MAX PLANCK INSTITUTE
OF QUANTUM OPTICS

Towards XUV Frequency Comb Spectroscopy of the 1s-2s Transition in He$^+$

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Testing QED by precision spectroscopy of Hydrogen-like systems

$E_{nlj}/h =$

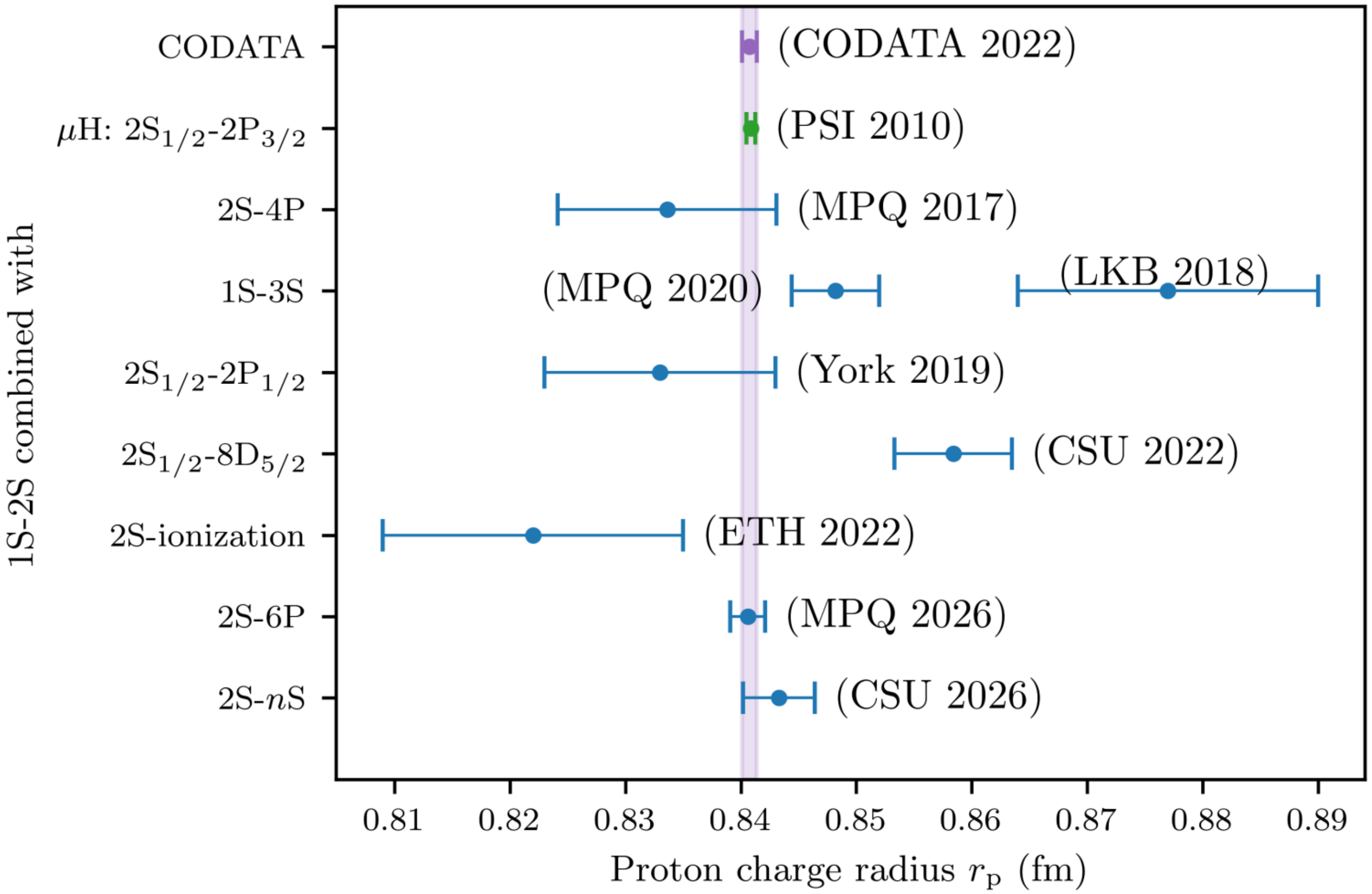
$\frac{C_{\mathrm{NS}}}{Z^2 n^3} r_N^2 \Big)$

Nuclear charge radius

- α: electron g-fa
- $\frac{m_e}{m_N}$: Penning tr

→ Two

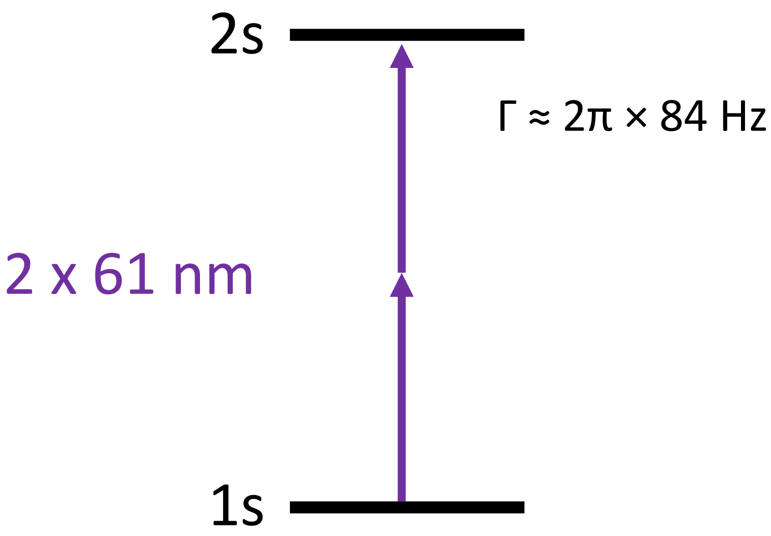
→ Mea



E. Tiesinga *et al.*, Rev. Mod. Phys. **93**, 025010 (2021)
D. Hanneke *et al.*, Phys. Rev. Lett. **100**, 120801 (2008)
L. Morel *et al.*, Nature **588**, 61 (2020)
S. Alighanbari *et al.*, Nature **644**, 69–75 (2025)

Target: 1s-2s Transition in He+

- Independent QED test (in combination with µHe+ measurements)
- Sensitive to higher order QED corrections (∝ $Z^{5\text{-}7}$)
- Trapped and cooled target → small systematics



J. Moreno *et al.*, Eur. Phys. J. D **77**, 67 (2023)
J.J. Krauth *et al.*, Nature **589**, 527–531 (2021)

Scanning Range

$$E_{nlj}/h = cR_\infty f_{nlj}\left(\alpha, \frac{m_N}{m_e}, \frac{r}{\lambda_C}\right)$$

Expected observational linewidth: 1 kHz

Parameters	Contribution to Uncertainty (He^+ 1s-2s)
Rydberg constant R_∞	$1\text{x}10^{-12}$ (10 kHz)
Nuclear charge radius $\frac{r}{\lambda_C}$	$7\text{x}10^{-12}$ (74 kHz)
Nucleus/electron mass $\frac{m_\mathrm{N}}{m_\mathrm{e}}$	$5\text{x}10^{-15}$ (45 Hz)
Fine structure constant α	$2\text{x}10^{-14}$ (166 Hz)

Hydrogen spectroscopy
μ-H + H (1s-2s), CODATA2022

μ-He spectroscopy [1, 2]

Mass ratio measurements
in Penning traps

Atomic recoil (atom interferometer)
g-2 measurement

Uncertainty from He^+ QED: $4\text{x}10^{-12}$ (36 kHz)

[1] J.J. Krauth *et al.*, Nature **589**, 527–531 (2021)

[2] S. S. Li Muli *et al.*, *Phys. Rev. Lett.* **134**, 032502 (2025)

He+ Spectroscopy for Testing QED

- Measuring the 1s-2s transition:
  - Better than ~ 400 kHz ($4x10^{-11}$)

    Determine R_∞ and contribute to the proton radius puzzle

  - Better than 74 kHz ($7x10^{-12}$)

    Determine charge radius, compare to μ-He measurement

  - Better than 36 kHz ($4x10^{-12}$)

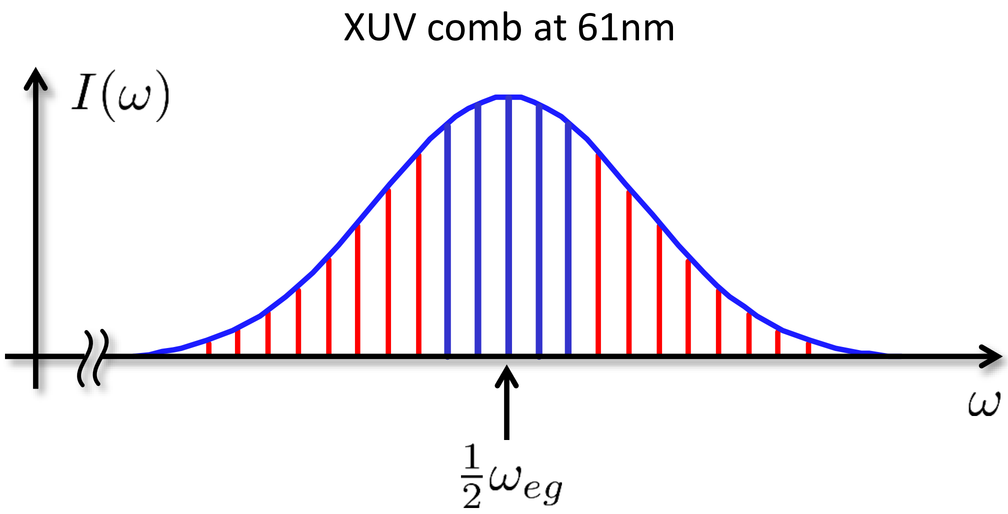
    QED theory uncertainty will be limitation in extracting charge radius and R_∞

- Measuring more transitions in $^4He^+$: QED test independent from μ-He and Hydrogen
- Measuring $^3He^+$: Get charge radii difference, compare with neutral He and μ-He

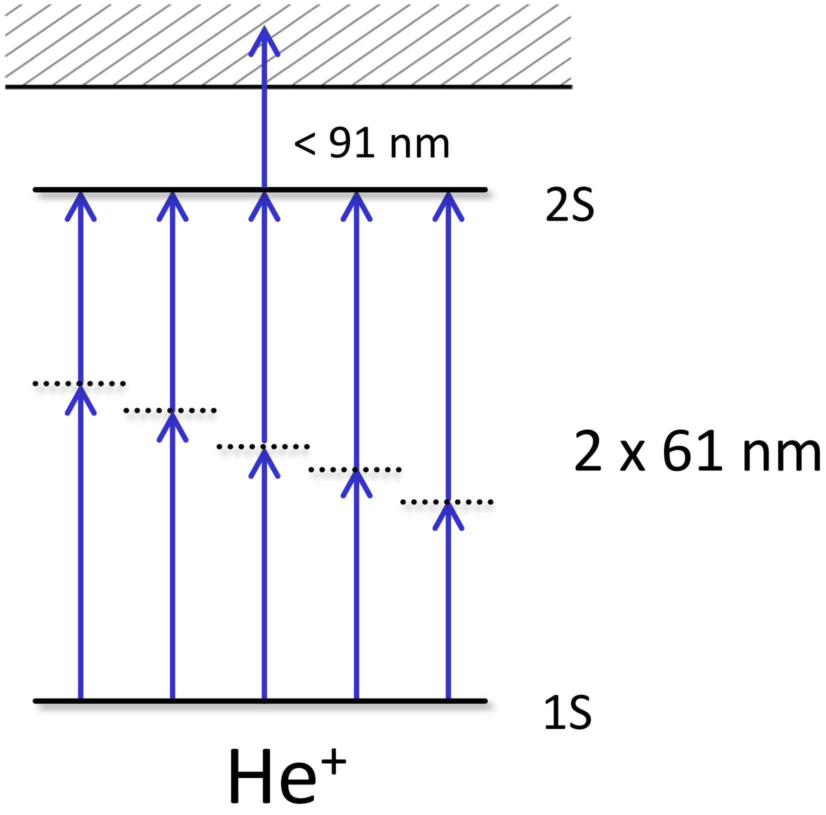
Sun, Y. R. and Hu, S.-M., *National Science Review* 7, 1818–1827 (2020)
The CREMA Collaboration, arXiv.2305.11679 (2023)

Direct Frequency Comb Spectroscopy

- Line width of a single comb mode
- Efficient nonlinear frequency conversion due to high peak power of pulsed laser
- As efficient as CW laser of same average power


XUV comb at 61nm

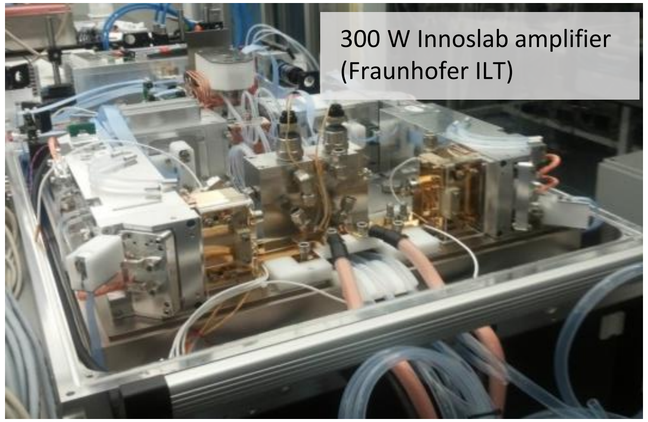
Spectroscopy signal: **He^{2+}**



He$^+$ spectroscopy setup: overview

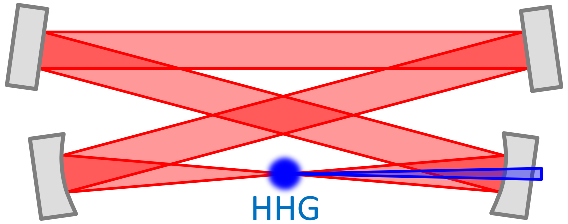
High-power IR frequency comb

Yb:KYW laser + amplifiers
@1030 nm

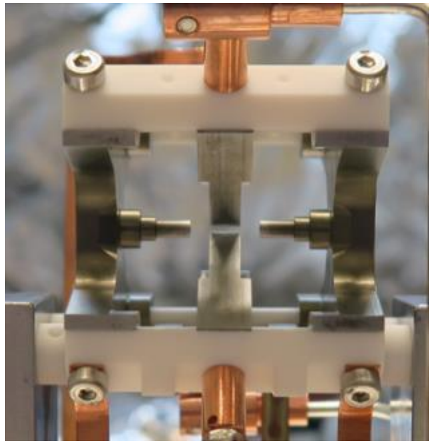

300 W Innoslab amplifier
(Fraunhofer ILT)

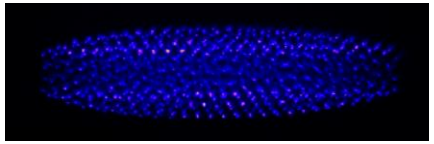
Frequency comb at 61 nm

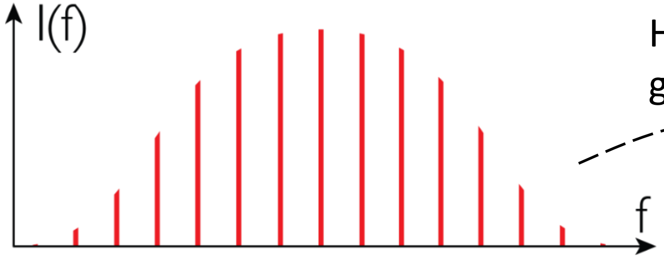
Intracavity
high-harmonic generation
17th harmonic



Trapped He$^+$ ions

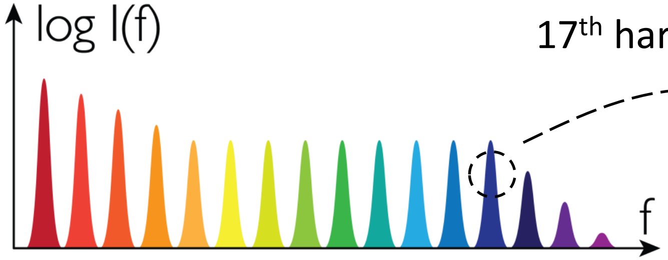






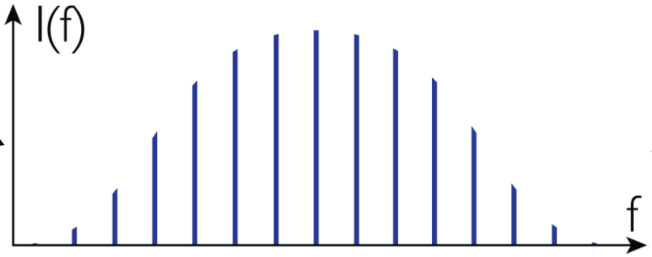
IR frequency comb
1030 nm

High-harmonic
generation



Odd-order
harmonics

17th harmonic



XUV frequency comb
61 nm

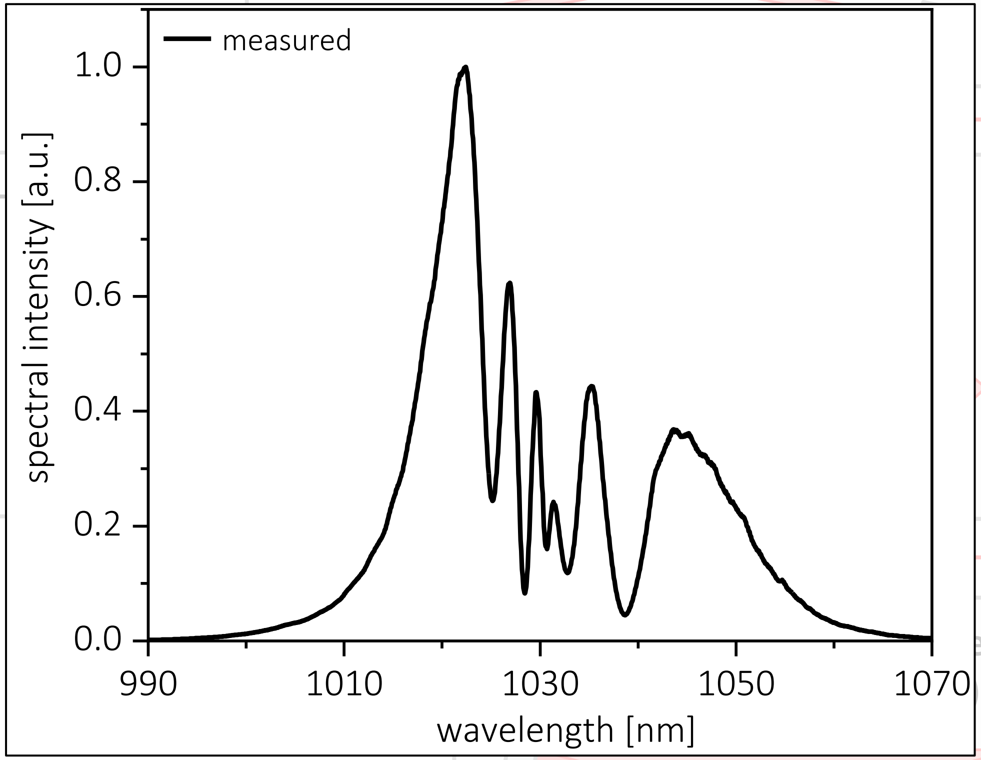
61 nm laser system

Seed laser

Yb:KYW oscillator (frequency comb)

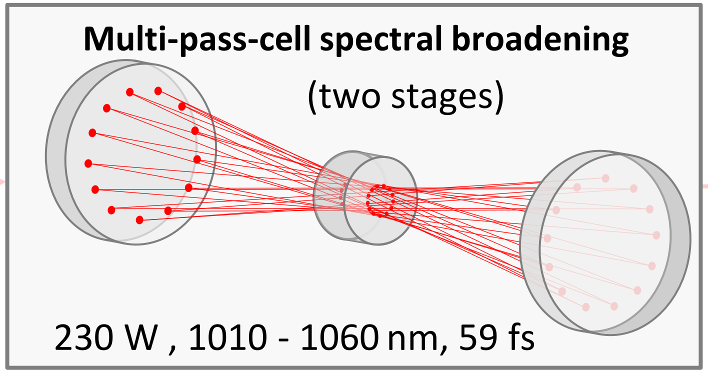
Amplification & compression

Yb:L



Multi-pass-cell spectral broadening

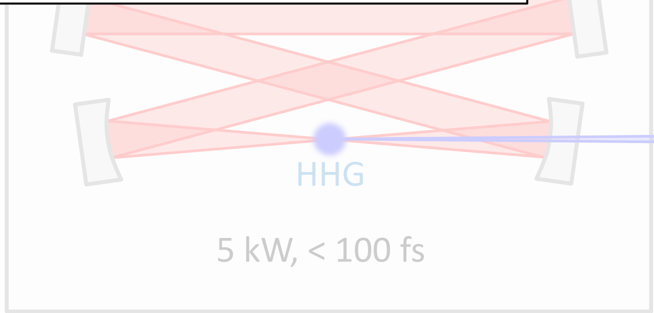
(two stages)



230 W , 1010 - 1060 nm, 59 fs

XUV comb generation

eration



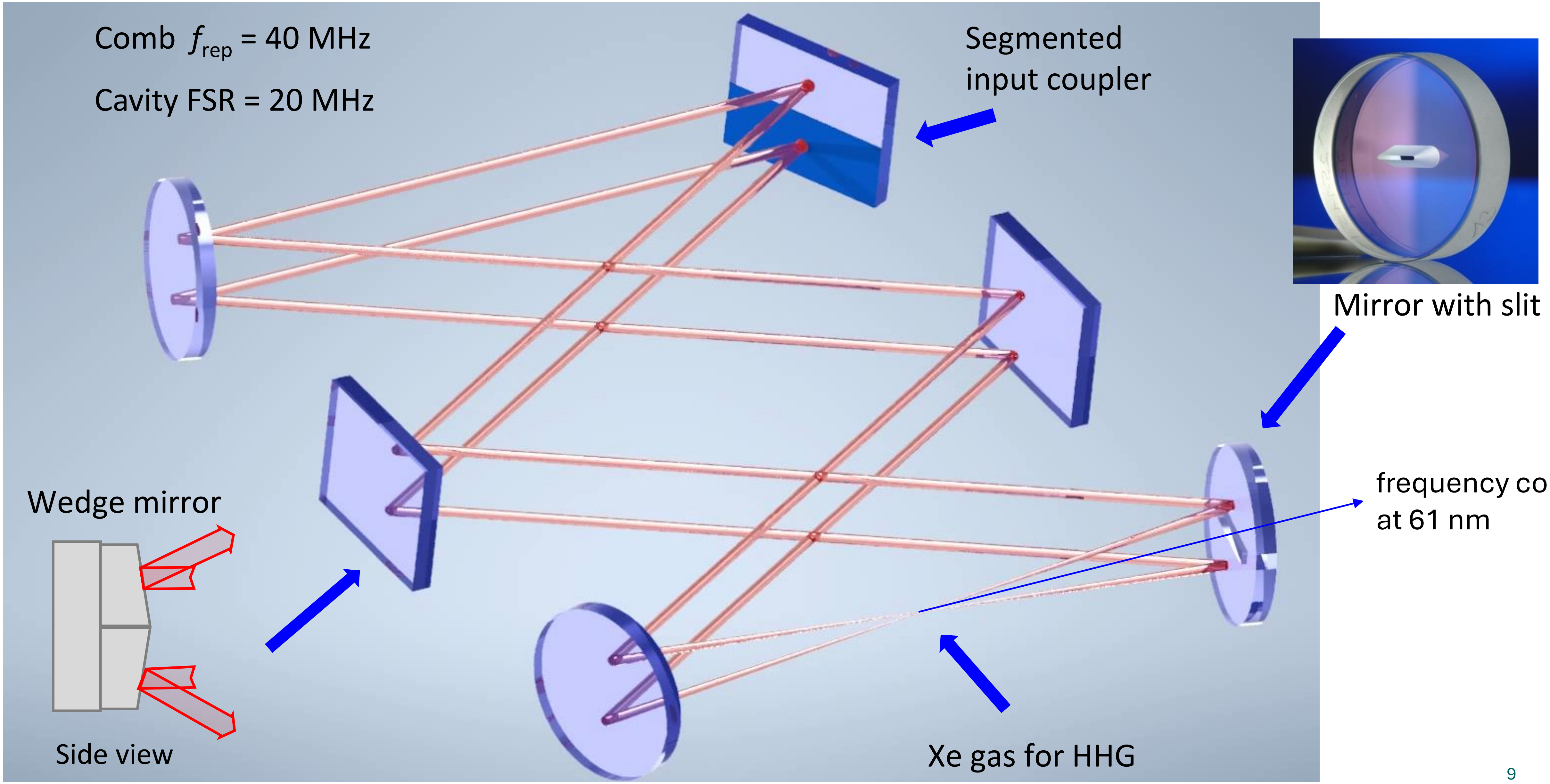
5 kW, < 100 fs

XUV comb

to He$^+$ trap

~ 30 µW at 61 nm

Enhancement Resonator for HHG



Comb f_{rep} = 40 MHz

Cavity FSR = 20 MHz

Segmented input coupler

Mirror with slit

frequency comb at 61 nm

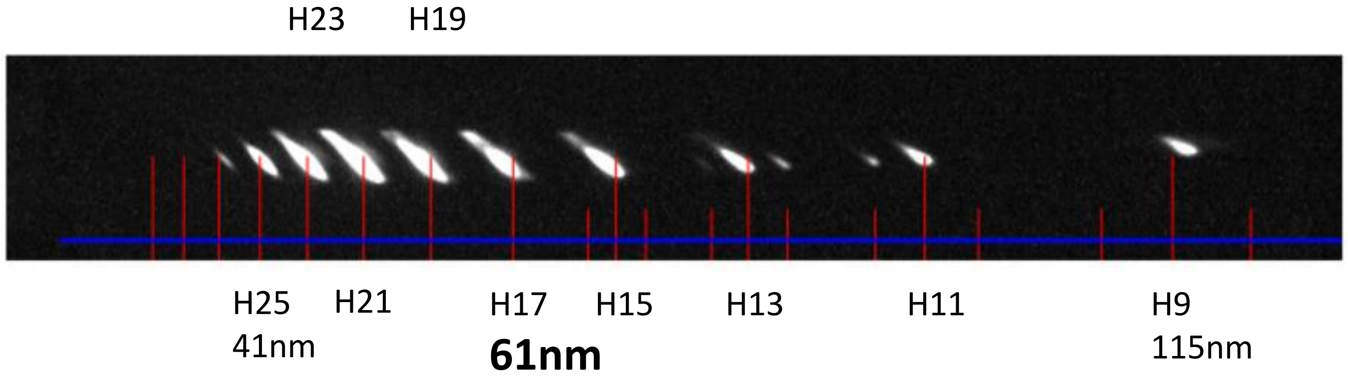
Wedge mirror

Side view

Xe gas for HHG

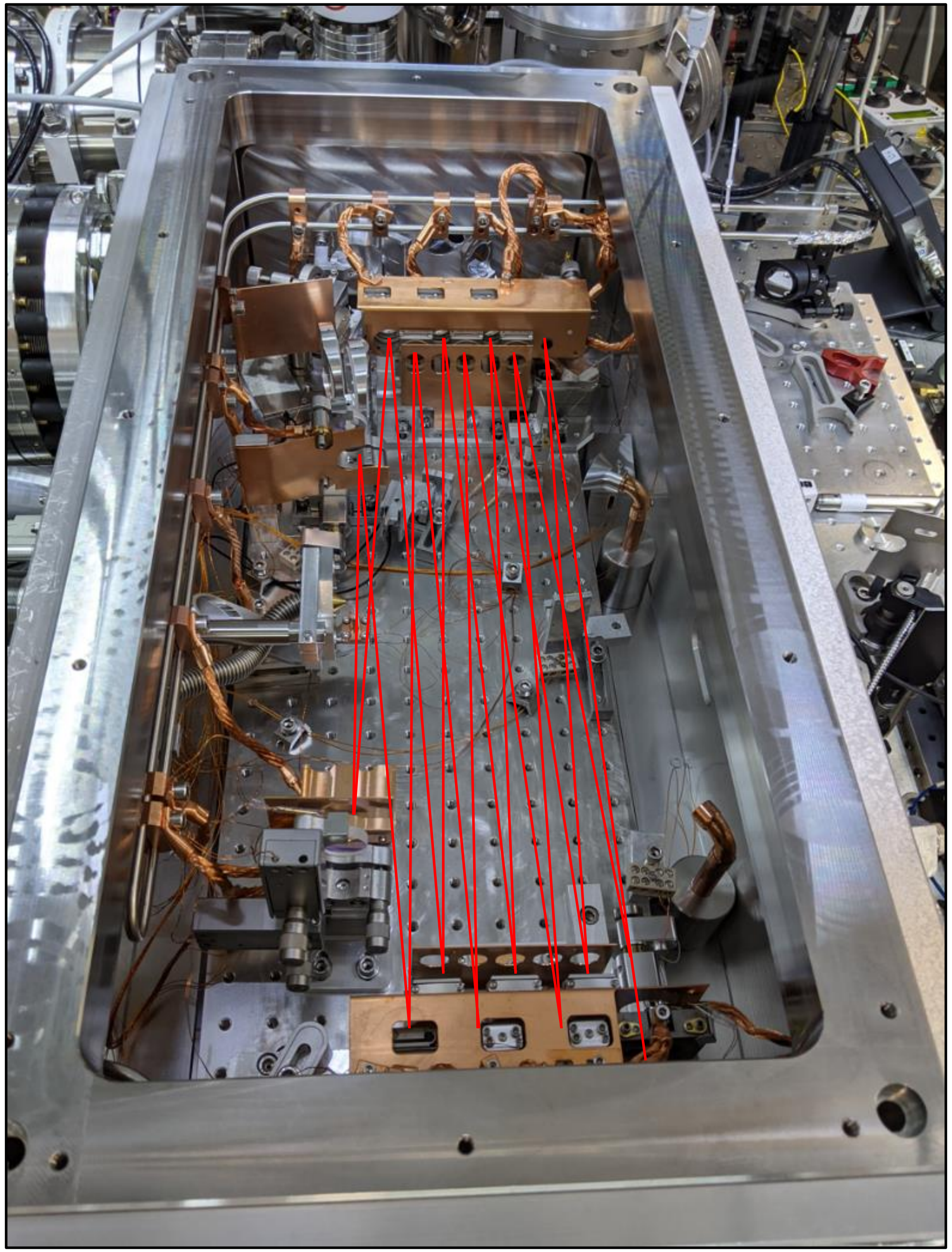
Wissenberg, S. H. *et al*., *Phys. Rev. Res*. **7**, 023071 (2025)

Optical frequency comb at 61 nm

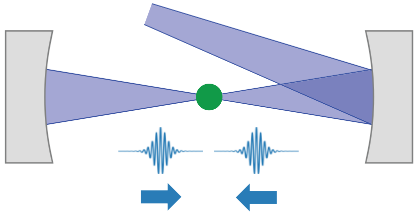


~30 µW at 61 nm

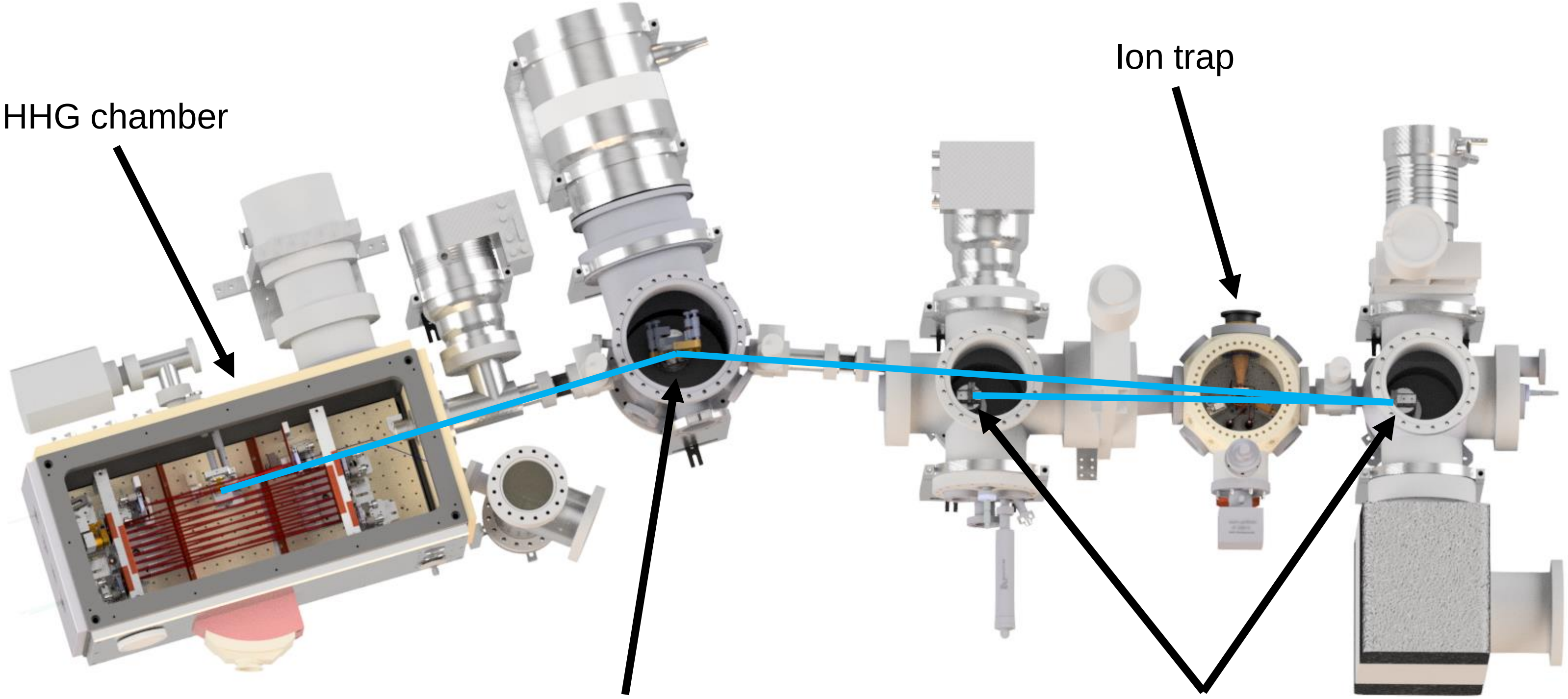
⟶ ~ 0.1 Hz signal rate (ionization)



XUV beam delivery to trapped He+



recoil- and Doppler-free
Anti-collinear excitation



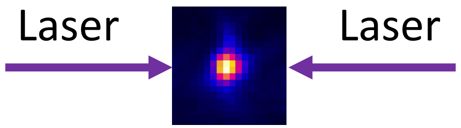
HHG chamber

Ion trap

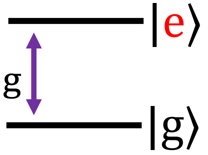
XUV grazing incidence mirror
(R=70% @ 61 nm)

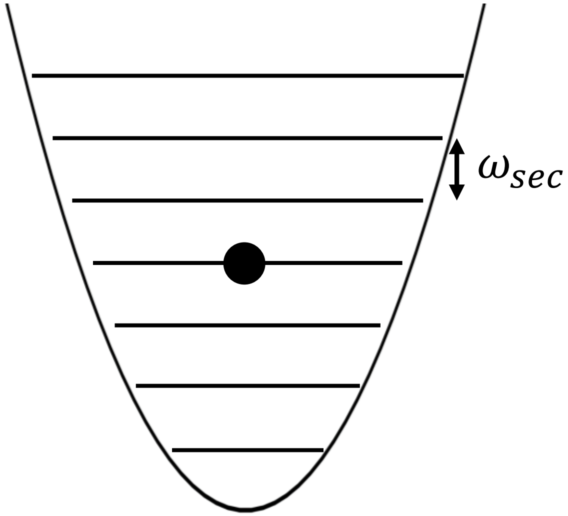
XUV focusing mirrors
(R=30% @ 61 nm)

Single Ion Laser Excitation in Harmonic Oscillator

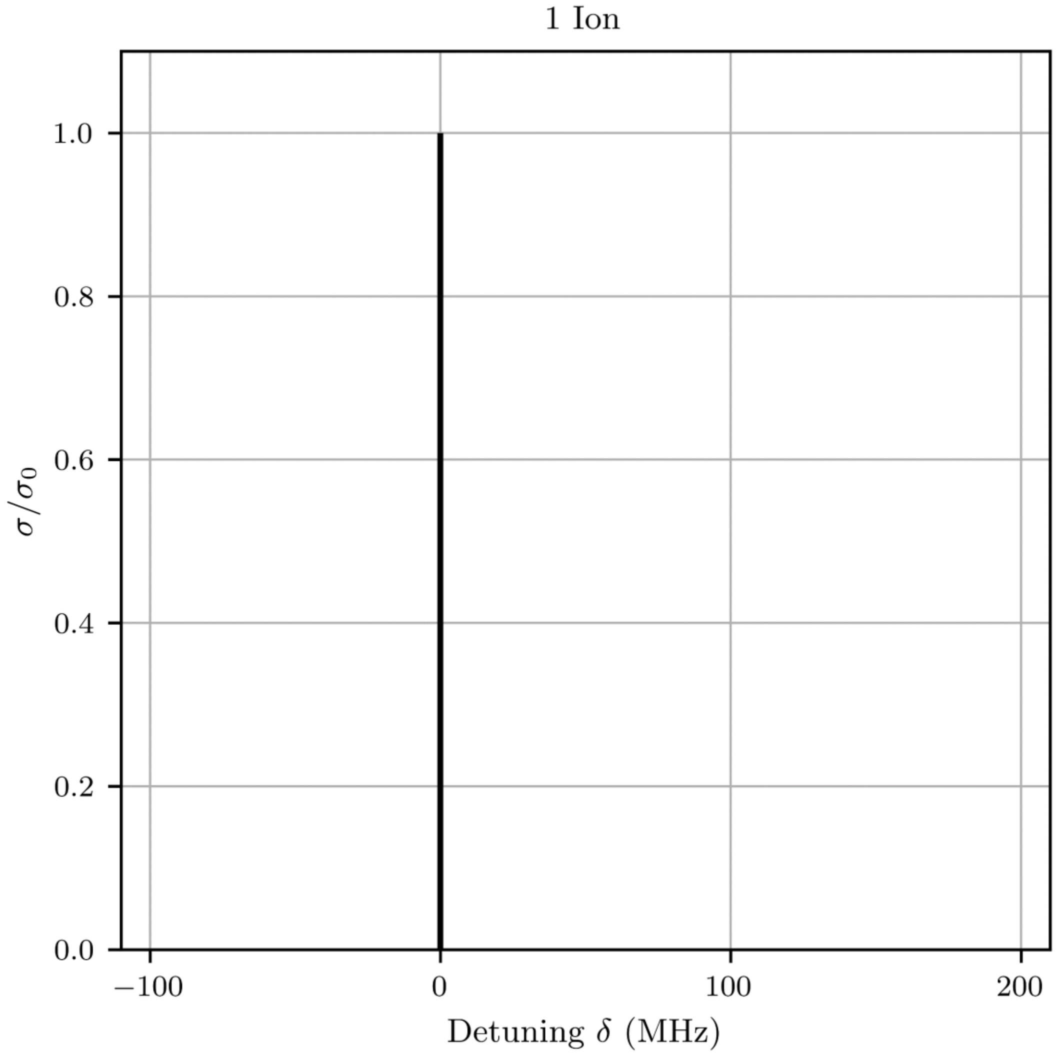


Excite electronic transition: ω_{eg}



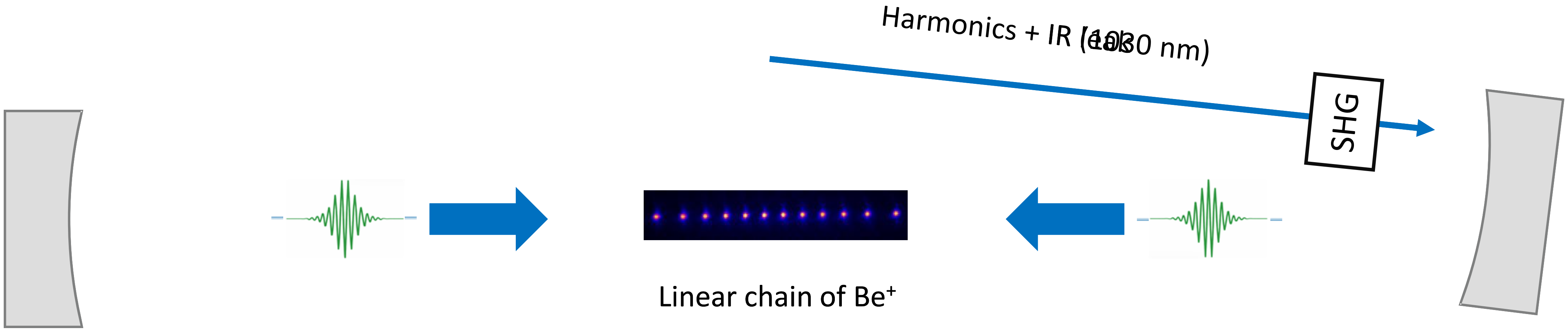


$$\omega_{rec} = \frac{\hbar k^2}{2m} \geq \omega_{\text{sec,ax}} \Rightarrow \eta = \sqrt{\frac{\omega_{rec}}{\omega_{sec}}} > 1$$



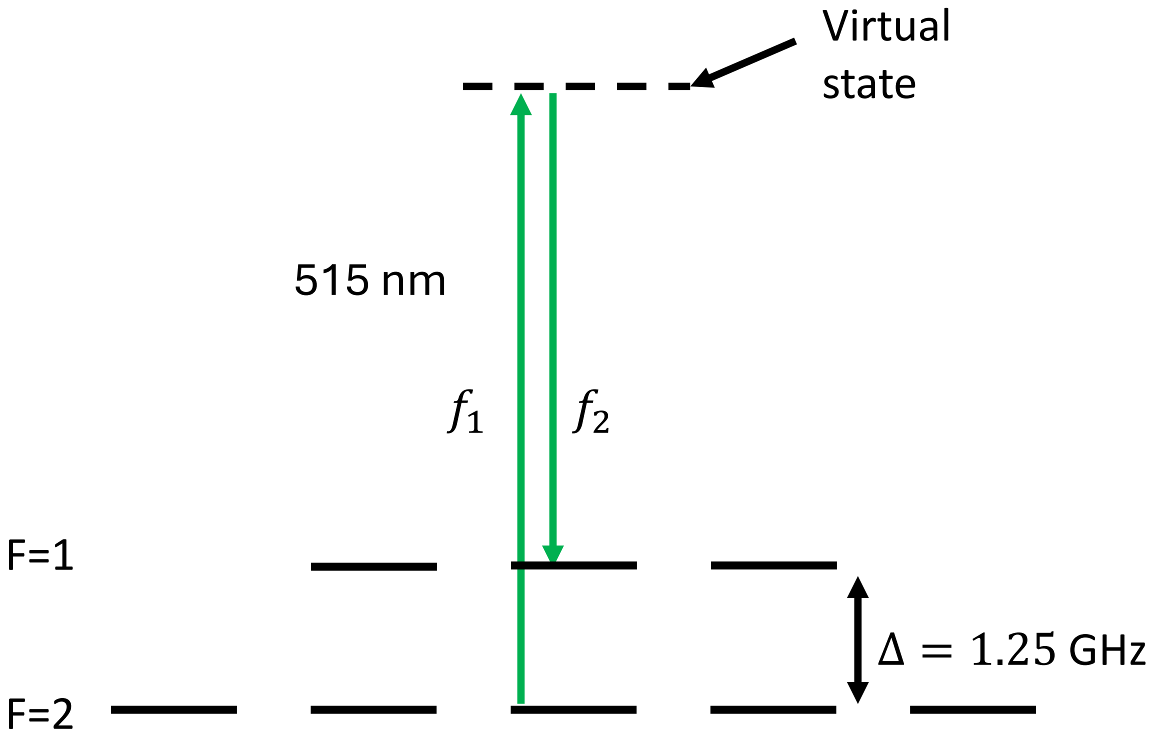
F. Egli et al., arXiv:2605.07942 (2026)

Spatial and Temporal Alignment of the XUV Beam



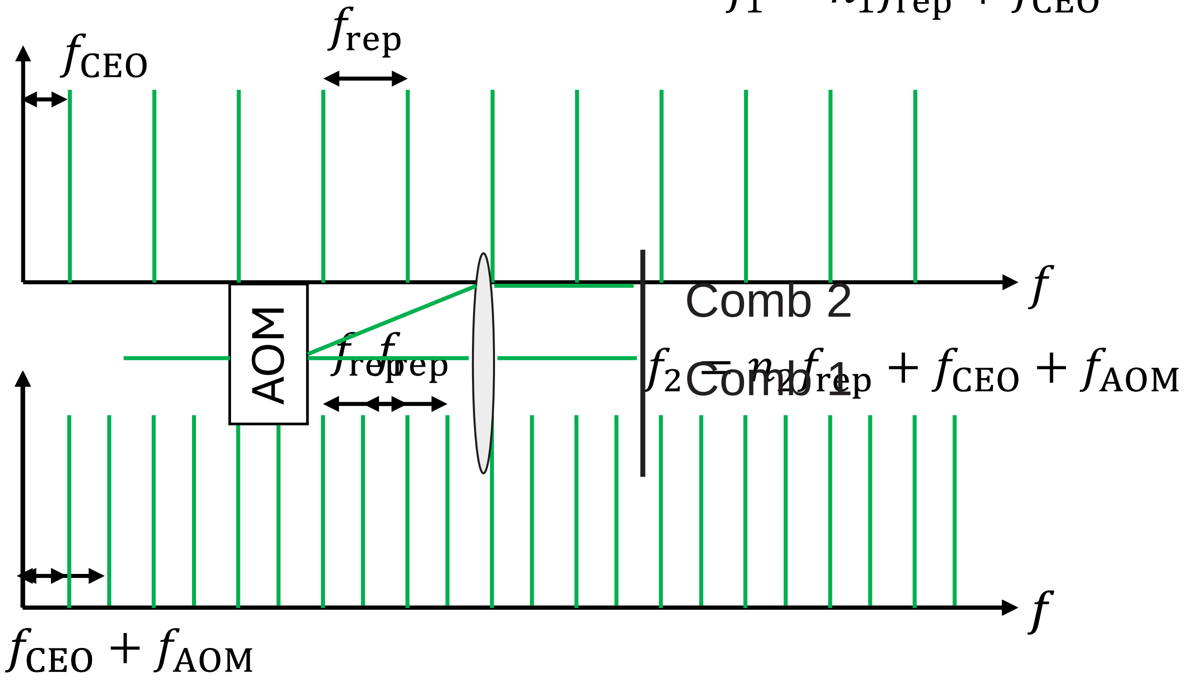
- ➤ Drive Raman transition in Be$^+$ with 515 nm pulses

Pulse Overlap: Raman Transitions in Be⁺ ground state HFS



$$|f_1 - f_2| = \Delta$$

$$f_1 = n_1 f_{\mathrm{rep}} + f_{\mathrm{CEO}}$$



$$f_2 = n_2 f_{\mathrm{rep}} + f_{\mathrm{CEO}} + f_{\mathrm{AOM}}$$

$$f_1 - f_2 = \underbrace{(n_1 - n_2)}_{\Delta n} f_{\mathrm{rep}} + f_{\mathrm{AOM}}$$

1.25 GHz

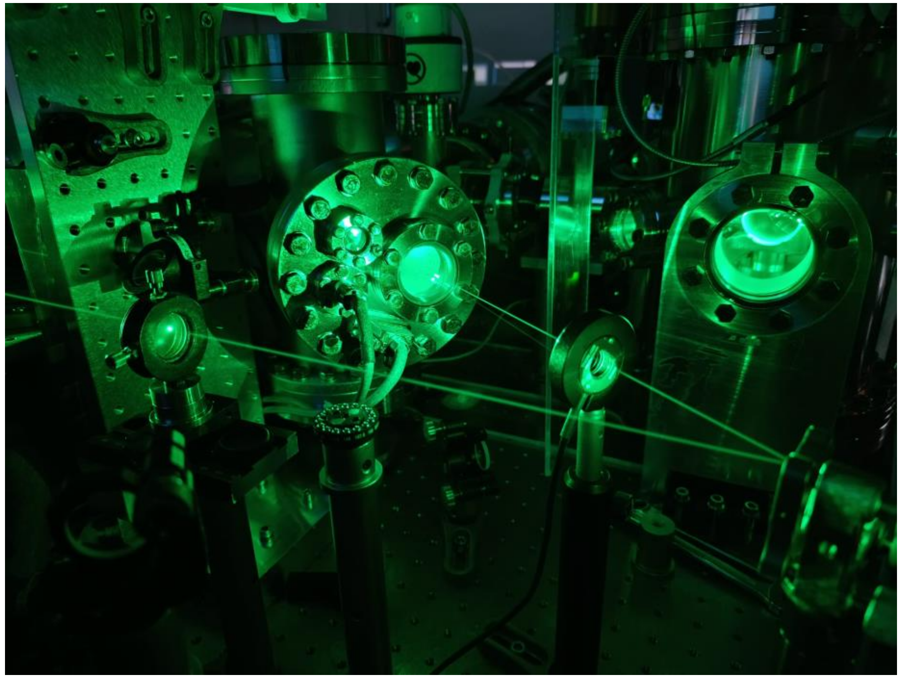
29

40 MHz

87 MHz

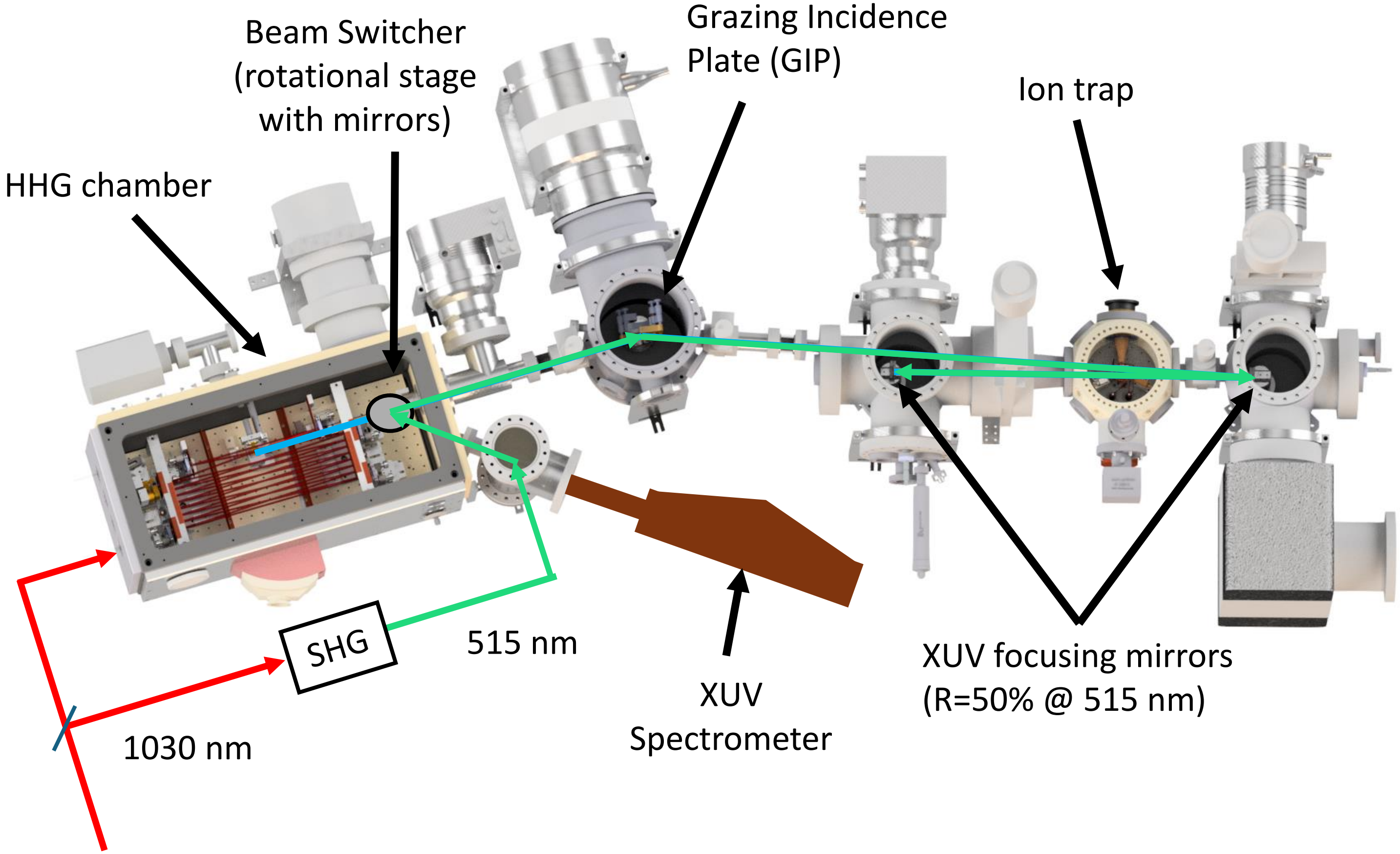
Paschke, A.-G. *et al., Phys. Rev. Lett.* **122**, 123606 (2019)

Pulse Overlap: Raman Transitions in Be^+ ground state HFS

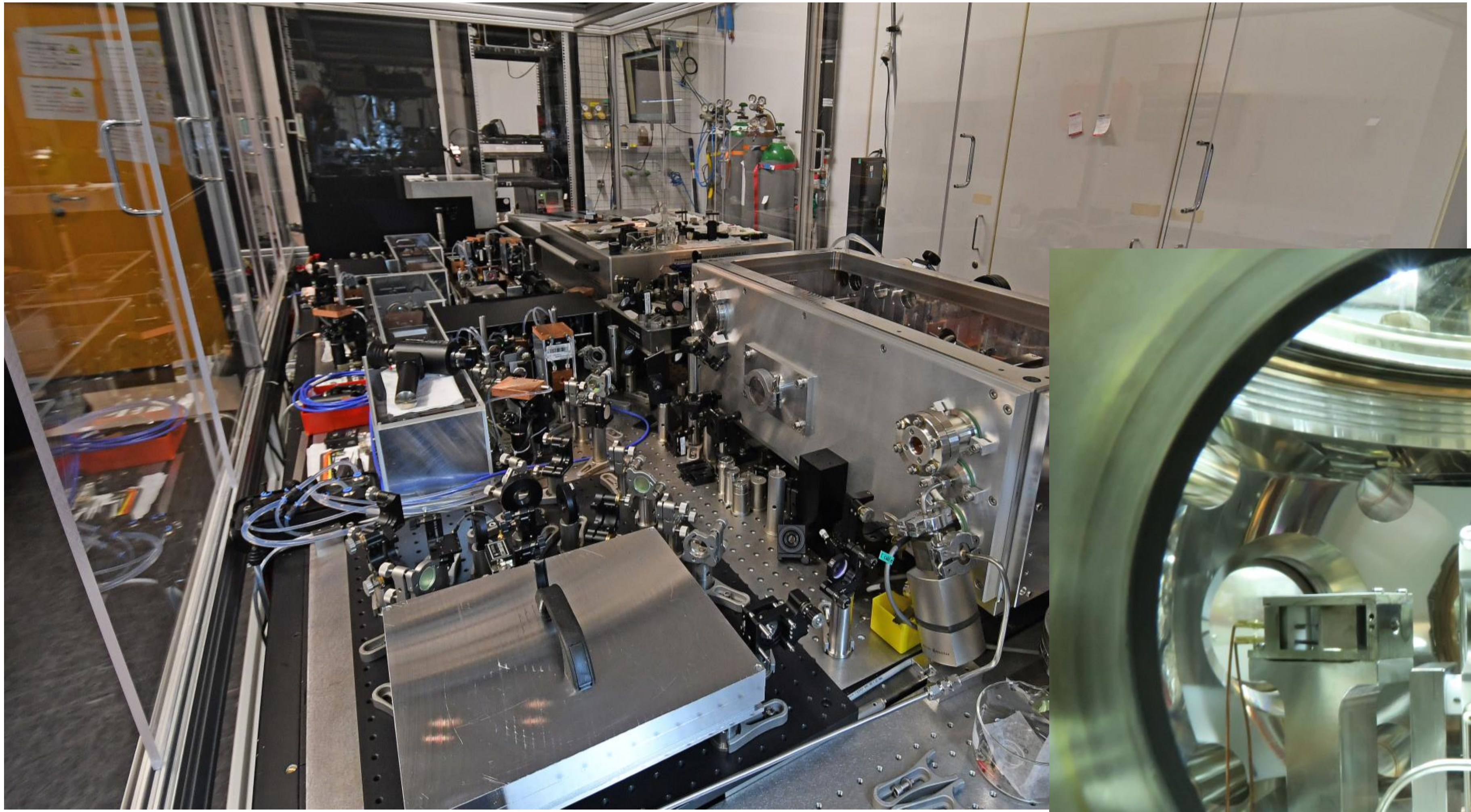


Achieved:
- Comb at 515 nm with ~ 4W (SHG from IR)
- Double pass AOM setup

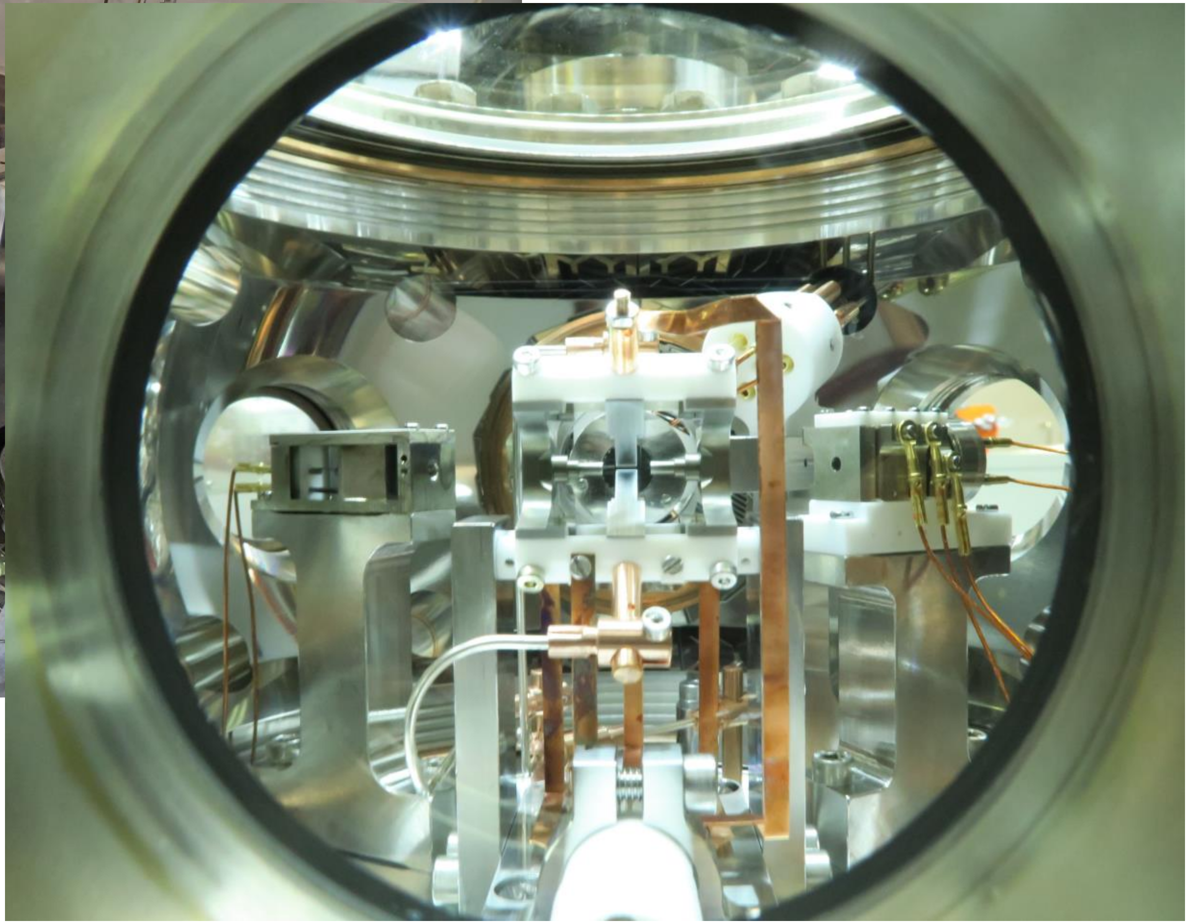
After losses: Power @ ions ~300 mW
Estimated π-time ~250 ms



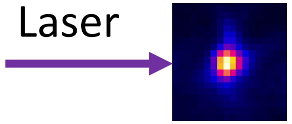
XUV frequency comb source



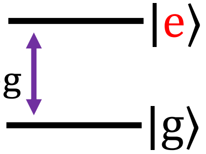
Ion trap

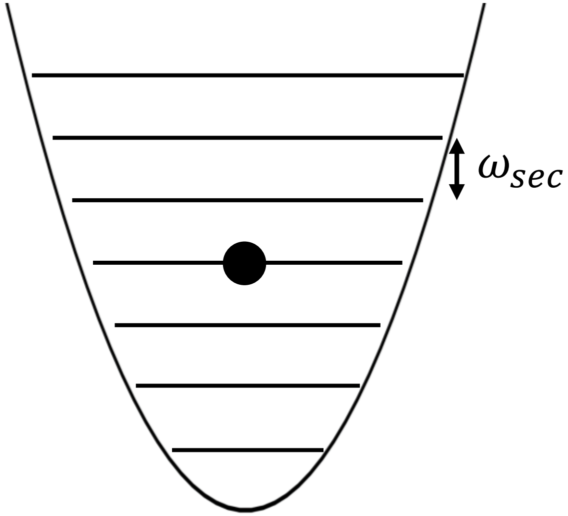


Single Ion Laser Excitation in Harmonic Oscillator

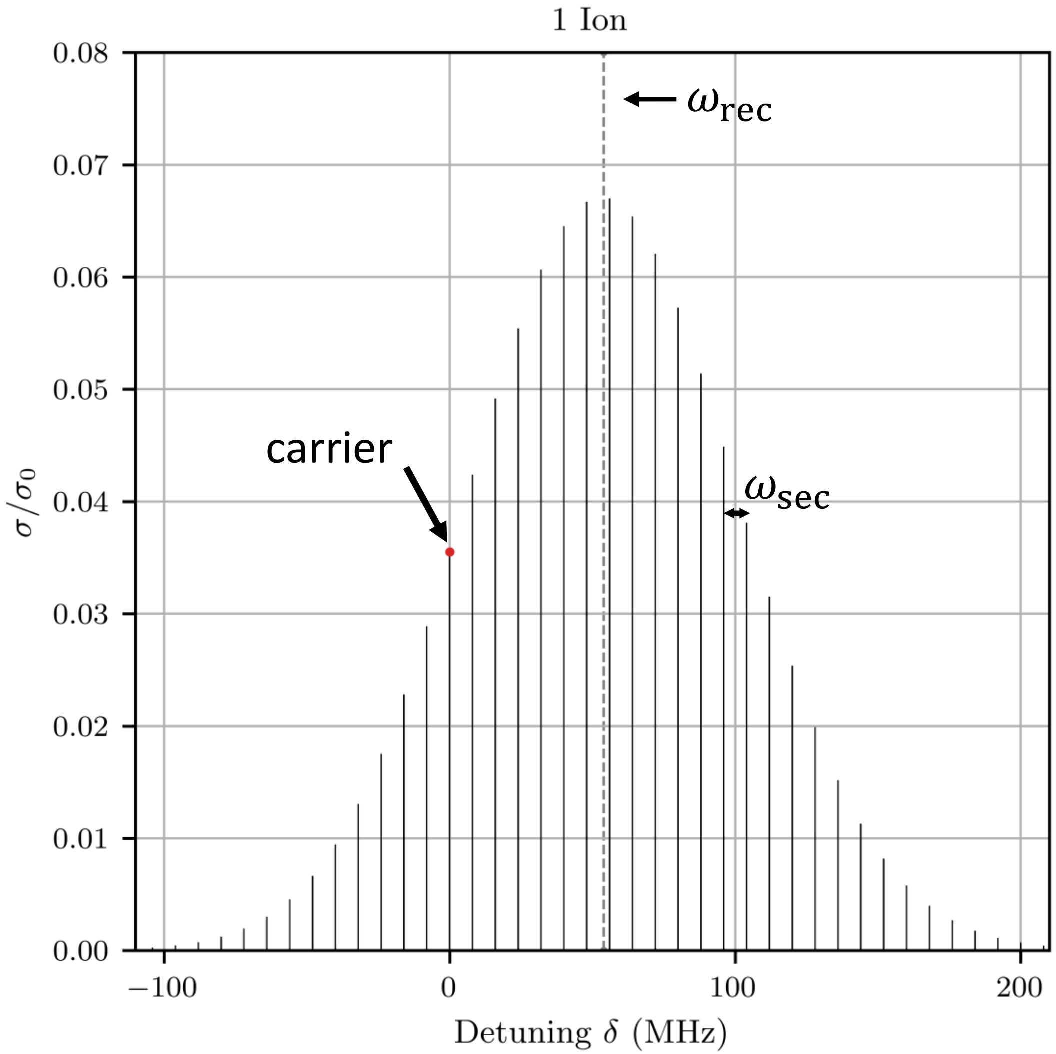


Excite electronic transition: ω_{eg}





$$\omega_{rec} = \frac{\hbar k^2}{2m} \geq \omega_{\mathrm{sec,ax}} \quad ➡ \quad \eta = \sqrt{\frac{\omega_{rec}}{\omega_{sec}}} > 1$$

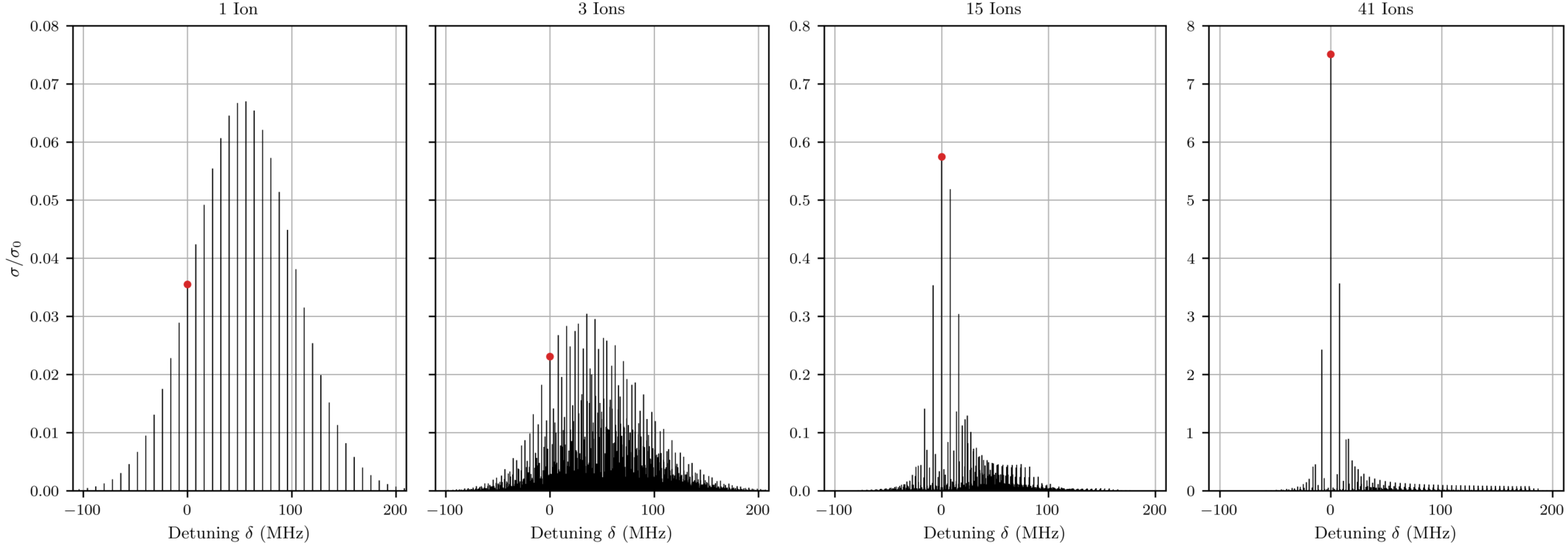


F. Egli et al., arXiv:2605.07942 (2026)

Carrier Revival in Linear Ion Chains

Sidebands $\Delta\mathbf{n} = (\Delta n_1, \dots, \Delta n_N)$
detuning $\delta = \sum_\alpha \Delta n_\alpha \omega_\alpha$

$\omega_{rec} = 2\pi \times 54$ MHz
$\omega_{sec} = 2\pi \times 8$ MHz
$T = 1$ mK



F. Egli et al., arXiv:2605.07942 (2026)

The He$^+$ team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Akira
Ozawa


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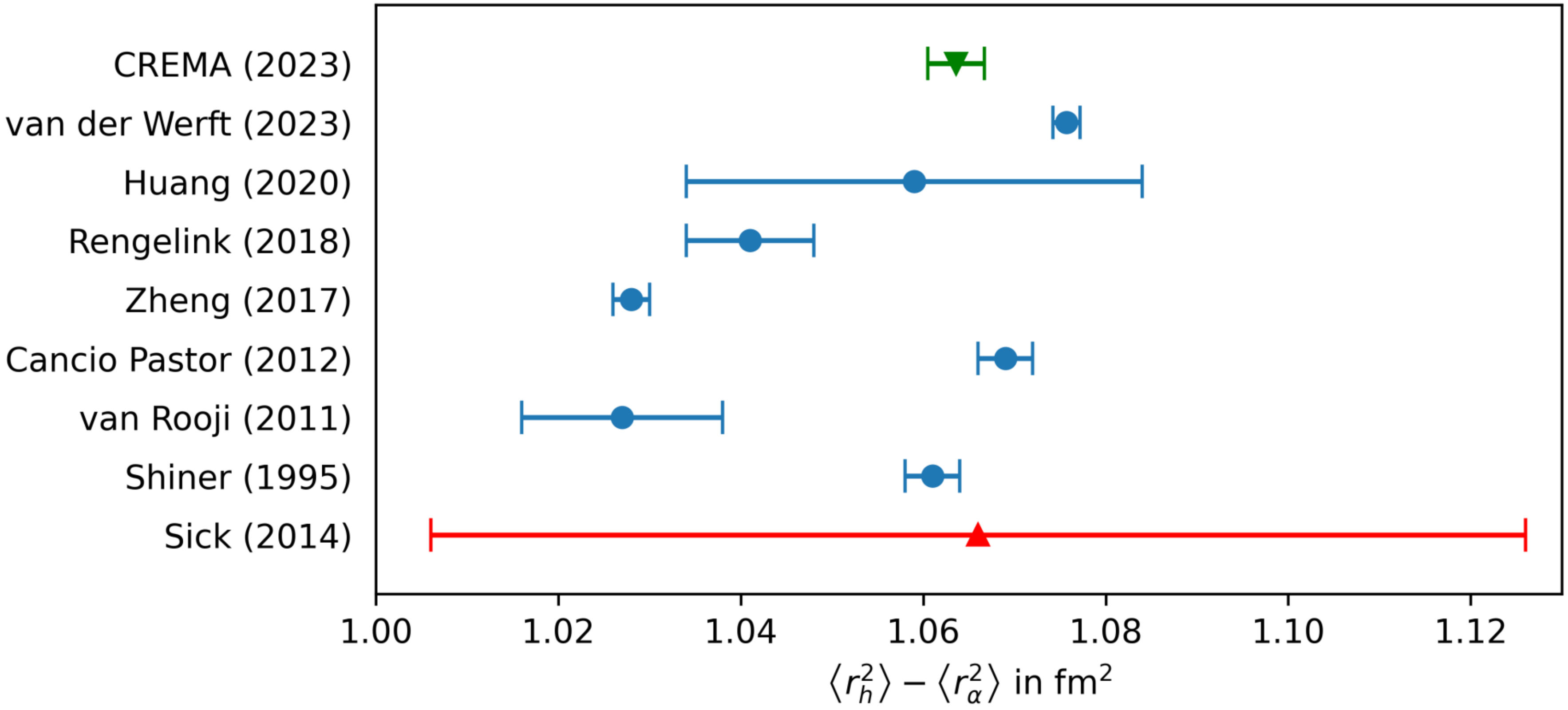
Uncertainty due to QED theory for He^+ 1s-2s transition

[1] Yerokhin A. and Shabaev V. M , Phys. Rev. A 93, 062514 (2016)
[2] Pachucki K. and Moro A. M, Phys. Rev. A 75, 032521 (2007)
[3] Karshenboim S. G et al. , Physics Letters B 795, 432–437 (2019)
[4] Karshenboim S. G et al. , Phys. Rev. A 100, 032515 (2019)
[5] Karshenboim S. G et al. , Phys. Rev. A 98, 022522 (2018)
[6] V. Yerokhin et al. , Annalen der Physik 531, 1800324 (2019)
[7] A.Czarnecki et al. , Phys. Rev. A 94, 060501 (2016)
[8] S. Laporta, Physics Letters B 800, 135137 (2020)
[9] Karshenboim S. G and Shelyuto V. A. , Phys. Rev. A 100, 032513 (2019)

Contribution	**Uncertainty (in kHz)**	
Relativistic Recoil	0	[1]
Nuclear Polarizability	3	[2]
Self Energy	0	
Vacuum Polarization	1	
Two Loop Corrections	32	[3-7]
Three Loop Corrections	9.5	[3,4]
Four Loop Corrections	0	[8]
Nuclear Size Correction to Self Energy	0	
Nuclear Size Correction to Vacuum Polarization	0	
Radiative Recoil	12	[9]
Nuclear Self Energy	0.6	
Total	**~36 kHz**	

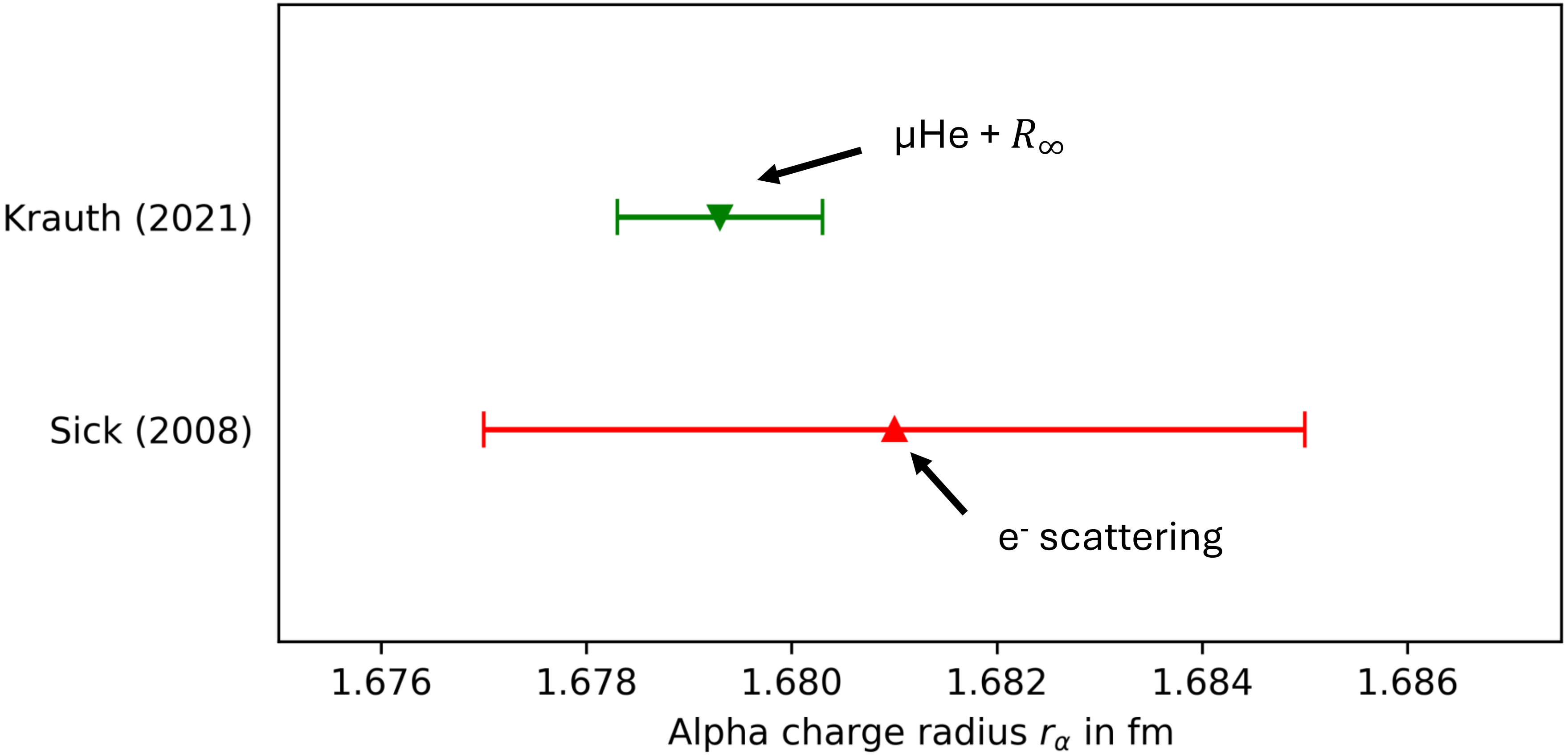
Total QED uncertainty : 36 kHz (4×10^{-12}) (preliminary)

Helium: Difference of Squared Charge Radii



Sun, Y. R. and Hu, S.-M., *National Science Review* **7**, 1818–1827 (2020)
The CREMA Collaboration, arXiv.2305.11679 (2023)

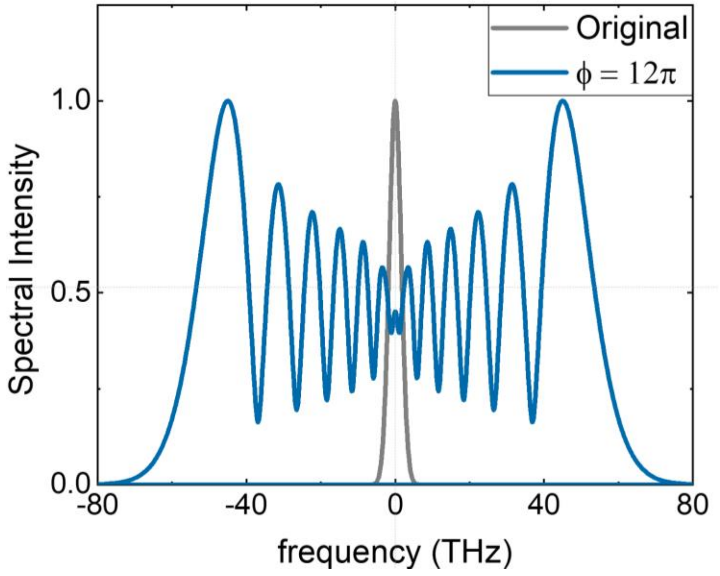
Helium Ions: Alpha Charge Radius



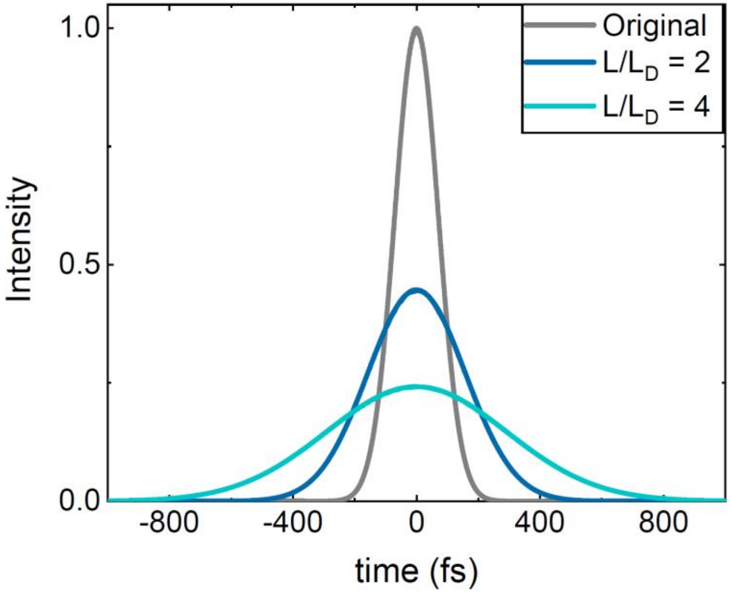
Krauth et al., *Nature* **589**, 527–531 (2021).

Understanding spectral broadening

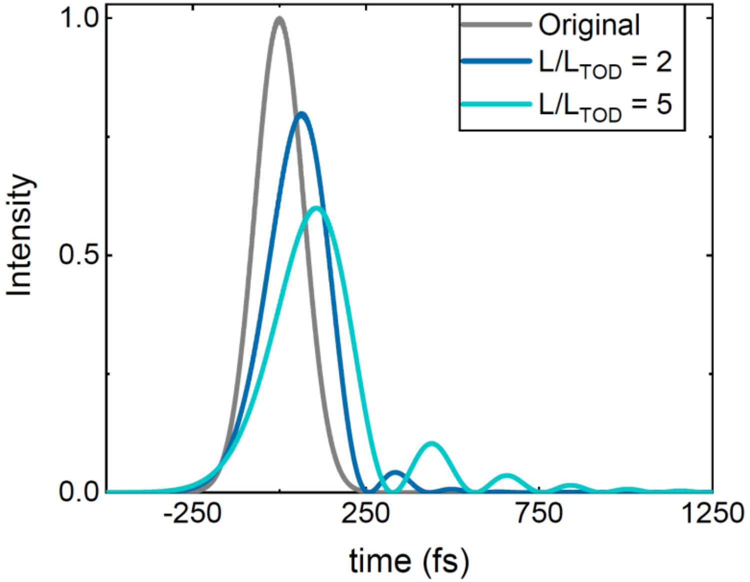
SPM
Self-phase modulation



GDD
Second-order dispersion

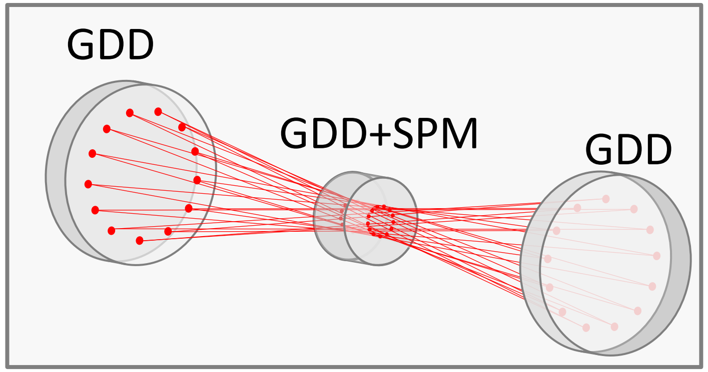


TOD
Third-order dispersion



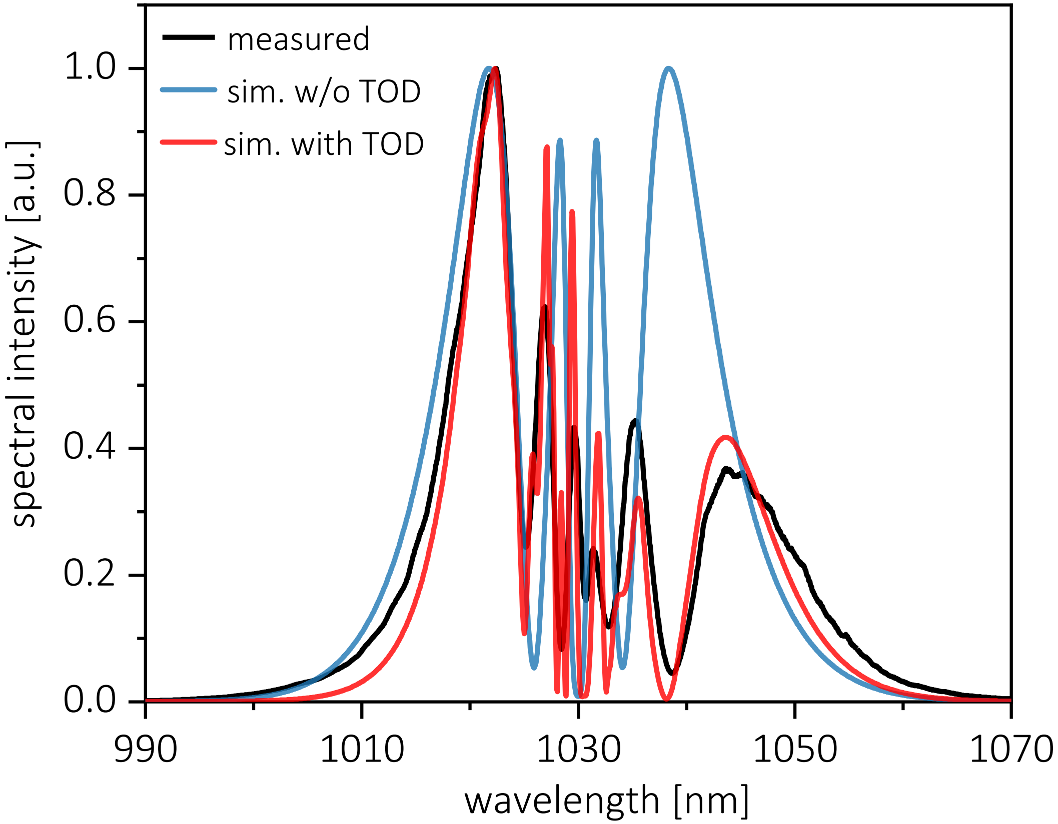
Not considering self-steepening, intrapulse Raman scattering…

Simulating multi-pass cell spectral broadening



Simulation of MPCSB

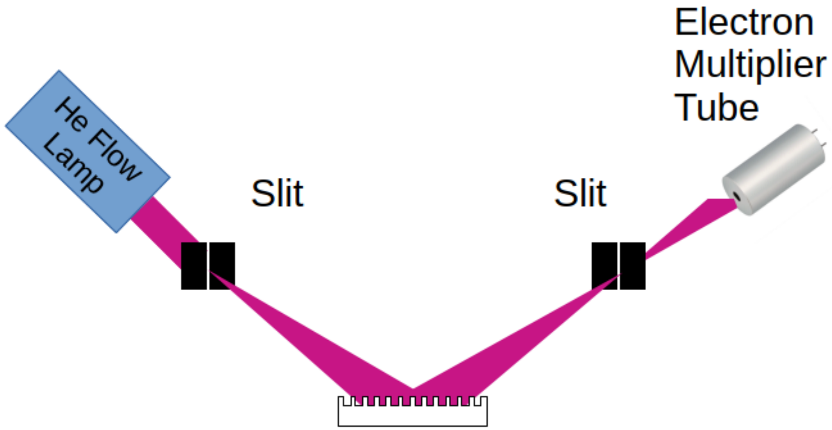
- GDD + SPM act together in **Split-step Fourier method**

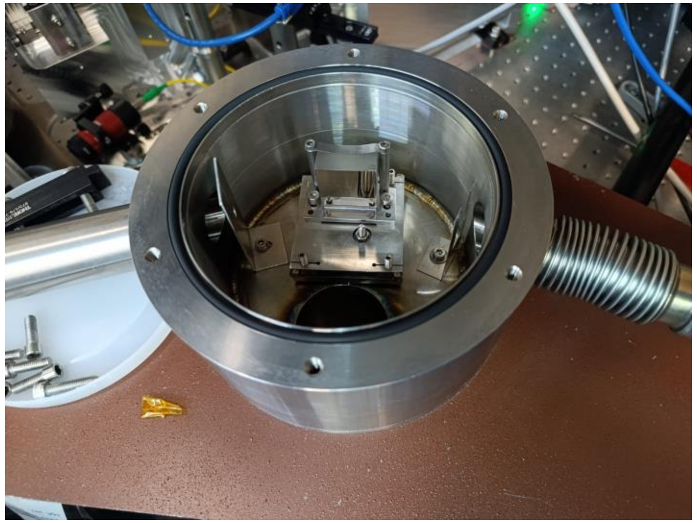


Asymmetry only explained with strong **TOD = – 0.5 ps^3** present before MPCSB!

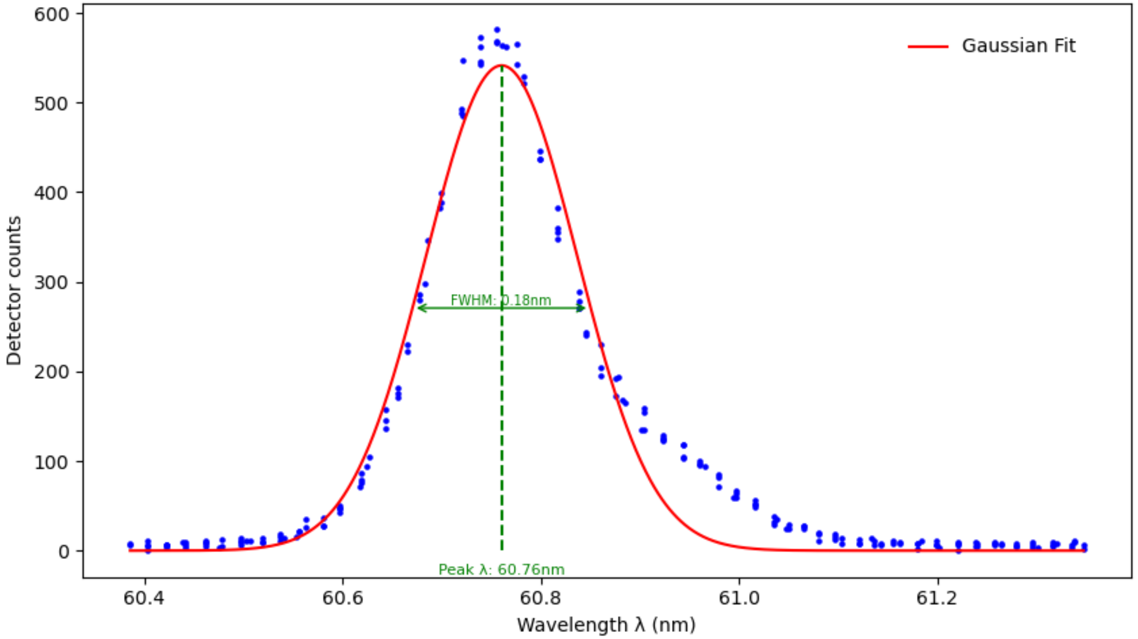
Agrawal, G. Nonlinear Fiber Optics. (Elsevier Inc, Cambridge, 2019)

XUV Spectrometer



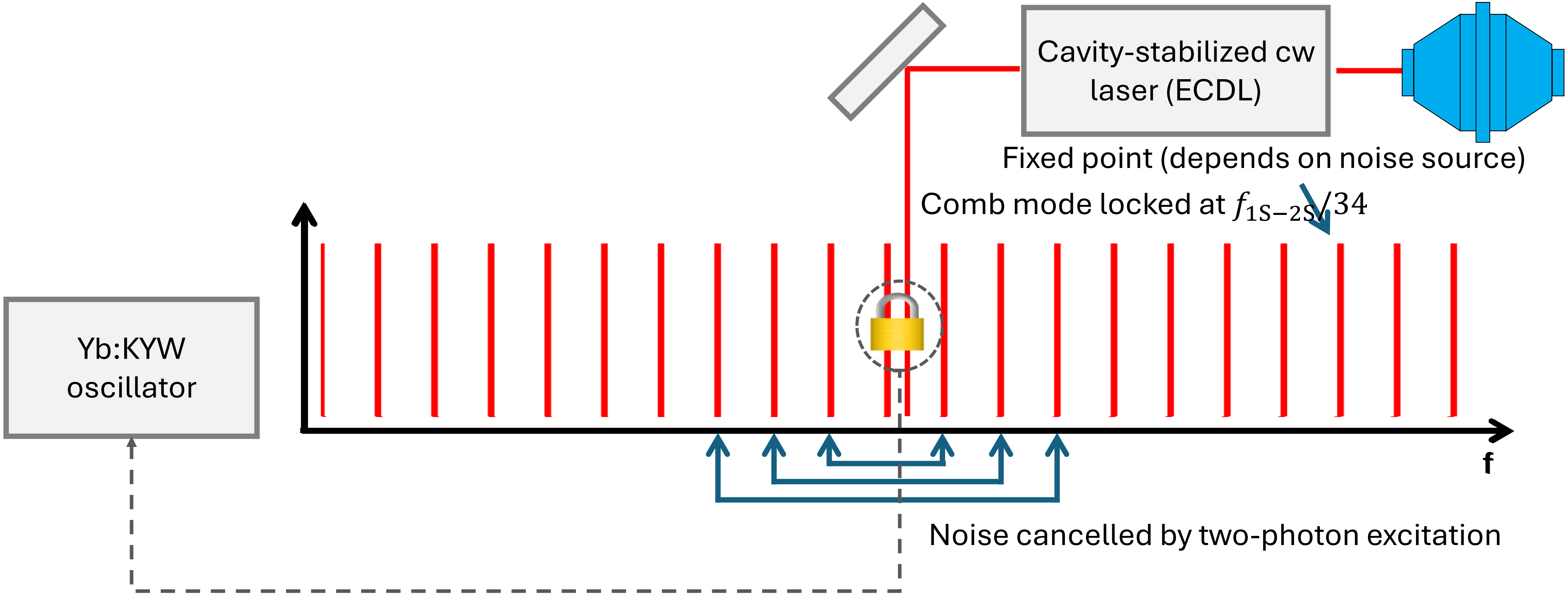


Response function obtained from He$^+$ lamp spectroscopy (second order diffraction of 1s – 2p emission at 30.4 nm)



- resolution 0.18 nm
- repeatability 0.0015 nm

Comb stabilization



Cavity-stabilized cw laser (ECDL)

Fixed point (depends on noise source)

Comb mode locked at $f_{1S-2S}/34$

Yb:KYW oscillator

Noise cancelled by two-photon excitation