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# Operating a $^{171}Yb^{+}$ Microwave Ion Clock in a Continuous Mode

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Microsemi

## ACES Project

- PI: Richard Overstreet
- PM: Mark Trainoff, Sam Stein
- Xianli Zhang, Jonathan Tallant
- Jay Noble, Dwayne Taylor, Armand Martins, Nakri Dao, David Guan, Mike Silveira, Dan Boschen

Georgia Institute of Technology

## 369-nm Laser

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## AM Fitzgerald

- MEMS Design: Carolyn White, Alissa Fitzgerald

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- Defense Advanced Research Projects Agency (DARPA)
- Program: Atomic Clocks with Enhanced Stability (ACES)
- Project: Portable Ion Clock Technology (PICT)

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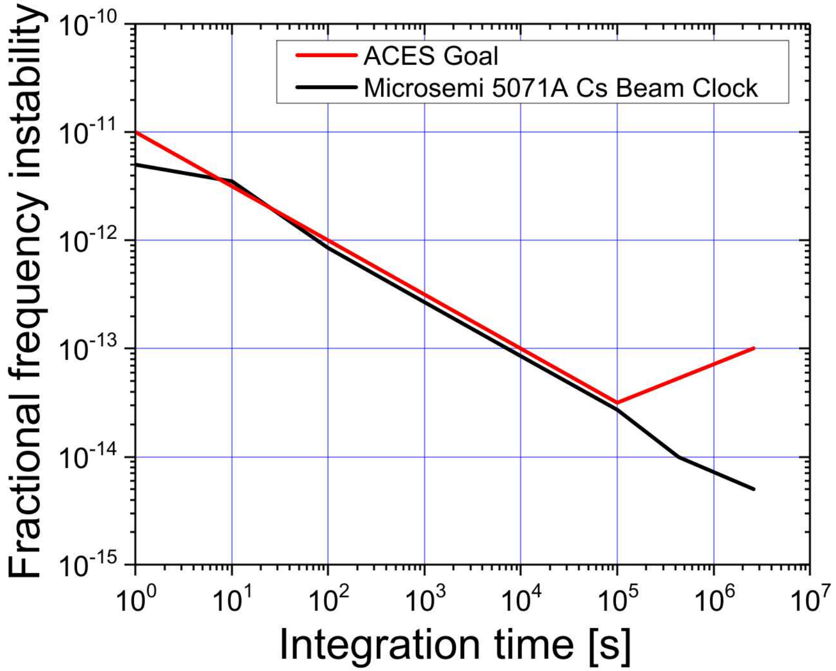
# Outline

- Introduction
- Pulsed Mode Ion Clock
  - Compact $^{171}Yb^{+}$ Ion Clock
- Continuous Mode Ion Clock
  - Light Shift
  - Clock Performance
- F-state and Yb-$H^{+}$ trapping
- 369-nm Vertical Cavity Surface Emitting Laser (VCSEL)
- Miniature Yb Source
- Conclusion

# ACES Project Goals and Applications

Achieve Cs Beam Clock performance in a mass and power constrained package

- 50 $cm^3$, 250 mW, $3\times10^{-14}$ performance
- Low environmental sensitivity
  - $10^{-15}$/C, $10^{-13}$/g, $10^{-13}$/Gauss,




Applications--Excellent timing for:

- Rapid GPS acquisition, and GPS denied navigation and timing
- Nano/pico (cube) satellites
- Pulsed radio and spread spectrum communications

Microsemi 5071A

Miniature primary frequency standard

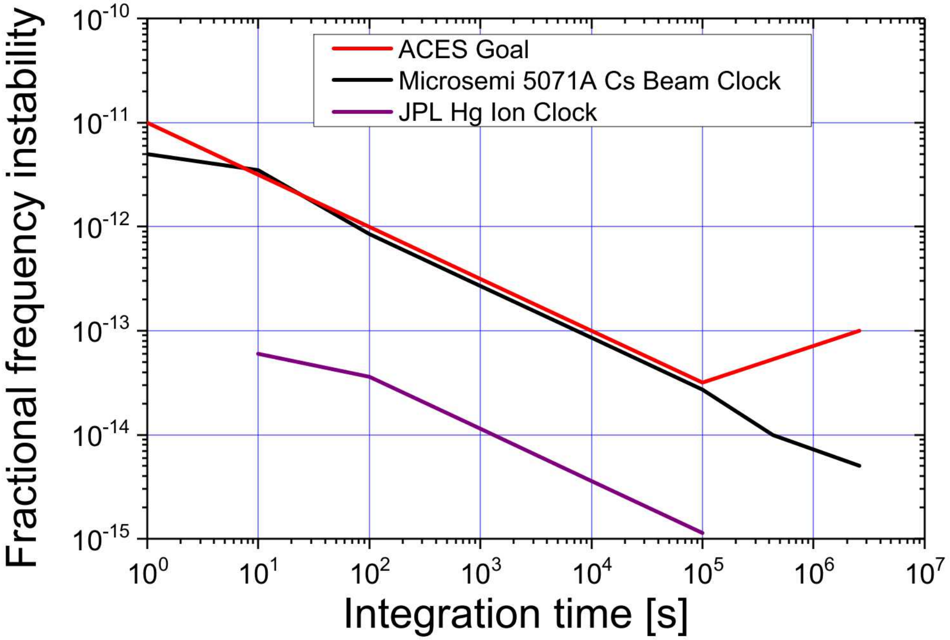
# Trapped Ion Clock for Miniaturization

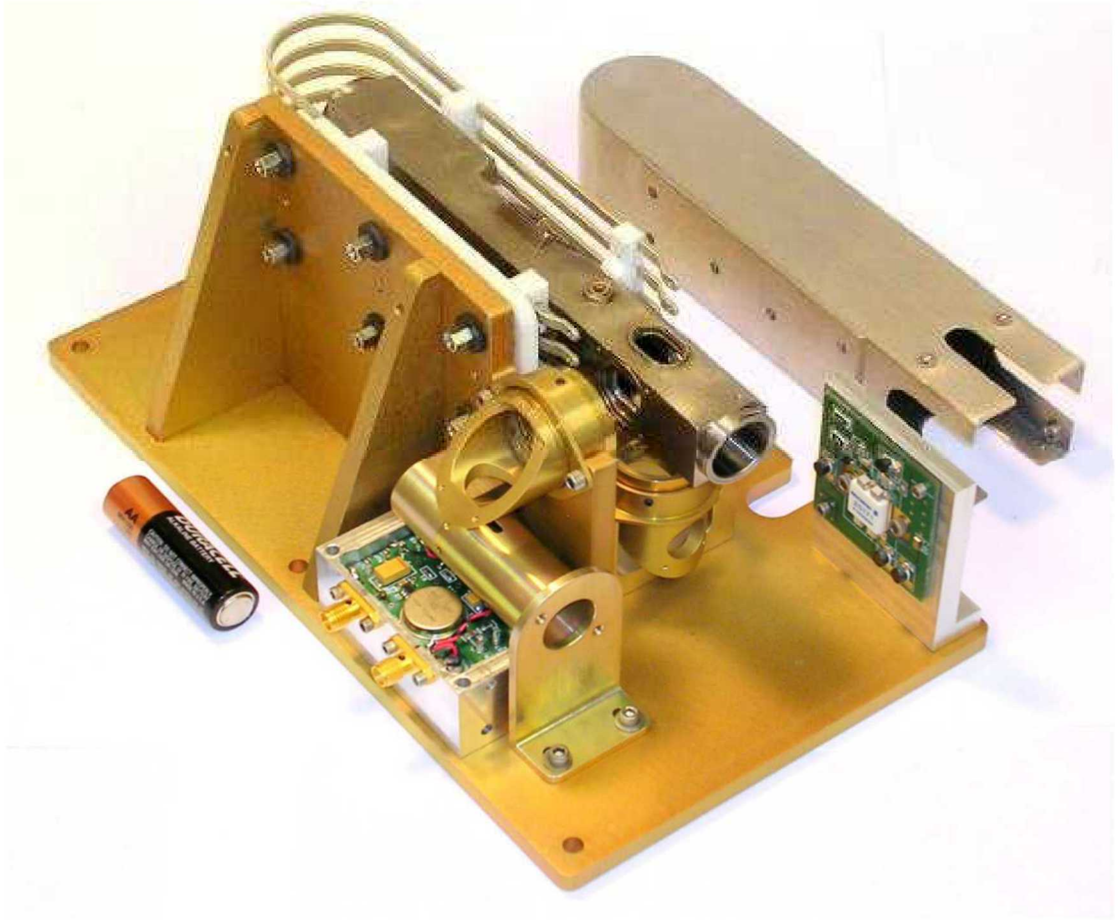
Trapped ion clocks are already compact while delivering excellent performance.

- Low mass, size, power
- Trapped ion lifetime: up to 10,000 hrs
- Coherence time: > 100s

Other approaches for ACES:

- Miniature fountain clock
- Miniature optical clock



$^{199}$Hg Trapped Ion Clock from JPL

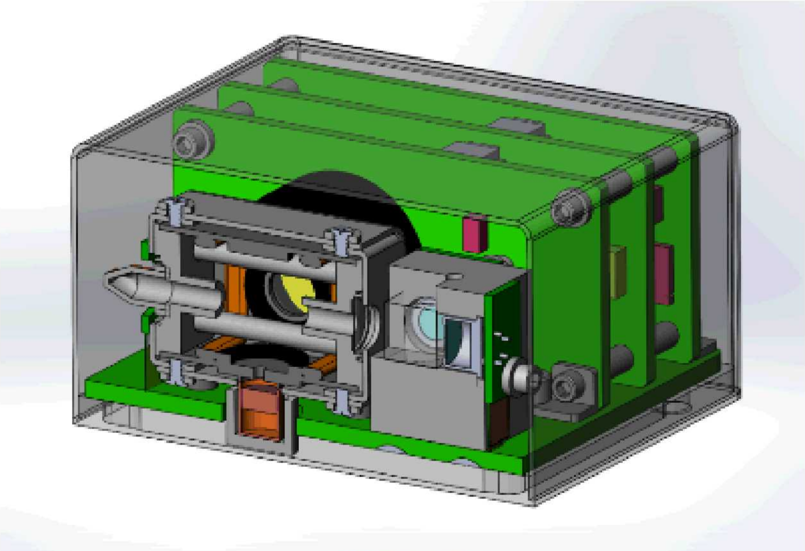
# Portable Ion Clock Technology (PICT)

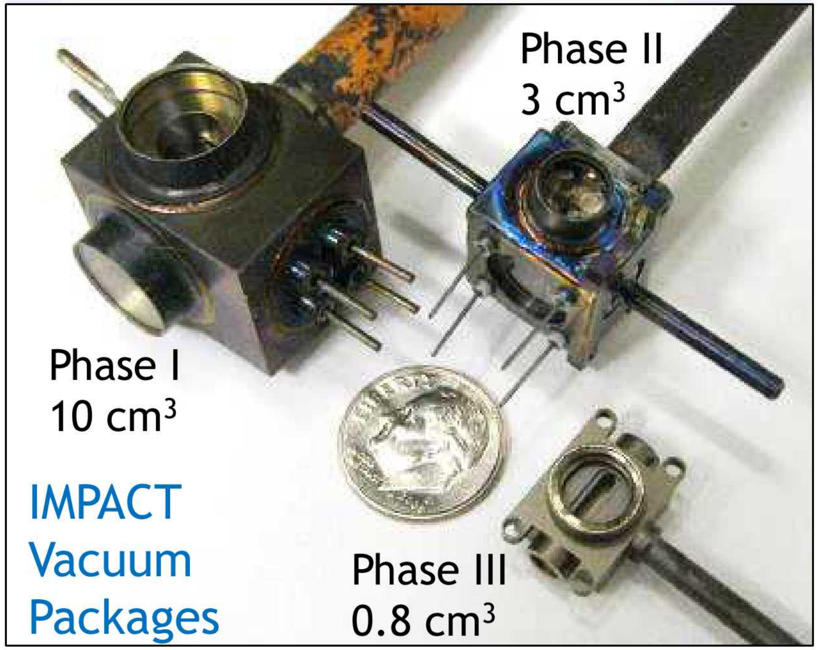
## Microwave Optical Double Resonance Clock Operation (Continuous Mode)

- Lasers and microwaves are on for continuous feedback
  - Fast attack time for use with degraded local oscillators
- Elimination of optical shutter
- Challenges: Signal to noise, bandwidth, light shift

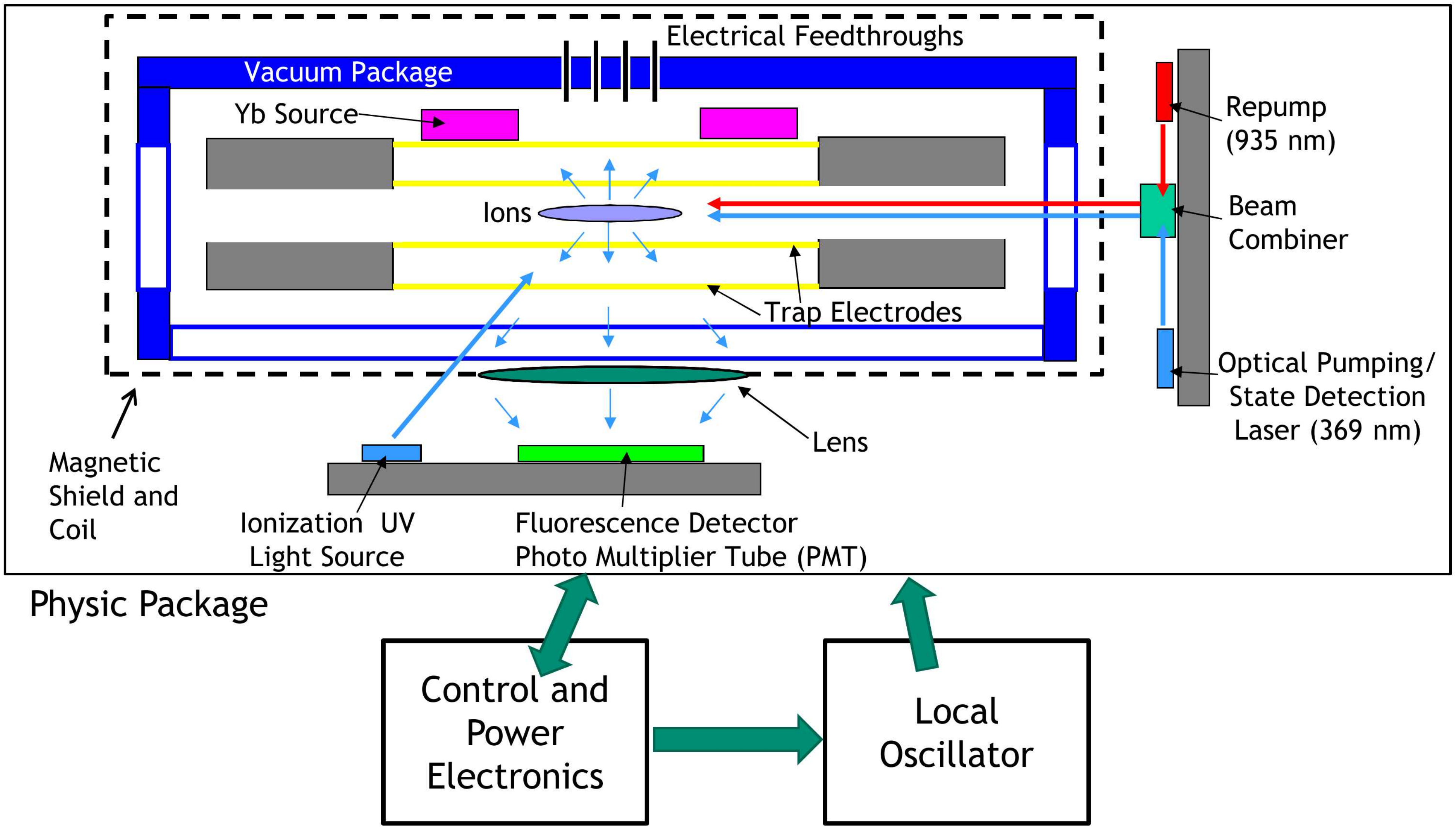
## Technology

- Passively pumped vacuum package
  - Challenges: F-state and $Yb\text{-}H^+$ trapping
- Optical pumping and detection VCSEL at 369 nm
  - Very challenging: Will be a first ever demonstration
- Low power, low phase noise microwave synthesis

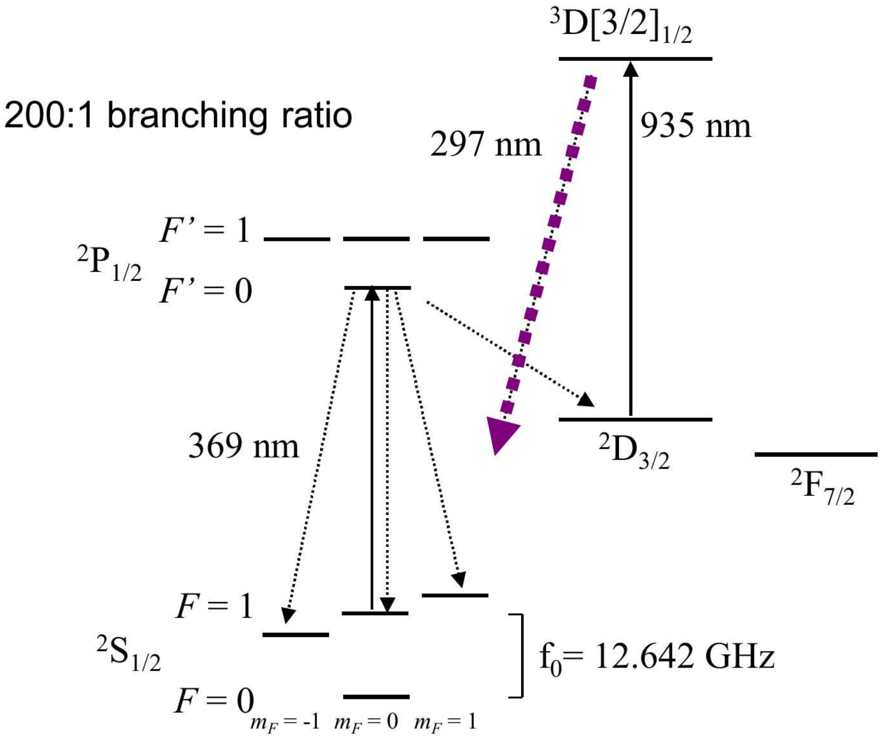




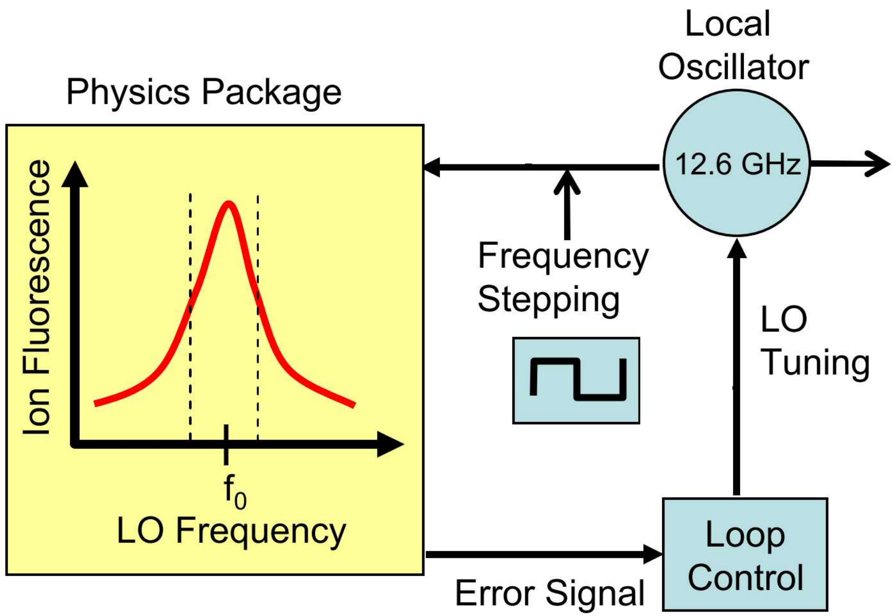
# Critical Elements of the $^{171}Yb^{+}$ Ion Clock

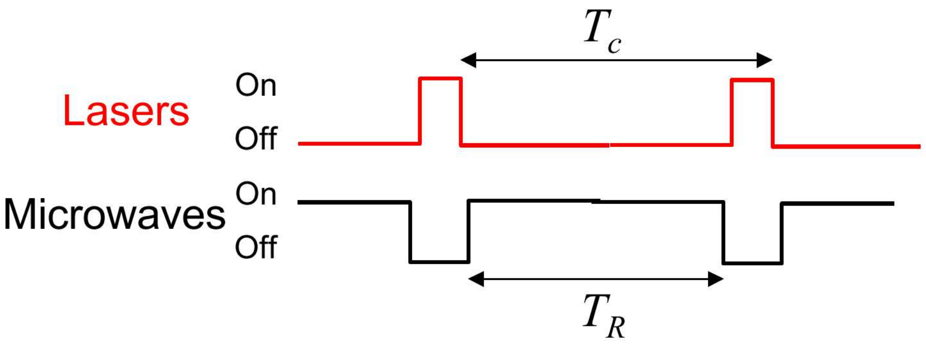


# Pulsed Mode $^{171}Yb^+$ Ion Clock



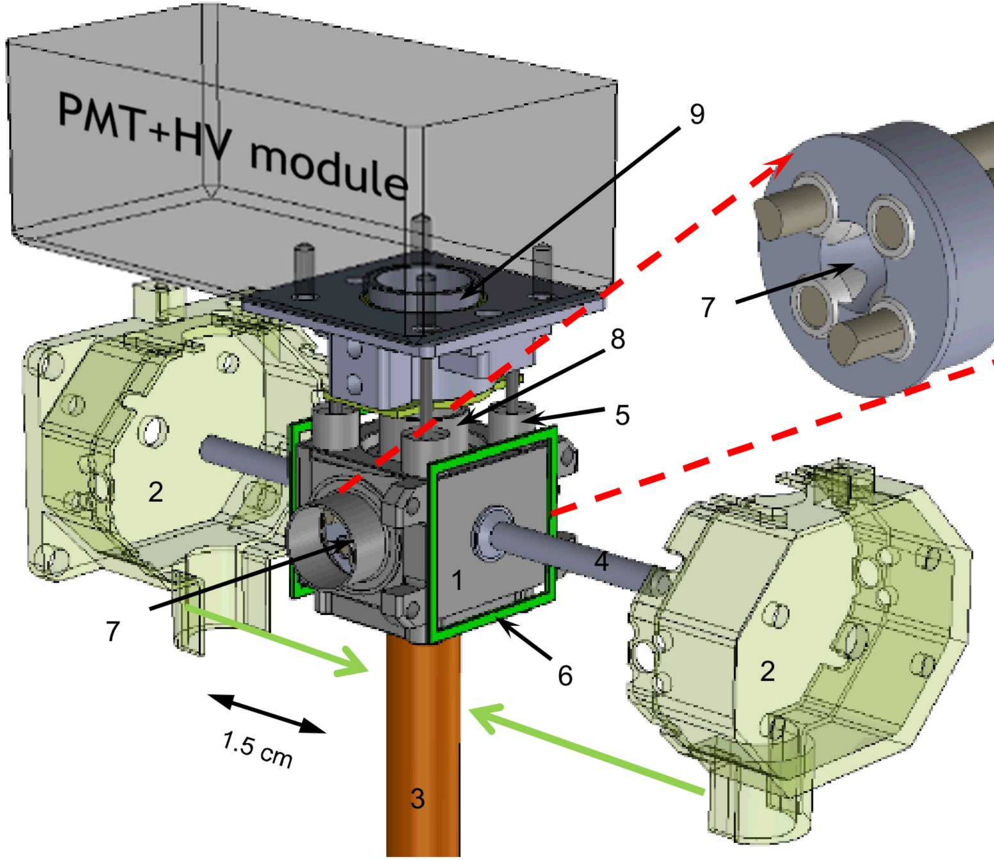

Photons/ion
369 nm: 300 – 500
297 nm: 1.5 – 2.5

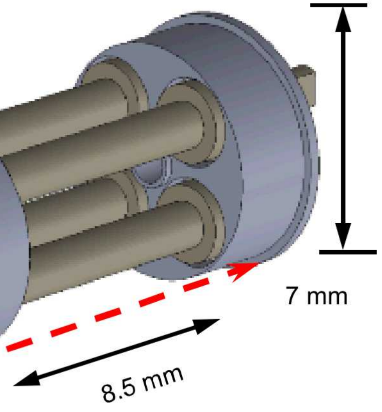


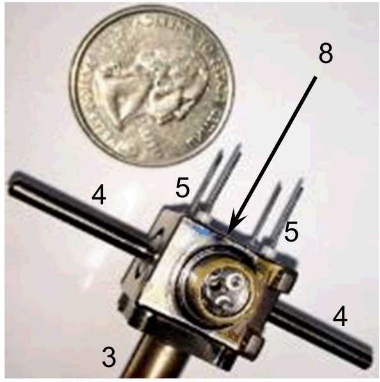



# 3 $cm^3$ Vacuum Package and Ion Trap

**Vacuum package w/ Detector** **Ion-trap electrodes**




1. Vacuum package
2. μ-metal shield
3. Copper pump-out tube
4. Yb oven appendage
5. Electrical feedthroughs
6. C-field coils
7. Laser port (sapphire)
8. Fluorescence collection window (sapphire)
9. Lens and filters tube

Jet Propulsion Laboratory
California Institute of Technology

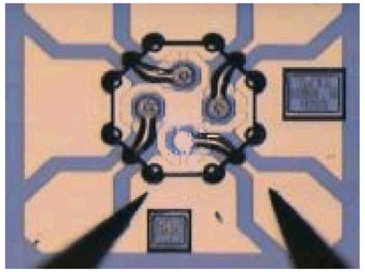
- Nan Yu
- John Prestage
- James Kellogg

- **Titanium body with sapphire windows.**
- **Linear Quadrupole RF Paul Trap**
- **Pinched off since April 25th, 2012**

- **Buffer gas cooling with He**
- **Getter Pumped.**
- **Trapped ion lifetime > 3 weeks.**

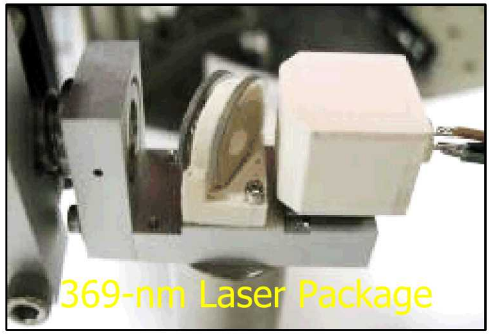
# Complete Physics Package (circa 2013)

Sandia
935nm VCSEL

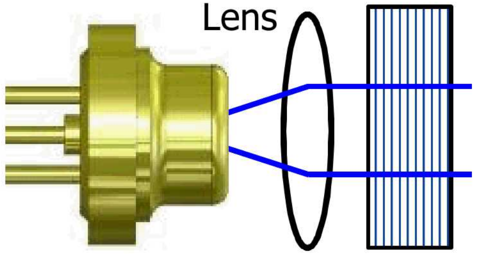


Integrated Optics

Physics Package Interface

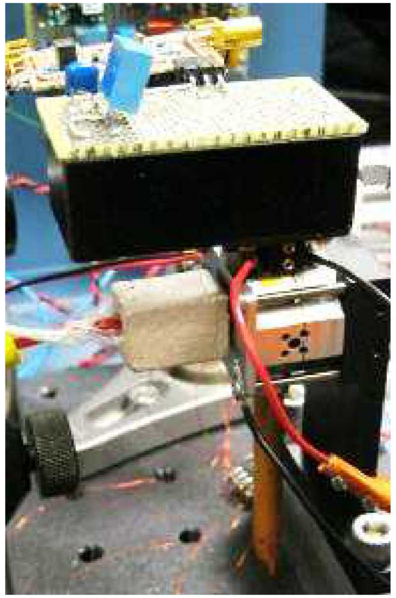


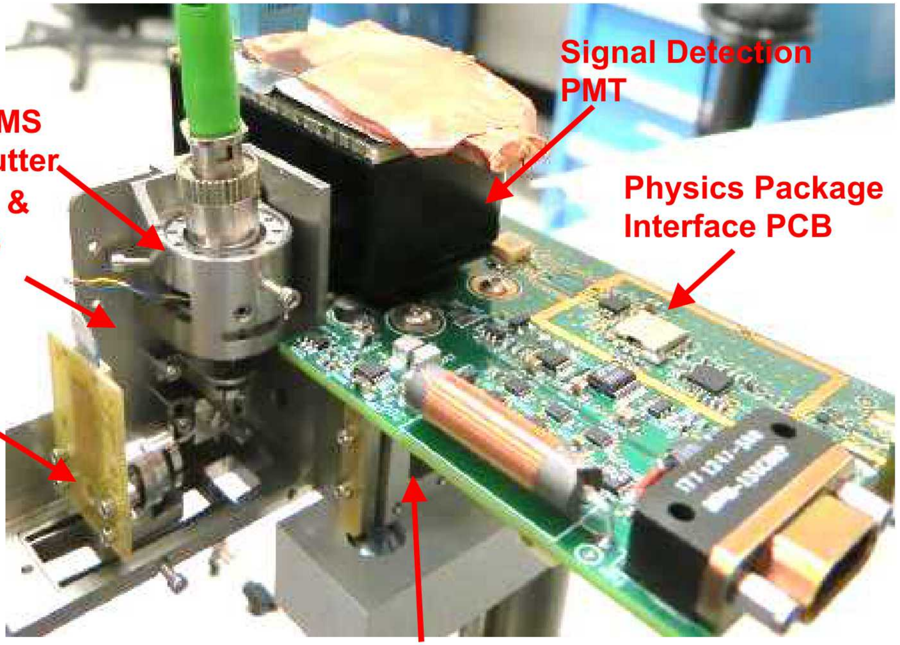

Ondax
369 nm ECDL



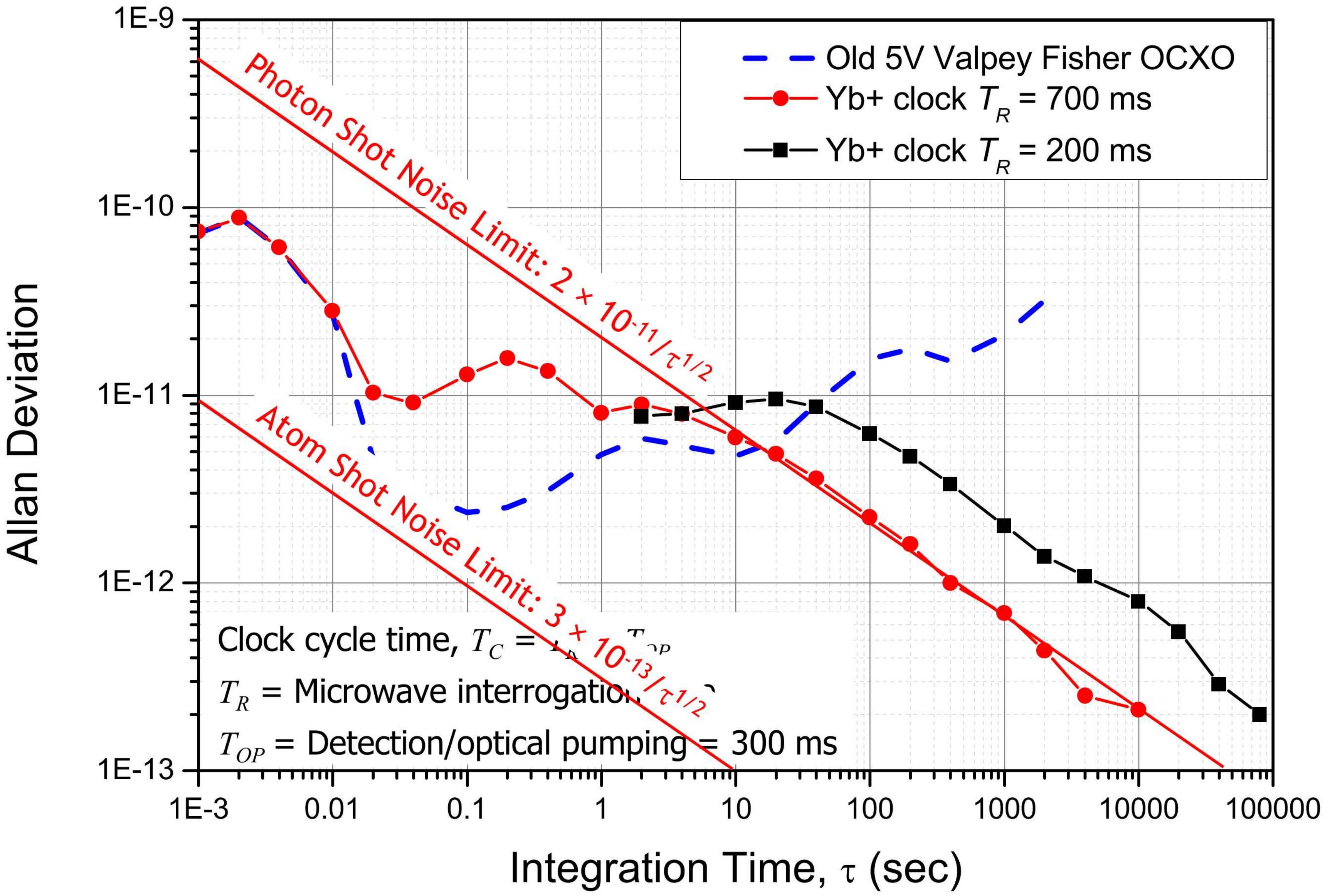

Preciseley
MEMS Shutter

Vacuum Package

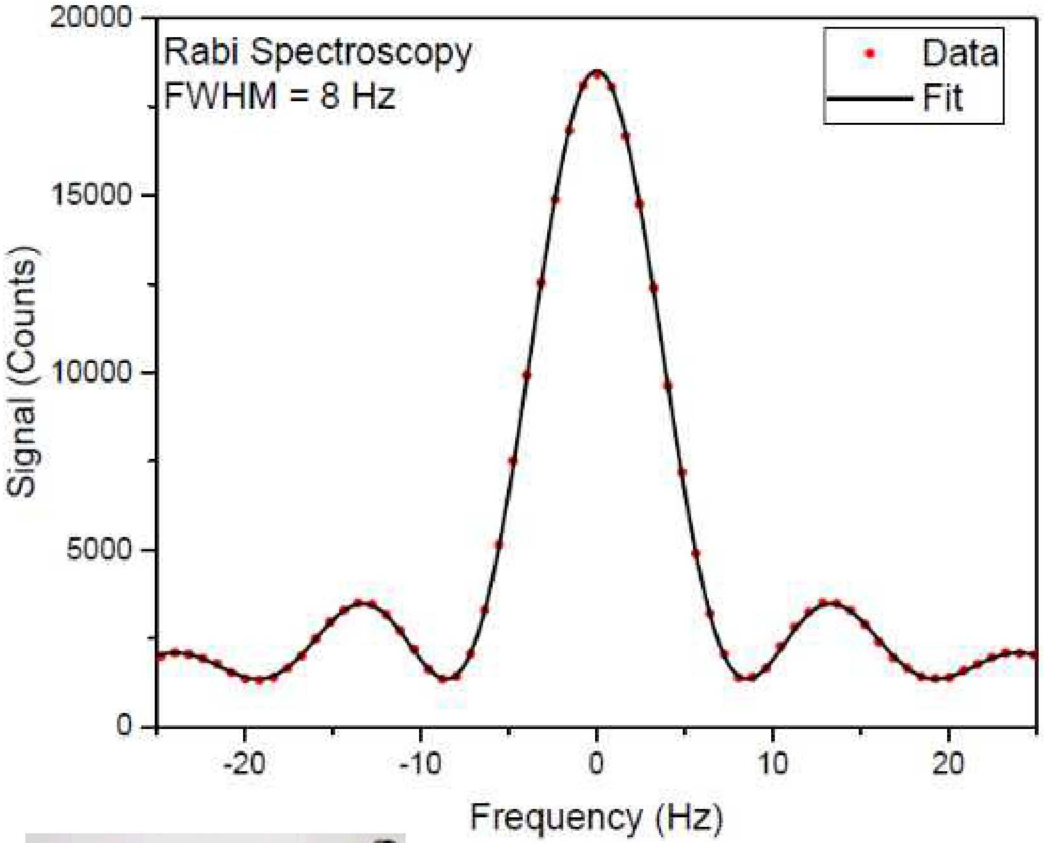


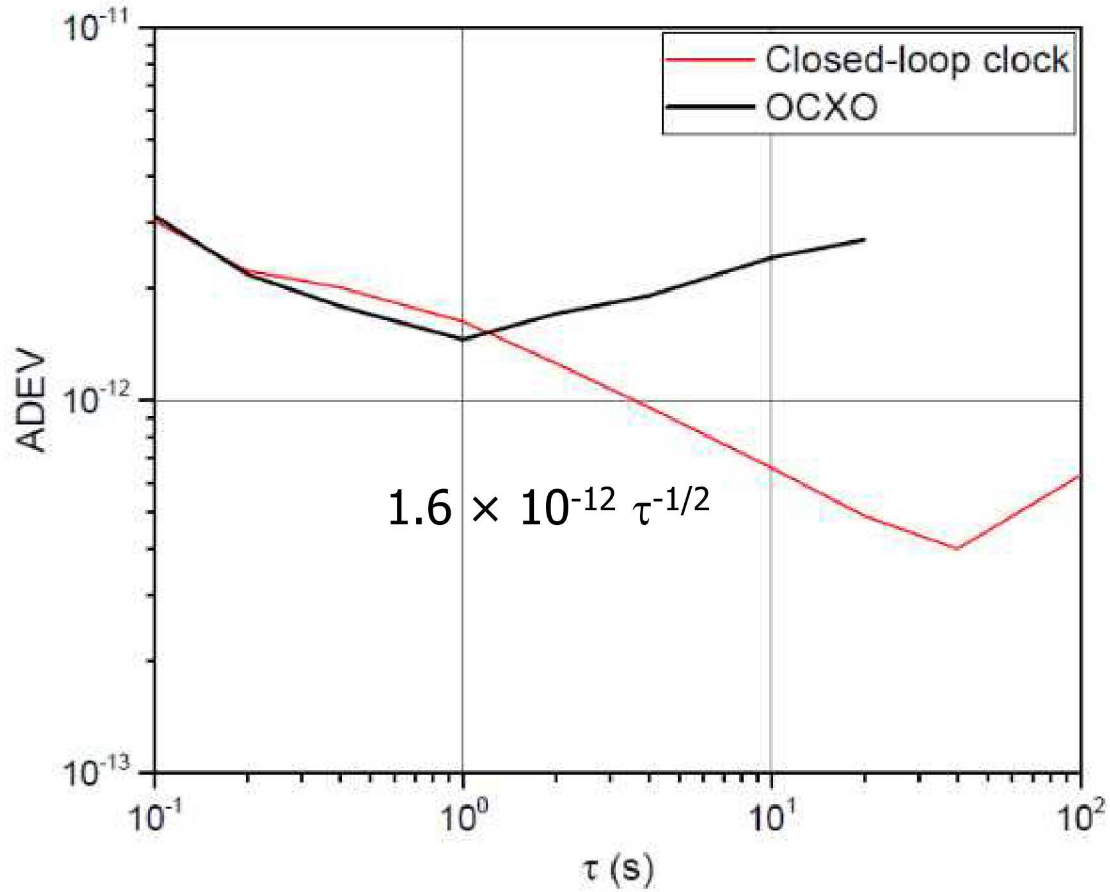


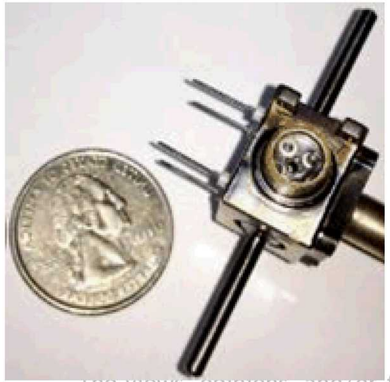
# Integrated Clock Performance: Pulsed Mode, 297 nm Fluorescence



# $^{171}Yb^{+}$ Ion Clock Performance: Pulsed Mode, 369 nm Fluorescence



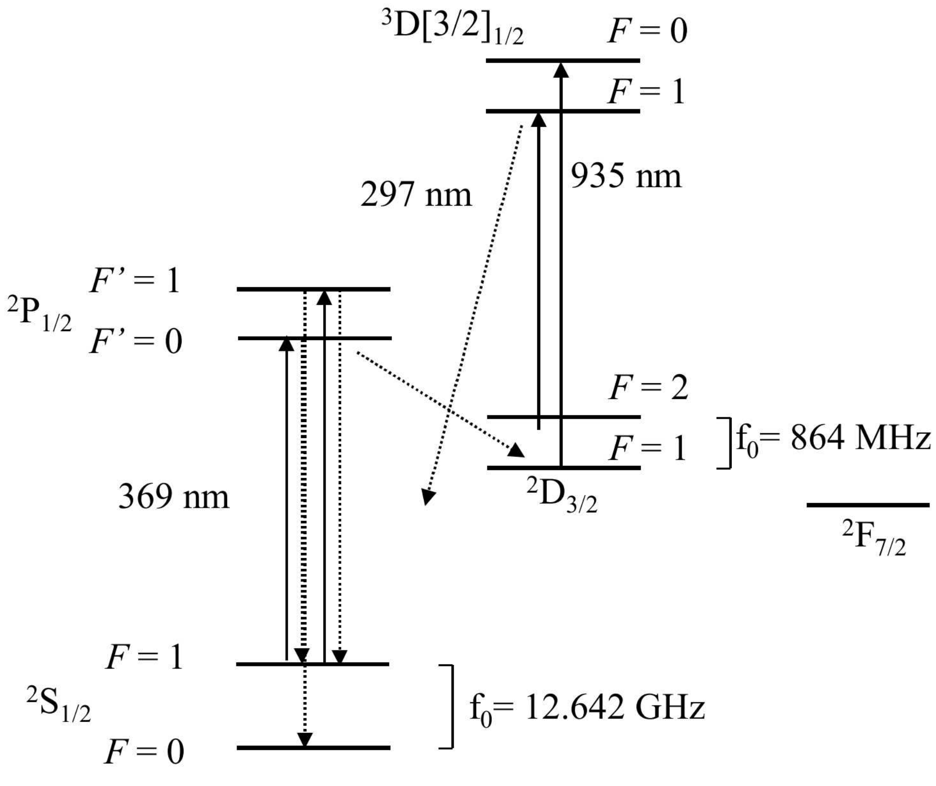
- Table top laser and vacuum system
- Clock cycle time, $T_C = T_R + T_{OP}$
- $T_R$ = 100 ms, $T_{OP}$ = 35 ms

D. R. Scherer et al., "Analysis of Short-Term Stability of Miniature $^{171}Yb^{+}$ Buffer Gas Cooled Trapped Ion Clock," arXiv:1802.04832, 2018.

Microsemi

David Scherer

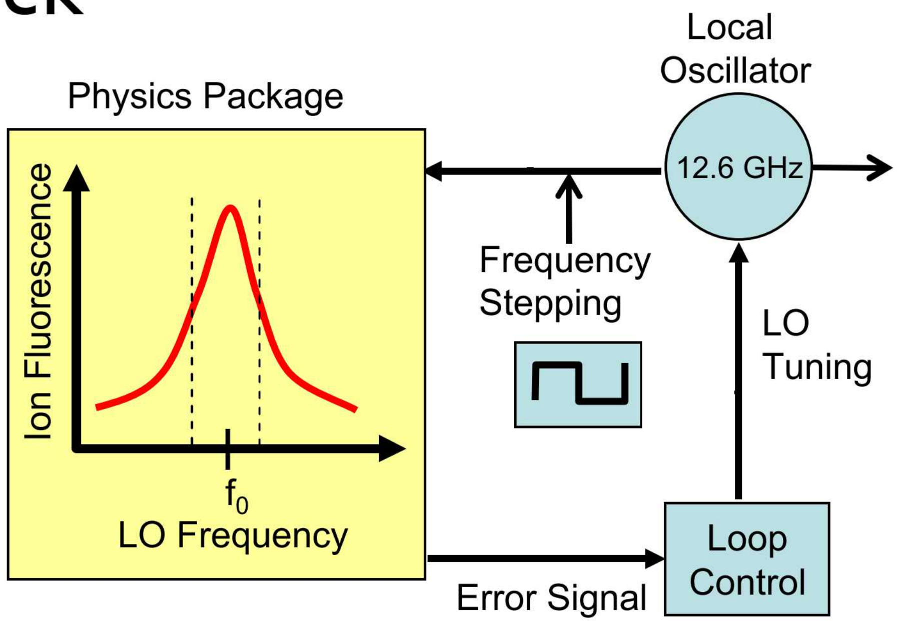
# Continuous Mode $^{171}Yb^+$ Ion Clock




Photons/ion

$F = 1 \rightarrow F' = 0$: $\alpha$ = 300 - 500

$F = 1 \rightarrow F' = 1$: $\alpha$ = 3




- Optical and microwave power broadening determine linewidth

$$FWHM = \frac{1}{\pi}\sqrt{\frac{\alpha}{2}\Omega^2 + \left(\frac{R_{369}}{2}\right)^2}$$

- $R_{369}$: optical pumping rate. $\Omega$: microwave Rabi frequency.
- Clock interrogation time set by the FWHM and optical pumping time

$$T_{OP} = \frac{\alpha}{\pi\ FWHM}$$

# Continuous Mode Optimization

Calculate stability at 1 s

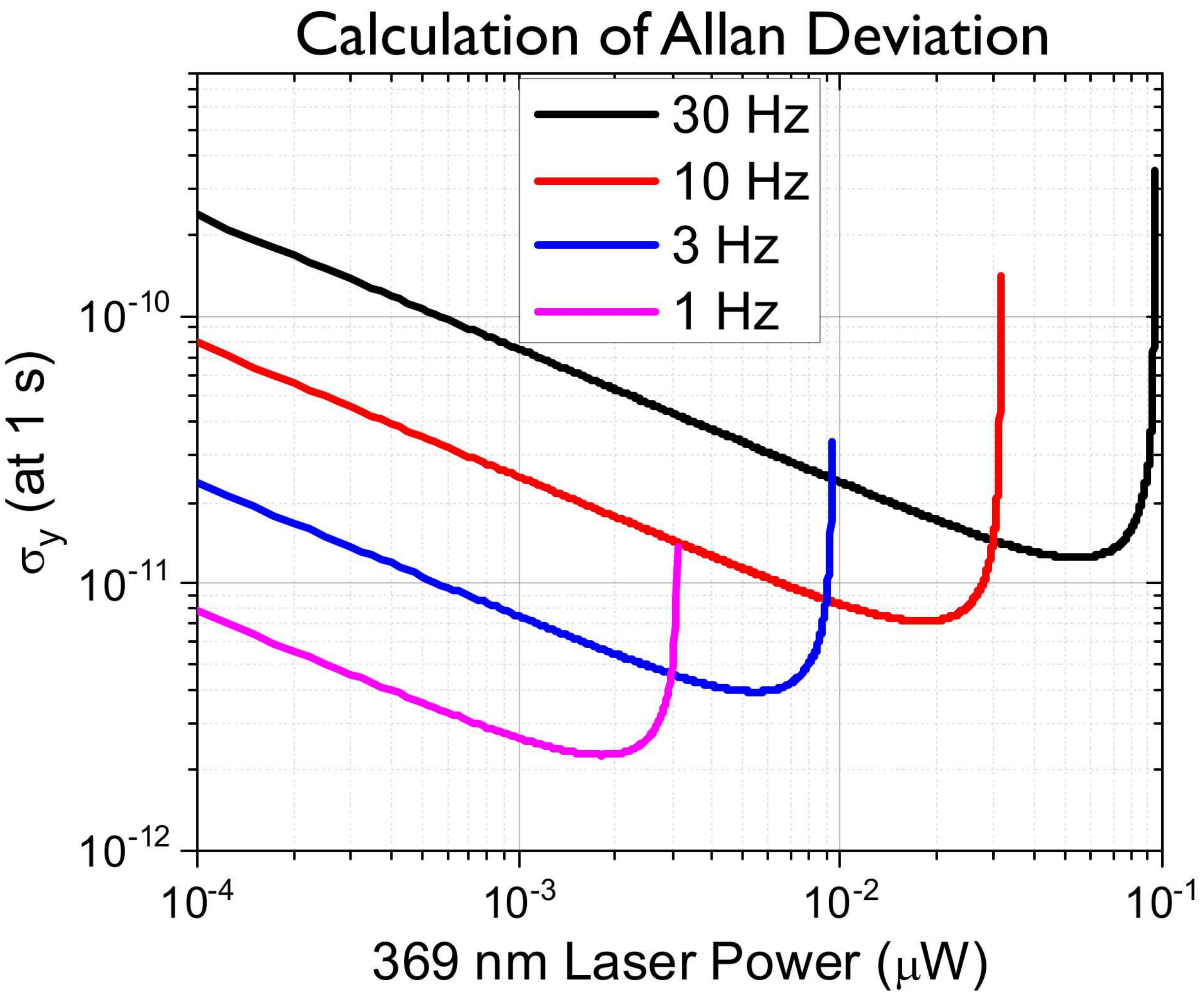
- $$\sigma_y = \frac{1}{Q \cdot SNR}$$
- Assume photon shot noise and fixed FWHM
- $$FWHM = \frac{1}{\pi}\sqrt{\frac{\alpha}{2}\Omega^2 + \left(\frac{R_{369}}{2}\right)^2}$$

Broad linewidth

- Fast attack time for locking local oscillator and lasers

Narrow linewidth

- Better stability
- Smaller light shift



# Light Shift Characterization of the Clock Transition

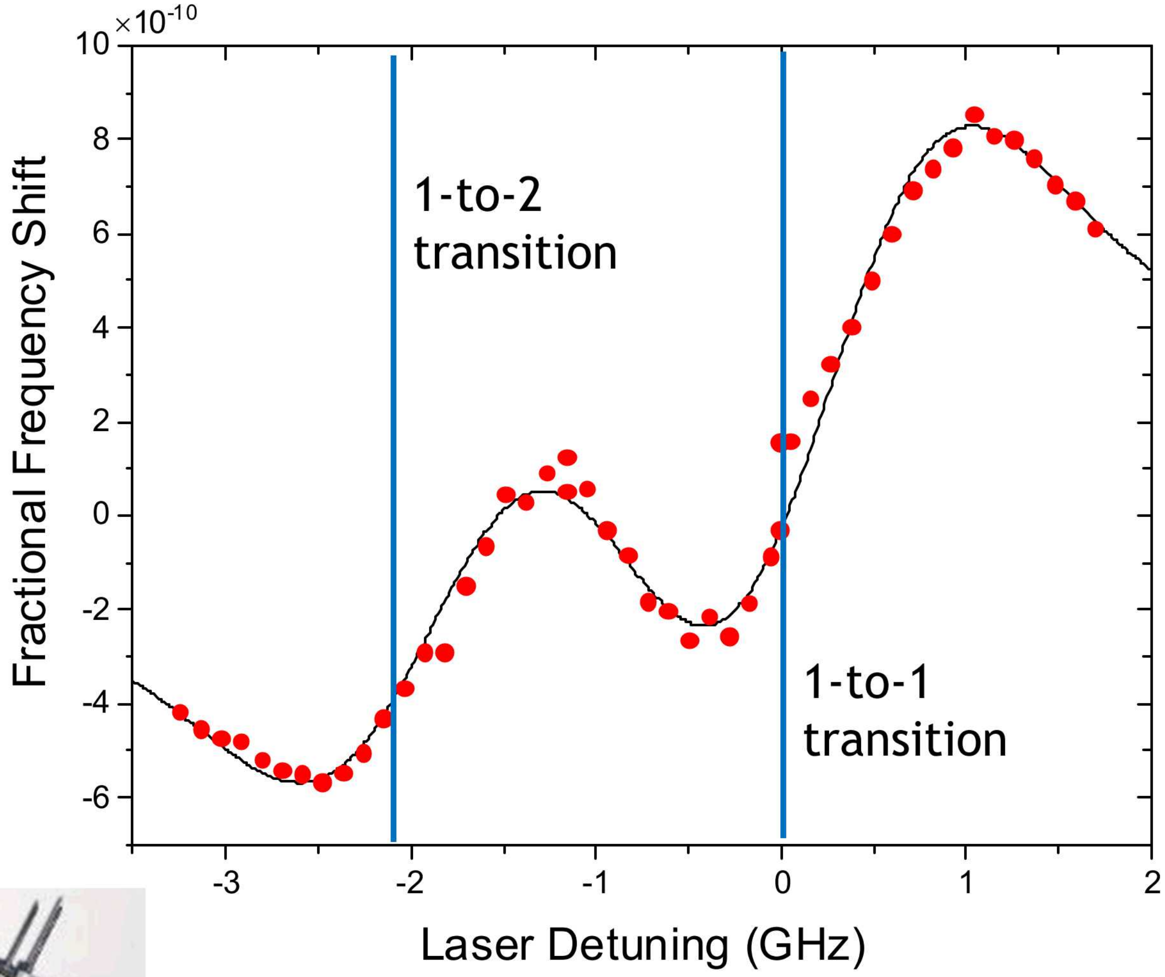
Tabletop lasers and electronics with sealed 3 $cm^3$ vacuum package

Experimentally measure the light shift

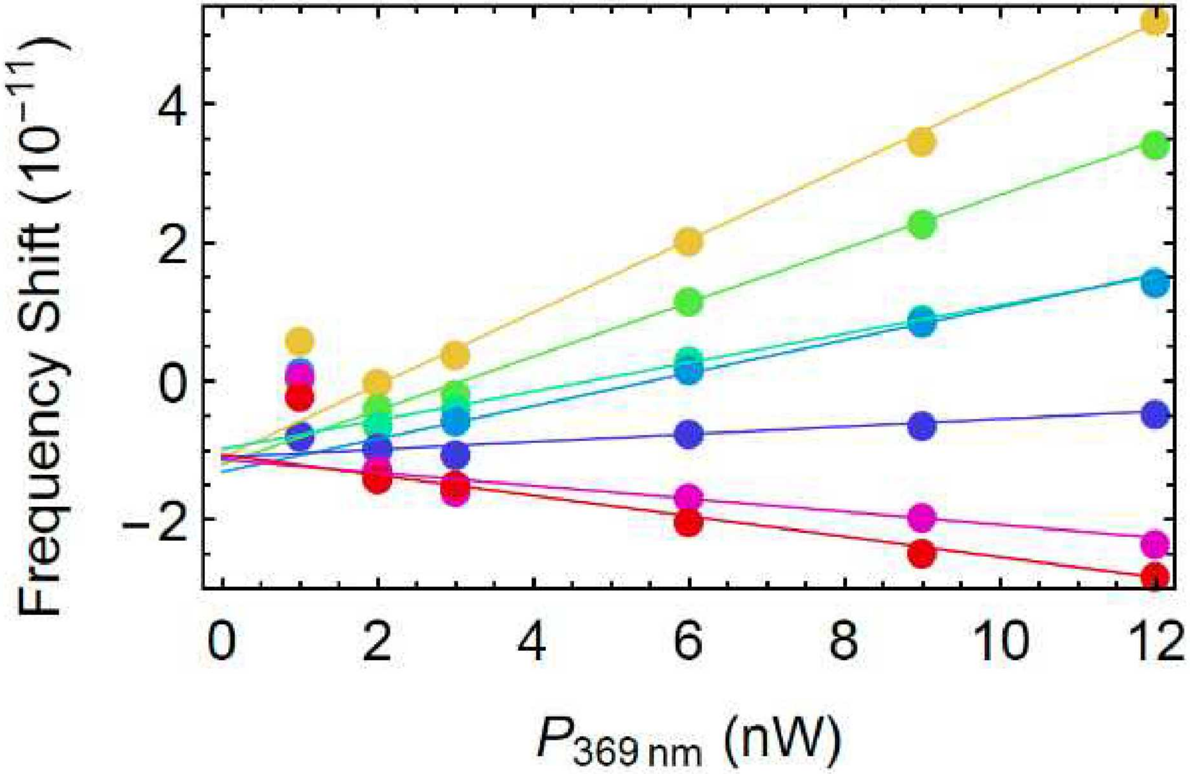
- FWHM = 30 Hz, $P_{369}$ = 220 nW
- Ion temperature = 1140 K

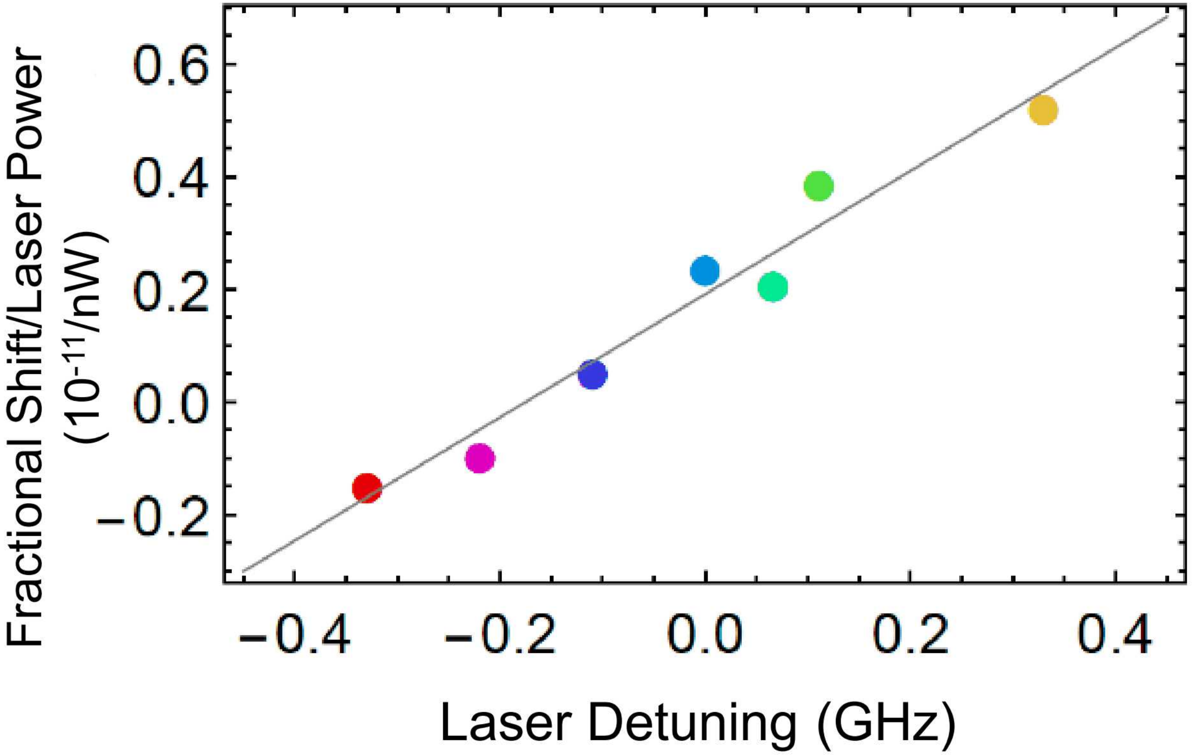
Calculation of the AC Stark Shift

- Include 369-nm laser intensity, detuning, and polarization and ion temperature
- Assume FWHM = 30 Hz
- Manually adjust frequency shift and detuning offsets and ion temperature
  - Ion temp = 1050 K




# Light Shift Sensitivity

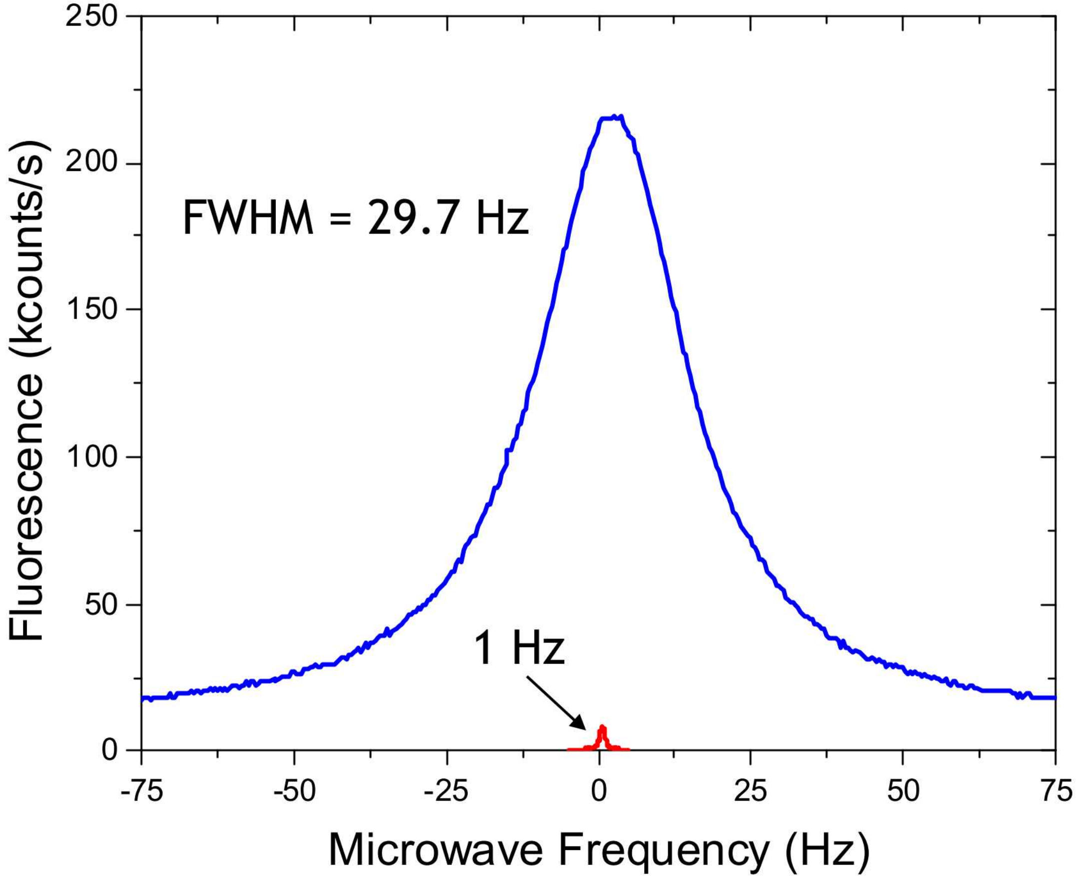


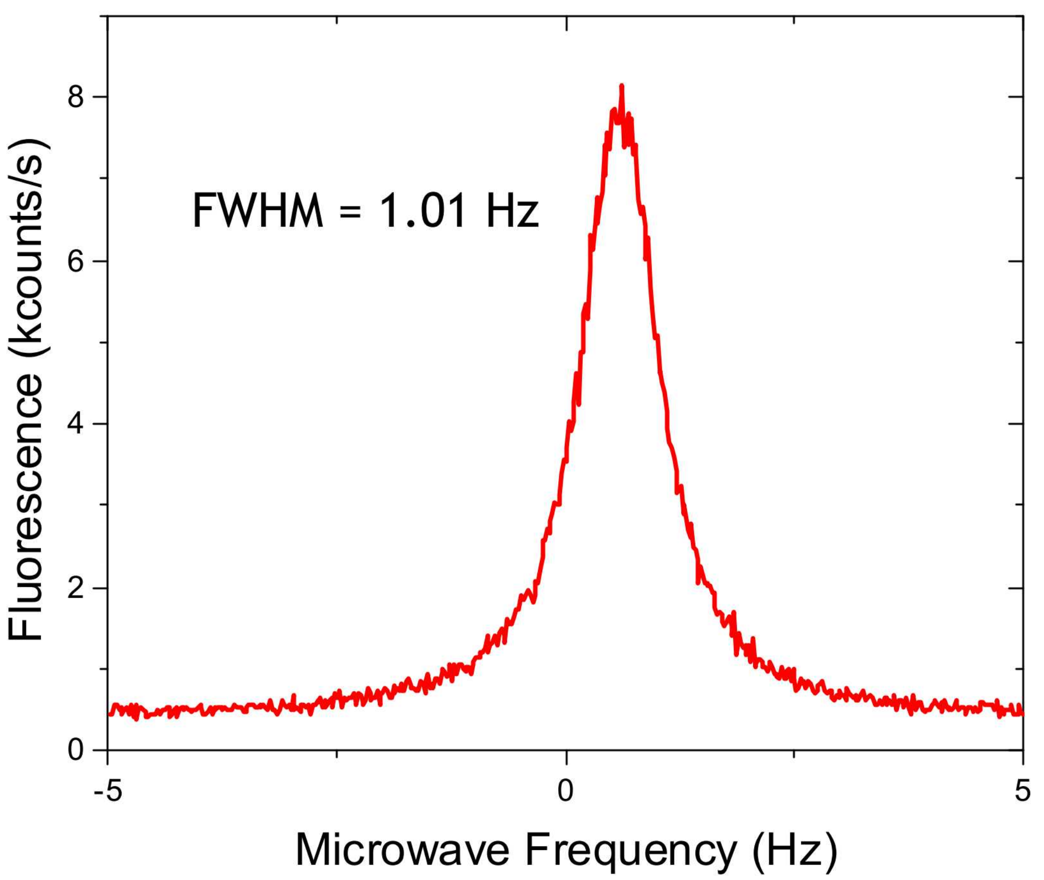




Light shift coefficient = $1.09 \times 10^{-11}$/(GHz nW)

- 1 Hz: 4.5 MHz laser stability for $\sigma_y = 10^{-13}$
- 30 Hz: 0.15 MHz laser stability for $\sigma_y = 10^{-13}$

# Clock Linewidth Measurements



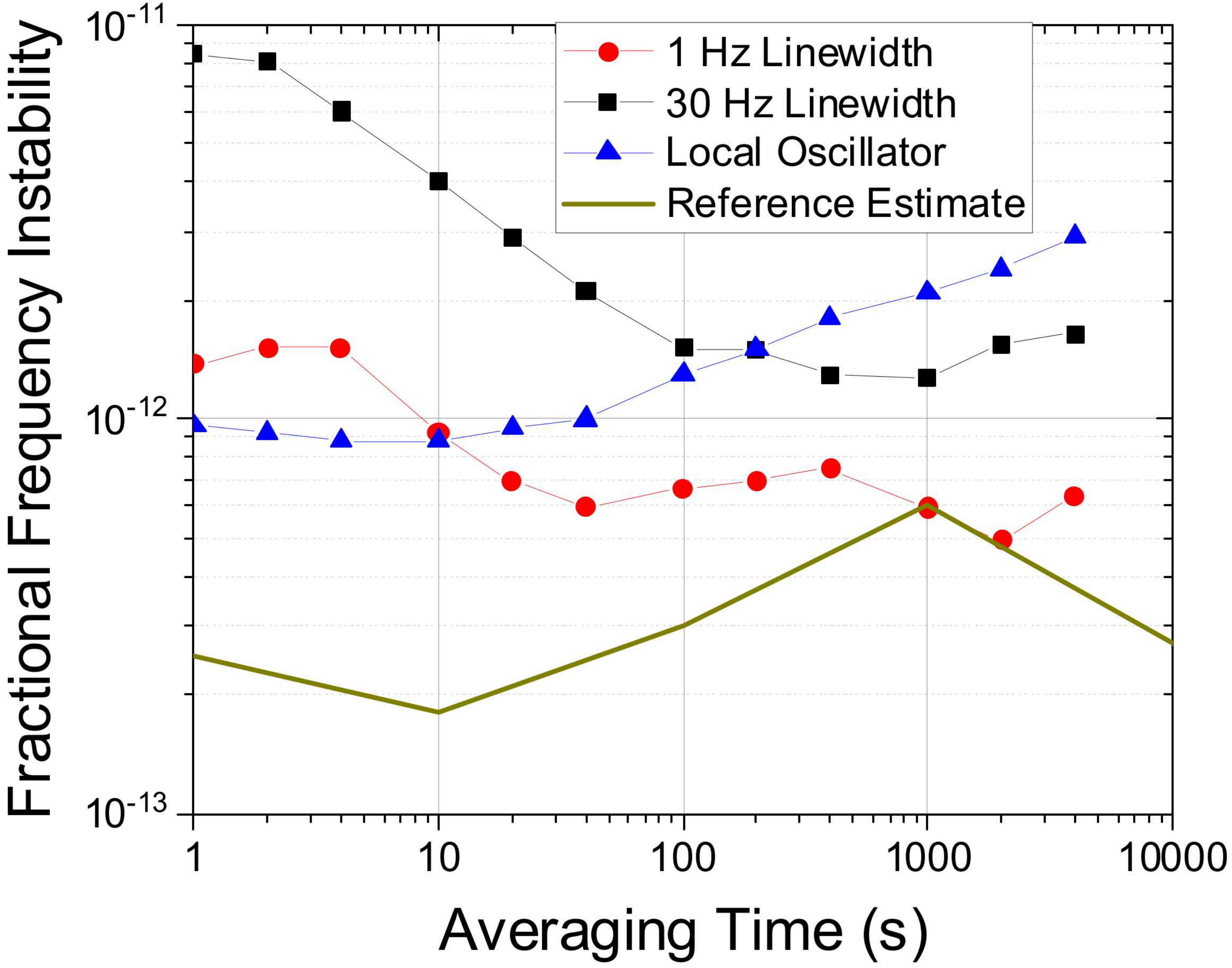
# Continuous-Mode Clock Stability

## Short-term stability

- 30 Hz: $1.3 \times 10^{-11}/\tau^{1/2}$
- 1 Hz: $3 \times 10^{-12}/\tau^{1/2}$

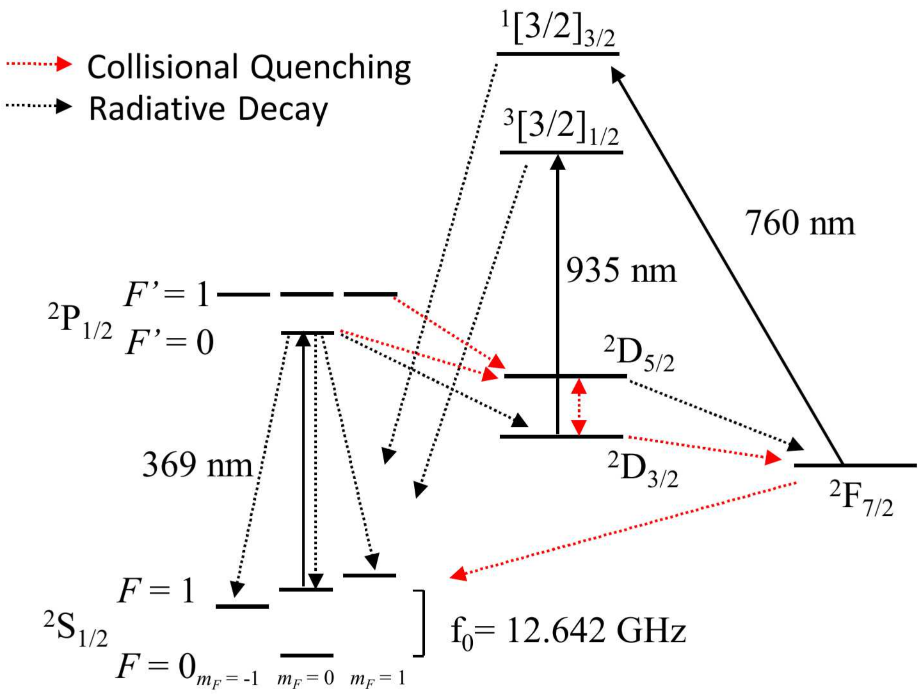
## Long-term stability

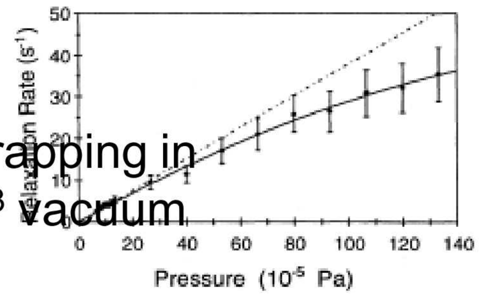
- 30 Hz: light-shift limited
- 1 Hz: reference limited



# F-State Trapping Problem

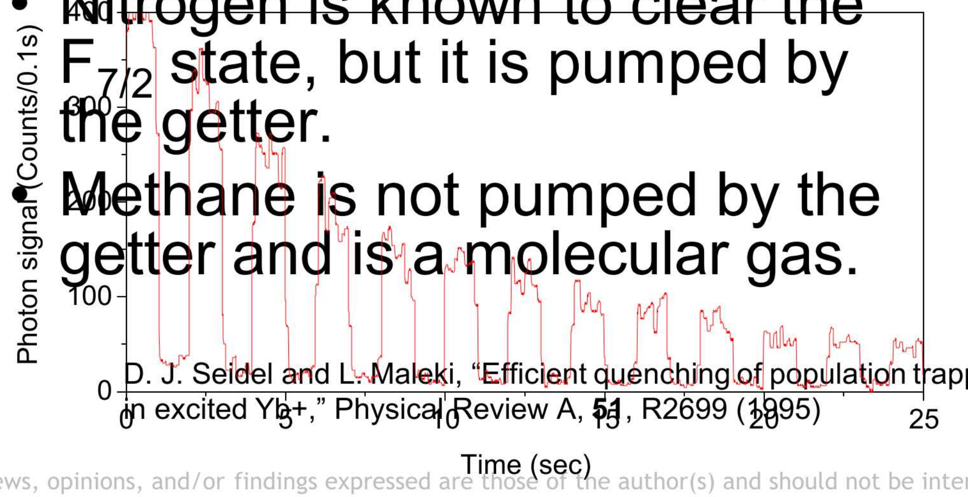
- Collisions of Yb ions in the $P_{1/2}$ and $D_{3/2}$ states with He will transfer Yb ions into the $F_{7/2}$ state.
- Noble gasses do not quench the $F_{7/2}$ state.
- Lasers at 760 nm, 638 nm, or 864 nm will clear the F-state.
  - Another laser is too complicated.
- Nitrogen is known to clear the $F_{7/2}$ state, but it is pumped by the getter.
- Methane is not pumped by the getter and is a molecular gas.




F-State trapping in the 3 cm$^3$ vacuum package.

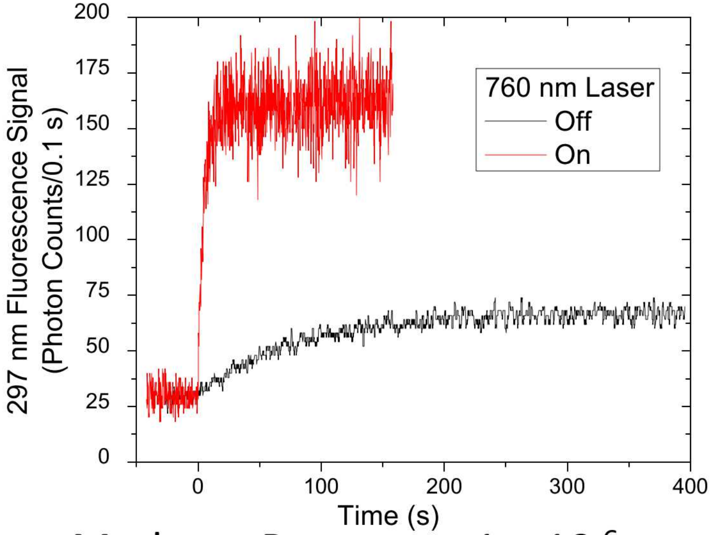
FIG. 3. Quenching rate of ytterbium's trap state vs $N_2$ buffer-gas pressure. The curved line represents a least-squares fit of the data to the polynomial $\Gamma_{31} = aP + bP^2$; $a = 3.63 \pm 0.12 \times 10^4$/s Pa and $b = -7.45 \pm 1.15 \times 10^6$/s Pa$^2$, while the straight line represents a linear least-squares fit to pressures $\leq 26.6 \times 10^{-5}$ Pa.



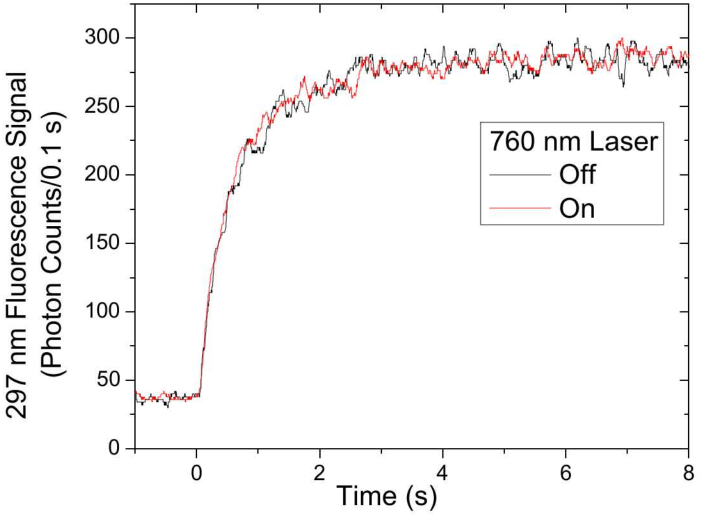

D. J. Seidel and L. Maleki, "Efficient quenching of population trapping in excited Yb+," Physical Review A, 51, R2699 (1995)

# Testing Methane as a Quenching Gas

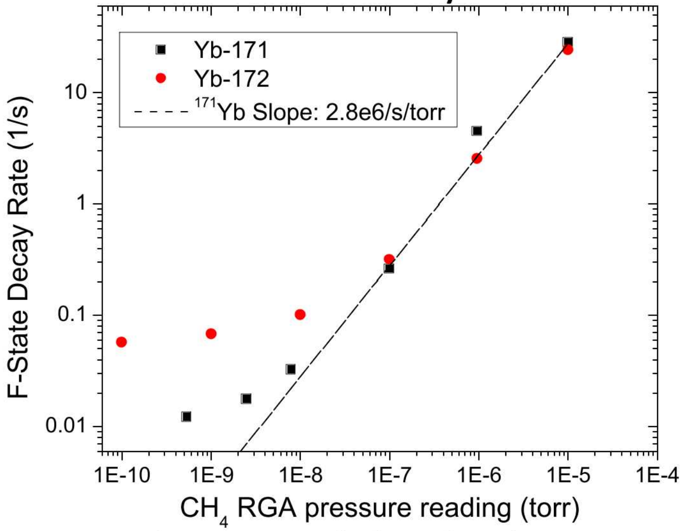
Methane Pressure = $5.3 \times 10^{-10}$



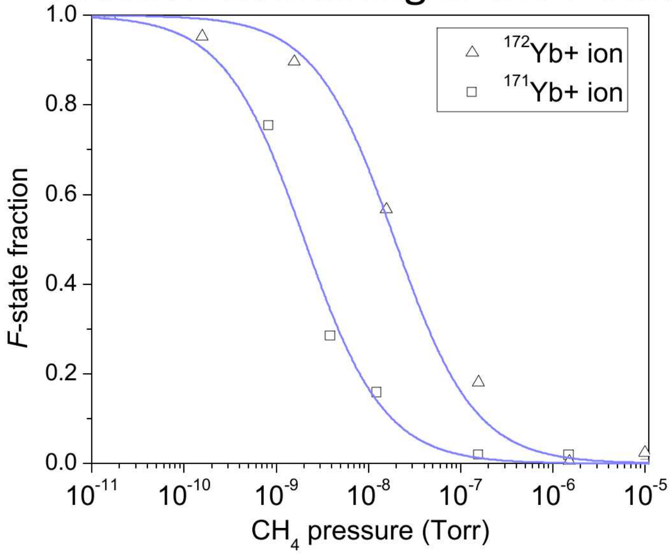

Methane Pressure = $1 \times 10^{-6}$




F-State Decay Rate




Fraction Remaining in the F-State



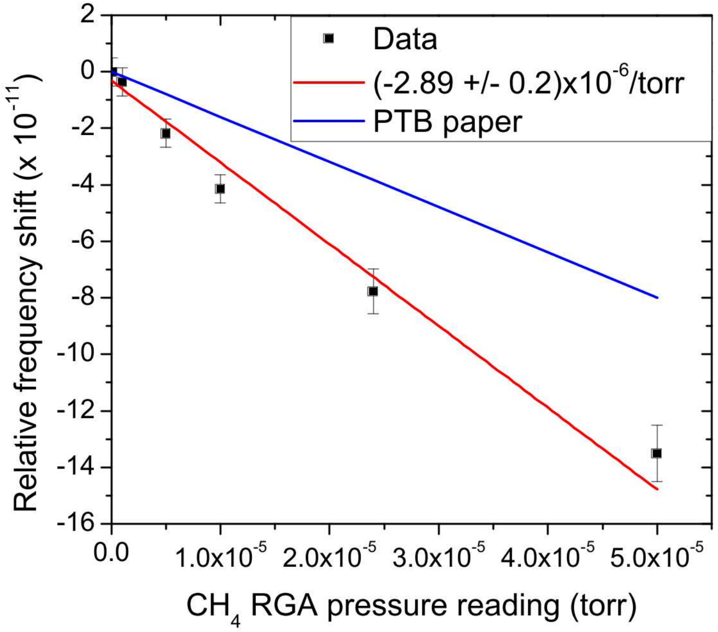

Jau, Y-Y., J. D. Hunker, and P. D. D. Schwindt. "F-state quenching with CH4 for buffer-gas cooled 171Y b+ frequency standard." *AIP Advances* 5.11 (2015): 117209.

# Effects of Methane on the Clock State

- Estimated methane pressure required for F-State quenching in $^{171}$Yb
  - $10^{-8}$ to $10^{-7}$ Torr
- F-state Fraction
  - < 20%

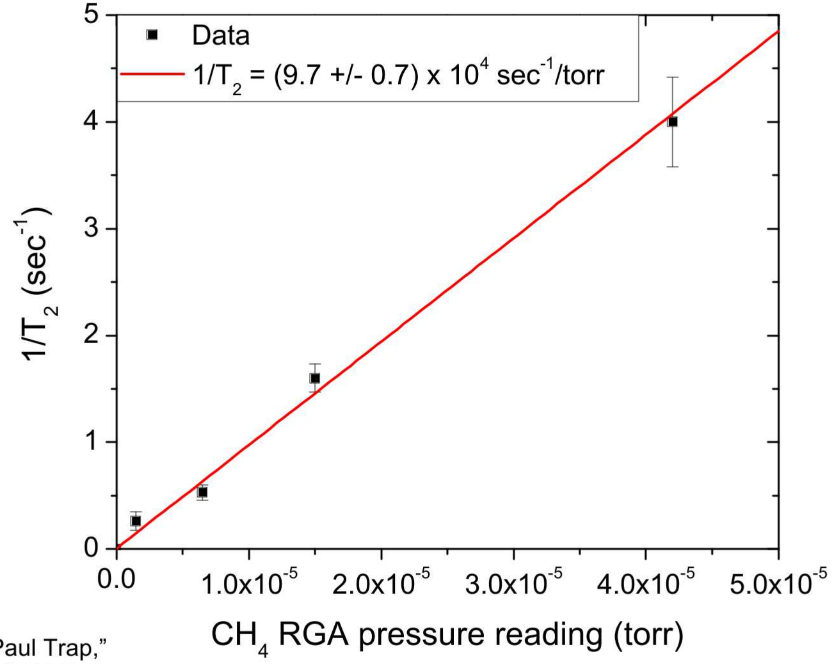
- Effects on the $^{171}$Yb ground state
  - Frequency shift due to collisions
    - $10^{-14}$ to $10^{-13}$
  - Relaxation and decoherence of $^{171}$Yb ground state due to collisions
    - $T_2$ = 1000 to 100 s

Frequency Pulling of Methane




A. Bauch, D. Schnier, and C. Tamm, "Microwave Spectroscopy of 171 Yb+ Stored in a Paul Trap," Proceedings of the 5th Symposium on Frequency Standards and Metrology, pp. 387–388, 1995.

Decoherence Rate in $^{171}$Yb Ground State

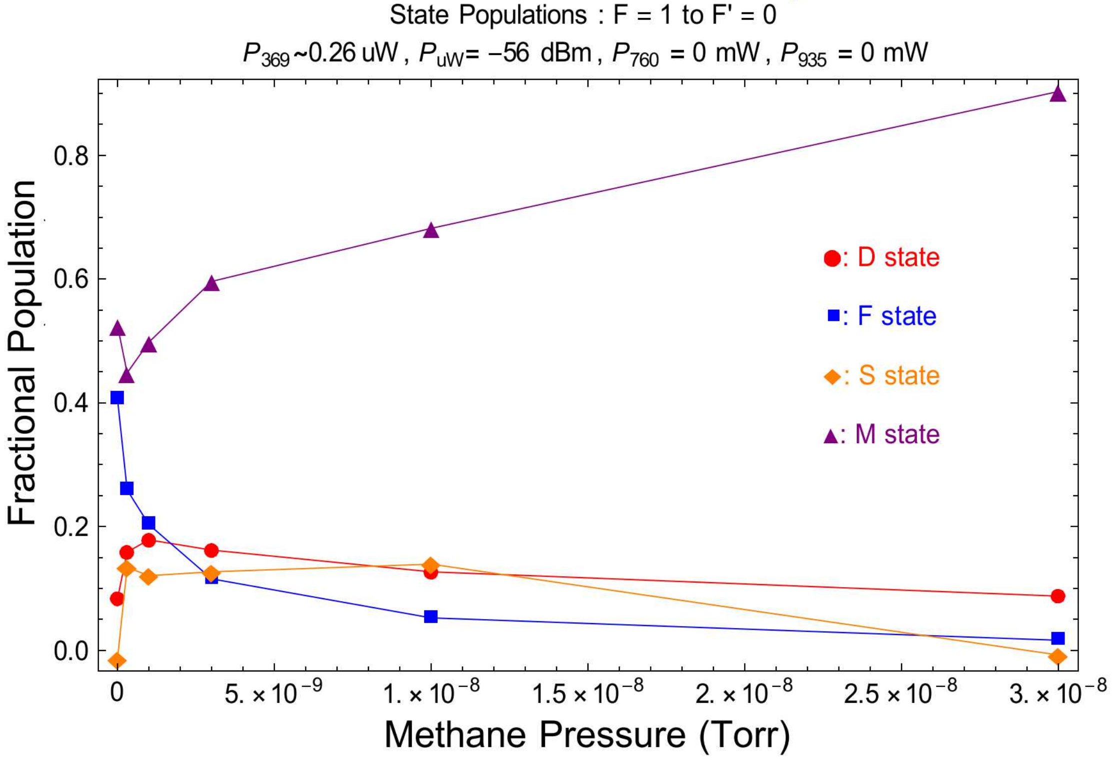


# Evidence for $YbH^+$

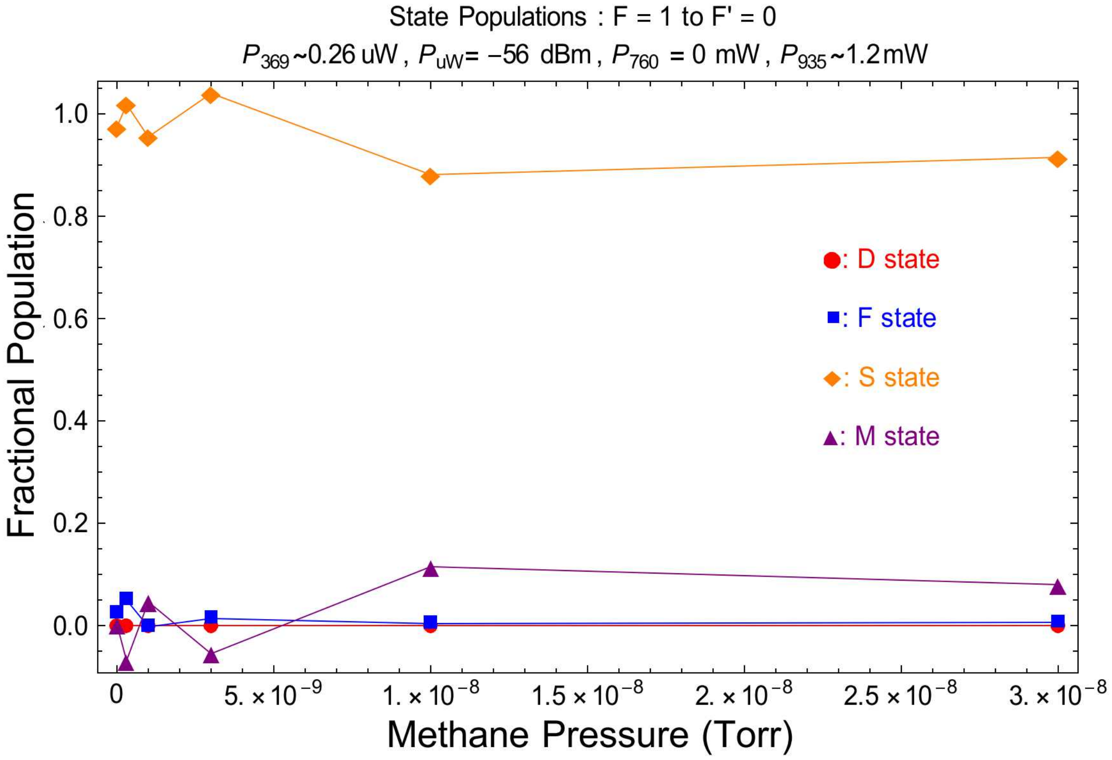
- Implement Continuous Mode clock
- Observe evidence for formation of $YbH^+$ molecule
- Increasing methane pressure gives more $YbH^+$

- Molecule formed out of the $D_{3/2}$ state
- Tuned to a $YbH^+$ dissociation transition at 369.482 nm and observe rapid signal recovery

## 369 nm Laser Only




## 369 nm and 935 nm Lasers



# Study of Packages Sealed since 2012

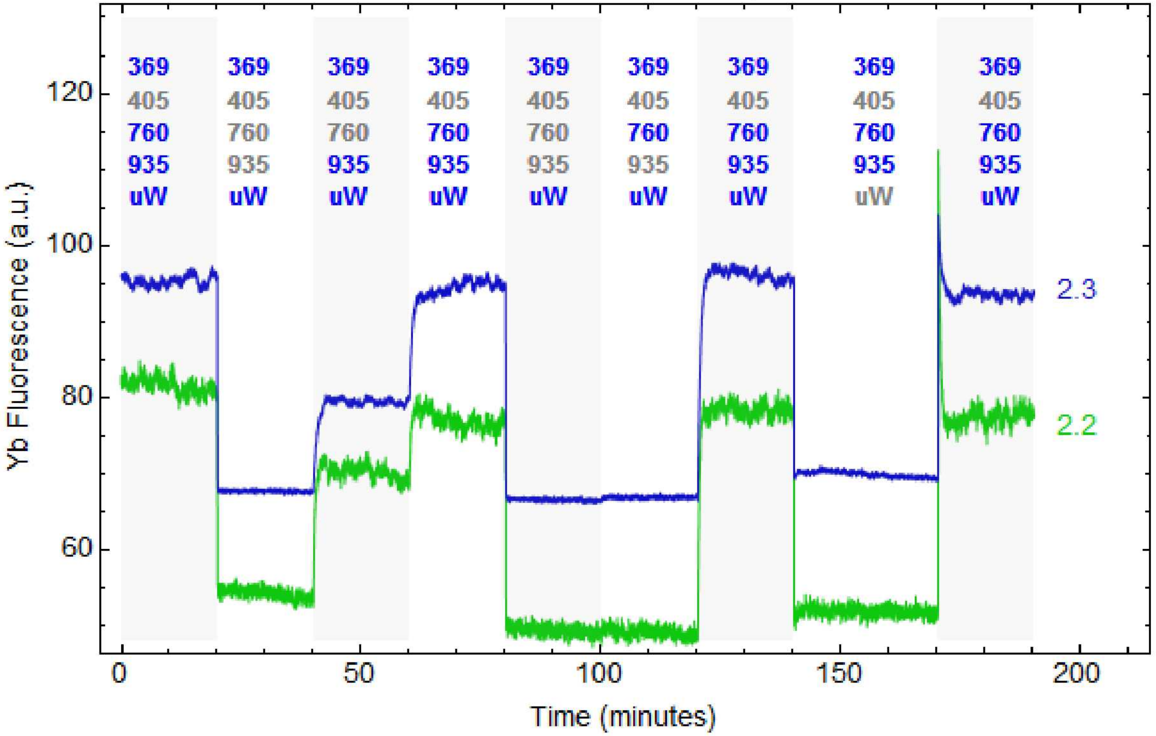

- IMPACT JPL Vacuum packages:
  - F-state and molecular state trapping present in both packages
- Continuous-Mode operation seems to suppress the trapped population likely due to low photon scattering rates

Populations with 935 nm Laser on

| Package | S-State | F-State | $YbH^+$ |
|---|---|---|---|
| JPL 2.2 | 31% | 13% | 56% |
| JPL 2.3 | 33% | 43% | 24% |

Pulsed-Mode Clock

369 nm laser: F = 1 → F' = 1, 10 μW

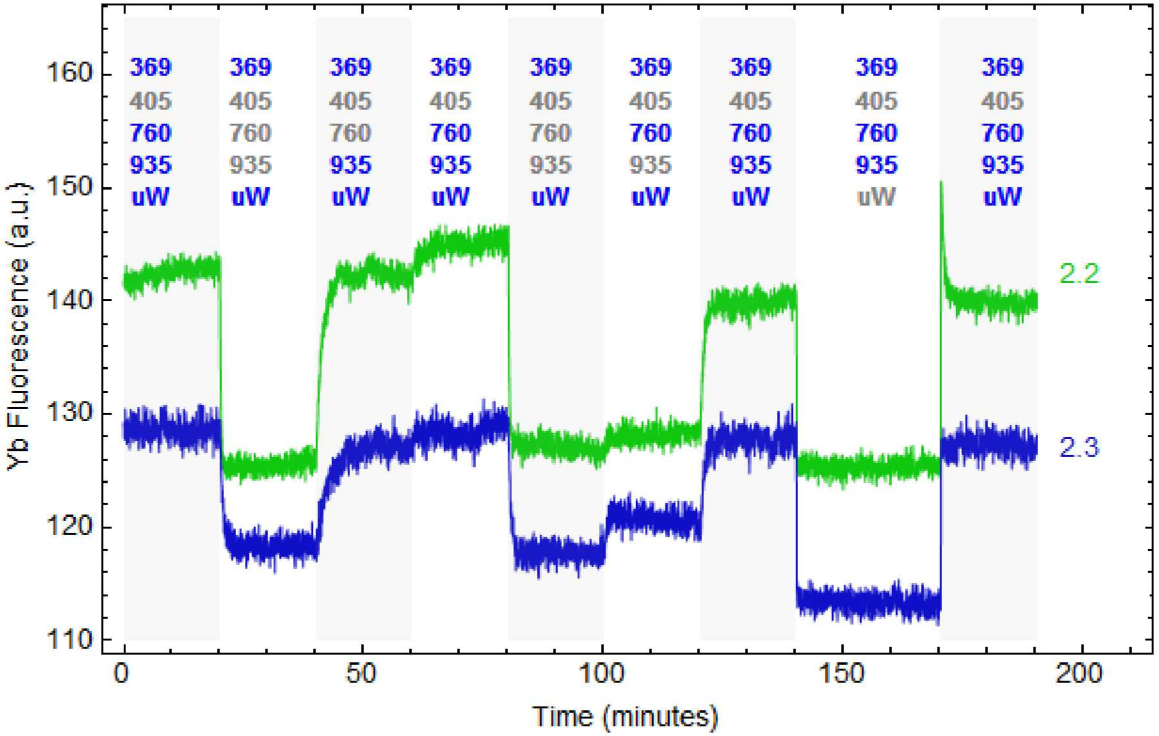



Populations with 935 nm Laser on

| Package | S-State | F-State | $YbH^+$ |
|---|---|---|---|
| JPL 2.2 | 57% | 9% | 34% |
| JPL 2.3 | 96% | 4% | 0% |

Continuous-Mode Clock

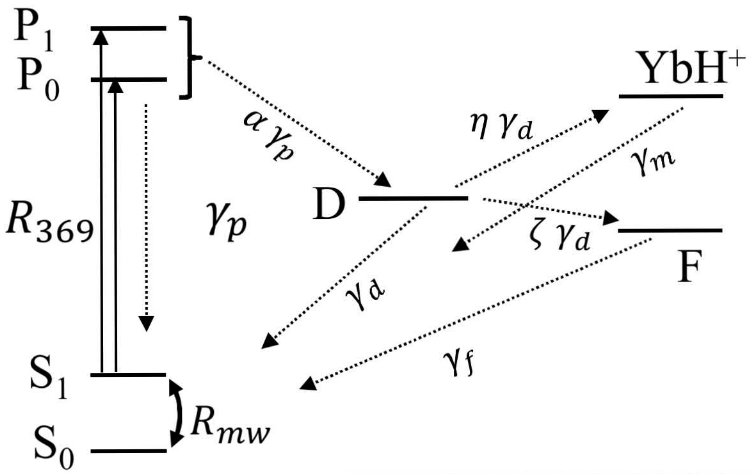
369 nm laser: F = 1 → F' = 1, 0.6/1.0 μW

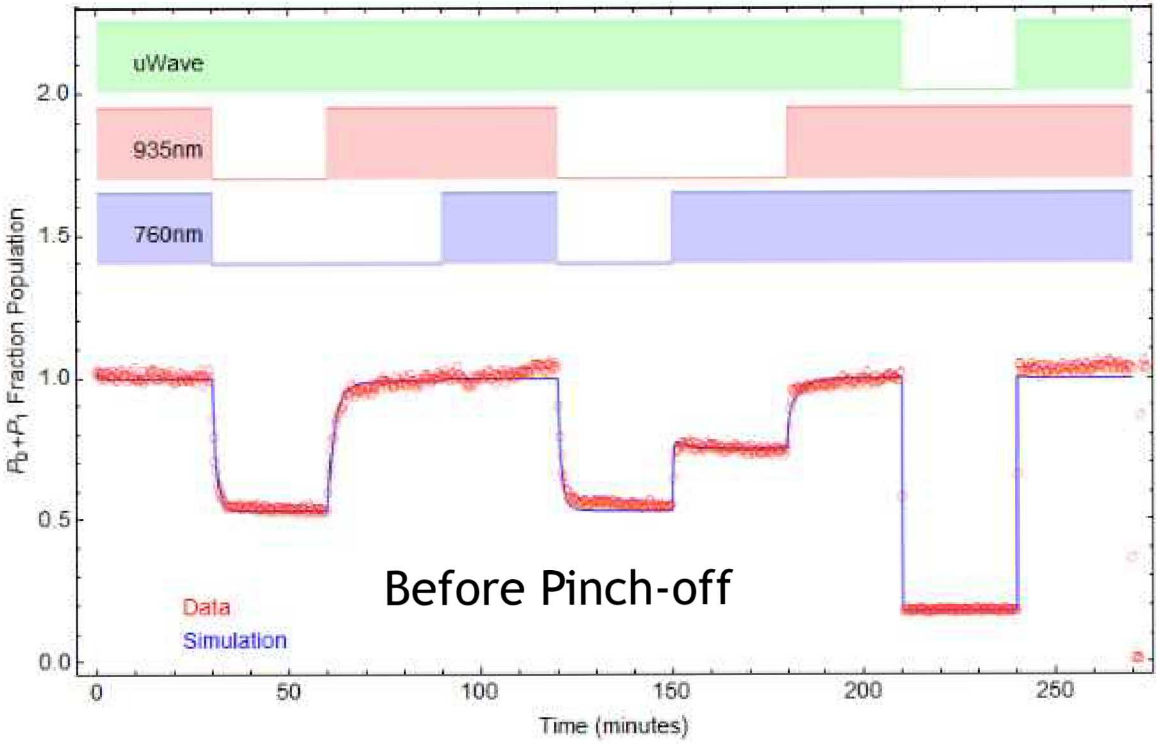


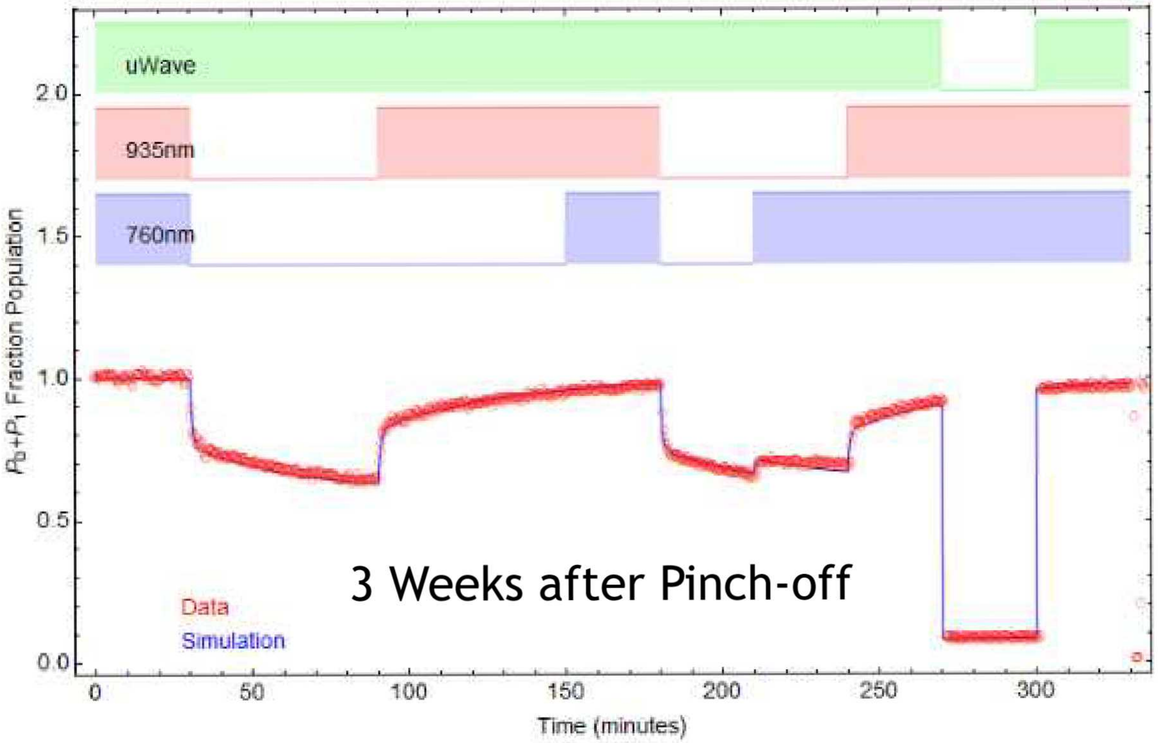
# Determining Rates (Preliminary Data)

Study rates into and out of the F-State and the $YbH^+$ molecule

Observe changes over time in a seals package

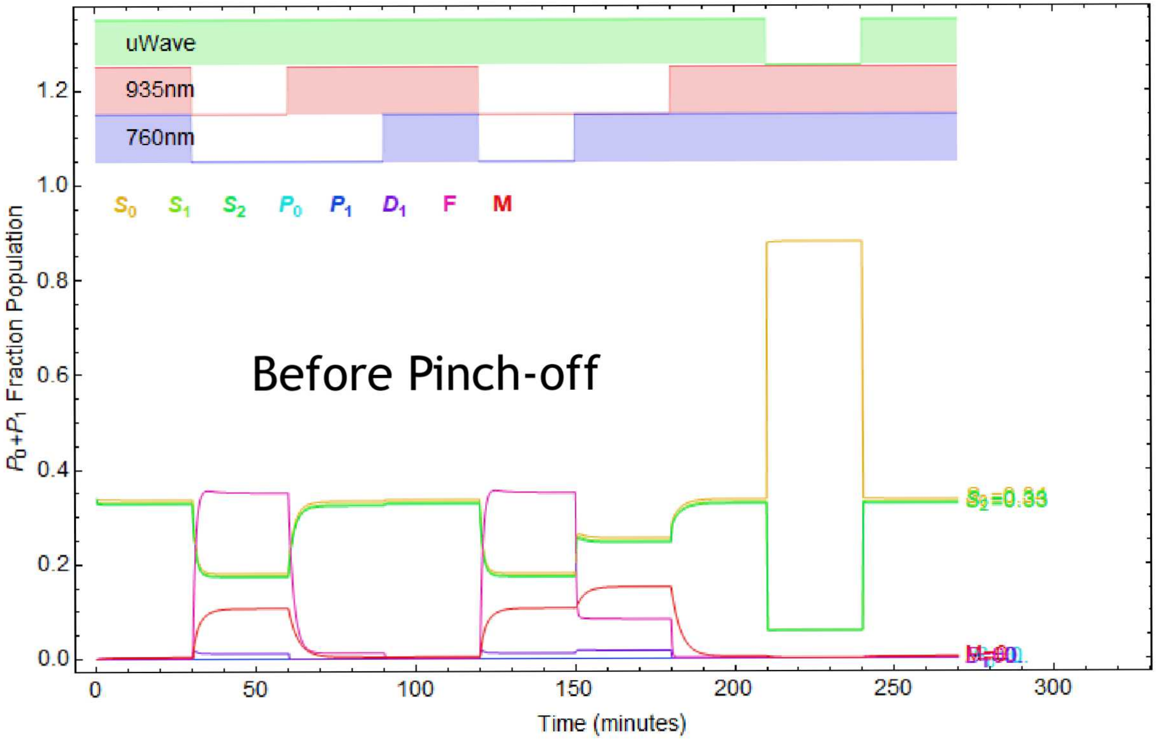


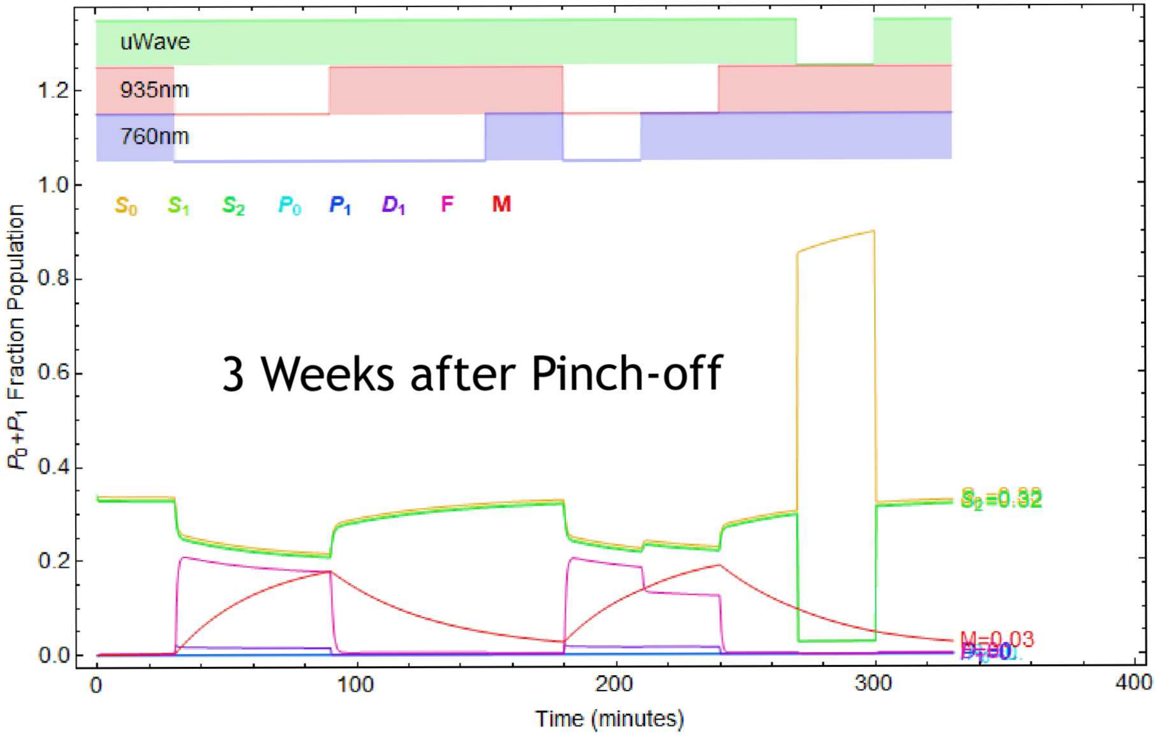



# Estimating the State Populations from the Model

More F-state trapping before pinch-off




More YbH+ trapping after pinch-off

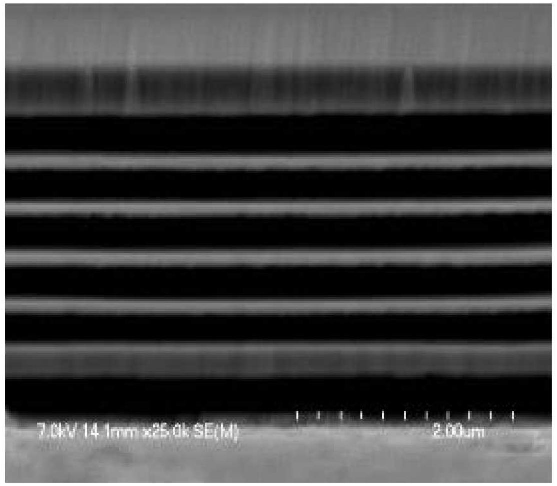


# 369-nm VCSEL

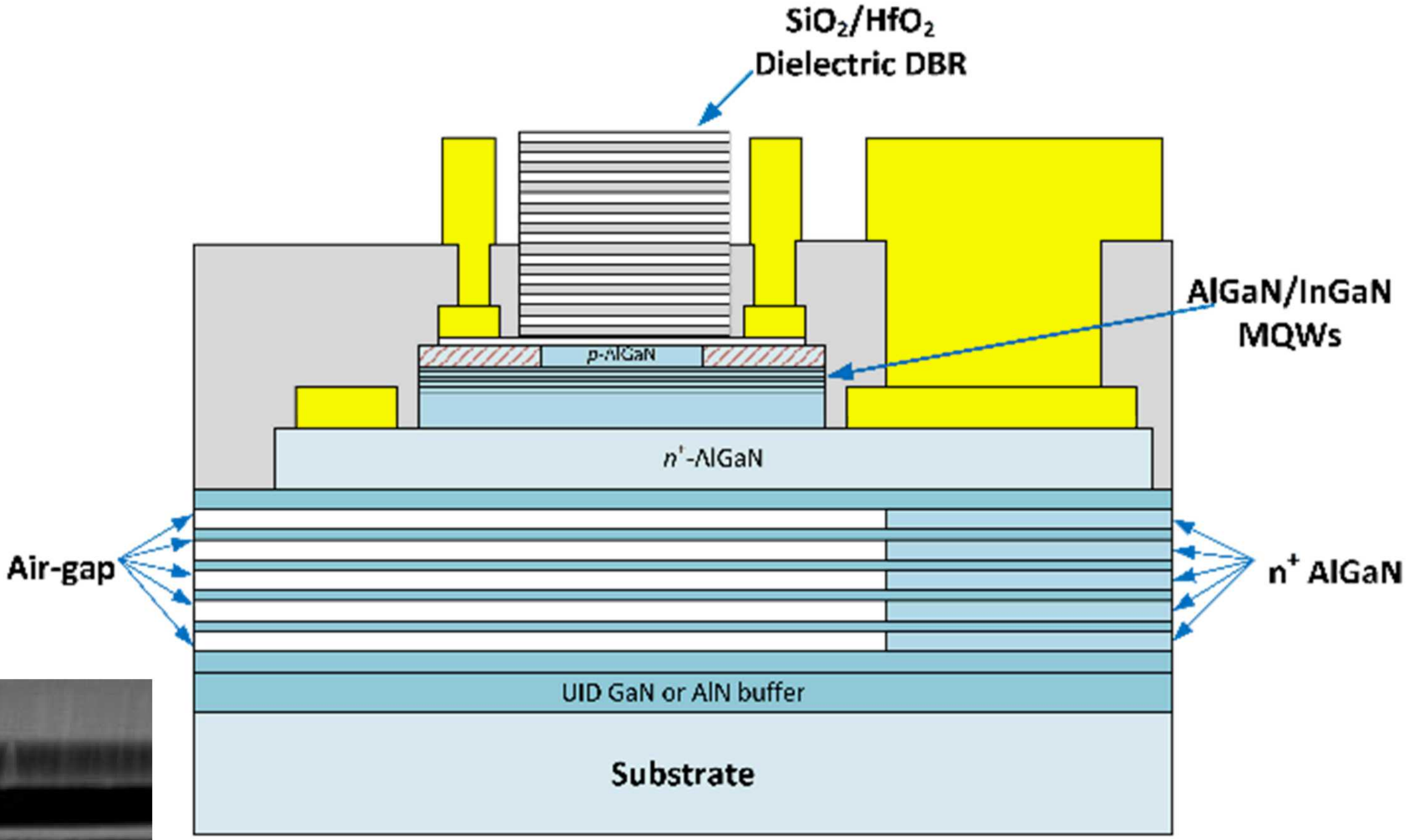
Georgia Institute of Technology

## Vertical Cavity Surface Emitting Laser (VCSEL)

- Develop hybrid-mirror DBR (HM-DBR) VCSEL with top dielectric DBR (DDBR) and bottom epitaxial semiconductor DBR (SDBR)
- Semiconductor DBR uses air gaps for high index contrast
- Demonstrated optically pumped laser operation
- Primary challenges
  - Current Injection
  - Heat extraction

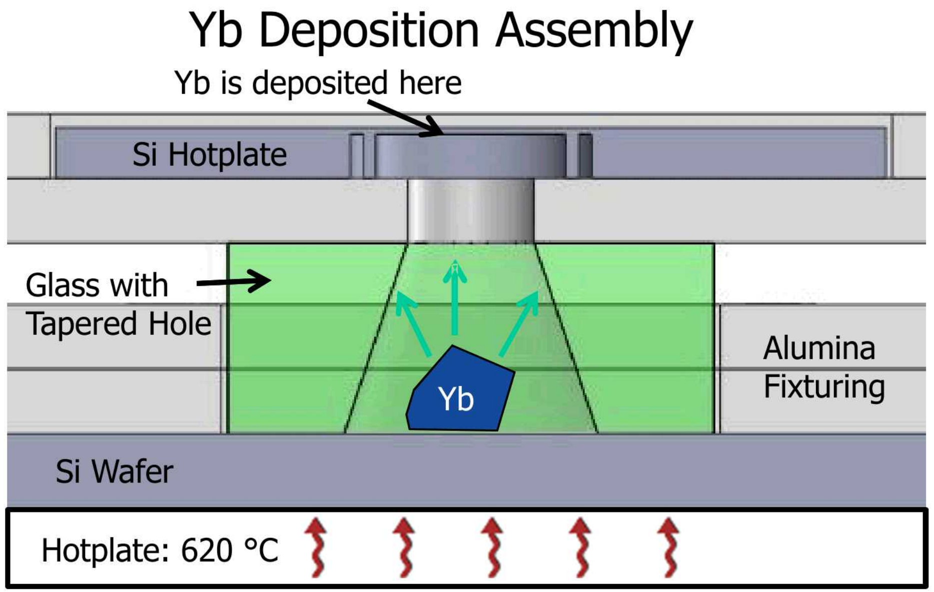


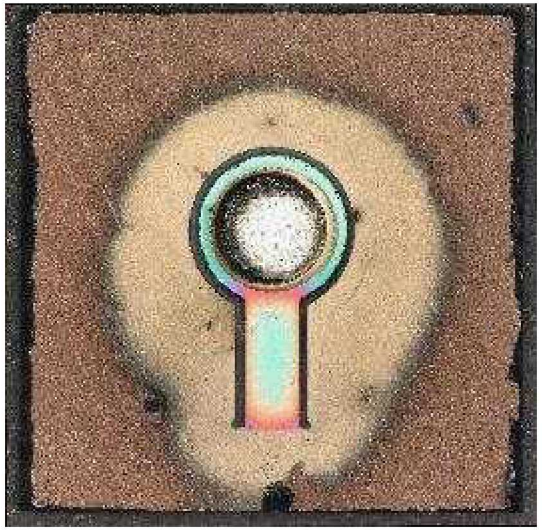

SEM of Air-Gap DBR

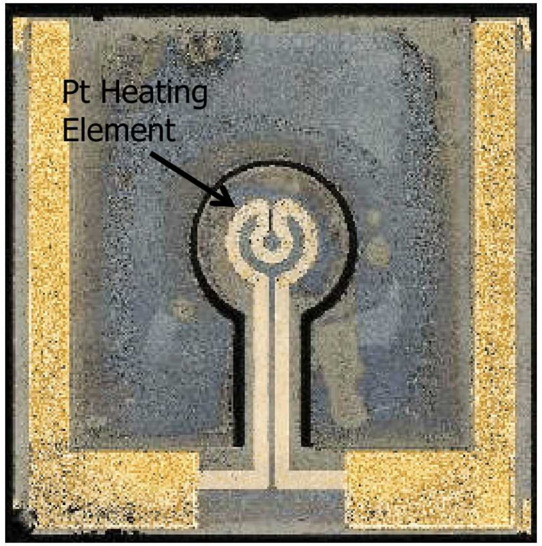


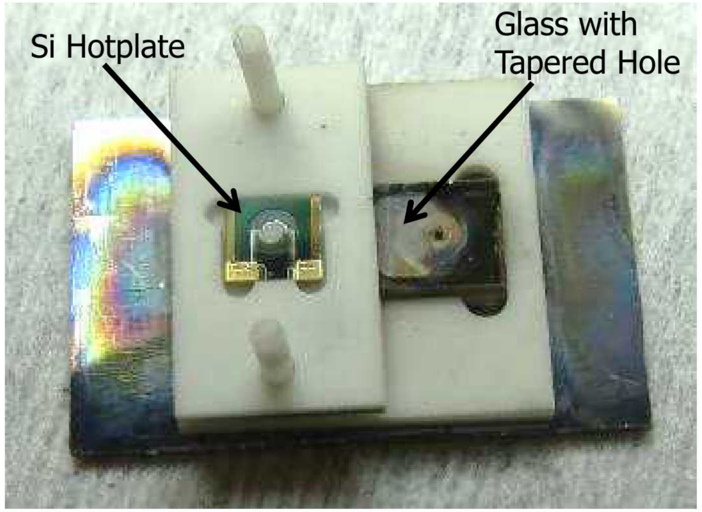
# Yb Source: Silicon Micro Hotplate

- Cup size: 0.7 mm and 0.9 mm diameter
- Evaporate Yb into the Si micro hotplates
- Heat base to 750 °C for 8 min in vacuum
- 30-50% is deposited into the Si micro hotplate: 0.2-0.6 mg
- Typical power for Yb evaporation: 1.5 V × 0.17 A = 255 mW



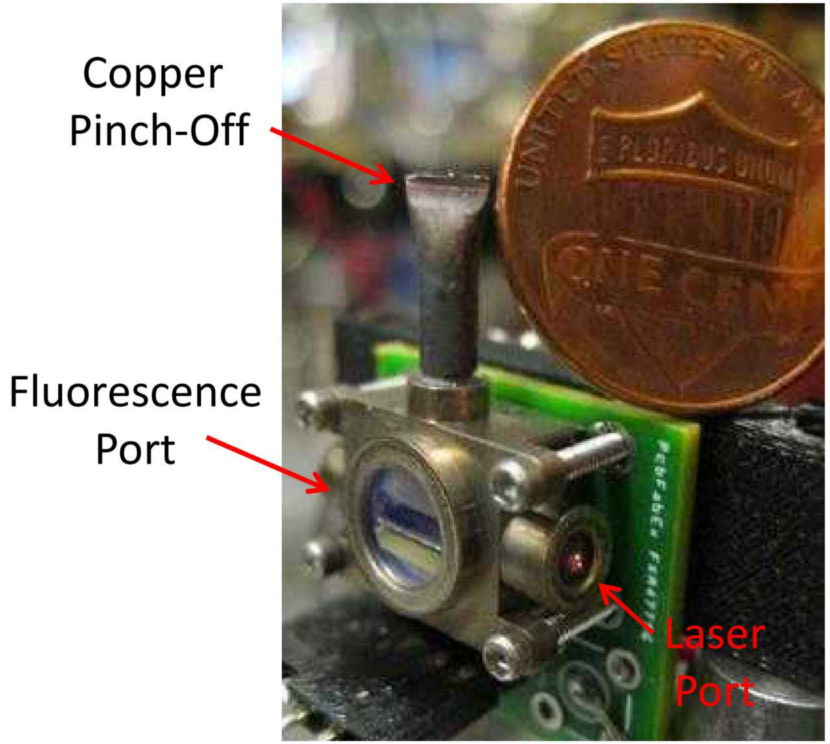





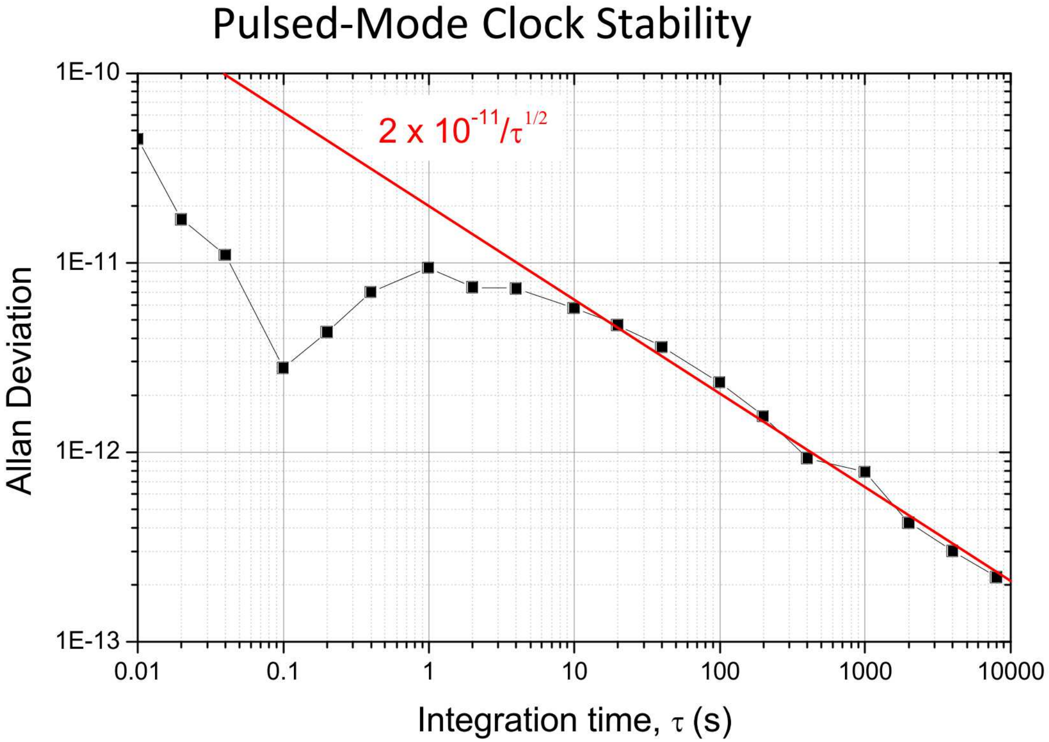



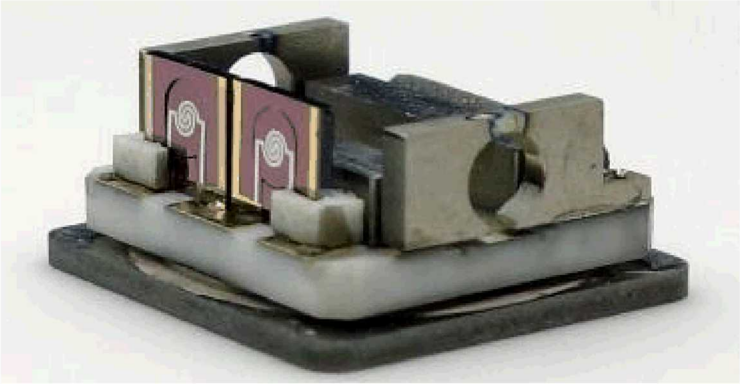
# Highly Miniaturized Vacuum Package: 1 $cm^3$

- The vacuum package was pinched-off on Thursday, October 30th, 2014.
- Trapped ion lifetime is ~50 hours.
- Pulsed-mode clock
  - $T_{microwave}$ = 700 ms
  - $T_{optical\ pumping}$ = 300 ms
- Magnetic field correlations removed




Schwindt, Peter DD, et al. "A highly miniaturized vacuum package for a trapped ion atomic clock." *Review of Scientific Instruments* 87.5 (2016): 053112.



# Conclusion

Clock performance determined by clock mode and fluorescence wavelength and collection efficiency

Compact clock with 369-nm fluorescence challenging

| System | Clock Mode | Fluorescence Wavelength | Short-Term Stability | Clock Linewidth |
|---|---|---|---|---|
| Compact Clock | Pulsed | 297 nm | $20 \times 10^{-12} \tau^{-1/2}$ | 1 Hz |
| Tabletop | Pulsed | 369 nm | $1.6 \times 10^{-12} \tau^{-1/2}$ | 8 Hz |
| Tabletop | Continuous | 369 nm | $3 \times 10^{-12} \tau^{-1/2}$<br>$13 \times 10^{-12} \tau^{-1/2}$ | 1 Hz<br>30 Hz |

Continuous mode can give fast attack time and no optical shutter

- But light shift must be controlled

Continuous mode does not have a problem with F-state or $YbH^+$ trapping

Future work: VCSEL development, compact clock design and construction