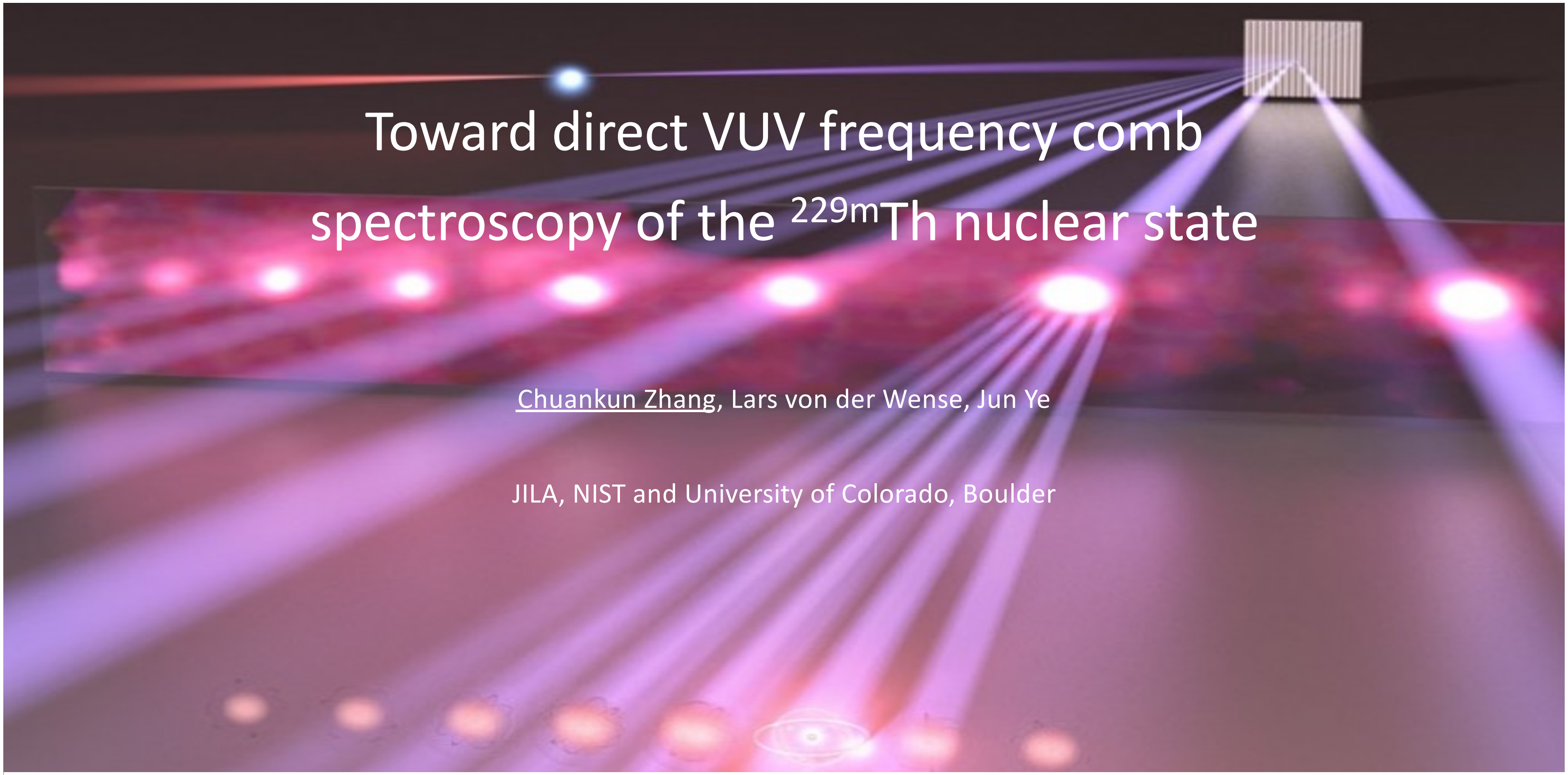


Toward direct VUV frequency comb spectroscopy of the ^{229m}Th nuclear state

Chuankun Zhang, Lars von der Wense, Jun Ye

JILA, NIST and University of Colorado, Boulder

New opportunities with a nuclear-based optical clock

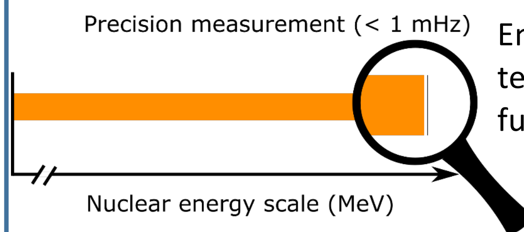
JILA

Accurate nuclear-based optical clock

Resistent to external perturbations
10^{-19} predicted clock accuracy

E. Peik et al., Europhys. Lett. **61,** 181 (2003)
C. J. Campbell et al., Phys. Rev. Lett. **108,** 120802 (2012)

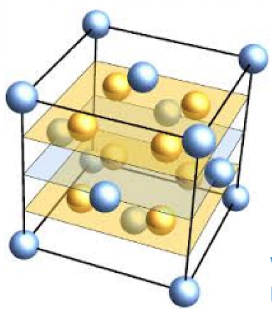
Sensitive probe for fundamental physics



Enhanced sensitivity for temporal variation of fundamental constants

V. V. Flambaum, Phys. Rev. Lett. **97,** 092502 (2006)
P, Fadeev et al., Phys. Rev. A **102,** 052833 (2020)

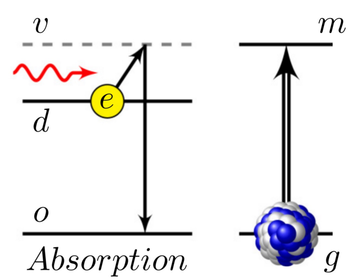
Solid-state optical clock



Decoupled from electronic states
Large statistics for high clock stability
Portable optical clock

W.G. Rellergert et al., Phys. Rev. Lett. **104,** 200802 (2010)
L. v.d.Wense et al., Eur. Phys. J. D **74,** 146 (2020)

A fundamentally new quantum system



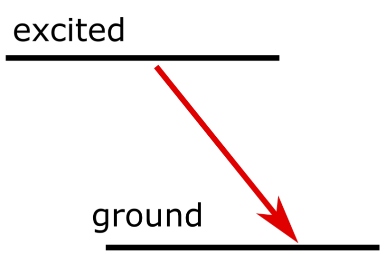
New probe for coupling between nuclear and electronic states

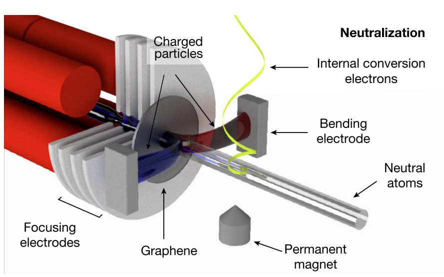
B. S. Nickerson et al., Phys. Rev. A **103,** 053120 (2021)

Improved energy determination made direct laser spectroscopy possible

JILA

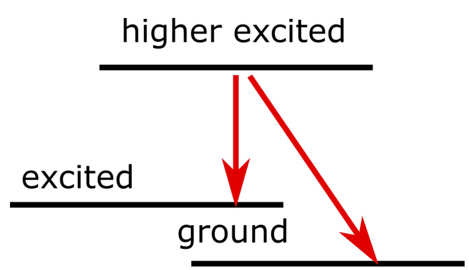
Probing direct decay

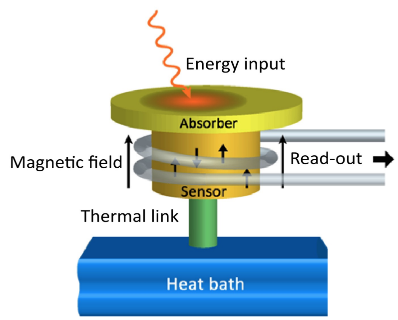




B. Seiferle et al., Nature **573,** 243 (2019)

Indirect γ-ray spectroscopy



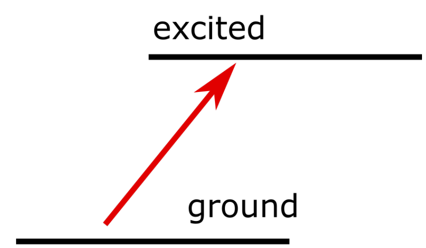


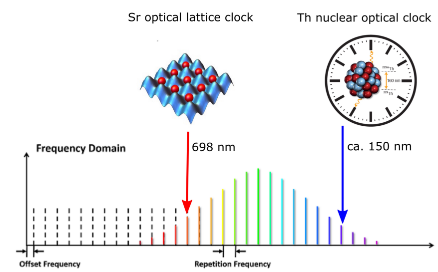
T. Sikorsky et al., Phys. Rev. Lett. **125**, 142503 (2020)

8.12 ± 0.11 eV
152.7 ± 2.1 nm

Promises
10^6 improvement

Direct laser excitation

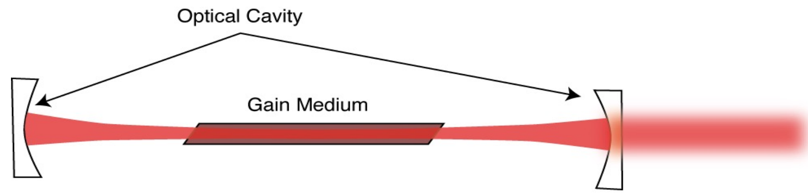




L. v.d.Wense, C. Zhang Eur. Phys. J. D **74**, 146 (2020)

No CW lasers operating at 8.1 eV (153 nm) today!

JILA



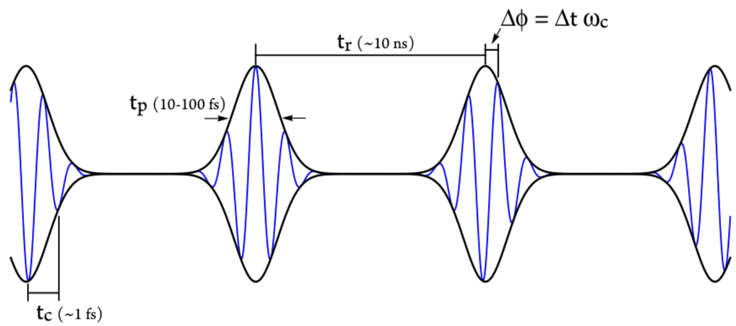
Direct lasing at 153 nm nearly impossible:

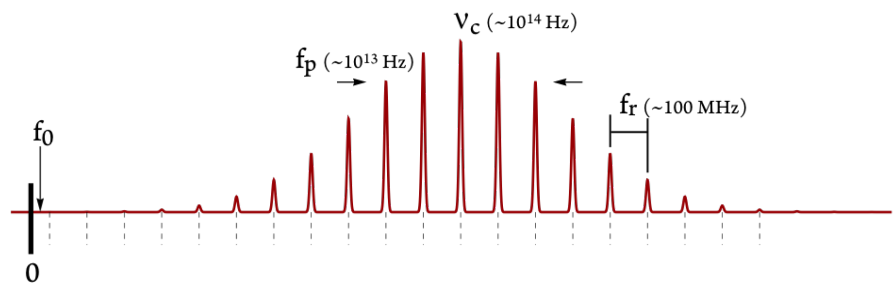
- Lack of transparent materials ⇒ No gain medium
- Poor optics performance ⇒ No high finesse cavity

Nonlinear frequency conversion to 153 nm:

- No phase-matched nonlinear crystals ⇒ Nonlinear conversion in gas/thin film ⇒ **Pulsed operation** for high peak intensity
- Drive nuclear clock transition ⇒ **Narrow laser linewidth** required

Optical Frequency Comb



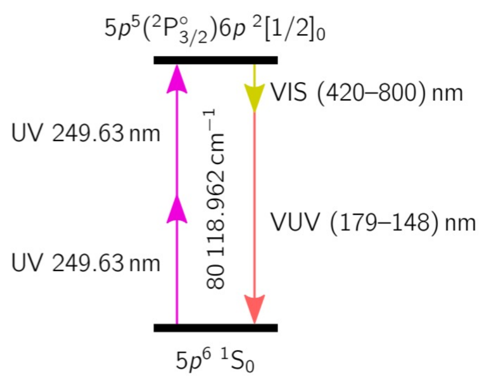


S. T. Cundiff et al., Rev. Mod. Phys. **75,** 325 (2003)

Laser systems for nuclear spectroscopy

JILA

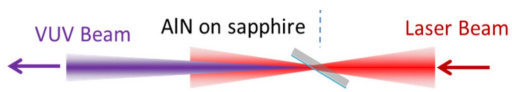
Resonant four-wave mixing



Broadband pulsed ns laser, suitable for intial transition search

J. Jeet, PhD thesis (2018)
E. Peik et al., Quantum Sci. Technol. **6,** 034002 (2021)
L. v.d.Wense et al., Hyperfine Interact **240,** 23 (2019)

5th harmonic of Ti:Sapph



Solid state coherent frequency comb
Low power (<1 µW demonstrated)

J. Seres et al., , Opt. Exp. **27**, 6618 (2019)

7th harmonic of Yb:fiber comb

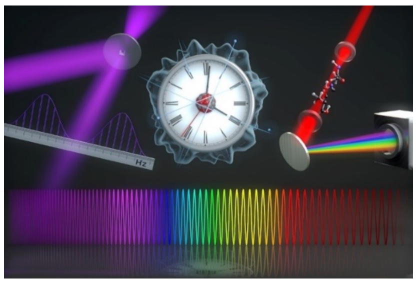
Coherent frequency comb
High power (>500 µW)

C. Zhang et al., Phys. Rev. Lett. **125,** 093902 (2020)
L. v.d.Wense, C. Zhang, Eur. Phys. J. D **74**, 146 (2020)

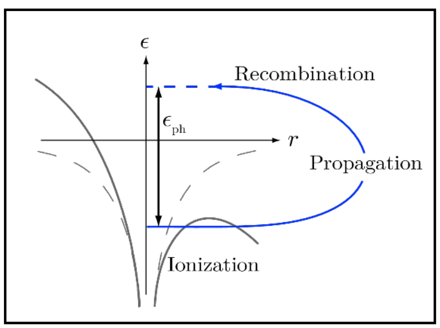
Frequency combs in the vaccum to extreme ultraviolet (XUV)

JILA

Precision spectroscopy



Strong field physics



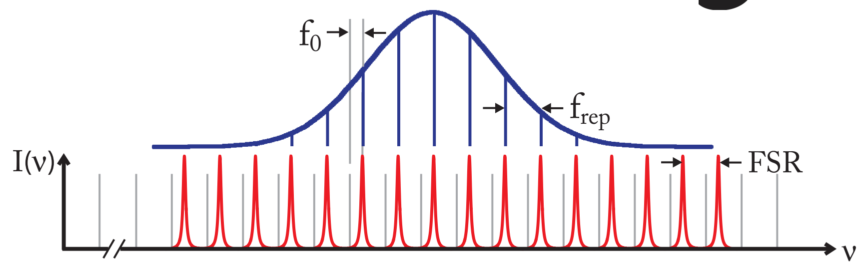
Frequency comb:
High repetition rate
(10s - 100s of MHz)

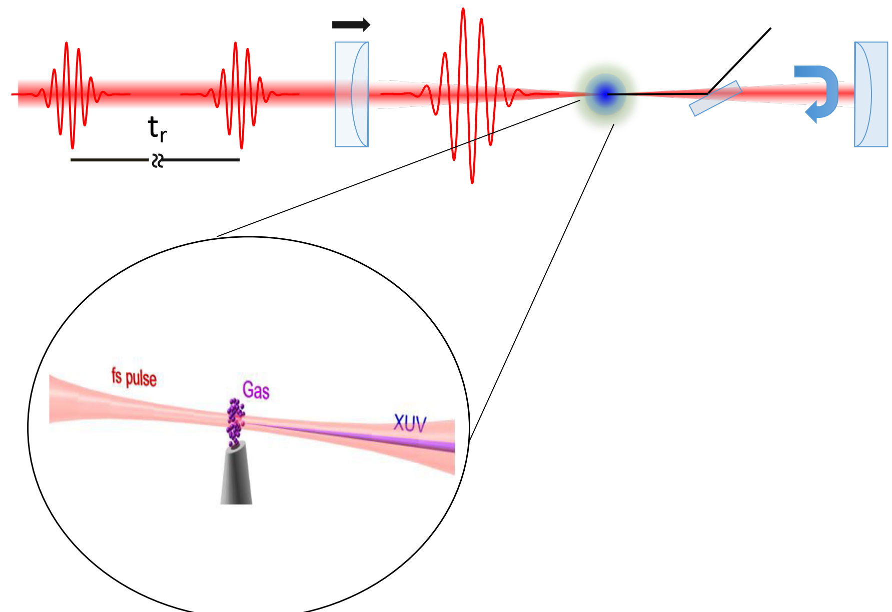
↓

coherent fs laser with
~ 10 kW of average power!

↑

Non-perturbative
harmonic generation:
High intensity
($10^{13} – 10^{15}$ W/cm^2)



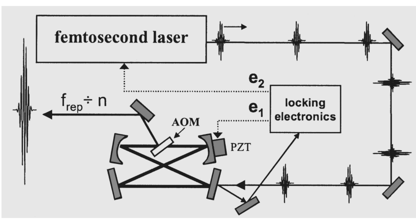


R. J. Jones et al., Phys. Rev. Lett. **94**, 193201 (2005)
C. Gohle et al., Nature **436**, 234 (2005)
I. Pupeza, C. Zhang et al., Nat. Photon. **15,** 175 (2021)

20 years of development effort for frequency combs in the XUV

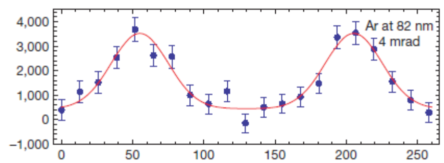
JILA

Enhancement cavity for IR comb



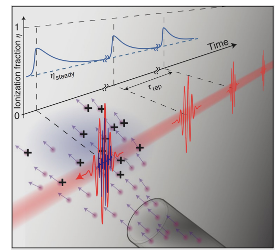
R. J. Jones et al., Opt. Lett. **27,** 1848 (2002)
R. J. Jones et al., Opt. Lett. **29,** 2812 (2004)

XUV comb spectroscopy



A. Cingöz et al., Nature **482**, 68 (2012)

Phase-matched XUV comb generation

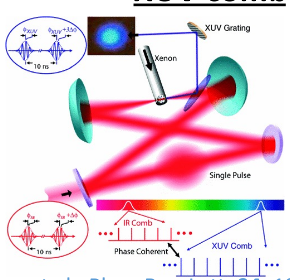


G. Porat et al., Nat. Photon. **12**, 387 (2018)

2000 2005 2010 2015 2020 Time

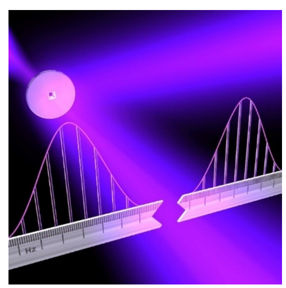
XUV comb

~100 pW



R. J. Jones et al., Phys. Rev. Lett. **94**, 193201 (2005)
C. Gohle et al., Nature **436**, 234 (2005)

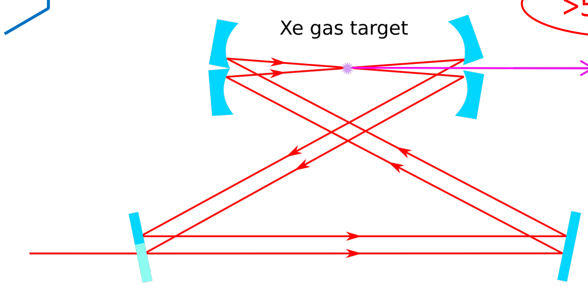
Coherence times > 1s



C. Benko et al., Nat. Photon. **8**, 530 (2014)

Efficient XUV outcoupling

>500 uW



C. Zhang et al., Phys. Rev. Lett. **125,** 093902 (2020)

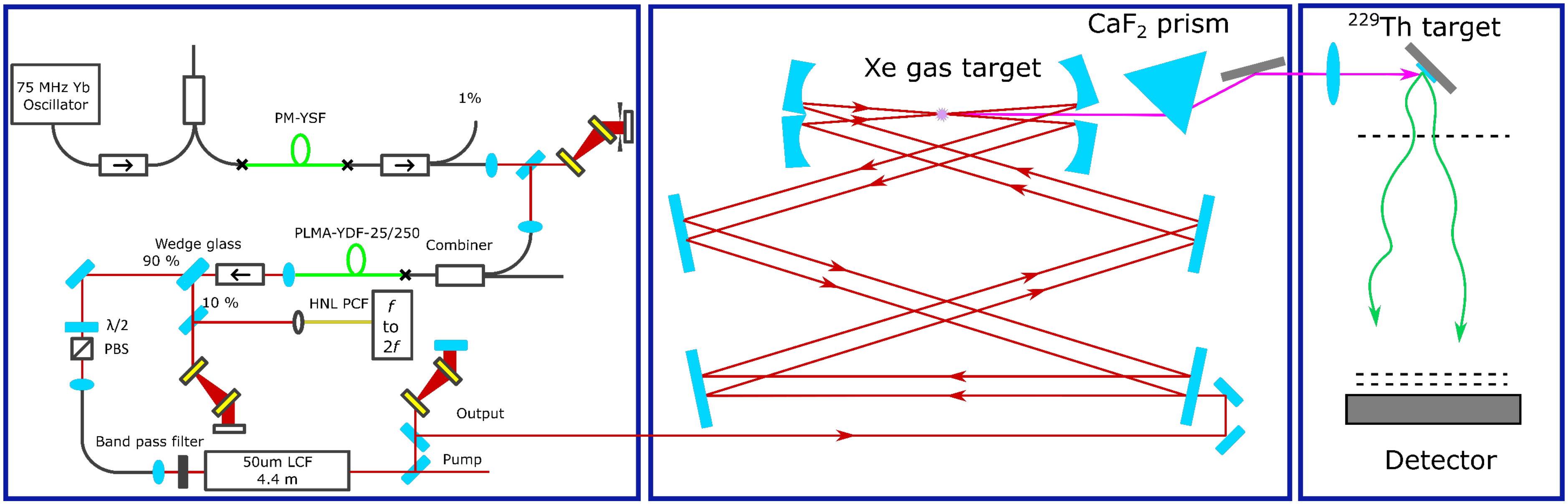
Experimental setup for ^{229m}Th nuclear spectroscopy

JILA

Tunable high-power Yb:fiber frequency comb

Enhancement cavity for 7^{th} harmonic generation

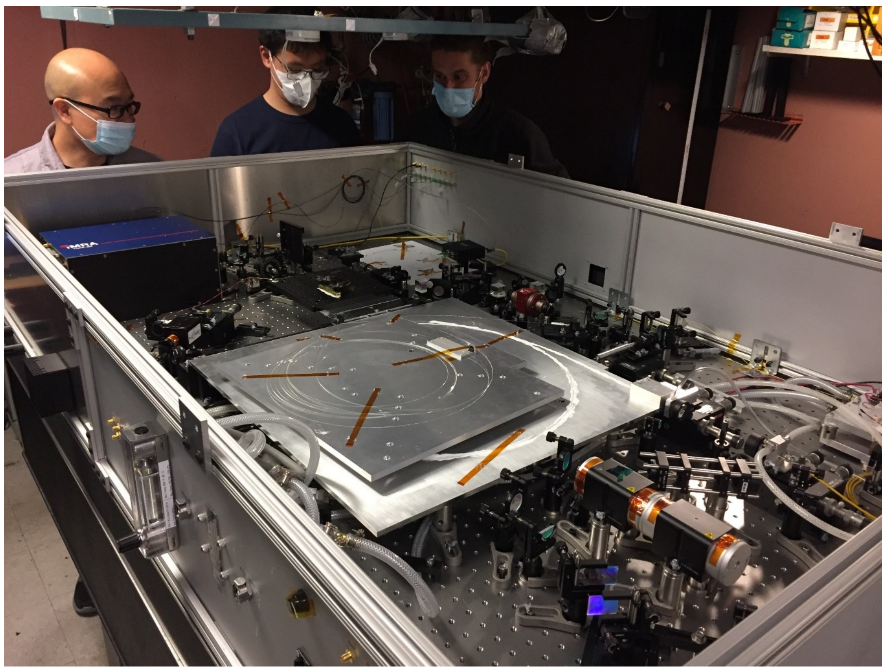
Detection system



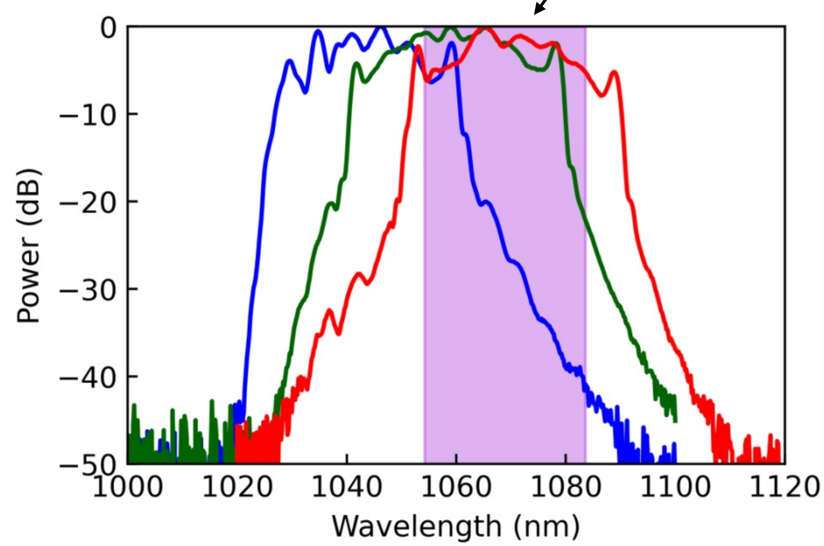
First tunable high-power Yb:fiber laser for ^{229m}Th spectroscopy

JILA

IMRA



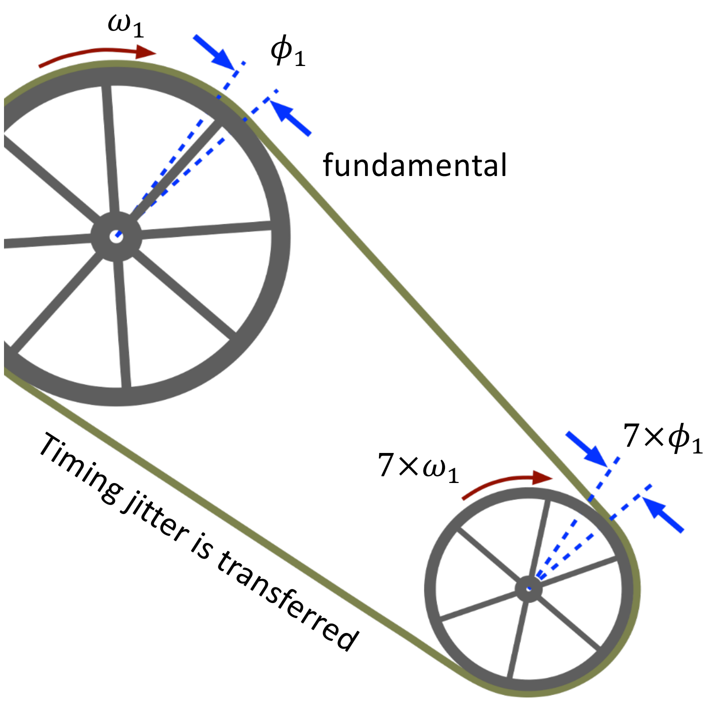
1-sigma uncertainty range of ^{229m}Th transition in 7th harmonic

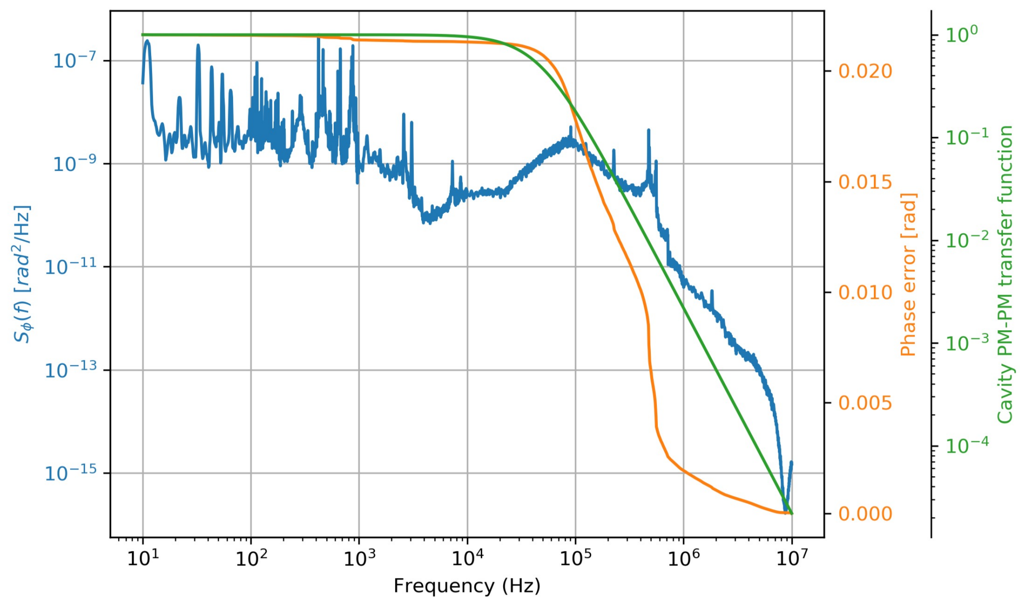


75MHz, 150 fs, 50W, central wavelength tunable from 1040 to 1070 nm

Low-phase-noise comb designed for coherent VUV frequency comb generation

JILA

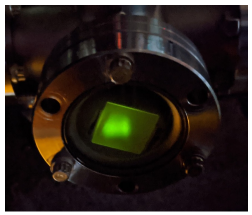


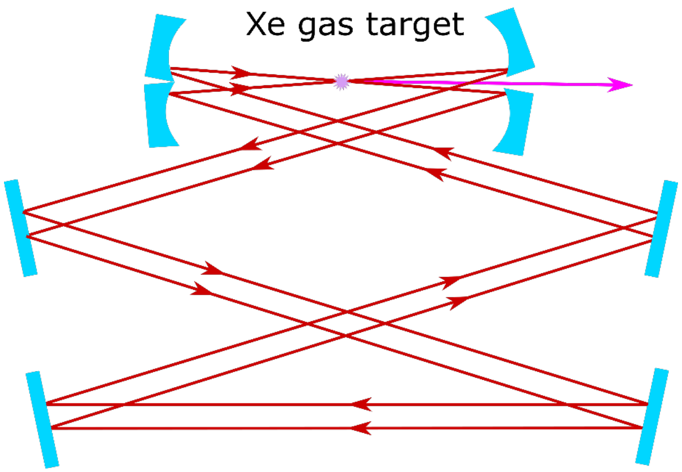


>97% power remains in VUV comb carrier

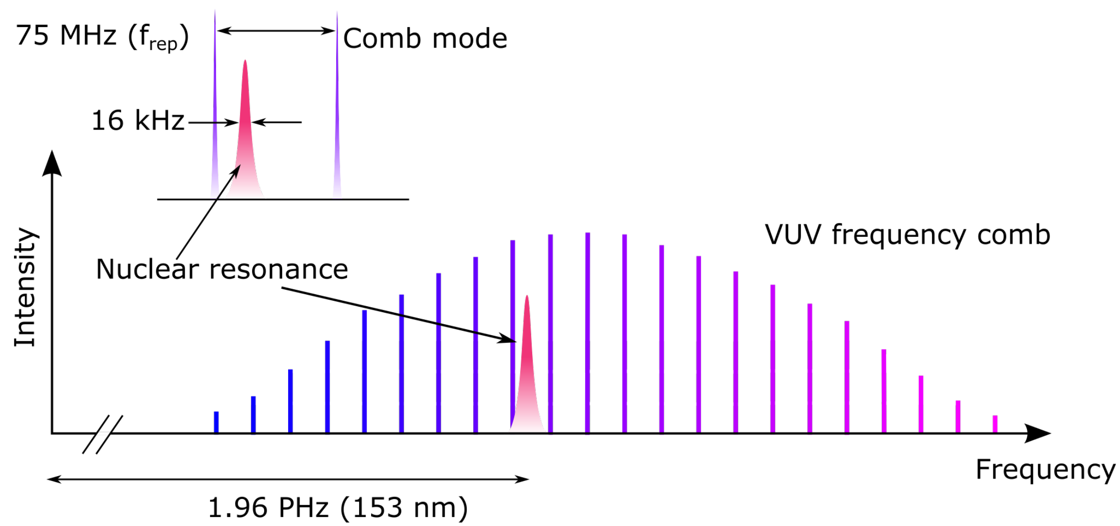
C. Benko et al., Nat. Photon. **8**, 530 (2014)
http://rubiola.org

VUV frequency comb



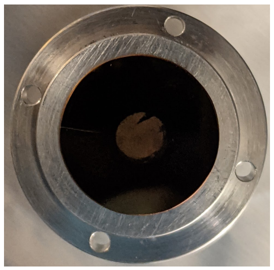


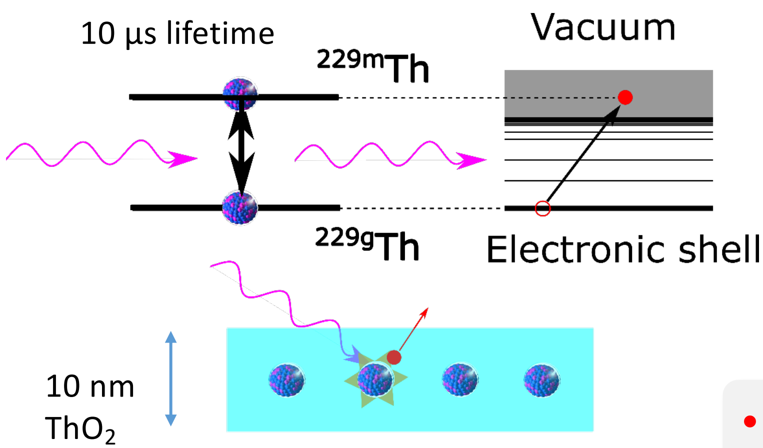
- 5 nW per frequency comb mode
- 10^5 comb modes scanning in parallel
- Direct determination of nuclear transition frequency

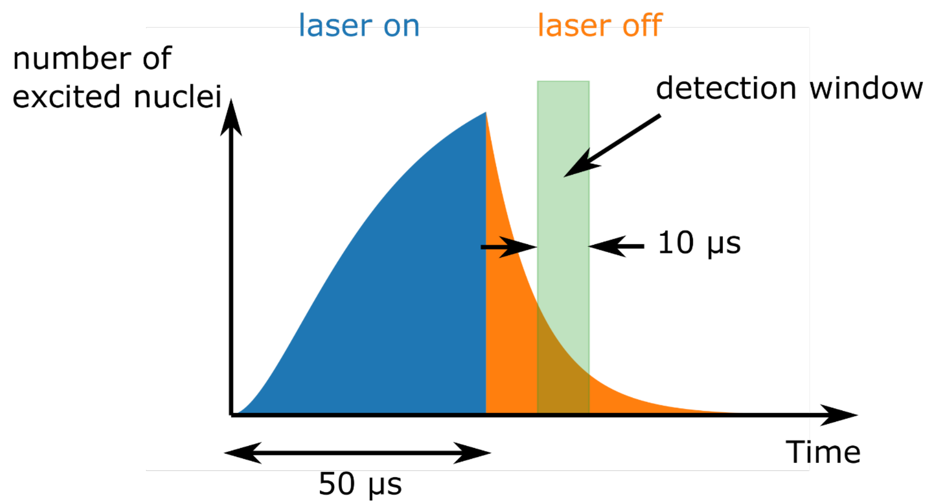


C. Zhang et al., Phys. Rev. Lett. **125,** 093902 (2020)
L. v.d.Wense, C. Zhang, Eur. Phys. J. D **74**, 146 (2020)

Laser excitation of the ^{229m}Th nuclear state in a solid state sample





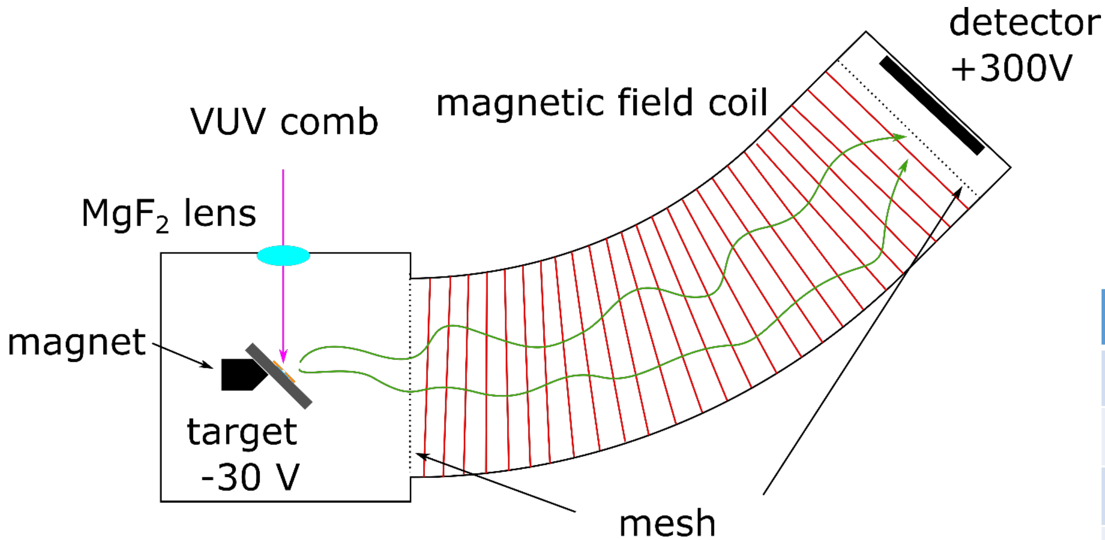


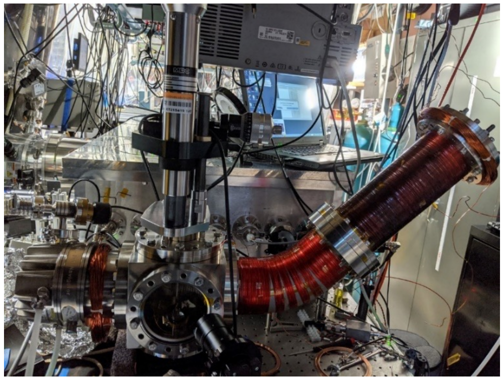
- 10^{13} nuclei irradiated in parallel
- Internal conversion channel for fast detection
- Electron detection allowing high SNR

L. v.d.Wense et al., Phys. Rev. Lett. **119,** 132503 (2017)
L. v.d.Wense, C. Zhang, Eur. Phys. J. D **74**, 146 (2020)

Detection system

JILA





Parameters	Values
Laser power	5 nW/mode
Laser linewidth	1 kHz
Sample thickness	10 nm
Quantum efficiency	5%
Detection efficiency	50%
Background	200 counts/s
SNR	50 in 3 hours

Summary and outlook

JILA

^{229m}Th energy determination

VUV frequency comb development

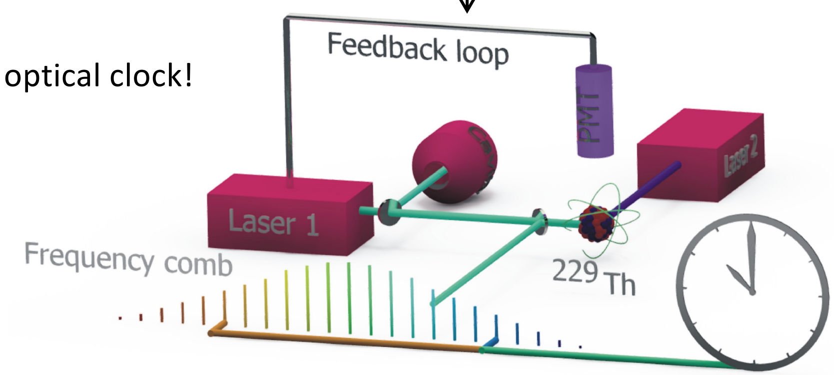
Novel spectroscopy scheme

↓

Direct frequency comb spectroscopy of ^{229m}Th

↓

^{229m}Th-based optical clock!




Thank you!
Jun Ye
Lars von der Wense
Jack Doyle