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

A Portable E1-M1 Optical Clock

Precision Time Measurement and a Novel Two-Photon Clock Scheme

E.A.ALDEN

Leanhardt Lab

Department of Physics, University of Michigan

E1-M1 Clock

A Hot Hg Clock

Experimental Progress

The Clock Transition

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

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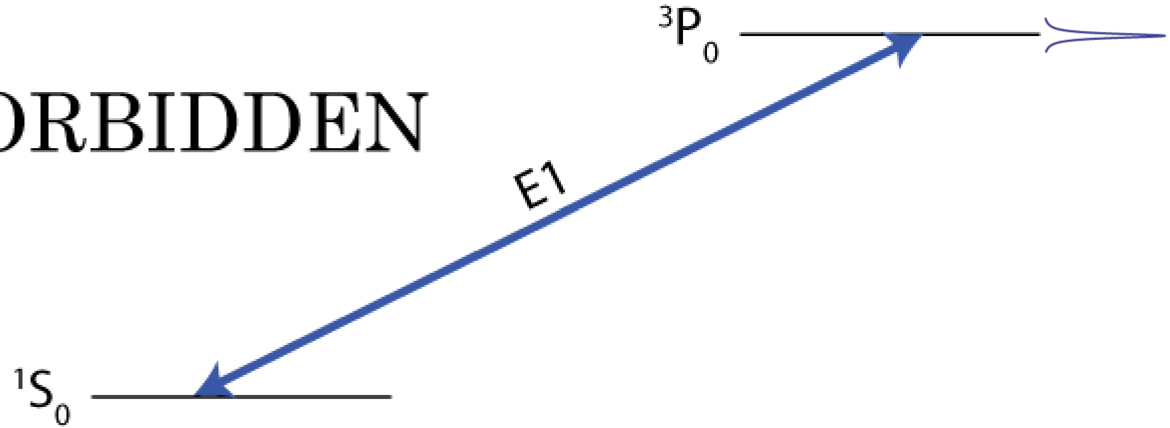
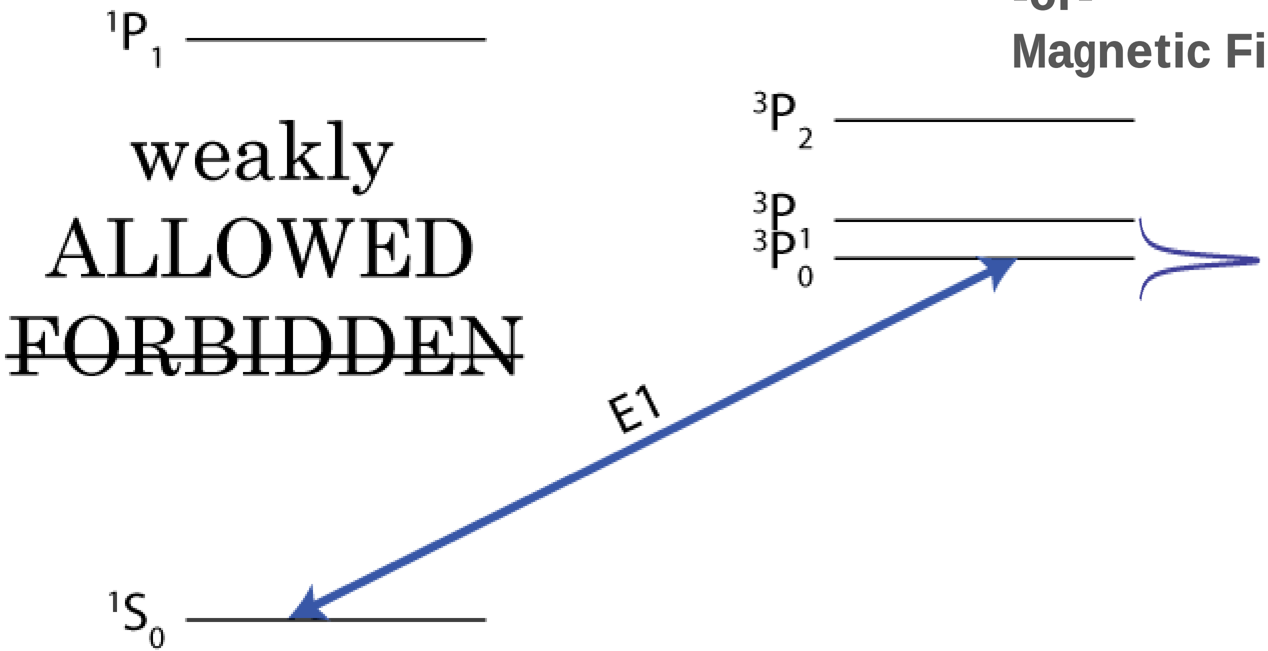


The Work-Around



Just Add:
- **Levels**
- **Nuclear Spin**

-or-

Magnetic Field

REQUIRES EXTENSIVE STATE PREPARATION

E1-M1 Clock
Novel Excitation Scheme

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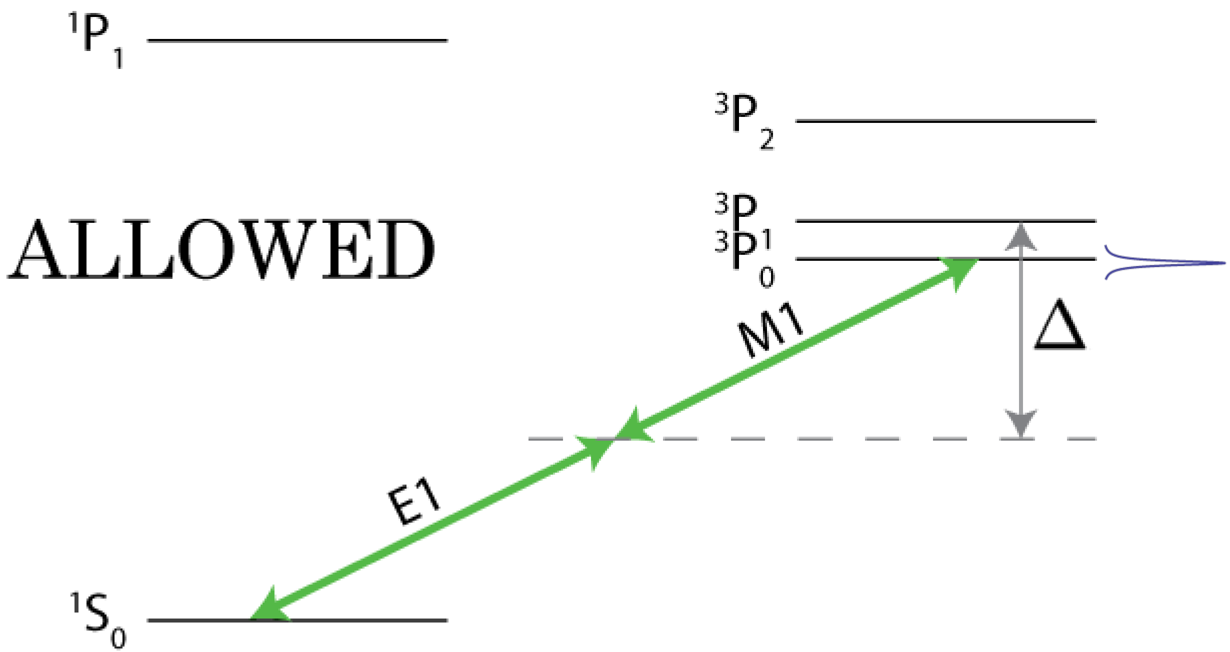
$$\sigma_\nu = \frac{\Delta\nu}{\nu}\sqrt{\frac{T}{\tau N f}}$$



Hot Clock
Vapor Cell

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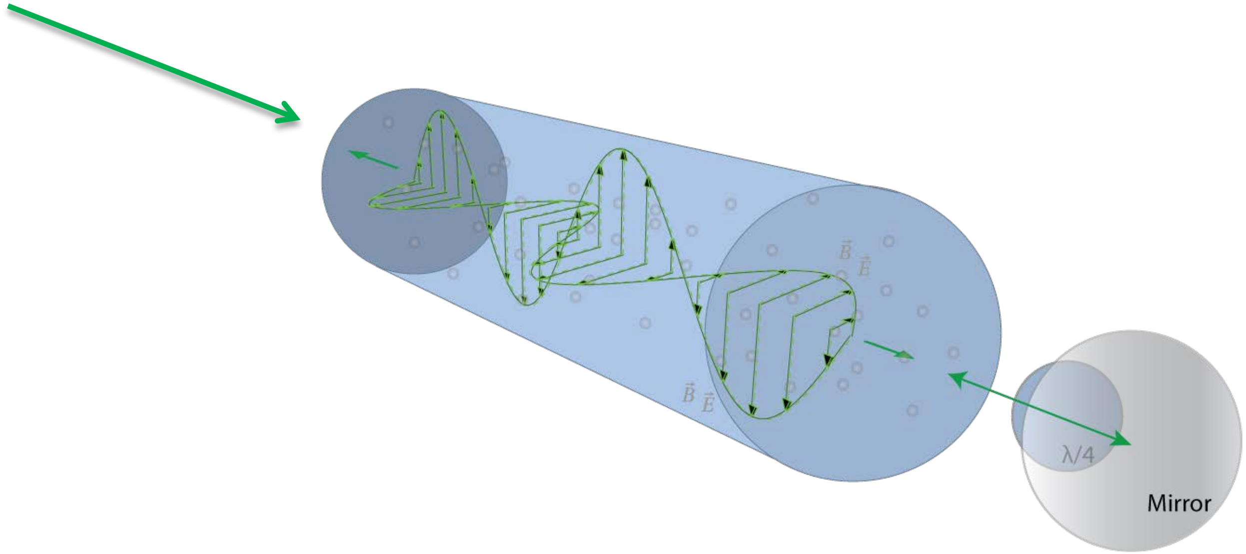
[Xe]$4f^{14}5d^{10}6s^2$
10.4375

- Dense atoms at room temperature
- First-order Doppler Broadening ELIMINATED

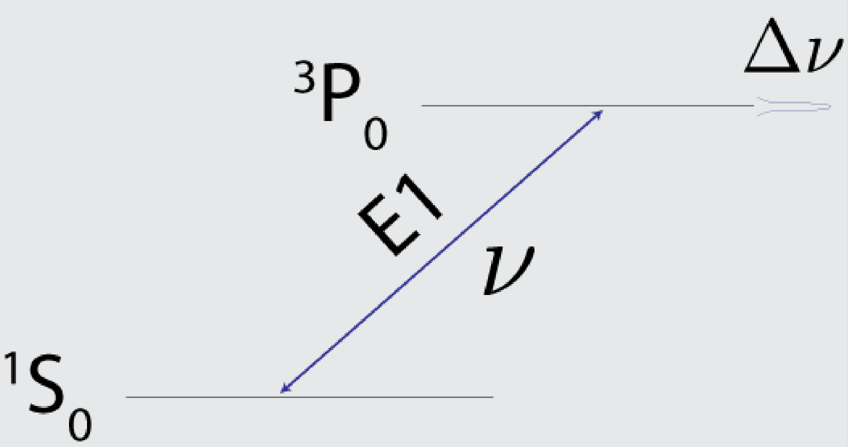


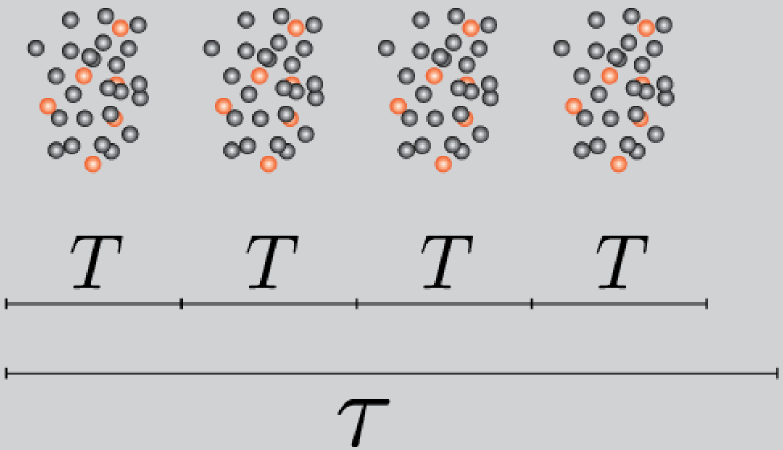
The Clock Transition

$\Delta\nu$ is the linewidth of the system
ν is the frequency of the sampling probe

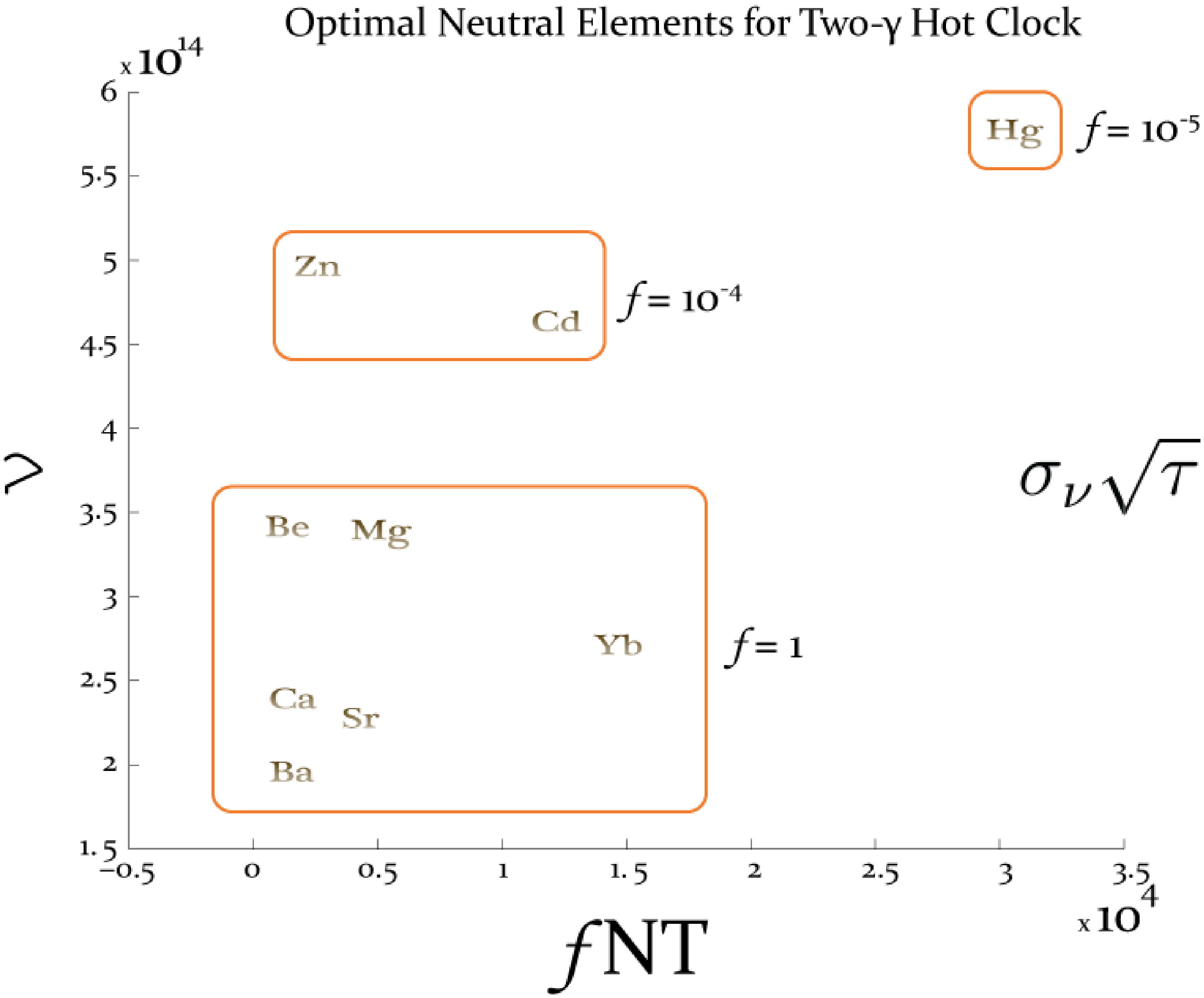
T is the time cycle of the experiment
τ is the total experiment time
N is the sample size per duty cycle
f is the fractional excitation

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





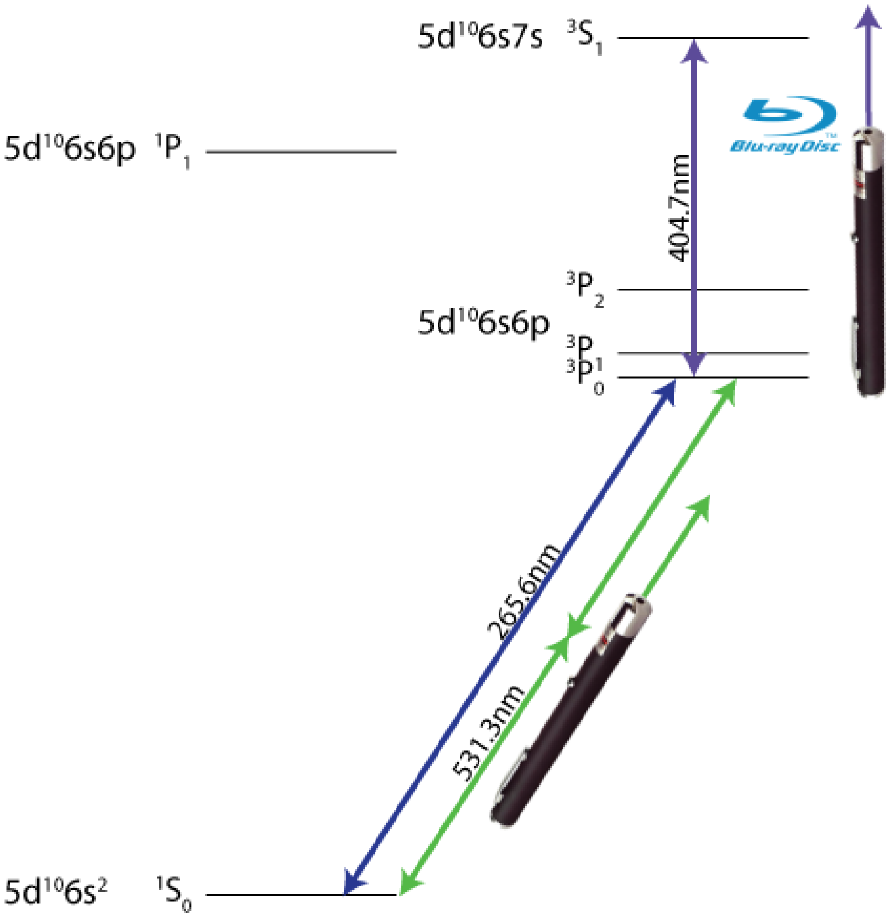
Candidate Elements



$$\sigma_\nu \sqrt{\tau} = \frac{1}{\nu\sqrt{f N T}}$$

Hot Hg Clock
Frequency Standard Proposal

Hot Hg Clock



Clock Stability vs. Size

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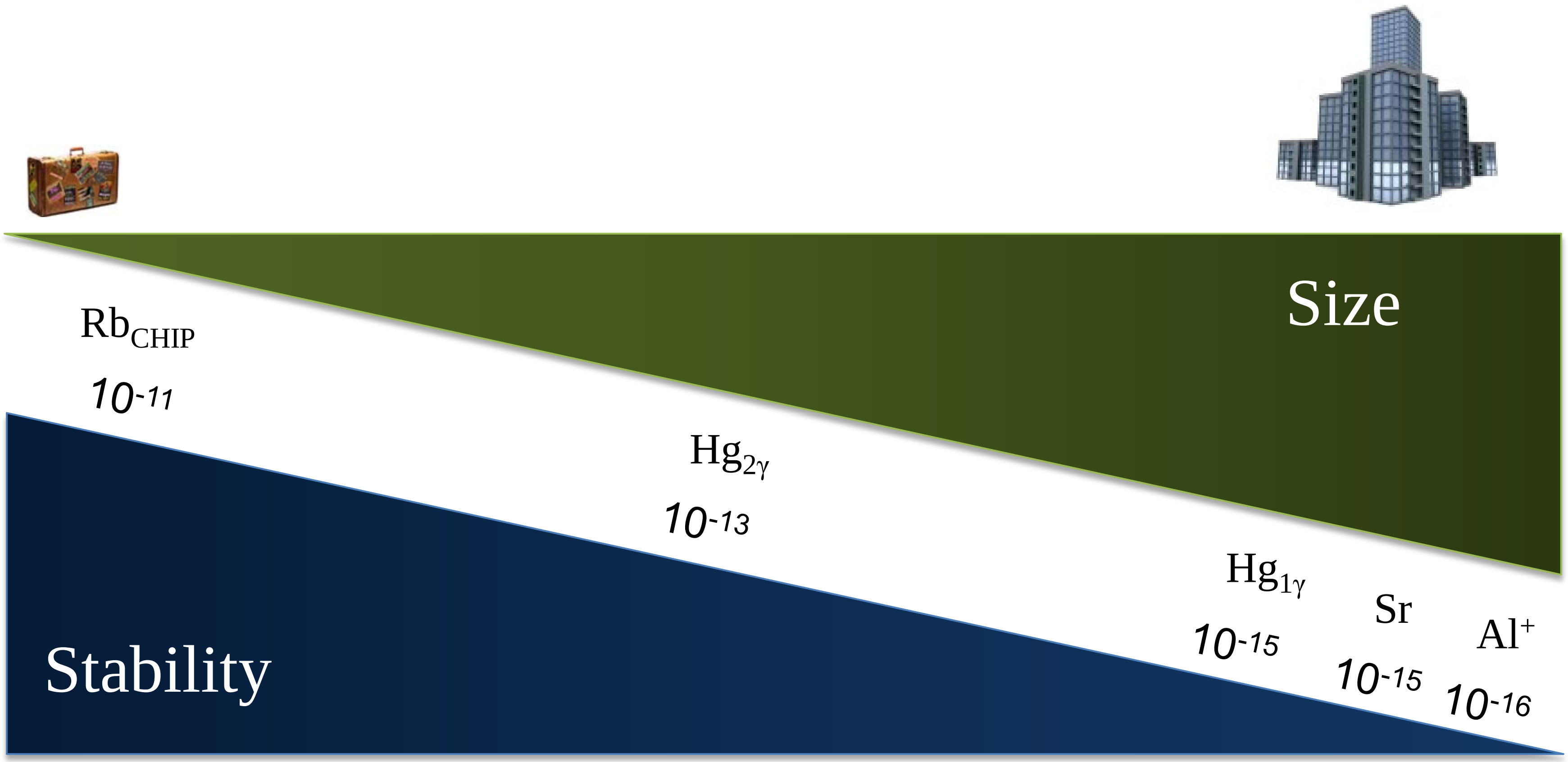

Rb_{CHIP}	Knappe et al OL 2005
$Hg_{1\gamma}$	McFerran et al IEEE 2012
Sr	Ludlow et al Science 2008
Al^+	Chou et al PRL 2011

E1-M1 Clock
Two-Photon Rabi Frequency

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

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 Broadening Mechanisms

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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

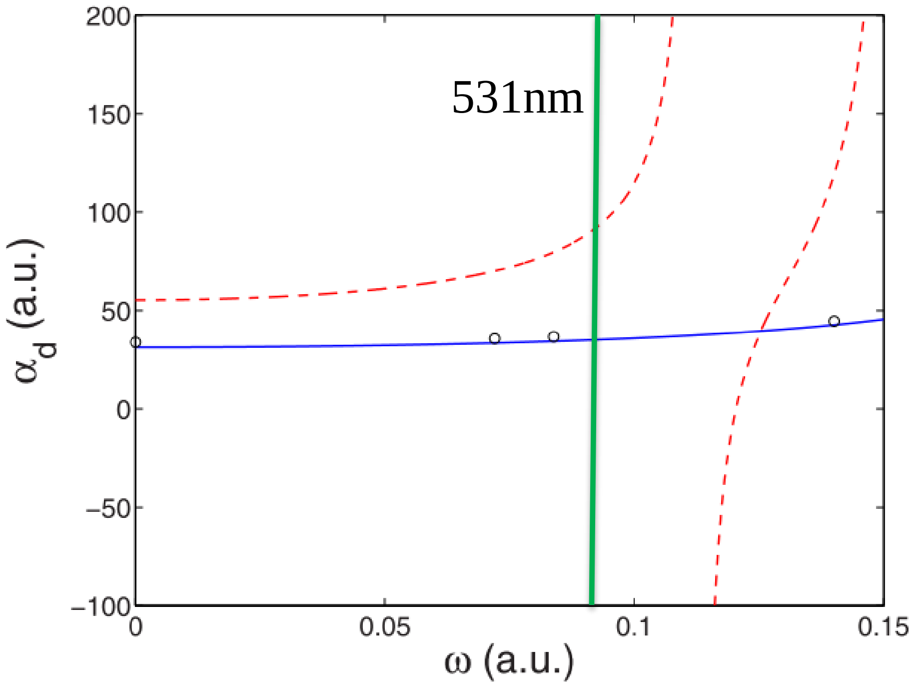
Vapor Cell @ 250° K

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

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

[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
Collision Broadening

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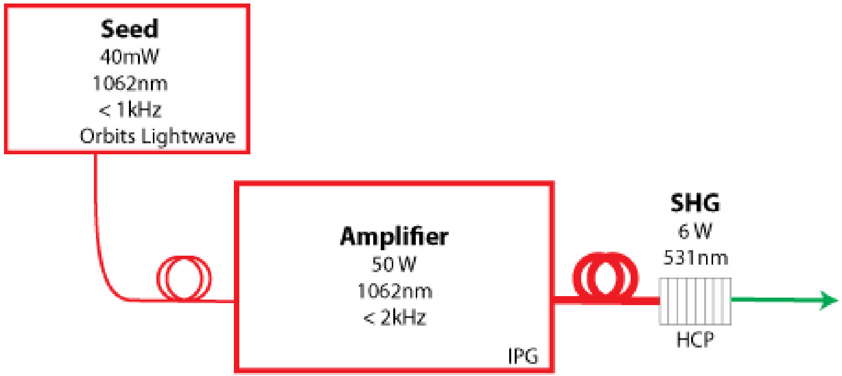
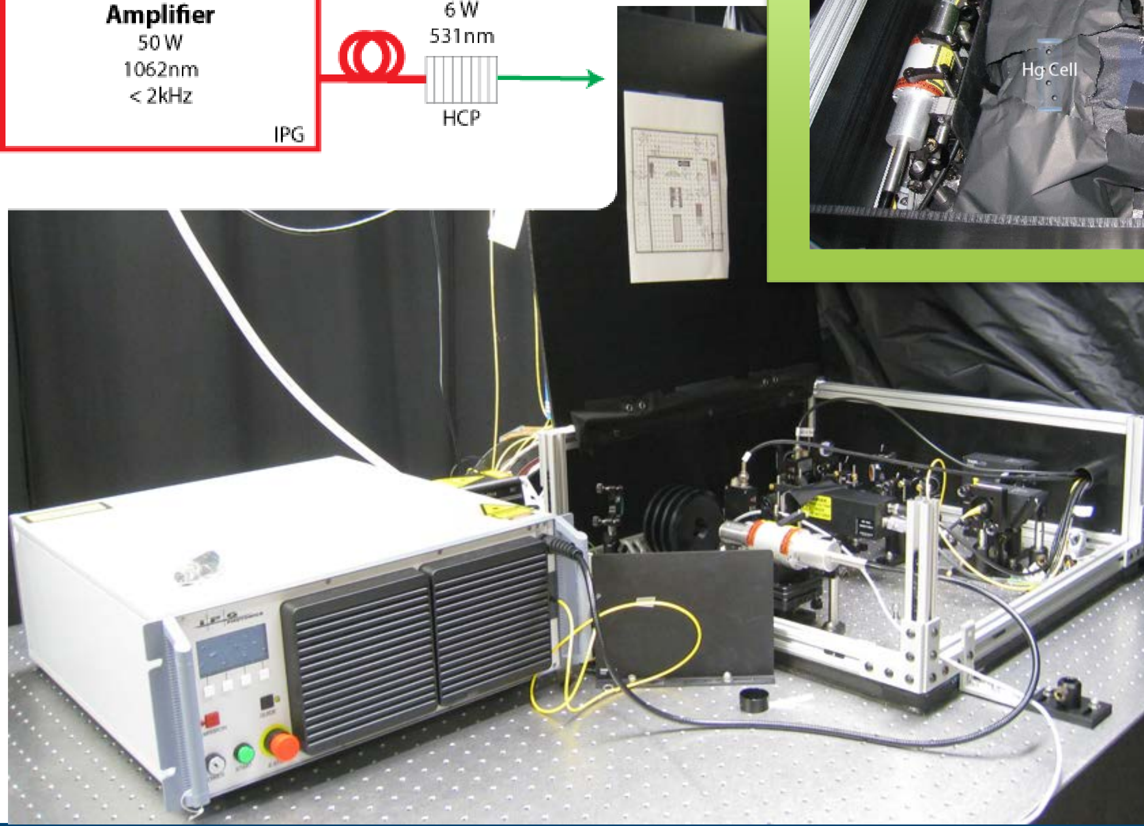
Total	4600
Stability $\sigma_\nu [\frac{1}{\sqrt{\tau}}]$	3.3×10^{-13}

Experimental Challenge:
Measure & Characterize
Collision Broadening

Experimental Progress
Laser System





Experimental Progress
I^2 Reference

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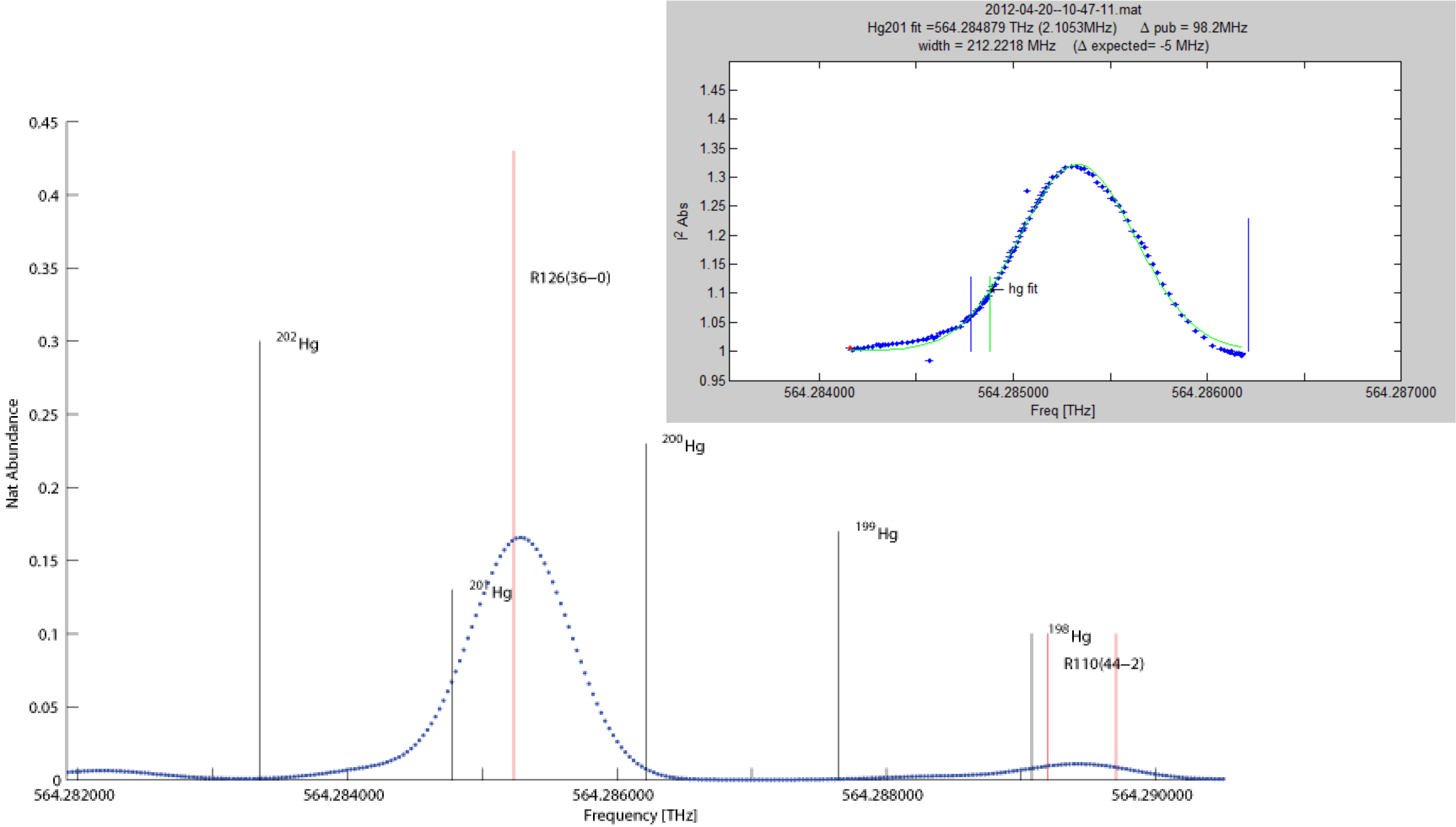

I^2 Gerstenkorn 1980
Hg Peterson PRL 2008

Summary

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

E1-M1 Allowed Transition

- Harnesses optical frequency standard advantages
- Doesn't require elaborate state preparation
- Hg is an excellent candidate atom

Funding: DARPA/ARO & AFOSR
Slides available at: http://www-personal.umich.edu/~ealden/