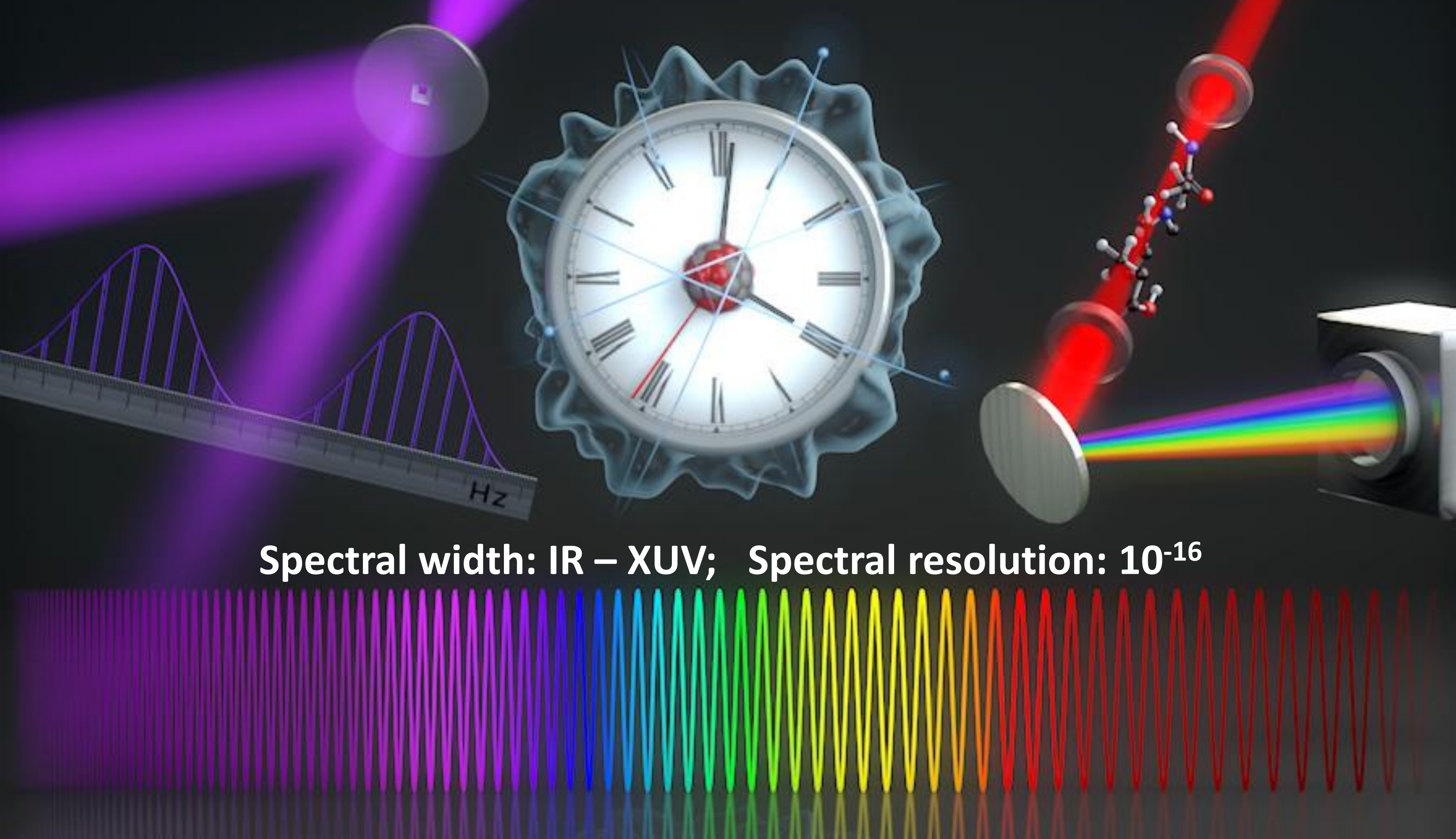
From XUV comb to X-ray comb?

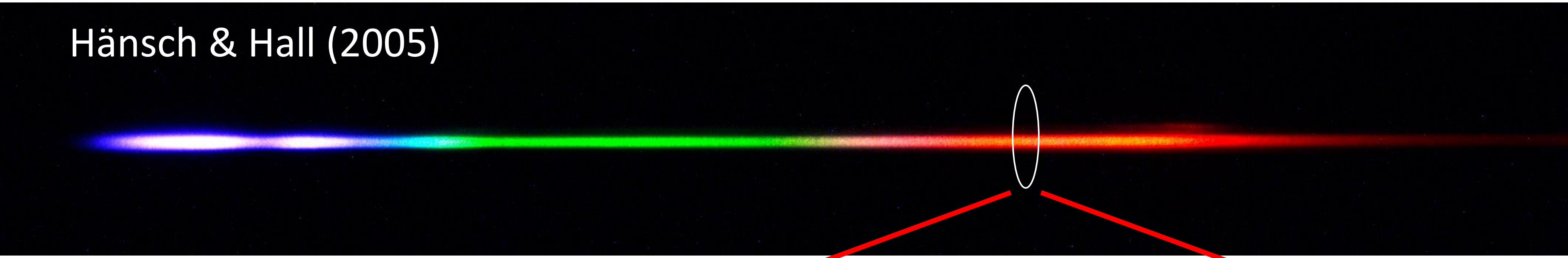
Jun Ye, JILA, NIST & Univ. of Colorado

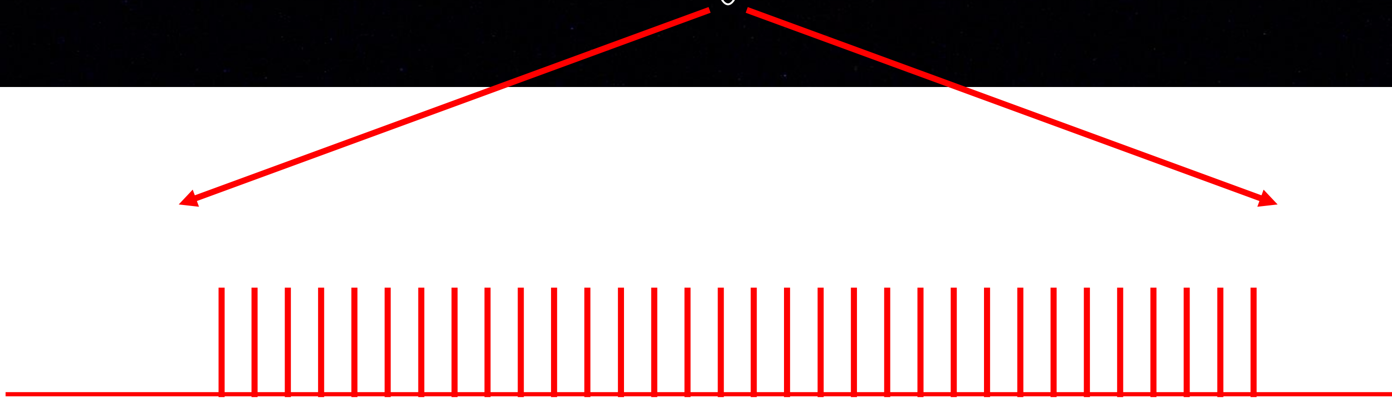


Spectral width: IR – XUV; Spectral resolution: 10^{-16}

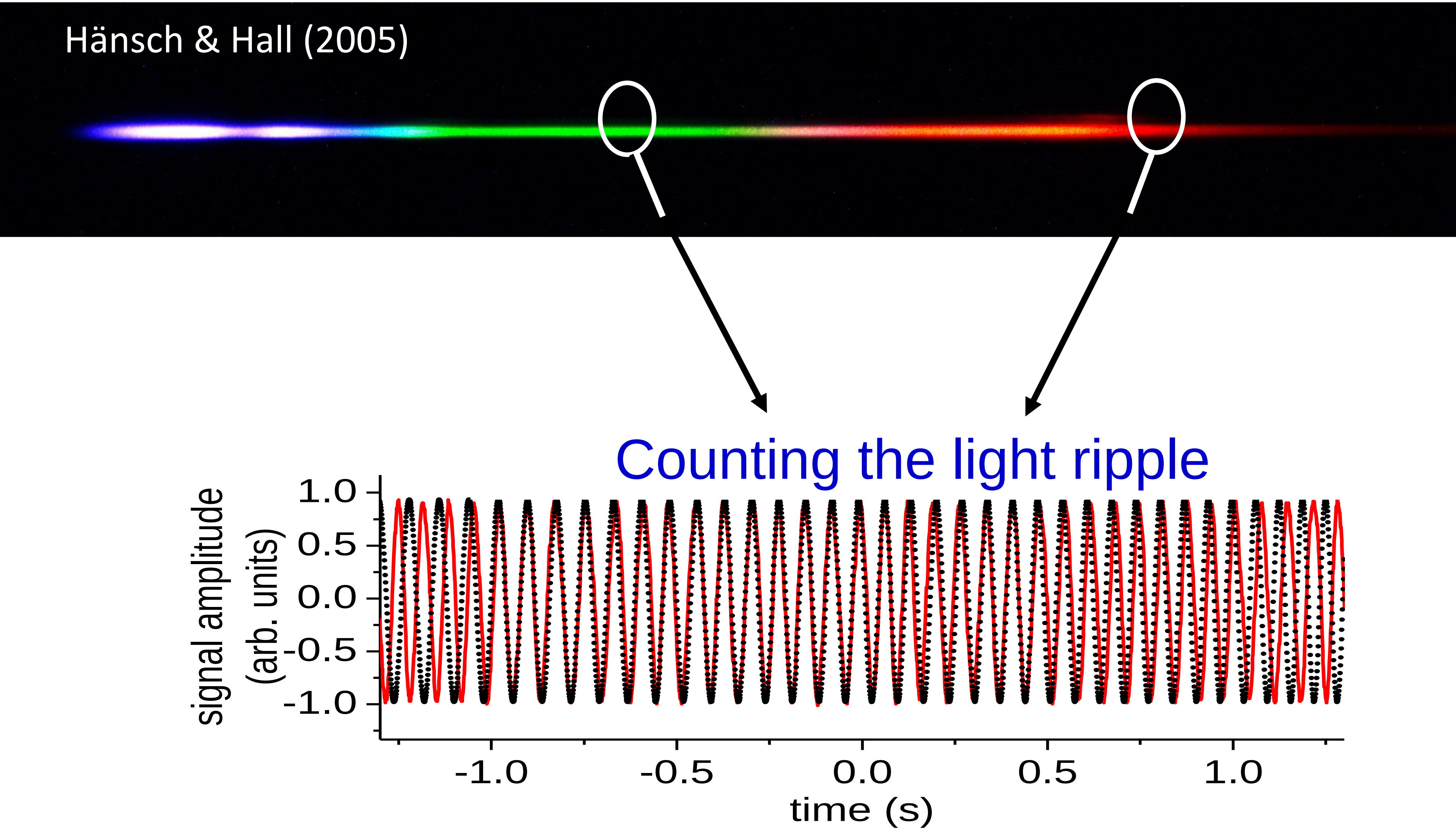
XFELO Workshop, Stanford, June 30, 2016

Optical frequency comb - millions of stable lasers



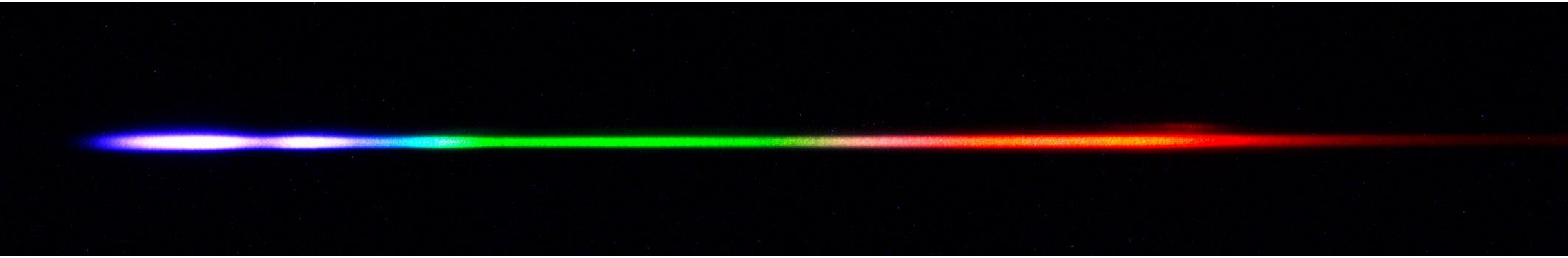


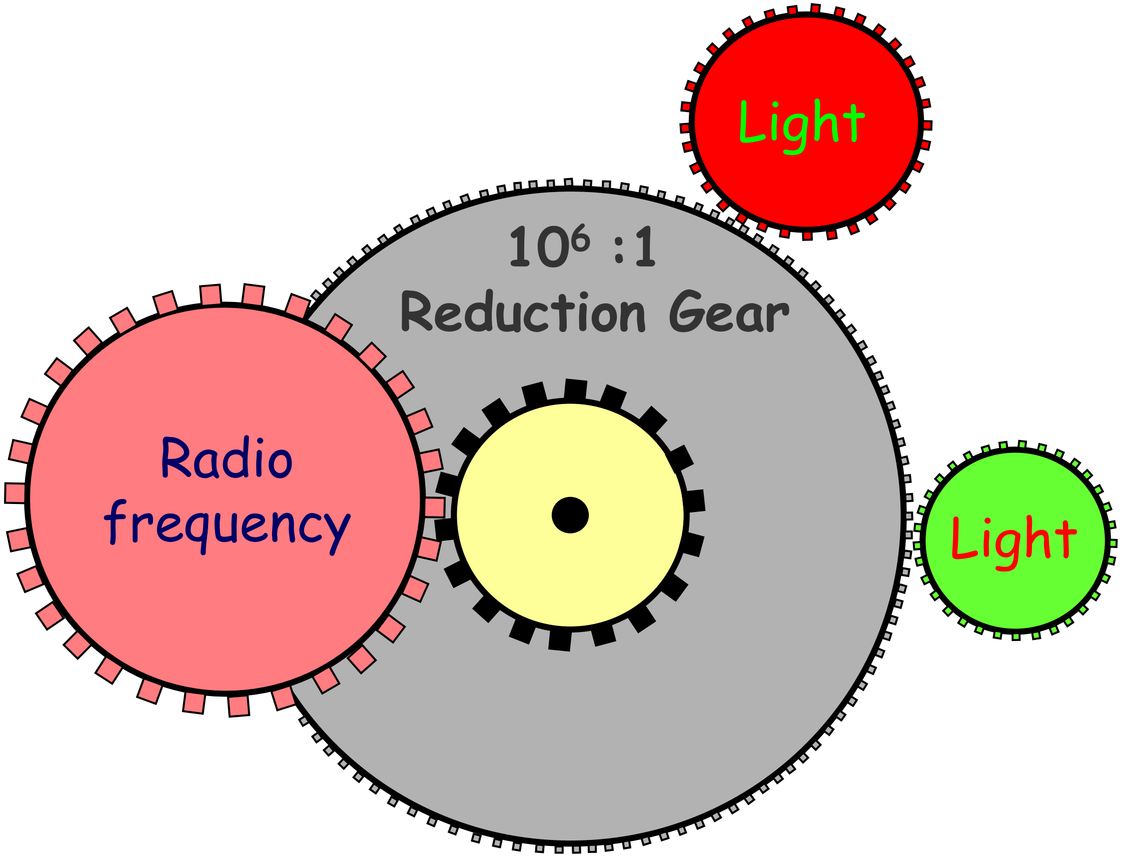
Optical frequency comb – millions of stable lasers



Optical coherence time > 1 s, anywhere in the visible, Nature Photon. **2**, 355 (2008).

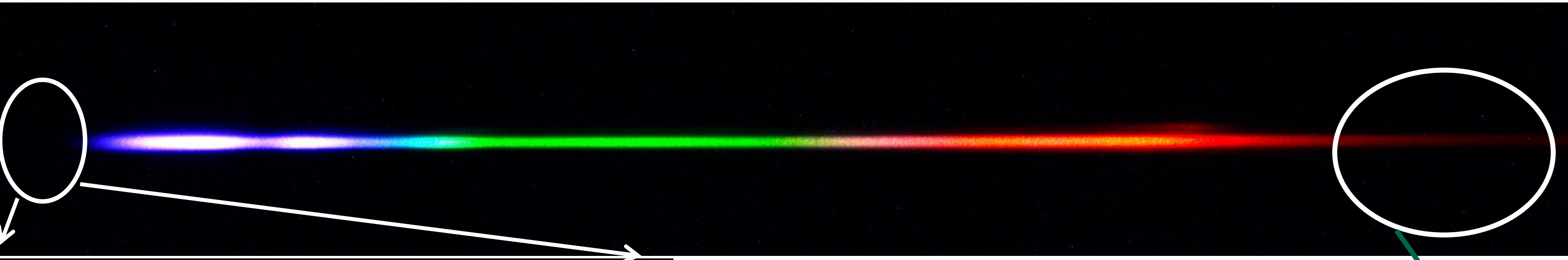
Optical frequency comb – millions of stable lasers

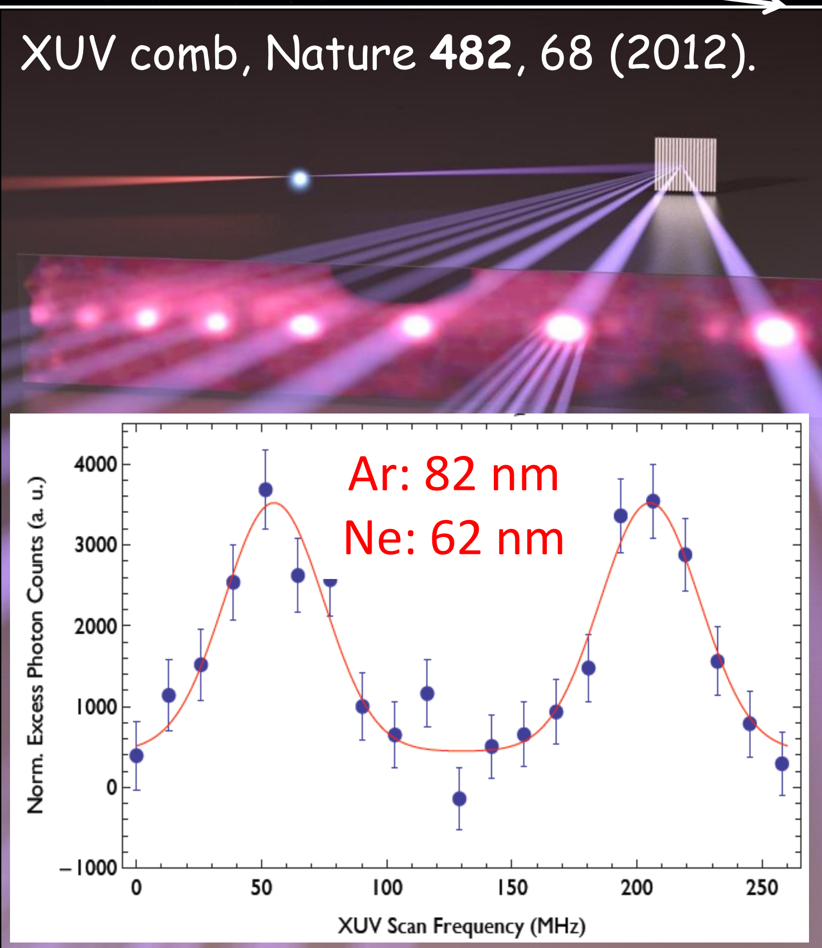


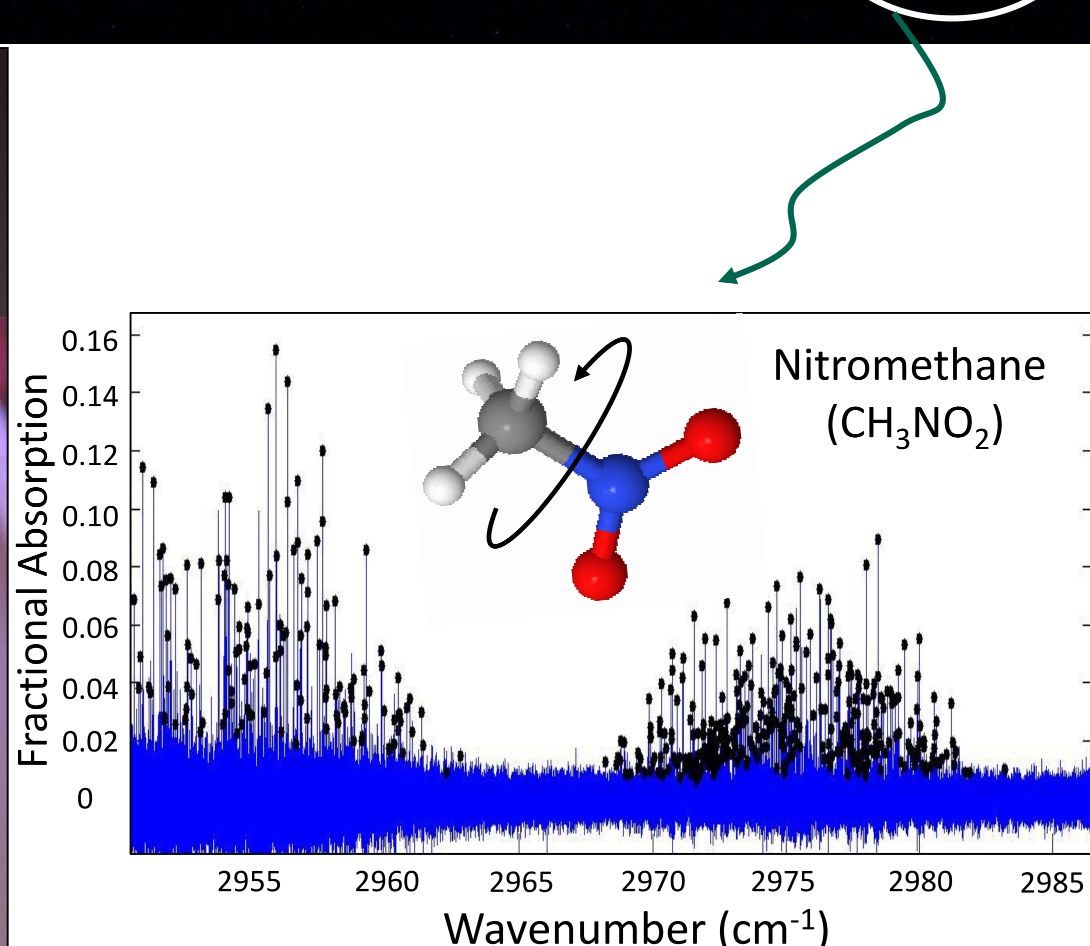


Optical coherence time > 1 s, anywhere in the visible, Nature Photon. **2**, 355 (2008).

Optical frequency comb – millions of stable lasers







Lessons from XUV comb

- How to produce XUV radiation at high repetition frequency ? (repetition period << decoherence time)

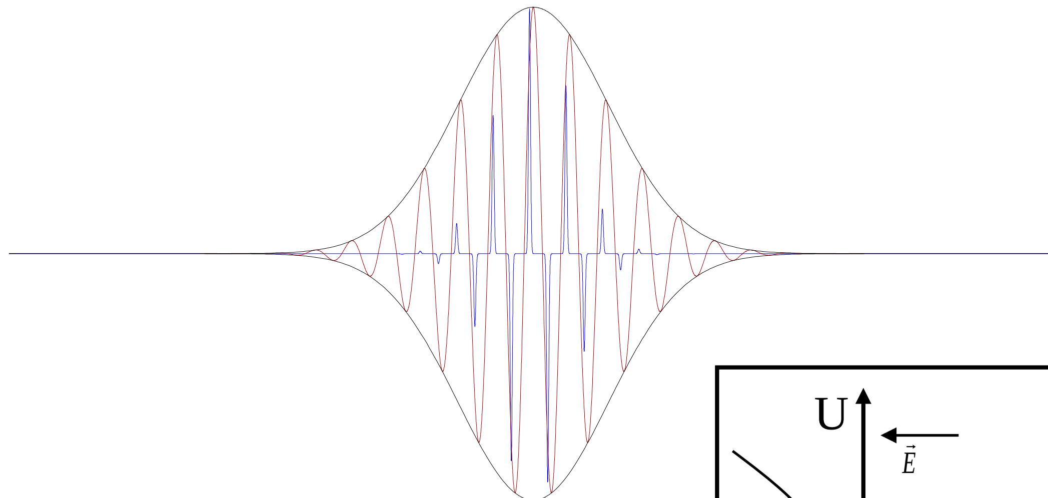
- How to scale up power of the coherent source for applications ?

- How to maintain coherence in the radiation & how to measure/characterize it ?

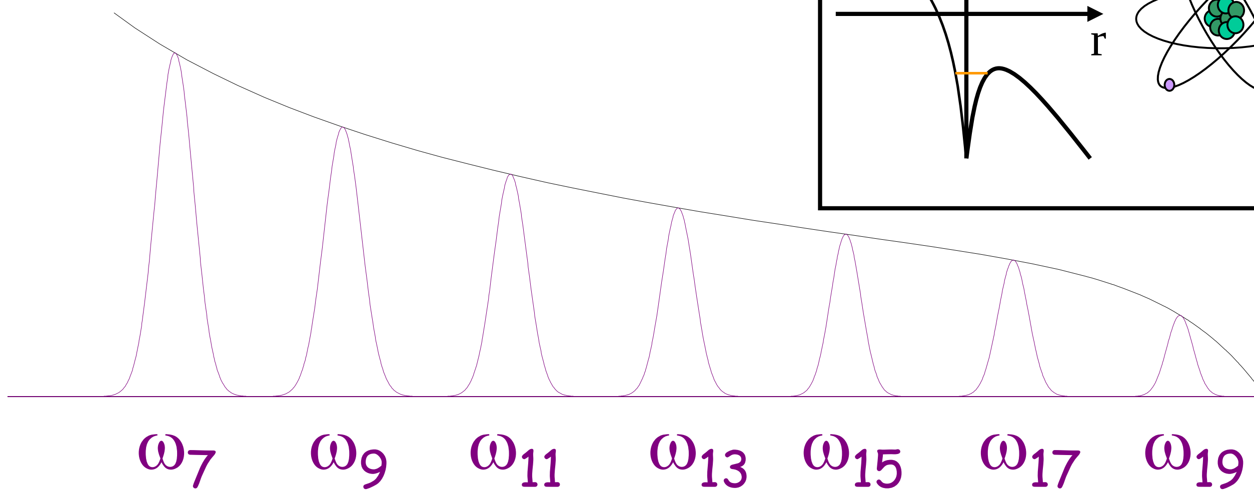
Coherent VUV and XUV radiation

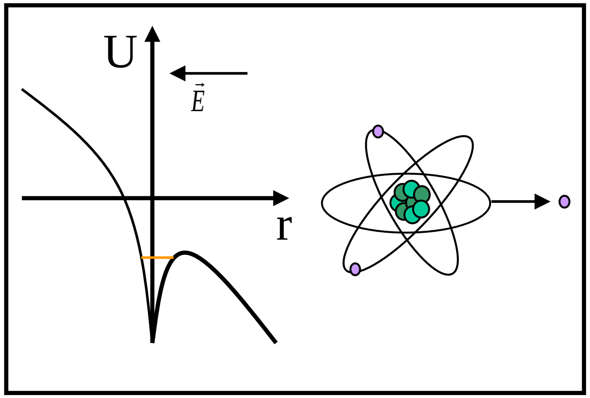
Harmonic Generation with a single IR pulse - *a train of attosecond pulses*

Time domain



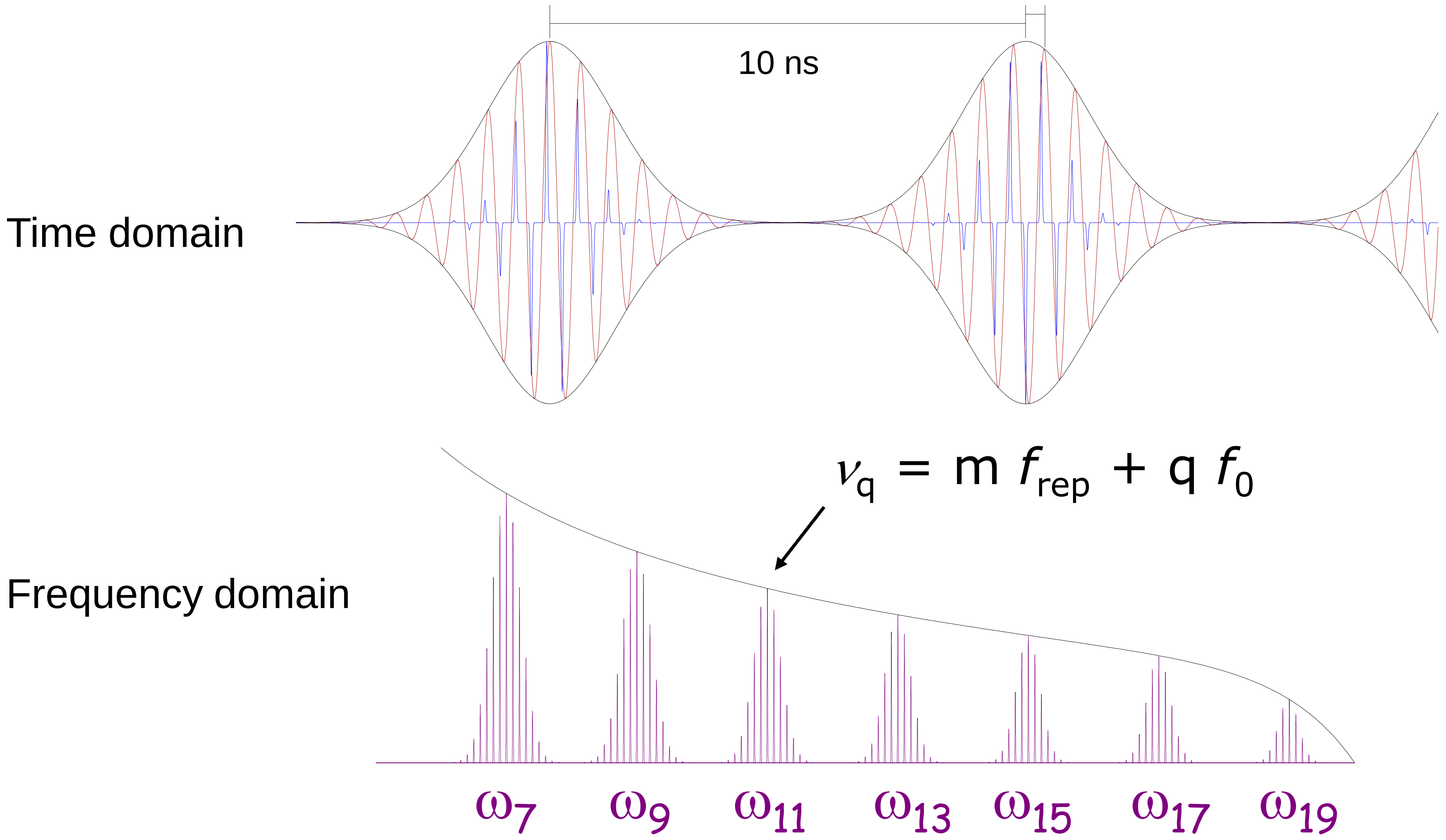
Frequency domain



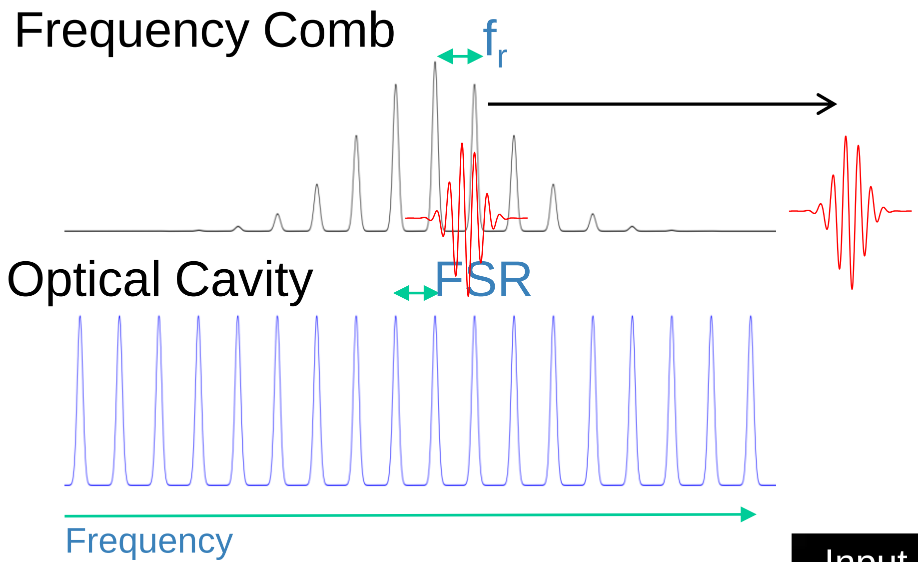


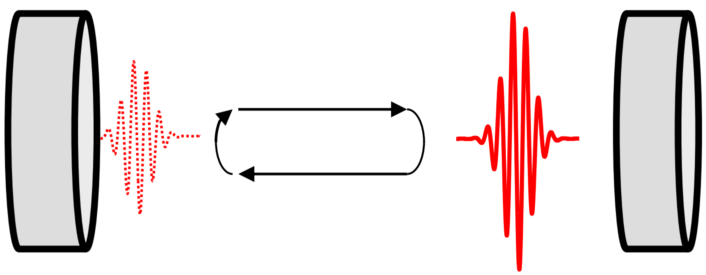
Coherent VUV and XUV radiation

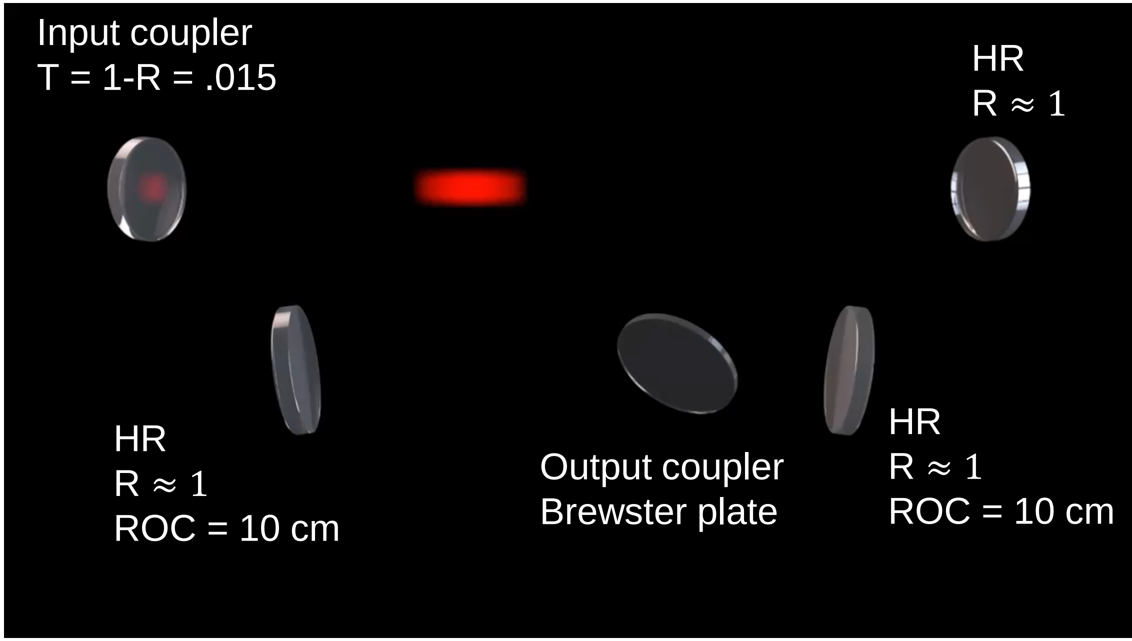
Harmonic Generation with a train of IR pulses-
The XUV frequency comb is born



Enhancement cavity for HHG







Typical Laser Parameters

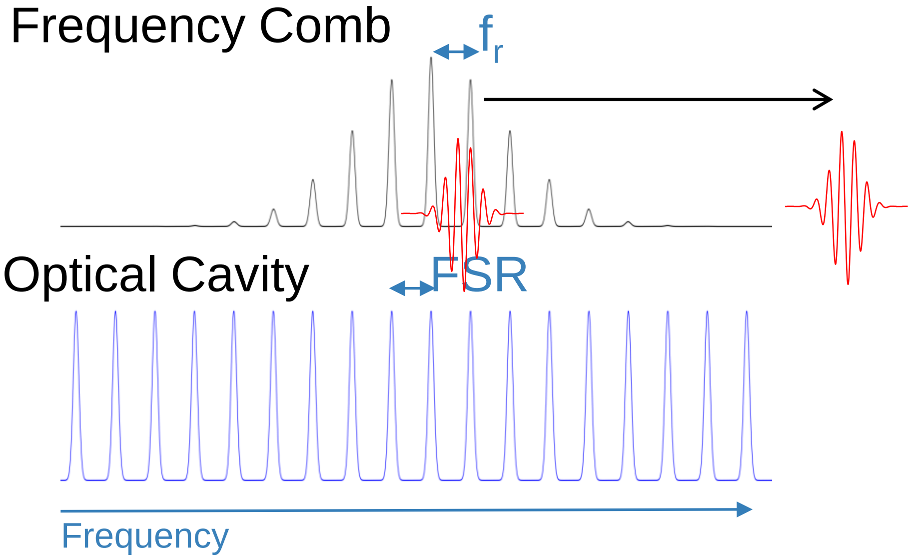
~ **0.5 μJ** pulse energy

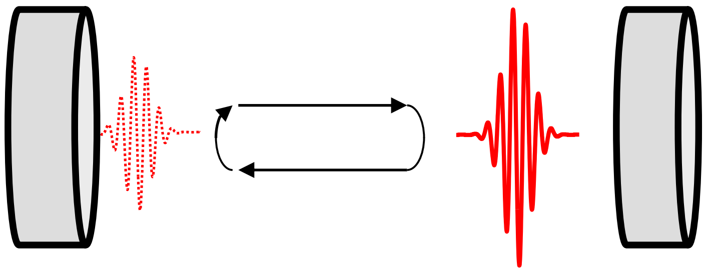
150 MHz repetition rates

10-80 W average power

1070 nm center wavelength

Enhancement cavity for HHG





Typical Intracavity Parameters

200-400 µJ pulse energy
150 MHz repetition rates
2-15 kW average power
Preserves repetition rate
Recycles unused light
"Tight focus" HHG

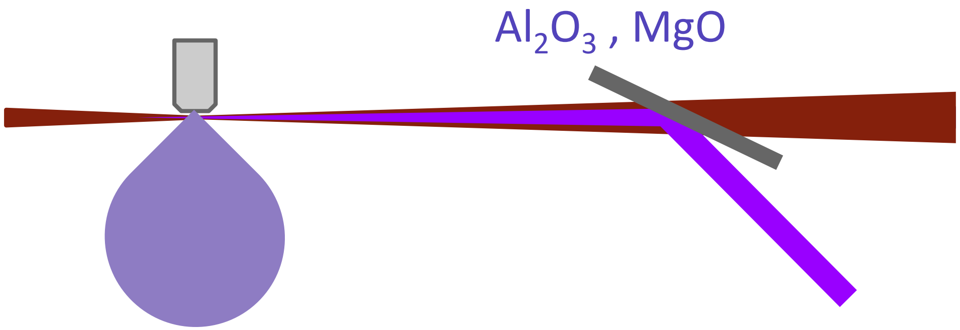
More power and more sensitivity.
Clean, well-defined mode.
Interaction length increase by $\frac{F}{\pi}$.

FSR = c/L

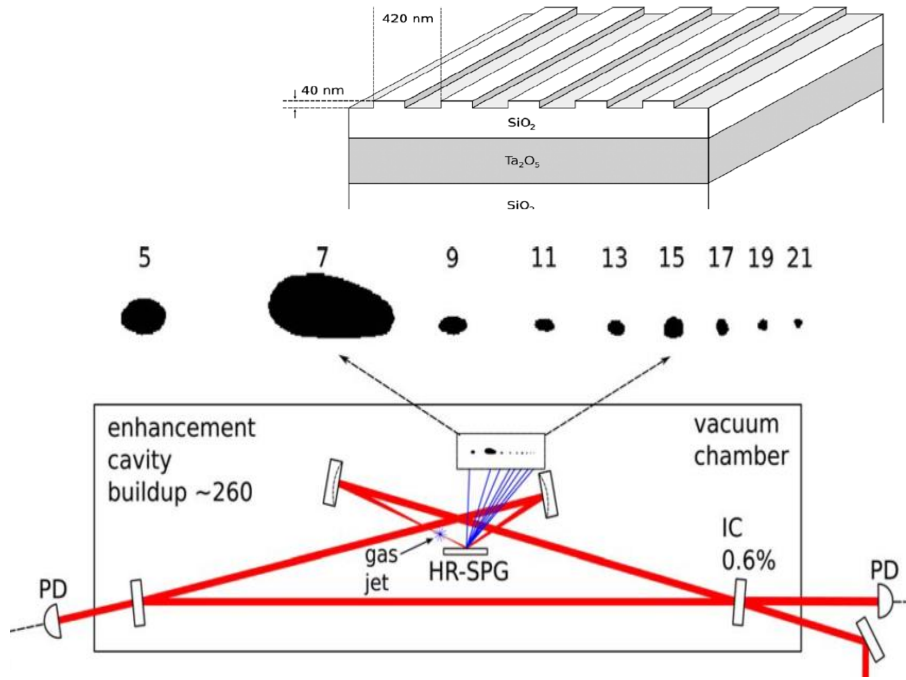
$$F = \frac{2\pi}{Loss}$$

Buildup = $T\frac{F^2}{\pi^2}$

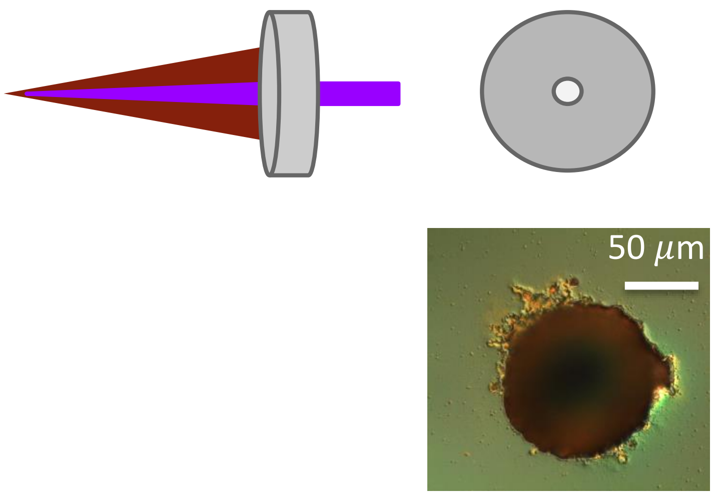
Out-coupling the XUV

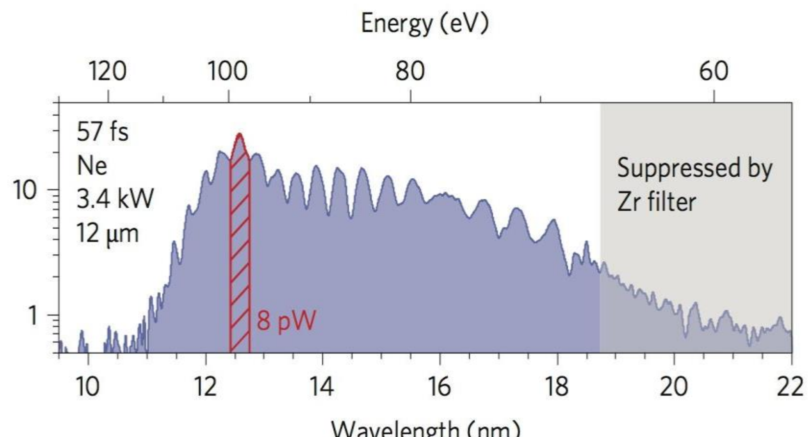


Jones *et al.* **PRL** (2005), Gohle *et al.* **Nature** (2005)



Yost *et al.* **Opt. Lett.** (2008)





Geometric output coupling is a promising route to XUV combs below 10 nm.

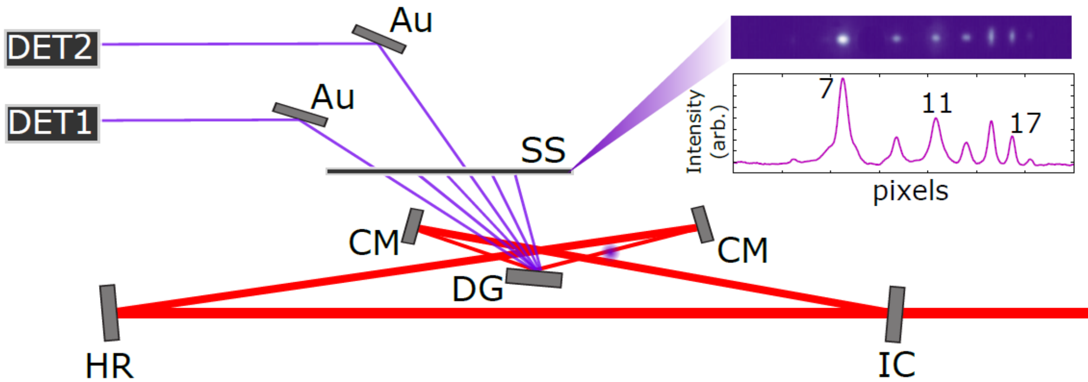
Moll *et al.* **Opt. Exp**. (2006)

Pupeza *et al.* **Nat. Phot.** (2013) Pupeza *et al.* **PRL** (2014)

The XUV laser pointer

Harmonic	Target parameters	Generated power	Outcoupled power	Photons/s generated
11^{th} , 12.7 eV	100 µm, 100 PSI, 4:1 mix	0.7 mW	60 µW	$3.4 \times 10^{14}\ \gamma/s$
17^{th}, 19.7 eV	100 µm, 100 PSI, 4:1 mix	0.63 mW	60 µW	$2 \times 10^{14}\ \gamma/s$
11^{th} , 12.7 eV	50 µm, 400 PSI, 4:1 mix	0.84 mW	71 µW	$4 \times 10^{14}\ \gamma/s$
11^{th} , 12.7 eV	50 µm, 275 PSI, 9:1 mix	0.93 mW	78 µW	$4.8 \times 10^{14}\ \gamma/s$

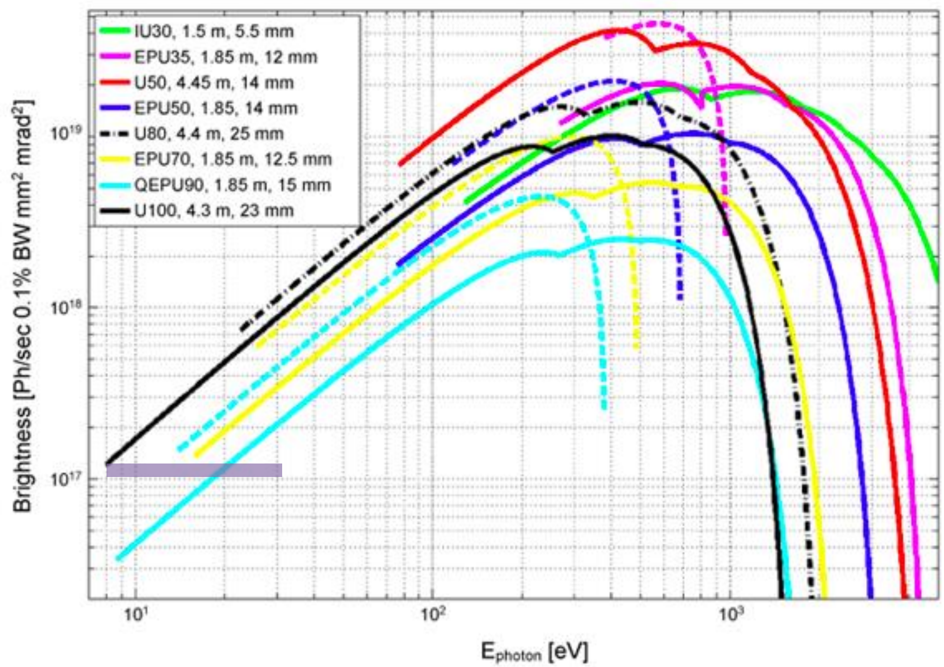
1.2×10^{17} photons /[s mm^2 $mrad^2$ .1% bandwidth]
¼ brightness of the ALS



Benko *et al.* In preparation. 2016

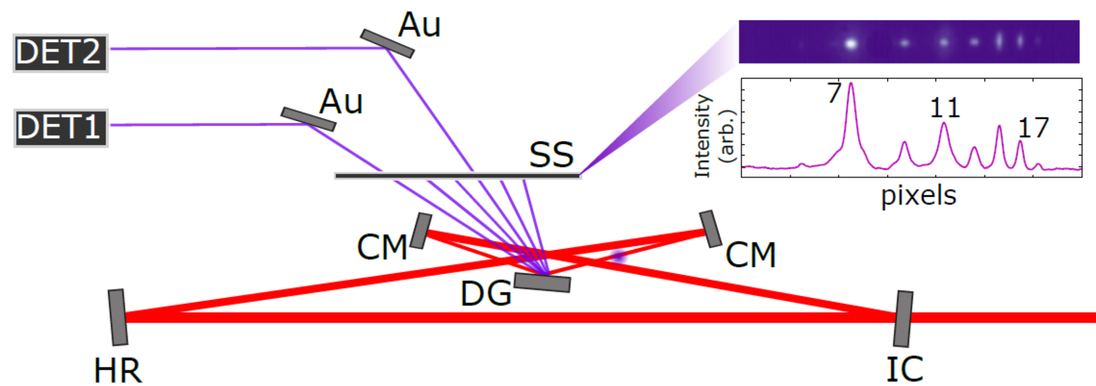
The XUV laser pointer

Harmonic	Target	Generated	Outcoupled power	Photons/s generated
			78 μW	4.8×10[illegible] γ/s



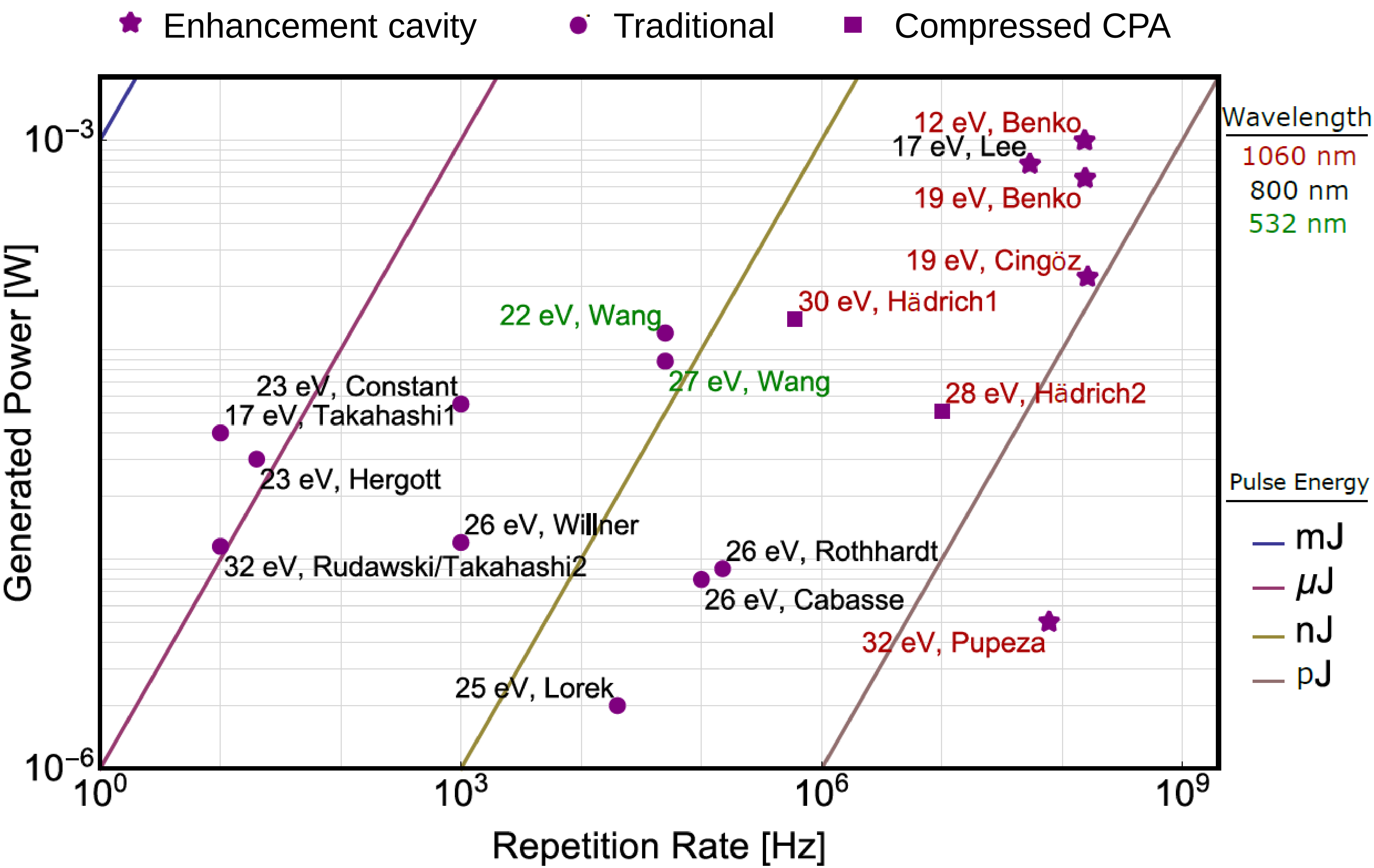
http://www-als.lbl.gov/index.php/beamlines/photon-source-parameters.html

1.2 x 10^{17} photons /[s mm² mrad² .1% bandwidth]
¼ brightness of the ALS



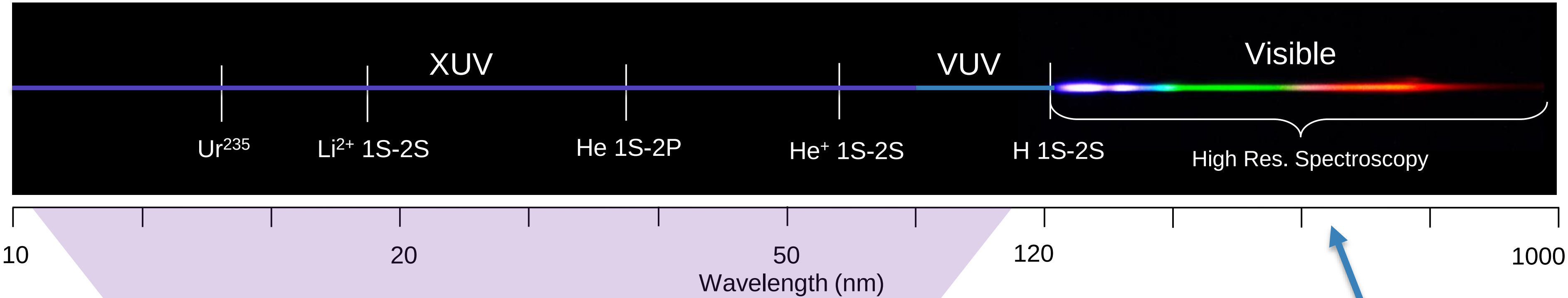
Benko *et al.* In preparation. 2016

Power scaling - HHG comparisons



Charting the extreme ultraviolet landscape

(Ultrahigh-resolution XUV spectroscopy)



Optical Atomic Clocks

Uncertainty of

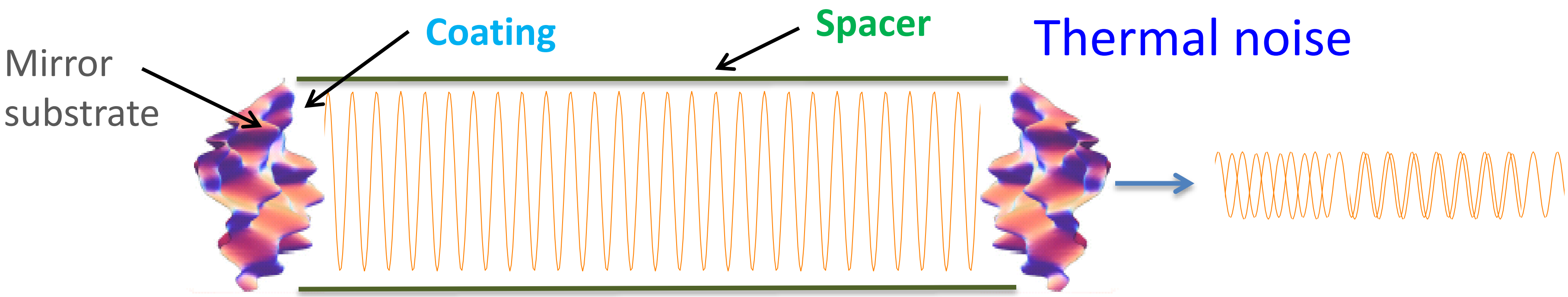
$$\frac{\Delta f}{f} = 10^{-18}$$

Laser stabilization

$$\frac{\Delta f}{f} = 10^{-16}$$

- High precision tests of QED in H, He and like ions ($\sim Z^4 - Z^6$).
- Next generation "nuclear" clocks in ^{229}Th and ^{235}U.
- **Generate coherent, laser-like radiation below 100 nm with frequency combs.**

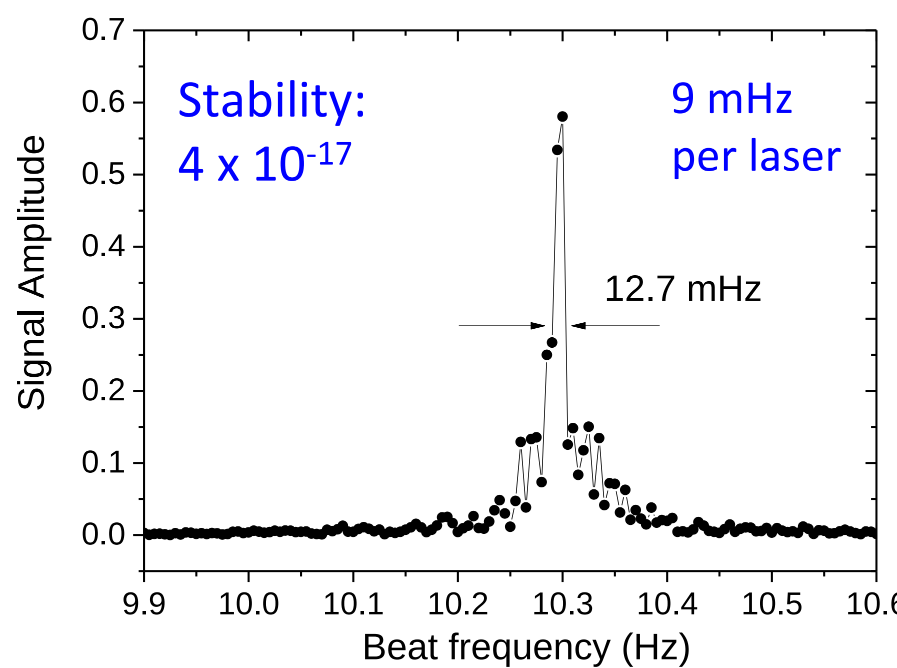
Optical coherence & spectral resolution



Cavity length $L \sim 1$ m → $\Delta L \sim 10^{-16}$ m (size of a nucleus: 10^{-14} m)

This level of optical coherence can be transferred to an optical comb

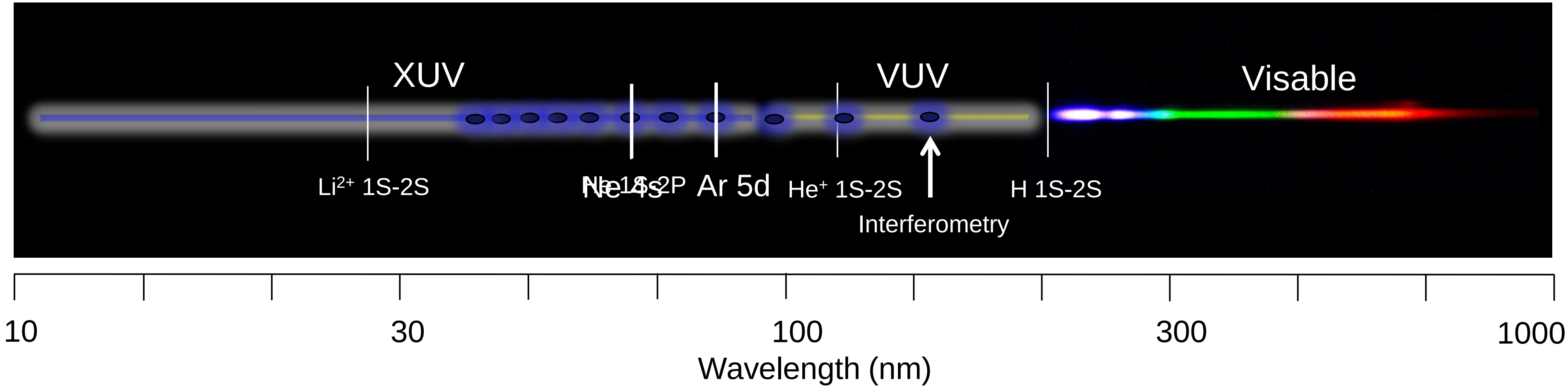
Coherence time
~1 min

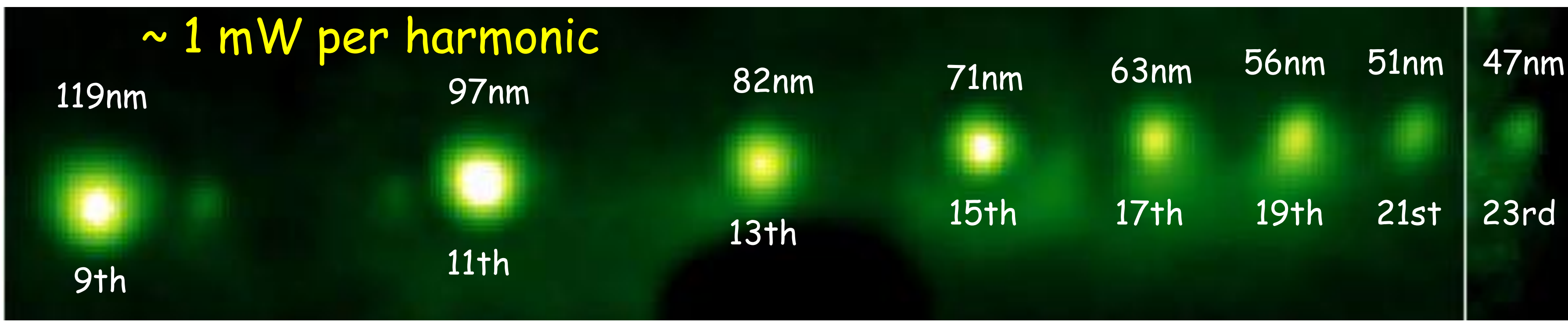


PTB – JILA
March 2016

Coherence test in XUV

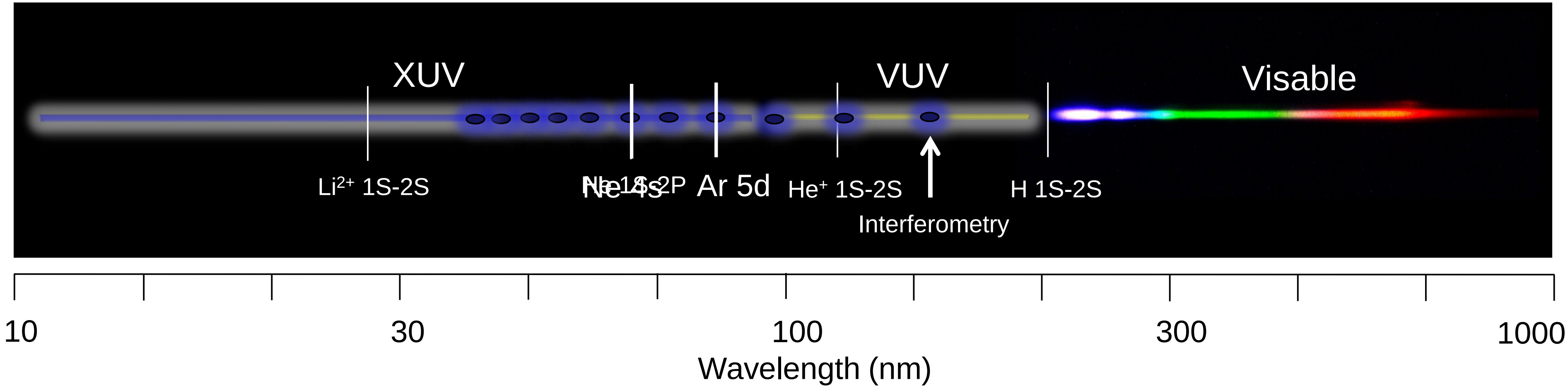
Yost *et al.*, Nature Phys. **5**, 815 (2009).

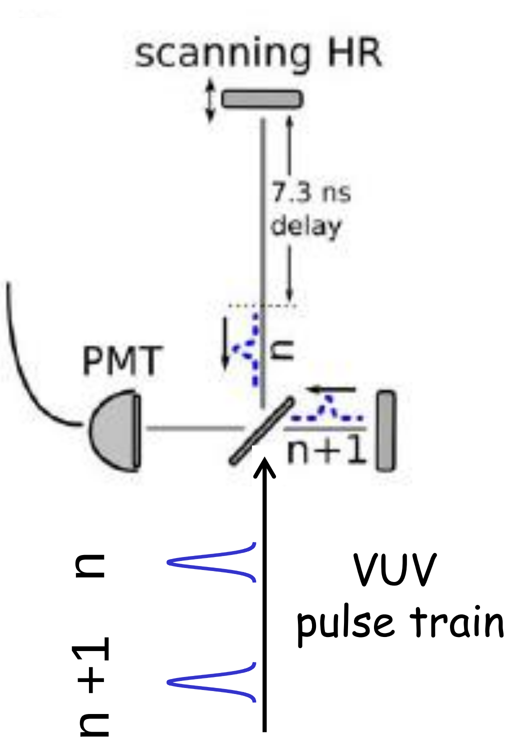




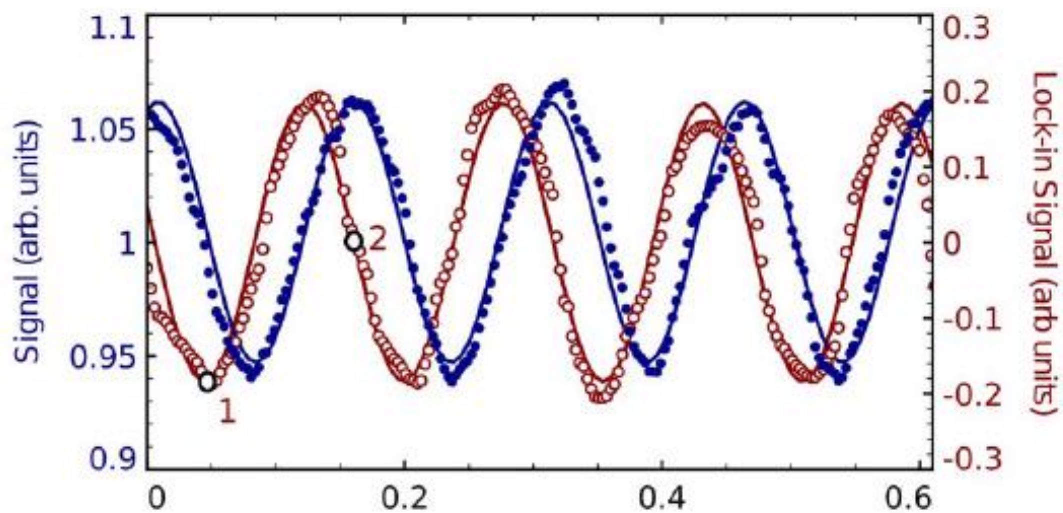
Coherence test in XUV

Yost *et al.*, Nature Phys. **5**, 815 (2009).



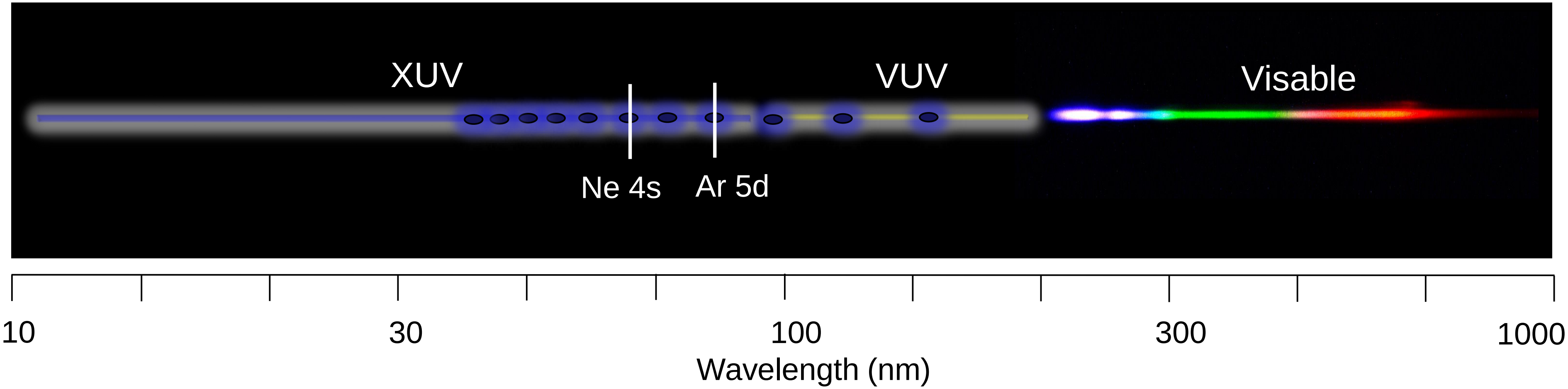


Interfere HHG pulses *n* and *n*+1 :

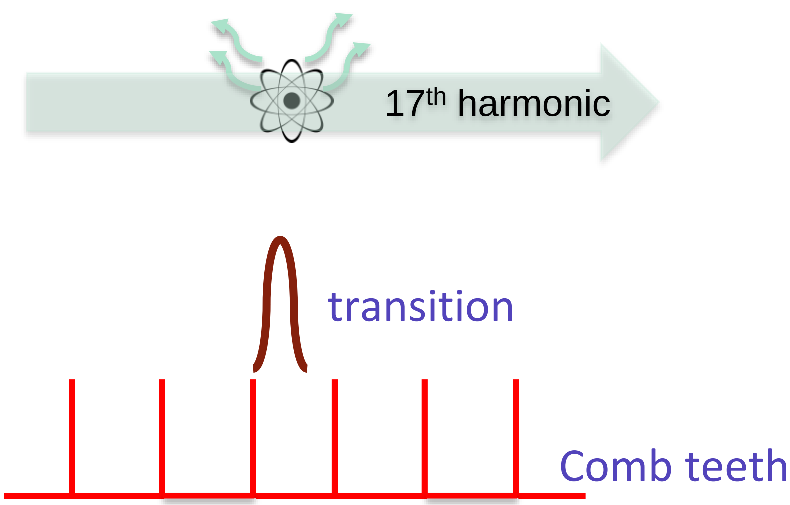


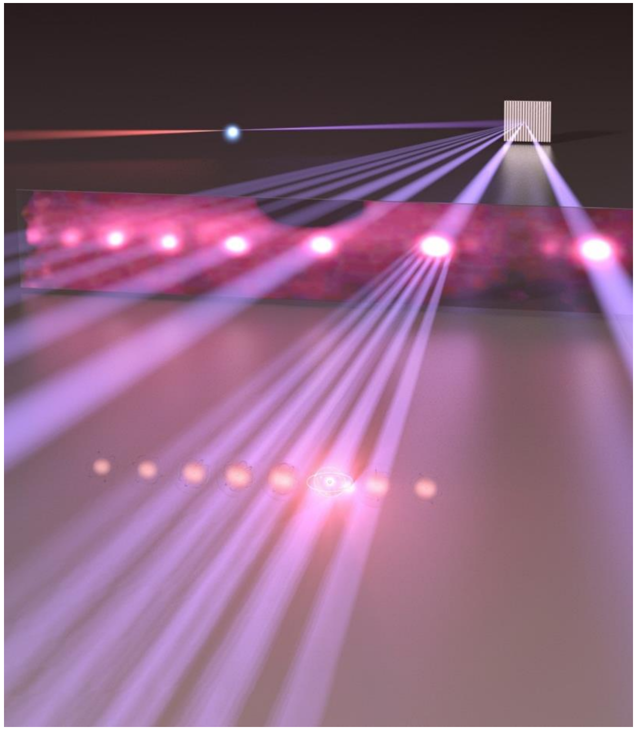
XUV frequency comb spectroscopy

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



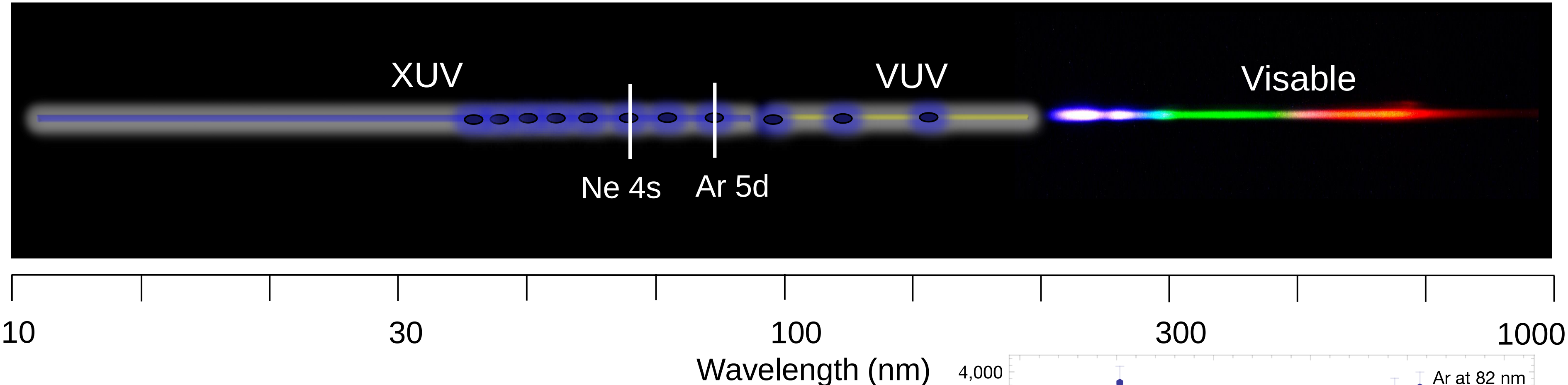
- Scan **single tooth** of XUV comb across resonance
- Direct fluorescence detection
- Transition linewidth ~10 MHz



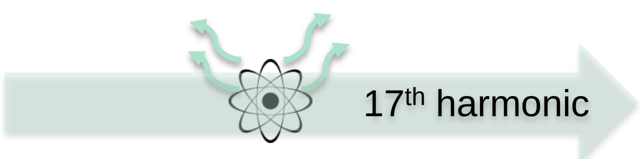


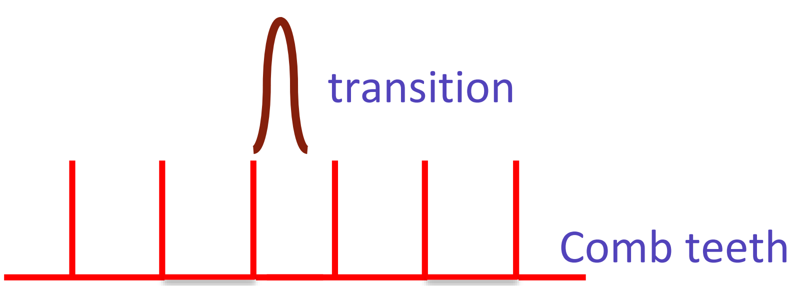
XUV frequency comb spectroscopy

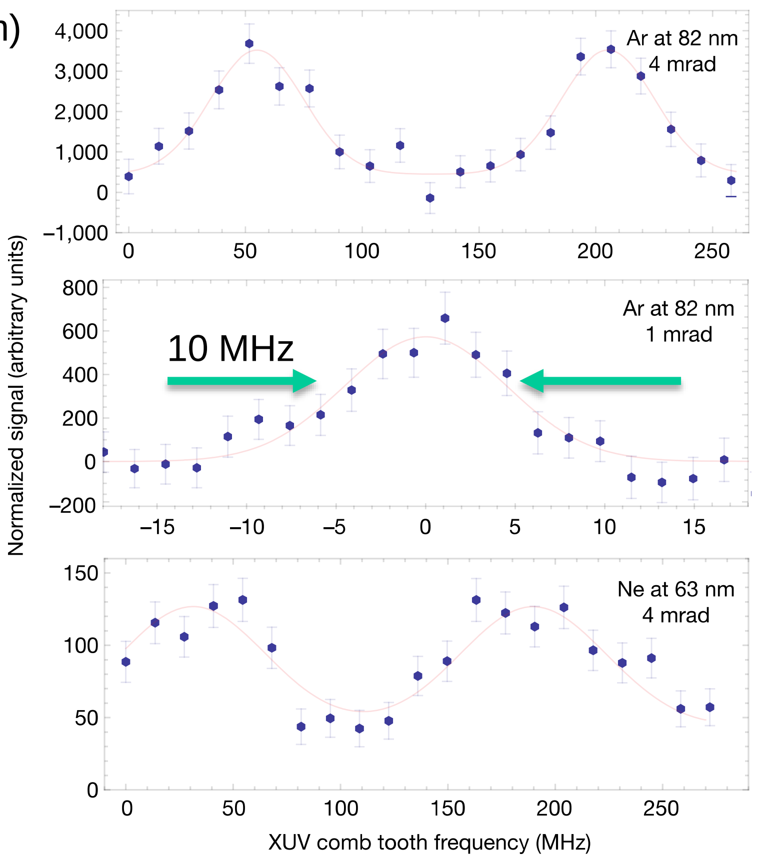
Cingöz *et al.*, Nature **482**, 68 (2012).



- Scan **single tooth** of XUV comb across resonance
- Direct fluorescence detection
- Transition linewidth ~10 MHz



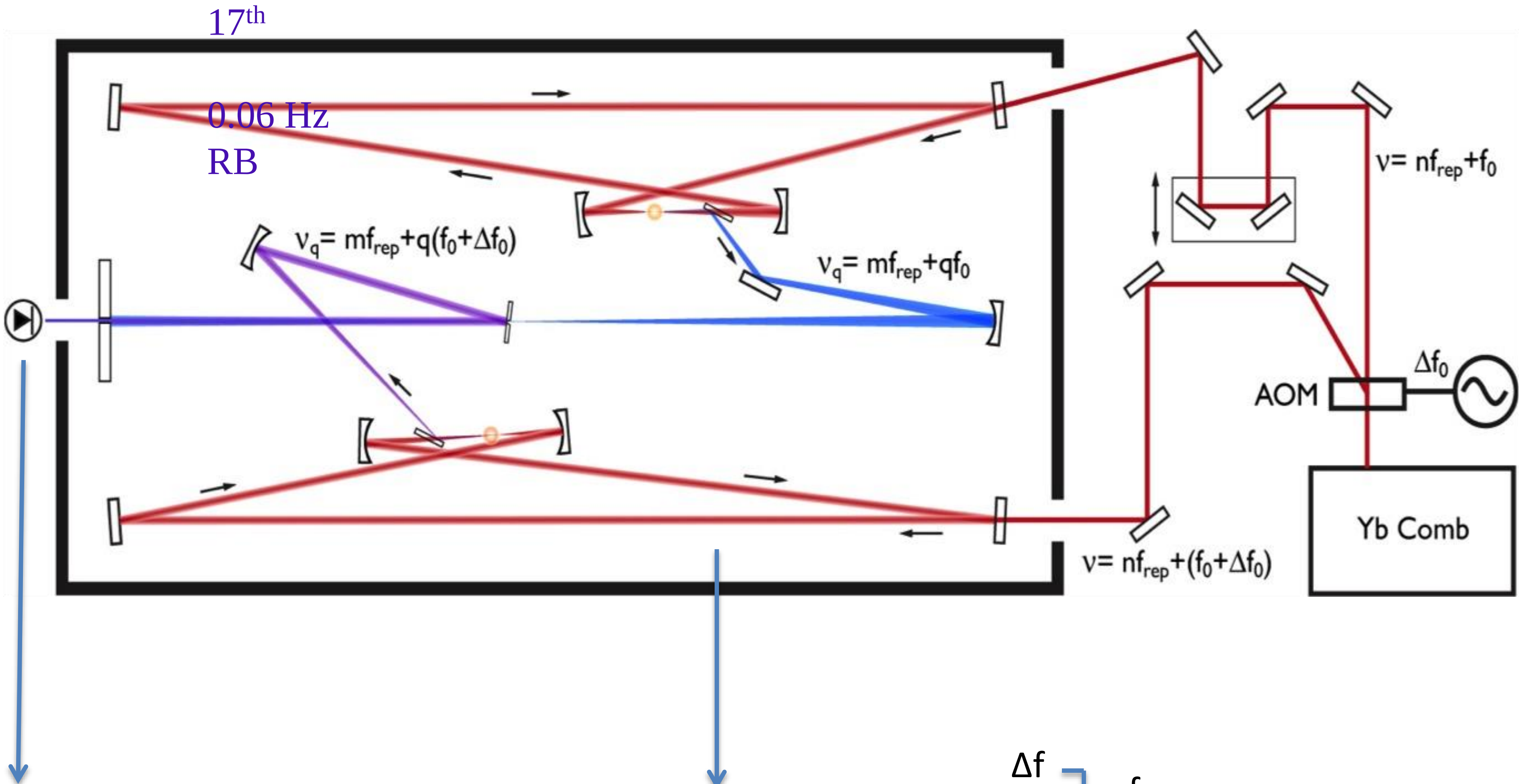




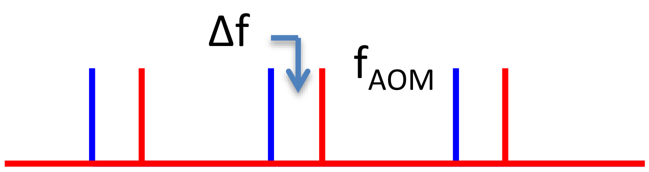
Heterodyne beat of two XUV combs

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

- Direct access to phase of XUV comb & attosecond physics



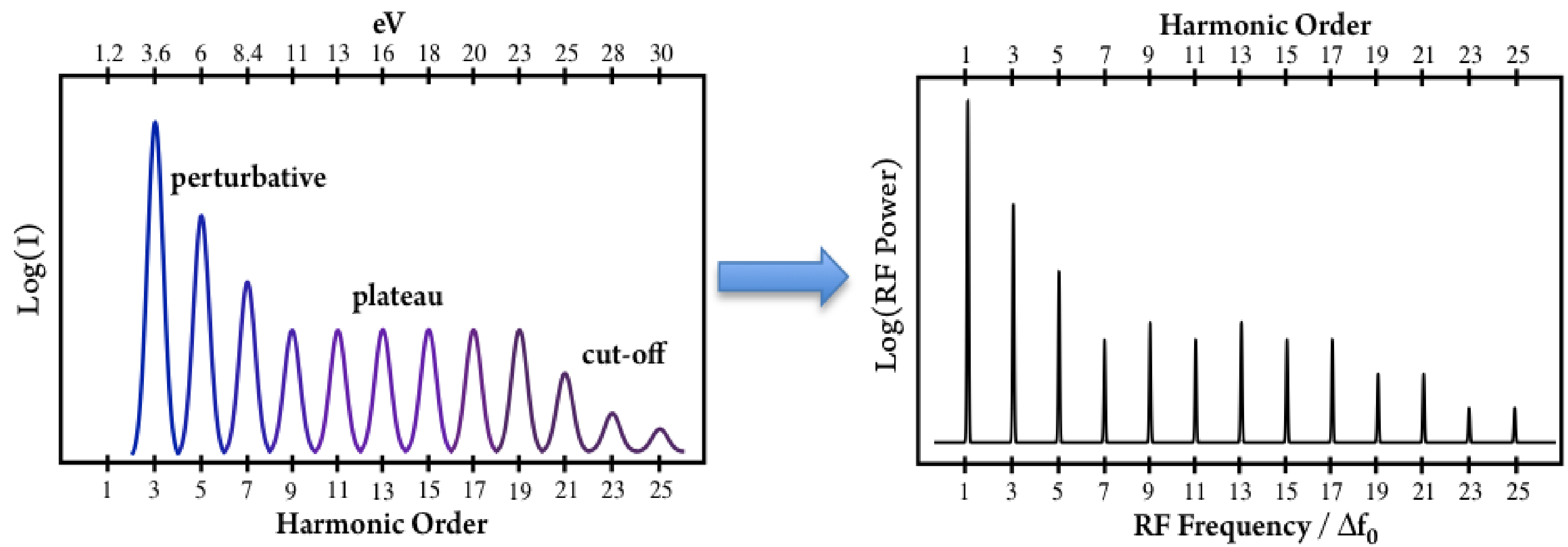
$$I = I_1 + I_2 + 2\,E_1 E_2^* [\cos(q\,\Delta f\ t) + \cos(q\ f_{aom} t)]$$



Heterodyne beat of two XUV combs

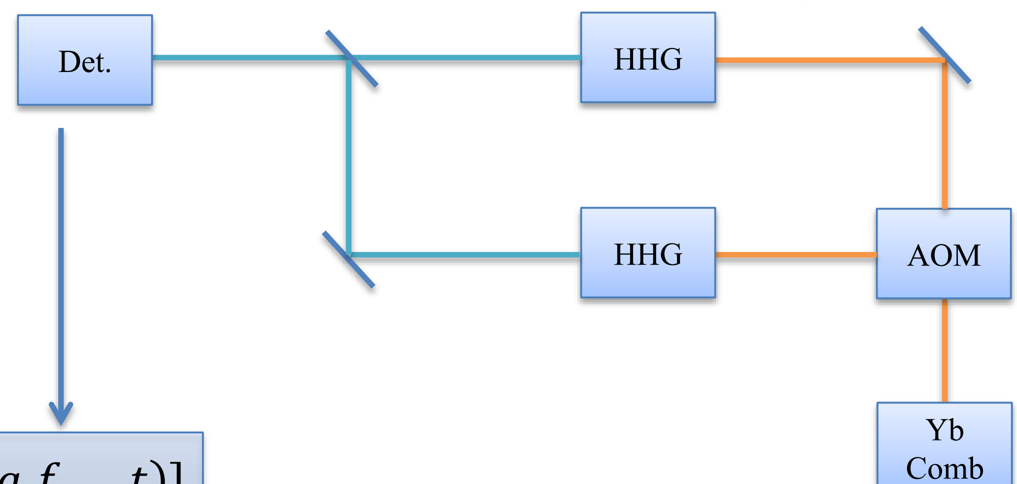
C. Benko *et al.*, Nature Photon. **8**, 530 (2014).

- Direct access to phase of XUV comb & attosecond physics



An XUV Interferometer

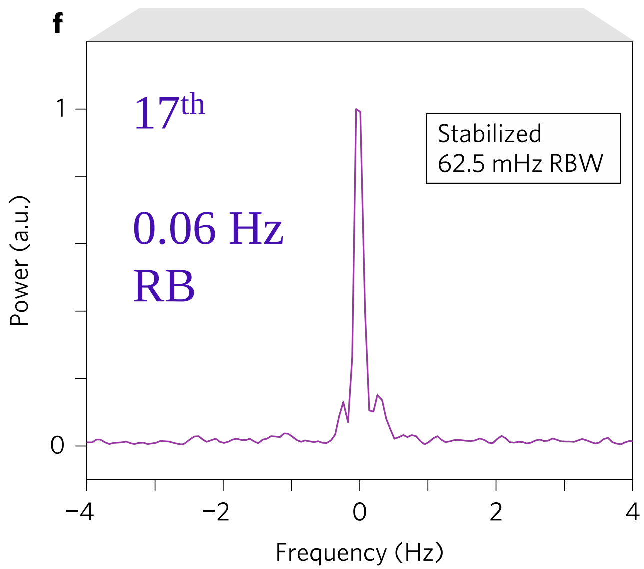
- Two independent HHG's
- Recombination in XUV
- Frequency offset in fundamental
- Each harmonic at a different beat frequency

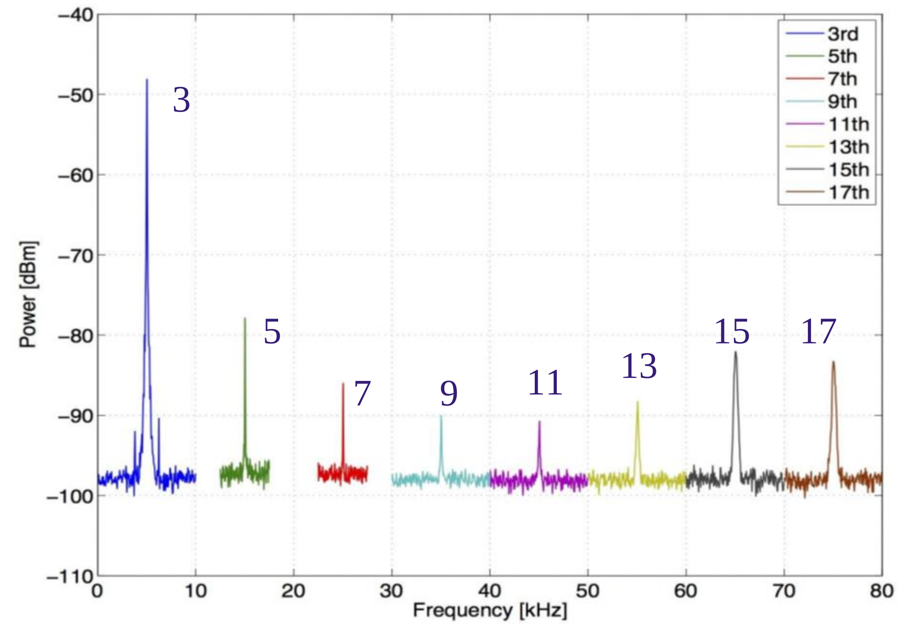


$$I = I_1 + I_2 + 2\, E_1 E_2^* [\cos(q\, \Delta f\ t) + \cos(q\, f_{aom} t)]$$

Heterodyne beat of two XUV combs

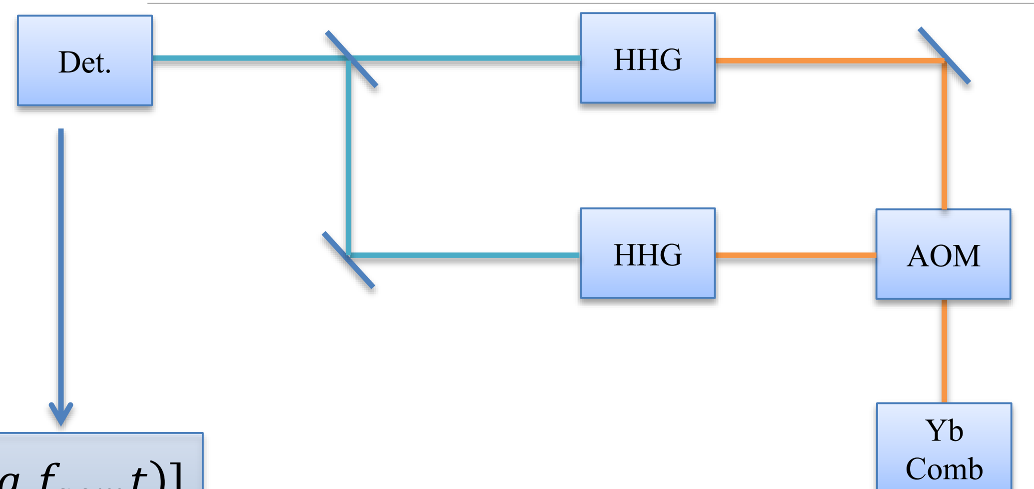
C. Benko *et al.*, Nature Photon. **8**, 530 (2014).





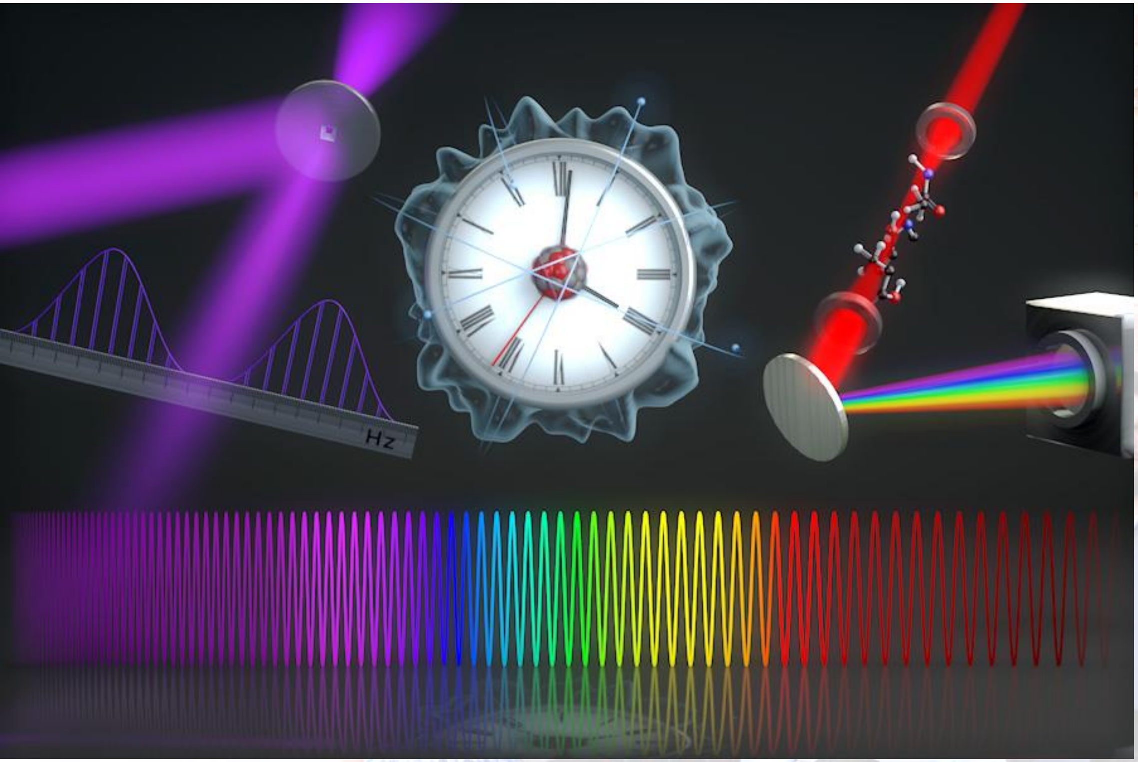
An XUV Interferometer

- Two independent HHG's
- Recombination in XUV
- Frequency offset in fundamental
- Each harmonic at a different beat frequency



$$I = I_1 + I_2 + 2\,E_1 E_2^{*}[\cos(q\,\Delta f\ t) + \cos(q\ f_{aom} t)]$$

XUV (& other) frequency combs



http://www.nsf.gov/ Discovery -- Combing frequencies

Christoph Heyl, Gil Porat, Stephen Schoun

XUV frequency combs for precision measurement, frequency metrology, and strong-field physics.

- **Very coherent light from 10 nm – 100 nm**
- **Among highest photon fluxes available on table-top**
- **“Simple” architecture with room for improvement**

I. Hartl, A. Ruehl, M. Fermann, IMRA America

F. Adler (Tiger Optics)
T. Alison (U. Stony Brook)
A. Cingöz (AOSense)
A.J. Fleisher (NIST)
A. Foltynowicz (Umea U.)
S. Foreman (U. San Fran)
K. Holman (Lincoln Lab)
L. Hua (Chin. Aca. Science)
D. Jones (U. British Columbia)
R. J. Jones (U. Arizona)
F. Labaye (U. Neuchatel)
A. Marian (MPG, Berlin)
P. Masłowski (U. Torun)
K. Moll (Precision Photon.)
A. Pe’er (Bar-Ilan U.)
T. Schibli (U. Colorado)
L. Sinclair (NIST)
M. Thorpe (Bridge Photon.)
D. Yost (Colo. State U.)

HHG Seed for XFEL

Gil Porat, Christoph Heyl,
Stephen Schoun

Demonstrated Experimentally

P_{avg}=80W, f_{rep}=154 MHz, τ=120fs, **λ=1μm** → Intracavity HHG 12 kW IR power, F~400 → ~1 mW at 12.7 eV (~3x10^6 photons/pulse)

Similar power up to 30 eV

- HHG cutoff photon energy scales as λ^2
- HHG efficiency scales as $\lambda^{-6.5}$
- λ=2μm driven HHG demonstrated 0.5 keV generation at f_{rep}= 10 Hz
- Frequency comb at λ=2μm soon to reach ~100 fs pulses at 50 MHz repetition rate with μJ pulse energy

Predicted

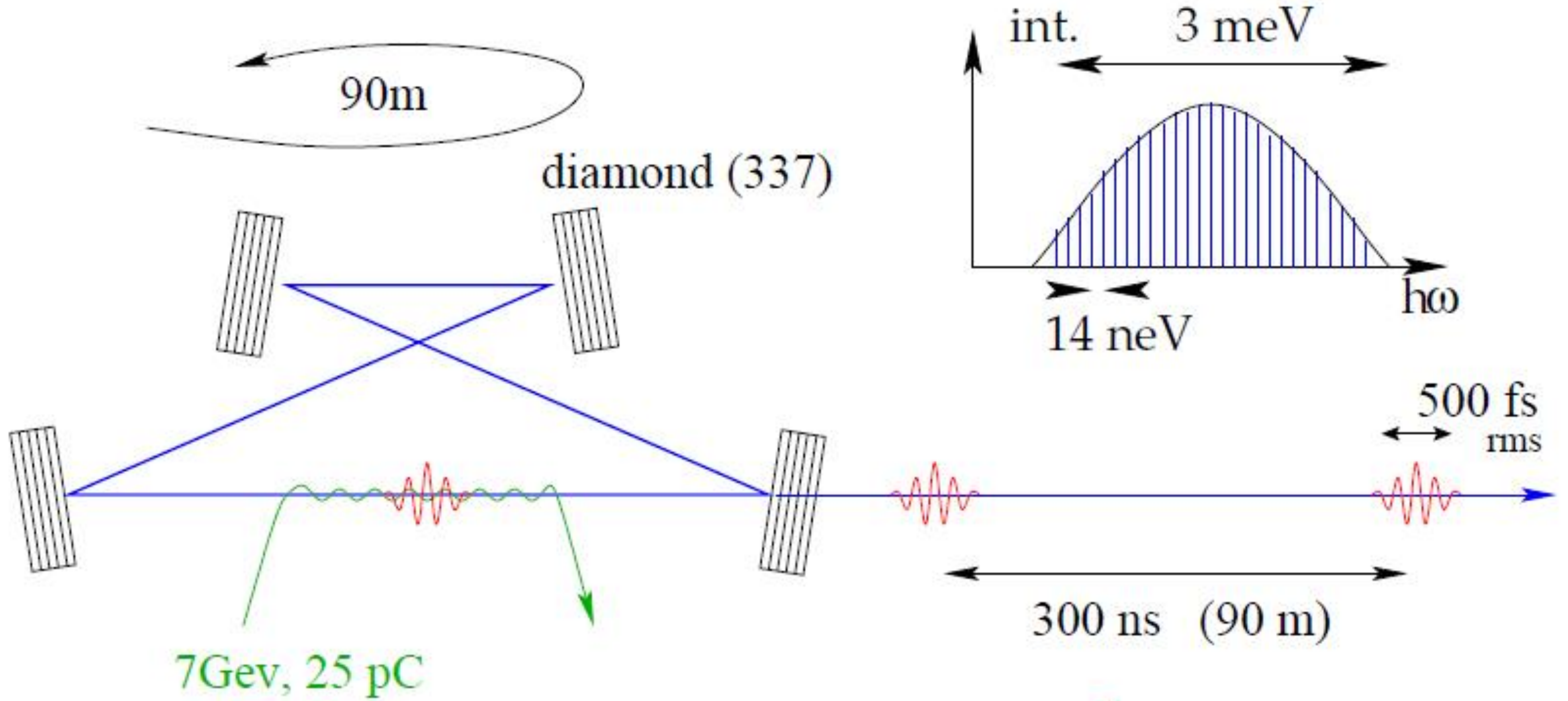
P_{avg}=150W, f_{rep}=50 MHz, τ=100fs, **λ=2μm** → Intracavity HHG 10 kW IR power, F~500 → ~10 - 100 μW at 0.5 keV (~10^3-10^4 photons/pulse)

A. D. Shiner et al., Phys. Rev. Lett. 103, 073902 (2009)
M.-C. Chen et al., Phys. Rev. Lett. 105, 173901 (2010)
F. Stutzki et al., Opt. Lett. 39, 4671 (2014)
G. D. Cole et al., Optica 3, 647, (2016)

Bernard Adams
Kwang-je Kim

XFELO

Design example: XFELO for 14.4 keV



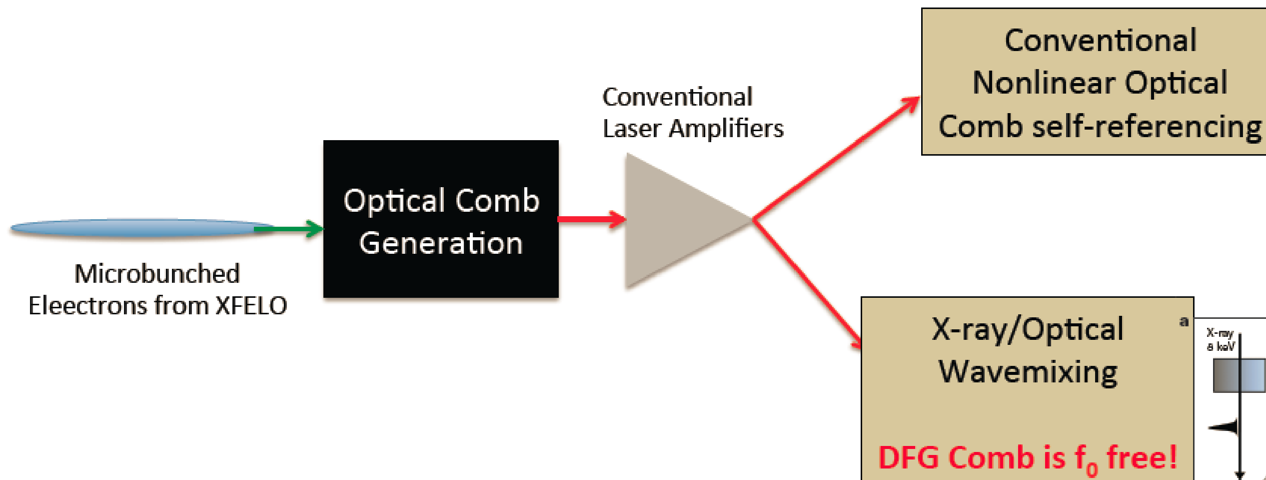
Kwang-Je Kim et al.: PRL **100**, 244802 (2008)
PRST-AB **12**, 030703 (2009)

$6.5 \cdot 10^8$ photons/pulse

parameters from R. Lindberg (ANL)

Leo Hollberg:
High resolution spectroscopy with X-ray comb

If you could…

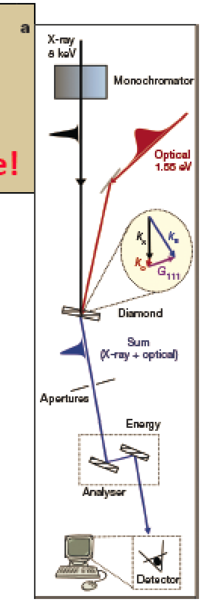


ARTICLE

doi:10.1038/nature11340

X-ray and optical wave mixing

T. E. Glover[1], D. M. Fritz[2], M. Cammarata[3], T. K. Allison[4], Sinisa Coh[5,6], J. M. Feldkamp[2], H. Lemke[2], D. Zhu[2], Y. Feng[2], R. N. Coffee[2], M. Fuchs[7], S. Ghimire[7], J. Chen[7,8], S. Shwartz[8], D. A. Reis[7,8,9], S. E. Harris[8,10] & J. B. Hastings[2]



Chris Corder & Tom Allison:
X-ray comb carrier-envelope phase?