Precision Time Measurement and a Novel Two-Photon Clock Scheme

An E1-M1 Clock

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Overview

E1-M1 Clock

A Hot Hg Clock

Experimental Progress

The Clock Transition

$$\sigma_\nu = \frac{\Delta\nu}{\nu}\sqrt{\frac{T}{\tau N}}$$

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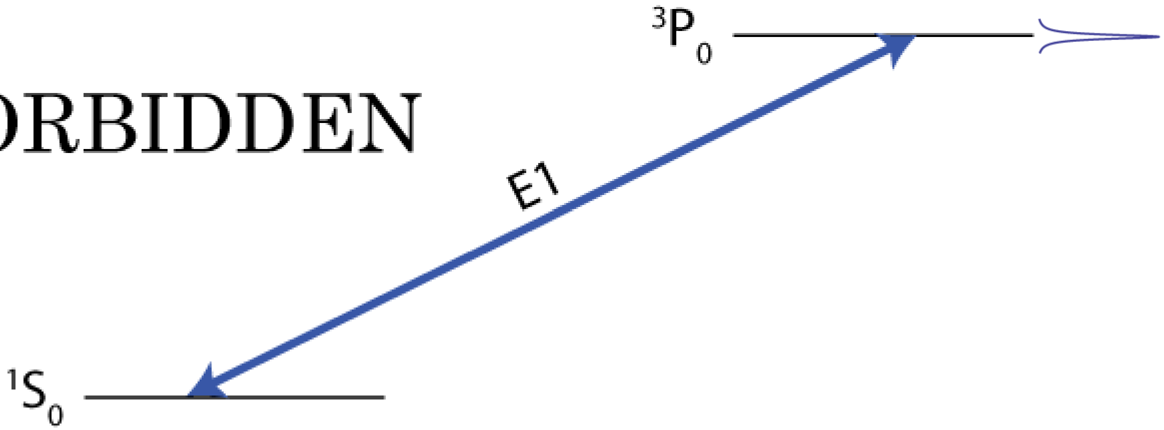


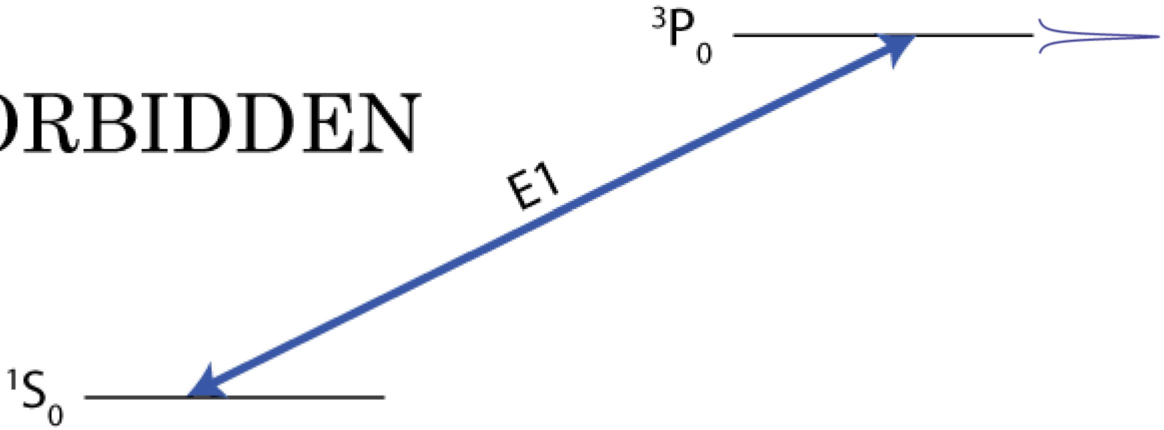
$\Delta\nu$ is the linewidth of the system
ν is the frequency of the sampling probe
T is the duty cycle of the experiment
τ is the total experiment time
N is the sample size per duty cycle

The Clock Transition

$$\sigma_\nu = \frac{\Delta\nu}{\nu}\sqrt{\frac{T}{\tau N}}$$

Clock Wisdom:
If you can’t relax, you can’t get excited.
You need to reduce the forbiddenness.

FORBIDDEN



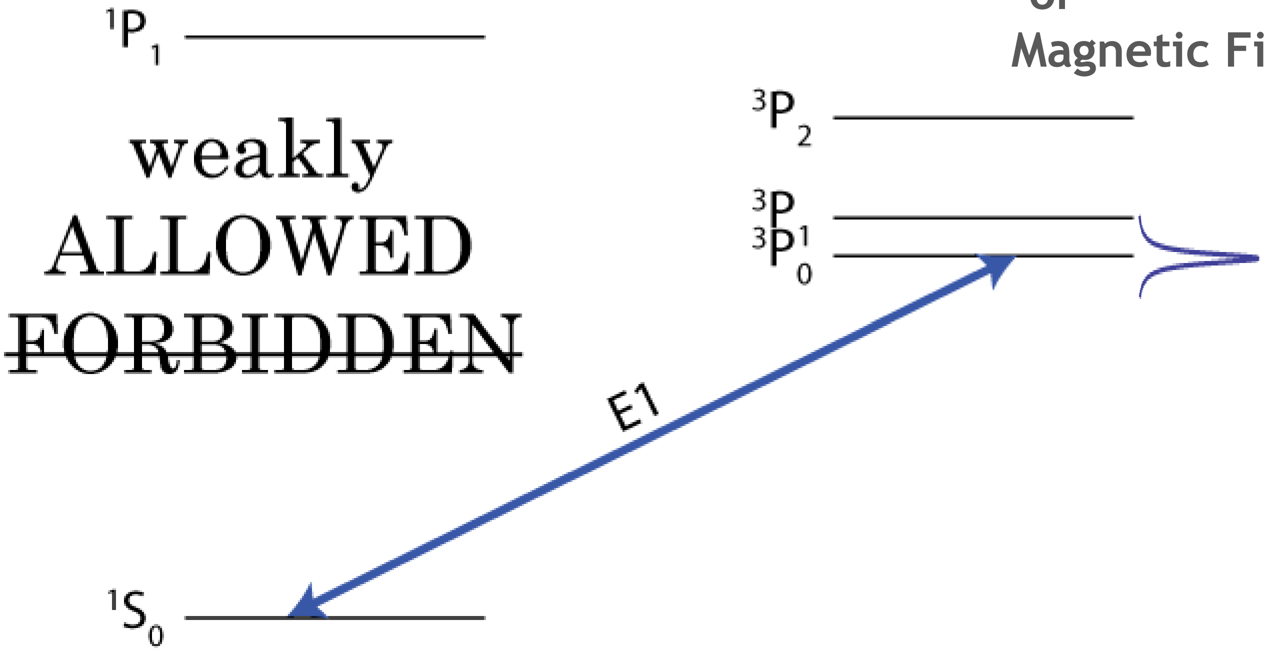
$\Delta\nu$ is the linewidth of the system
ν is the frequency of the sampling probe
T is the duty cycle of the experiment
τ is the total experiment time
N is the sample size per duty cycle

The Work-Around

Just Add:
- Levels
- Nuclear Spin

-or-

Magnetic Field



weakly

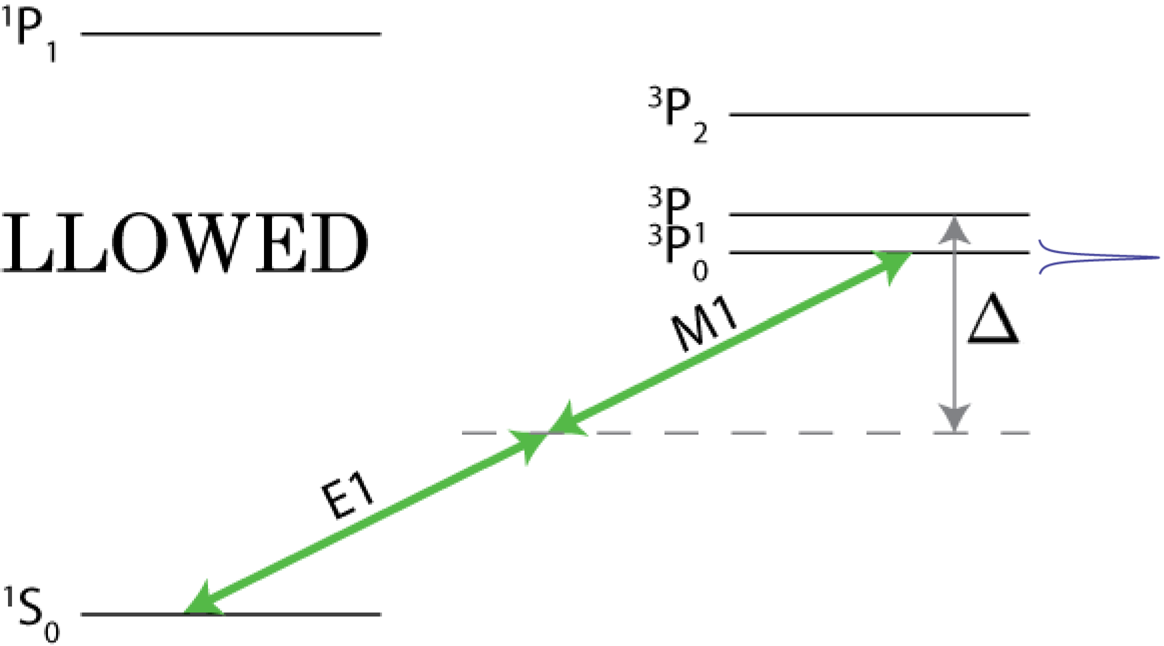
ALLOWED

~~FORBIDDEN~~

E1-M1 Clock
Novel Excitation Scheme

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

$$\sigma_\nu = \frac{\Delta\nu}{\nu}\sqrt{\frac{T}{\tau N}}$$



ALLOWED

E1-M1 Clock
Two-Photon Rabi Frequency

$$\Omega_{2\gamma} = \frac{2I}{\hbar^2 c^2 \epsilon_0} \frac{\langle {}^3P_0|\mu|{}^3P_1\rangle_{M1} \langle {}^3P_1|d|{}^1S_0\rangle_{E1}}{\Delta} \approx 2I \cdot 10^{-5}\,[\mathrm{Hz}]$$

I is the excitation laser intensity
$\langle {}^3P_0|\mu|{}^3P_1\rangle_{M1}$ is the magnetic dipole matrix element
$\langle {}^3P_1|d|{}^1S_0\rangle_{E1}$ is the electric dipole matrix element
Δ is the detuning of an excitation photon's energy from the intermediate ${}^3P_1$ level

It is experimentally feasible to achieve $I > 10^{10}[\frac{W}{m^2}]$

Hot Hg Clock
Frequency Standard Proposal

80 $^1S_0$
Hg
Mercury
200.59
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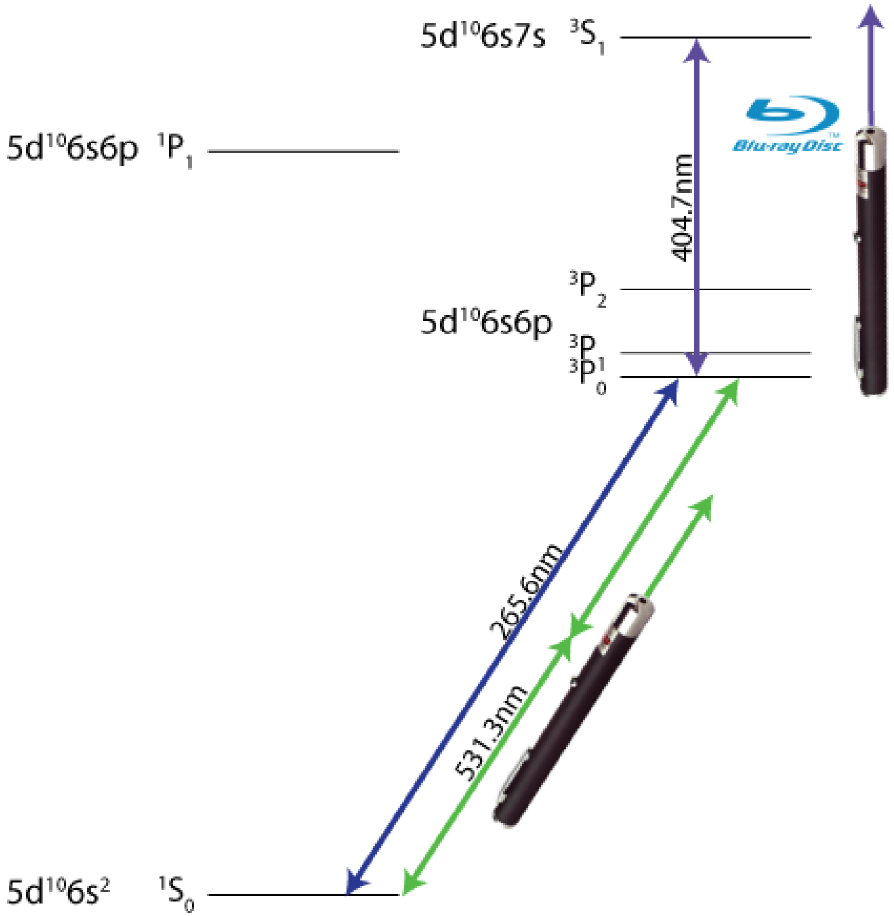
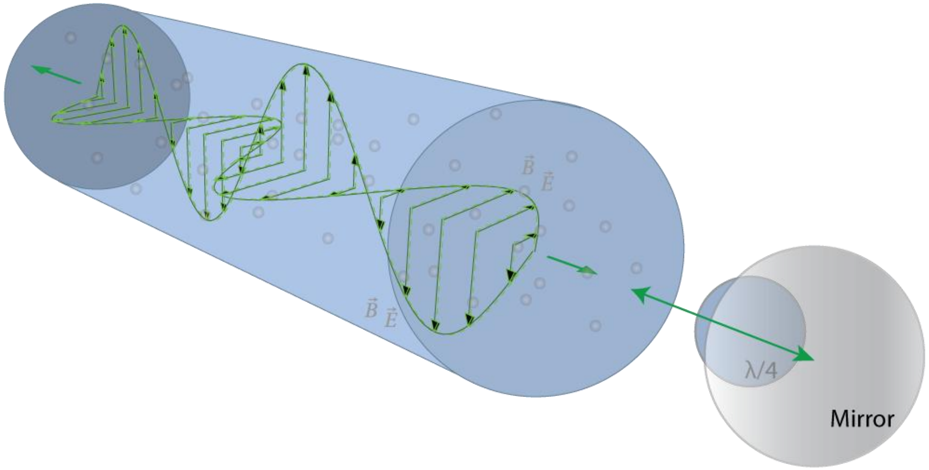
10.4375

Hot Hg Clock

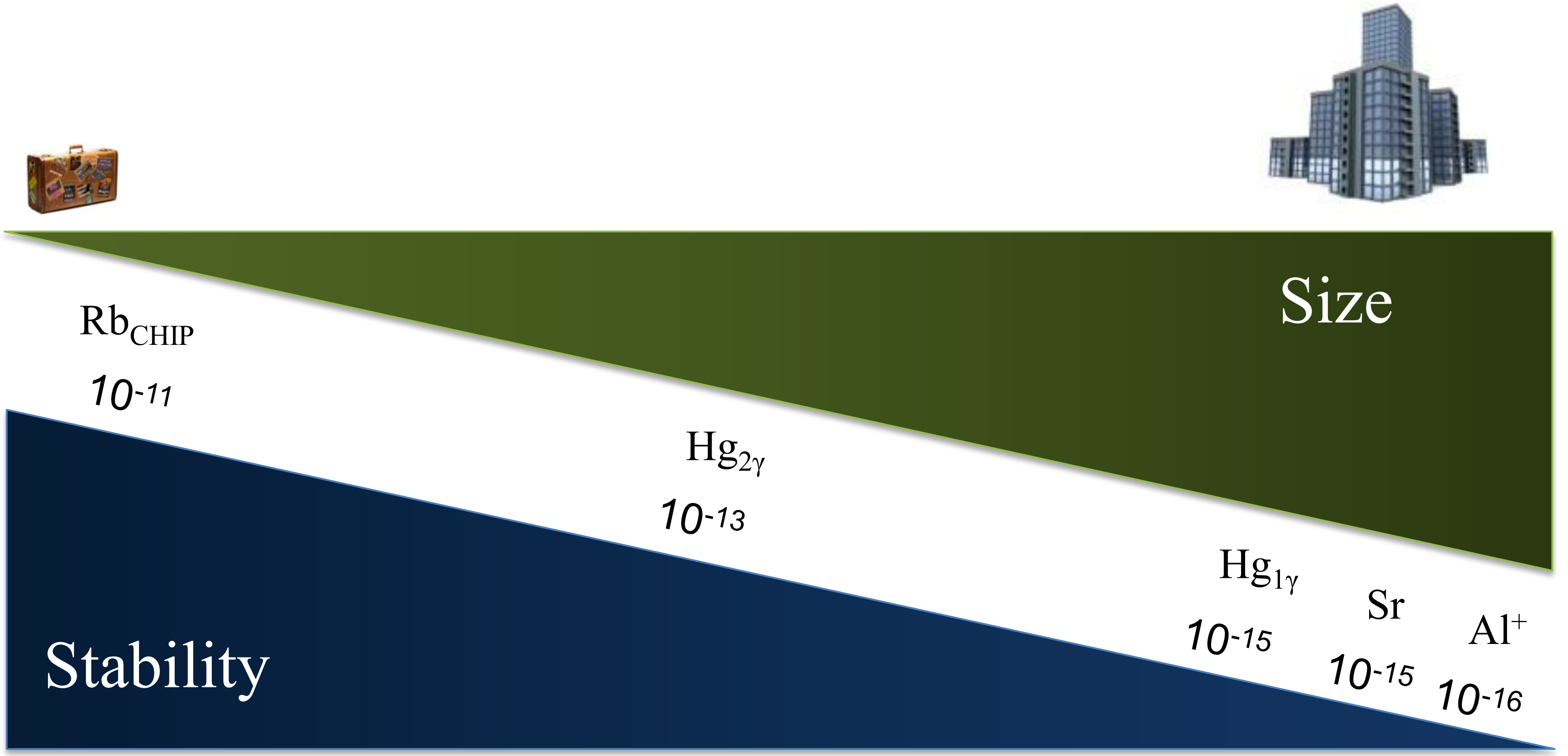


Hot Hg Clock
Vapor Cell

- 10^{13} Hg atoms/cm^3 @ 293 K
- First-order Doppler Broadening



Clock Stability vs. Size



$\mathrm{Rb}_{\mathrm{CHIP}}$

10^{-11}

$\mathrm{Hg}_{2\gamma}$

10^{-13}

$\mathrm{Hg}_{1\gamma}$

10^{-15}

Sr

10^{-15}

Al^+

10^{-16}

$\mathrm{Rb}_{\mathrm{CHIP}}$	Knappe et al OL 2005
$\mathrm{Hg}_{1\gamma}$	McFerran et al IEEE 2012
Sr	Ludlow et al Science 2008
Al^+	Chou et al PRL 2011

Hot Hg Clock
Broadening Mechanisms

Broadening Mechanism	Hot Clock $\delta\nu$ [Hz]
Blackbody Radiation	$0.2^{[1]}$
Natural	$1^{[2]}$
Stark Shift Clock	$56^{[3]}$
Doppler (2nd-order)	41
Doppler (1st-order)	306
Collision_{vapor}	3900
Collision_{wall}	710
Total	4600

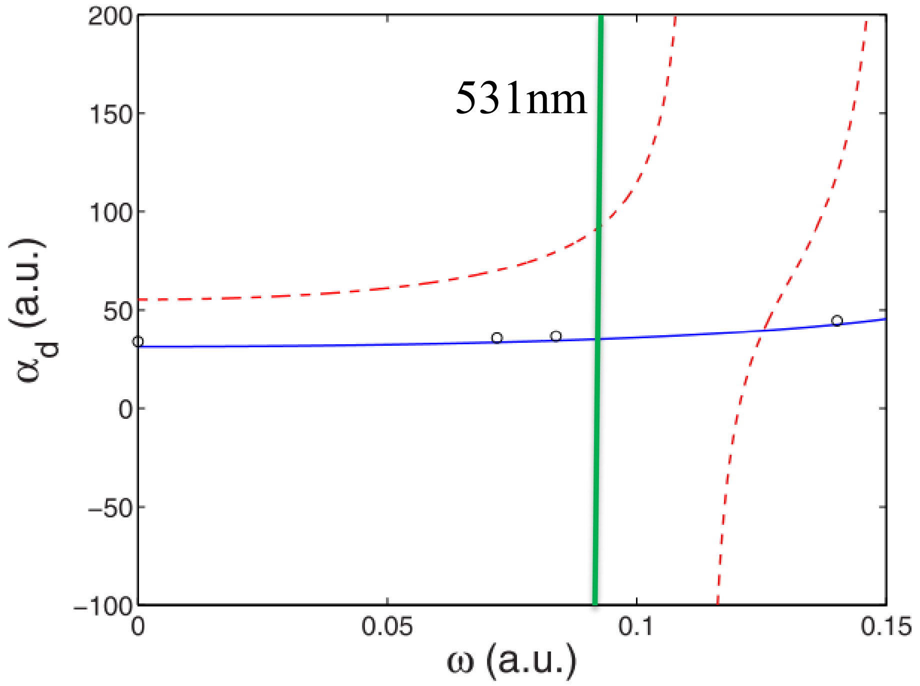
Stability $\sigma_\nu[\frac{1}{\sqrt{\tau}}]$ 3.3×10^{-13}

Vapor Cell @ 250° K

531nm beam:
D = 2mm
P = 10 W

[1] Hachisu, PRL 2008
[2] Mishra, Spectroscopy 2008
[3] Ye, Wang, PRA 2008

Hot Hg Clock
AC Stark Shift



$$\Delta\nu_{STARK} = 5.5\text{kHz}$$

$$\sigma = 56\text{ Hz} / 100mW$$

Experimental Challenge:
Precise Power Metrology

PHYSICAL REVIEW A **78**, 014502 (2008)
Anpei Ye (叶安培) and Guangfu Wang (王广福)*

Special Thanks to Guangfu Wang for furnishing the exact values at 531nm

Hot Hg Clock
First-Order Doppler Broadening

80 $^1S_0$
Hg
Mercury
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10.4375

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Stability $\sigma_\nu[\frac{1}{\sqrt{\tau}}]$	3.3×10^{-13}

1μ Radian

Experimental Challenge:
Precise Retro-Alignment

Hot Hg Clock
Collision Broadening

Broadening Mechanism	Hot Clock $\delta\nu$ [Hz]
Blackbody Radiation	0.2[1]
Natural	1[2]
Stark Shift Clock	56[3]
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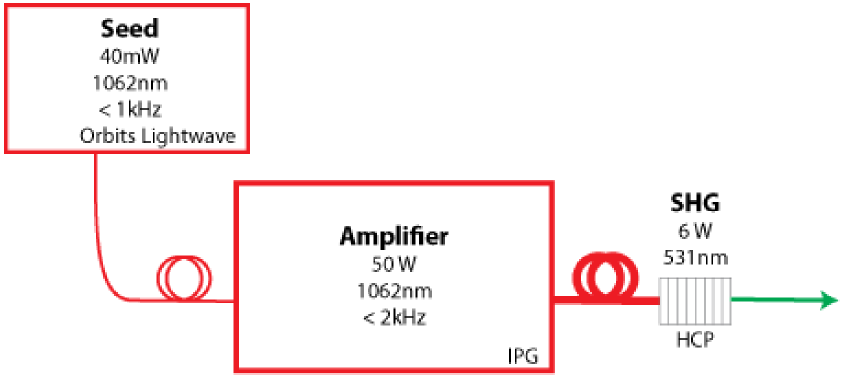
Experimental Challenge:
Measure & Characterize
Collision Broadening

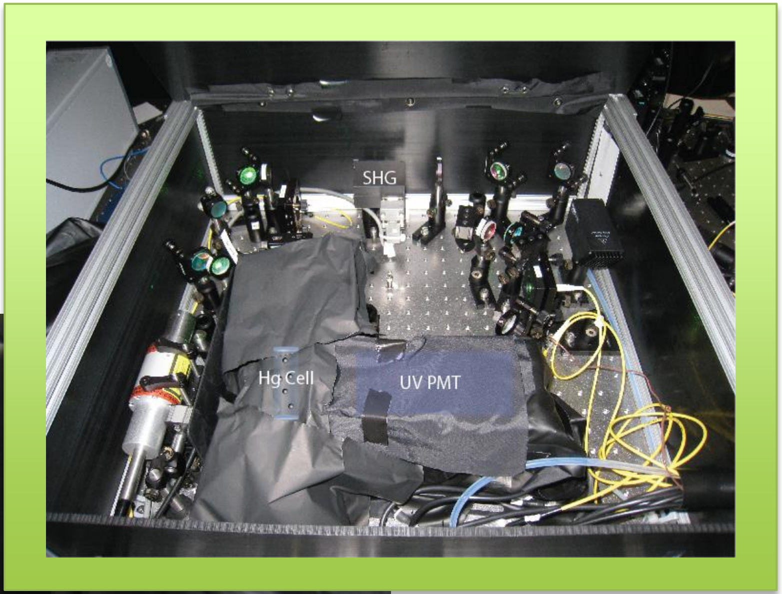
Experimental Progress
Laser System

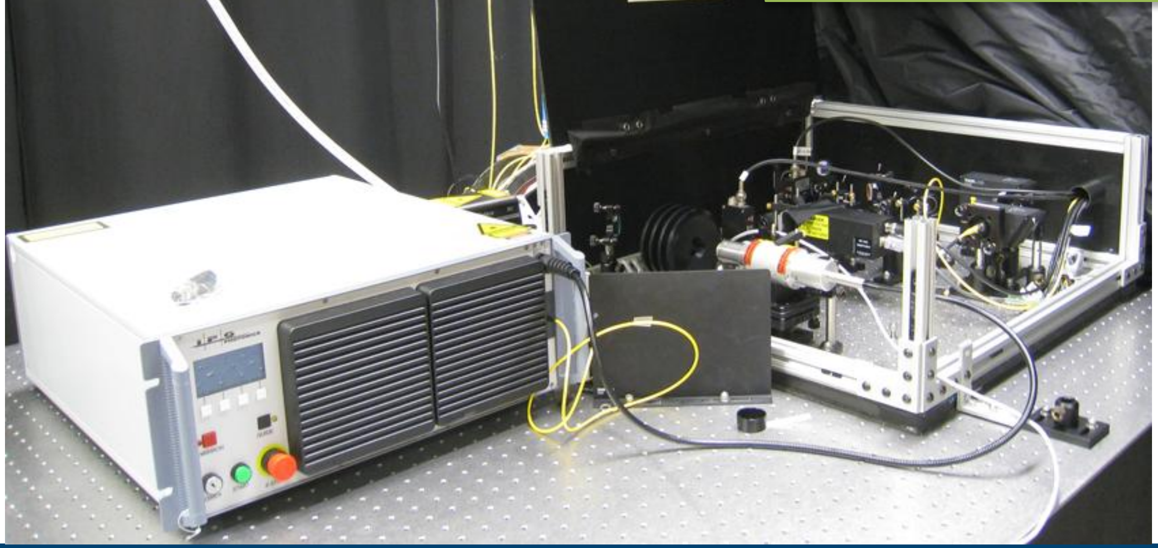


Seed
40mW
1062nm
< 1kHz
Orbits Lightwave

Amplifier
50 W
1062nm
< 2kHz
IPG

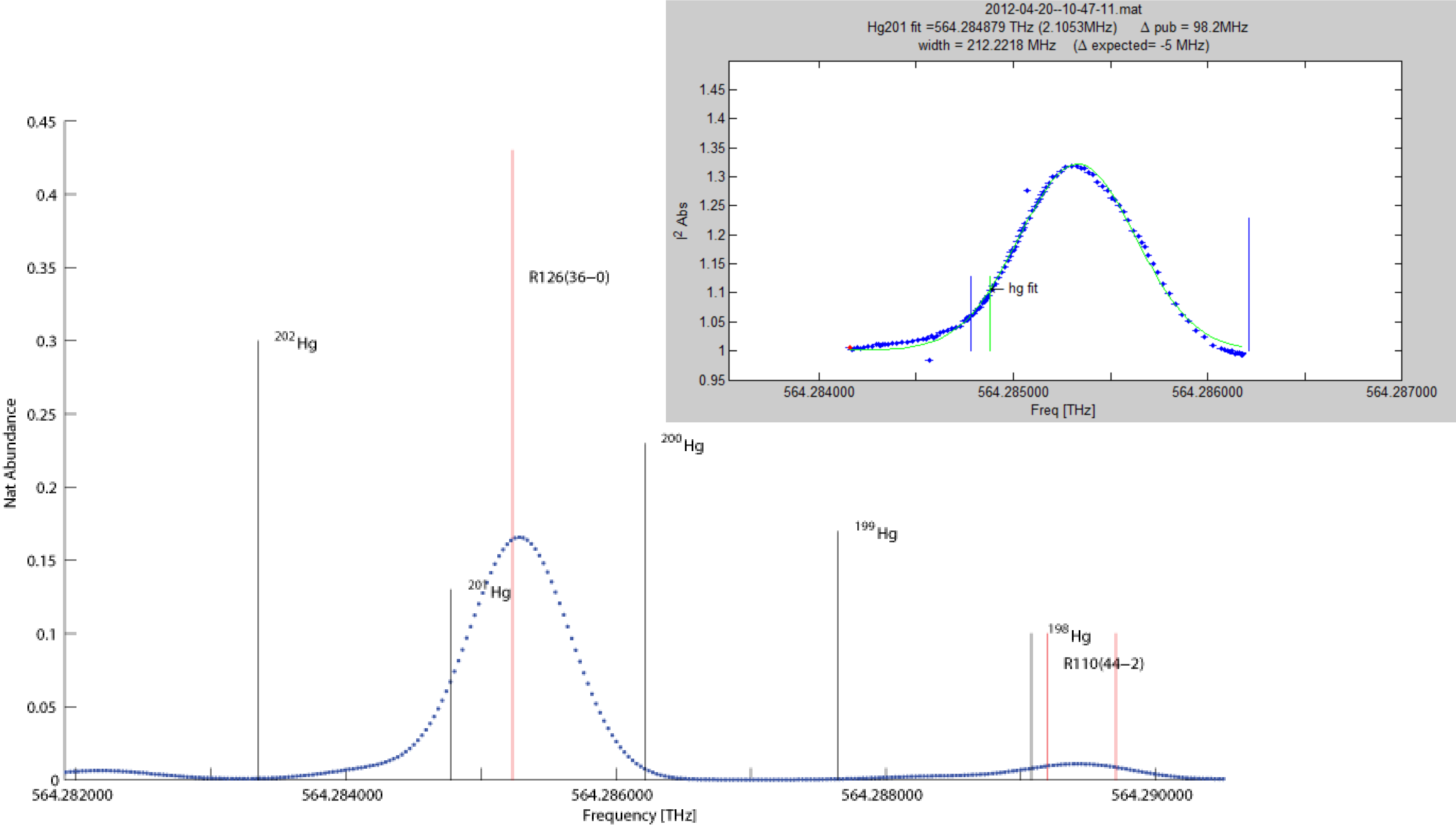
SHG
6 W
531nm
HCP





Experimental Progress
I^2 Reference

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375



I^2 Gerstenkorn 1980
Hg Peterson PRL 2008

Next Steps

Novel Observation

E1-M1 Optical Access to a Clock Level

Bosonic Spectroscopy of Clock Level

Optimal Clock

Collision Effects

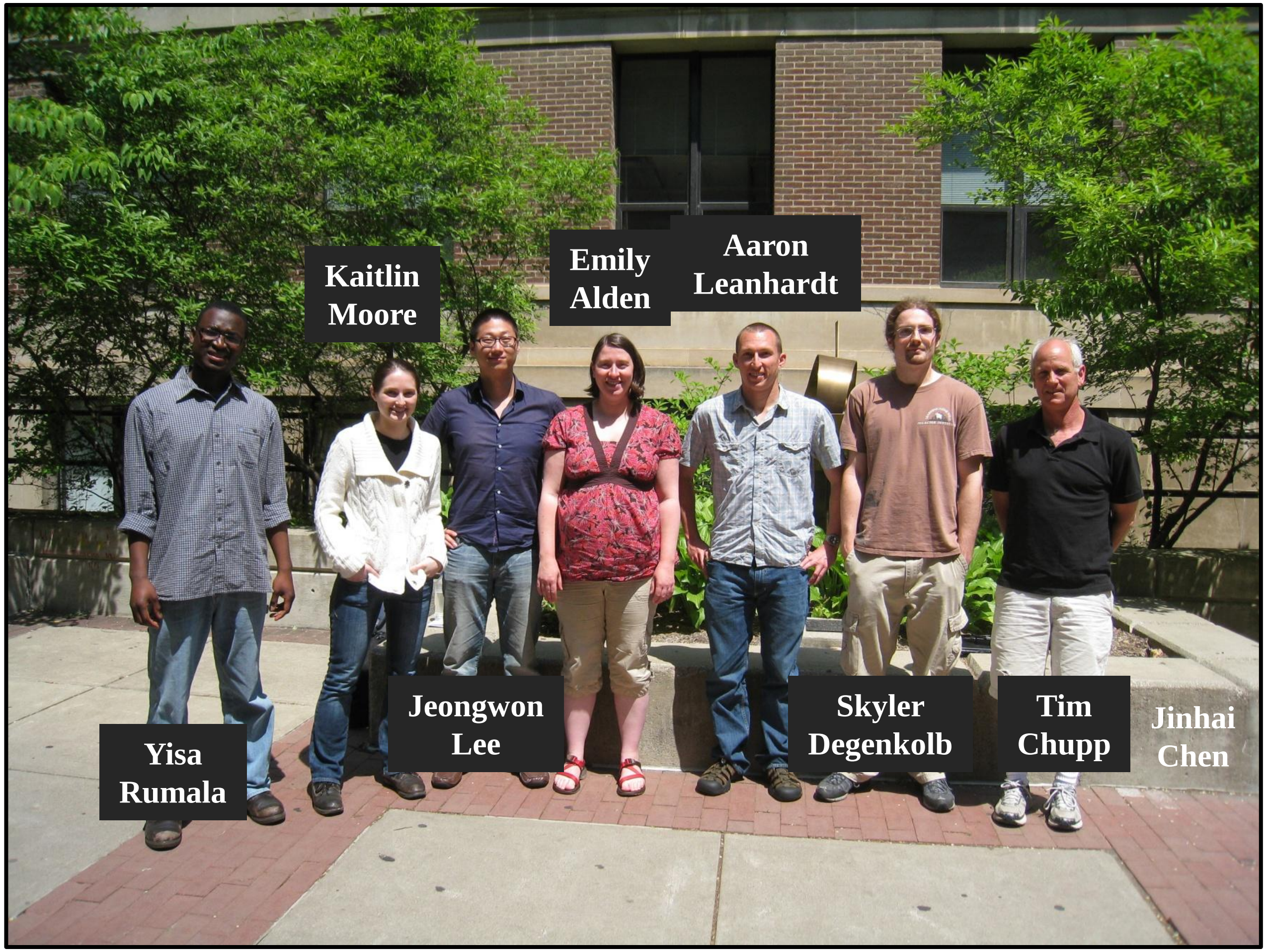
Stark Shift

Atom Number
Temperature

Thank You

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

Leanhardt Lab

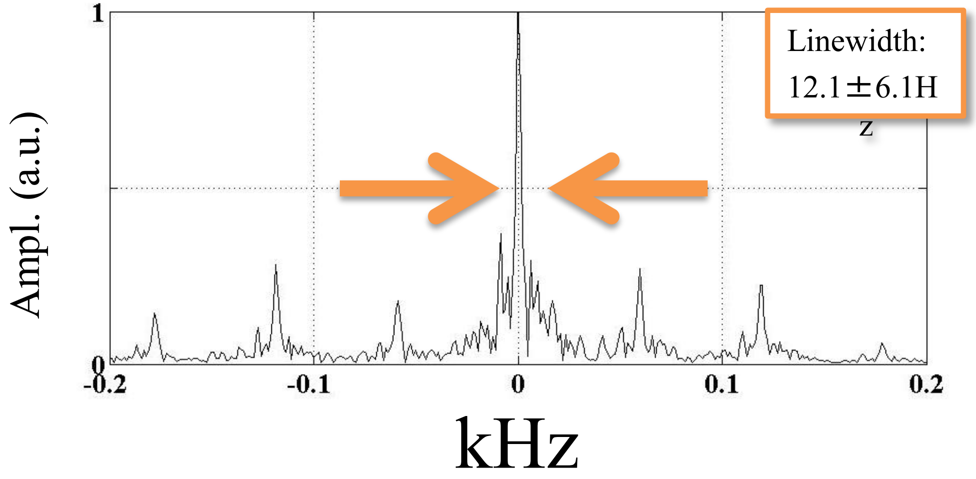


- Funding:
  DARPA/ARO
  AFOSR

Slides available at: http://www-personal.umich.edu/~ealden/

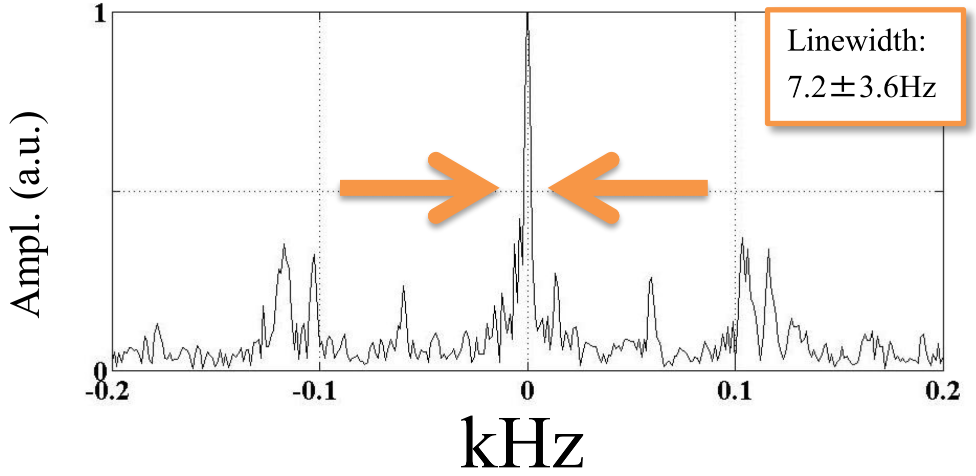
Fourier Limited
Seed & Amplifier Homodyne

Seed
with
Seed



Linewidth:
12.1±6.1Hz

Seed
with
Amplifier

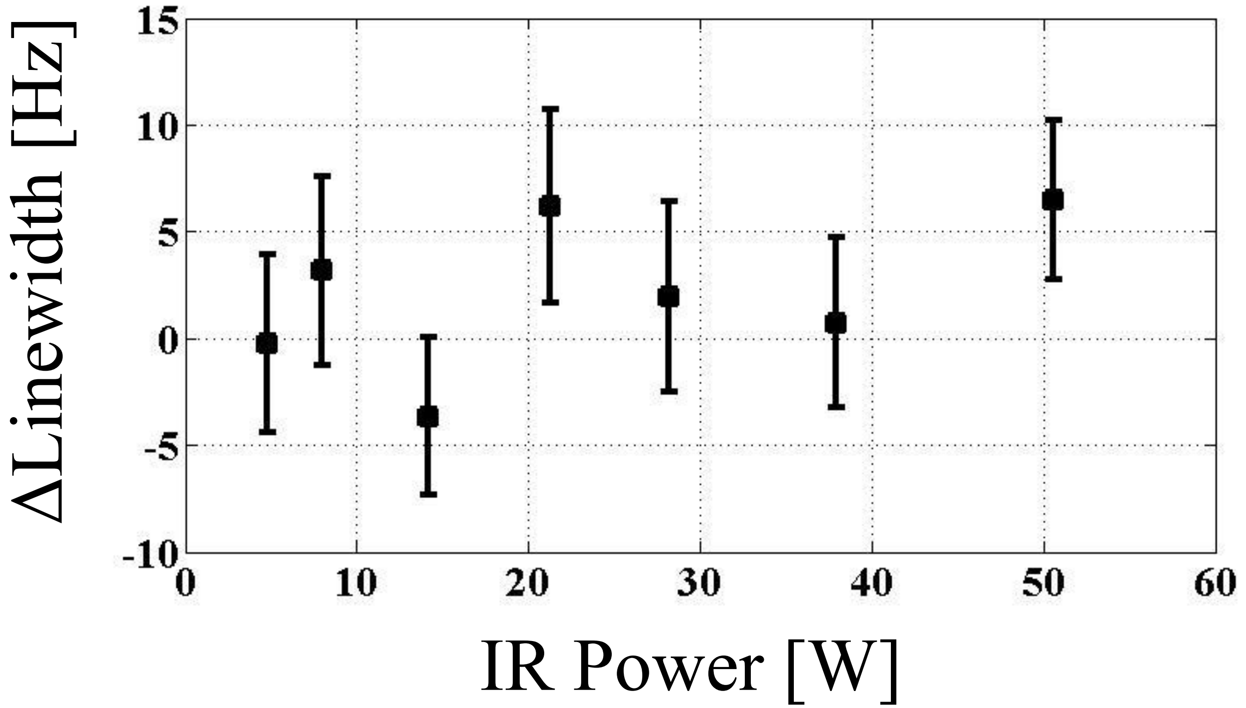


Linewidth:
7.2±3.6Hz

1062 nm
14.2W

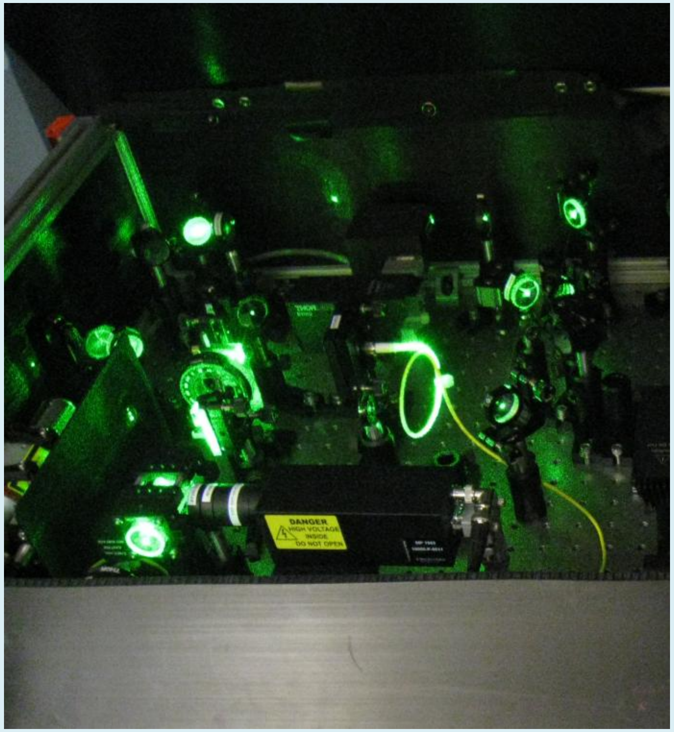
Laser Characterization

- Increasing amplifier power:



- After replacing the amplifier in the system, measurements show no systematic change in the linewidth of the beat note.

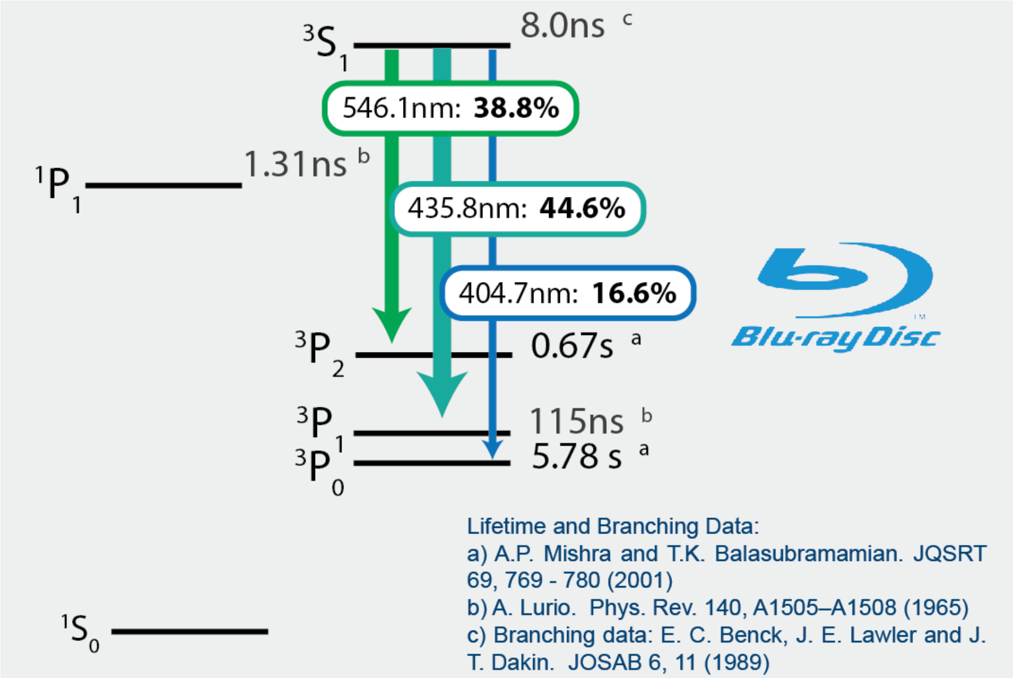
Cold Hg Clock



Advantages

- Dense MOT

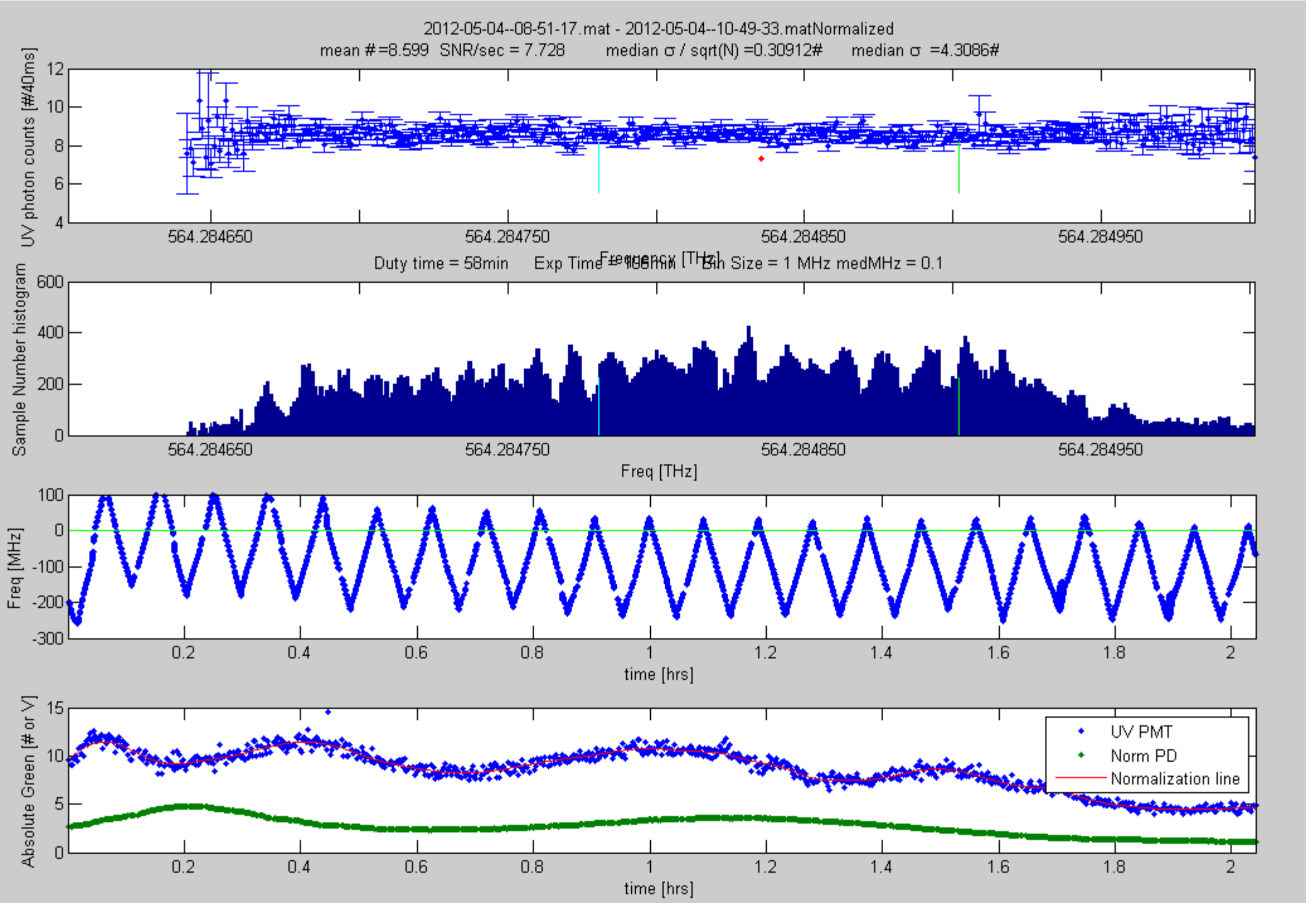
3S1 - Detection



Lifetime and Branching Data:
a) A.P. Mishra and T.K. Balasubramamian. JQSRT 69, 769 - 780 (2001)
b) A. Lurio. Phys. Rev. 140, A1505–A1508 (1965)
c) Branching data: E. C. Benck, J. E. Lawler and J. T. Dakin. JOSAB 6, 11 (1989)

- QE 435:
  OD 2.64
  0.2%
- SNR:
  7 counts/sec

Sample Scan


2012-05-04--08-51-17.mat - 2012-05-04--10-49-33.matNormalized
mean # =8.599 SNR/sec = 7.728 median σ / sqrt(N) =0.30912# median σ =4.3086#
UV photon counts [#/40ms]
12
10
8
6
4
564.284650
564.284750
564.284850
564.284950
Frequency [THz]
Duty time = 58min Exp Time = 106min Bin Size = 1 MHz medMHz = 0.1
Sample Number histogram
600
400
200
0
564.284650
564.284750
564.284850
564.284950
Freq [THz]
Freq [MHz]
100
0
-100
-200
-300
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [hrs]
Absolute Green [# or V]
15
10
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [hrs]
UV PMT
Norm PD
Normalization line