Probing the Variation of Fundamental Constants with Polar Molecule Microwave Spectroscopy

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OUTLINE

- Background
  - Importance of variation
  - Why should fundamental constants vary?
  - Current state of affairs
- Our experiment
  - Producing cold, slow laboratory OH
  - Measuring Λ-doublet transition frequencies
- Future work
  - New experiment based on Th-229 nuclear transition

Why should we care if the fundamental constants vary?

- They’re supposed to be constant
- Varying fundamental constants violate both Lorentz invariance and CPT symmetry.

Why should we think the fundamental constants could vary?

- Attempts to unify gravity predict (or allow for) space-time varying fundamental constants

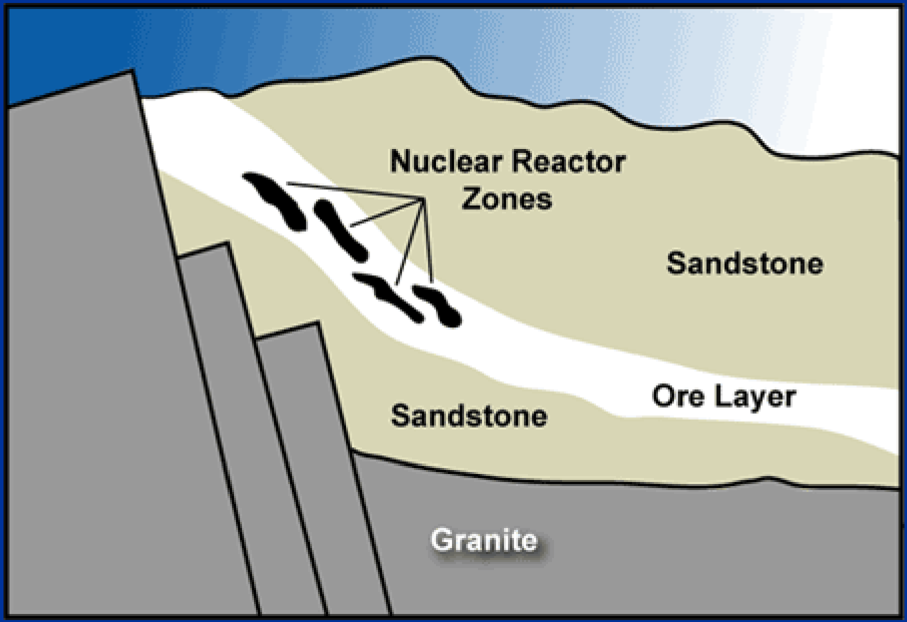
0 (2004).

Why should they be constant?

- Interac th dark energy quintessence field leads to varying fundamental constants.
  - –Quintessence - photon interaction $\rightarrow \delta_i \alpha \neq 0$
  - –Quintessence - electron interaction $\rightarrow \delta_i m_e \neq 0$

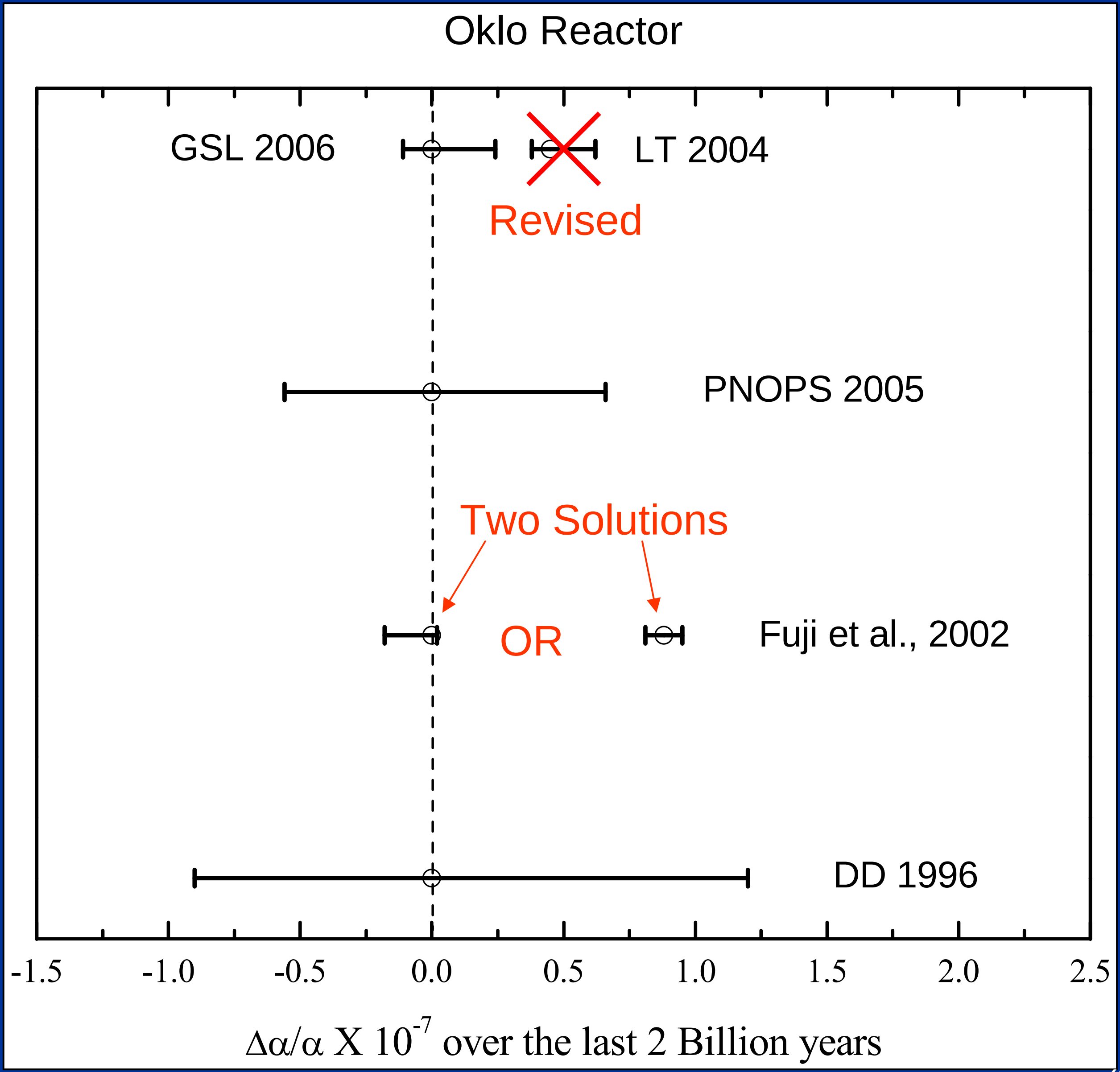
Physics Today **57,** No. 7, 40 (2004).

Oklo Natural Nuclear Reactor



- Currently ^{238}U ~ 99.3% and ^{235}U ~ 0.7%
- 2 billion years ago ^{235}U ~ 4% (typical reactor concentrations)
- Neutron capture cross-section for ^{149}Sm sensitive to $\Delta\alpha$ because of 97.3 meV resonance.

Taken from: http://www.ocrwm.doe.gov/factsheets/doeymp0010.shtml



Consistent with zero:

$$\frac{\Delta\alpha}{\alpha} \leq 1(10^{-17})\text{yr}^{-1}$$

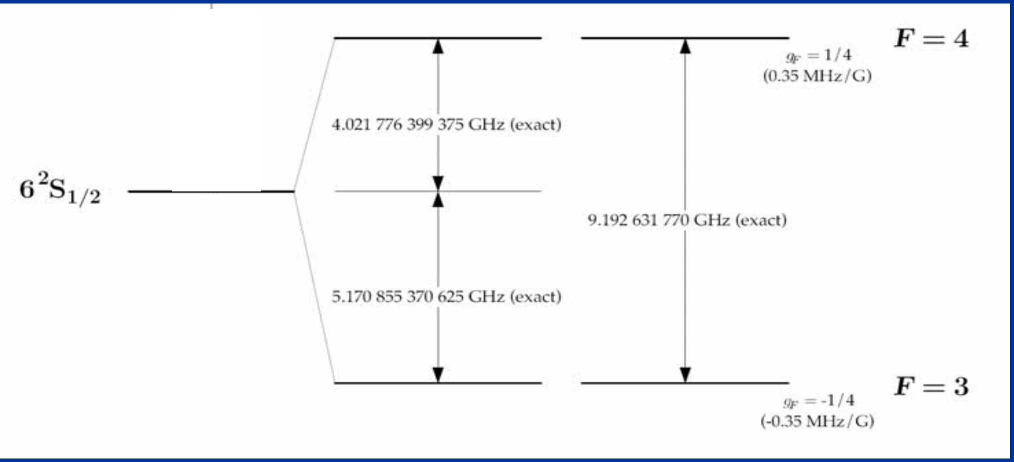
(LT 2004) PRD 69 121701
(PNOPS 2005) arXiv: hep-ph/0506186
(DD 1996) Nucl. Phys. B480 37
Fujii et al., AriXiv:hep-ph0205206
(GSL 2006) PRC 74 024607

Atomic clock measurements

Simple Idea:
Measure atomic transition frequencies and see if they vary with time

Problem:
To measure a frequency you need a 'clock' (i.e. another frequency)

Solution:
Use Cs hyperfine transition as a reference



Optical transitions:

$\nu_i \sim Ry\, F_i(\alpha)$

Hyperfine transitions:

$\nu_j \sim \alpha^2 (\mu_{Cs}/\mu_B) Ry\, F_j(\alpha)$

Relativistic Correction:

$F(\alpha) \sim \alpha^N$

Fractional variation:

$$\frac{d}{dt}\ln\left[\frac{\nu_{Optical}}{\nu_{Cs}}\right] = (N_{Optical} - N_{Cs} - 2)\frac{\dot{\alpha}}{\alpha} - \frac{d}{dt}\ln\left[\frac{\mu_{Cs}}{\mu_B}\right]$$

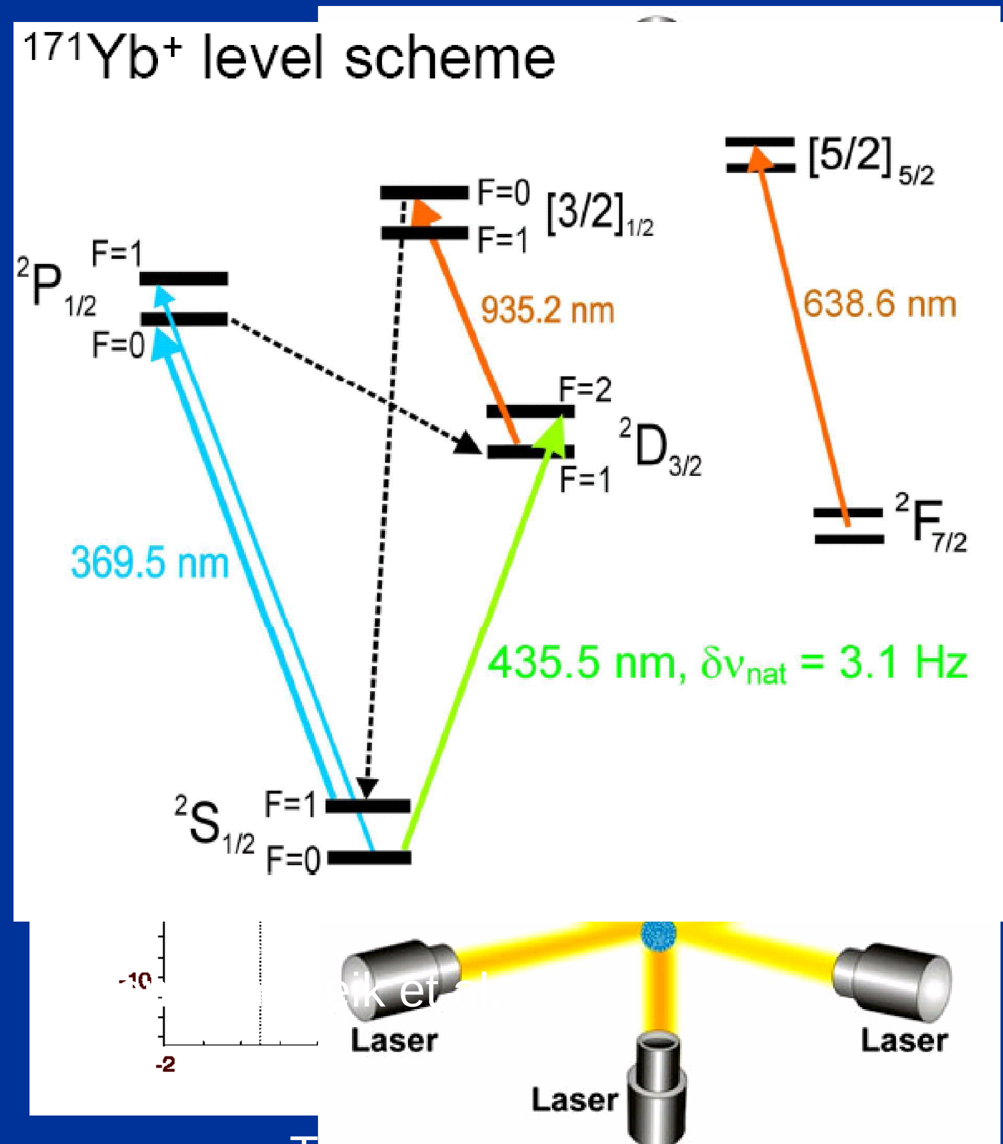
$N_{Cs} = 0.8$

$N_{Hg+} = -3.2$

Atomic clock measurements

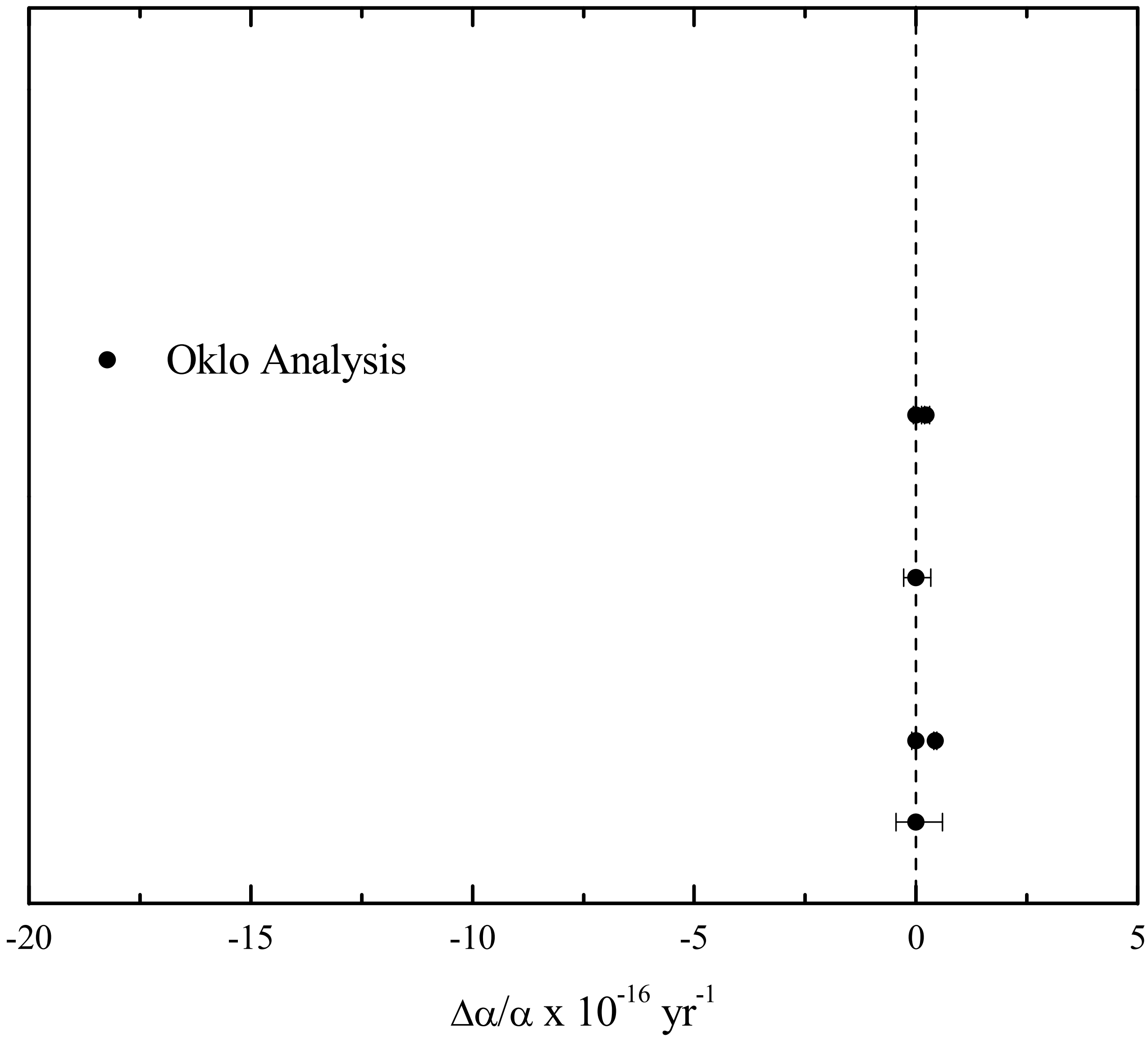
<u>Several **excellent** experiments:</u>

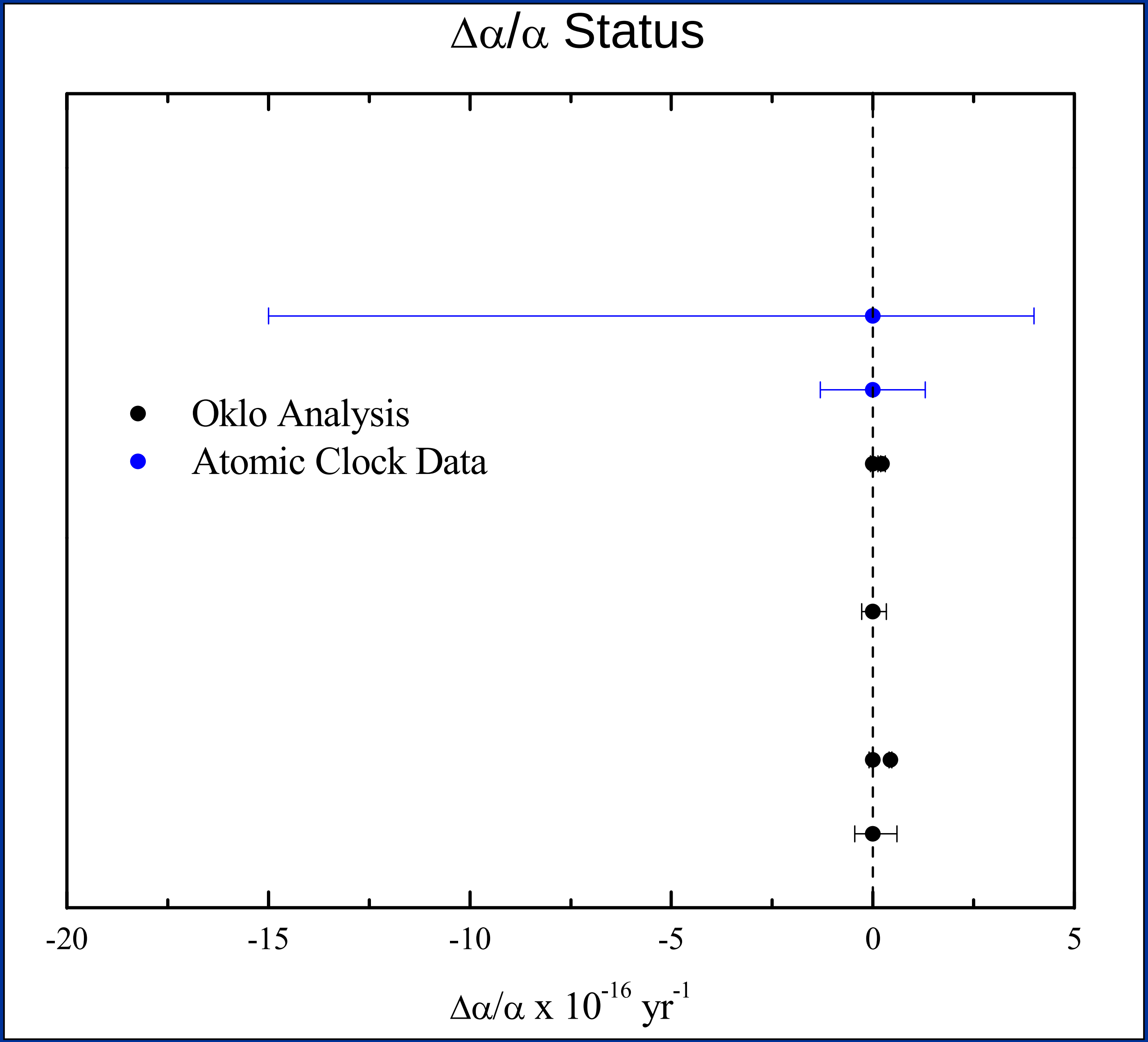
- $^{199}Hg^{+}$ vs. Cs
- H vs. Cs
- $^{171}Yb^{+}$ vs. Cs
- Rb vs. Cs
- Future: Sr, Yb, Ca, Al^{+}…



Taken from PRL 98 070801

$\Delta\alpha/\alpha$ Status





Atomic Clock Data:
PRL 98 070801

Astrophysical measurements

Quasar Absorption:

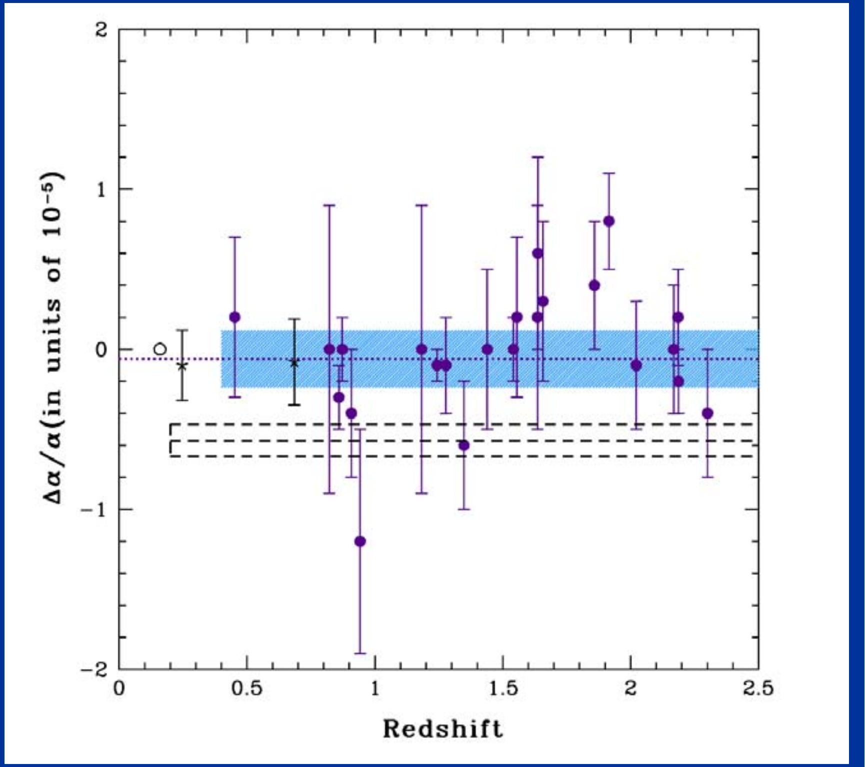
- Conceptually the same as atomic clock measurements.
- Quasars emit over a large spectrum
    - Look for absorption from gas between the quasar and us

Other possibilities from astrophysics:

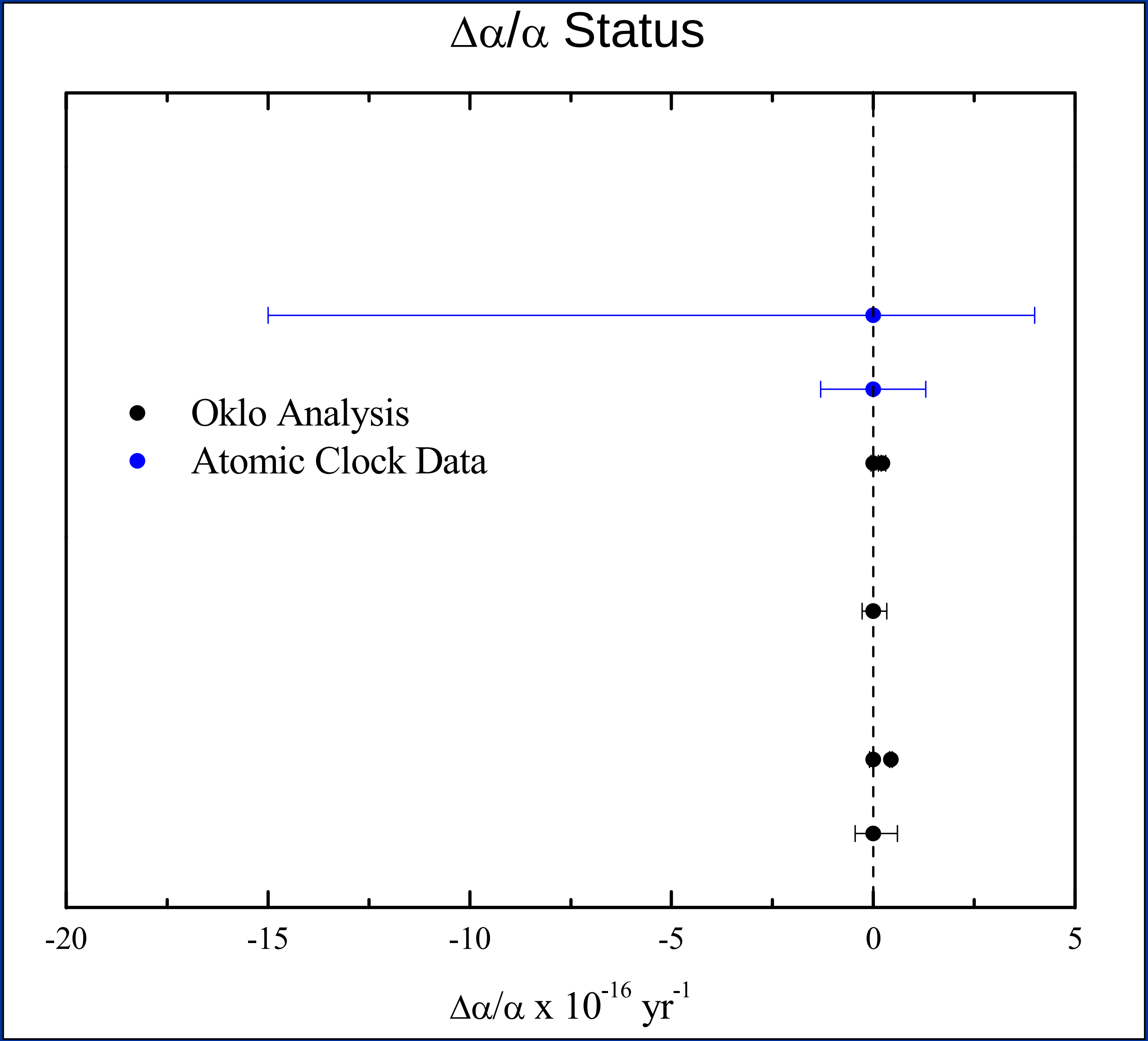
- Non-zero $\Delta\alpha$ causes change to the CMB pattern. Look back to z ~ 1000, $\Delta\alpha \sim 10^{-3}$

  PRD 60, 023516

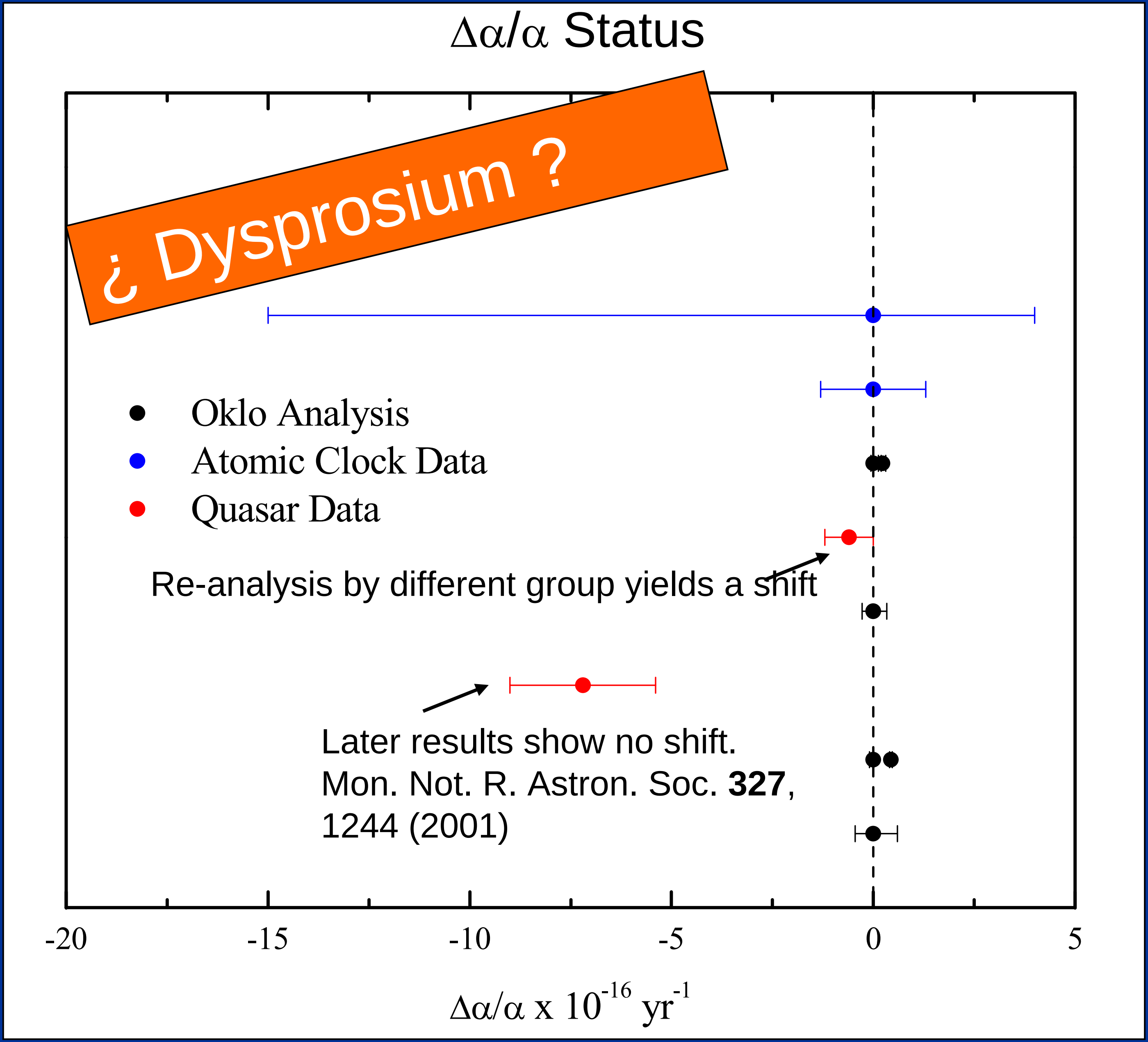
- Big Bang Nucleosynthesis



Taken from: R.Srianand et al PRL, 92 121302



Atomic Clock Data:
PRL 98 070801



Quasar Data:
PRL 87 091301
PRL 92 121302

Atomic Clock Data:
PRL 98 070801

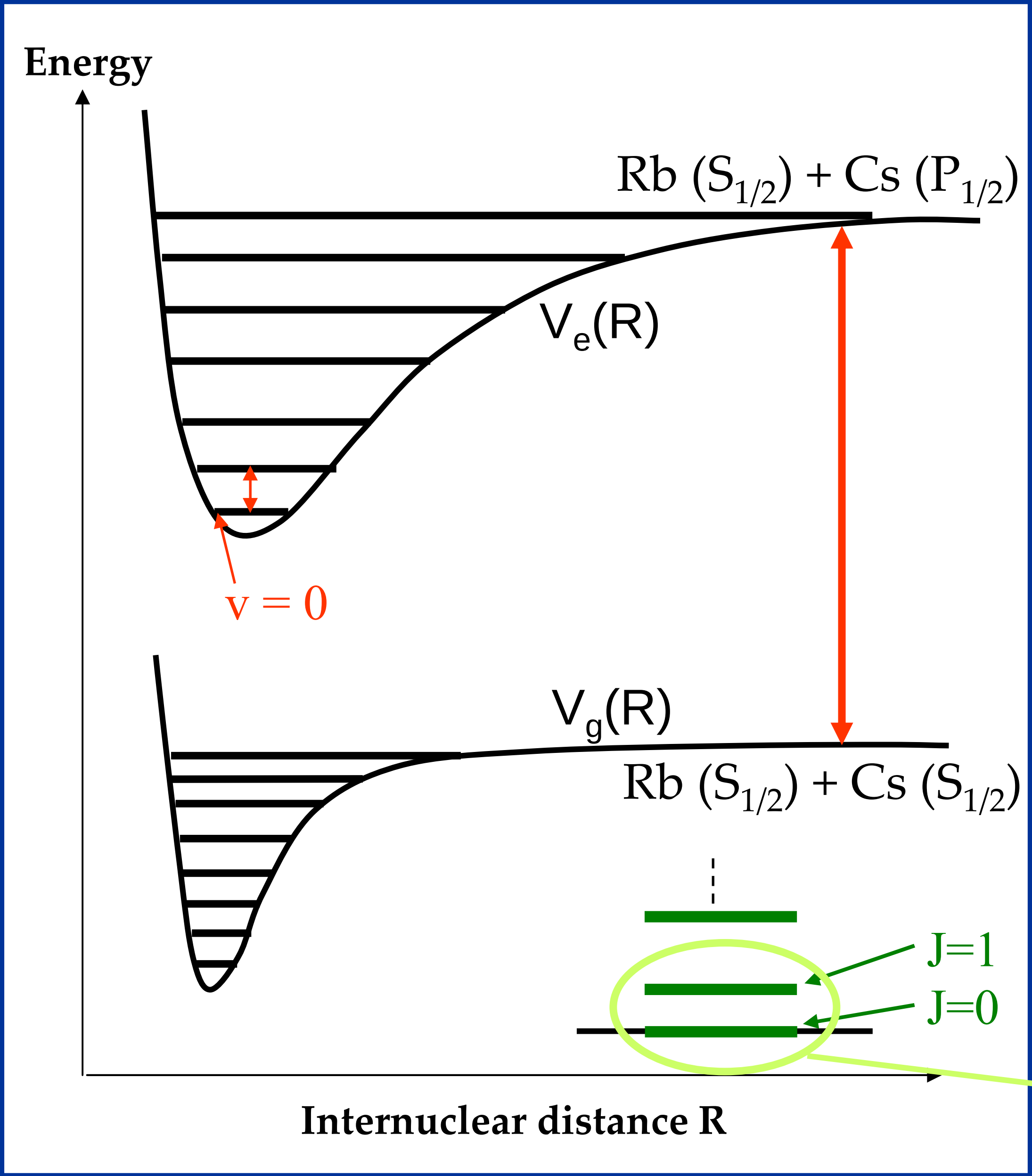
Recap

- Modern epoch (and then some) consistent with zero
  - Constraints are rapidly improving with no end in sight

- Early universe not so clear
  - Lack of control of systematics in astrophysical measurements neccesitates the need for an ‘ultimate’ check

OH Mega-masers allow interrogation of the early universe AND have an ‘ultimate’ check for systematics

Molecular structure: What is a molecule?

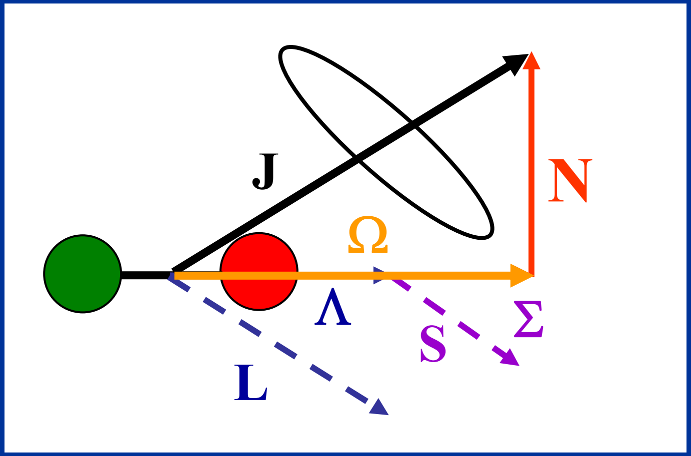


- Electronic potentials
  ~ 300 THz (~ 1.5 eV)
- Vibrational levels
  ~ 0.1 - 1 THz
- Rotational levels
  ~ 0.1 - 1 GHz

Two levels for qubit

PA Primer: Electronic state labeling

- Heteronuclear diatomic molecules possess only axial symmetry
  - different good quantum numbers than for atoms

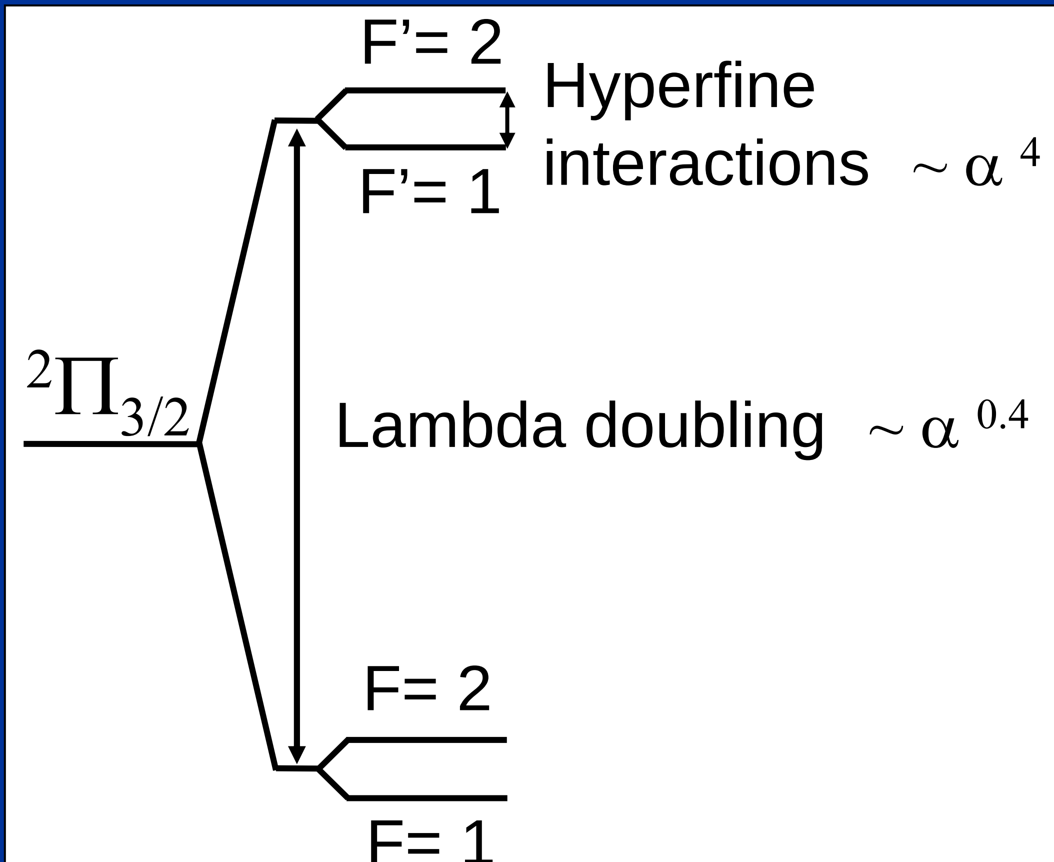


- $\Omega = |\Lambda + \Sigma|$
- $\mathbf{J} = \mathbf{\Omega} + \mathbf{N}$

- Electronic potentials are labeled as $^{2\Sigma+1}\Lambda_{\Omega}$
  - Σ, Π, Δ, ... states for Λ = 0, 1, 2, ...
  (i.e., $^{3}\Sigma_{1}$ state has Λ=0, Σ=1, Ω=1)

- Good quantum #'s are Λ, Σ, Ω, J, m_J (or just Ω, J, m_J)

Using OH transitions to constrain α



OH megamasers

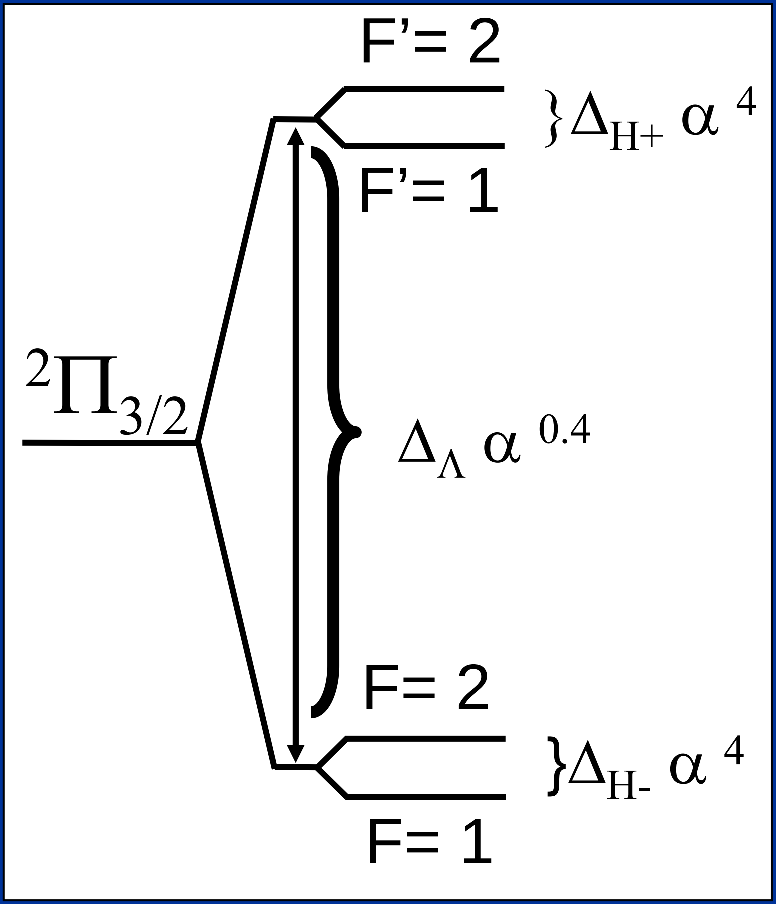
Darling, Phys. Rev. Lett **91**, 011301 (2003).
Chengalur *et al*., Phys. Rev. Lett. **91**, 241302 (2003).
Kanekar *et al*., Phys. Rev. Lett. **93**, 051302 (2004).

Allows for measurements of multiple transitions from the same gas cloud (Doppler shifts constrained and self check on systematics from closure)

Previous uncertainly in laboratory based experiments is 100-200 Hz, which leads to $\Delta\alpha/\alpha \sim 10^{-5}$

ter Meulen & Dymanus, Astrophys. J. **172**, L21(1972).

Using OH transitions to constrain α



Astronomical observation:

$\omega_{11} = \Delta_\Lambda\, \alpha_o^{\ 0.4} - 1/2(\Delta_{H+}\text{-}\Delta_{H+})\, \alpha_o^{\ 4} + RS_{11}$

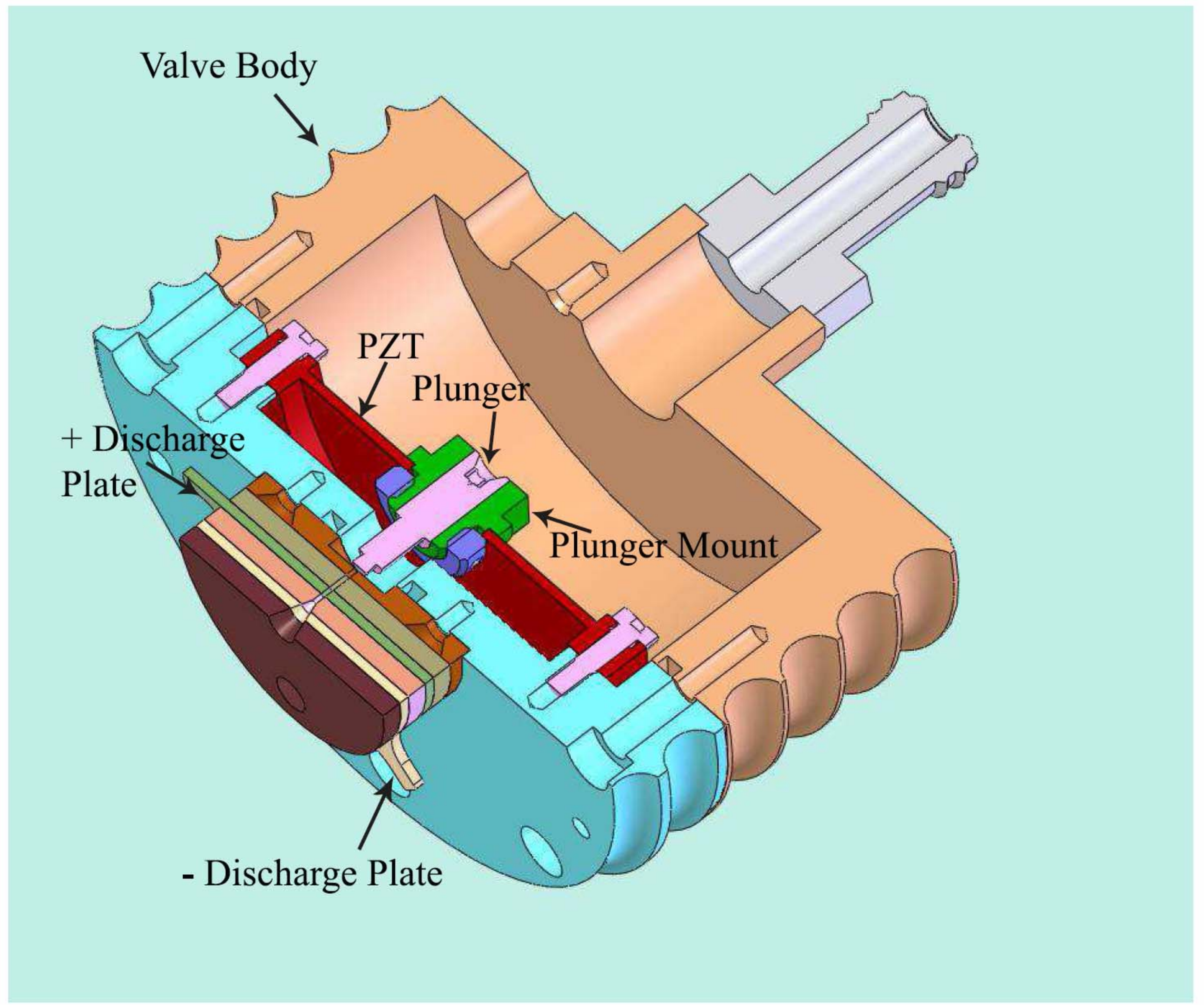
$\omega_{22} = \Delta_\Lambda\, \alpha_o^{\ 0.4} + 1/2(\Delta_{H+}\text{-}\Delta_{H+})\, \alpha_o^{\ 4} + RS_{22}$

Lab measurement:

$\omega_{11} = \Delta_\Lambda\, (\Delta\alpha + \alpha_o)^{0.4} - 1/2(\Delta_{H+}\text{-}\Delta_{H+})\, (\Delta\alpha + \alpha_o)^{4}$

$\omega_{22} = \Delta_\Lambda\, (\Delta\alpha + \alpha_o)^{0.4} + 1/2(\Delta_{H+}\text{-}\Delta_{H+})\, (\Delta\alpha + \alpha_o)^{4}$

First make the molecules : Sourcery

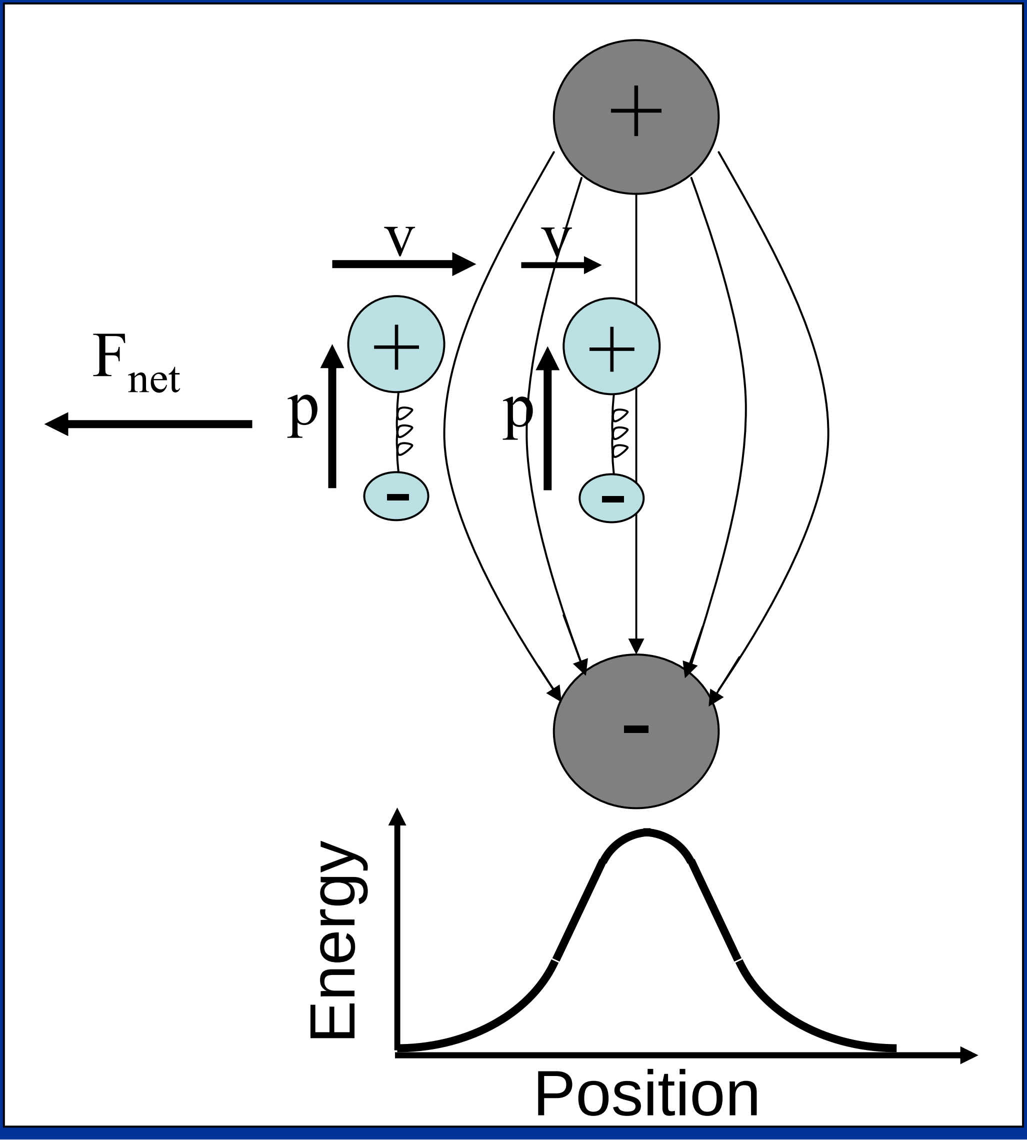


Supersonic Expansion:

-Cold molecules moving at a few 100 m/s.

Stark deceleration

Second step: slow the molecules in to the rest frame of the lab



Conservative process, no cooling

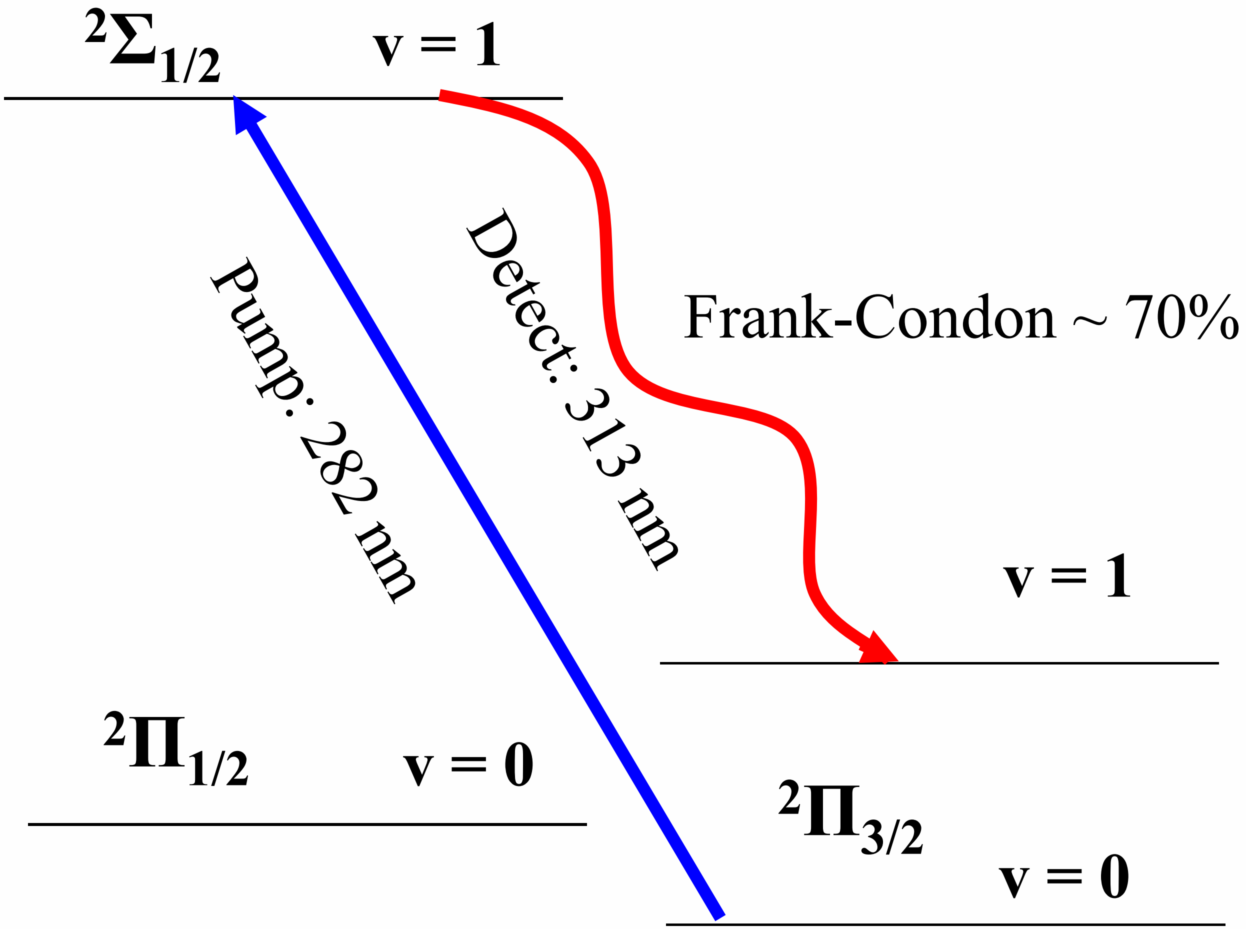
Phase space selection

Phase space area linked to the deceleration angle (ϕ_0)

Phase space rotation (constant density)

Resembles a pendulum driven by a constant torque

Basic energy structure of OH



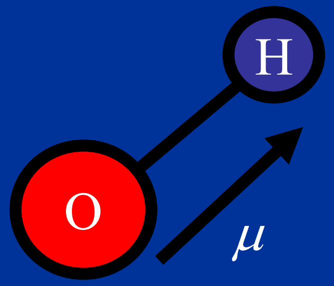
Basics:

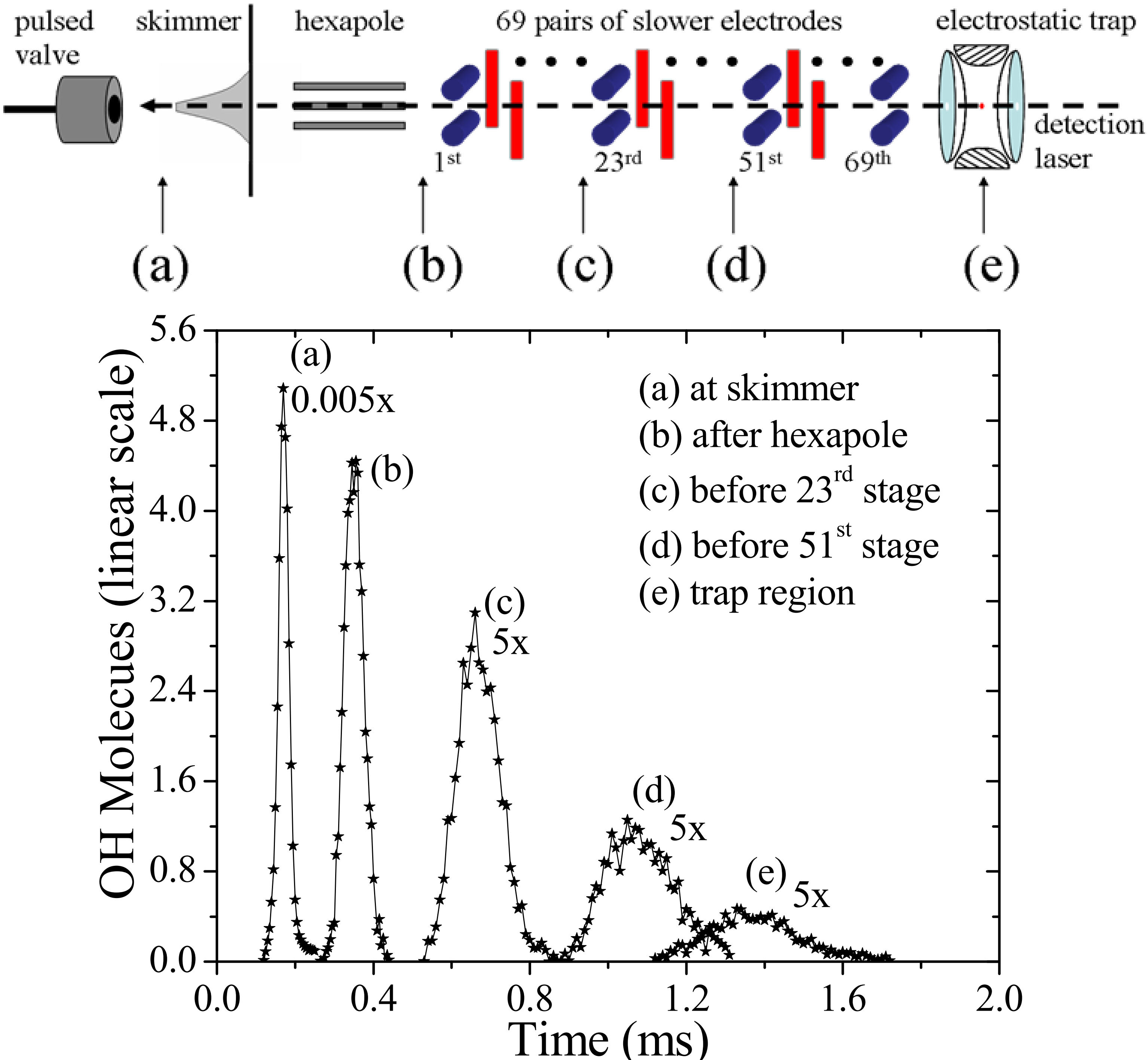
-Discharge H_2O in Xe

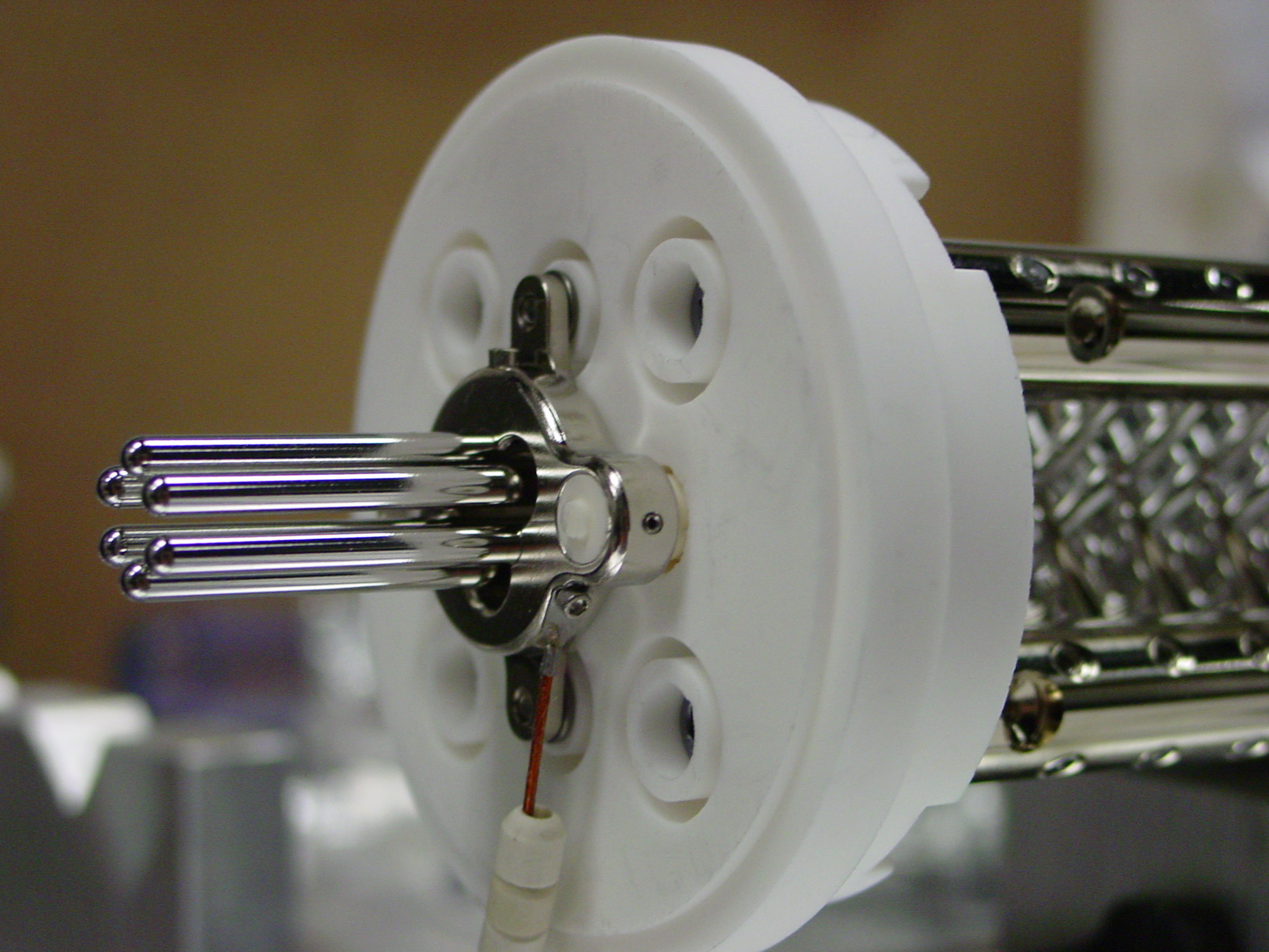
-Ground State $^2\Pi_{3/2}$

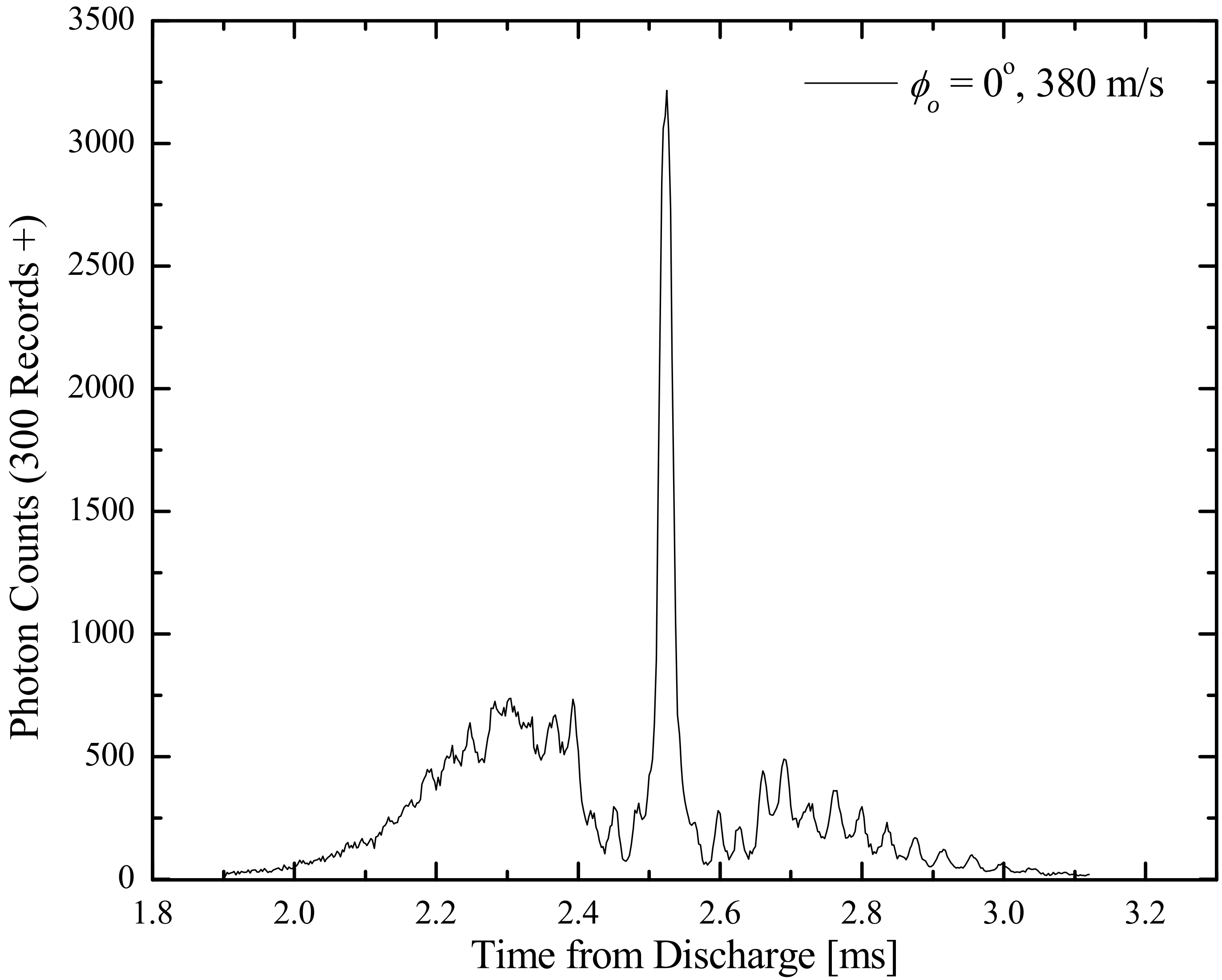
-λ doublet spacing ~1.7 GHz

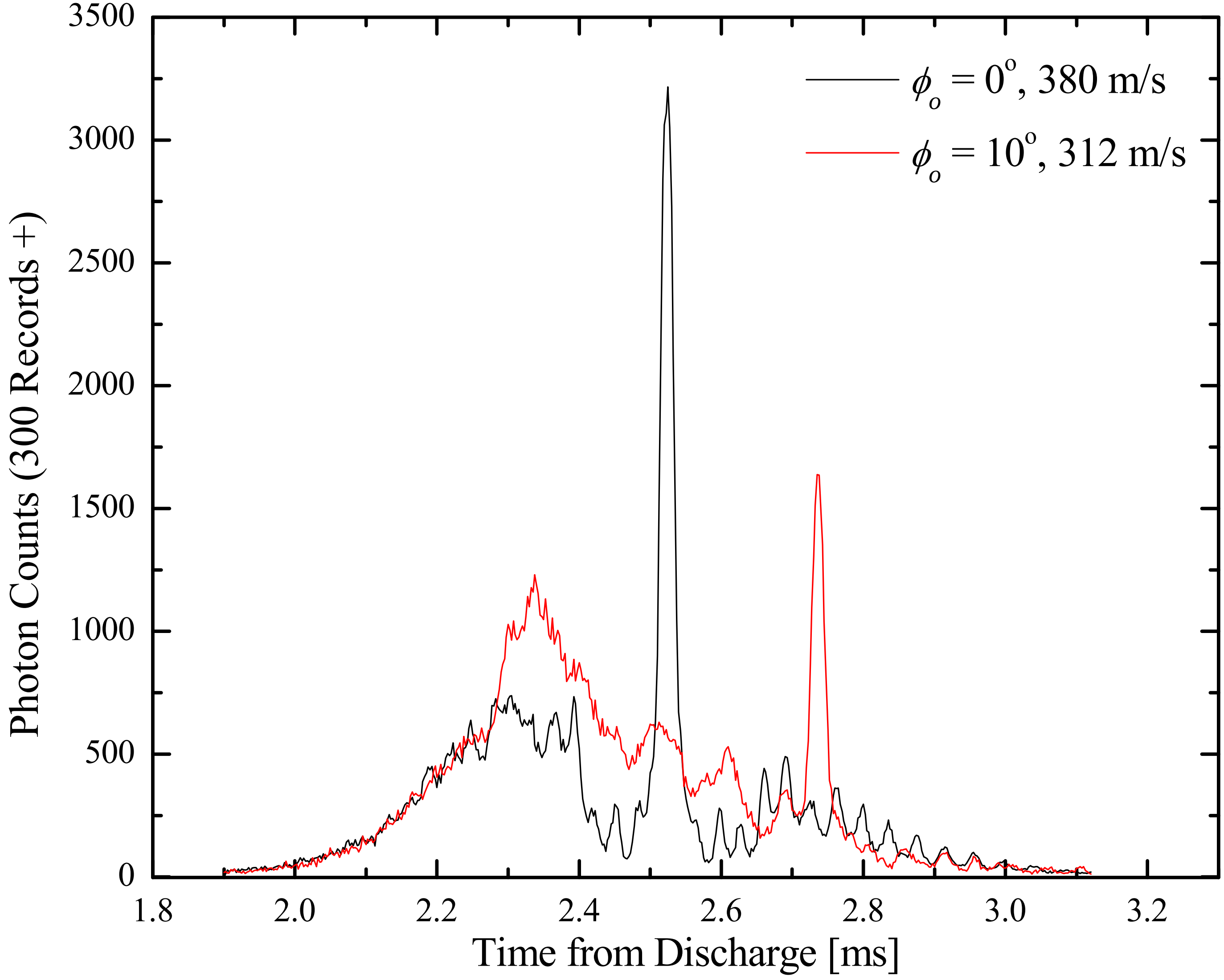
-μ = 1.67D



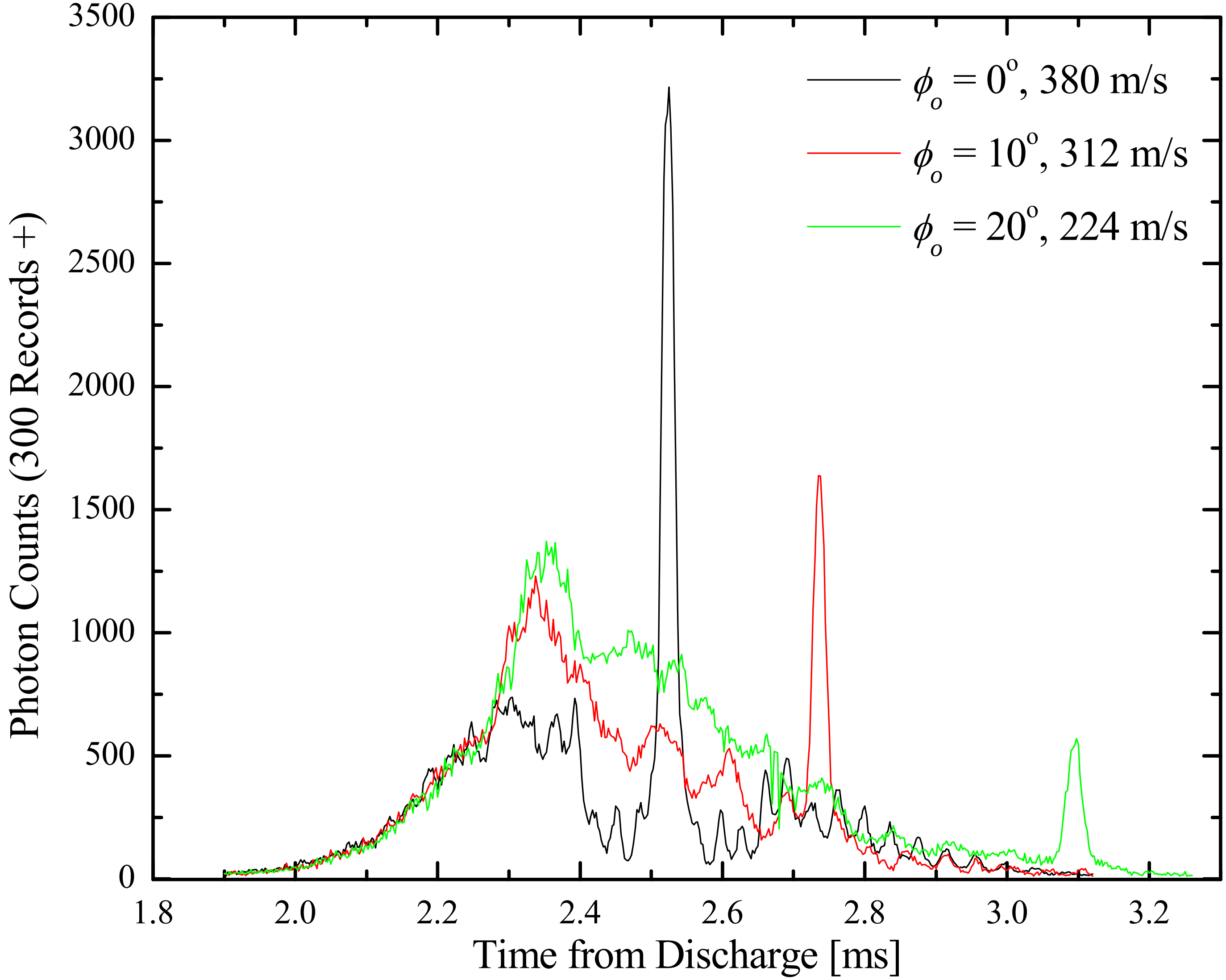

pulsed valve
skimmer
hexapole
69 pairs of slower electrodes
electrostatic trap
1st
23rd
51st
69th
detection laser
(a)
(b)
(c)
(d)
(e)
OH Molecues (linear scale)
Time (ms)
0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
0.0
0.4
0.8
1.2
1.6
2.0
(a) 0.005x
(b)
(c) 5x
(d) 5x
(e) 5x
(a) at skimmer
(b) after hexapole
(c) before 23rd stage
(d) before 51st stage
(e) trap region




ϕ_o = 0°, 380 m/s
Photon Counts (300 Records +)
Time from Discharge [ms]
0
500
1000
1500
2000
2500
3000
3500
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2

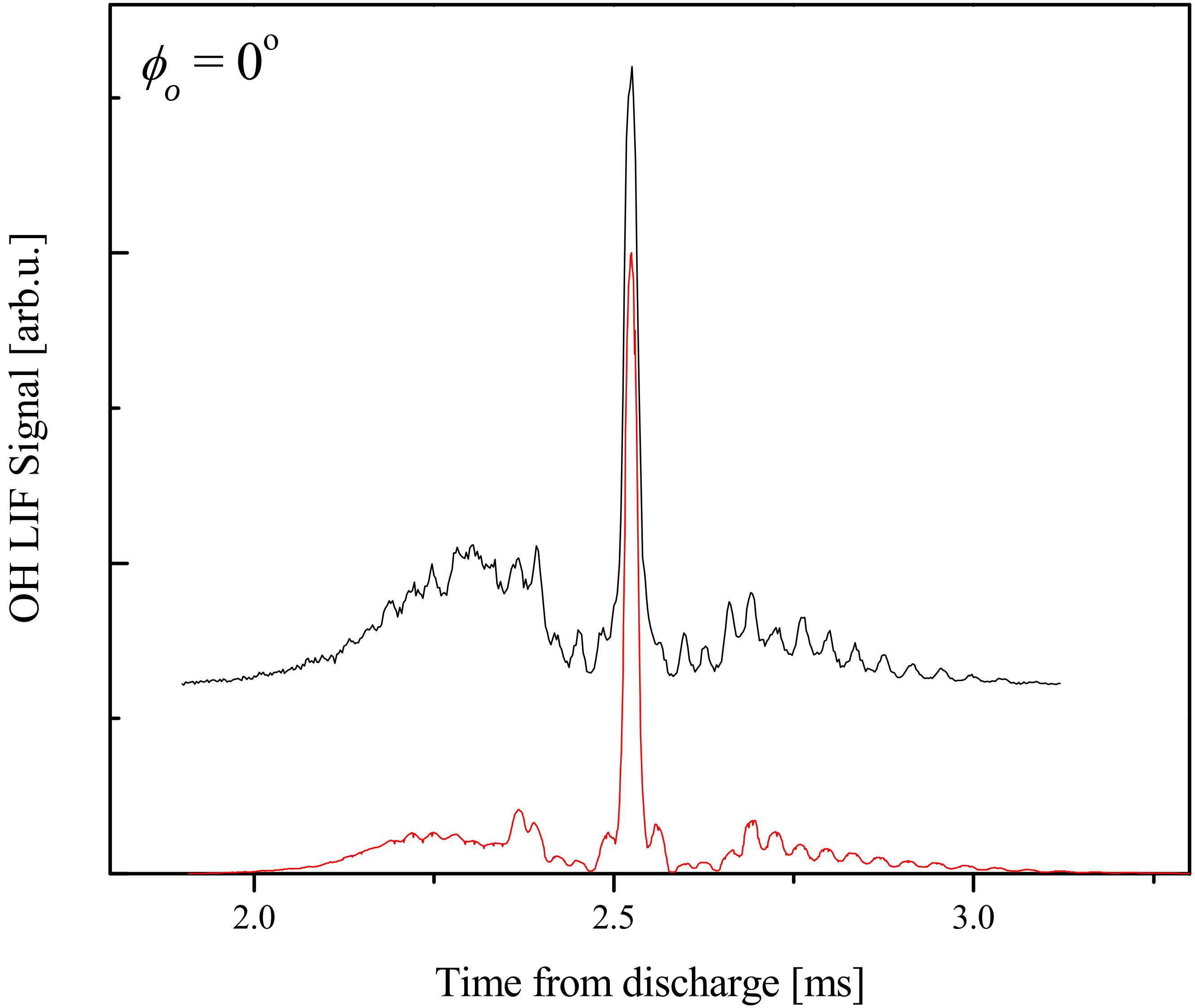


3500
3000
2500
2000
1500
1000
500
0
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
Photon Counts (300 Records +)
Time from Discharge [ms]
ϕ_o = 0°, 380 m/s
ϕ_o = 10°, 312 m/s



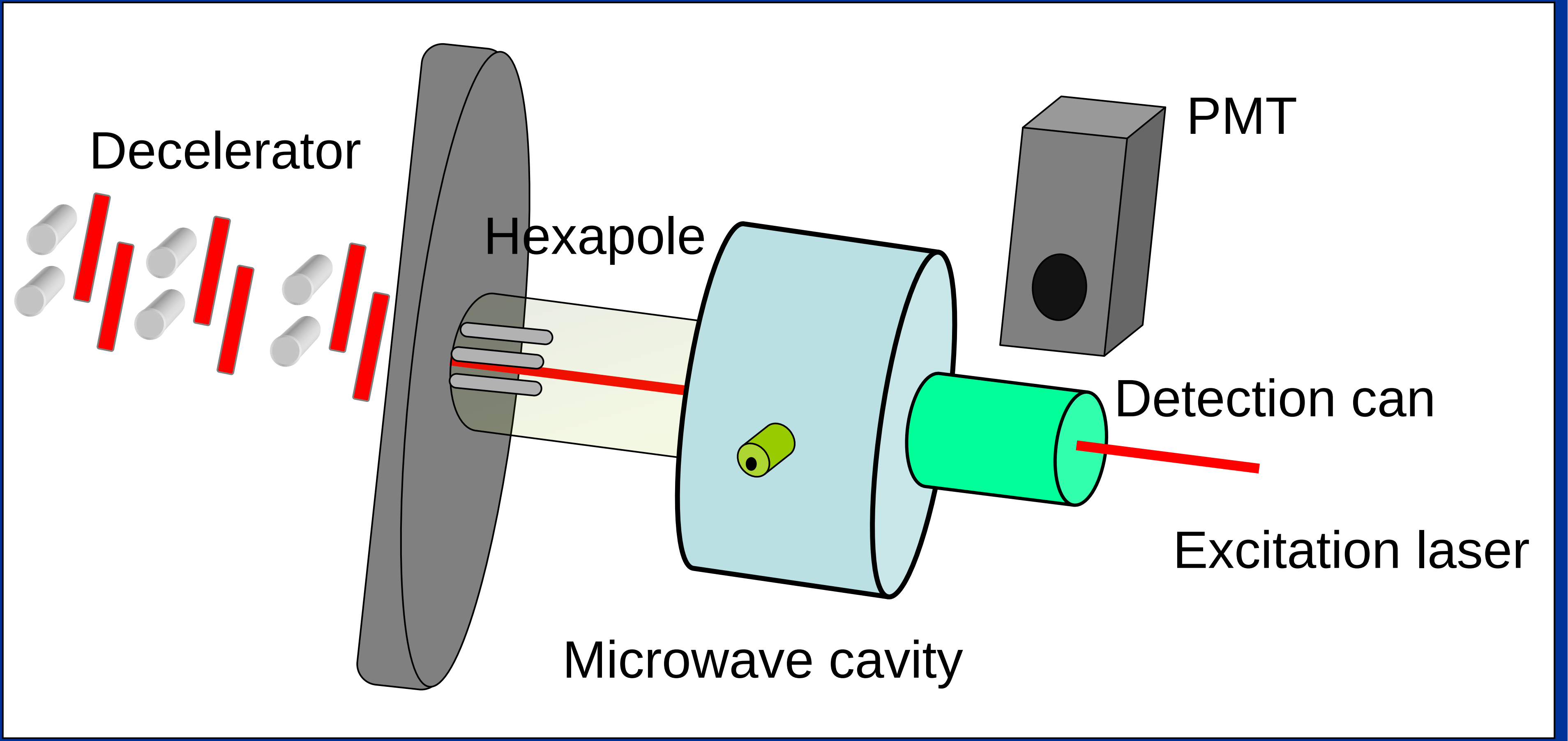
ϕ_o = 0°, 380 m/s
ϕ_o = 10°, 312 m/s
ϕ_o = 20°, 224 m/s
Photon Counts (300 Records +)
Time from Discharge [ms]
0
500
1000
1500
2000
2500
3000
3500
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2

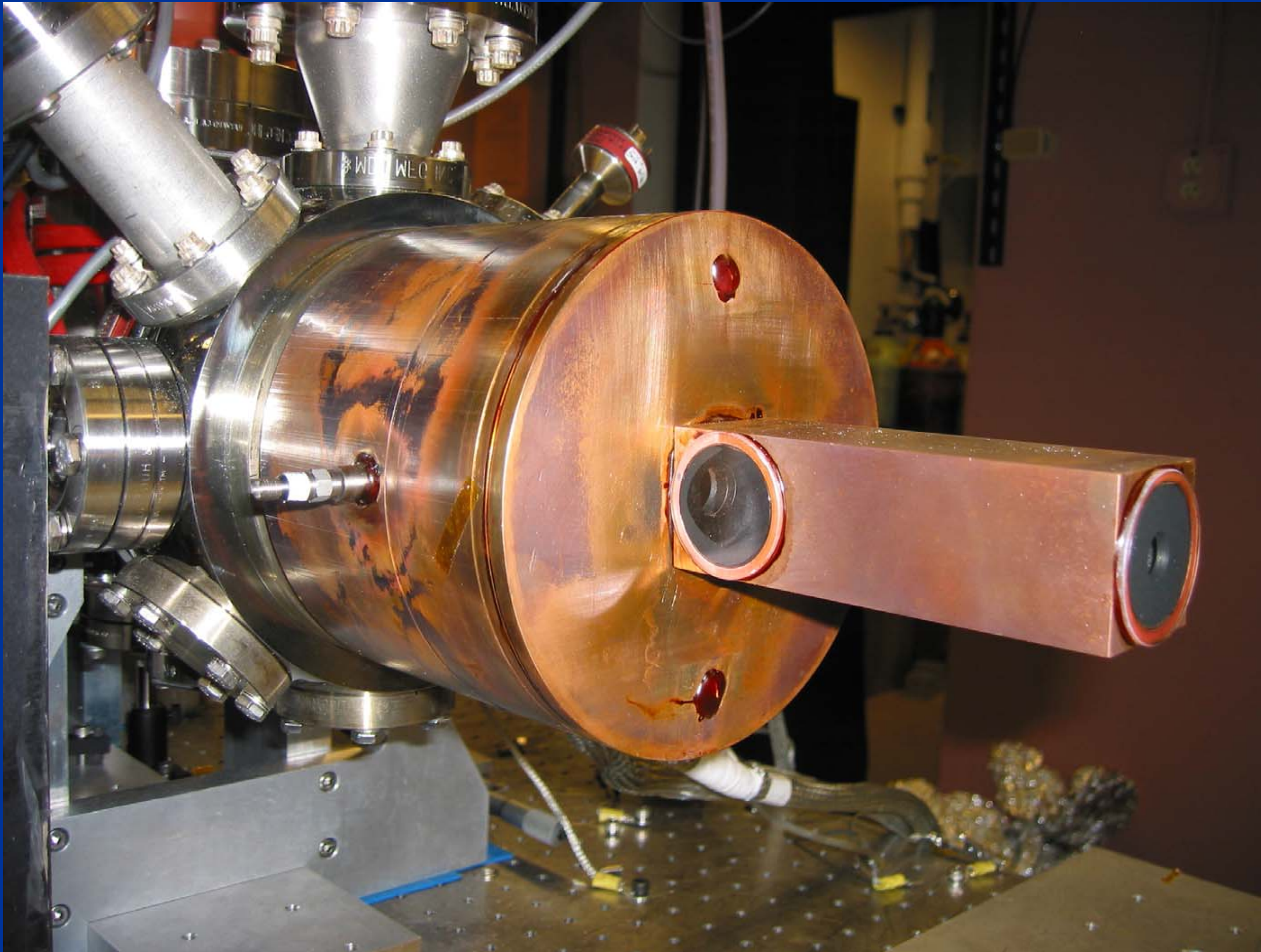
3D Monte Carlo Simulation Results



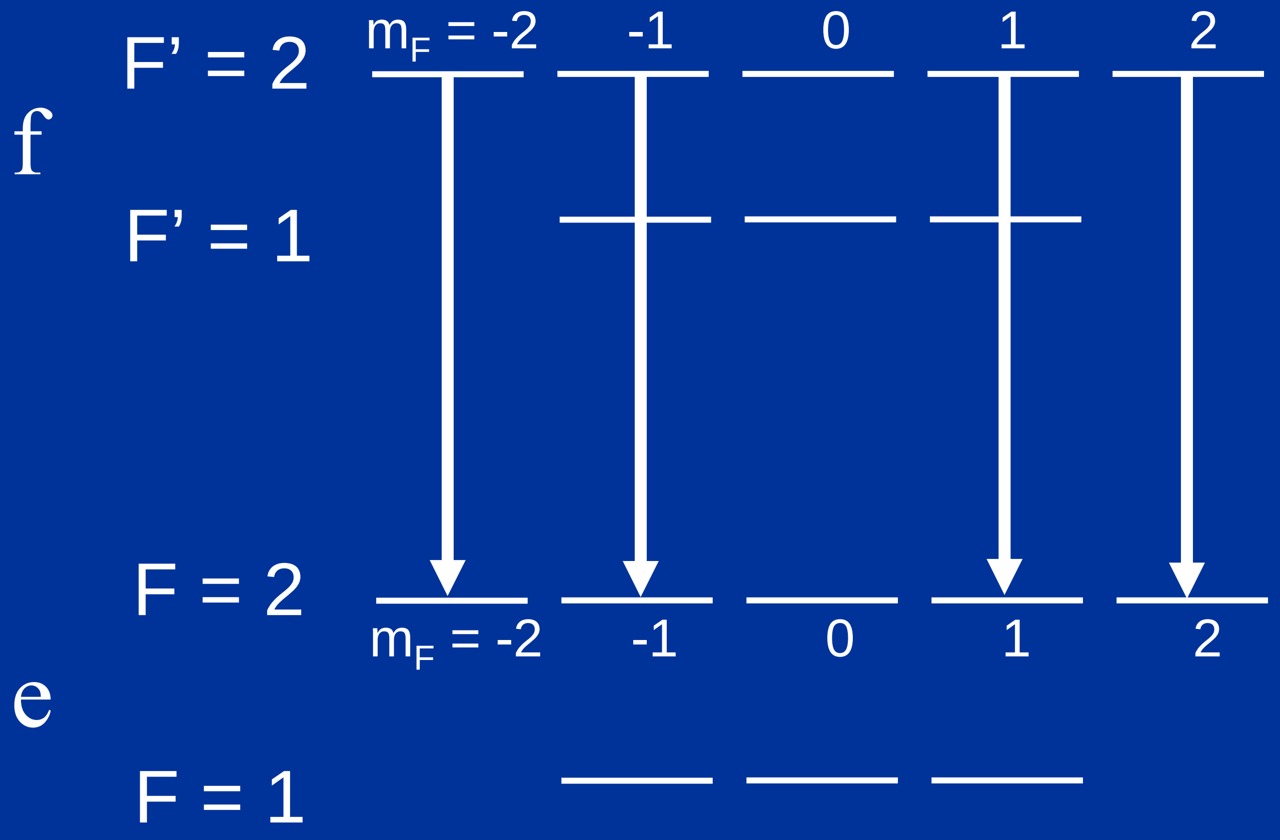
Experimental Set-up

- All metal detection area
- Slowed OH beam





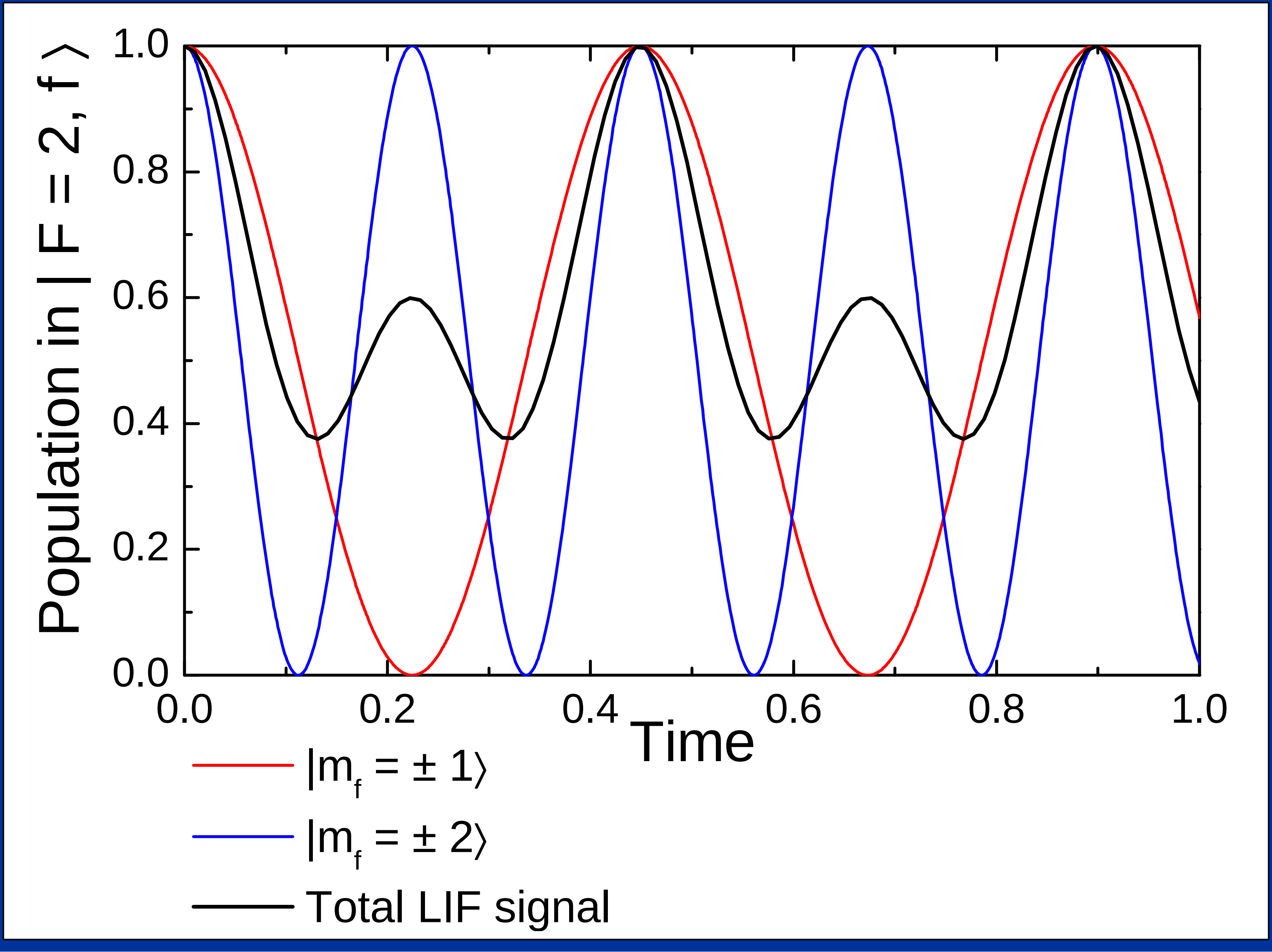
Hyperfine structure



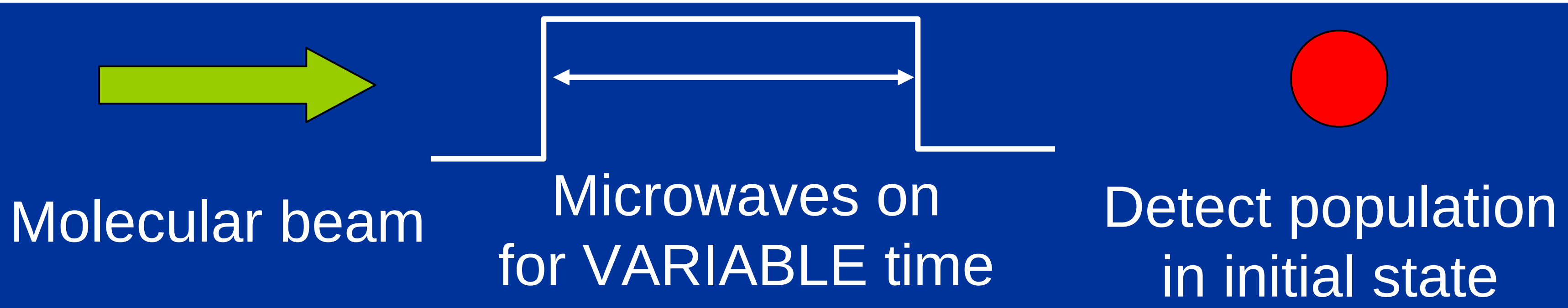
$$\langle \mu_e \rangle_{\pm 2} = 2 \times \langle \mu_e \rangle_{\pm 1}$$

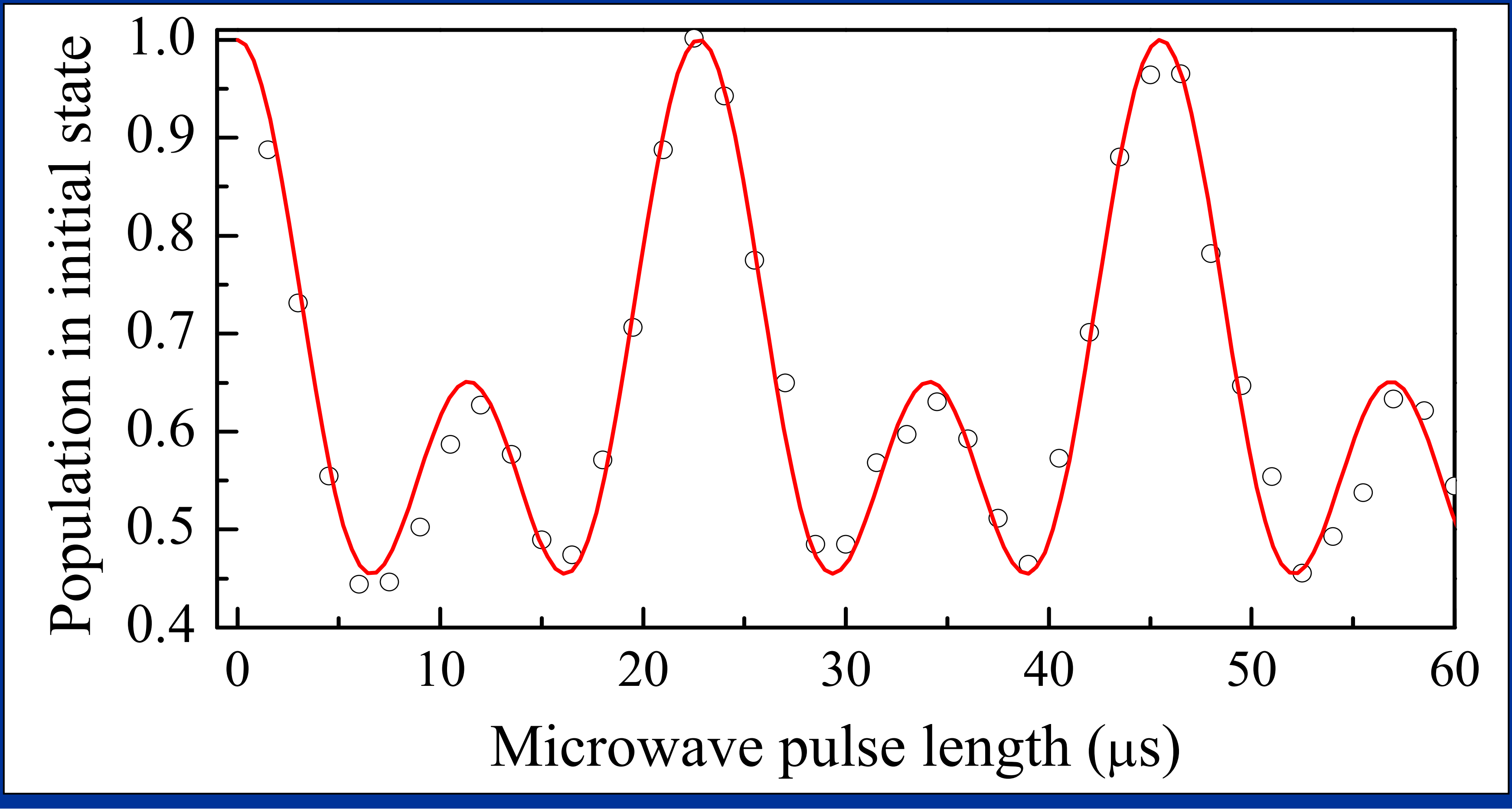
Transition dipoles are different by a factor of two.

Double Rabi flopping

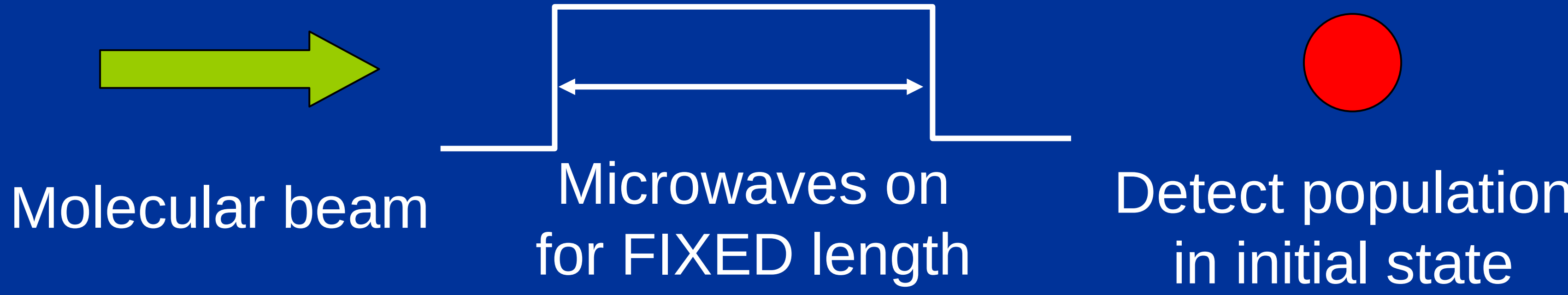


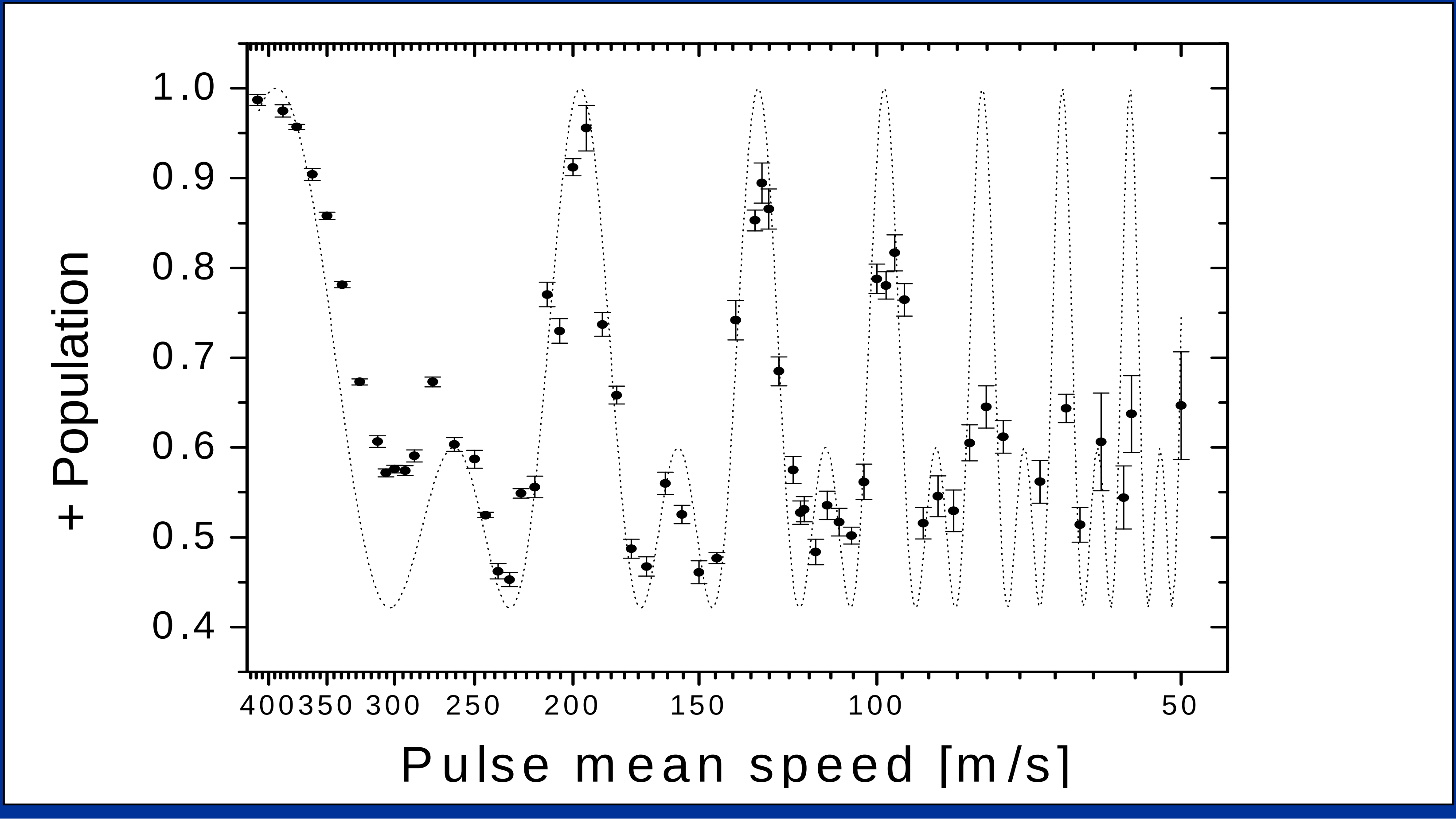
Rabi flopping (F' =2 →F =2)



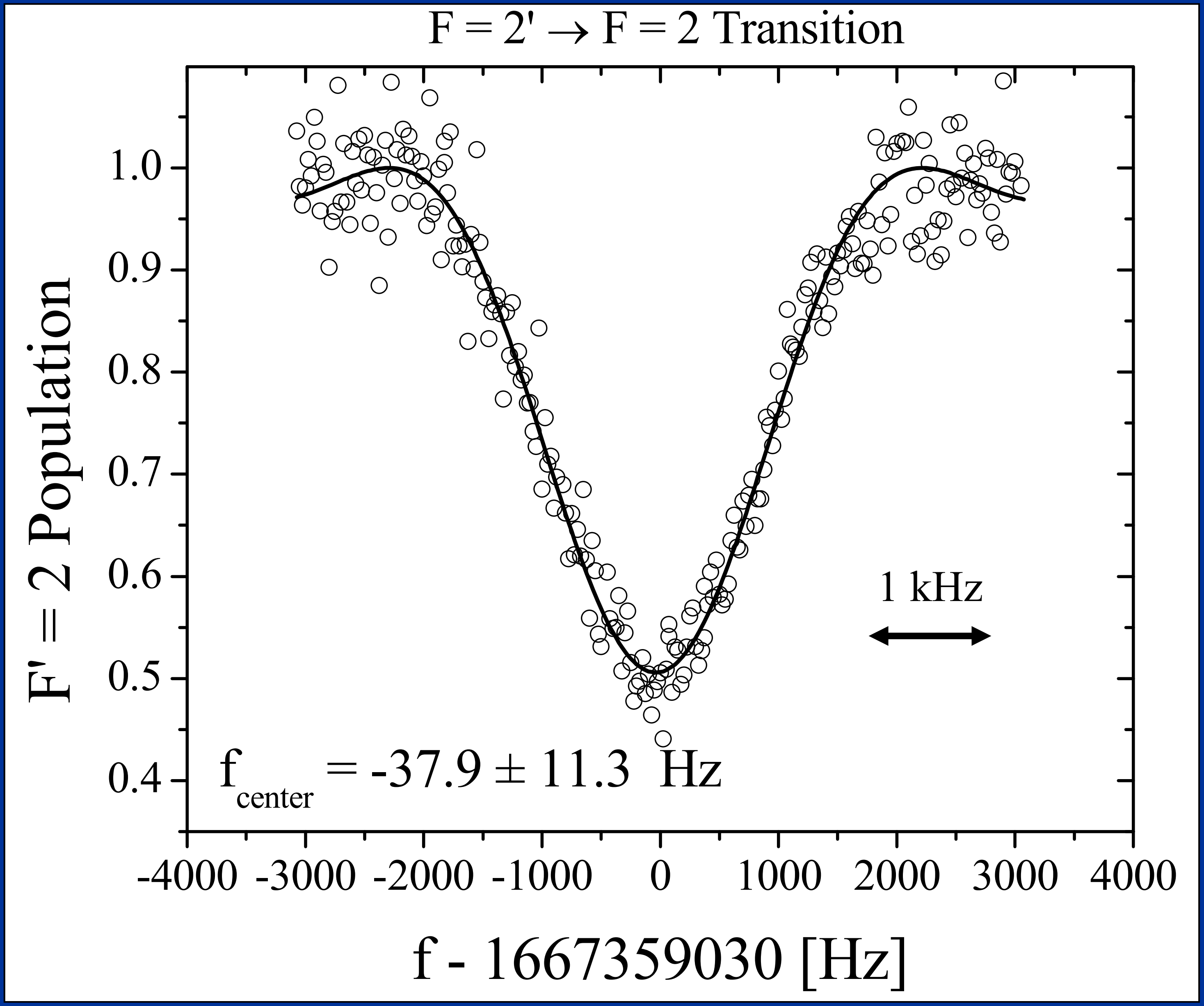


Rabi flopping (F’ =2 →F =2)



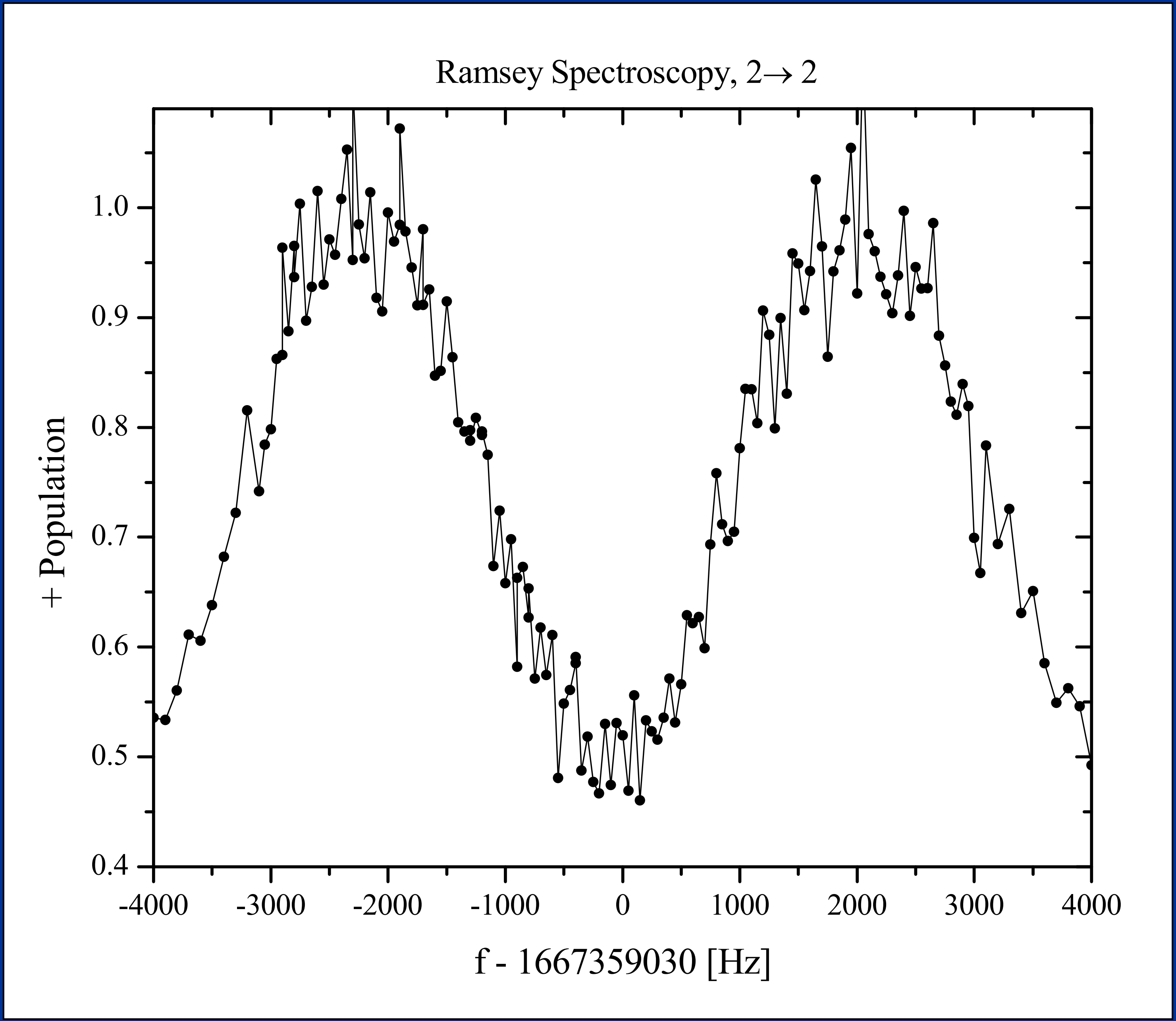


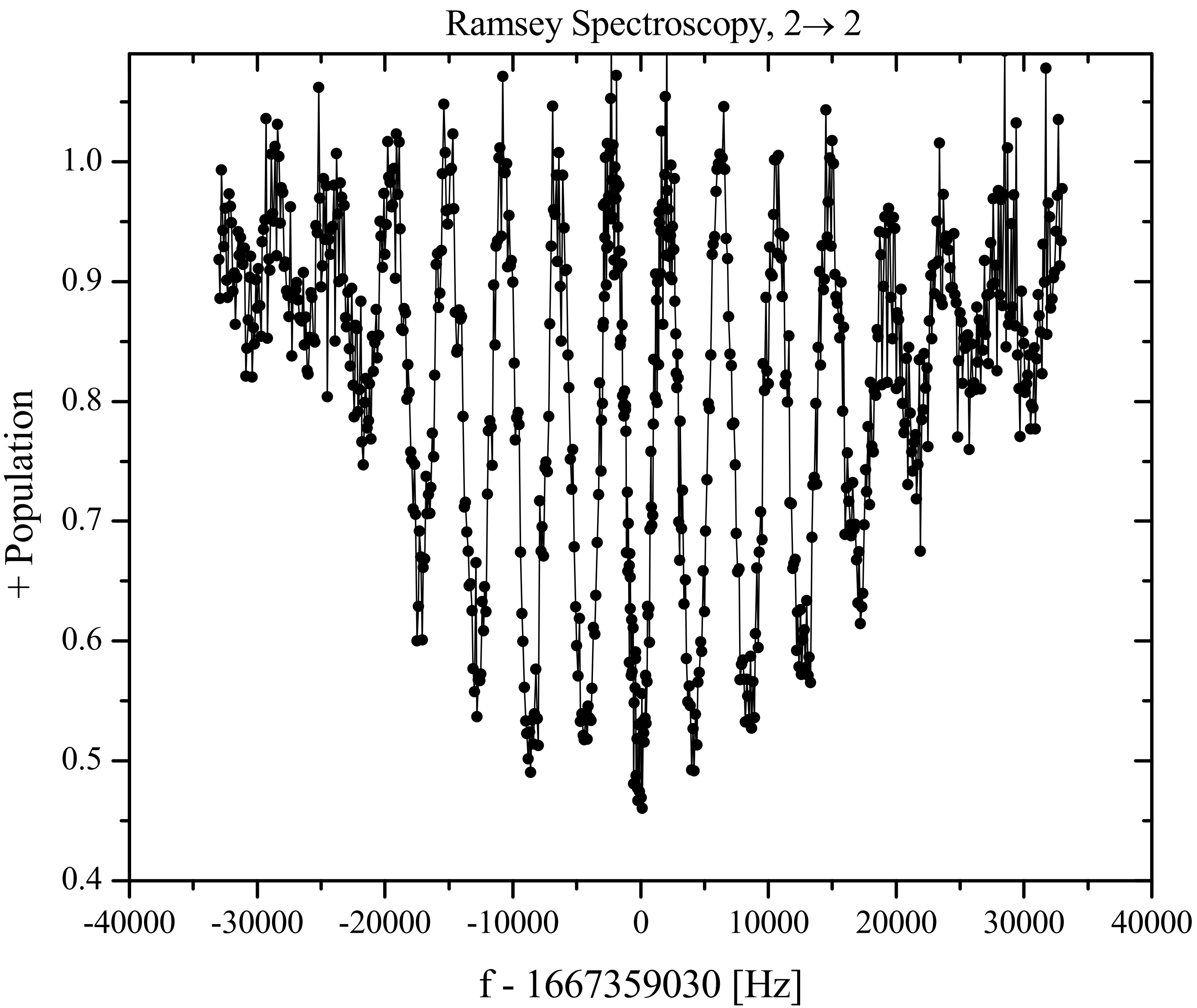
Transition lineshape and center



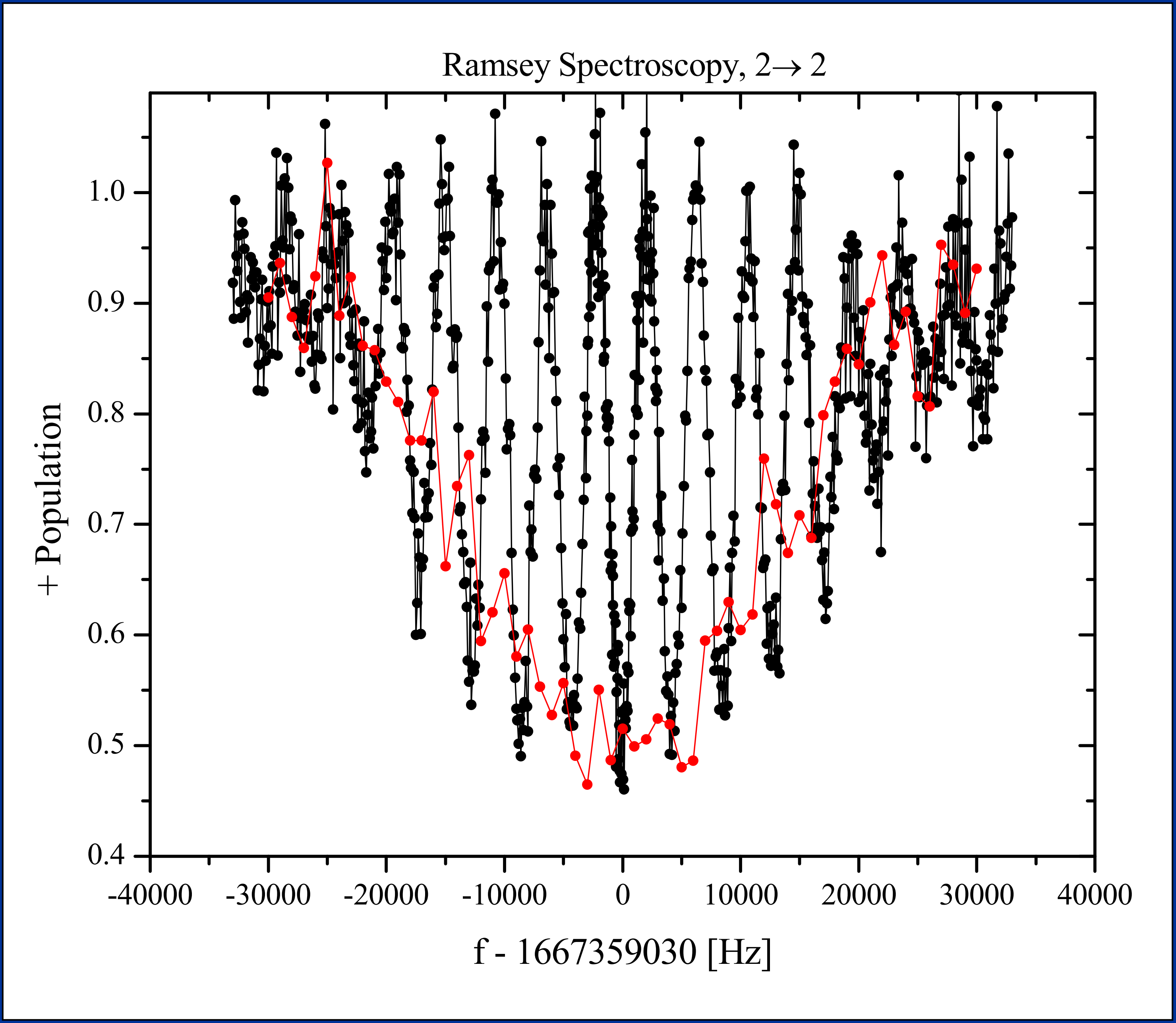
At fixed beam speed and pulse duration:

Vary detuning

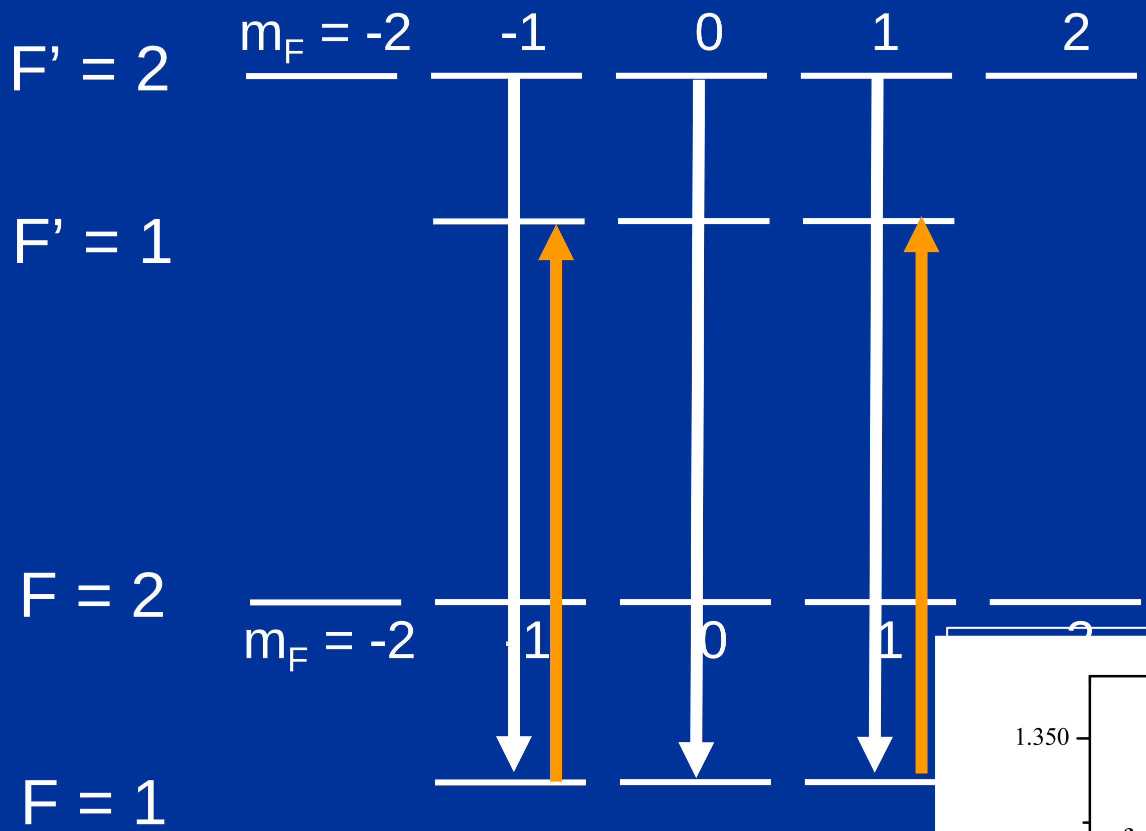

Ramsey Spectroscopy, 2→ 2
+ Population
1.0
0.9
0.8
0.7
0.6
0.5
0.4
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
f - 1667359030 [Hz]

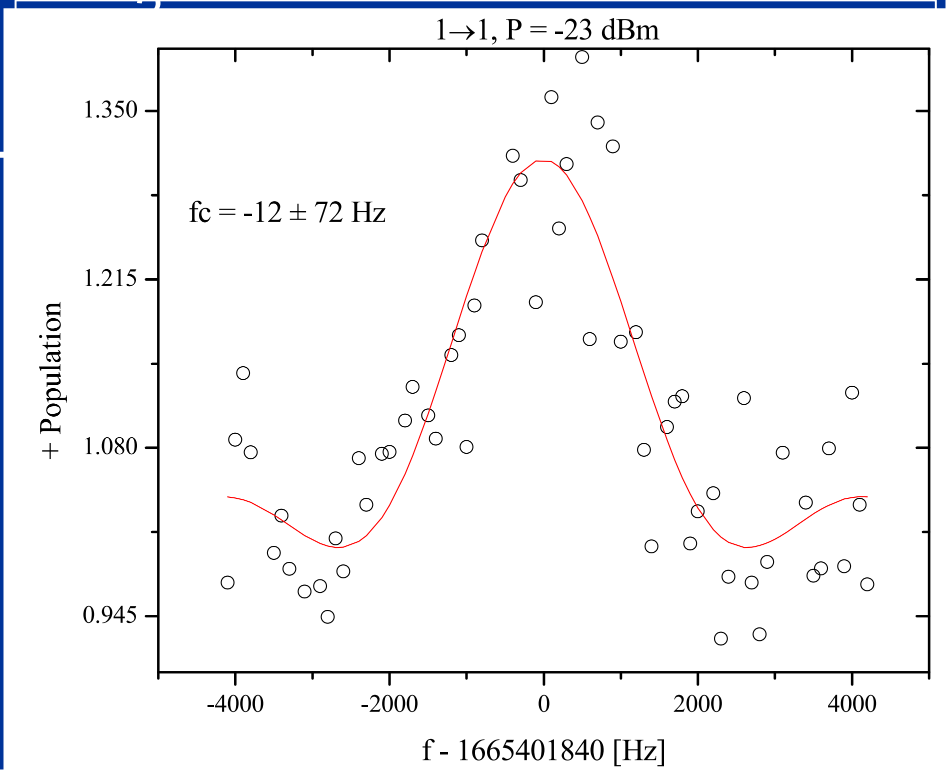


Ramsey Spectroscopy, 2→ 2
+ Population
f - 1667359030 [Hz]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
-40000
-30000
-20000
-10000
0
10000
20000
30000
40000

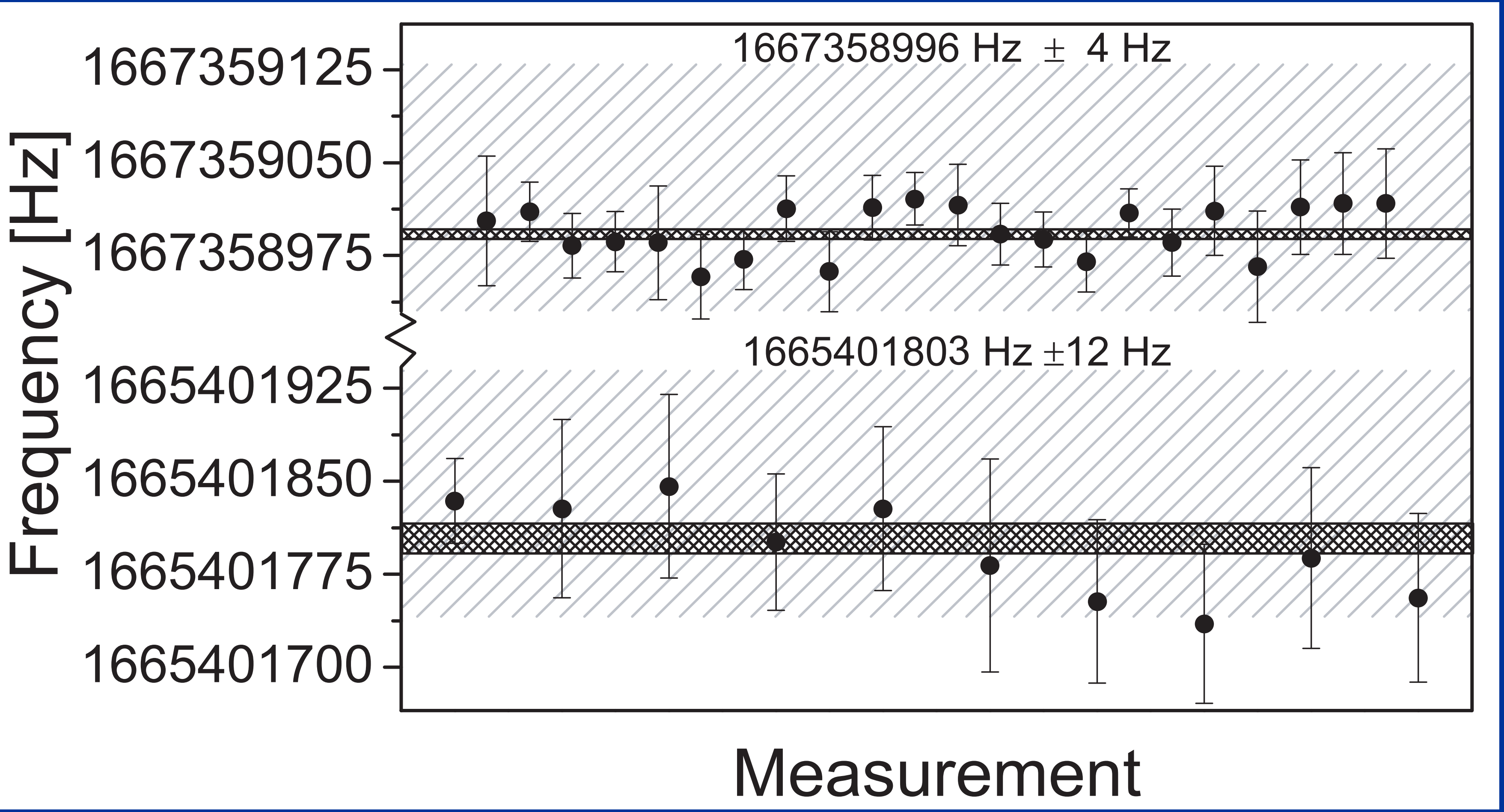

Ramsey Spectroscopy, 2→ 2
+ Population
f - 1667359030 [Hz]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
-40000
-30000
-20000
-10000
0
10000
20000
30000
40000

F’ = 1 to F = 1 Transition





Line Center Summary



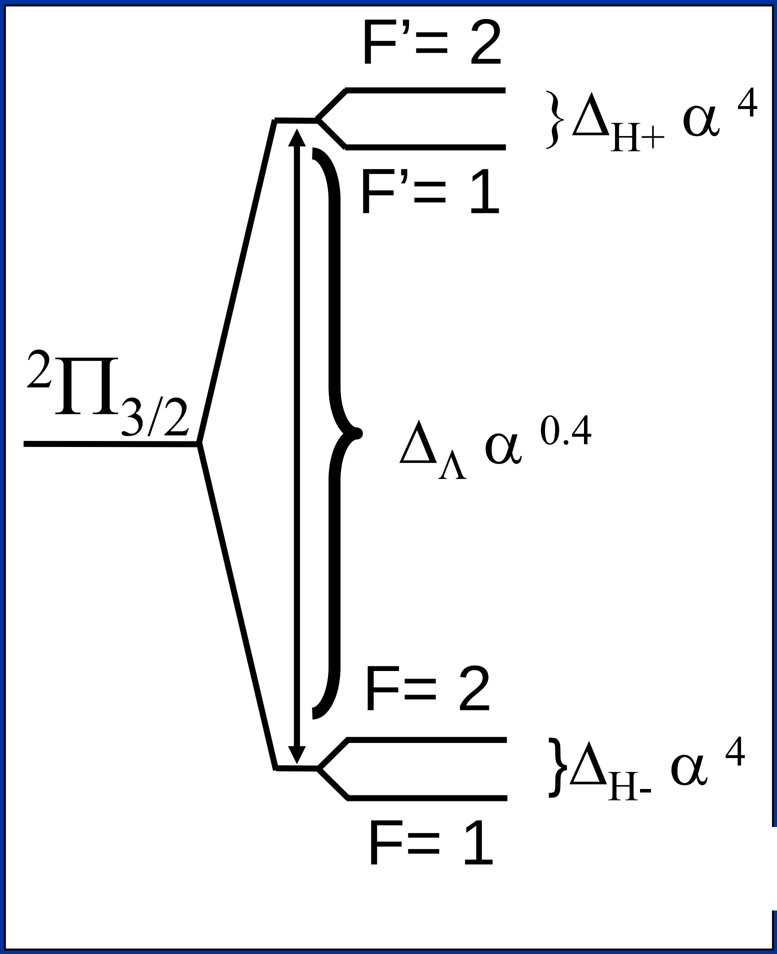
$\Delta\alpha/\alpha$?

- This measurement will allow an order of magnitude improvement:

$$\Delta\alpha/\alpha = 1 \text{ ppm over } 10^{10} \text{ years}$$

  - » Same as atomic clocks if assume time derivative is linear
  - » Can probe spatial changes
- Still waiting on astrophysical result...
  - – Over 100 hours of data taken on GBT, but analysis is bogged down by some terrestrial noise
  - – New data set from Arecibo being analyzed (N. Kanekar)
- The future is bright
  - – Because the frequency is in the cooled L-band no resolution limits yet
  - – New telescopes coming on-line in the next 10 years can approach our resolution with only a few hours of data collection

Using OH transitions to constrain α



Astronomical observation:

$$\omega_{11} = \Delta_{\Lambda}\ \alpha_o^{\ 0.4} - 1/2(\Delta_{H+}-\Delta_{H+})\ \alpha_o^{\ 4} + RS_{11}$$
$$\omega_{22} = \Delta_{\Lambda}\ \alpha_o^{\ 0.4} + 1/2(\Delta_{H+}-\Delta_{H+})\ \alpha_o^{\ 4} + RS_{22}$$

Lab measurement:

$$\omega_{11} = \Delta_{\Lambda}\ (\Delta\alpha + \alpha_o)^{0.4} - 1/2(\Delta_{H+}-\Delta_{H+})\ (\Delta\alpha + \alpha_o)^{4}$$
$$\omega_{22} = \Delta_{\Lambda}\ (\Delta\alpha + \alpha_o)^{0.4} + 1/2(\Delta_{H+}-\Delta_{H+})\ (\Delta\alpha + \alpha_o)^{4}$$

Dirty secrets:

1. $\Delta H_+ \approx \Delta H_-$ reduces the effect of the α^4 term

Use Satellite lines

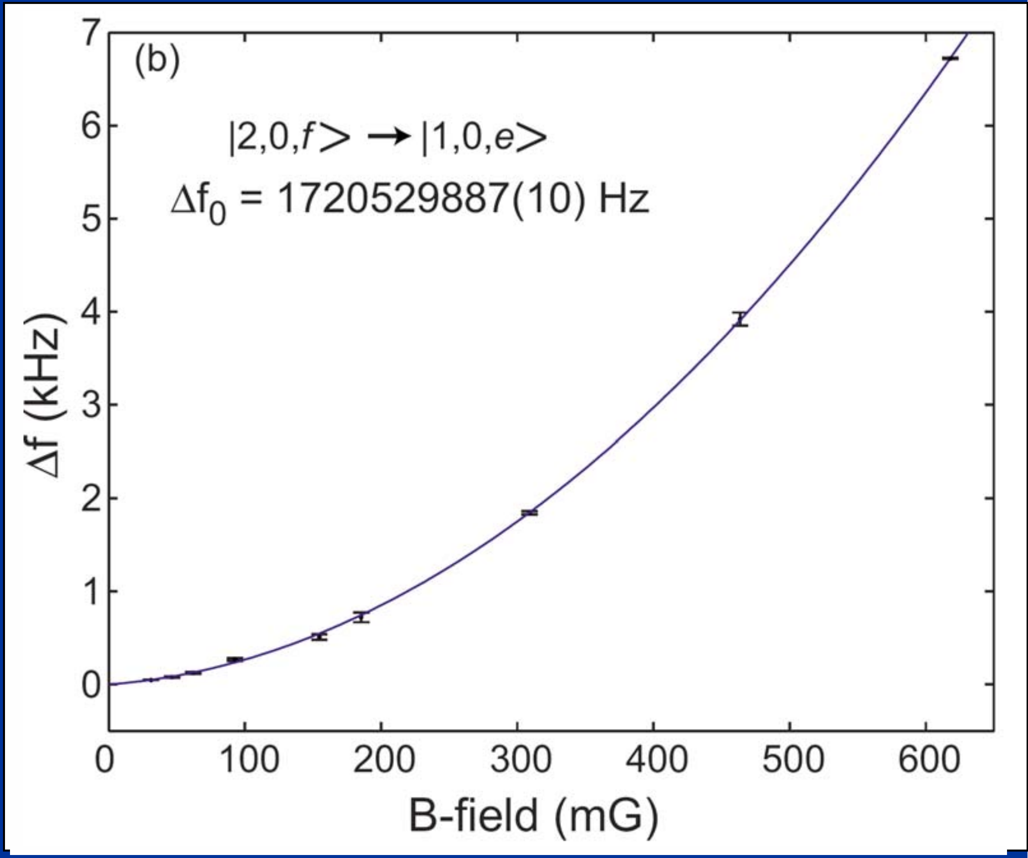
these transitions depend weakly on α.

Use all 4 lines… really just want to see something first

2. What about the other constants?

Measuring the Satellite Lines

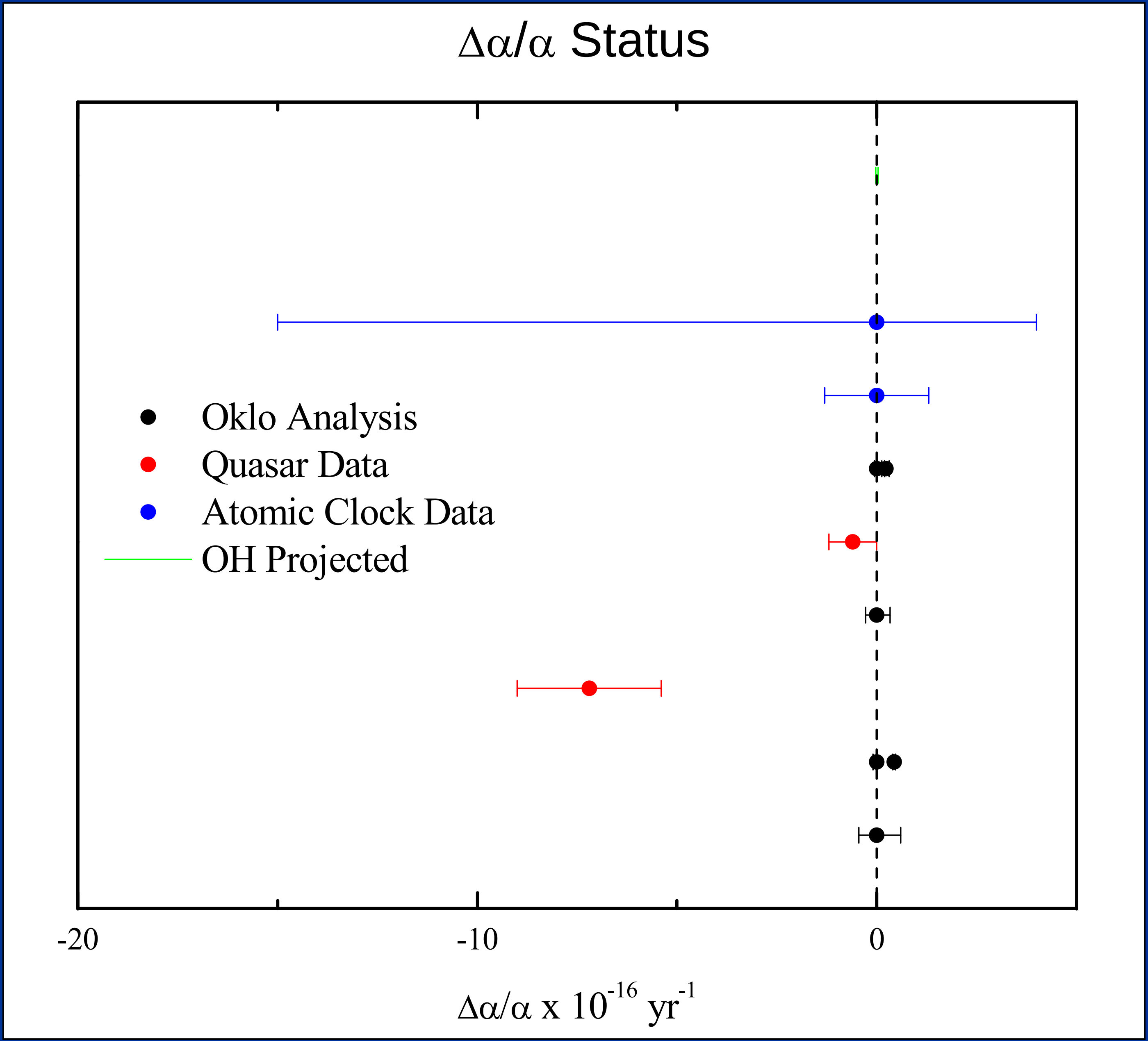
- Satellite lines are much more sensitive to magnetic fields
  - Main lines: ~ kHz/Gauss
  - Satellite lines: ~MHz/Gauss
- In our experiment we could apply a very uniform field



ν_{12} = 1 612 230 825 (15) Hz

ν_{21} = 1 720 529 887 (10) Hz

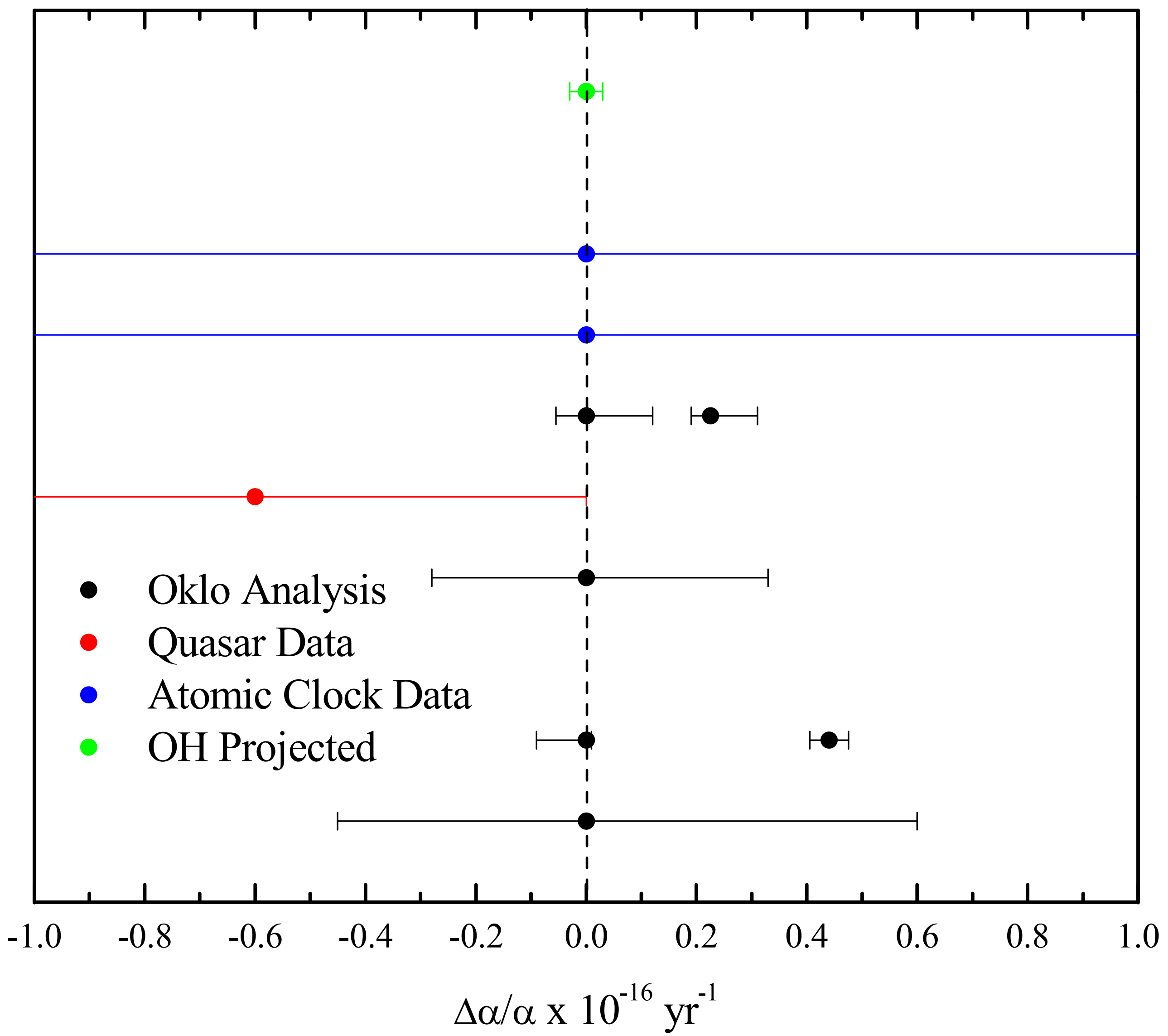
$\Delta\alpha/\alpha$ = 30 ppb over 10^{10} years



Quasar Data:
PRL 87 091301
PRL 92 121302

Atomic Clock Data:
PRL 98 070801

$\Delta\alpha/\alpha$ Status



Quasar Data:
PRL 87 091301
PRL 92 121302

Atomic Clock Data:
PRL 98 070801

Th-229 (Yale)

- Transition frequency is (probably) fantastically sensitive to constant variation:

$$\frac{\delta\omega}{\omega} \approx 10^5 \left(4\frac{\delta\alpha}{\alpha} + \frac{\delta X_q}{X_q} + \frac{\delta X_s}{X_s} \right)$$

$$X_q = \frac{m_q}{\Lambda_{QCD}}, X_s = \frac{m_s}{\Lambda_{QCD}}$$

V. Flambaum, arXiv:physics/0604188

- Linewidth is ridiculously small: $< 100\ \mu$Hz

- The greatest clock ever

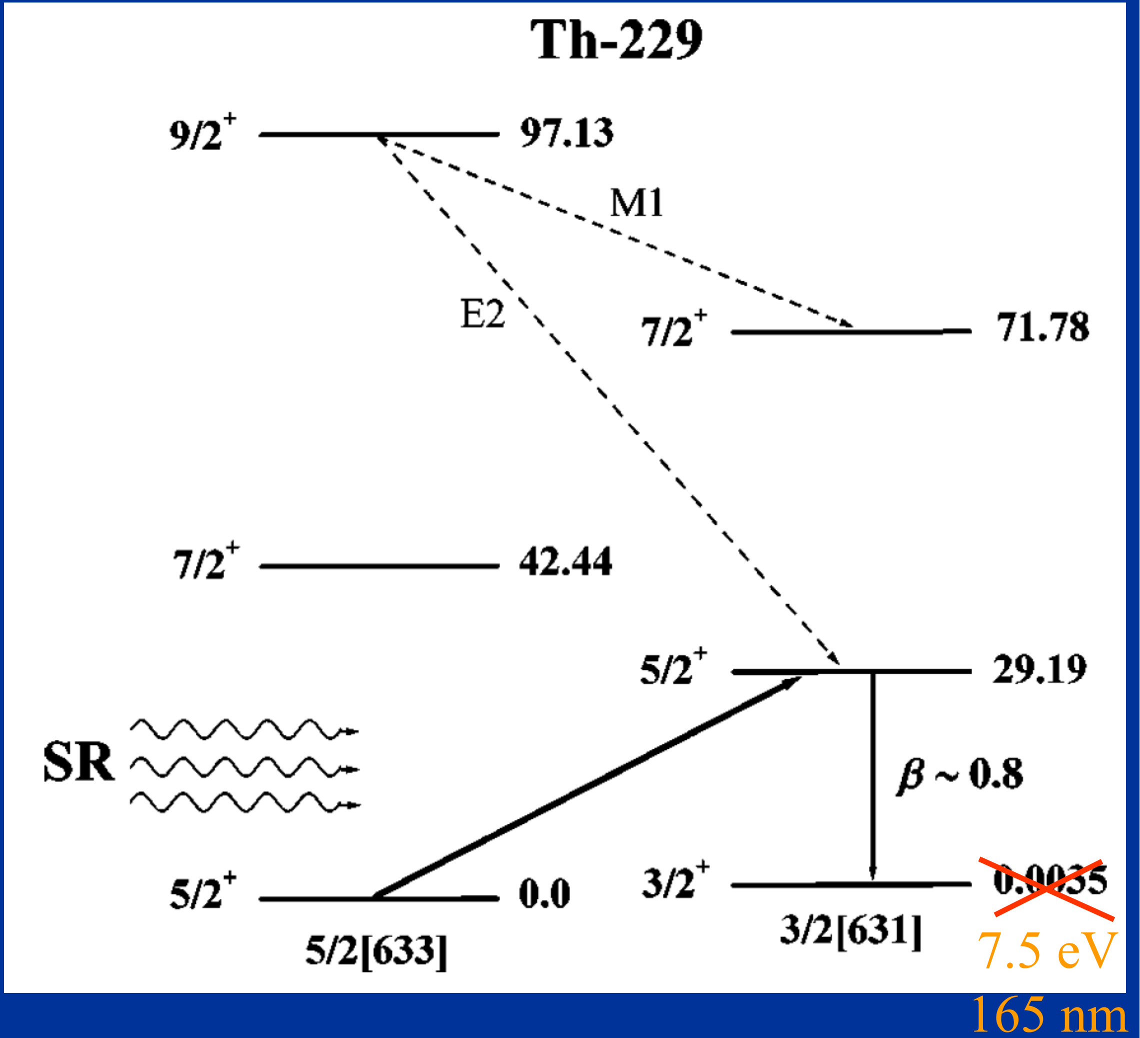


Figure taken from PRC **61** 064308

Th-229

How do you optically observe a nuclear transition?

Previous proposals (incomplete):

~~**Vapor cell-like experiments**~~

1. Gas Discharge Cell: Excite the metastable nuclear state via "inverse internal conversion" and look for decay of the state: photons and alphas.

   Inamura et al., Hyperfine Interactions (2005).

2. Trap laser-cooled Th^{3+} and detect the metastable state by monitoring the frequency of a hyperfine sensitive transition of the valence electrons as you scan a laser hoping to excite the nuclear state.

   E. Peik, Europhys. Lett **61** 181 (2003).

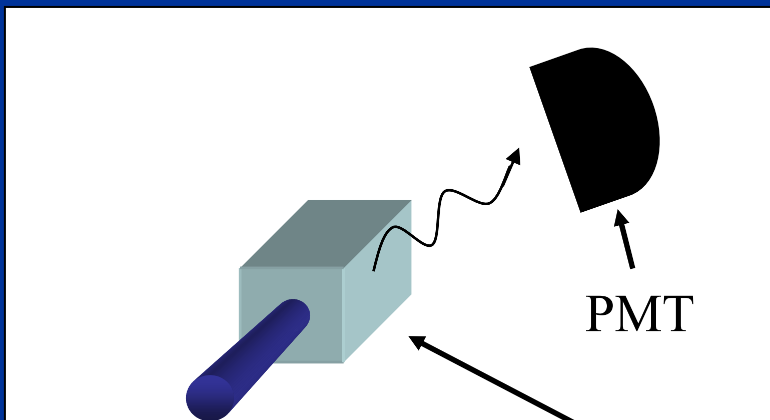
Having an optically accessible nuclear transition is very unique. What are the properties it has that electronic transitions don't?

1. Less sensitive to it's environment than electronic transitions.
2. Changes the nuclear spin of the atom.
3. Decay products

1 + 2 + 3 → Put it in a solid to look for transitions (and do NMR spectroscopy or look for decay products)

Th-229

General Idea (first we just need to see the state):



VUV transmissive material doped with Th-229

Tunable laser @ 165 nm ± 10 nm

- H_2 Raman Cell
- Eventually you'll want a nice CW laser
- VUV comb

A few notes about detection:

1. TIR makes solid angle of detection ~ 4π
2. PMTs are excellent here (QE ~ 40%!)
3. Use of monochromator and exploiting the long time scale should give excellent background discrimination.
4. NMR detection of the change in **I** is potentially background free. (Th^{232} has **I** = 0)
5. Also look at decay spectrum.

Th-229

What are the possibilities for VUV transmissive materials?

Readily available

1. CaF_2
2. MgF_2
3. LiF

} Th, ThF_3, or ThF_4?

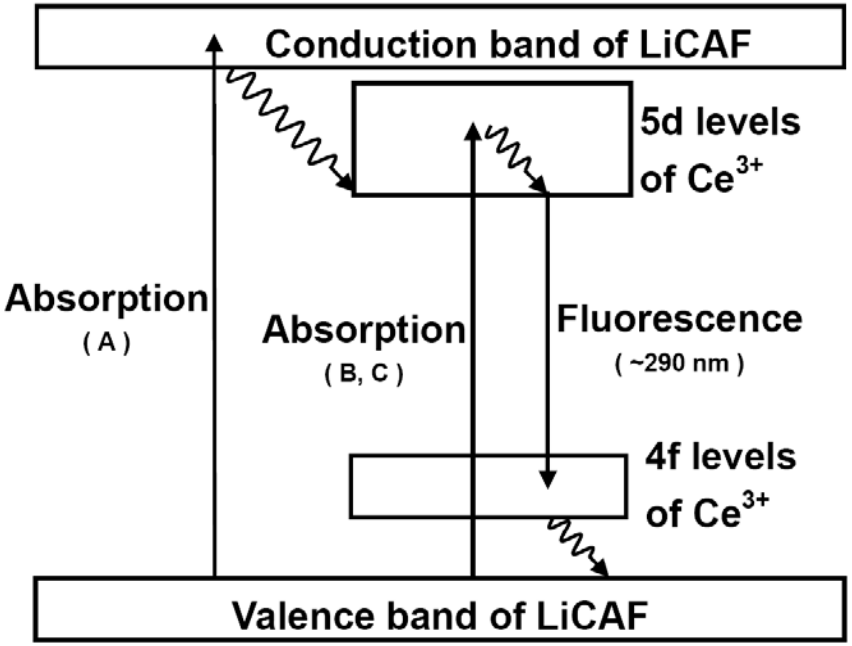
4. Modified Fused Silica (157 nm photo-lithograpy)?

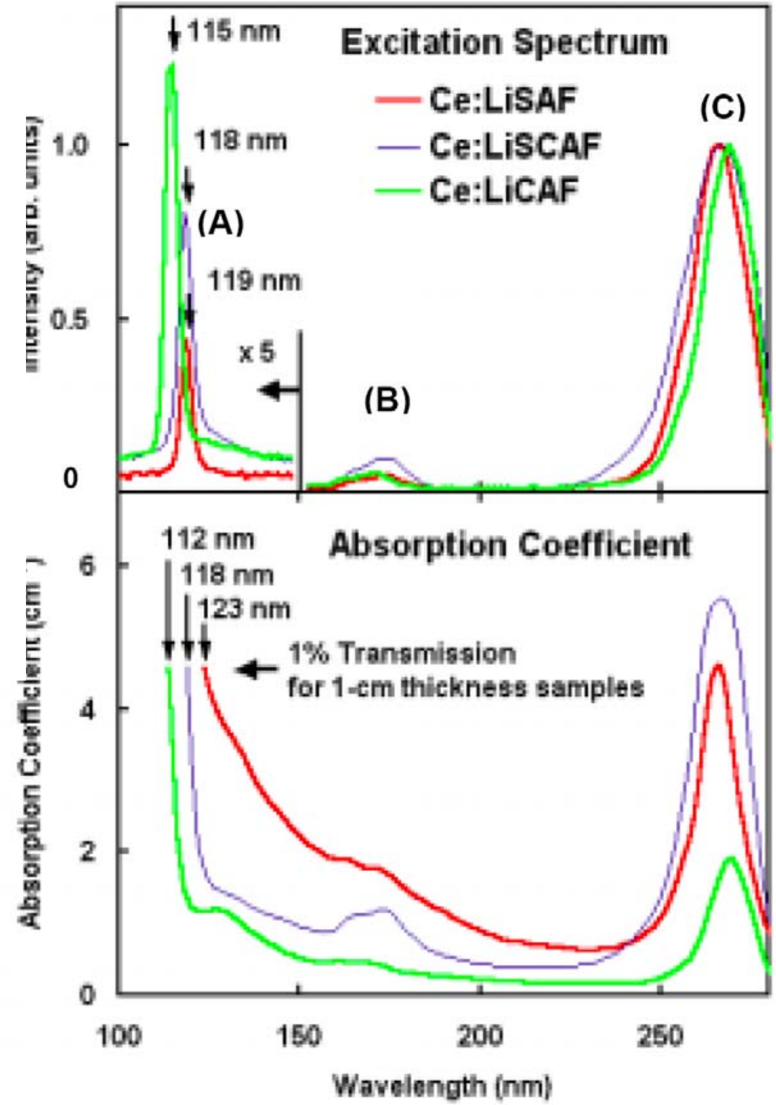
	Ionization Energy
Th	6.1 eV
Th^{+1}	11.5 eV
Th^{+2}	20 eV
Th^{+3}	28.8 eV

Not so easy

1. **Ce:LiSAF**
2. **Ce:LiCAF**

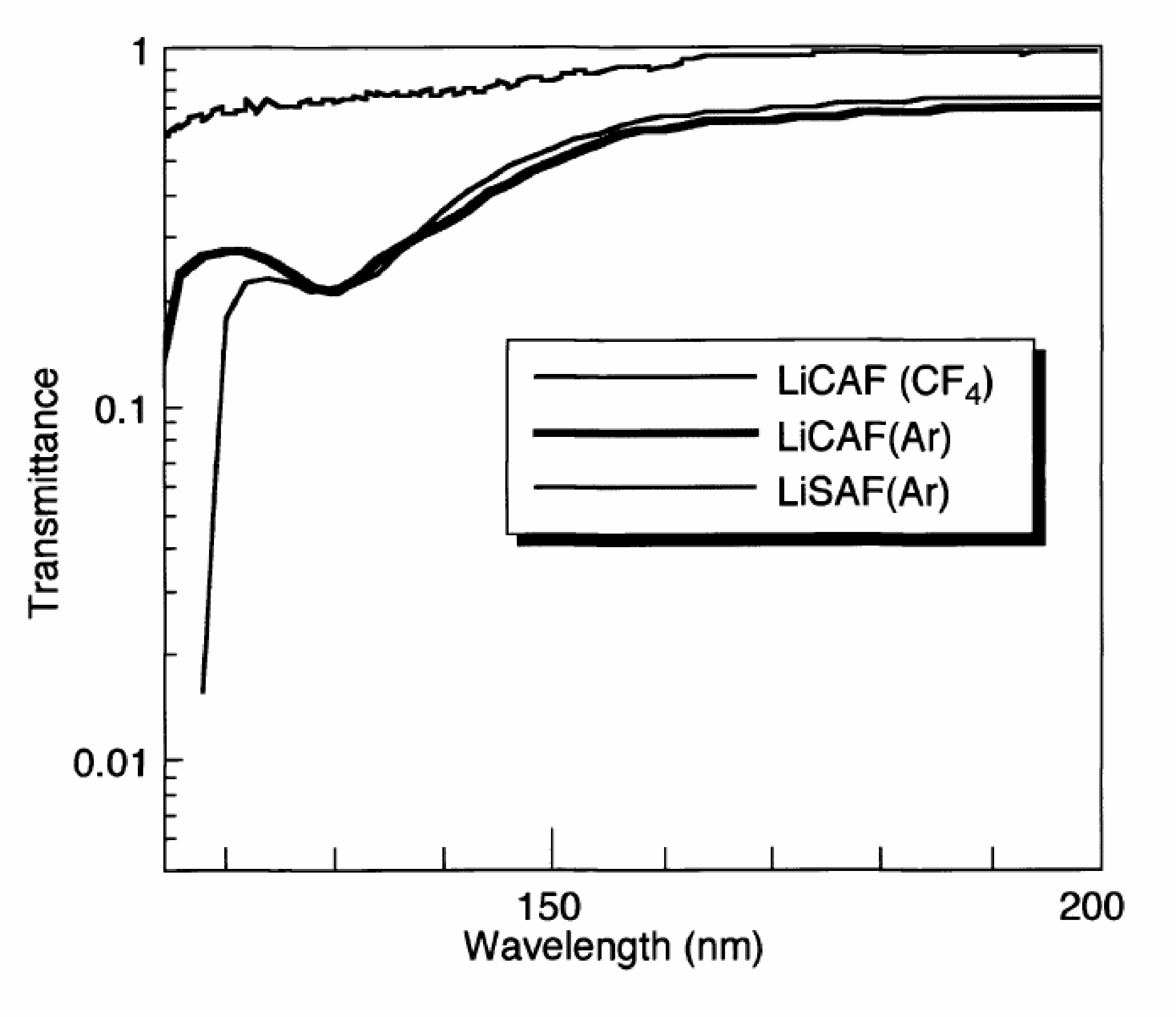
- High transmission down to 110 nm
- Developed for tunable UV lasers around 300 nm based on Ce^{3+}.
- Crystal developed specifically to handle large amounts of UV power AND to maintain the Ce^{3+} level structure!
- Would expect Th^{3+} to not be modified so could verify its presence by strong absorption on the d $\rightarrow$ f line ($\tau \sim 10$ ns).





- 5s and 5p level shield 4f electron from crystal field
- Seems band gap is large

Taken from: J. Crystal Growth **211** (2000) 302.



Cryst. Res. Technol. **36** 801 (2001)

Th-229

Back of the envelope signal-to-noise calculation:

Resonant cross-section:

$$\sigma = \frac{\lambda^2}{2\pi}\frac{\Gamma}{\Delta\omega_L}$$

Parameters:

$\Gamma = 2\pi$ (10 μHz)

λ= 165 nm

For $\Delta\omega_L$ = 1 cm^{-1} , P = 10 μJ, 10 ns pulse, 1 mm X 1 mm XTAL:

$N_{Excited} = N_{Total}\ \sigma\ N_{photons}$

Th-229 Specific Activity:
0.161 μg/μCi

N_{Total}	After one pulse: $\Gamma N_{Excited}(t = 0)$	After 12 hrs: $\Gamma N_{Excited}(t = 1)$	Absorption: $Exp[-n\,\sigma\,L]$
1 μCi	0.3	2.0(10^5)	1.4 (ppb)
10 μCi	3	2.0(10^6)	14 (ppb)
100 μCi	30	2.0(10^7)	1.4 (ppm)
1 mCi	300	2.0(10^8)	14 (ppm)

Th-229

Possible "flies":

1. Th-229: $50, 000 per mg
2. Fabrication of XTAL, Thorium is radioactive (7900 yr half life)
3. 165 nm laser system
4. Electron Bridge mechanism
5. Background from long-time scale fluorescence in crystal (?)
6. Forming of color centers, leading to more of #5.
7. Broadening due to Hyperfine coupling to electronic cloud and/or nuclear electric quadrupole moment