

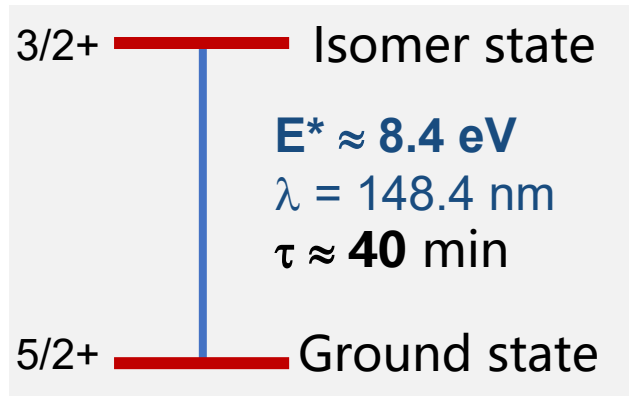
# Continuous-wave laser spectroscopy of the Th-229 nuclear transition

**Shiqian Ding**

**Department of Physics, Tsinghua University**

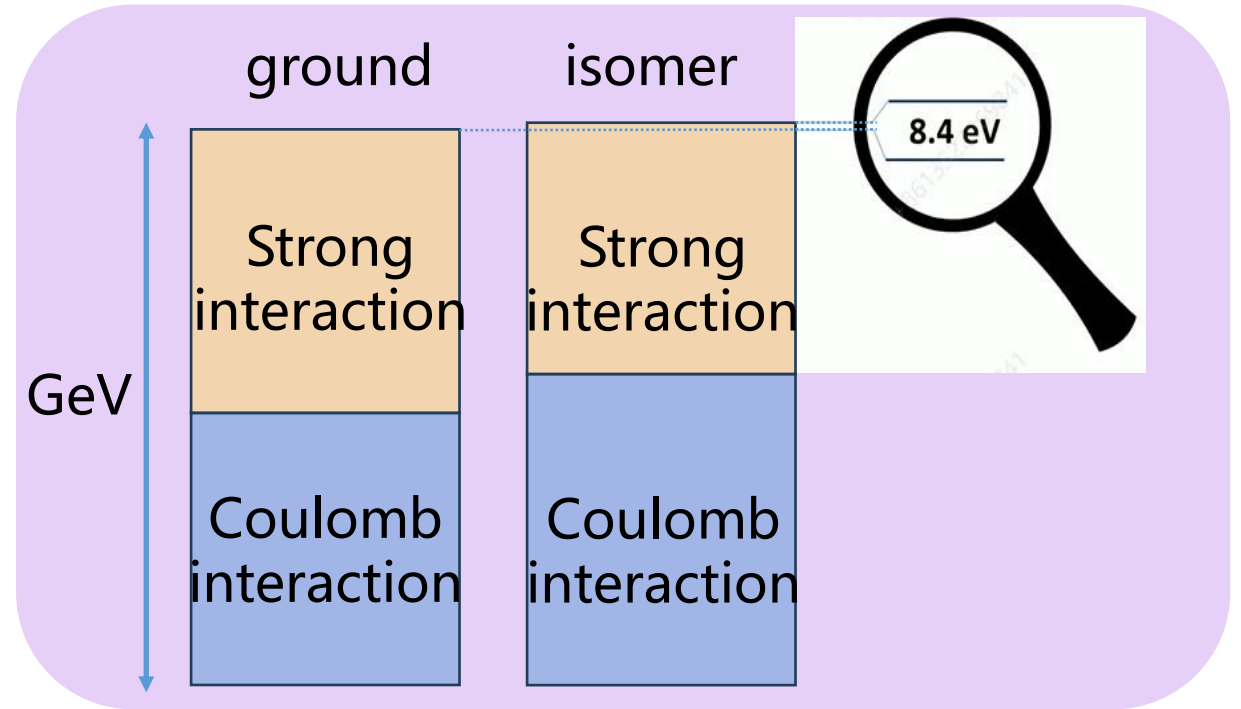


# Th-229 isomer transition



$^{229\text{m}}\text{Th}$   $\Delta E/E \sim 10^{-19}$

The lowest energy among all 200,000 nuclear excited states



Small size and multipole moments



Insensitive to EM field

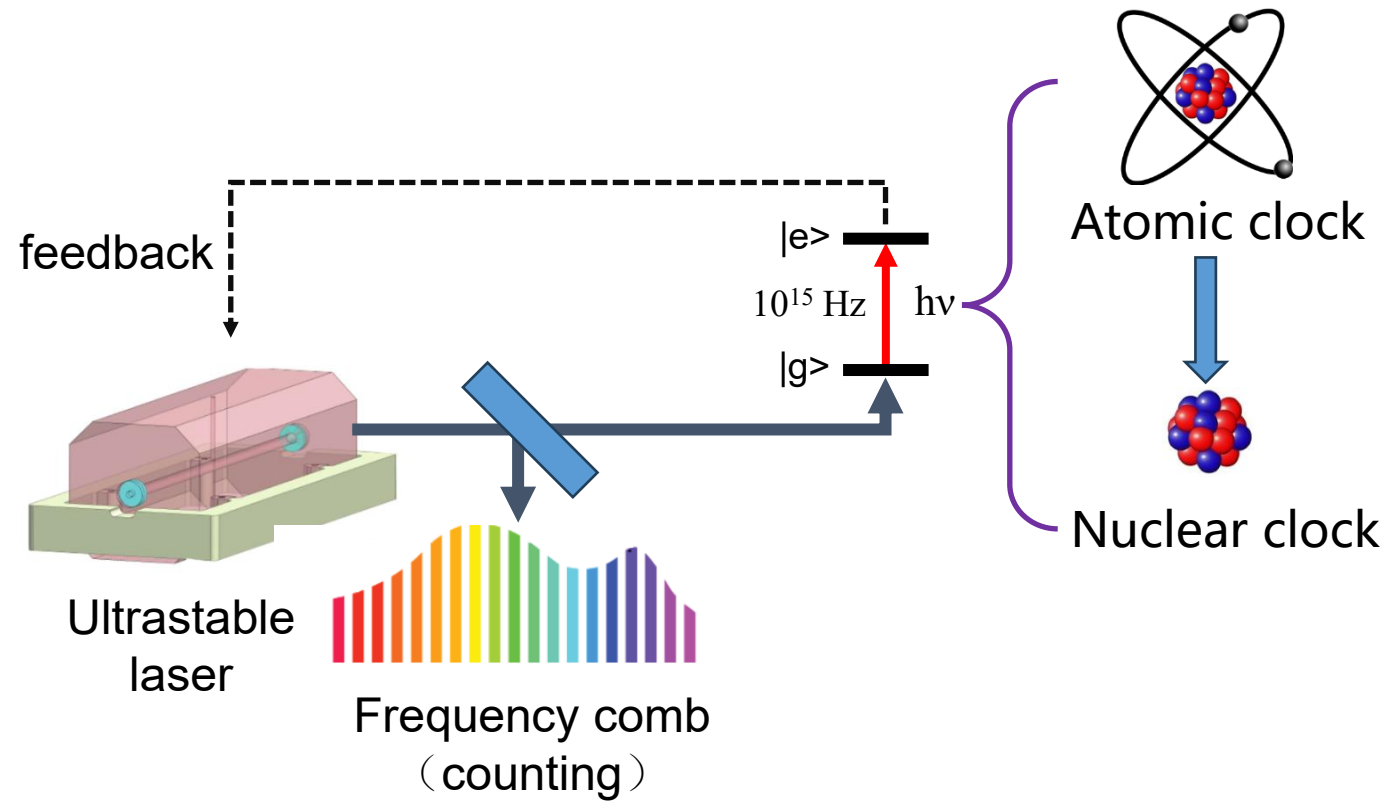
Lowest-energy nuclear excited state



Only nuclear transition accessible to lasers

Nuclear clock  
Solid state clock

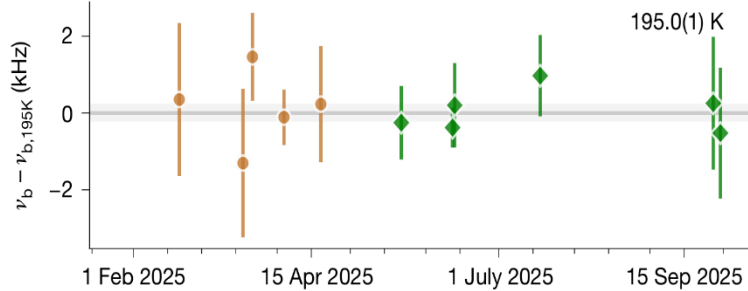
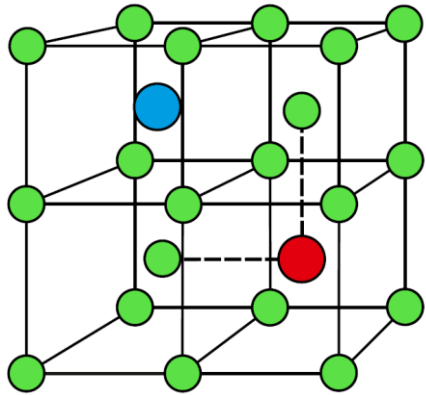
# Nuclear optical clock



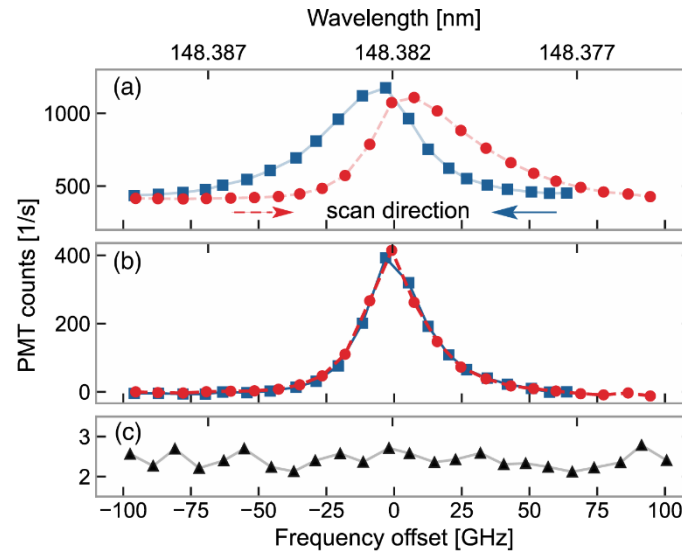
# Nuclear laser spectroscopy of Th-229

Th-doped crystal

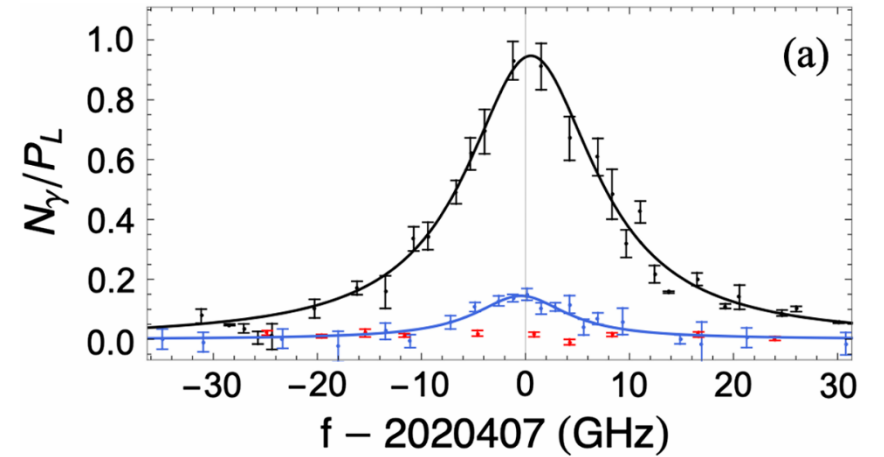
● F<sup>-</sup> ● Ca<sup>2+</sup> ● Th<sup>4+</sup>



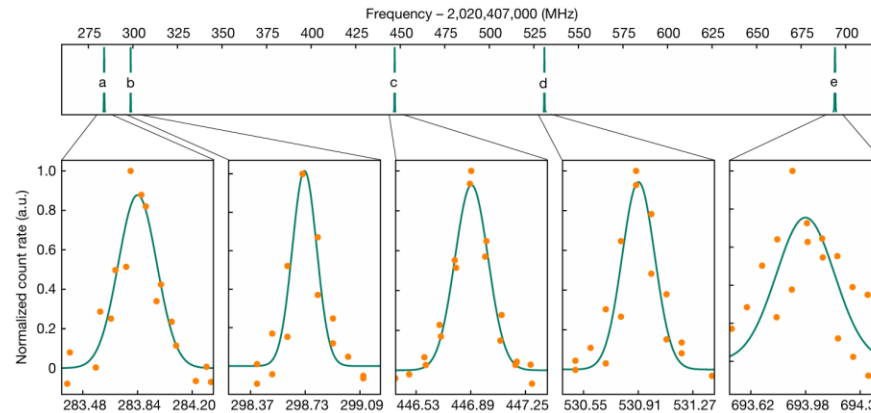
JILA, Nature 650, 72 (2026)



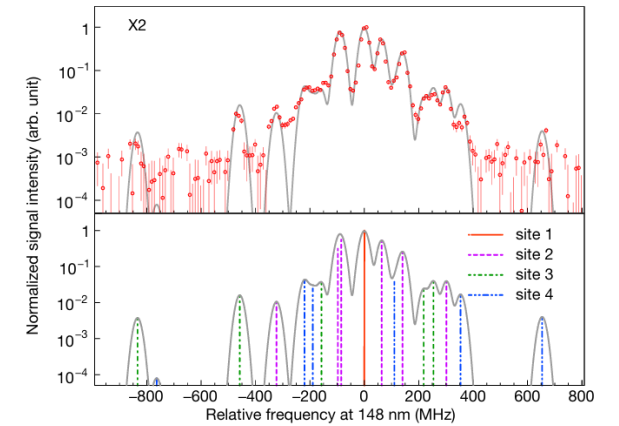
PTB, PRL 132, 182501(2024)



UCLA, PRL 133, 013201 (2024)



JILA, Nature 633, 63 (2024)



Okayama, arXiv:2509.00041 (2025)

# CW 148 nm laser: nonlinear crystal

Problems:

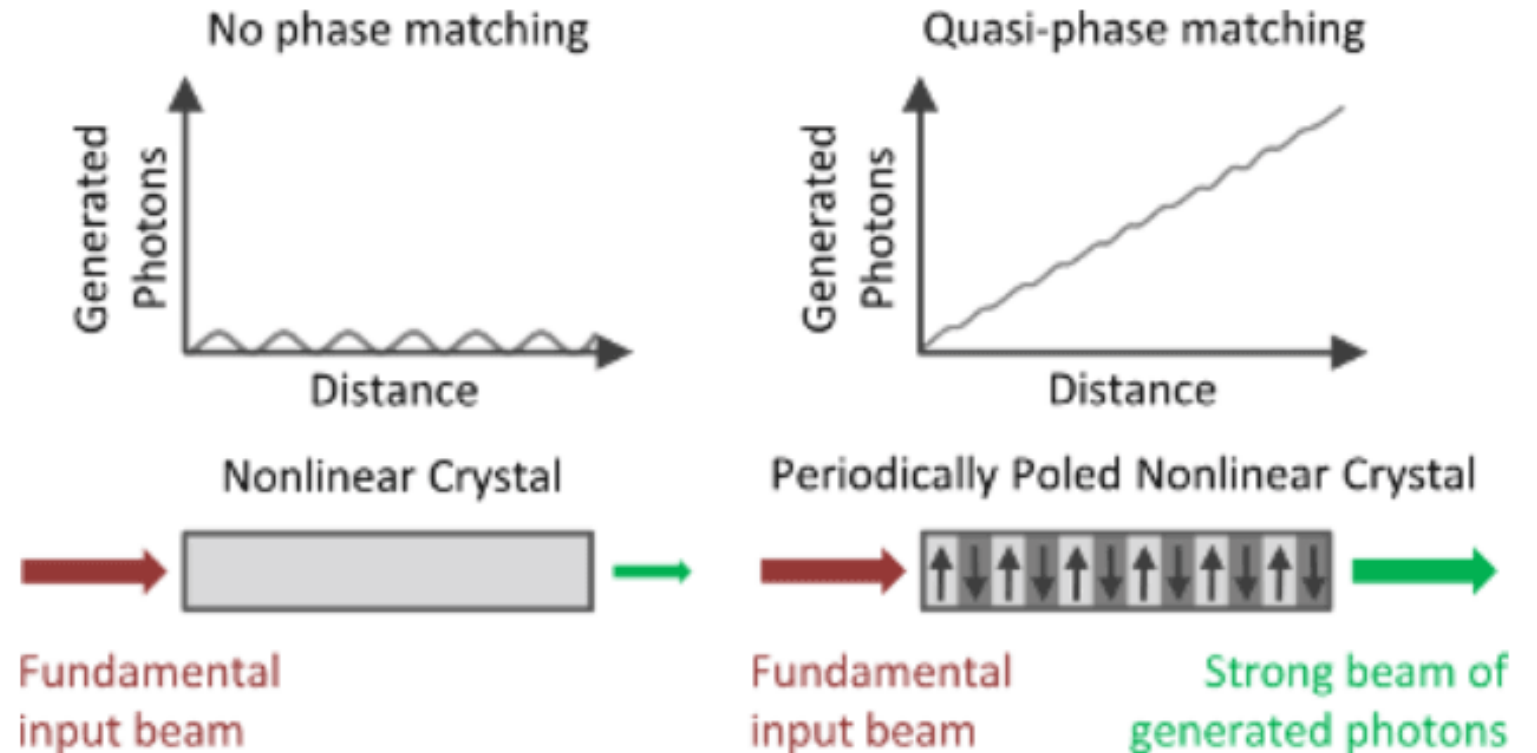
Strong absorption

Phase matching is hard

1.3 nW @ Peik group PTB

V. Lal et. al, Optica 12, 1971 (2025)

1 uW @ Ye group JILA



# CW VUV laser: four-wave mixing in Hg vapor

VOLUME 83, NUMBER 19

PHYSICAL REVIEW LETTERS

8 NOVEMBER 1999

## Continuous Wave Coherent Lyman- $\alpha$ Radiation

K. S. E. Eikema, J. Walz, and T. W. Hänsch

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

(Received 7 July 1999)

We describe the first coherent generation of continuous wave radiation at 121.56 nm. A yield of  $3 \times 10^8$  photons/sec (0.5 nW) has been achieved by four-wave mixing in mercury vapor. This continuous Lyman- $\alpha$  source could be used for laser cooling and precision spectroscopy of both hydrogen and antihydrogen.

PACS numbers: 42.65.Ky, 32.80.Pj

VOLUME 86, NUMBER 25

PHYSICAL REVIEW LETTERS

18 JUNE 2001

## Continuous Coherent Lyman- $\alpha$ Excitation of Atomic Hydrogen

K. S. E. Eikema,\* J. Walz,† and T. W. Hänsch

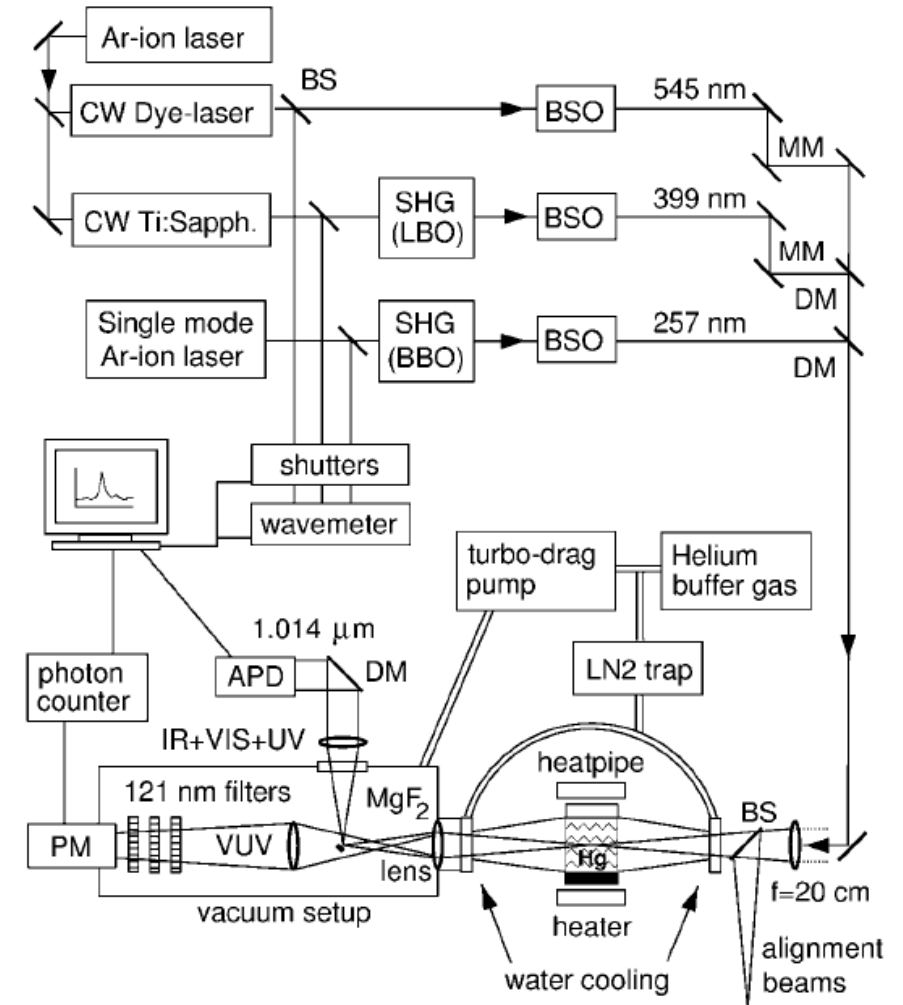
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

(Received 21 February 2001)

The  $1S-2P$  transition in atomic hydrogen has been observed for the first time with almost natural linewidth. We employ a unique source of continuous coherent Lyman- $\alpha$  radiation based on four-wave mixing in mercury. The output of the source has been improved 40-fold to yield 20 nW. This demonstration shows that laser cooling and detection with continuous Lyman- $\alpha$  radiation has excellent prospects for future experiments with antihydrogen.

DOI: 10.1103/PhysRevLett.86.5679

PACS numbers: 32.30.Jc, 32.70.Jz, 32.80.Pj, 42.65.Ky

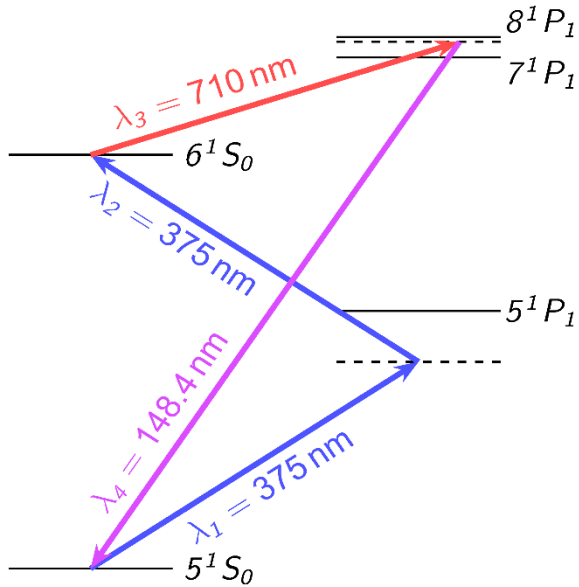


Layman- $\alpha$  @ 121.56 nm

K. S. E. Eikema, J. Walz, and T. W. Hänsch, PRL 83, 3828 (1999)

K. S. E. Eikema, J. Walz, and T. W. Hänsch, PRL 86, 5679 (2001)

# CW 148 nm laser: four-wave mixing (FWM) in Cd vapor



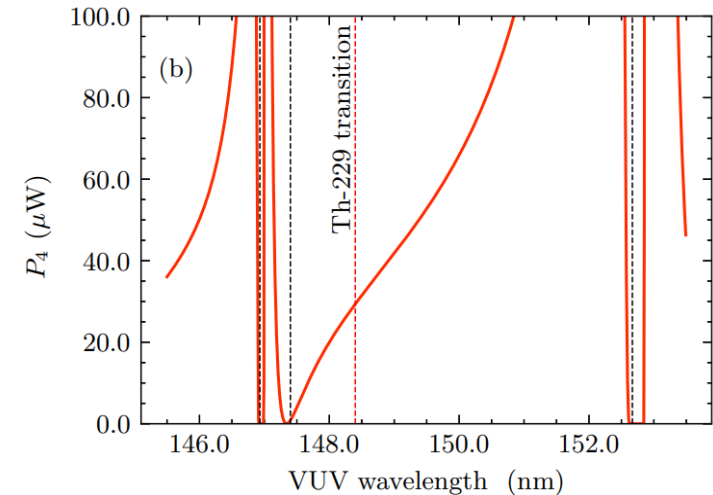
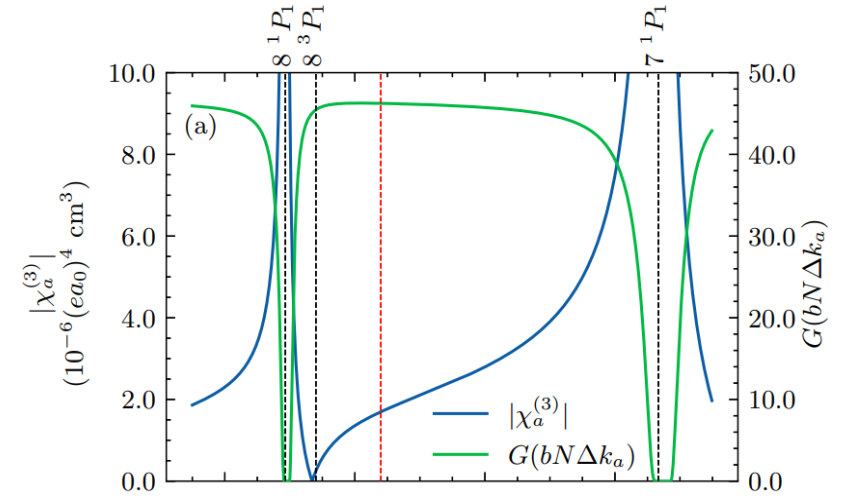
- Large nonlinearity
- Strong fundamental power
- Low melting point (321 °C)
- Narrow linewidth?

$$P_4 = \frac{9}{4} \frac{\omega_1 \omega_2 \omega_3 \omega_4}{\pi^2 \epsilon_0^2 c^6} \frac{1}{b^2} \left( \frac{1}{\Delta k_a} \right)^2 |\chi_a^{(3)}|^2 P_1 P_2 P_3 G(bN \Delta k_a)$$

$b$  Confocal parameter, twice Rayleigh range

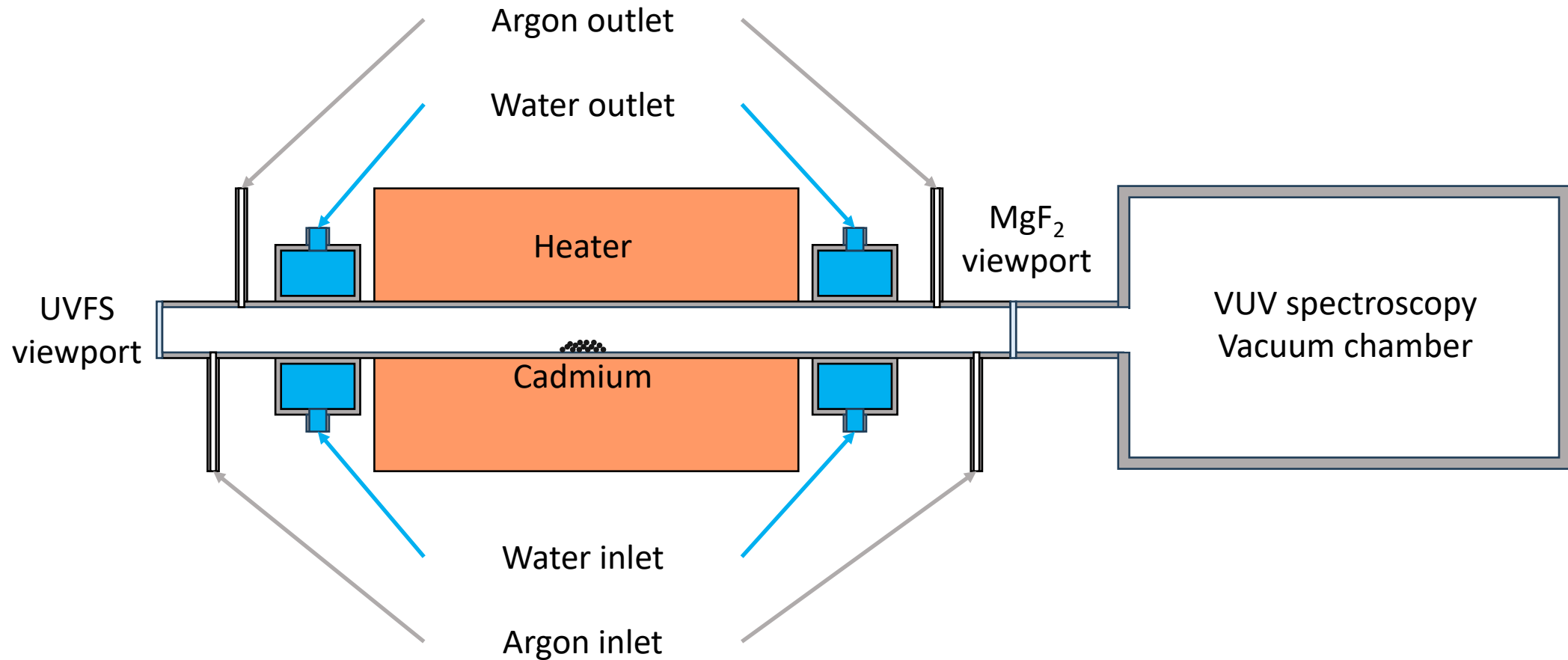
$\chi_a^{(3)}$  Third-order susceptibility

$G(bN \Delta k_a)$  Phase matching factor

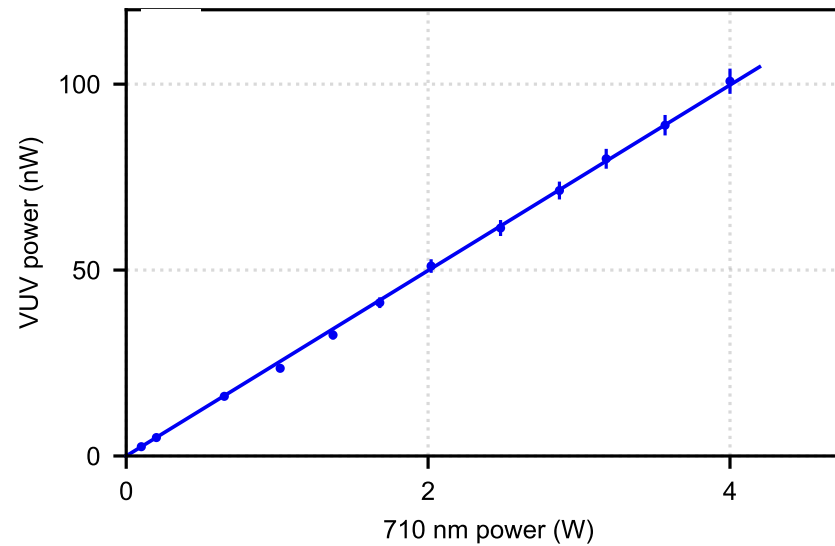
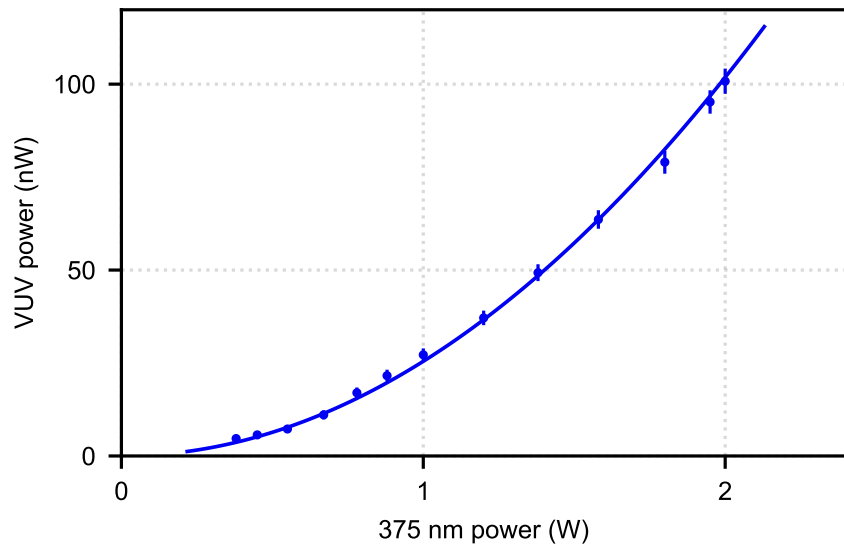
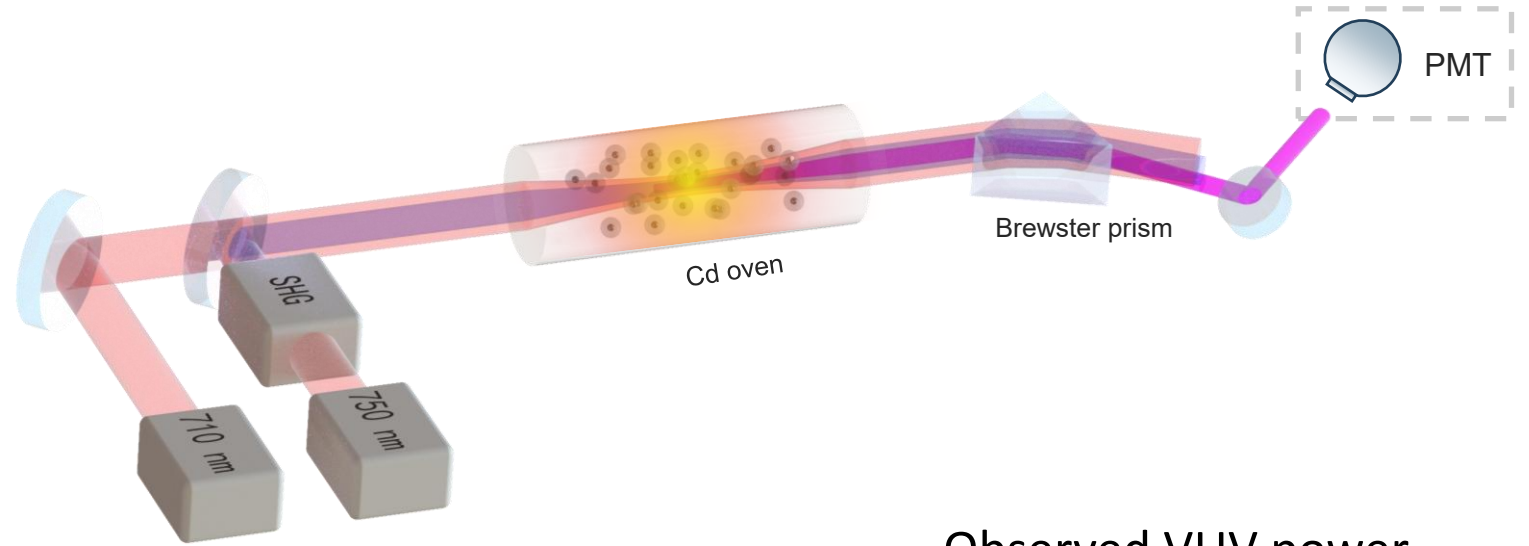
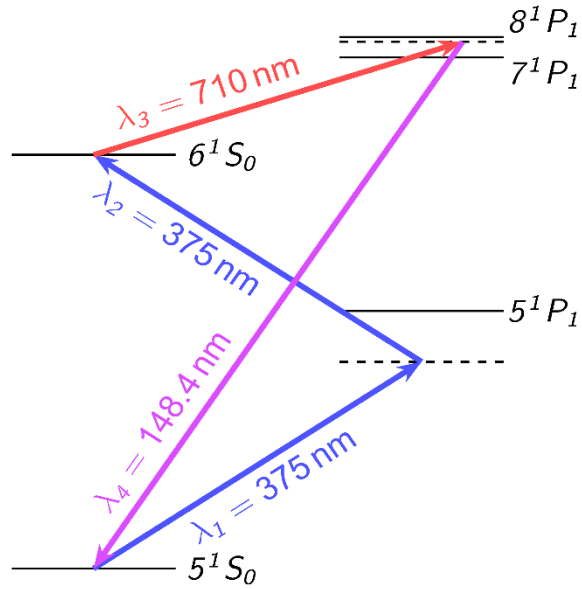


PRA 112, 022807 (2025)  
Phys. Rev. Appl. 25, 024034 (2026)

# CW 148 nm laser: four-wave mixing (FWM) in Cd vapor

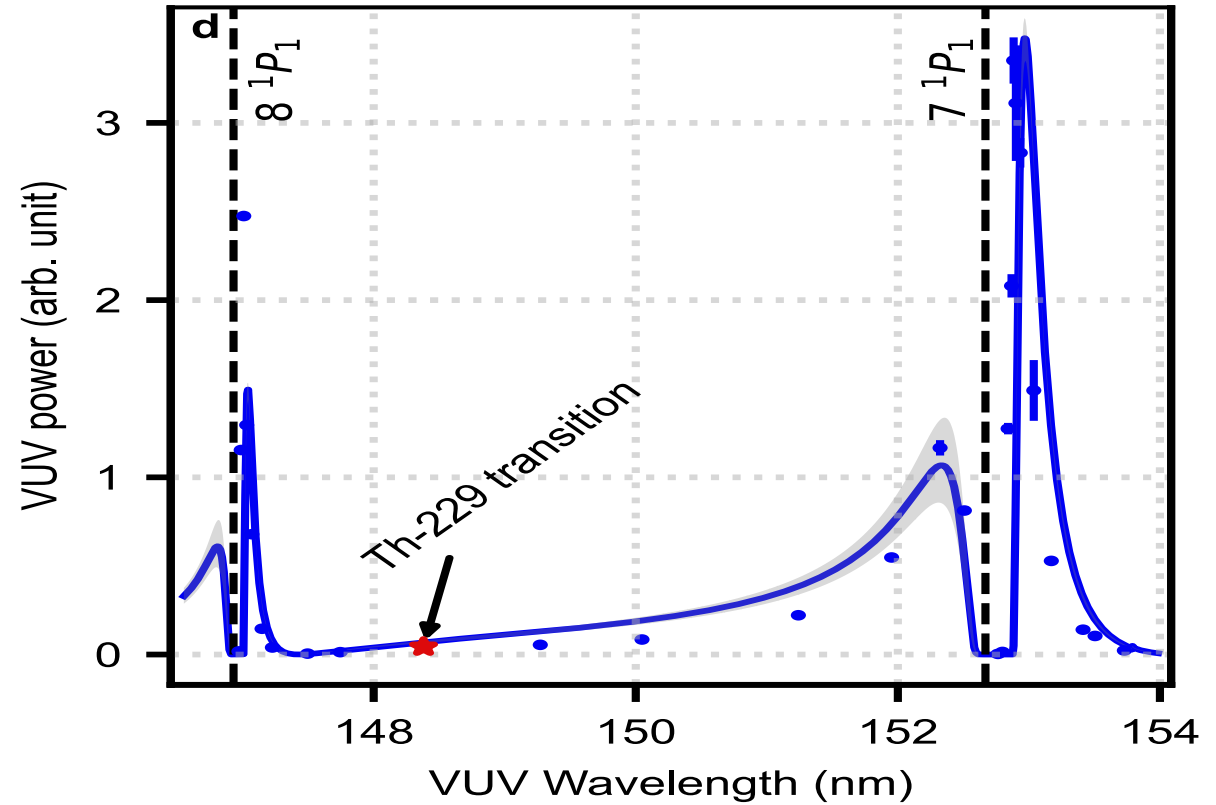
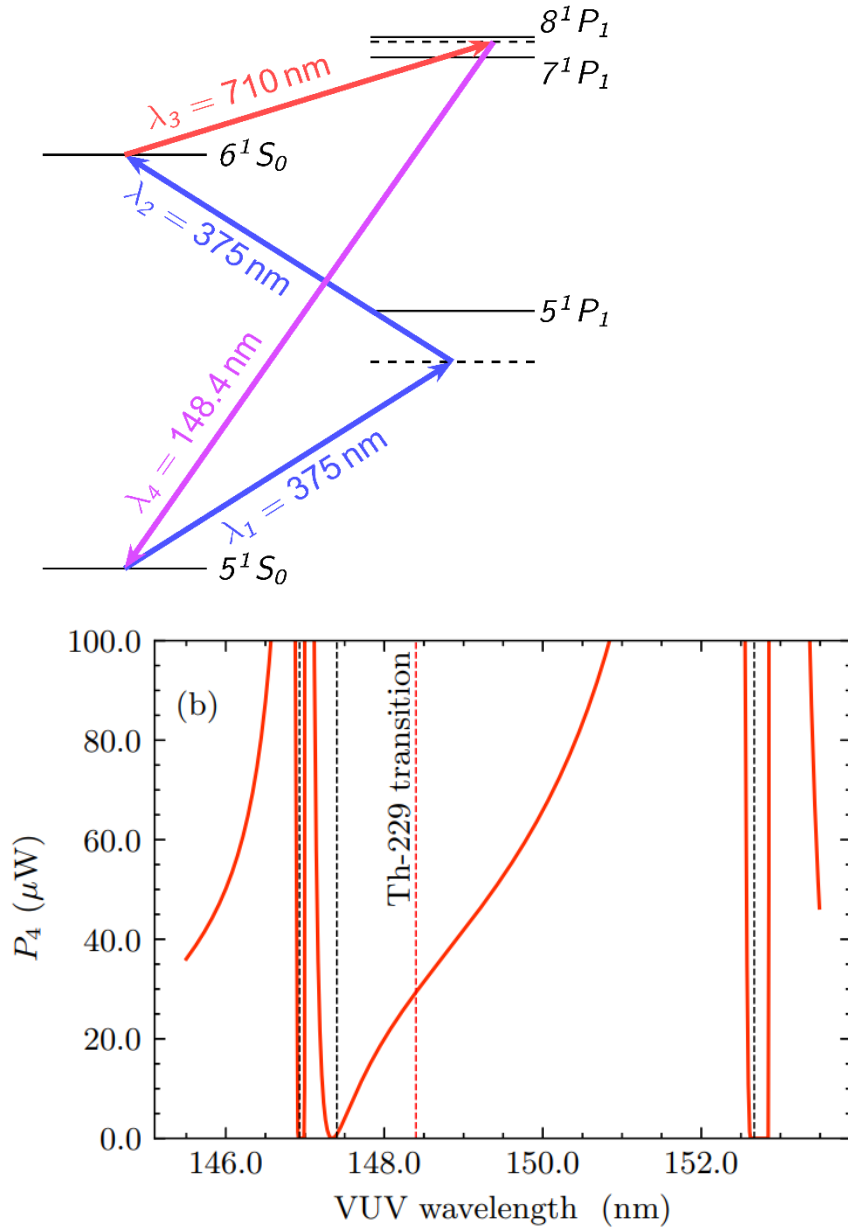


# CW 148 nm laser: four-wave mixing (FWM) in Cd vapor



Observed VUV power agrees well with theory

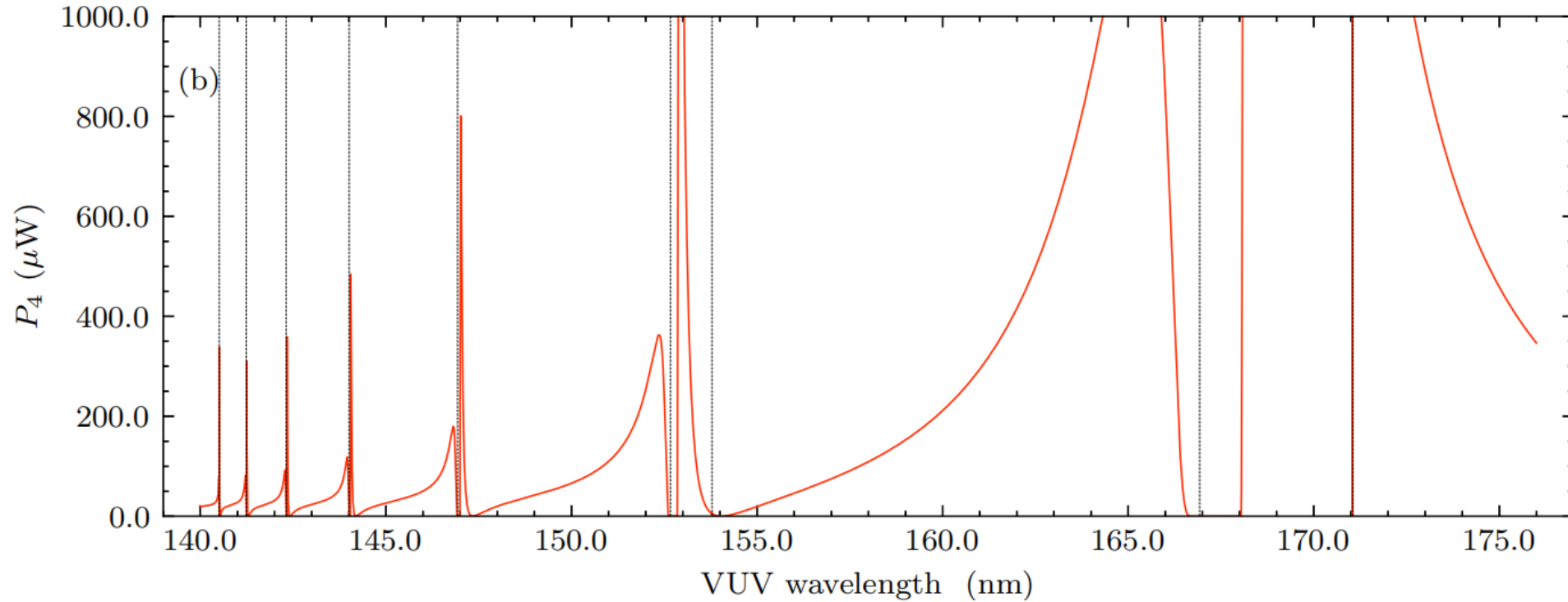
# CW 148 nm laser: wavelength tunability



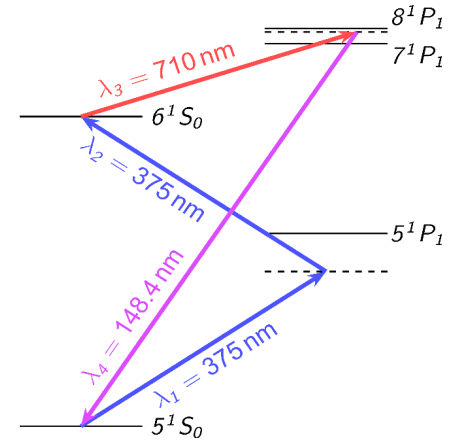
Phys. Rev. Appl. 25, 024034 (2026)

Nature 650, 852 (2026) 10

# CW 148 nm laser: wavelength tunability



Very widely tunable from 140 nm to 175 nm



**Linewidth of the four-wave mixing VUV laser?**

# Phase noise induced by high-harmonic generation

ARTICLES

PUBLISHED ONLINE: 22 JUNE 2014 | DOI: 10.1038/NPHOTON.2014.132

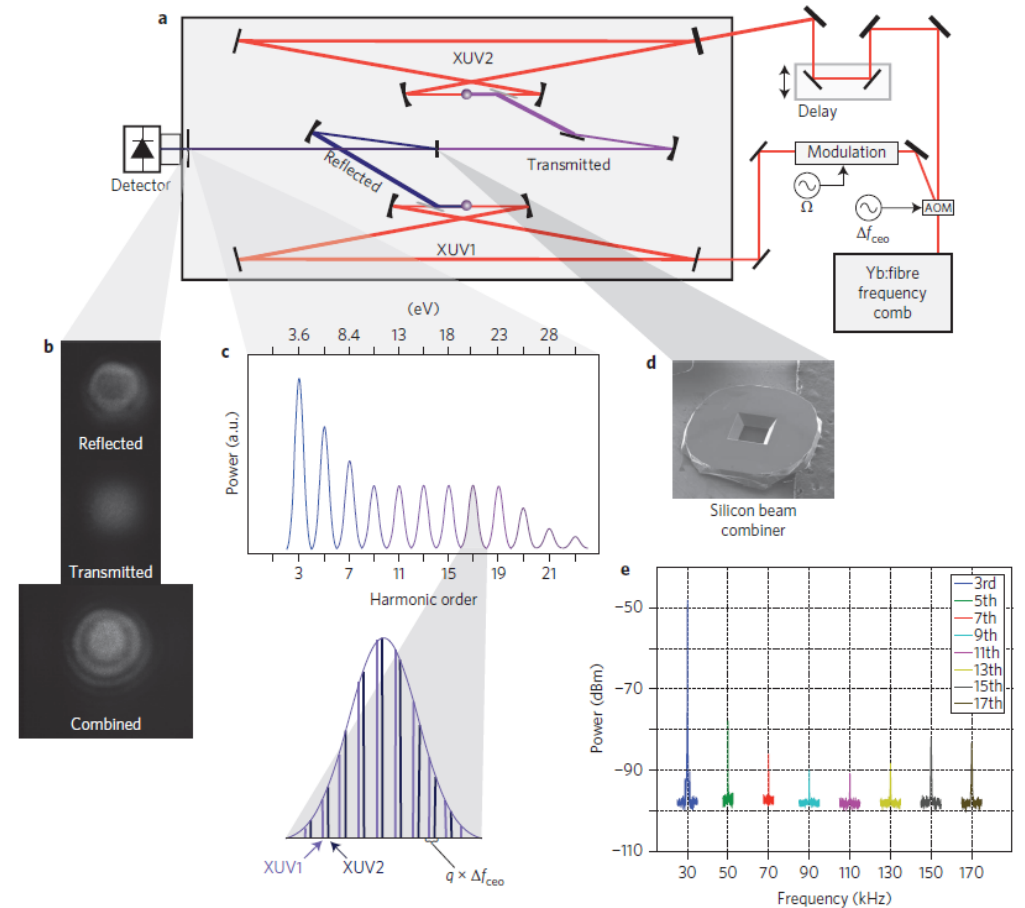
nature  
photonics

## Extreme ultraviolet radiation with coherence time greater than 1 s

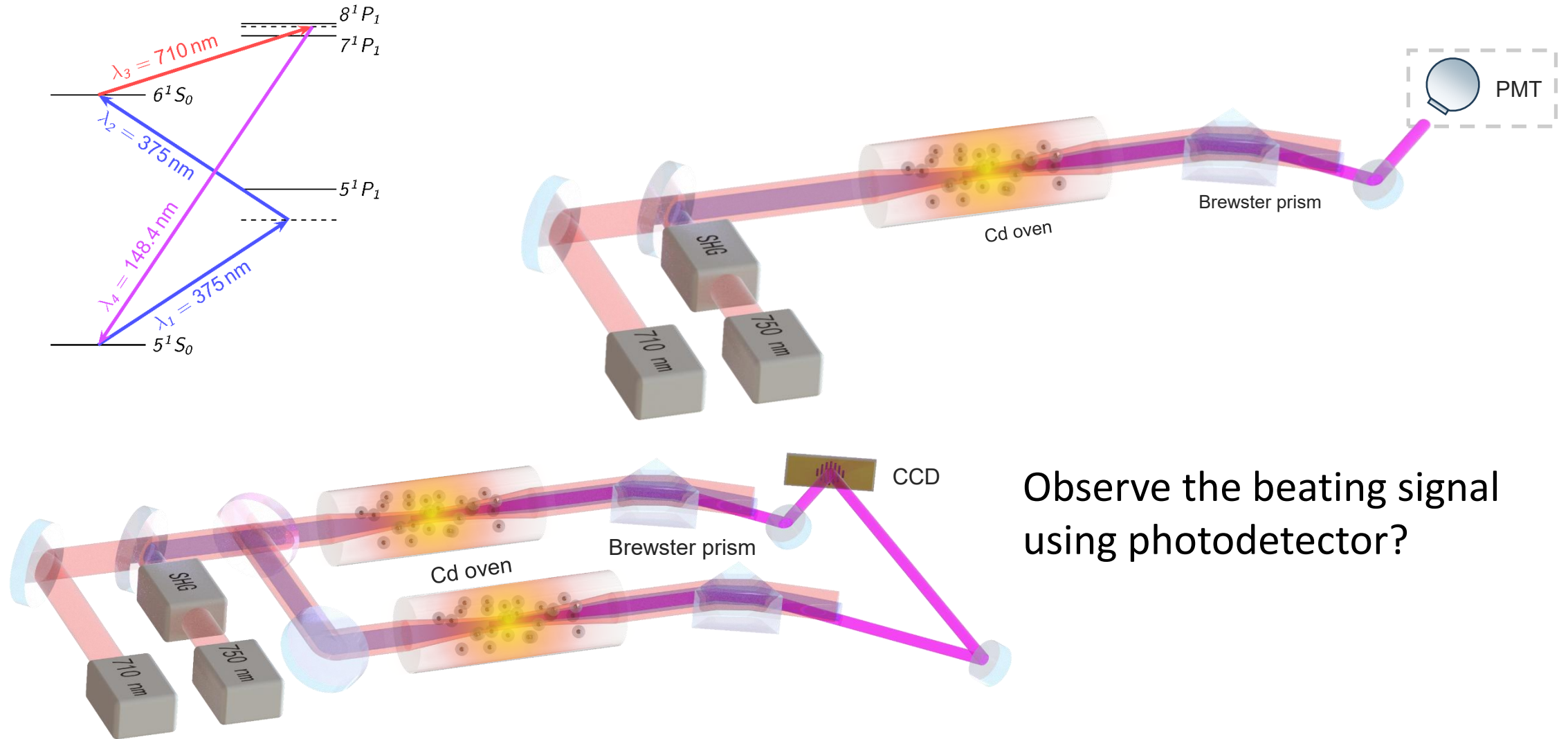
Craig Benko<sup>1\*</sup>, Thomas K. Allison<sup>1,2</sup>, Arman Cingöz<sup>1†</sup>, Linqiang Hua<sup>1,3</sup>, François Labaye<sup>1</sup>, Dylan C. Yost<sup>1†</sup> and Jun Ye<sup>1\*</sup>

Many atomic and molecular systems of fundamental interest possess resonance frequencies in the extreme ultraviolet (XUV) where laser technology is limited and radiation sources have traditionally lacked long-term phase coherence. Recent breakthroughs in XUV frequency comb technology have demonstrated spectroscopy with unprecedented resolution at the megahertz level, but even higher resolutions are desired for future applications in precision measurement. By characterizing heterodyne beats between two XUV comb sources, we demonstrate the capability for sub-hertz spectral resolution. This corresponds to coherence times  $>1$  s at photon energies up to 20 eV, more than six orders of magnitude longer than previously reported. This work establishes the ability of creating highly phase-stable radiation in the XUV with performance rivaling that of visible light. Furthermore, by direct sampling of the phase of the XUV light originating from high-harmonic generation, we demonstrate precise measurements of attosecond strong-field physics.

How coherent is the (CW and resonance-enhanced) four-wave mixing process?



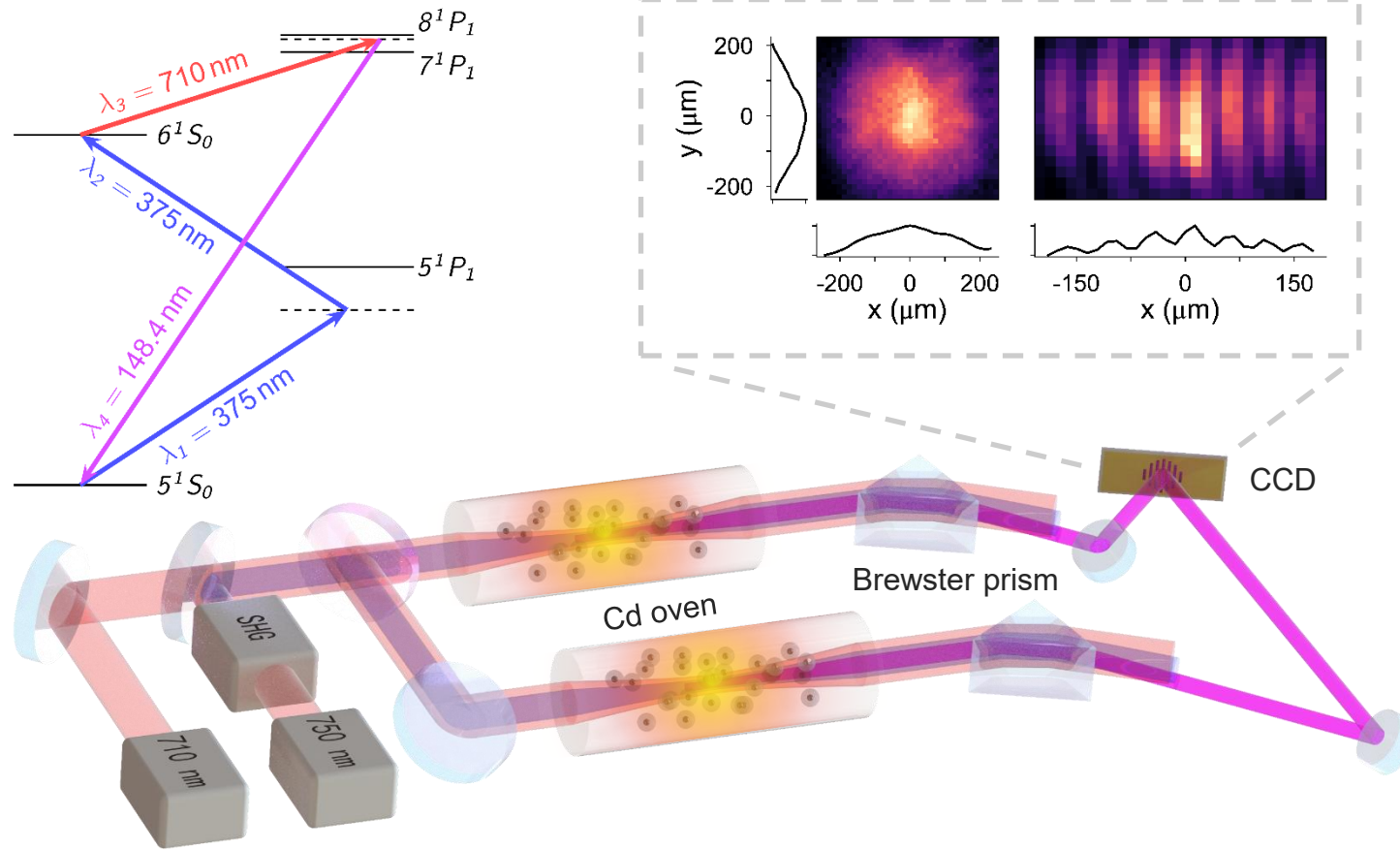
# CW 148 nm laser: phase noise induced by FWM



Observe the beating signal using photodetector?

Beating of separately generated VUV beams

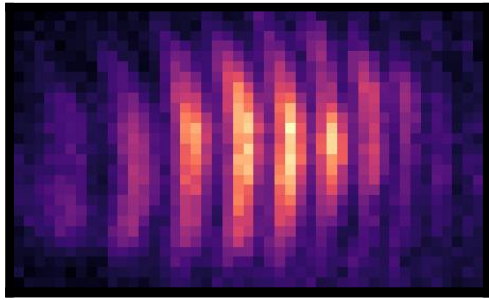
# CW 148 nm laser: phase noise induced by FWM



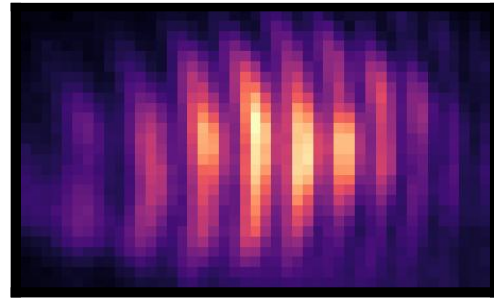
High-contrast fringes with 10 second exposure time

Beating of separately generated VUV beams

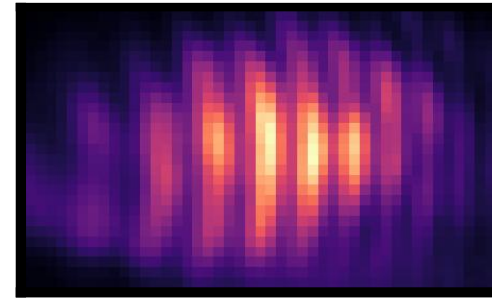
# CW 148 nm laser: phase induced by FWM



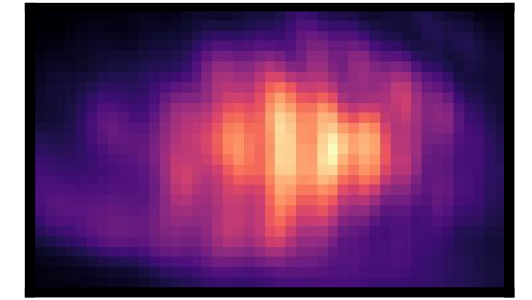
$\tau = 0.5 \text{ s}$



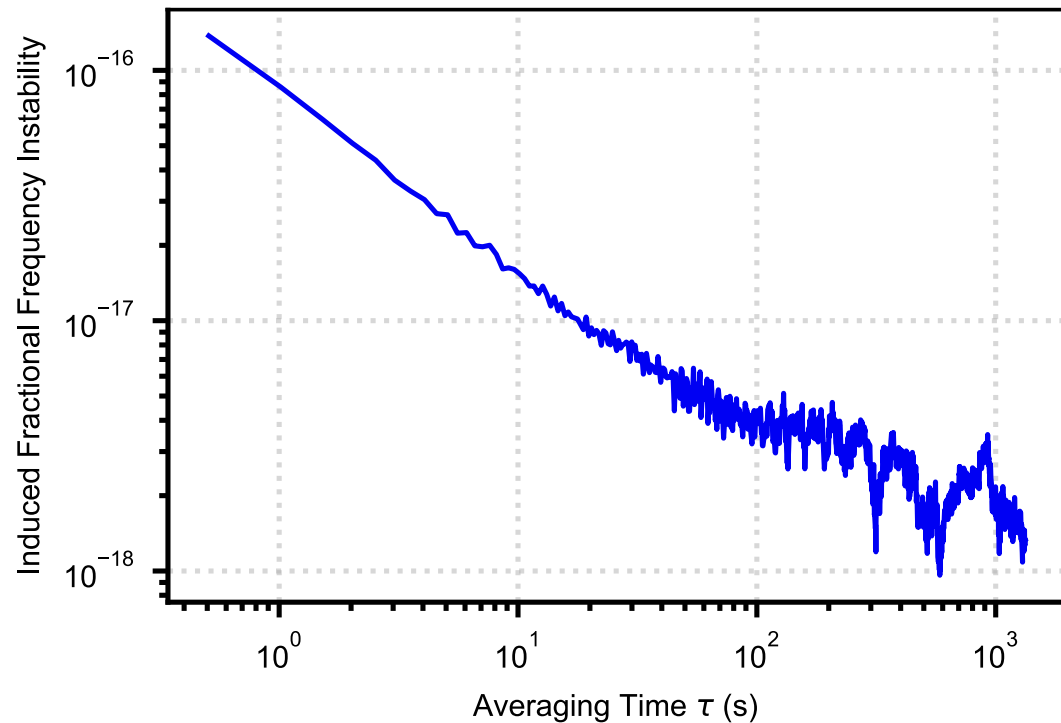
$\tau = 5 \text{ s}$



$\tau = 50 \text{ s}$



$\tau = 500 \text{ s}$



➤ Doppler shift of fundamental beams in the atomic rest frame

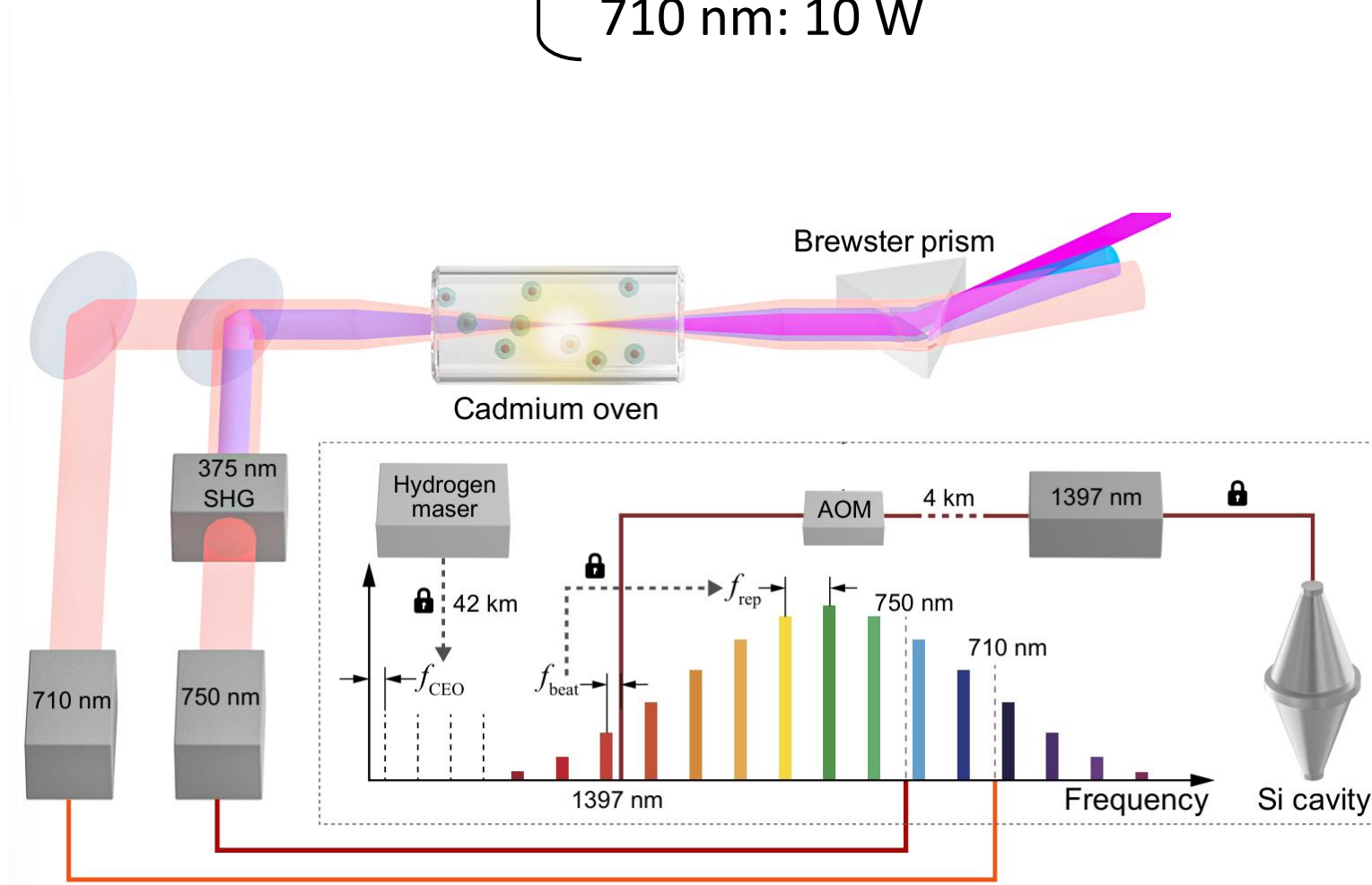
=

Frequency transformation of the generated VUV field back into the lab frame

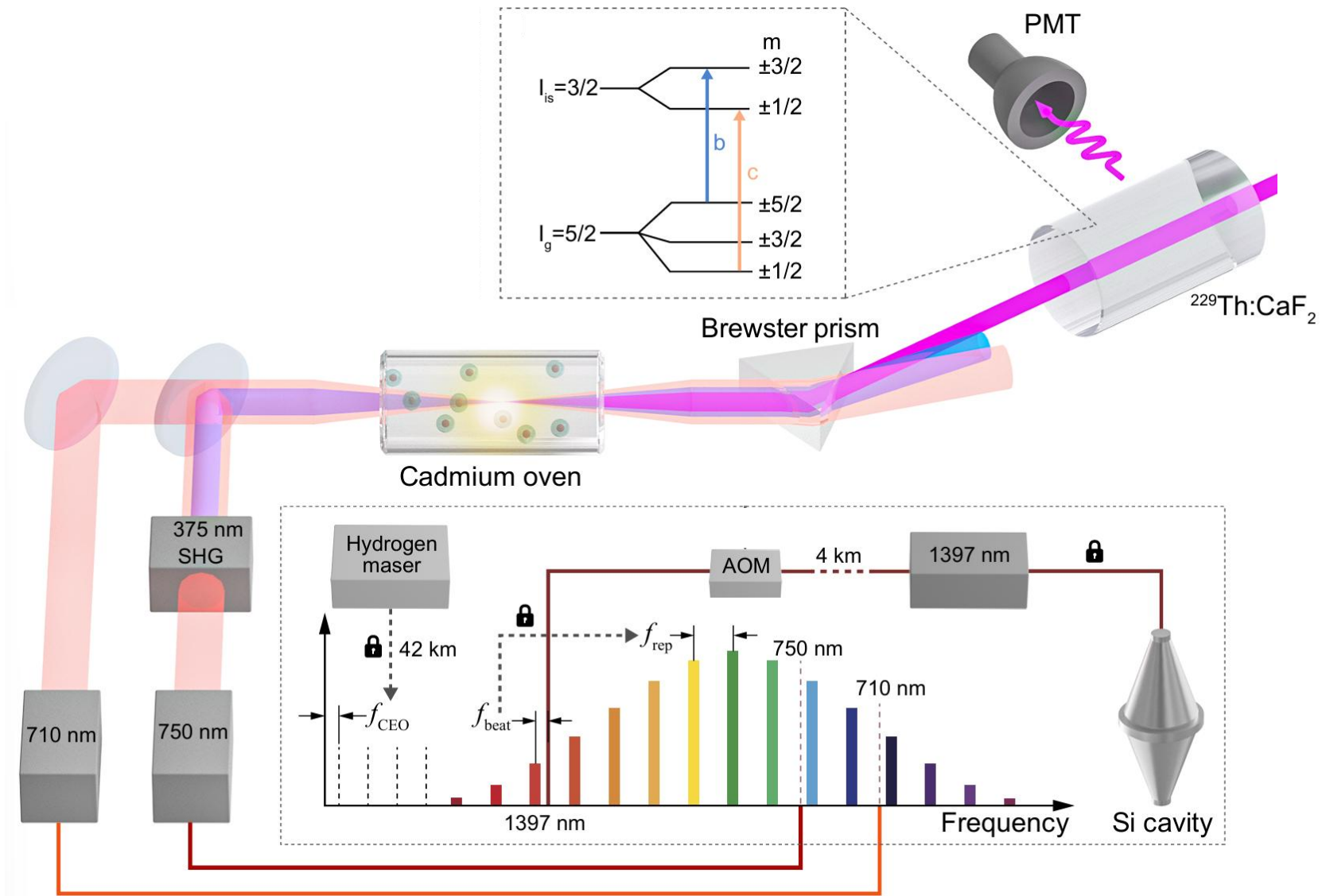
➤ Dephasing due to collisions is not relevant since only virtual states are involved.

# CW 148 nm laser: improved power and linewidth

Fiber-based lasers  $\left\{ \begin{array}{l} 375 \text{ nm: } 5 \text{ W} \\ 710 \text{ nm: } 10 \text{ W} \end{array} \right.$   $\longrightarrow$  148 nm: 10  $\mu$ W



# CW laser fluorescence spectroscopy



Thorsten Schumm  
(TU Wien)

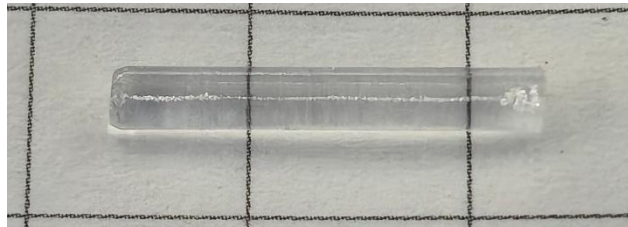


Eric Hudson  
(UCLA)

# CW laser fluorescence spectroscopy

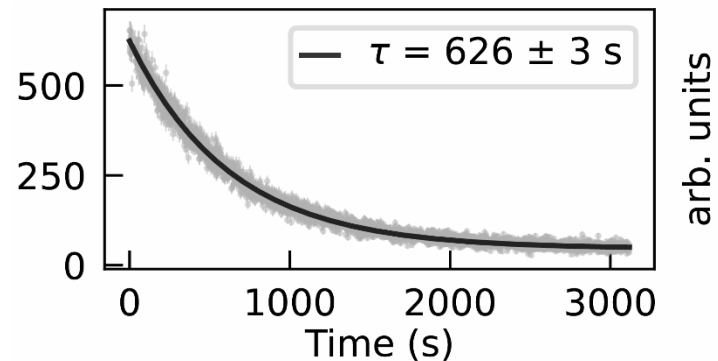
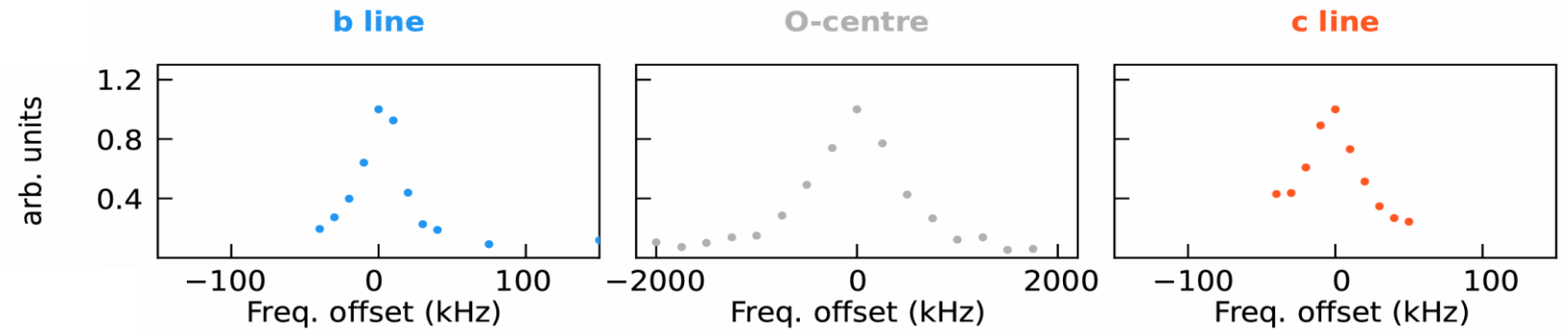
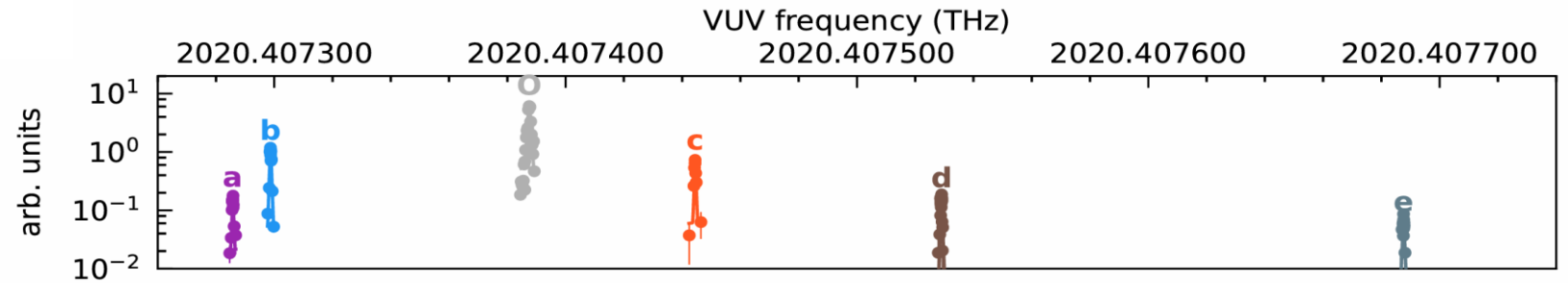


Yin Hang (SIOM)



S1

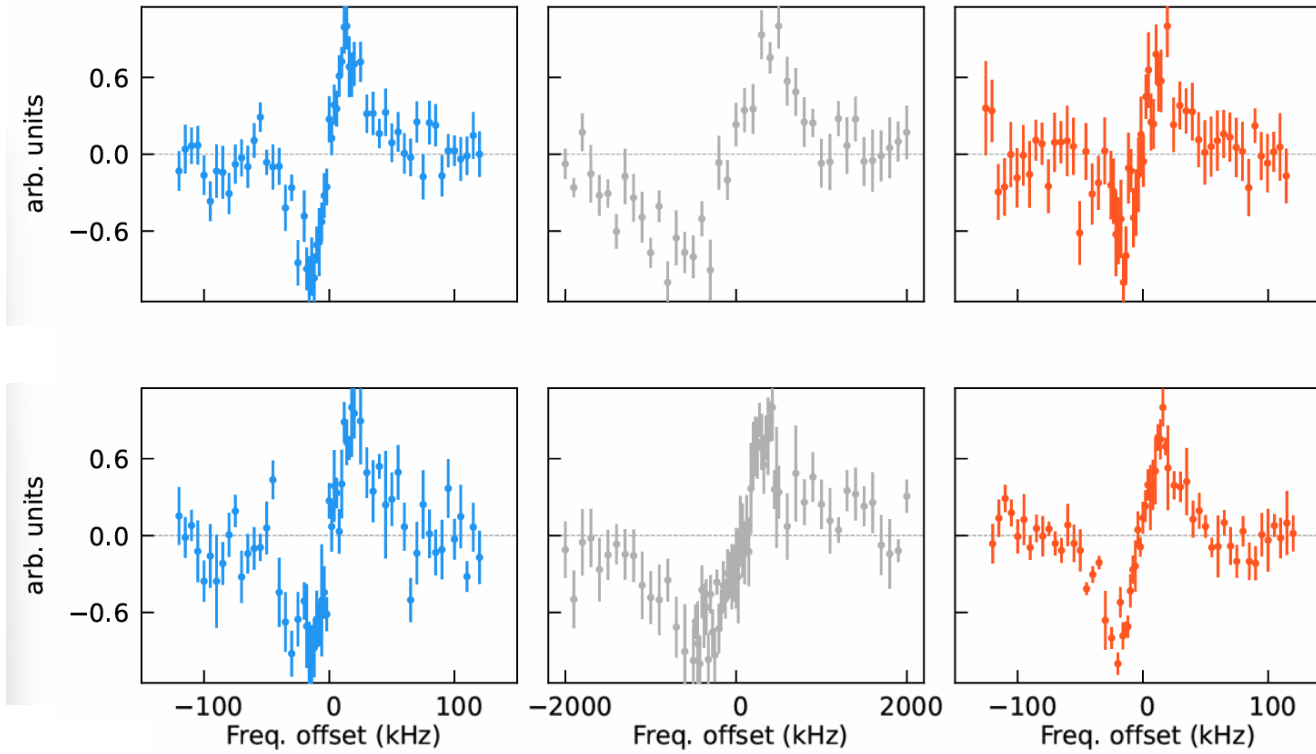
- Bridgman-Stockbarger method
- Concentration  $8 \cdot 10^{16}/\text{cm}^3$
- Diameter 1.5 mm, length 9.6 mm



➤ Slow decay



# CW laser absorption spectroscopy

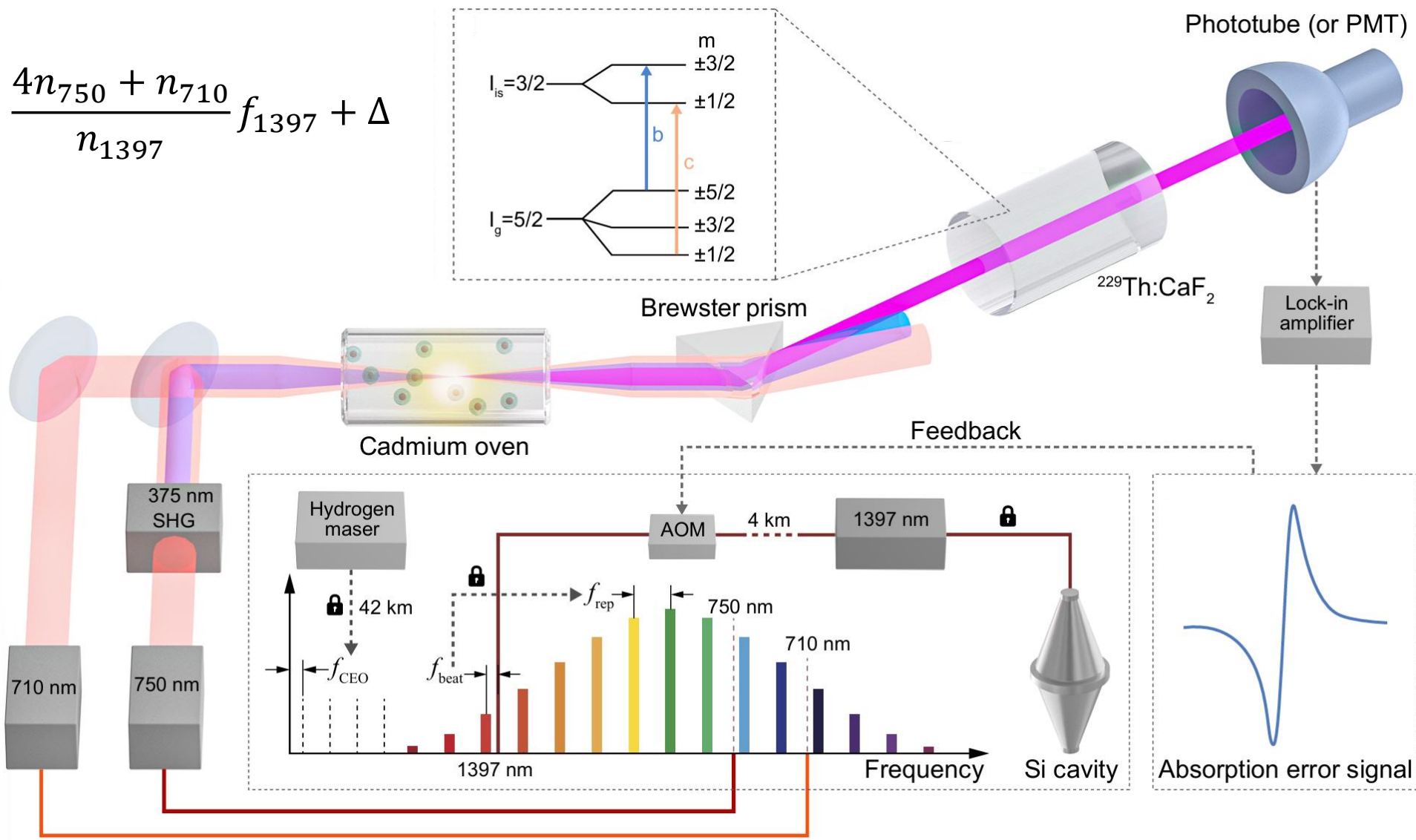


- S1+PMT
- Each data, 80 seconds

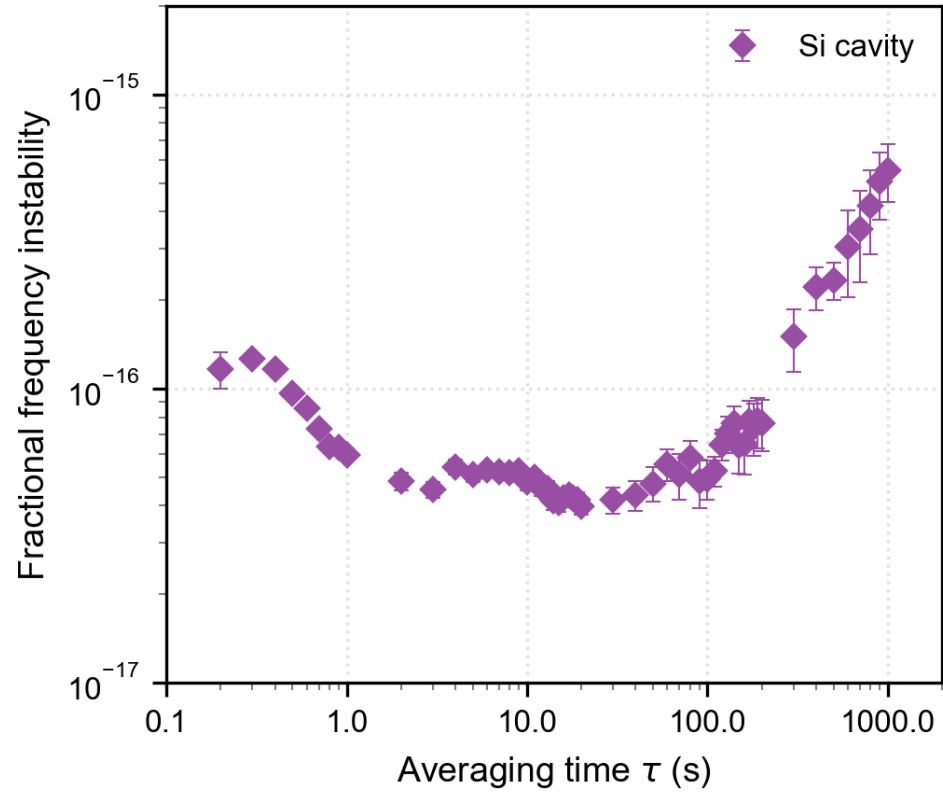
- S1+Phototube
- Each data, 40 seconds

# Close the feedback loop

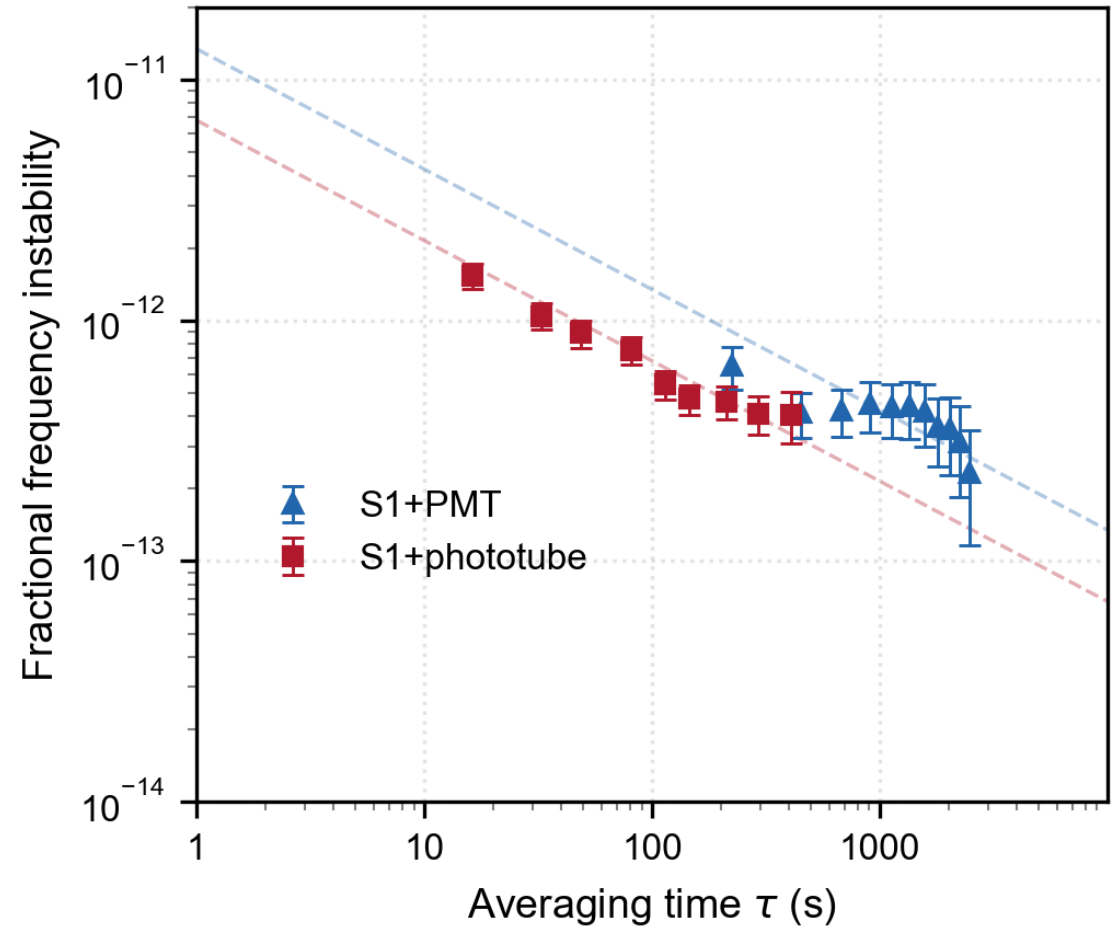
$$f_{148} = \frac{4n_{750} + n_{710}}{n_{1397}} f_{1397} + \Delta$$



# Close the feedback loop with S1 crystal



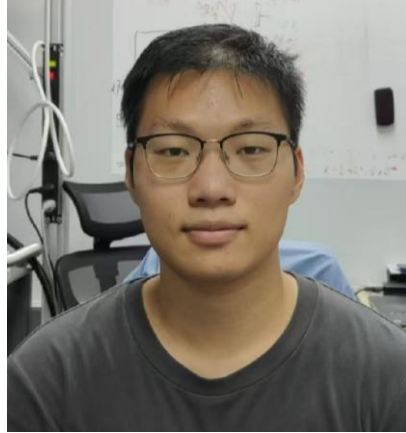
X. Zhang, Science Bulletin 70, 3337 (2025)



# Fabrication of TS1 crystal



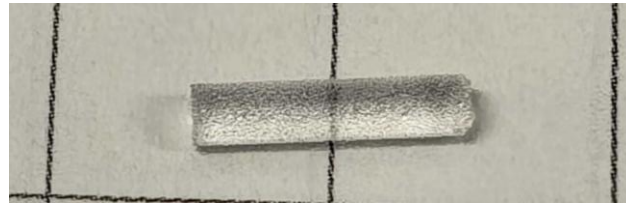
Beichen Huang



Qi Xiao



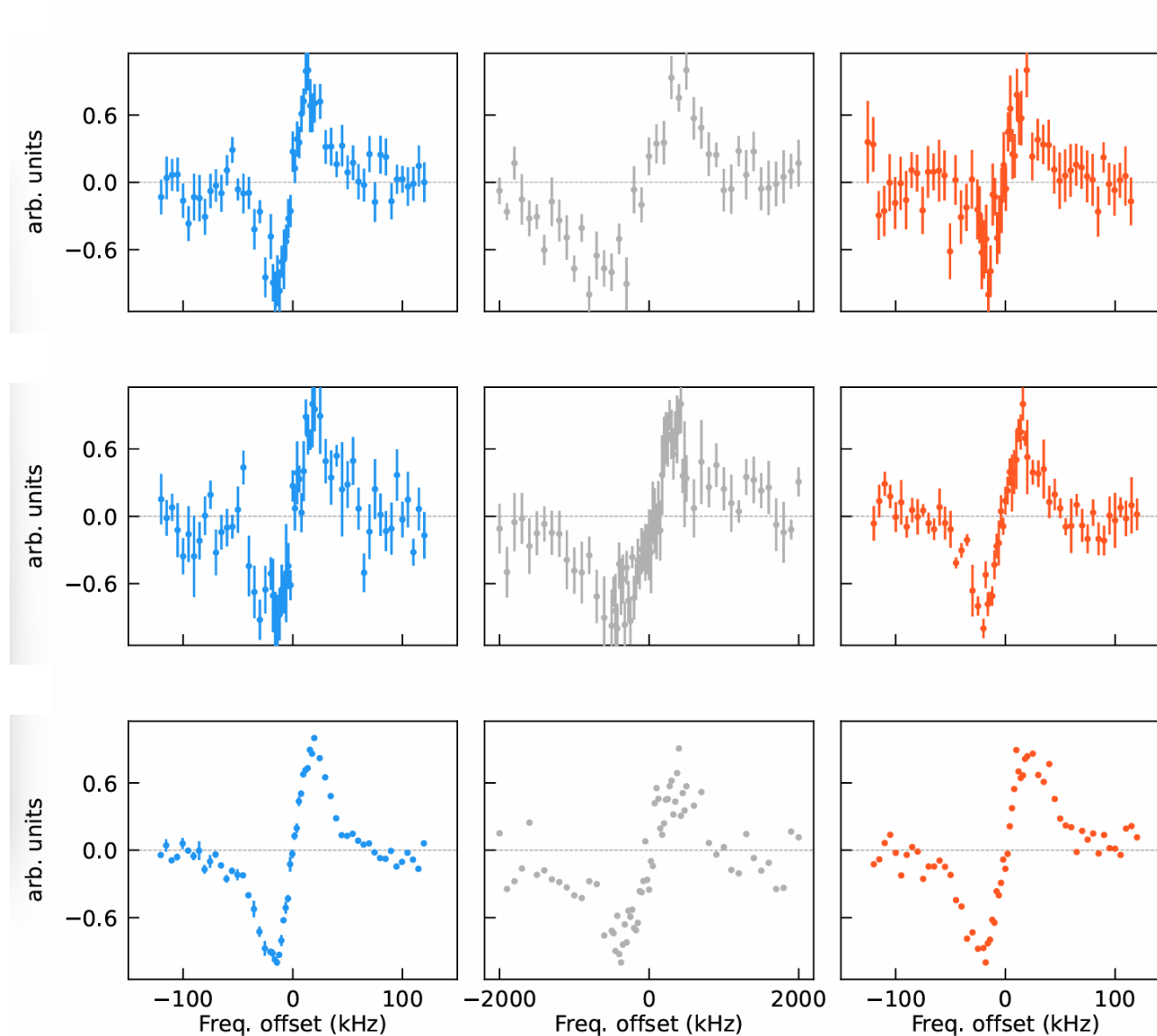
Liangbi Su (SIC)



TS1

- Extremely limited Th-229, single chance for crystal growth
- Temperature-gradient technique
- Concentration  $2.2 \times 10^{17}/\text{cm}^3$
- Diameter 1.09 mm, length 4.94 mm

# CW laser absorption spectroscopy

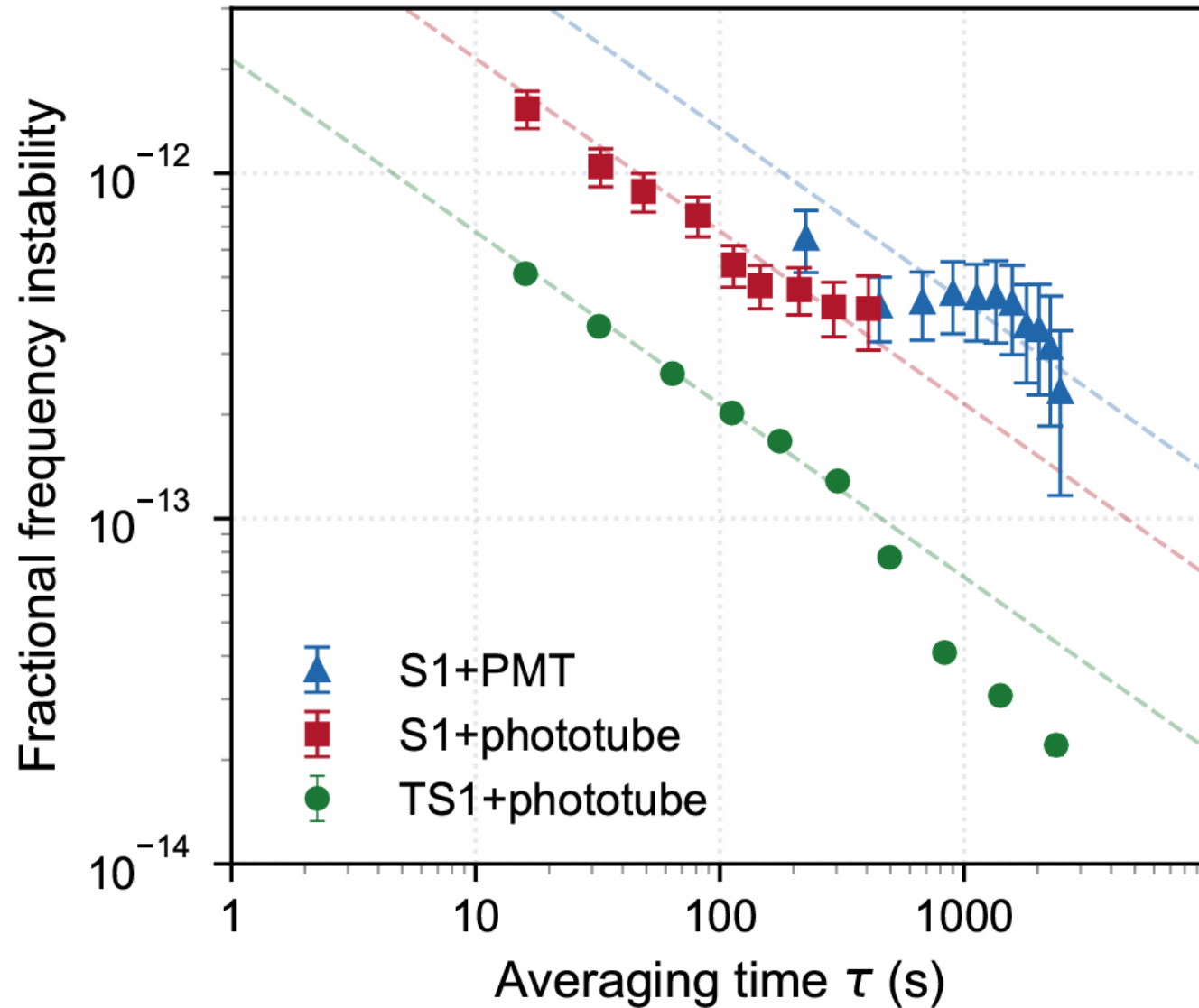


- S1+PMT
- Each data, 80 seconds

- S1+Phototube
- Each data, 40 seconds

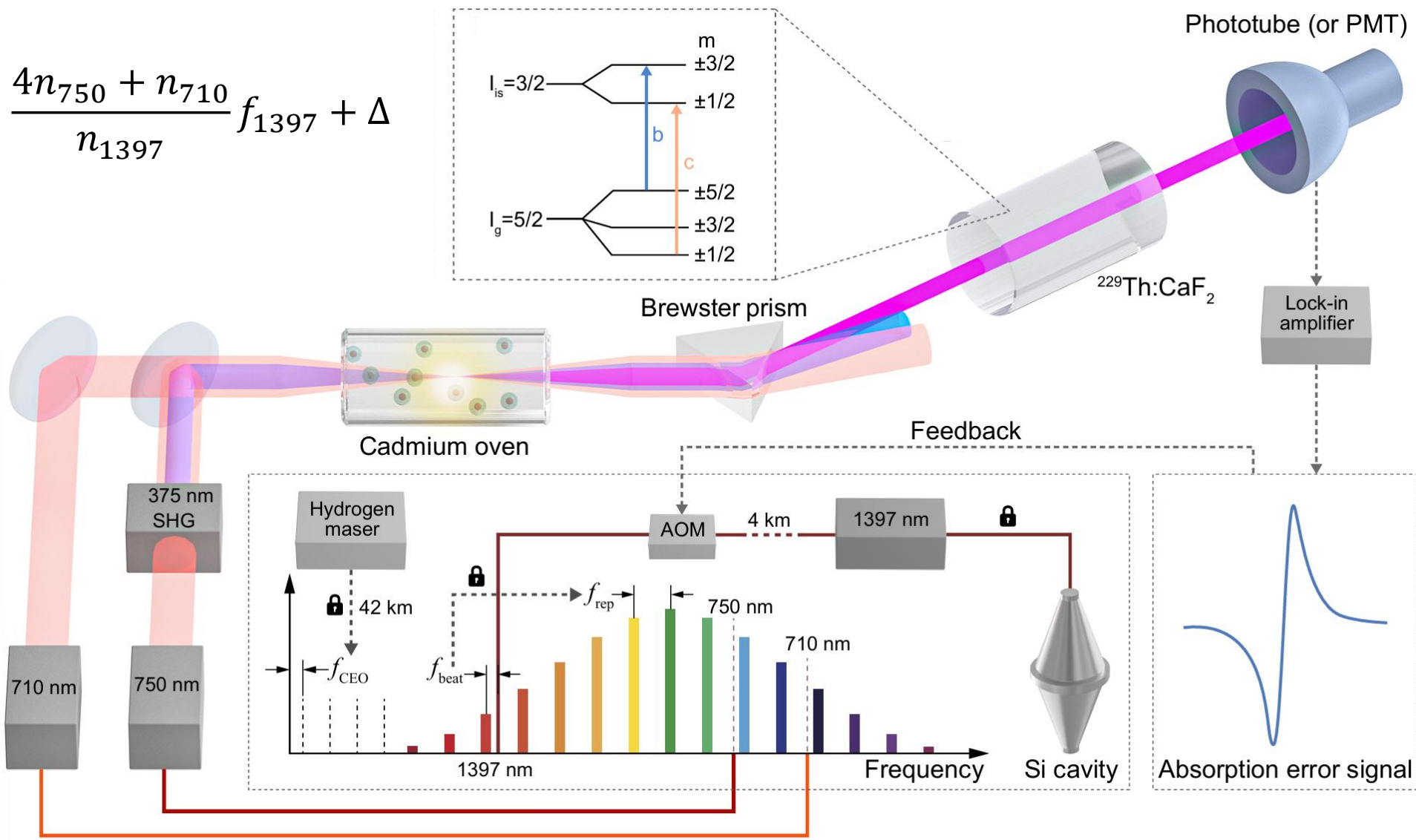
- TS1+Phototube
- Each data, 10 seconds

# Characterization of clock operation

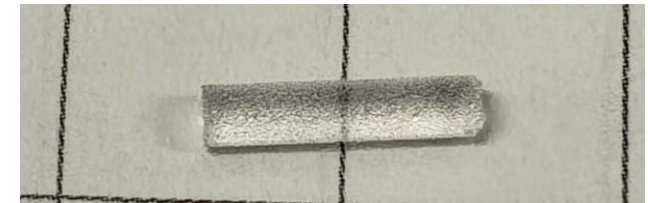
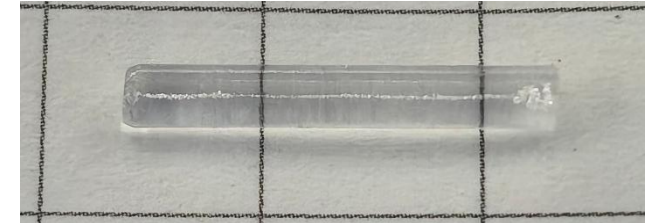
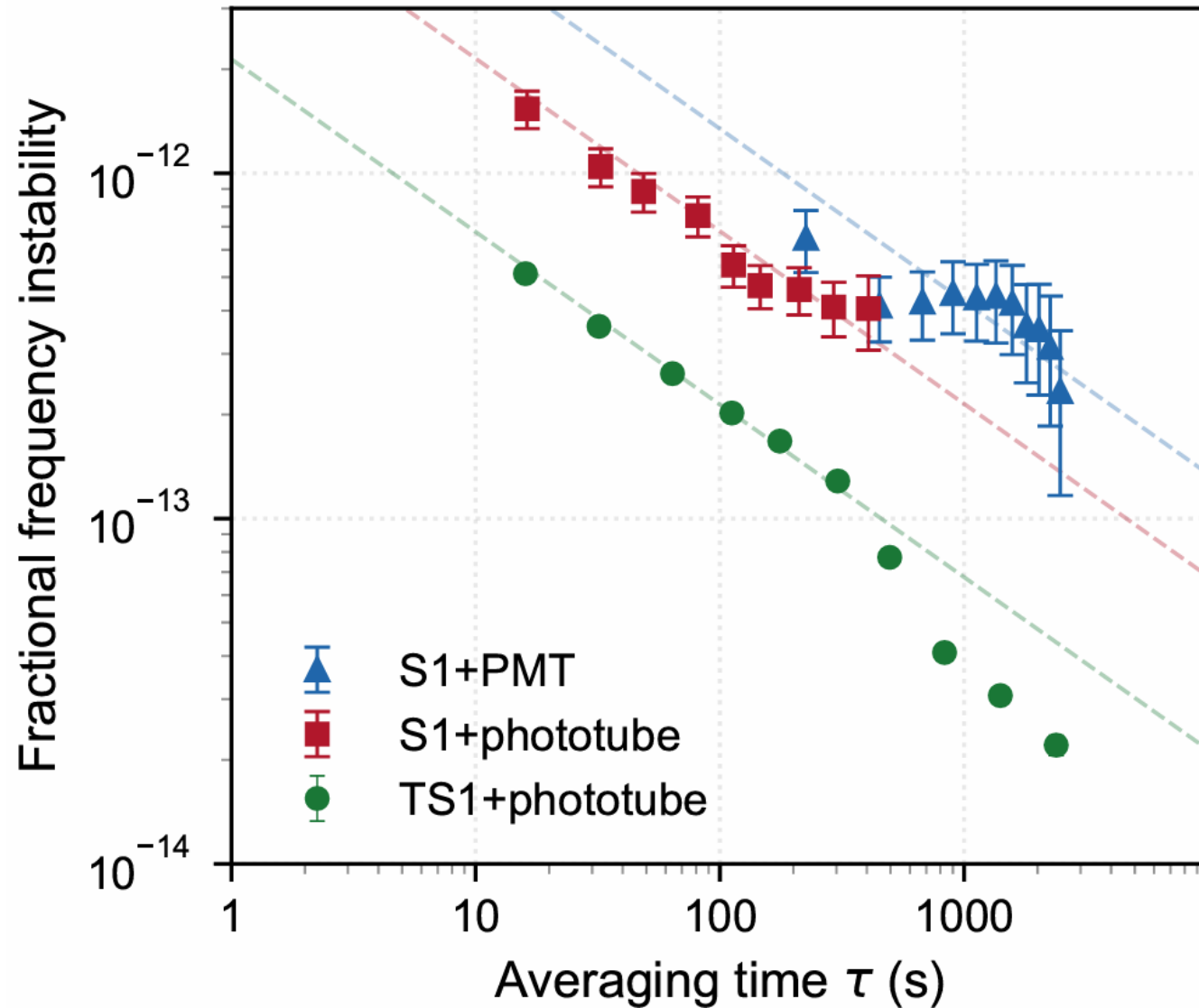


# Close the feedback loop

$$f_{148} = \frac{4n_{750} + n_{710}}{n_{1397}} f_{1397} + \Delta$$



# Characterization of clock operation

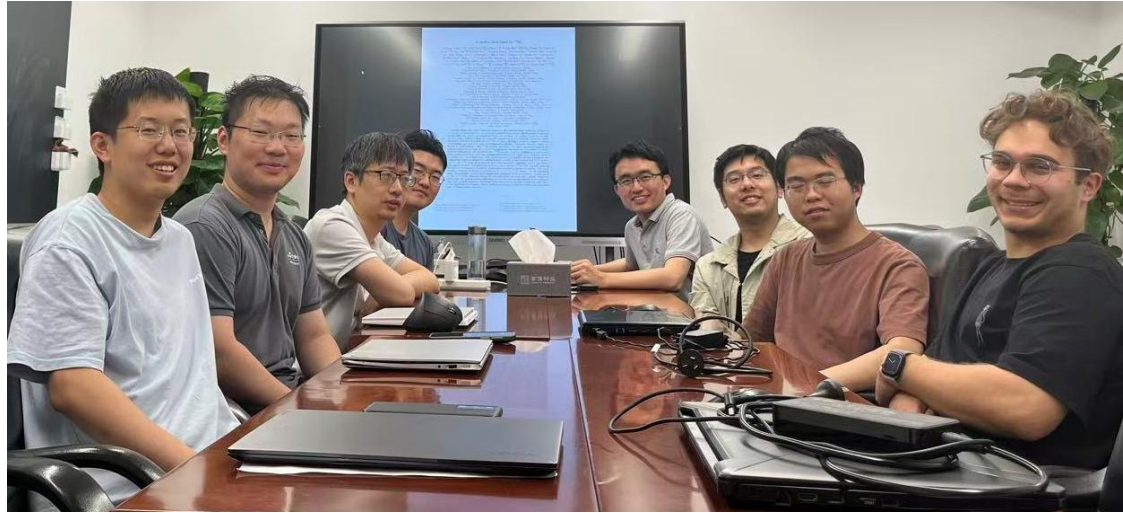


Frequency reproducibility  $10^{-13}$

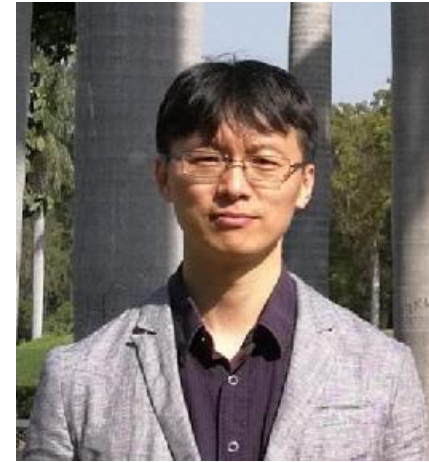
# Summary: CW laser spectroscopy and clock operation

- **CW 148 FWM generation in Cd vapor**
- **Phase noise and linewidth**
- **$^{229}\text{Th}:\text{CaF}_2$  crystal growth**
- **Fluorescence spectroscopy**
- **Absorption spectroscopy**
- **Clock operation**

# Acknowledgement



Tsinghua team



Yigen Lin (NIM)



Xibo Zhang (PKU)



Yin Hang (SIOM)



Liangbi Su (SIC)

