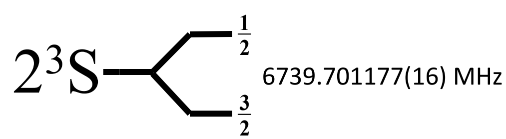
- Method (1): Think very hard.
- Method (2): Turn all the knobs and see what happens.
- Method (3): (Take your result) - (Known value) and call this your error

Is there a calibration method available for our technique?

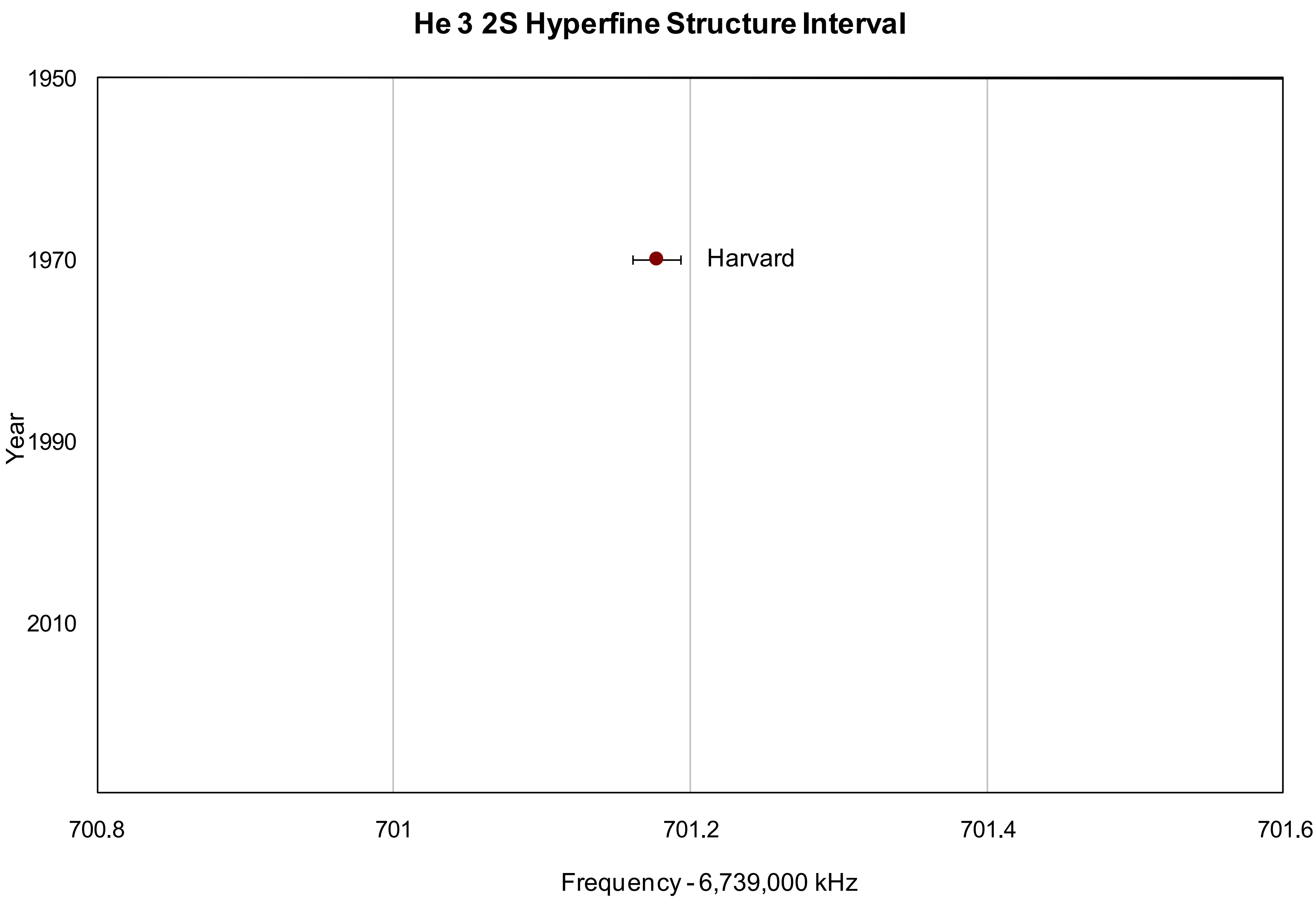
Calibration?

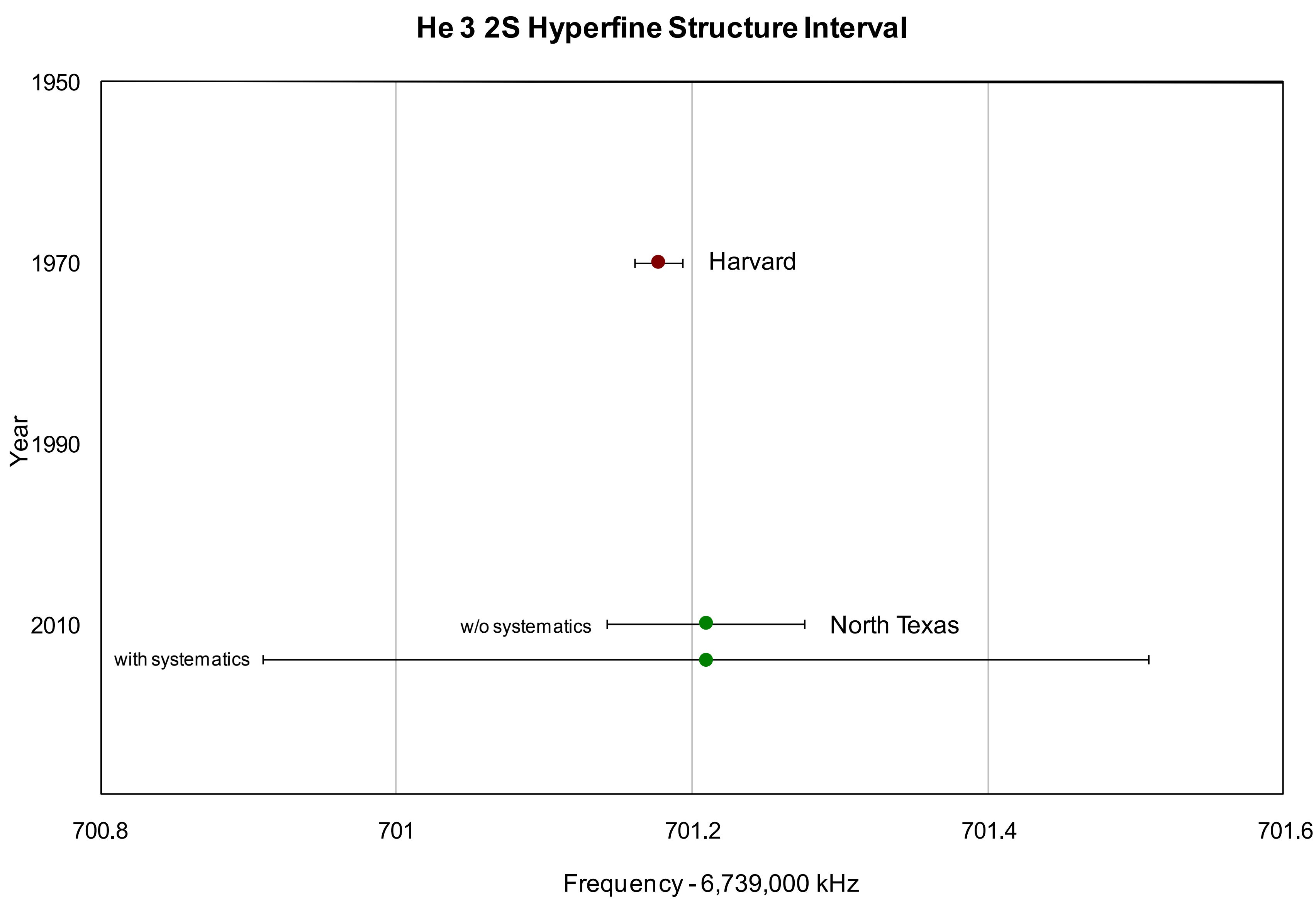
The hyperfine splitting in the 2^3S metastable state of helium-3 is a very well know value. This serves as a remarkable consistency check of this experimental method.

Helium-3 2^3S Hyperfine Splitting

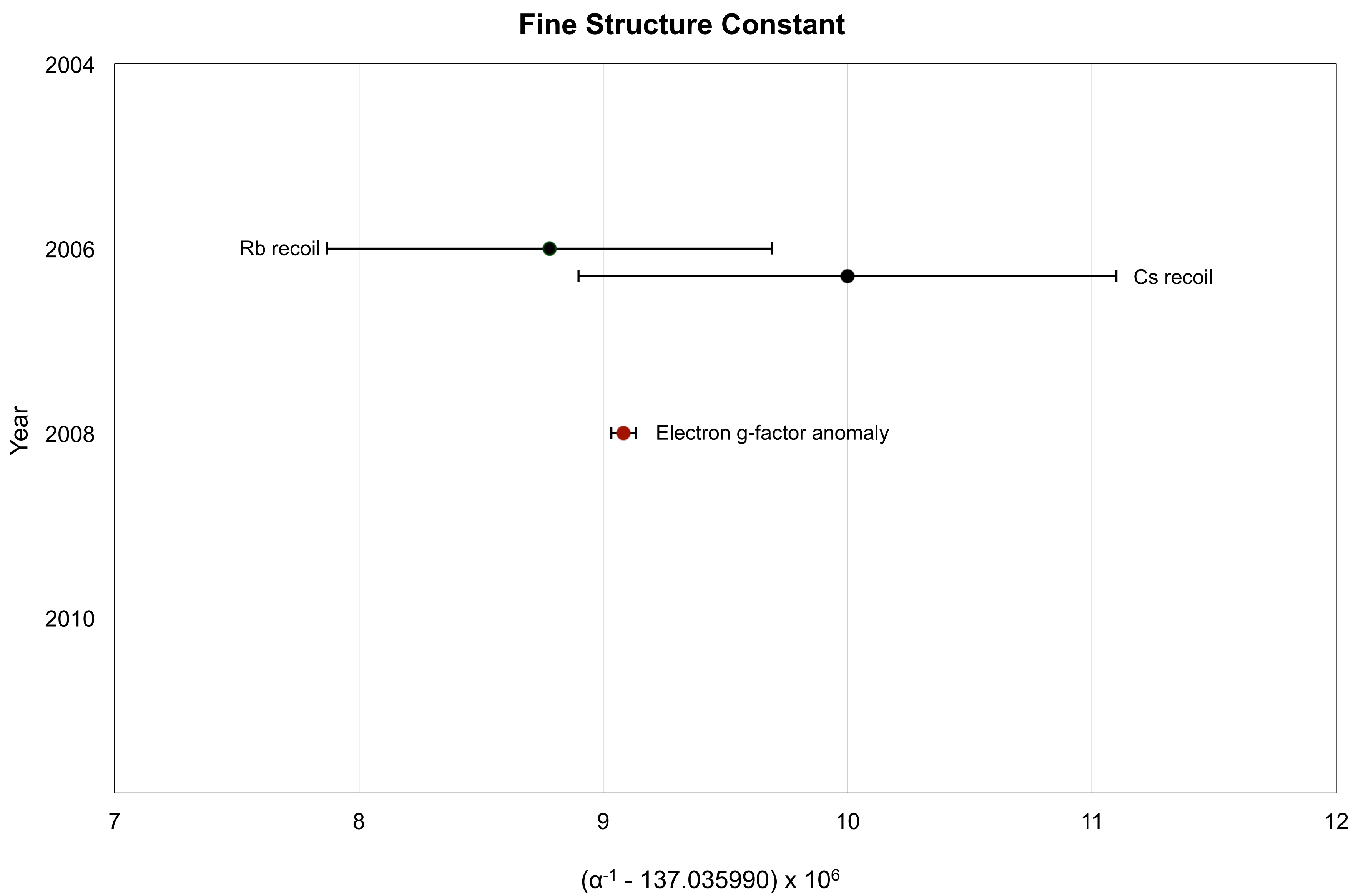


S. D. Rosner and F. M. Pipkin, Phys. Rev. A **1**, 571 (1970)

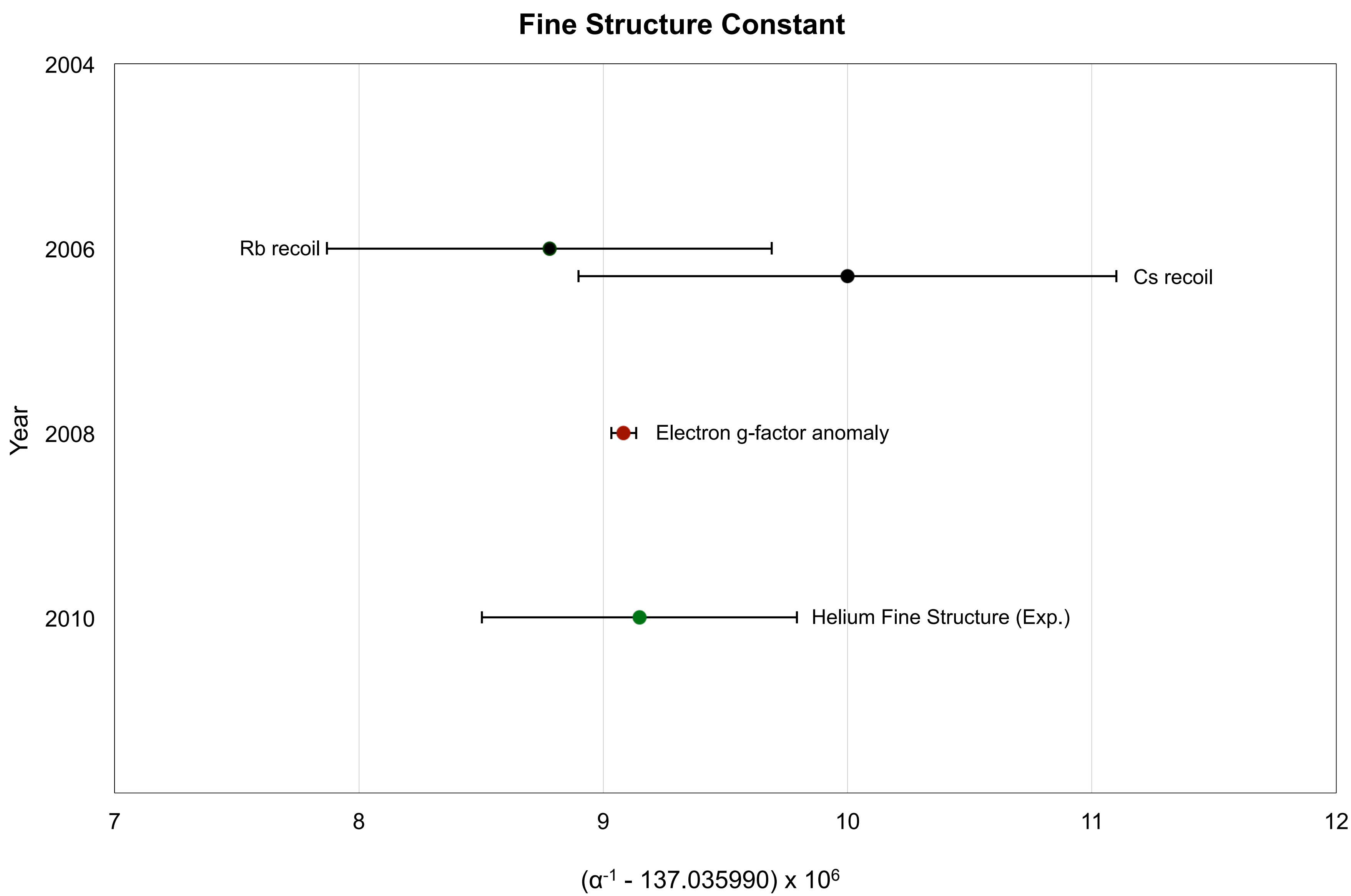

He 3 2S Hyperfine Structure Interval
1950
1970
1990
2010
Year
Harvard
700.8
701
701.2
701.4
701.6
Frequency - 6,739,000 kHz

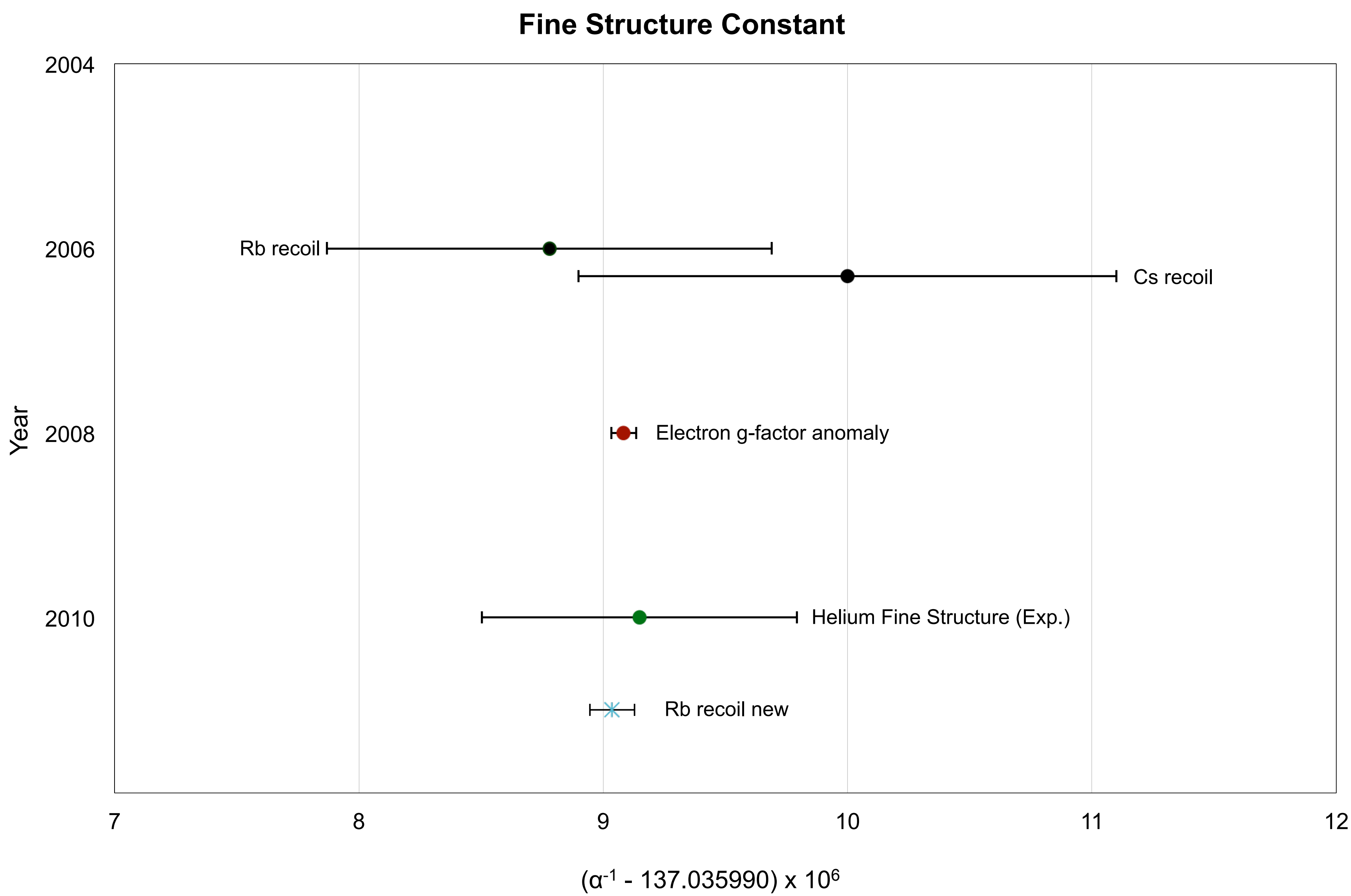


He 3 2S Hyperfine Structure Interval
Year
1950
1970
1990
2010
Harvard
w/o systematics
North Texas
with systematics
700.8
701
701.2
701.4
701.6
Frequency - 6,739,000 kHz

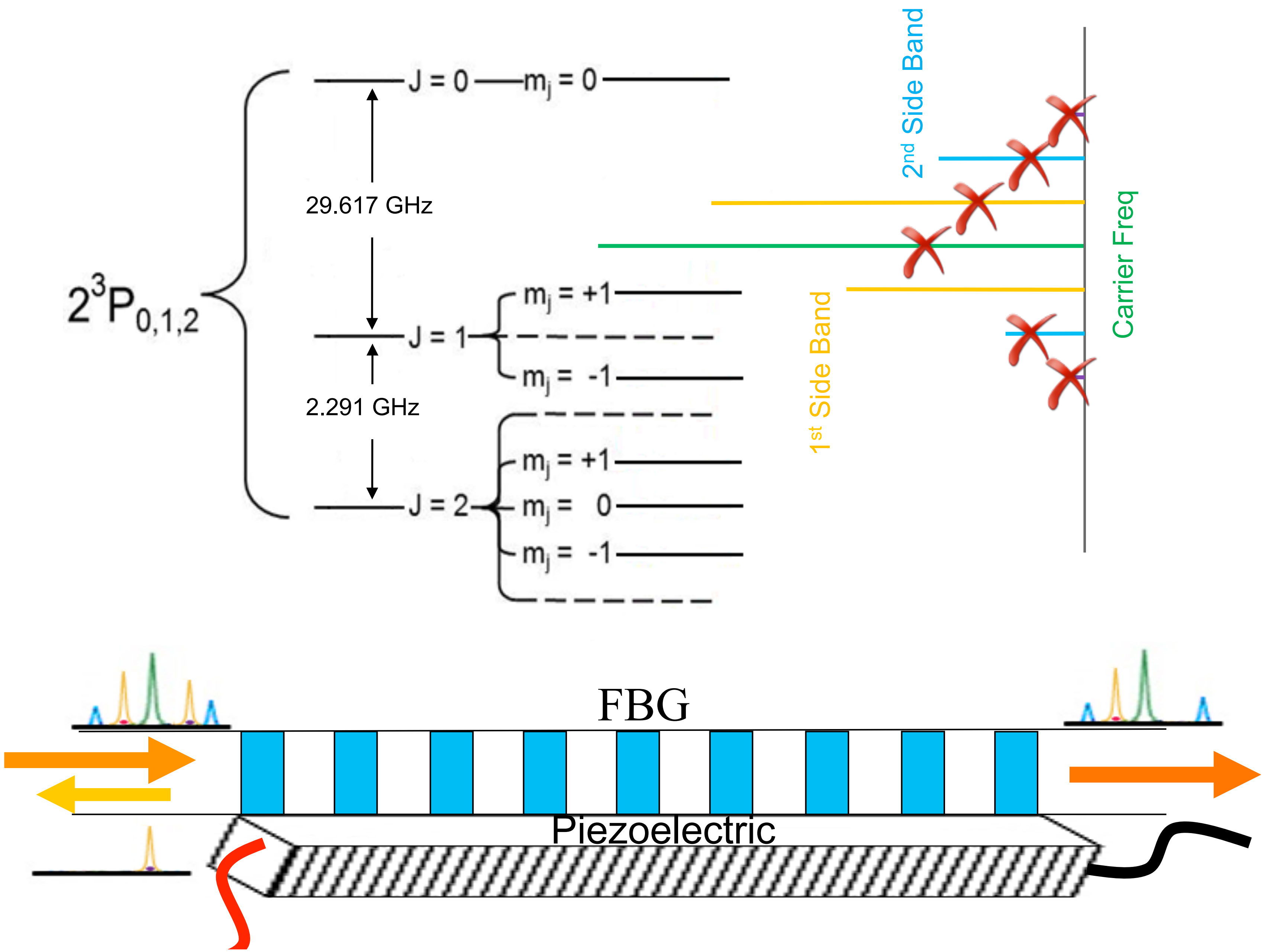


Fine Structure Constant
2004
2006
2008
2010
Year
Rb recoil
Cs recoil
Electron g-factor anomaly
7
8
9
10
11
12
(α-1 - 137.035990) x 106

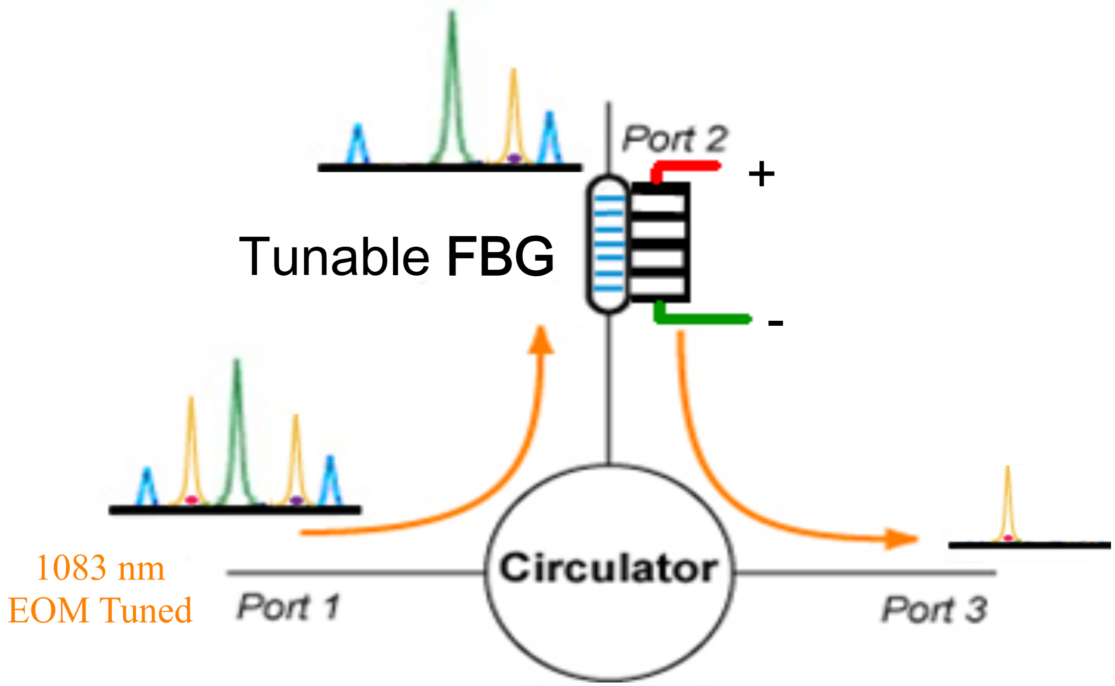

Fine Structure Constant
2004
2006
2008
2010
Year
Rb recoil
Cs recoil
Electron g-factor anomaly
Helium Fine Structure (Exp.)
7
8
9
10
11
12
(α-1 - 137.035990) x 106


Fine Structure Constant
Year
2004
2006
2008
2010
Rb recoil
Cs recoil
Electron g-factor anomaly
Helium Fine Structure (Exp.)
Rb recoil new
7
8
9
10
11
12
(α^-1 - 137.035990) x 10^6

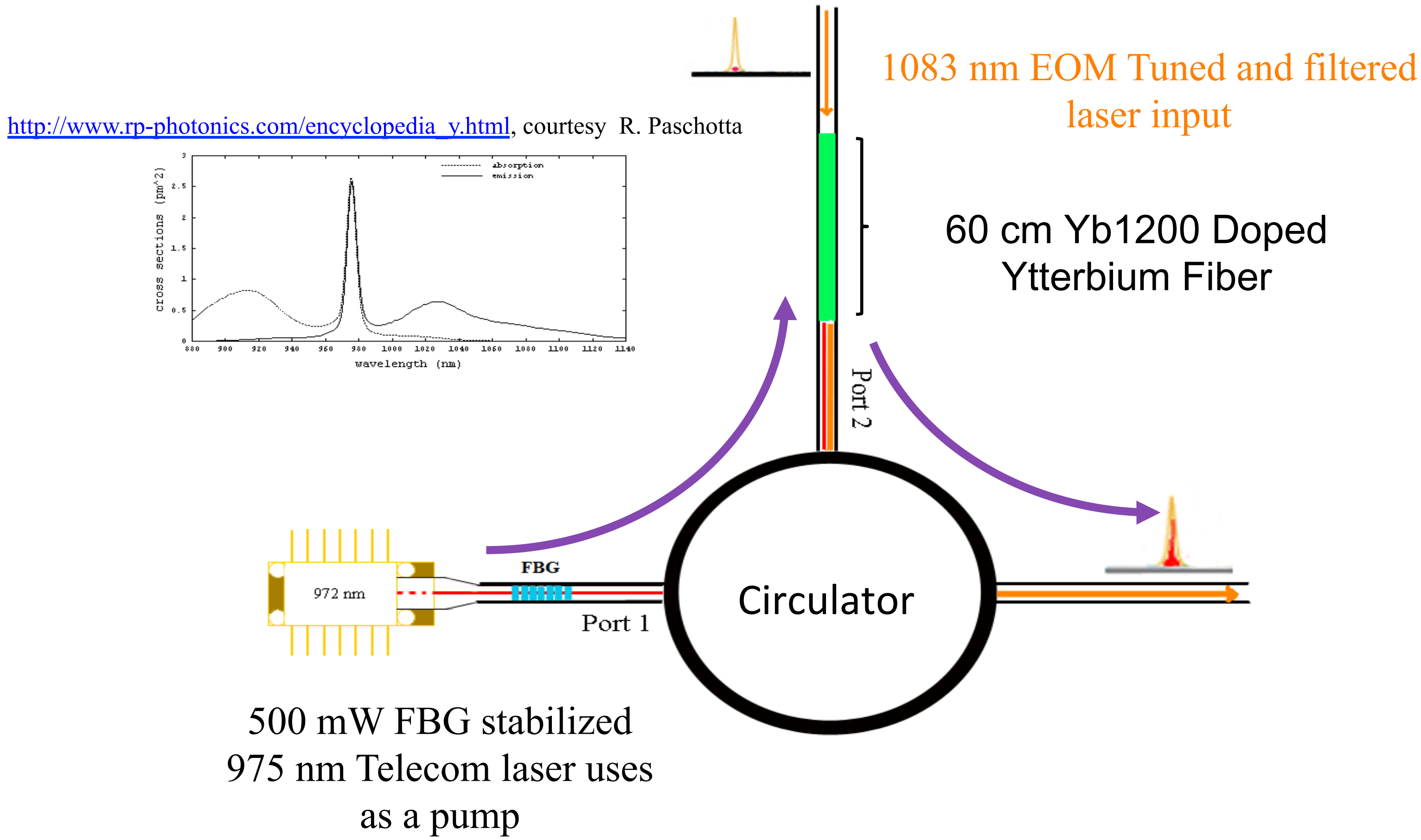
Improvements – tunable sideband selection



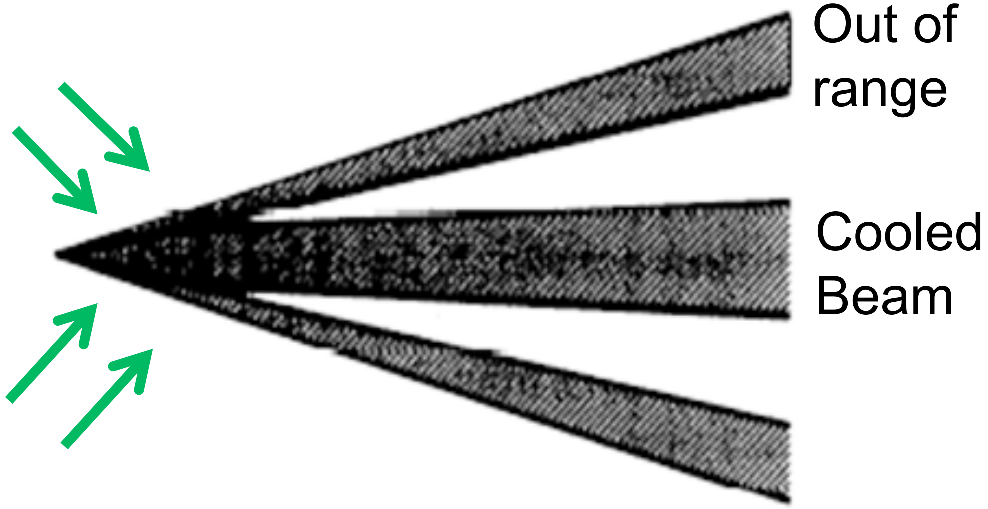
Improvements – tunable sideband selection



Improvements – tunable sideband selection

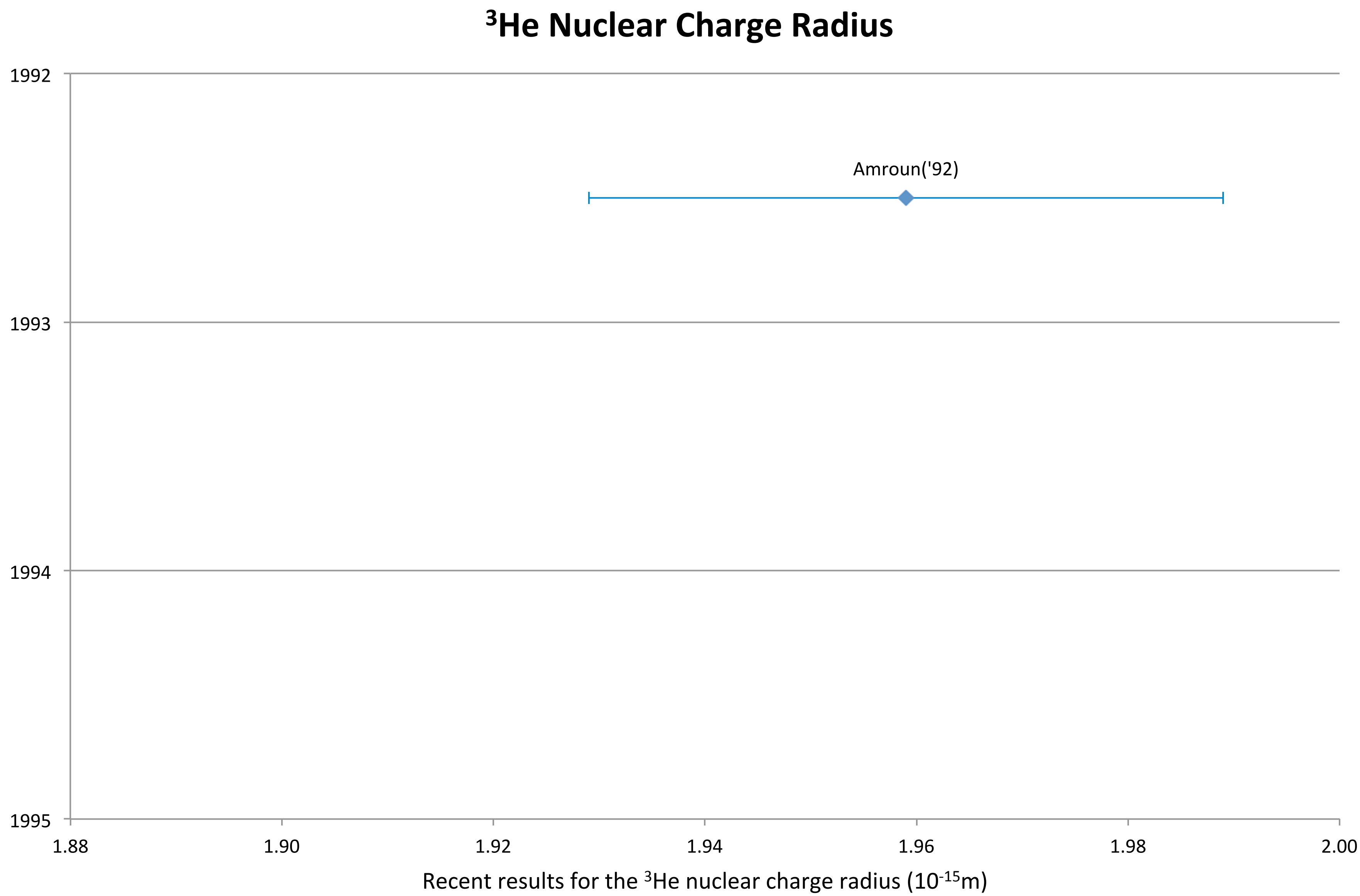


Improvements – Transverse Laser Cooling

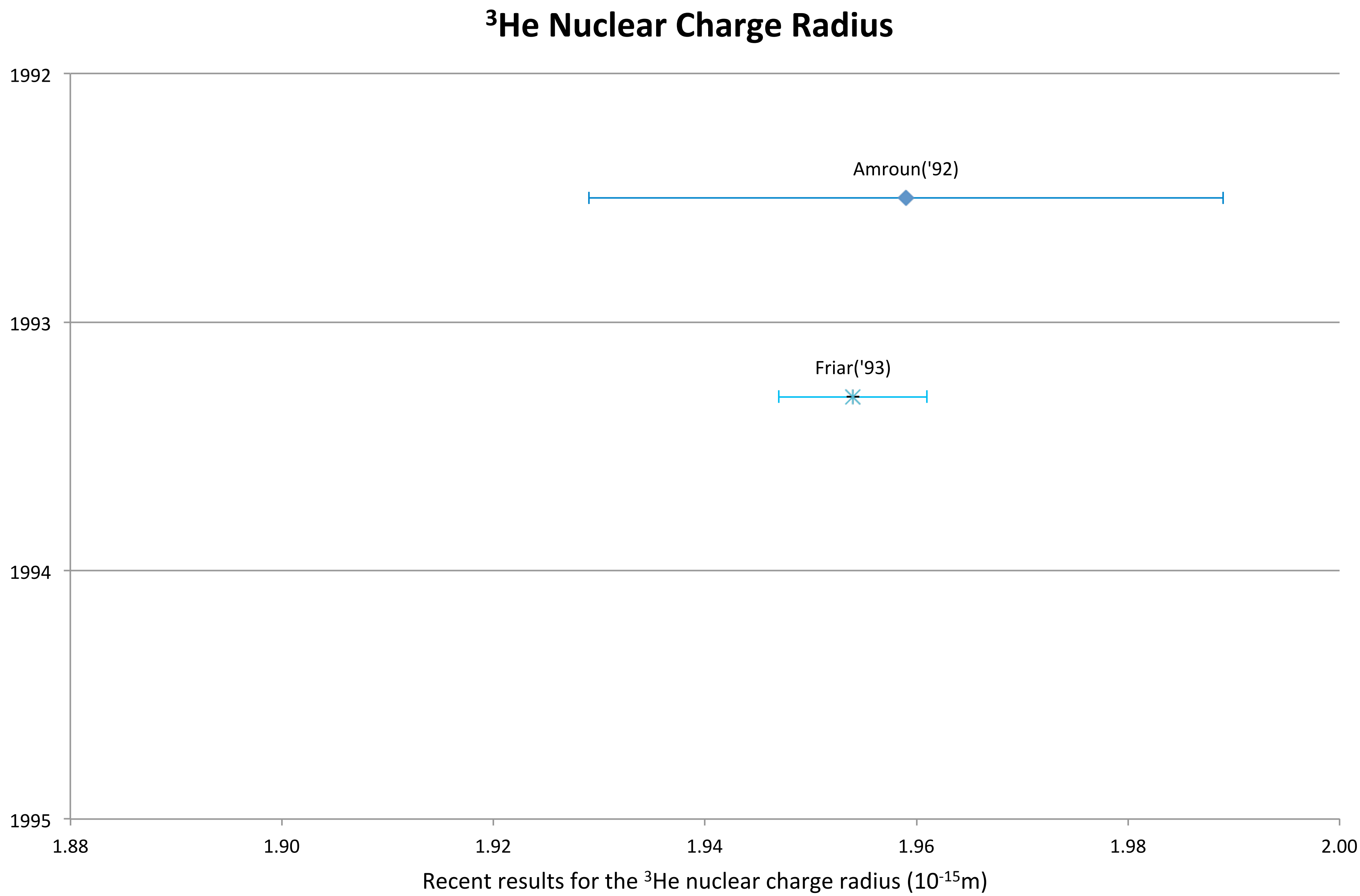


2S-2P Helium Isotope Shift

- Once all mass dependent effects are calculated, the nuclear volume effect dominates the uncertainty.
- Can use this to determine the nuclear size.
- Test predictions of few-body nuclear physics
- Verifies underlying non-relativistic zeroth order approach (justification chiral perturbation theory)

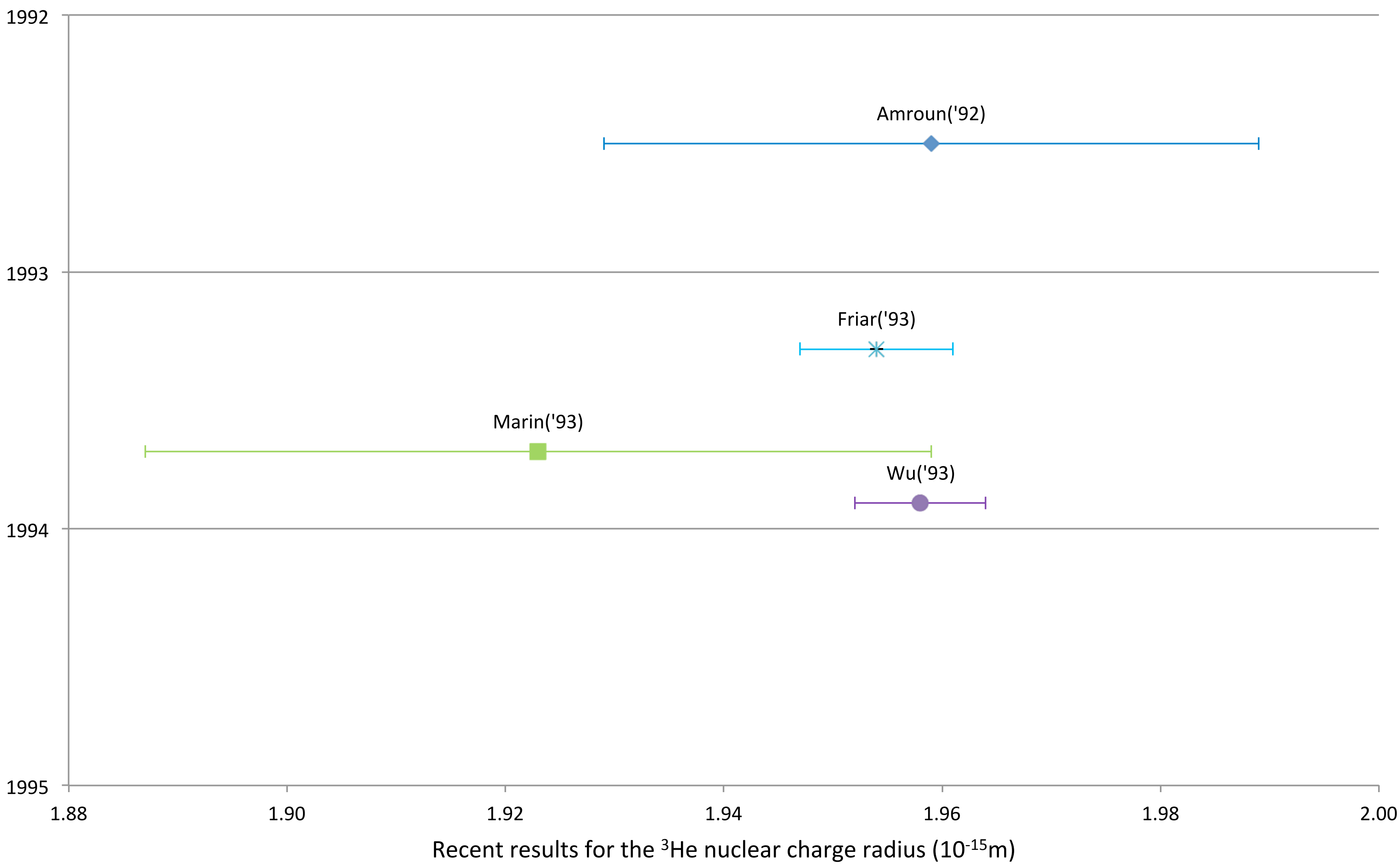


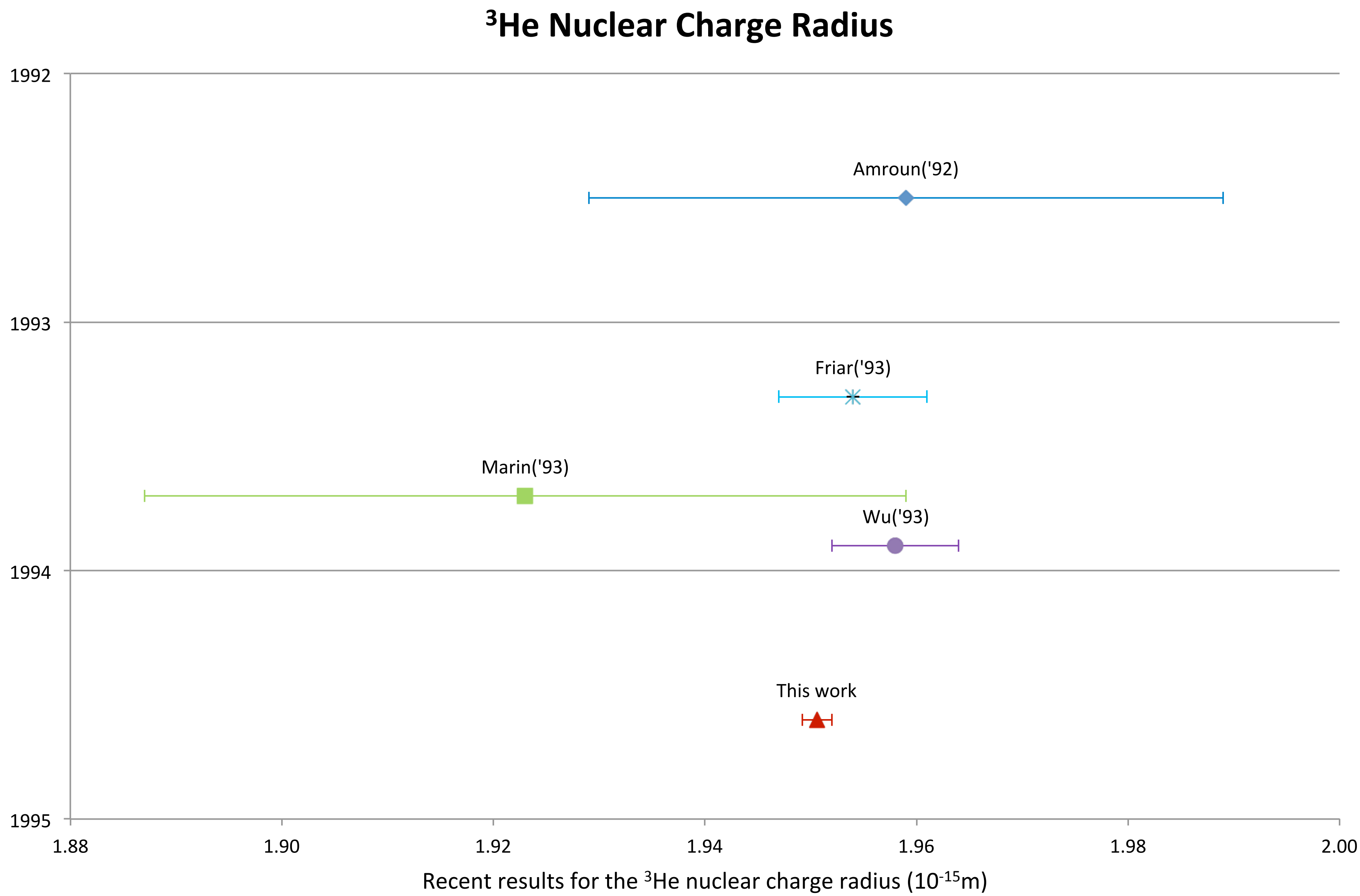
³He Nuclear Charge Radius
1992
1993
1994
1995
Amroun('92)
1.88
1.90
1.92
1.94
1.96
1.98
2.00
Recent results for the ³He nuclear charge radius (10⁻¹⁵m)



^{3}He Nuclear Charge Radius
1992
1993
1994
1995
Amroun('92)
Friar('93)
1.88
1.90
1.92
1.94
1.96
1.98
2.00
Recent results for the ^{3}He nuclear charge radius (10^{-15}m)

^{3}He Nuclear Charge Radius

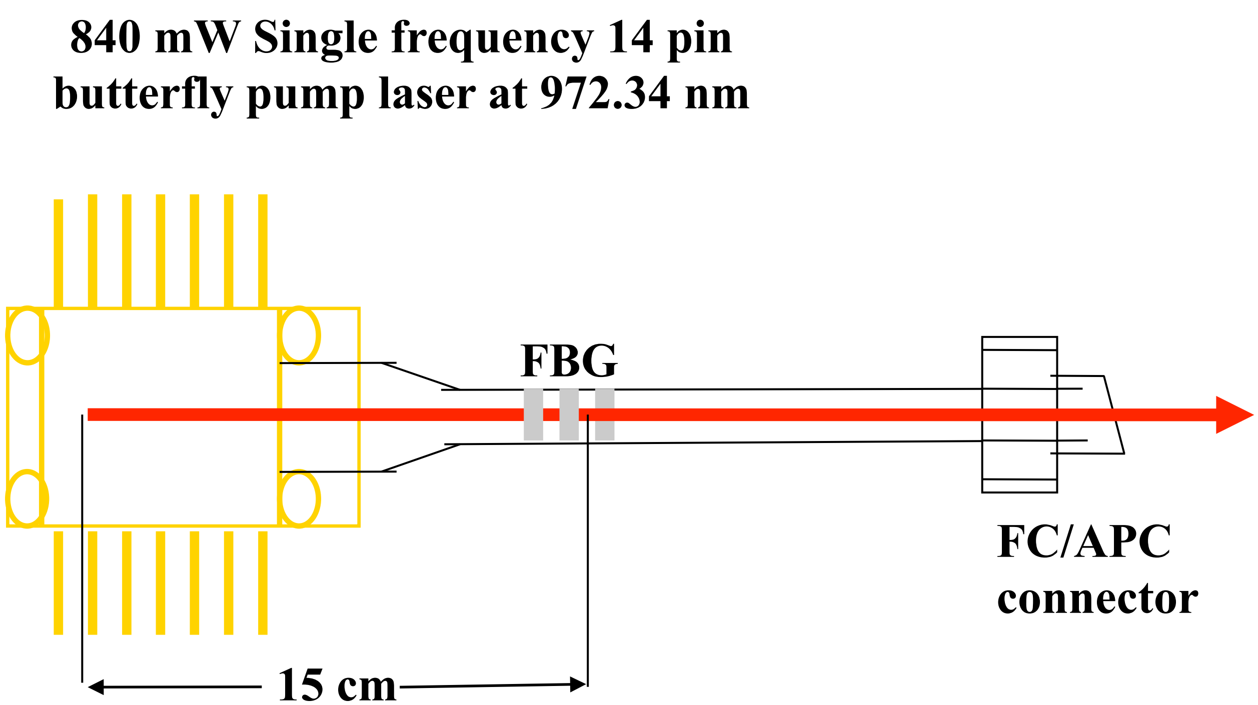



³He Nuclear Charge Radius
1992
1993
1994
1995
Amroun('92)
Friar('93)
Marin('93)
Wu('93)
This work
1.88
1.90
1.92
1.94
1.96
1.98
2.00
Recent results for the ³He nuclear charge radius (10⁻¹⁵m)

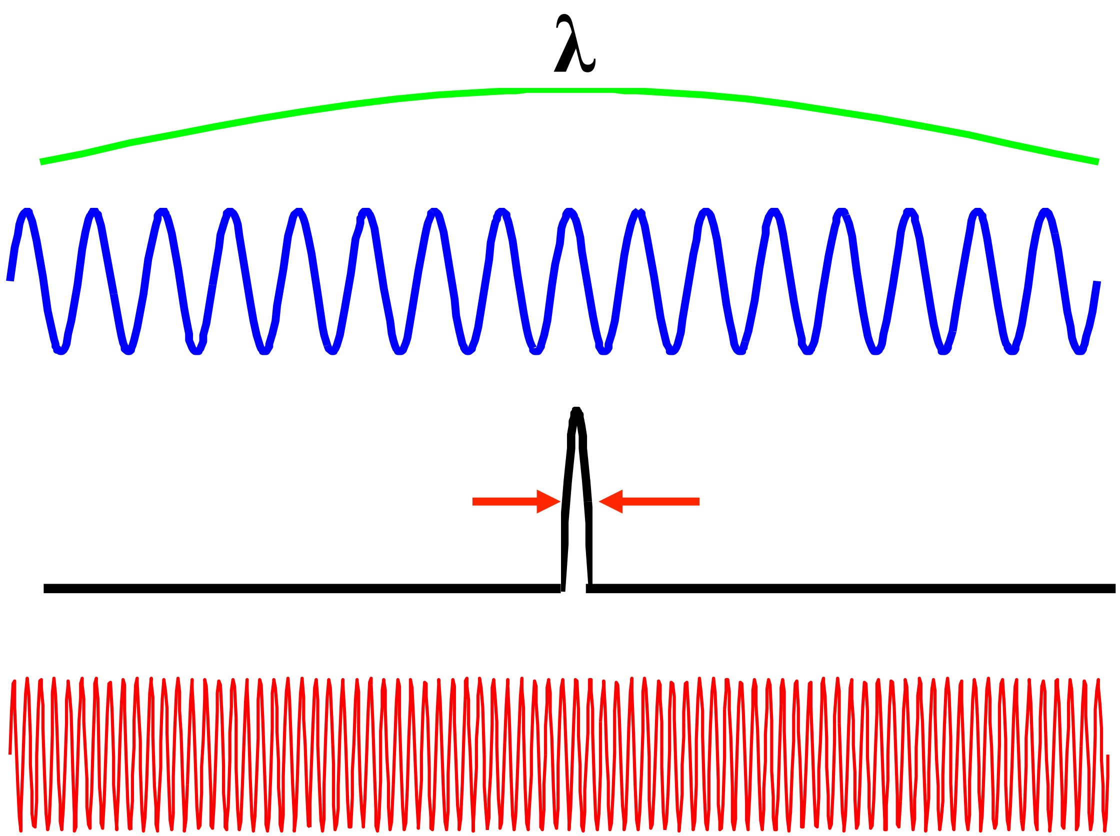
What about Tritium Size?

- Nuclear Physics very similar
- Experiment Very Different
- 1S-2S transition isotope shift
- Need a convenient tunable laser source

Convenient Laser Source



Single Frequency Operation



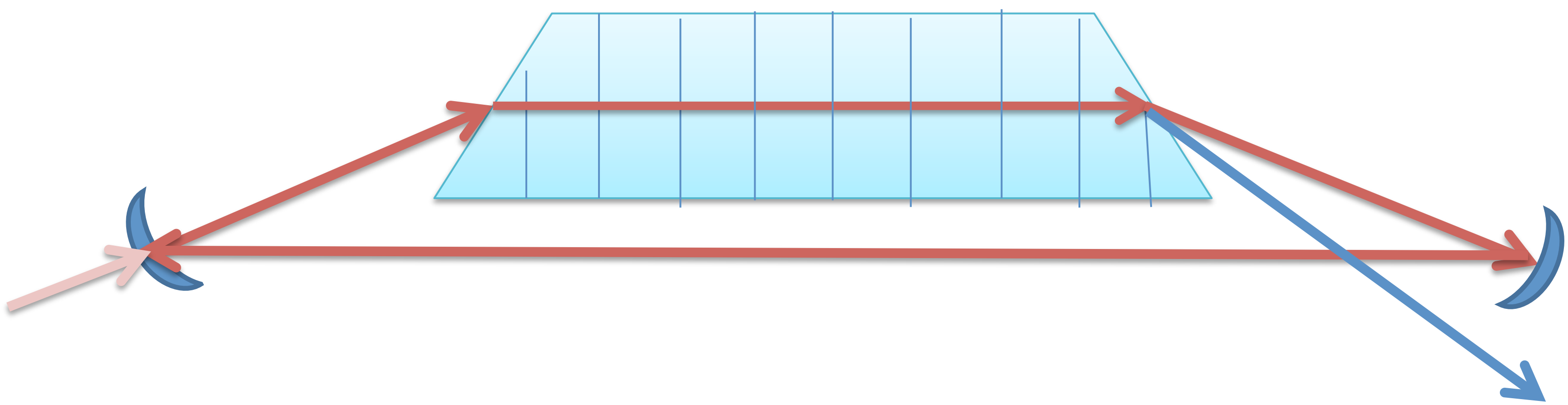
Laser medium

10 GHz FSR of the internal laser diode cavity

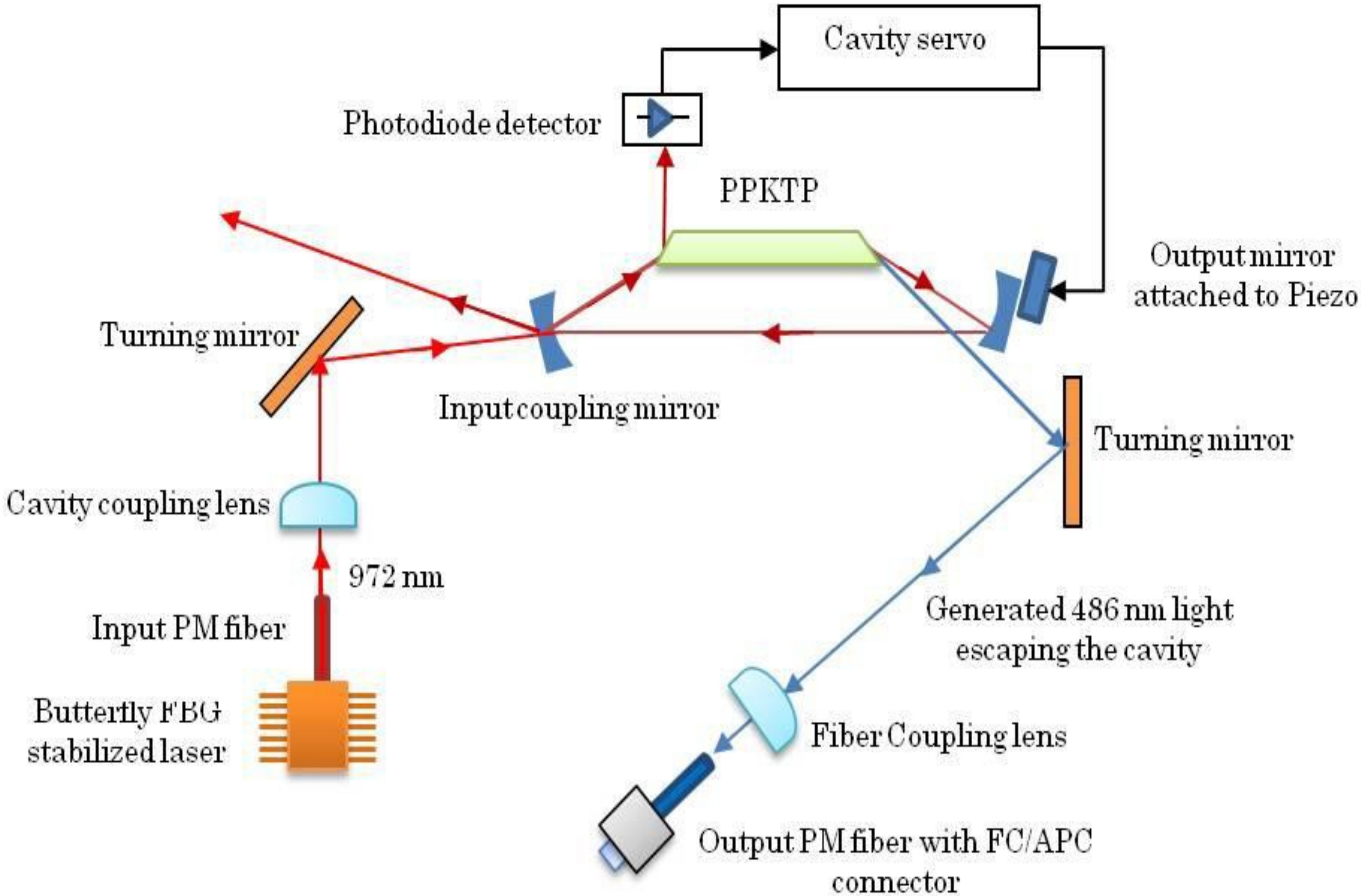
3 GHz FBG linewidth at FWHM

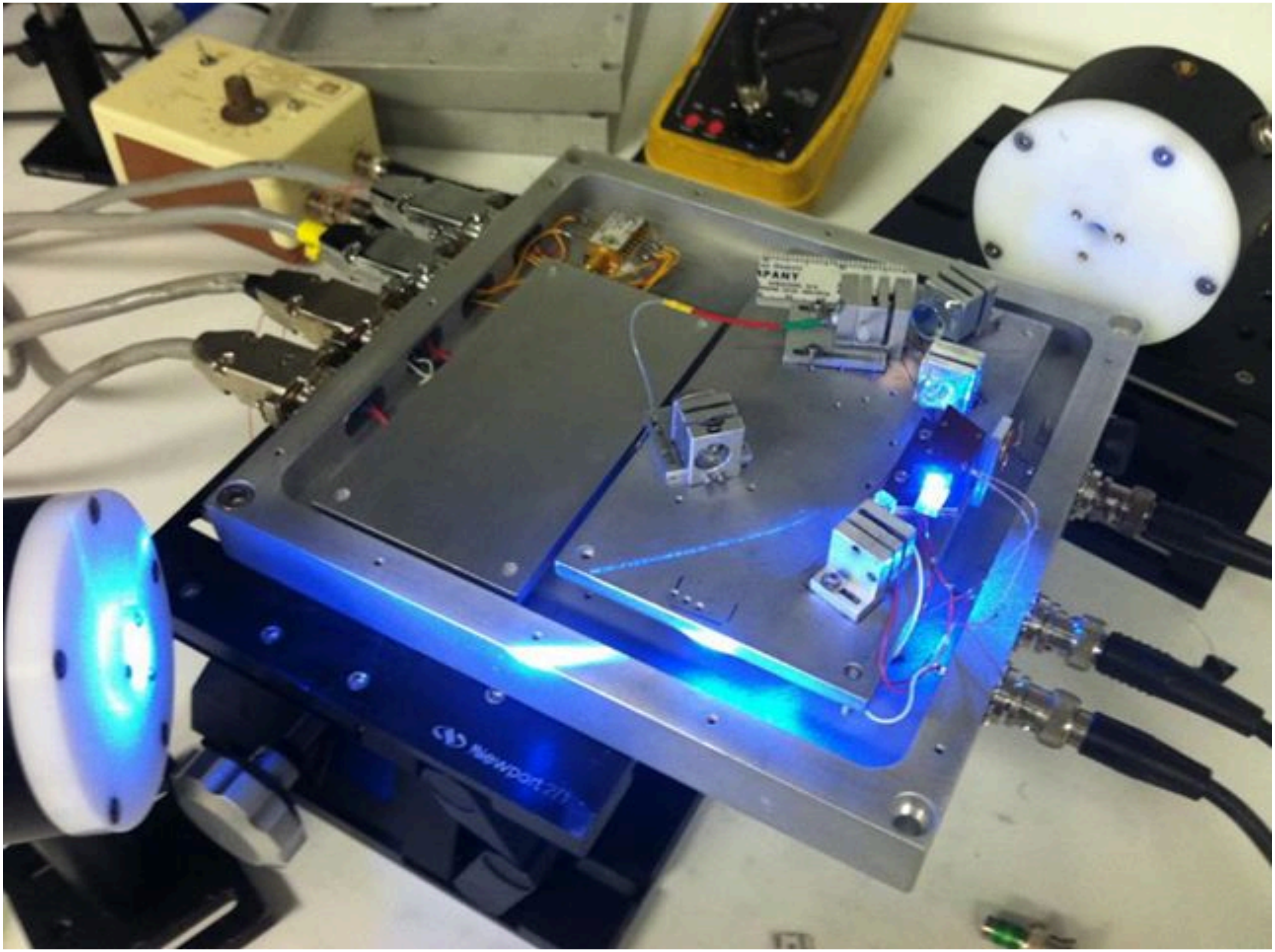
700 MHz mode space correspond to 15 cm distance from laser diode to FBG.

Doubling Cavity Geometry

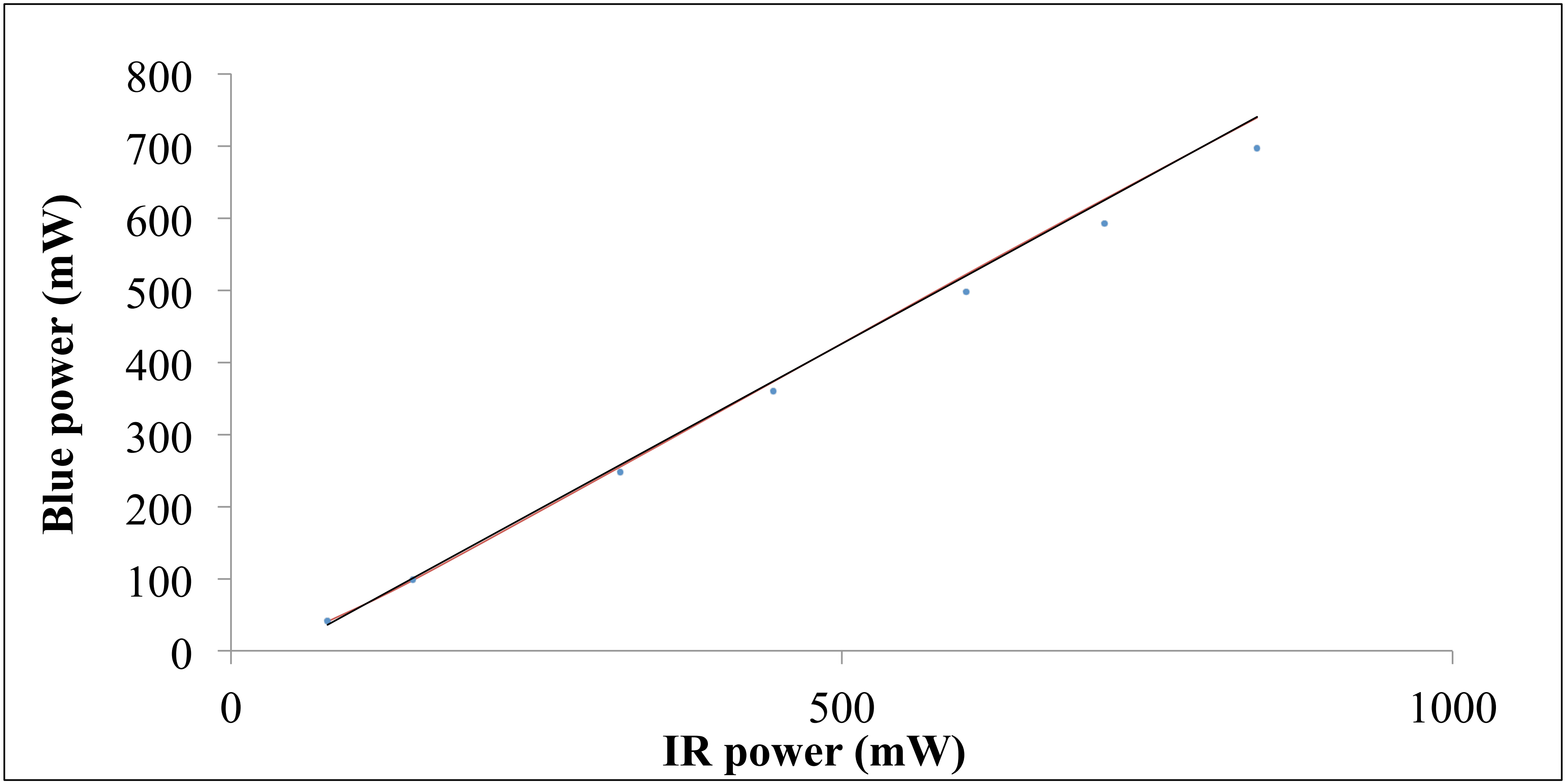


Doubling Cavity Geometry (Patented)




Newport

Blue Output Power vs. IR Input Power



Blue Conversion Efficiency vs. IR Input Power

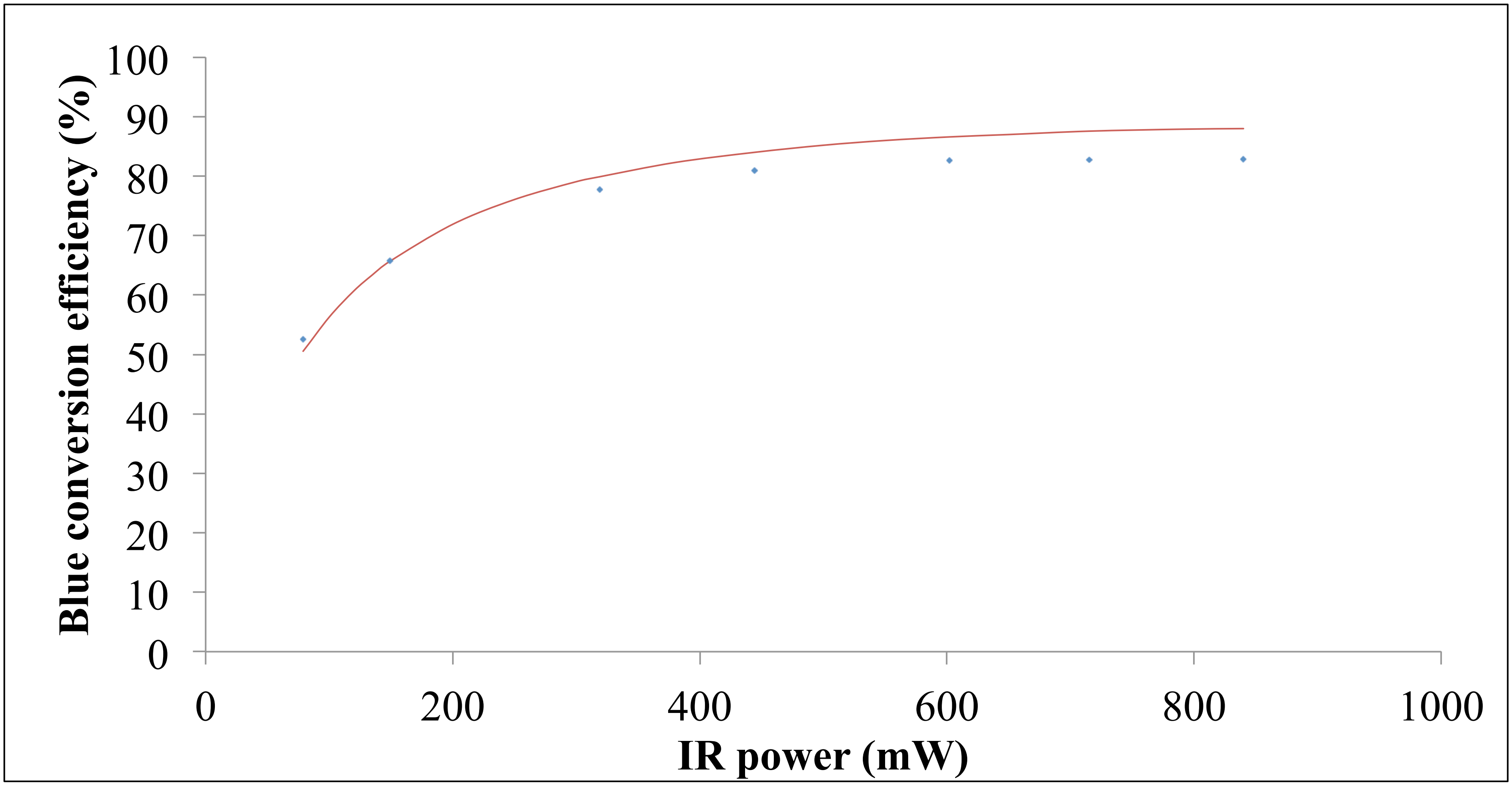


TABLE I. Efficiency and Loss budget (%).

Source	Efficiency	Loss (100 – Eff.)
Blue Transmission & Absorption	95	5
IR Mode Coupling	96	4
Linear Efficiency & Loss	97	3
Polarization allignment	99	1
Blue induce defocussing	93	7
Blue Fiber Coupling	87	13
Total	81	19
	71	29

Wall Plug Efficiency = 21.4%

Better Crystal: PPSLT vs. PPKTP

Type of Crystal	Nonlinearity of d33 (pm/V)	Index of refraction at 972 nm	Index of refraction at 486 nm	Conversion Efficiency η (%)	Blue Absorption in 20 mm crystal
PPKTP	14.9	1.83	1.90	1.35	5 %
PPSLT	13.8	2.14	2.22	0.76	0.3 %

VOLUME 7, NUMBER 118 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan

(Received July 21, 1961)

Efficiency = $5.6 \times 10^{-10}/3.0 = 1.9 \times 10^{-10}$

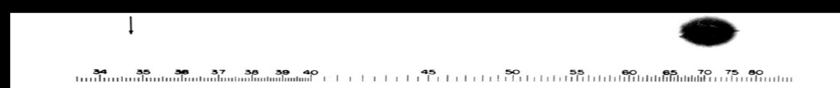


FIG. 1. A direct reproduction of the first plate in which there was an indication of second harmonic. The wavelength scale is in units of 100 A. The arrow at 3472 A indicates the small but dense image produced by the second harmonic. The image of the primary beam at 6943 A is very large due to halation.

Physics and Precision

- Scientific explanations applicable to a wide range of physical phenomena
- No less important is the ability to test some physical systems to great precision
- Provides a remarkable test and a remarkable confirmation of the believe that physical laws underlie the operation of our natural world

Laser Studies of Basic Atoms and Nuclei – an Olympics of Precision

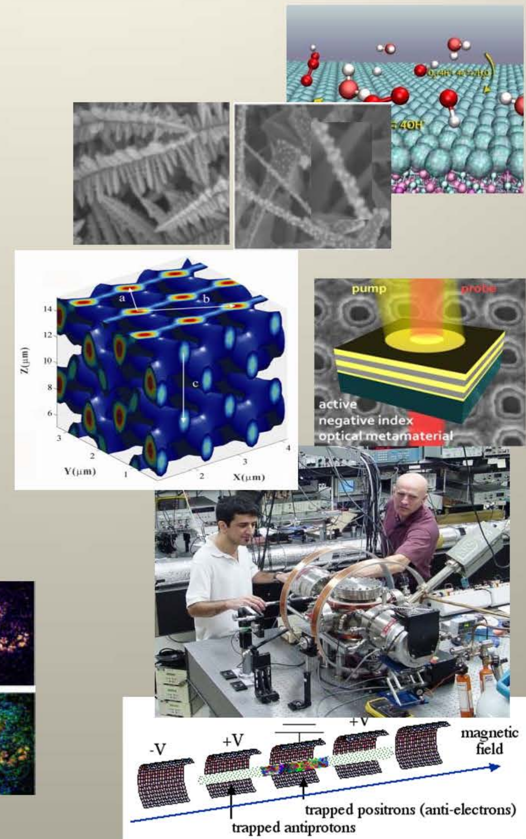
So you wish to conquer in the Olympic games, my friend? And I too, by the Gods, and a fine thing it would be! But first mark the conditions and the consequences, and then set to work. You will have to put yourself under discipline; to eat by rule, to avoid cakes and sweetmeats; to take exercise at the appointed hour whether you like it or no, in cold and heat; to abstain from cold drinks and from wine at your will; in a word, to give yourself over to the trainer as to a physician. Then in the conflict itself you are likely enough to dislocate your wrist or twist your ankle, to swallow a great deal of dust, or to be severely thrashed, and, after all these things, to be defeated.

Epictetus (c. 55–c. 135), Greek stoic philosopher. Encheiridion, no. 29b, trans. by T.W.H. Rolleston (1881).


E=ma2
E=mb2
E=?
EVOLUTION SERIES
STIGA
AEROTECH

Department Research Areas, Focused and Groups Efforts

- Astronomy and Astrophysics
- **Atomic, Molecular, and Optical Physics**
- Carbon Physics: Graphene
- Chaos and other Non-linear Science
- Global Climate
- **Condensed Matter Physics**
- Ion beam characterization and modification of materials



- **Materials modeling**
- Microwave spectroscopy
- **Nanomaterials synthesis and characterization**
- **Optical Device Physics**
- **Photonics, Plasmonics, and Biosensing**
- Precision Atomic Spectroscopy
- Plasma Science