ELISS2023

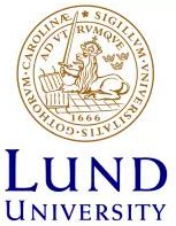
ELI Summer School | 29 Aug – 1 Sep 2023

Dolní Břežany, Czech Republic

Attosecond pulse generation: strong laser fields and extreme nonlinear optics

Anne-Lise Viotti

Lund University



2023-08-29

Dolní Břežany, Czech Republic

eli

IMPULSE

IMPULSE is funded by the European Union's Horizon 2020 programme under grant agreement No. 871161

“Attosecond”

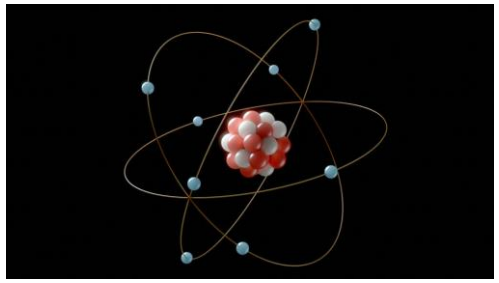
10^{18} seconds

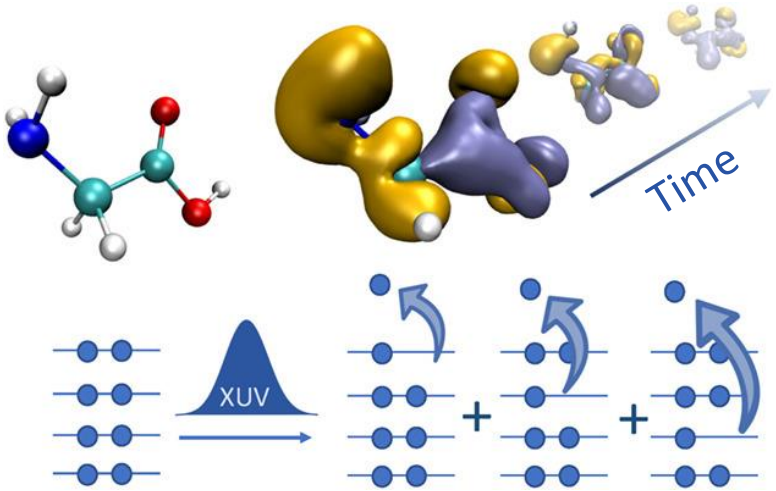
10^{0} seconds

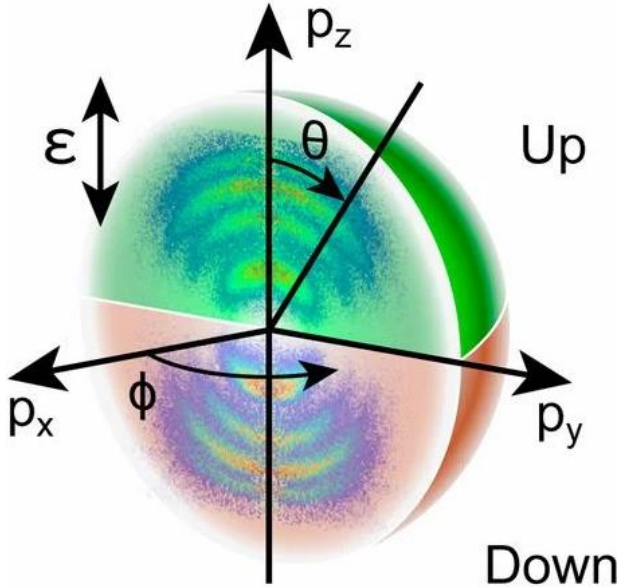
10^{-18} seconds

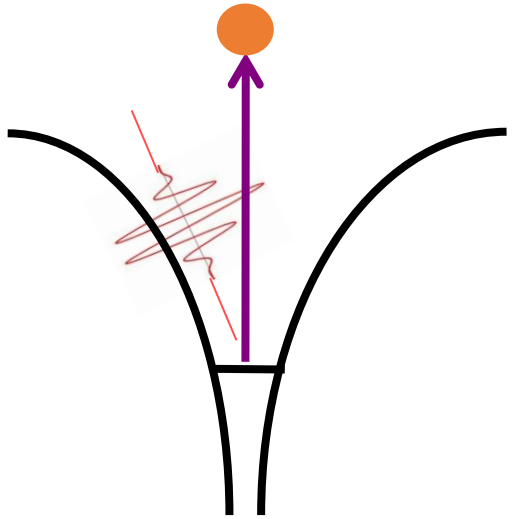
Observables:

Photoelectrons
Charge migration
Correlations
Delays
Fields…





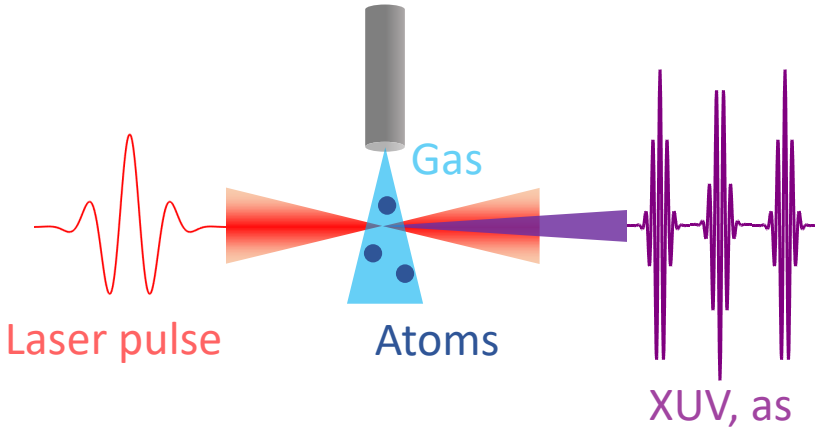


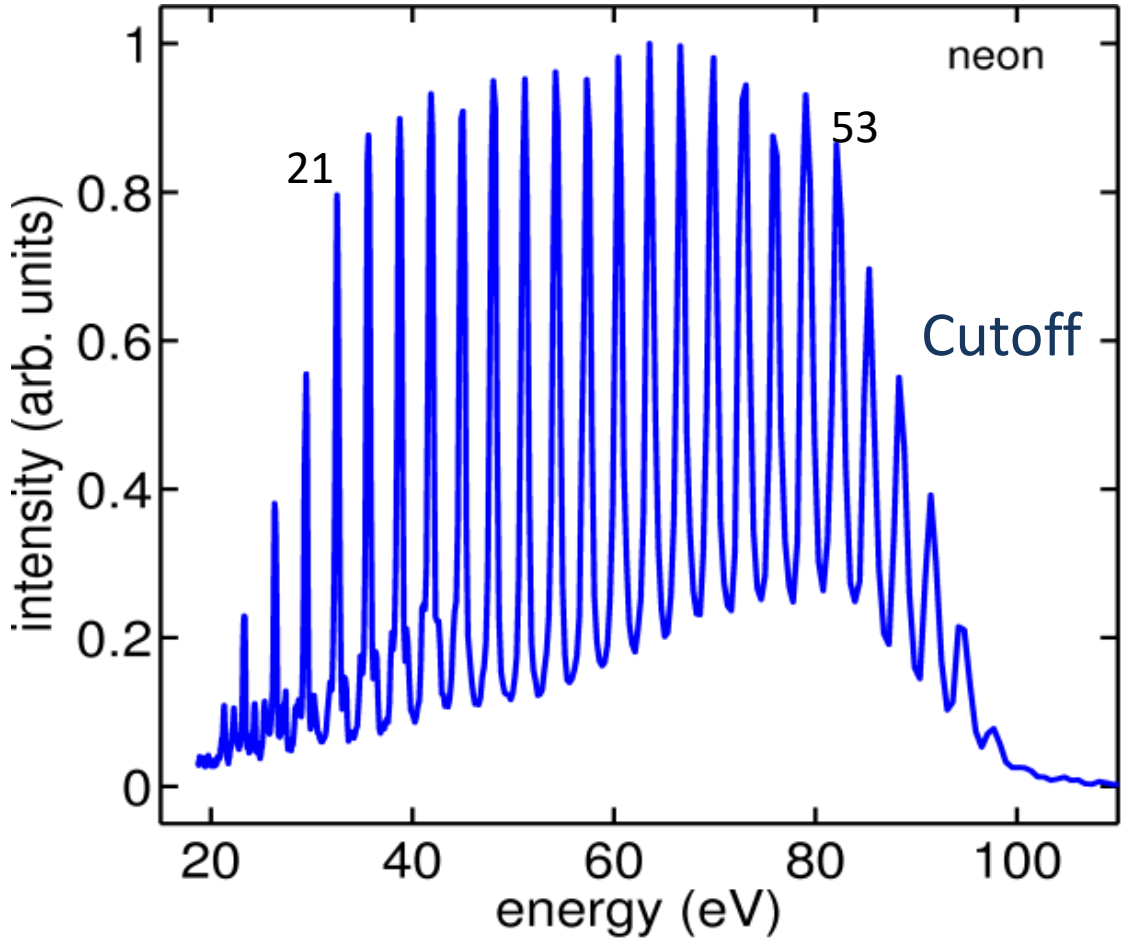


A. Palacios and F. Martín, Adv. Rev. 10 (2020).

Y.-C. Cheng et al., PNAS 117 (2020)

Attosecond pulses by high-order harmonic generation in gases (HHG)

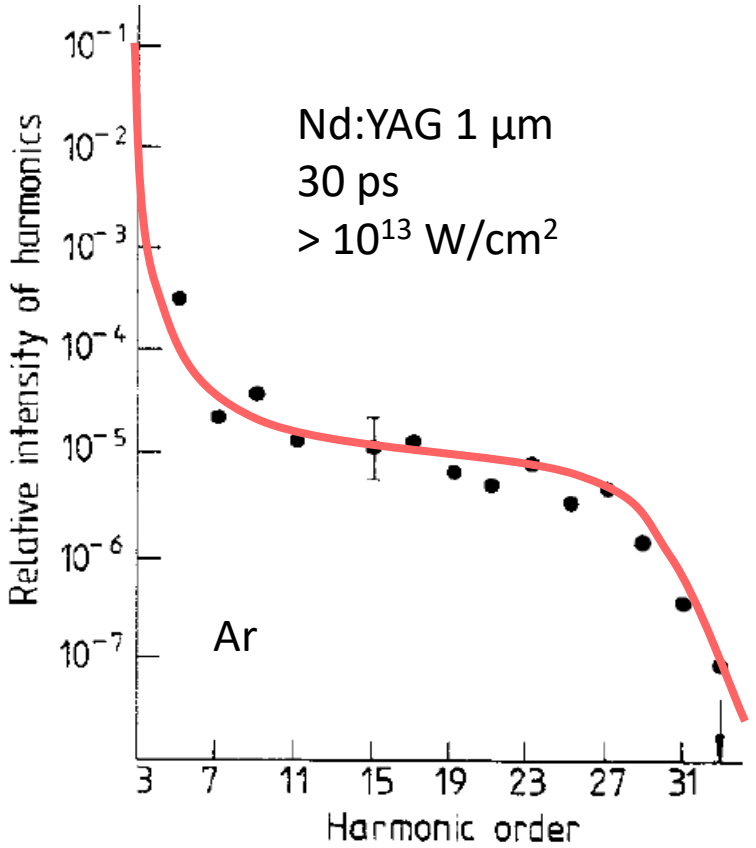


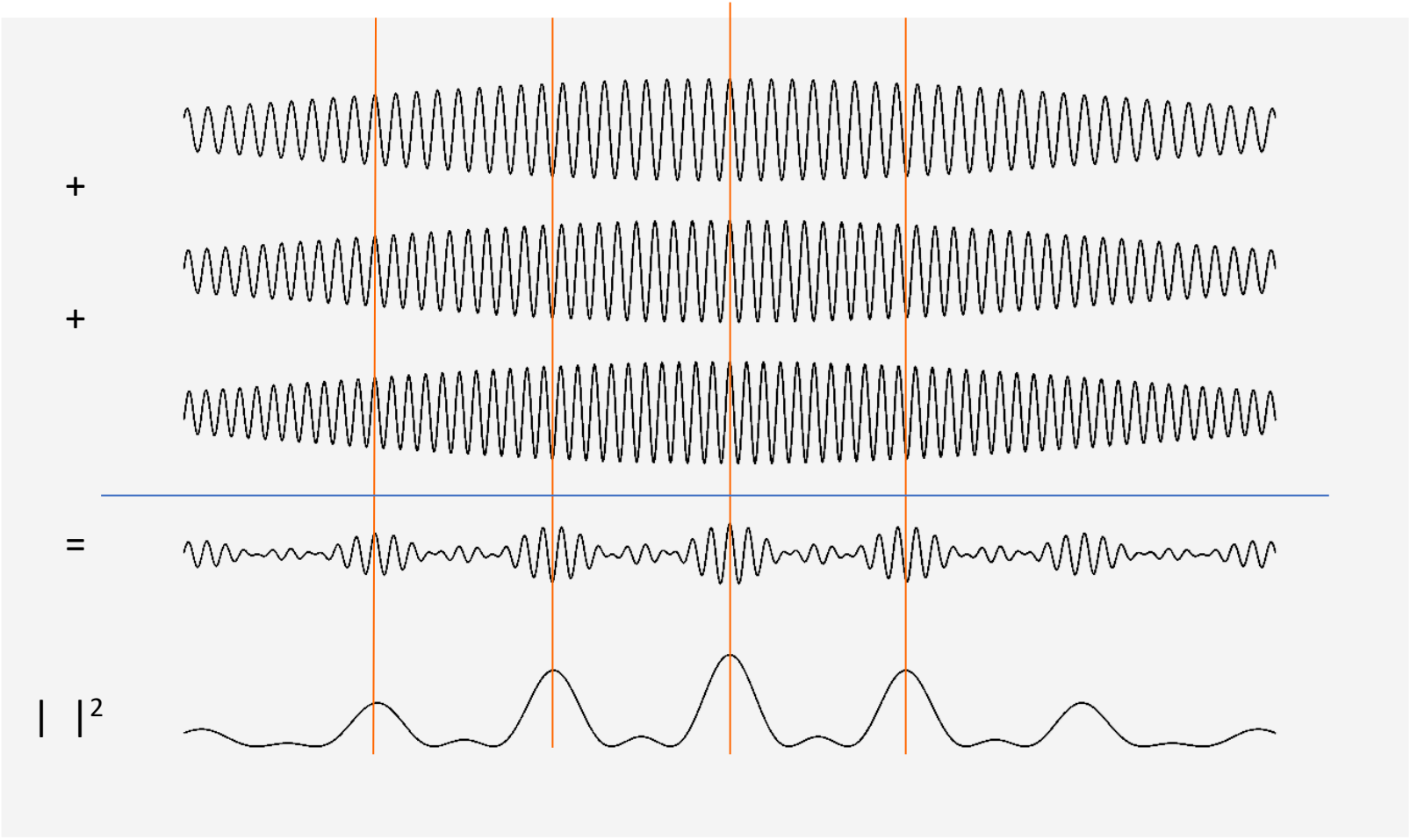


M. Ferray et al., J. Phys. B 21 (1988).

A. McPherson et al., JOSA B 4 (1987).

Attosecond pulse generation via HHG



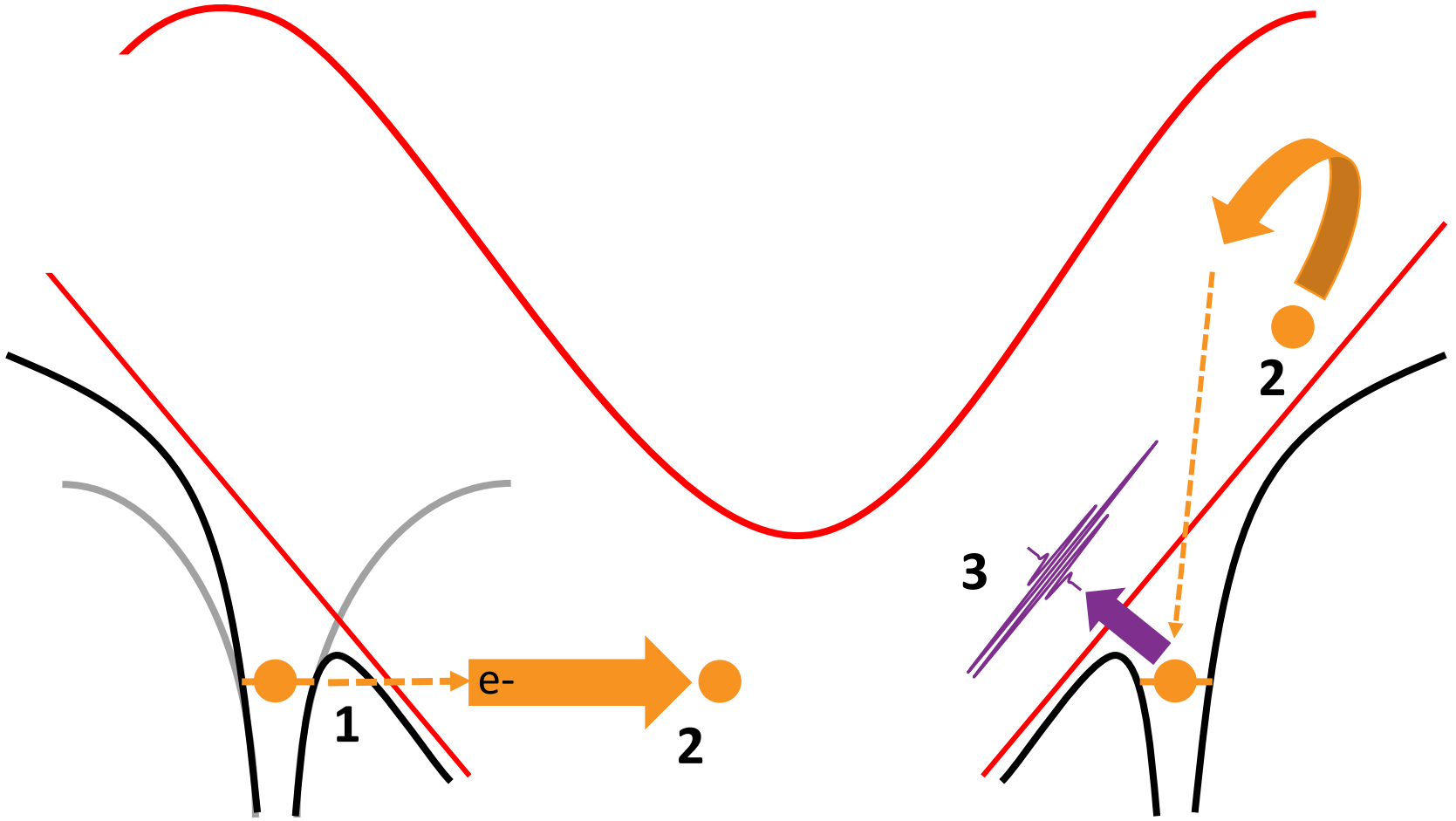


M. Ferray et al., J. Phys. B 21 (1988).

G. Farkas and C. Toth, Phys. Rev. Lett. A 168 (1992).

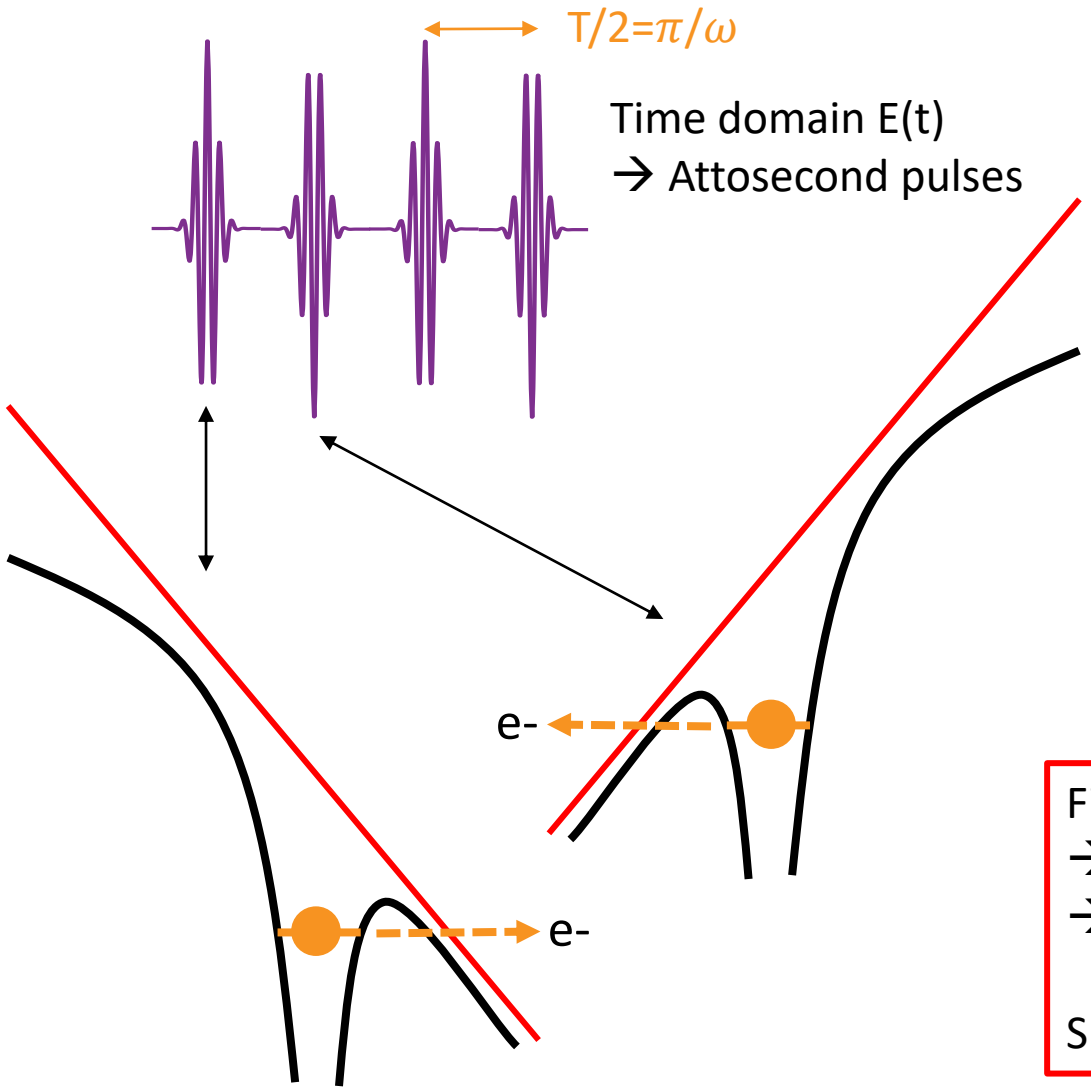
S. E. Harris et al., Opt. Commun. 100 (1993).

The three step model – a physical picture for HHG



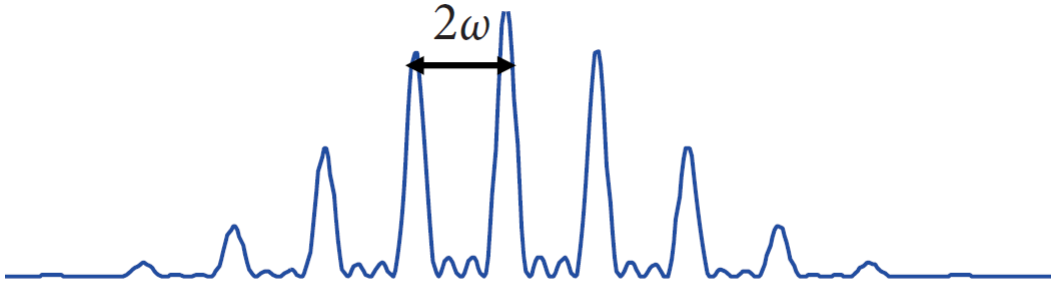
K. J. Schafer et al., Phys. Rev. Lett. 70 (1992). *P. B. Corkum, Phys. Rev. Lett. 71 (1994).*

Properties of HHG light



Time domain E(t)
→ Attosecond pulses

Frequency domain $|E(\omega)|^2$
→ High odd order harmonics



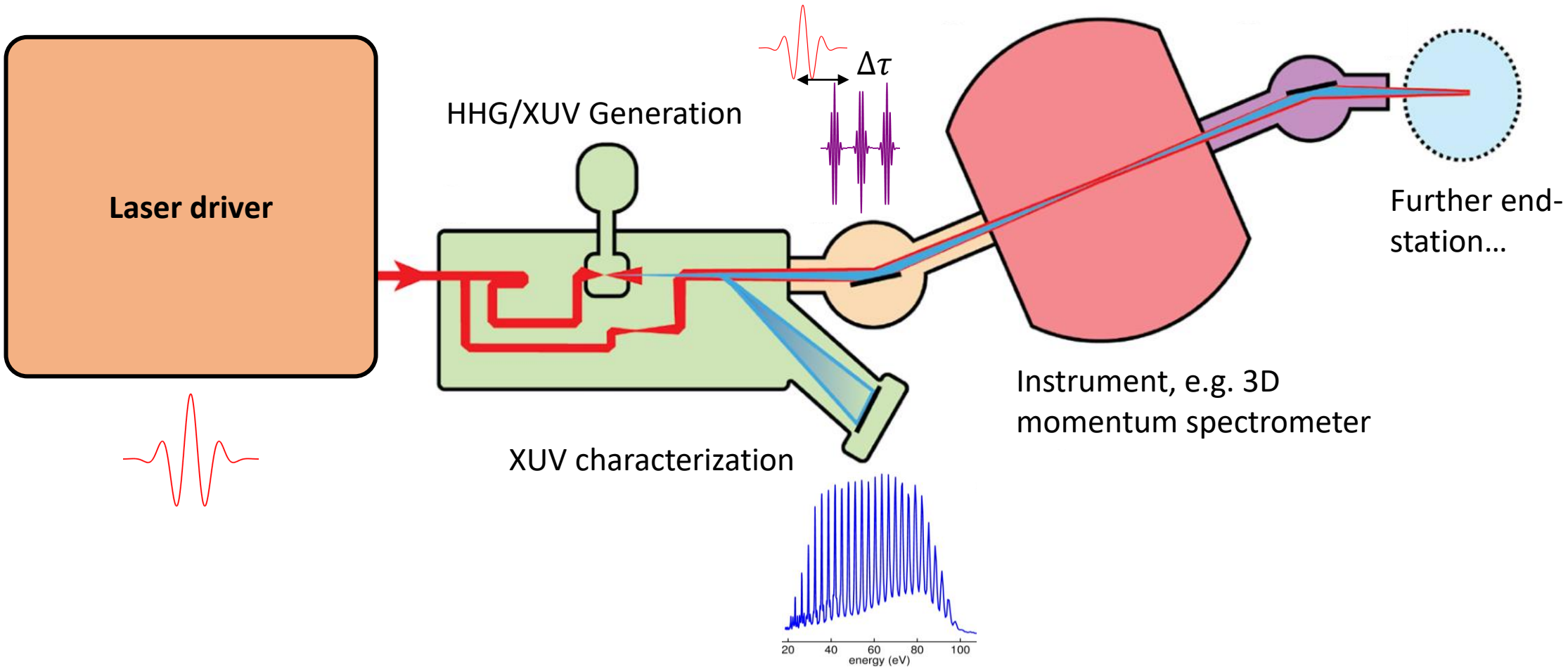
First measured attosecond pulses in 2001:
→ 250 as (train of pulses)
→ 450 as (isolated)

Shortest isolated pulse: 43 as (2017)

A. L'Huillier, chapter 10 in "Attosecond and XUV Physics" (Wiley, 2013).

P. M. Paul et al., Science 292 (2001).
M. Hentschel et al. Nature 414 (2001).
T. Gaumnitz et al., Opt. Express 25 (2017).

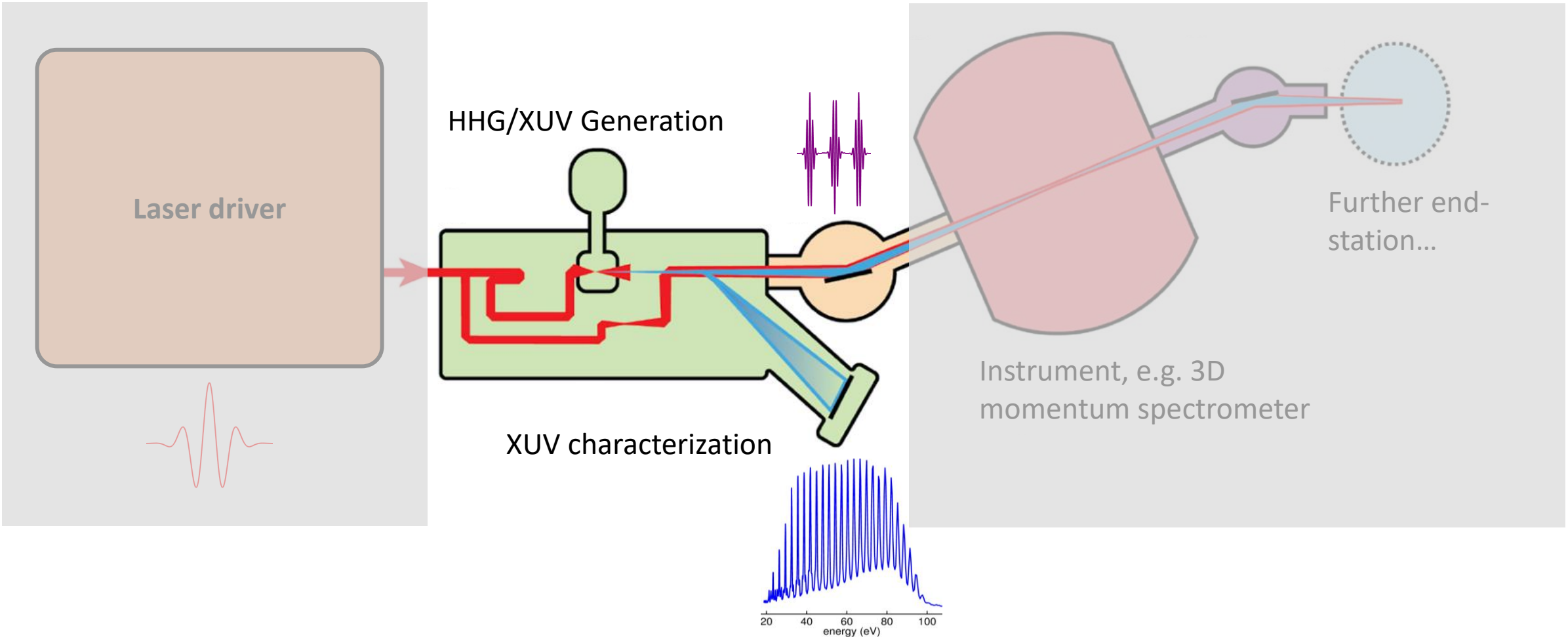
A typical Attosecond beamline



Footprint: ~1 m to > 50 m!

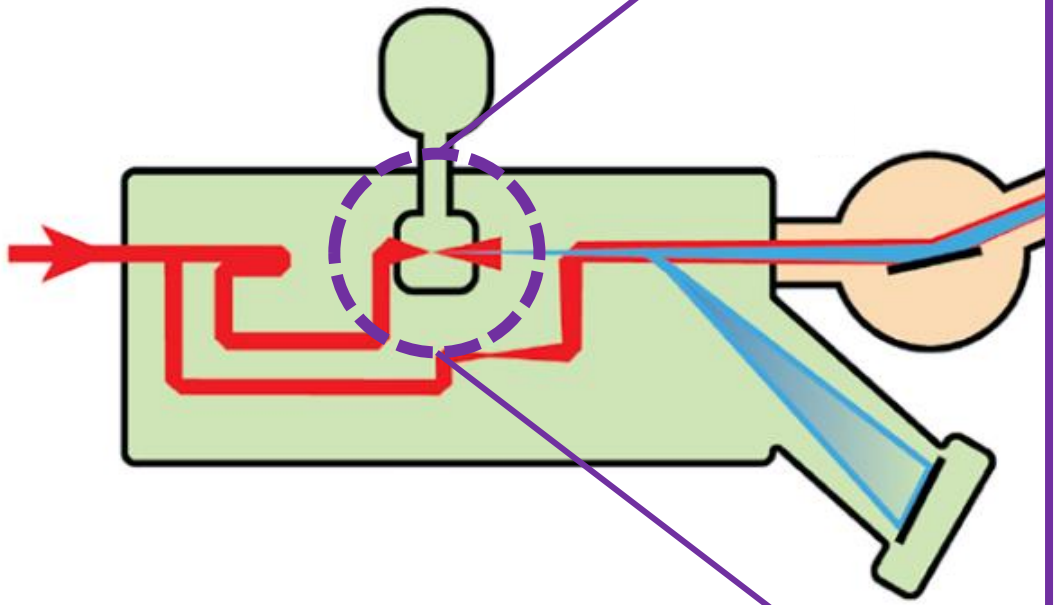
S. Mikaelsson et al., Nanophoton. 10 (2020).

A typical Attosecond beamline

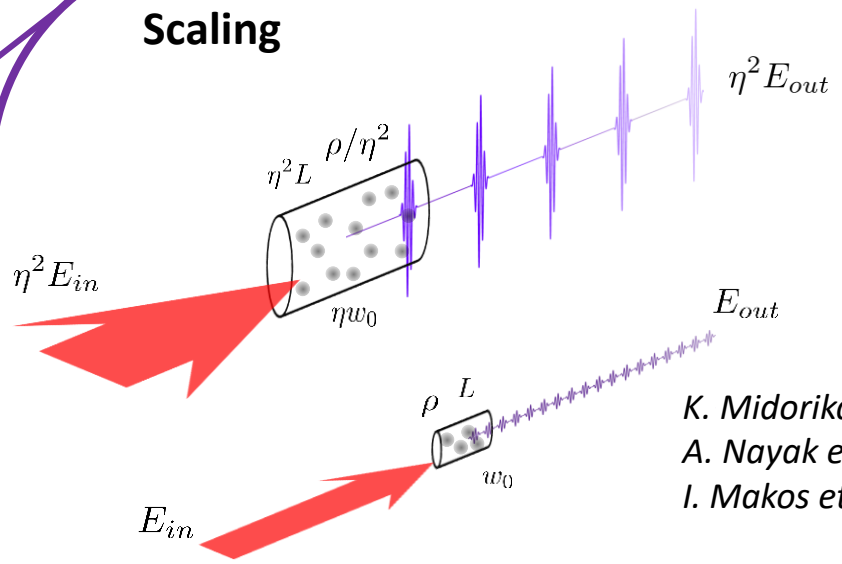


S. Mikaelsson et al., Nanophoton. 10 (2020).

Versatility and challenges of HHG beamlines



Scaling



µJ energies

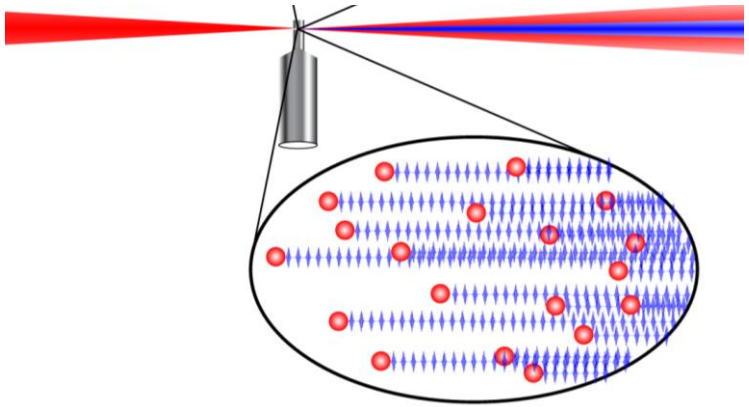
K. Midorikawa, Jpn. J. Appl. Phys. 50 (2011).
A. Nayak et al., Phys. Rev. A 98 (2018).
I. Makos et al., Sci. Rep. 10 (2020).

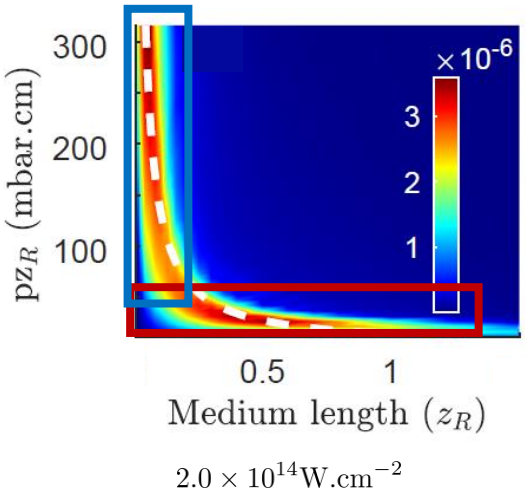
mW average powers

R. Klas et al., PhotoniX 2 (2021).

C. M. Heyl et al., Optica 3 (2016).

Phase-matching

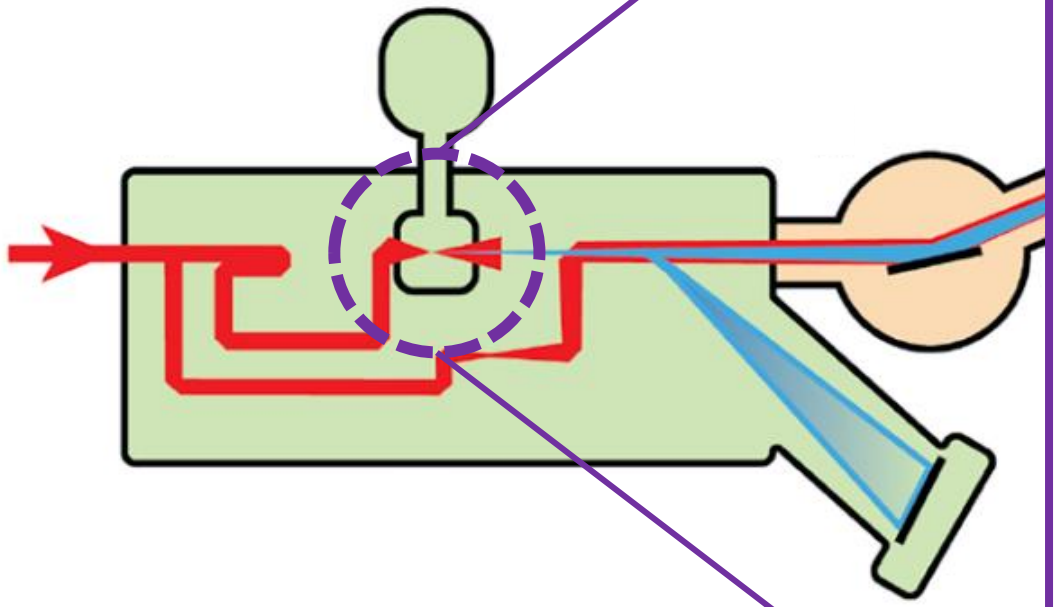


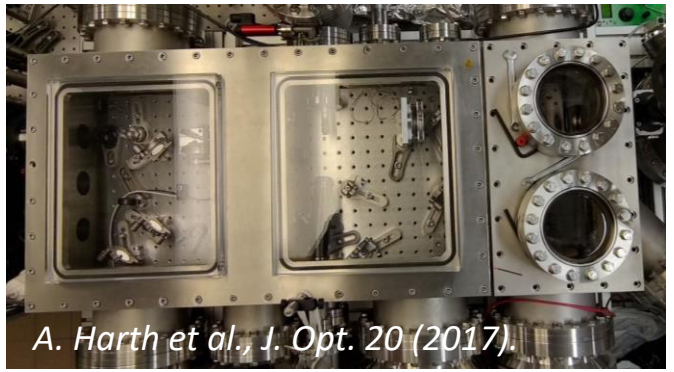


$2.0 \times 10^{14} \mathrm{W.cm^{-2}}$

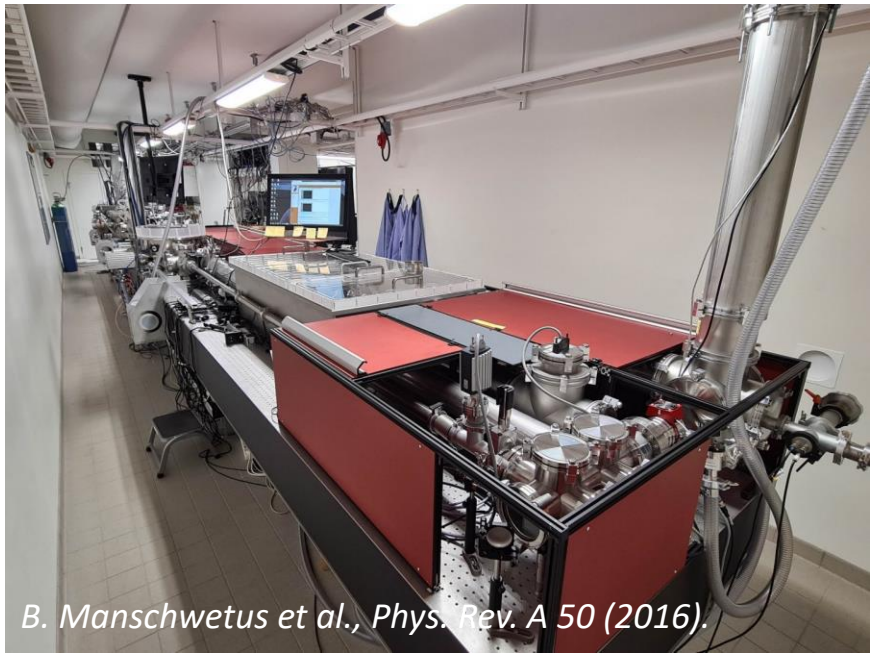
R. Weissenbilder et al., Nat. Rev. Phys. 4 (2022).

Versatility and challenges of HHG beamlines





Lund 200 kHz laser
µJ → short focusing,
small target



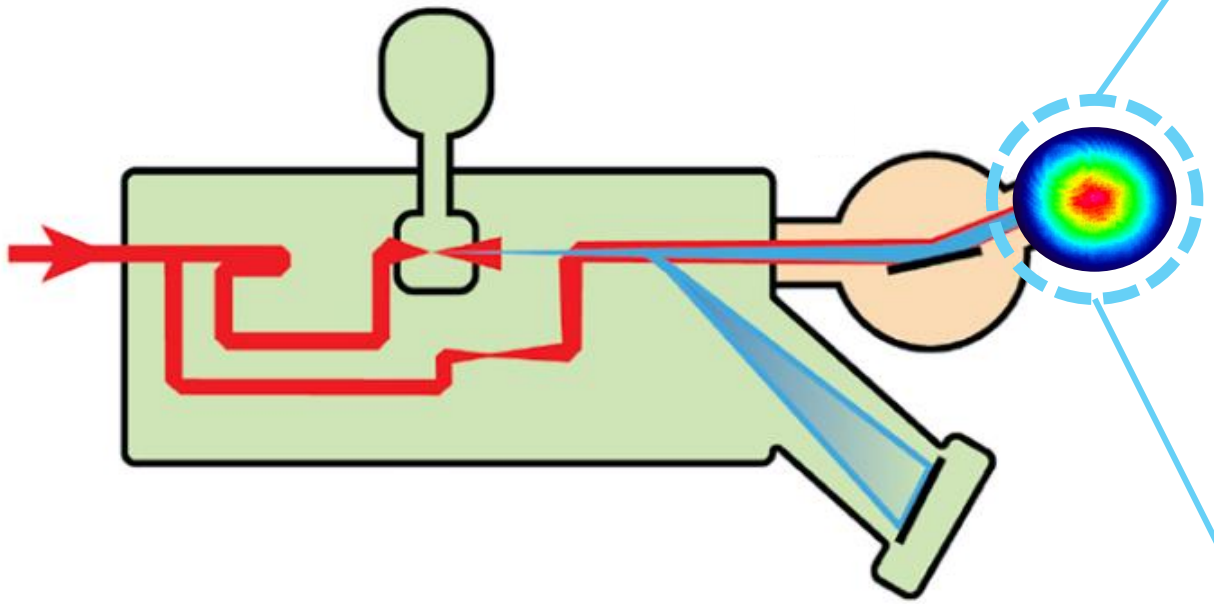
Lund TW laser
mJ → long focusing,
longer gas cell

SYLOS long GHHG beamline:

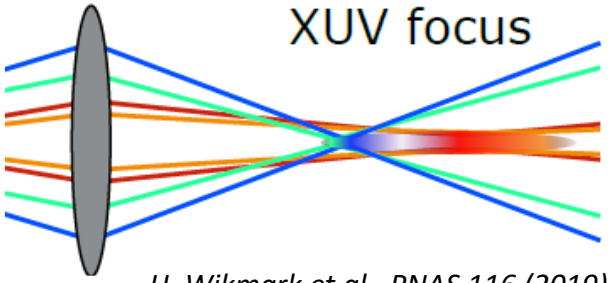
Gas cell 50 cm - 6 m
Up to 55 m beamline!

S. Kühn et al., J. Phys. B: At. Mol. Opt. Phys. 50 (2017).

Versatility and challenges of HHG beamlines



XUV wavefront

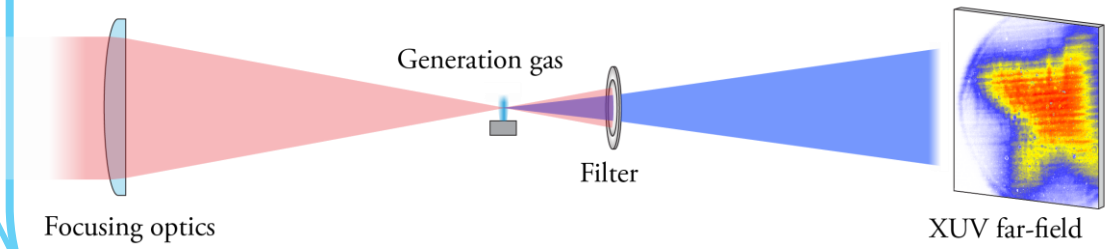


H. Wikmark et al., PNAS 116 (2019).

Chromatic aberrations

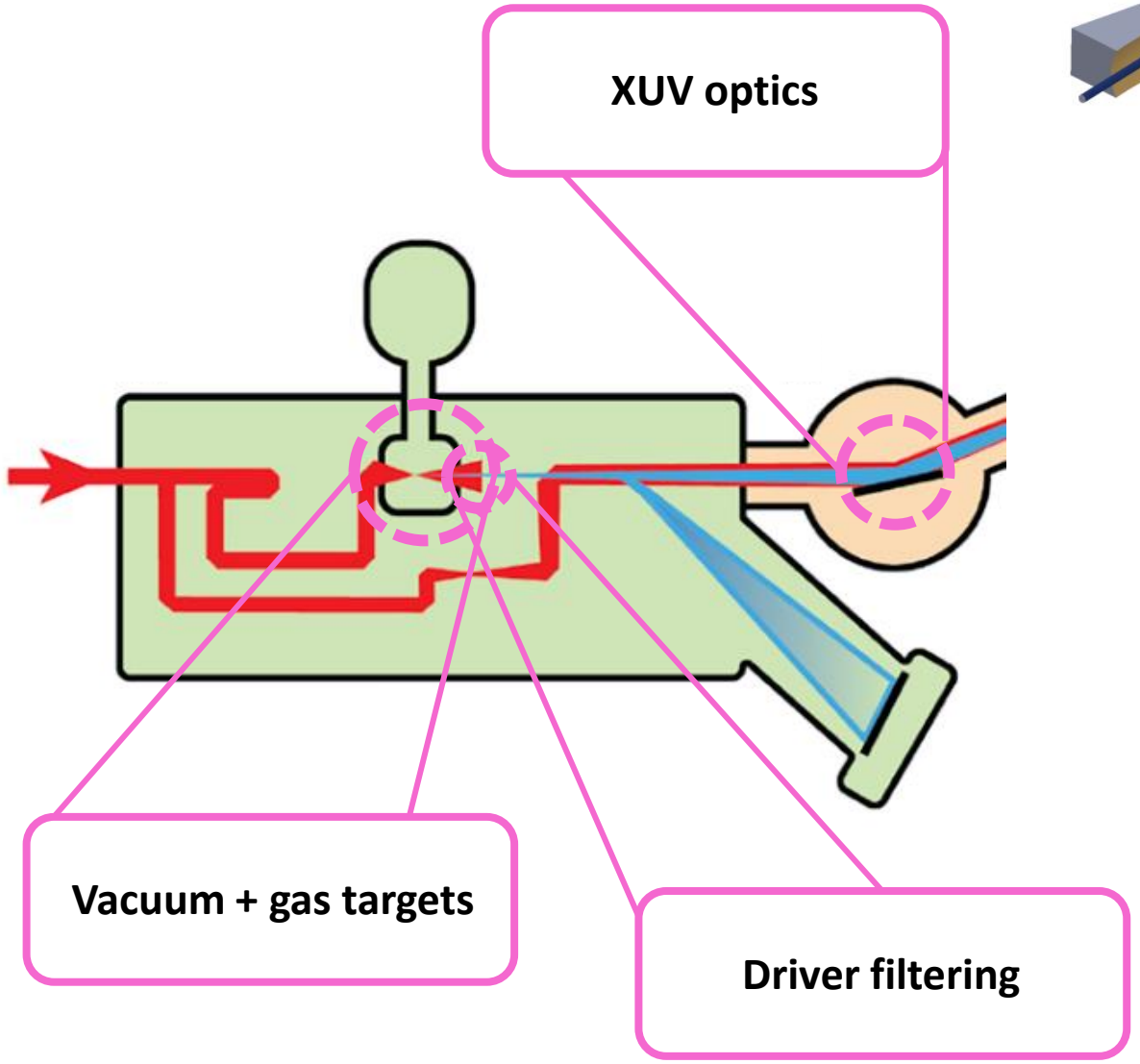
Spatio-temporal couplings

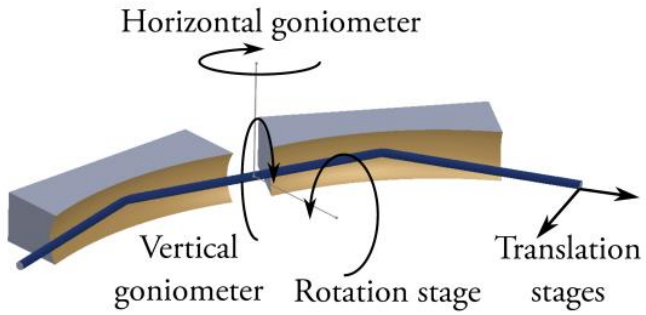
Astigmatism…



M. Plach et al., arXiv:2308.08018 (2023).

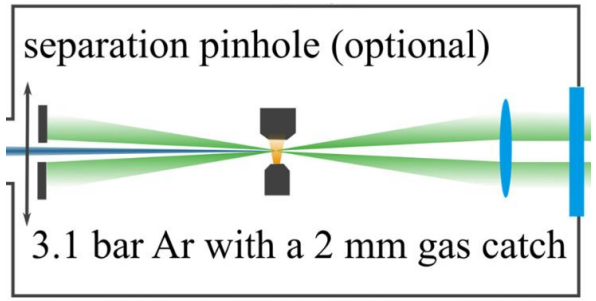
Versatility and challenges of HHG beamlines



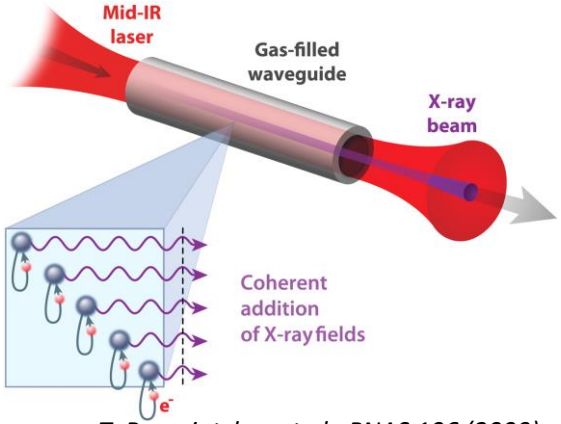


H. Coudert-Alteirac et al., Appl. Sci. 7 (2017).

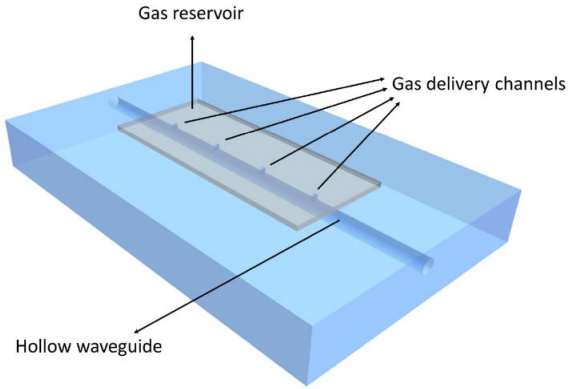
Luxel



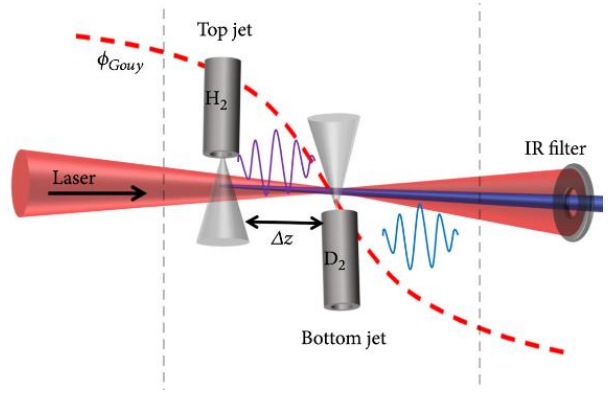
R. Klas et al., Opt. Express 26 (2018).



T. Popmintchev et al., PNAS 106 (2009).

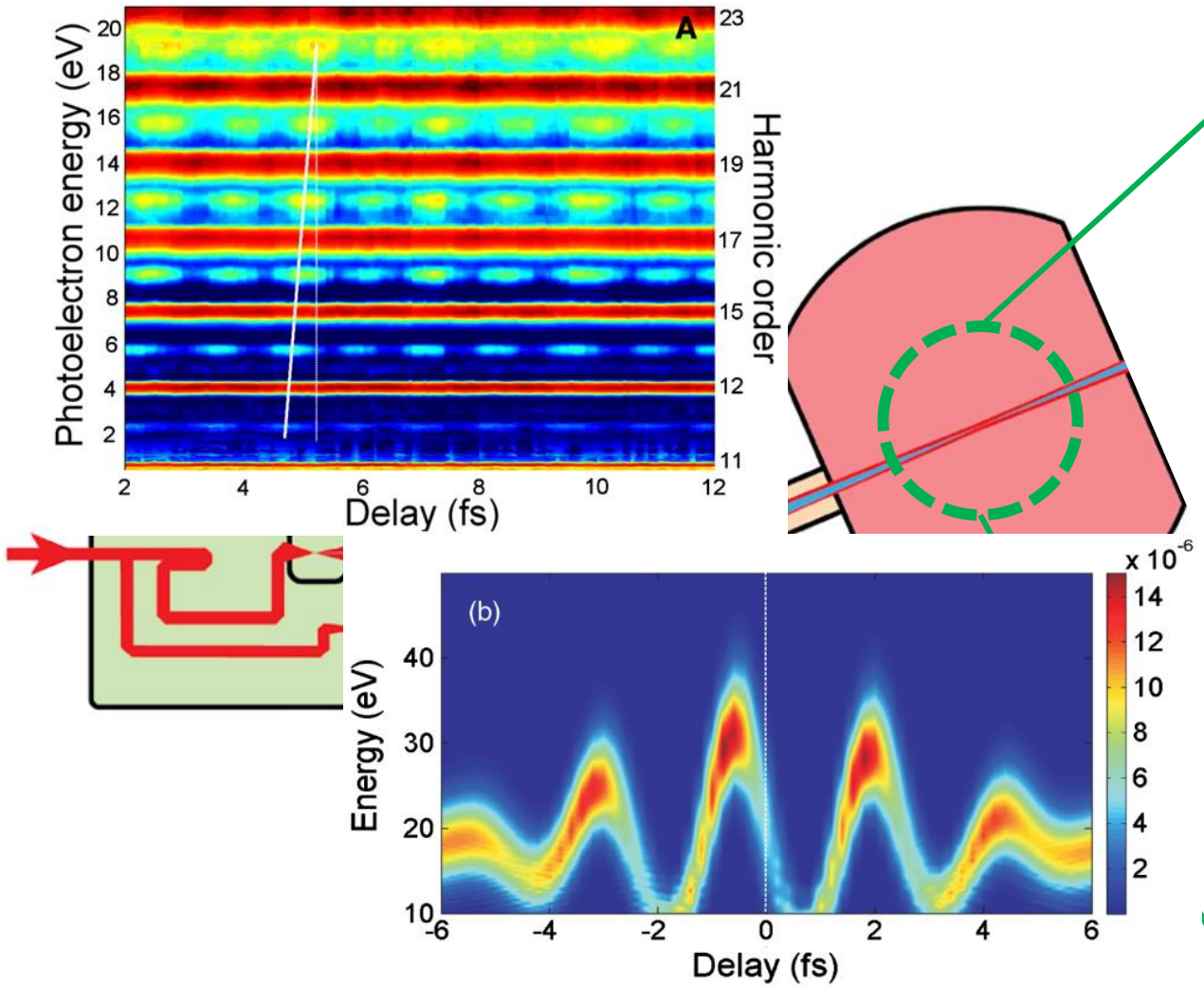


A. G. Ciriolo et al., J. Phys. Photonics 2 (2020).



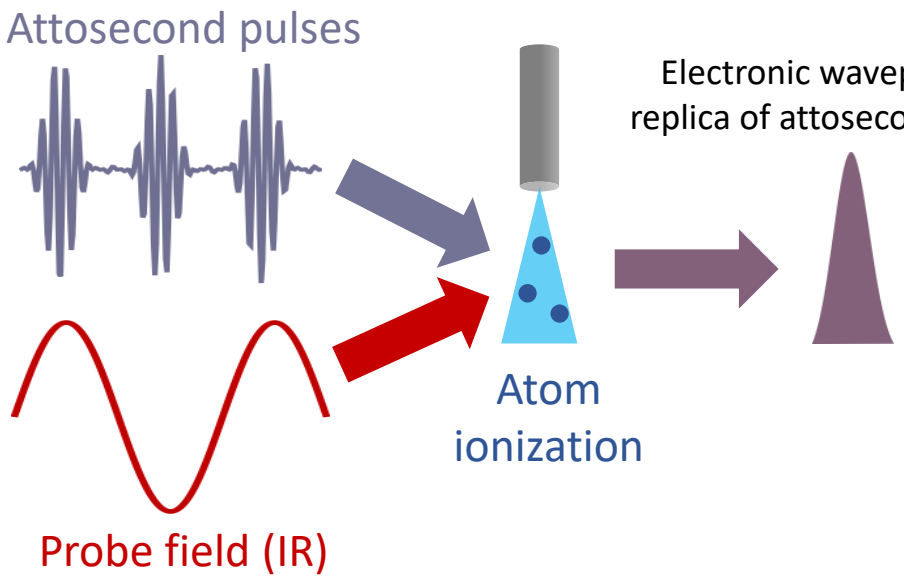
M. H. Mustary et al., Ultrafast Science (2022).

Attosecond pulse characterization

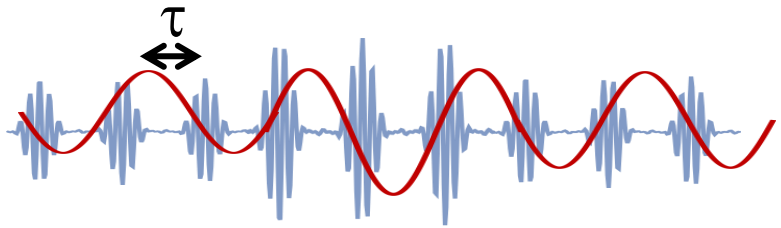


P. M. Paul et al., Science 292 (2001).
H. G. Muller, Appl. Phys. B 74 (2002).
J. Itatani et al., Phys. Rev. Lett. 88 (2002).
P. Mairesse et al., Science (2003).
C. Liu et al., Phys. Rev. Lett. 111 (2013).

Cross-correlation measurement

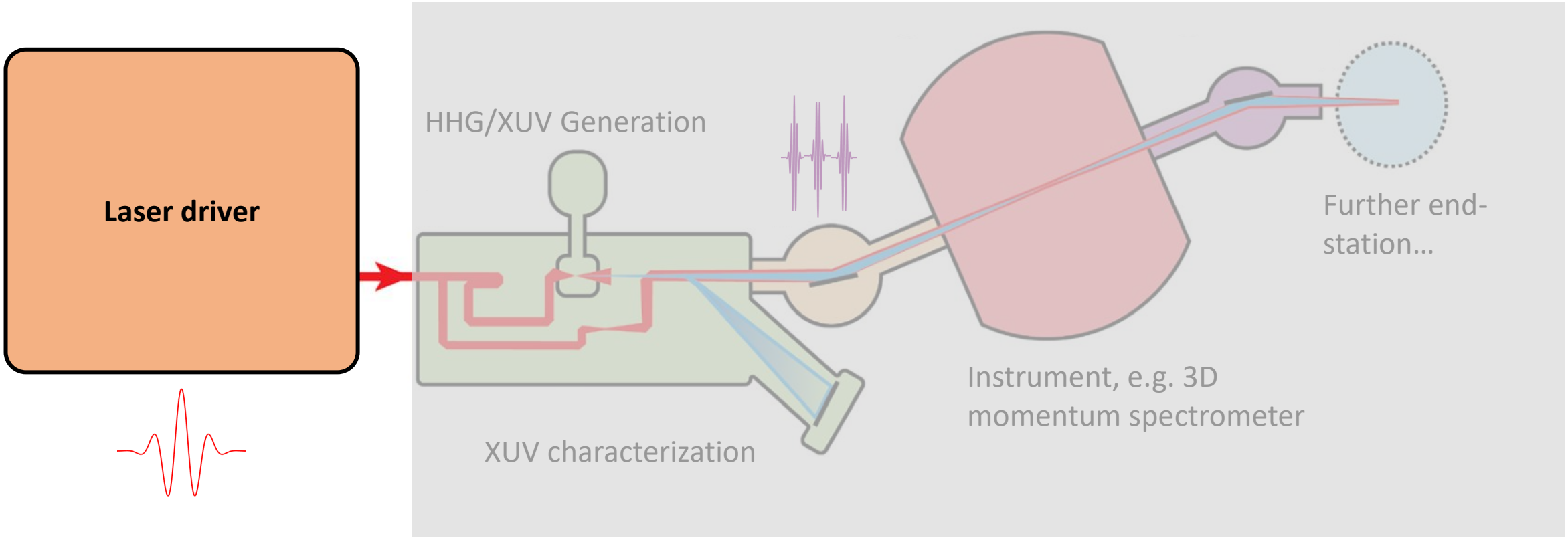


Interferometry technique: RABBIT (APT)



Strong-field technique: Streaking (IAP)

Tailored drivers for HHG



Isolated attosecond pulse vs. Attosecond pulse train

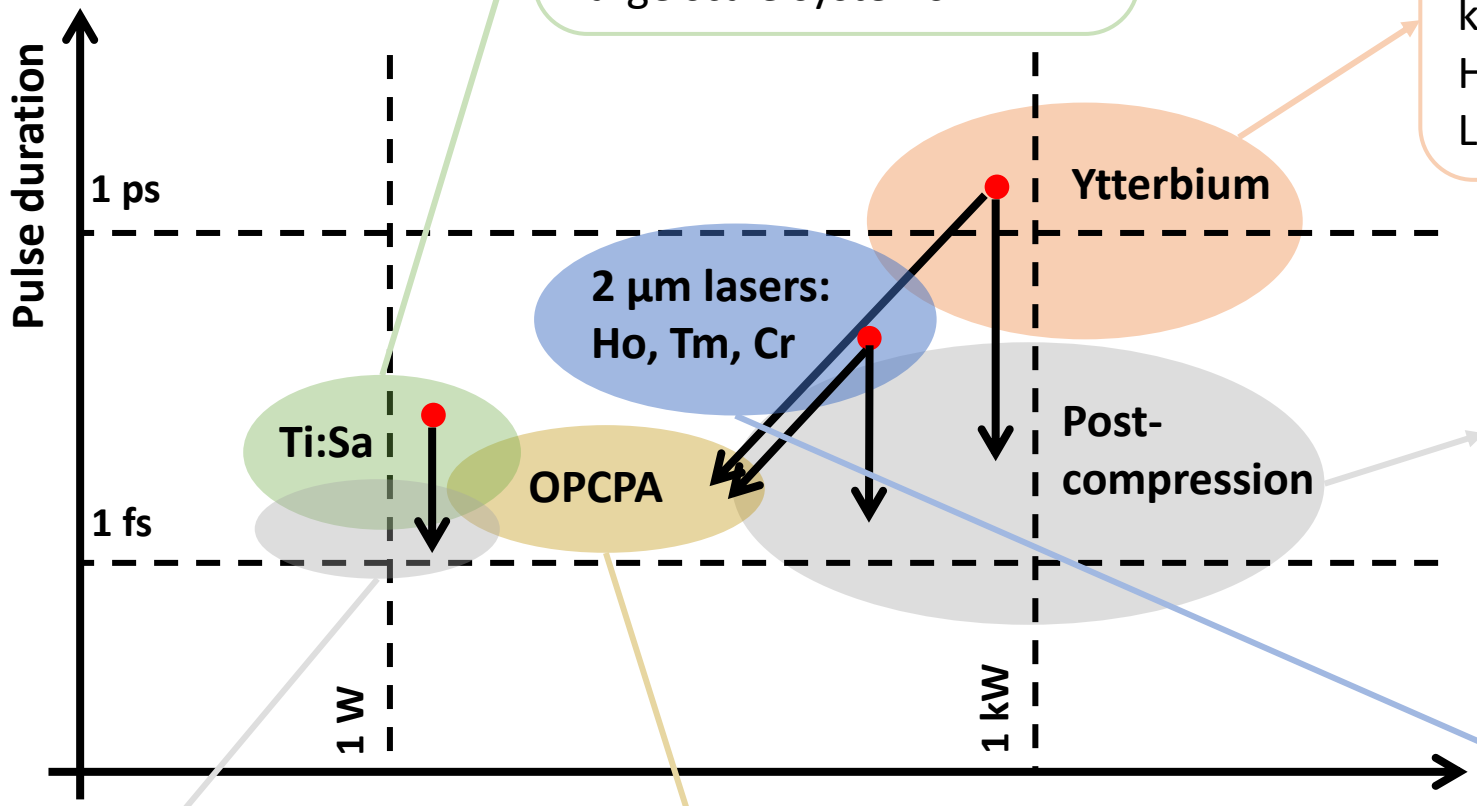
High flux XUV

High photon energies

Broadband XUV vs. narrowband XUV

High yield XUV

Laser drivers for HHG



APT

Workhorse of HHG field

@800 nm

10s-100s mJ laser energies
Short pulses < 30 fs
Large scale systems

Industrial grade systems
@1 µm
kW average power (scalable)
High repetition rates
Long pulses… (> 300 fs, > 1 ps)

5-50 fs pulses at few 100s W

High rep rates → detection of rare events
High powers, high efficiency → high flux XUV

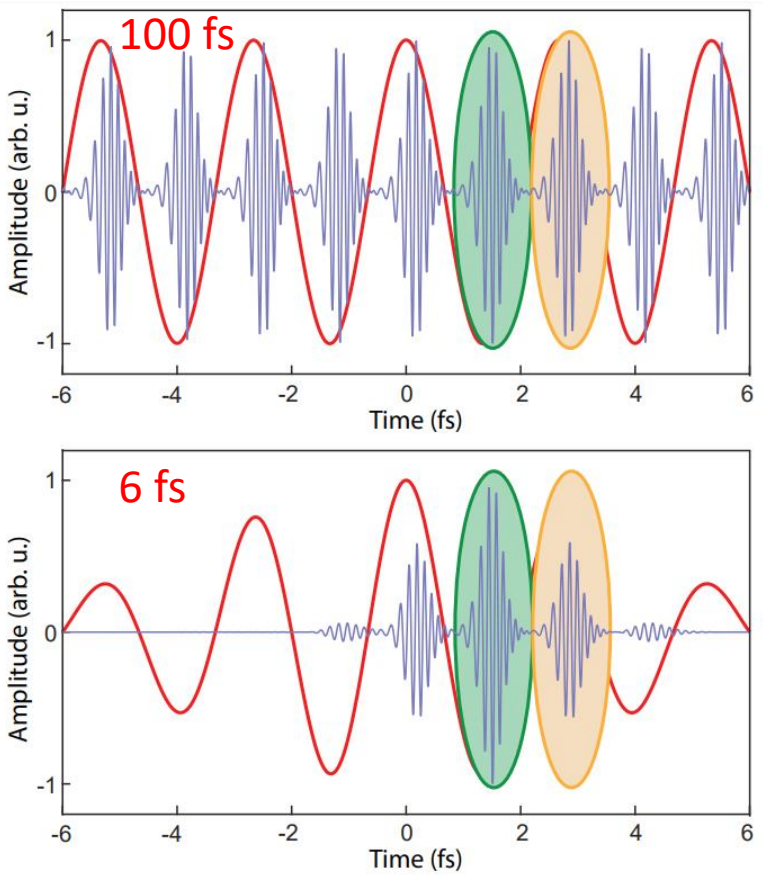
Higher XUV photon energies

Post-compressed Ti:Sa
< 10 fs **@800 nm**

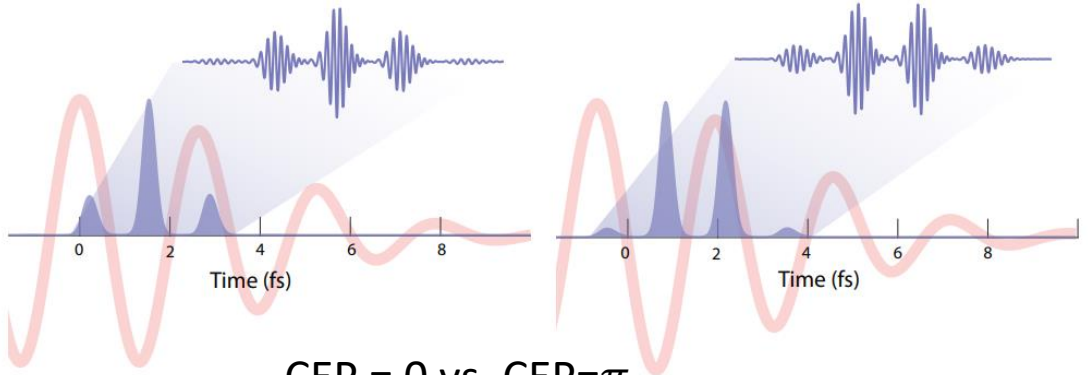
IAP

Few cycle pulses
Excellent contrast
Complex/Low efficiency

Laser drivers for HHG – Attosecond Pulse train / Isolated Attosecond pulse

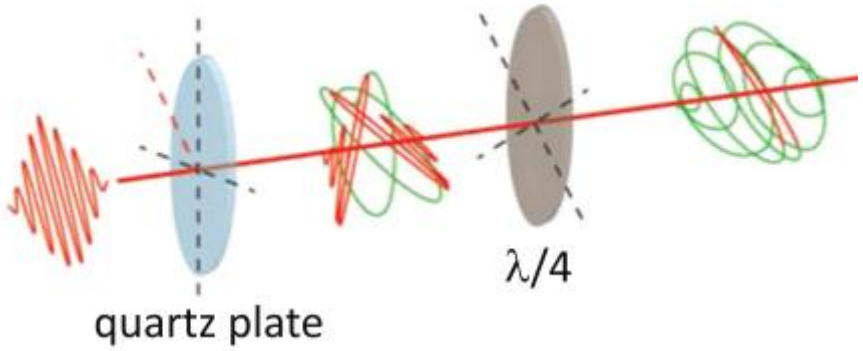


Controlling the carrier-envelope phase is important



CEP = 0 vs. CEP=π

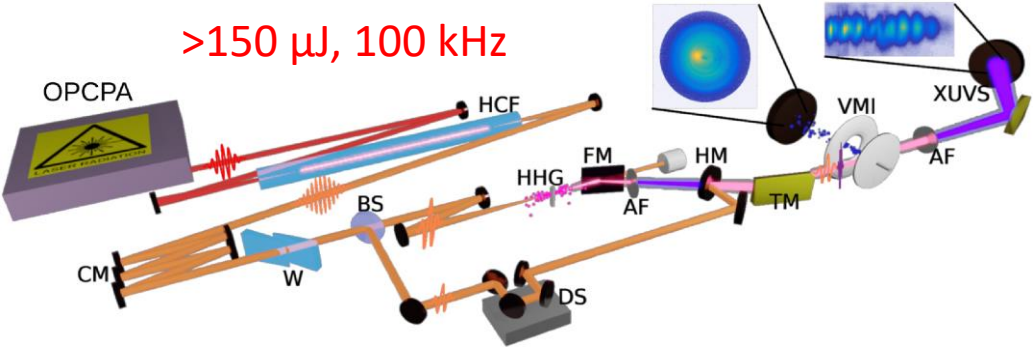
Polarization gating

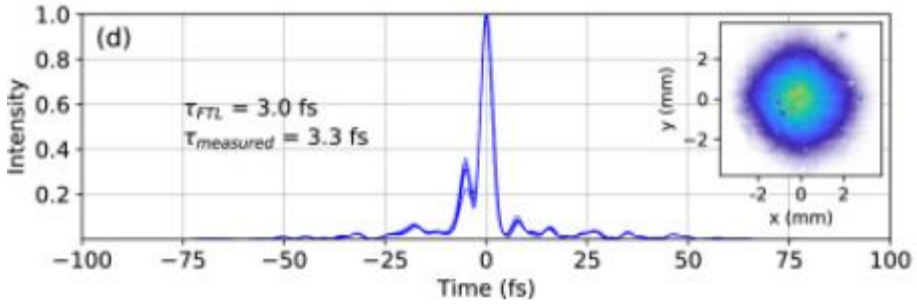


S. Mikaelsson, doctoral thesis (2021).
H. R. Telle et al., Appl. Phys. B 69 (1999).
G. Sansone et al., Science 314 (2006).
M. Hentshell et al., Nature 414 (2001).
F. Calegari et al., J. Phys. B: At. Mol. Opt. Phys. 49 (2016).

Laser drivers for HHG – OPCPA / Waveform synthetizer

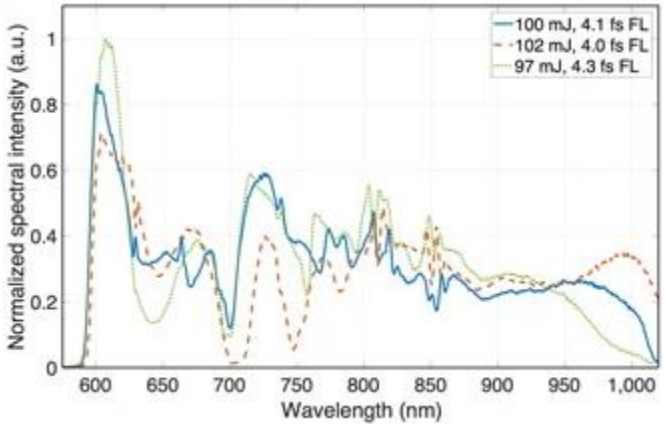
>150 µJ, 100 kHz

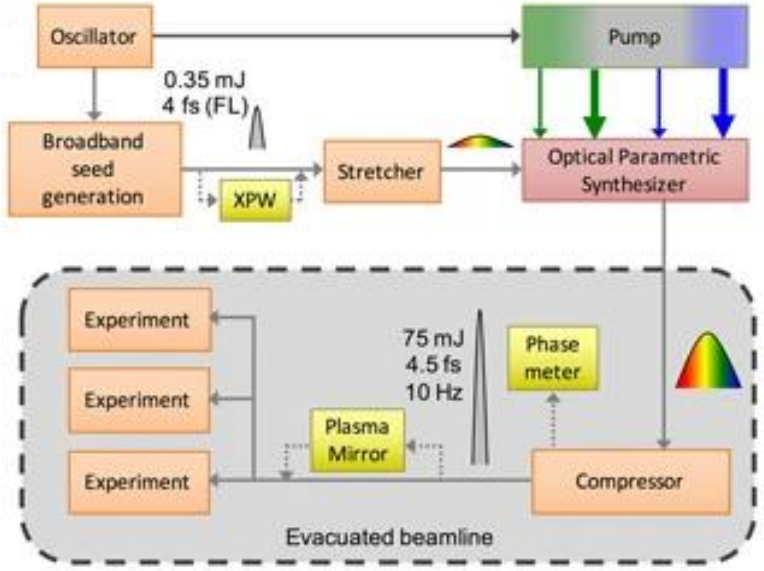




F. Furch et al., Opt. Lett. 42 (2017).
T. Witting et al., Optica 9 (2022).

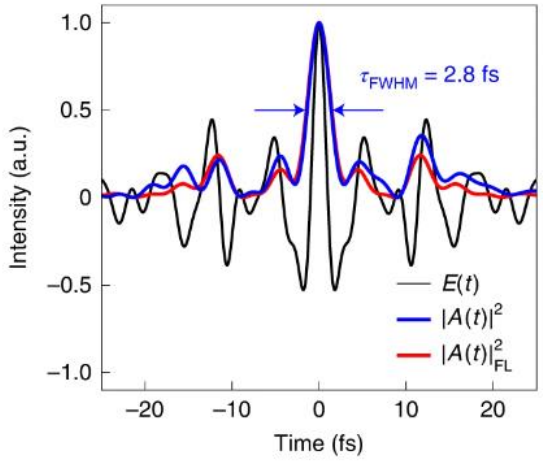
100 mJ, 10 Hz

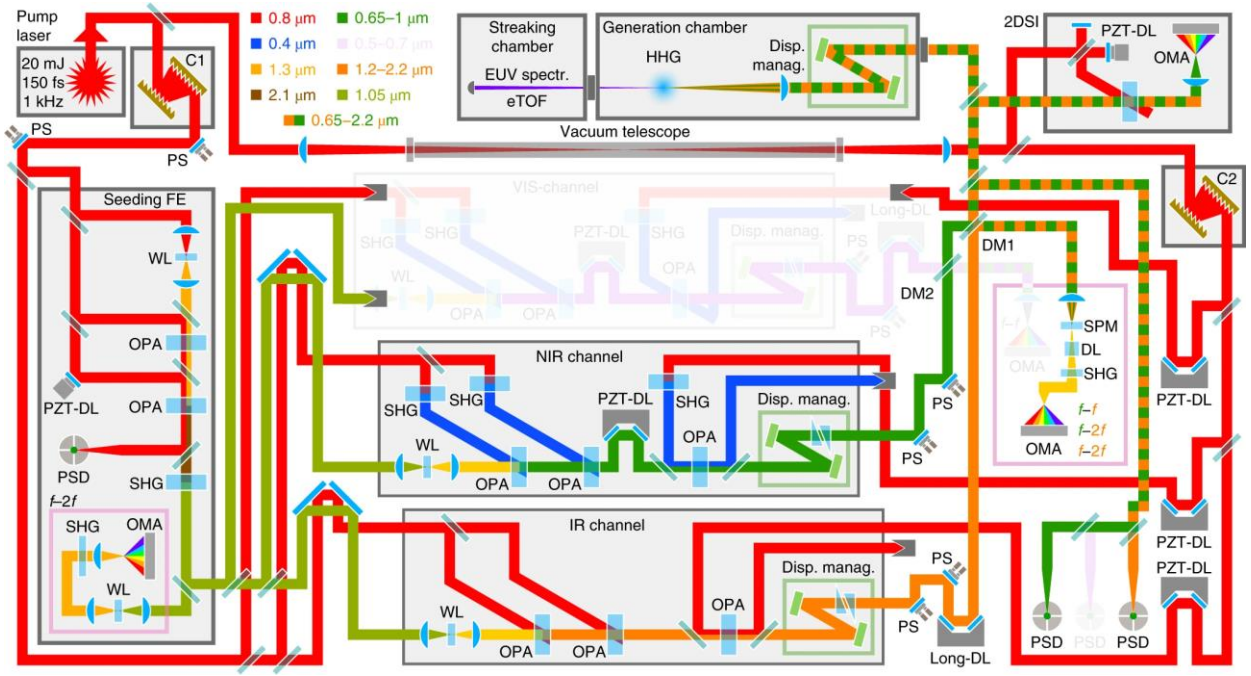




D. E. Rivas et al., Sci. rep. 7 (2017).

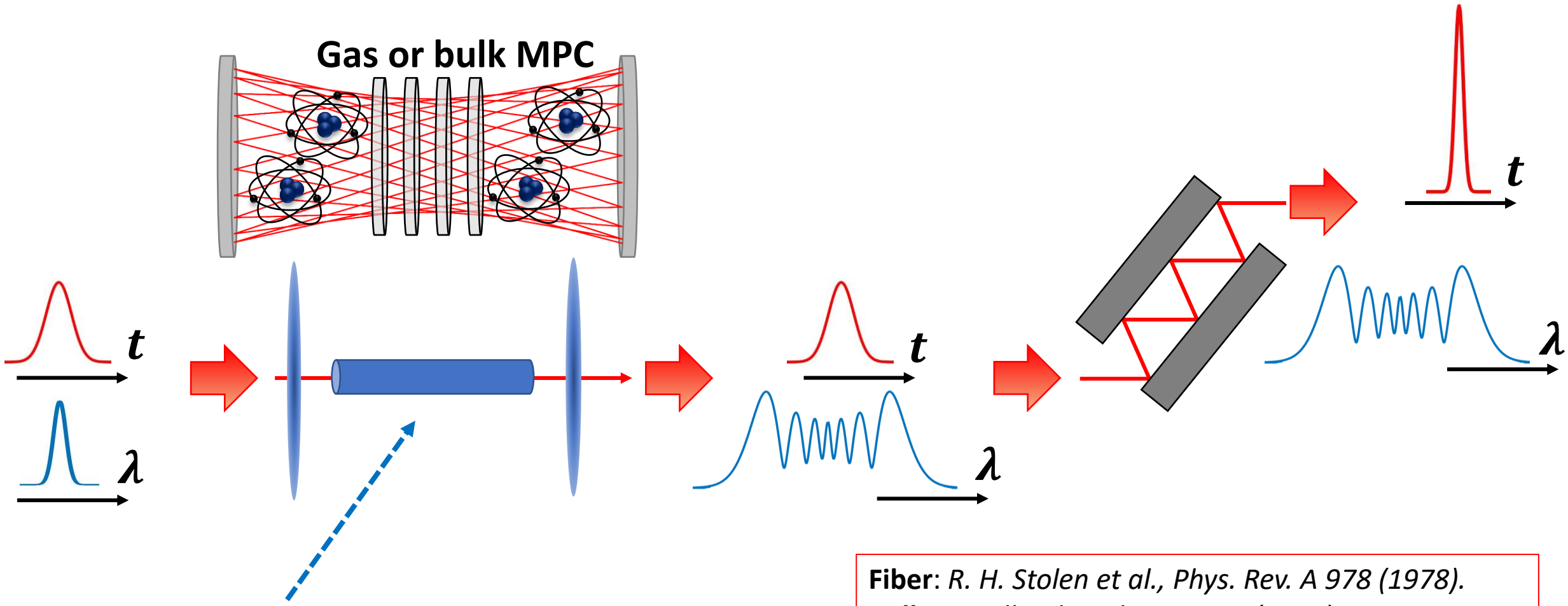
mJ, 1 kHz





G. M. Rossi et al., Nat. Photon. 14 (2020).

Laser drivers for HHG – Post-compression

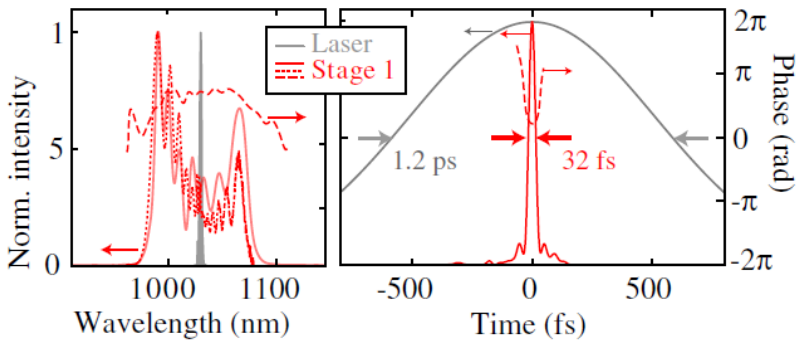


Guiding structure: filament, capillary, fiber…

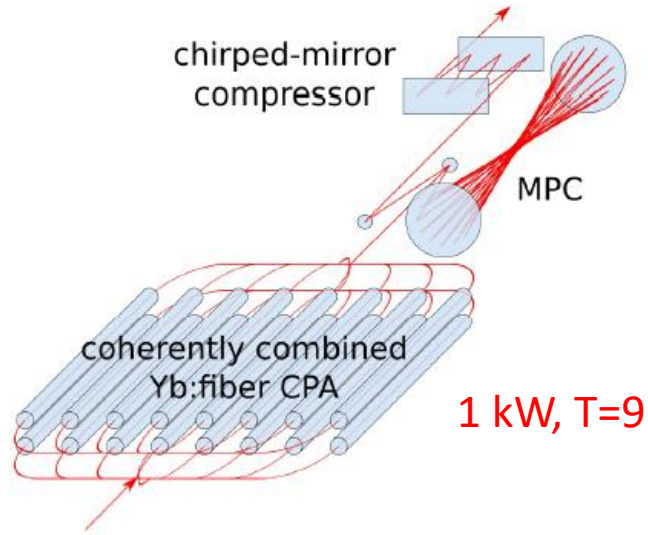
Fiber: *R. H. Stolen et al., Phys. Rev. A 978 (1978).*
Bulk: *C. Rolland et al., JOSAB 5 (1988).*
HCF: *M. Nisoli et al., Appl. Phys. Lett. 68 (1996).*
Multi-plate: *C.-H- Lu et al., Optica 1 (2014).*
Multi-pass cells: *J. Schulte et al., Opt. Lett. 41 (2016).*

T. Nagy et al., Advances in Physics X 6 (2021).

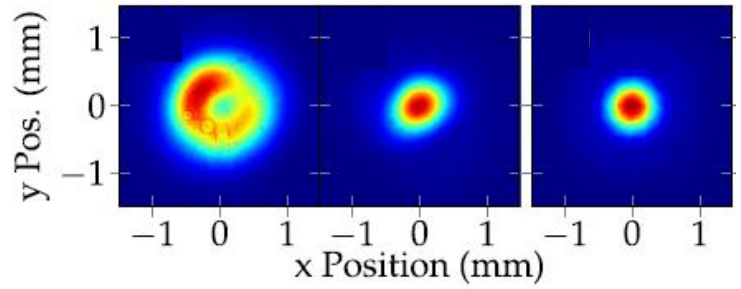
Laser drivers for HHG – Post-compression in multi-pass cells



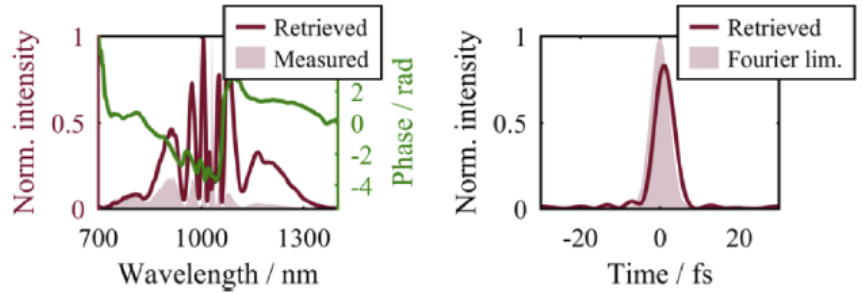
Comp. ratio > 37, 2 mJ, 200 W burst
2 stages: > 120 times



1 kW, T=96%, 31 fs



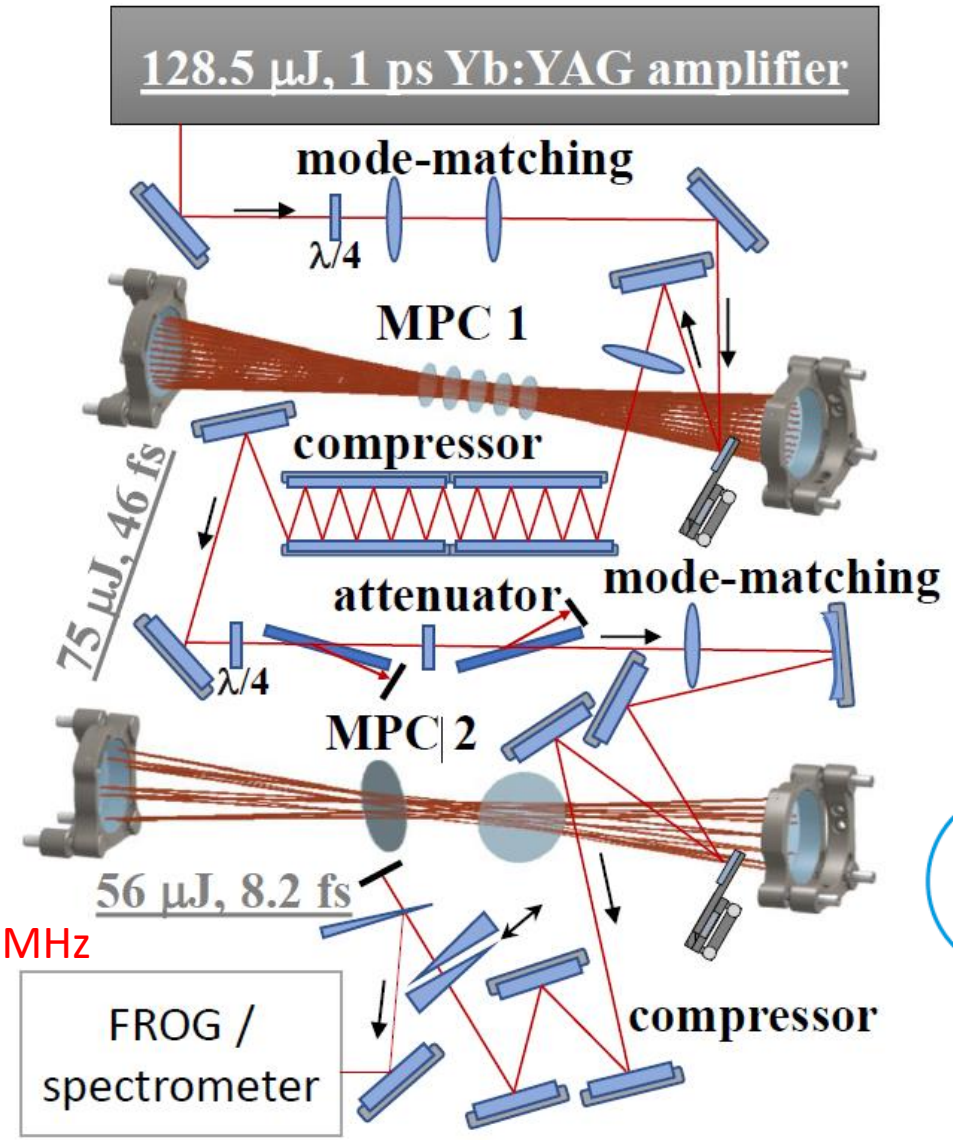
108 mJ, 37 fs with donut mode
200 mJ, < 50 fs in 12 m cell

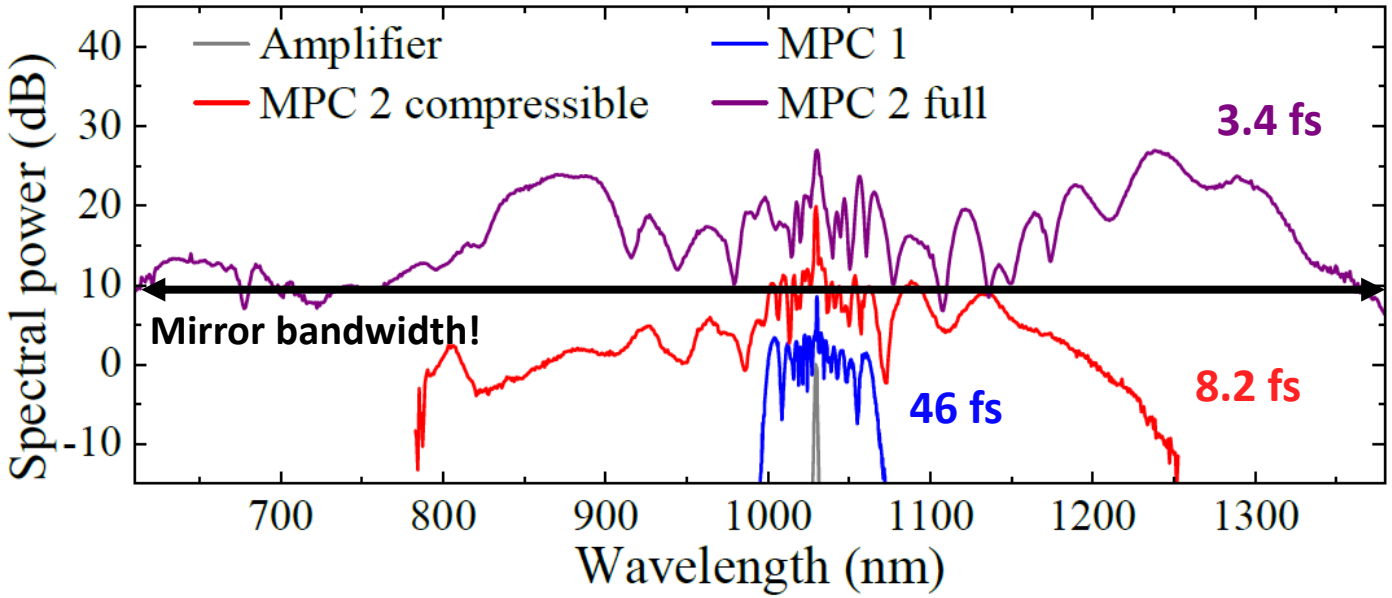


5.8 fs, 1.07 mJ, 107 W → > 100 GW

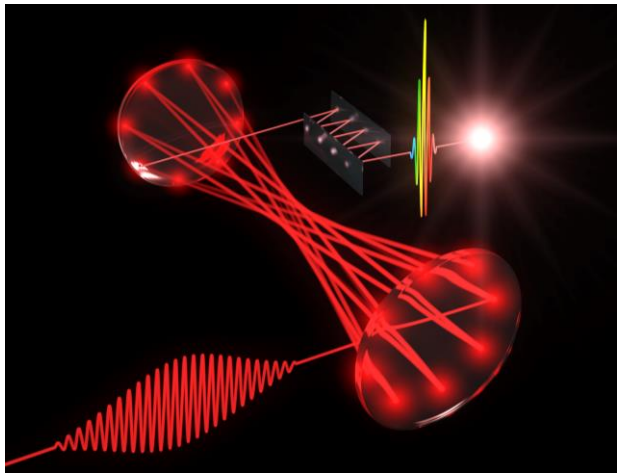
P. Balla et al., Opt. Lett. 45 (2020).
Y. Pfaff et al., Opt. Express 31 (2023).
C. Grebing et al., Opt. Lett. 45 (2020).
A.-L. Viotti et al., Opt. Lett. 48 (2023).
M. Kaumanns et al., Opt. Lett. 46 (2021).
S. Hädrich et al., Opt. Lett. 47 (2022).

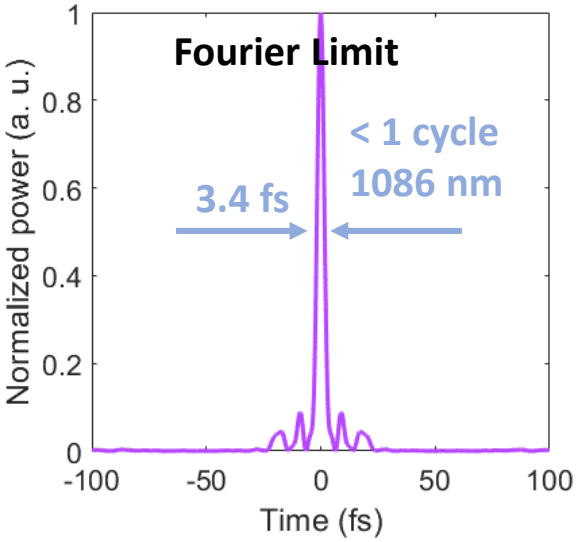
Laser drivers for HHG – Post-compression





- Sub-cycle pulse transformed limited
- > 200 fold spectral broadening
- > 120 fold pulse shortening

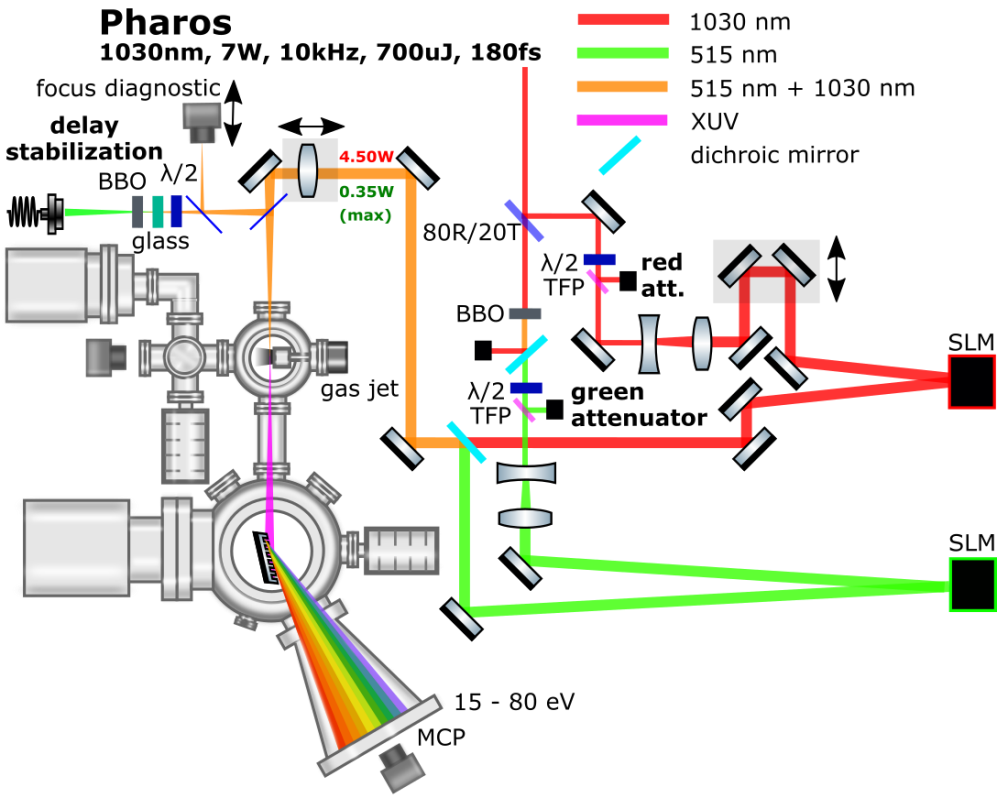




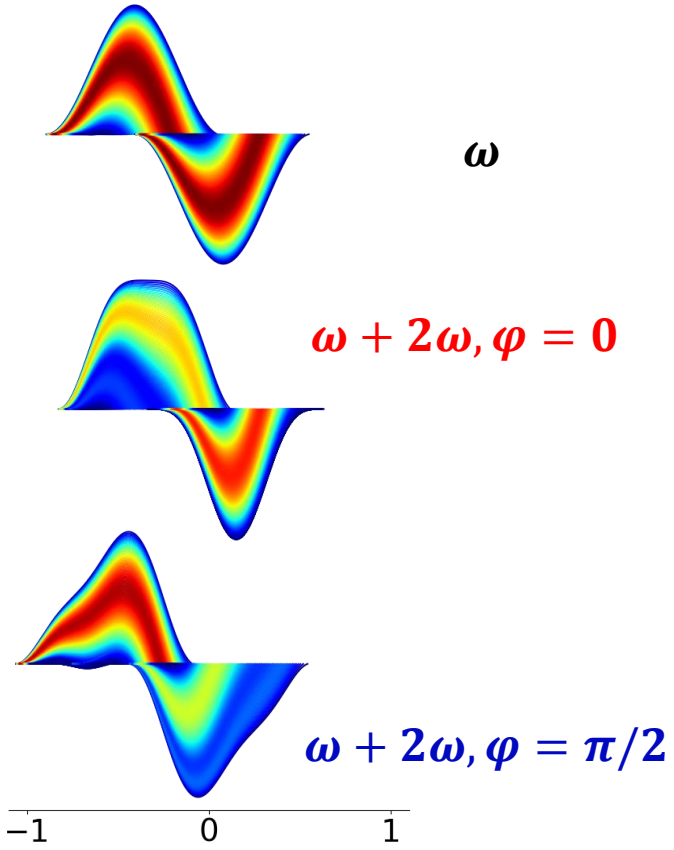
A.-L. Viotti et al., Opt. Lett. 48 (2023).

Laser drivers for HHG – Multi-color driver

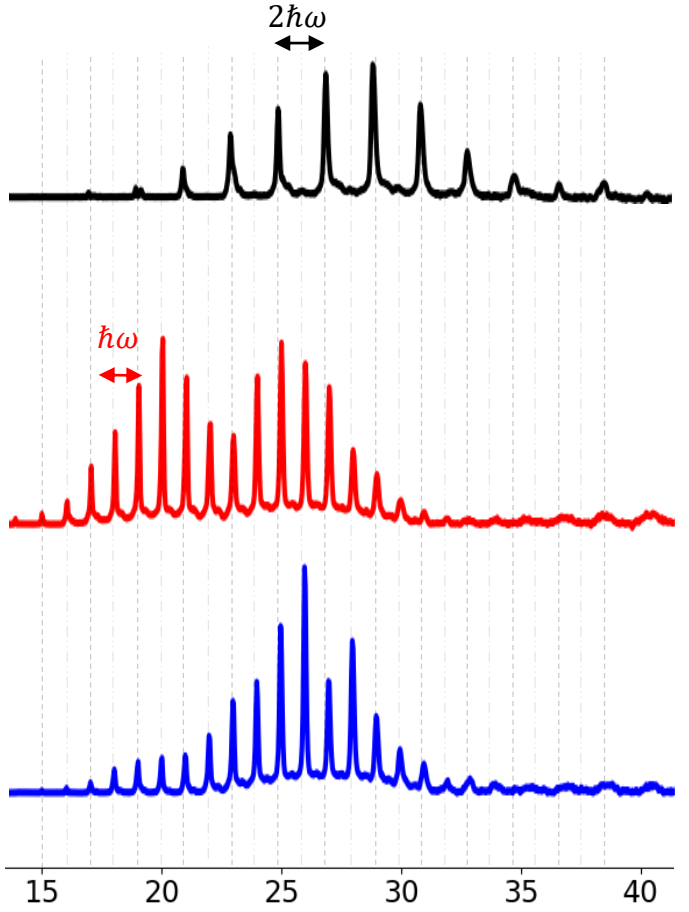
Control in experiment over second harmonic intensity ratio and phase



Classical electron trajectories

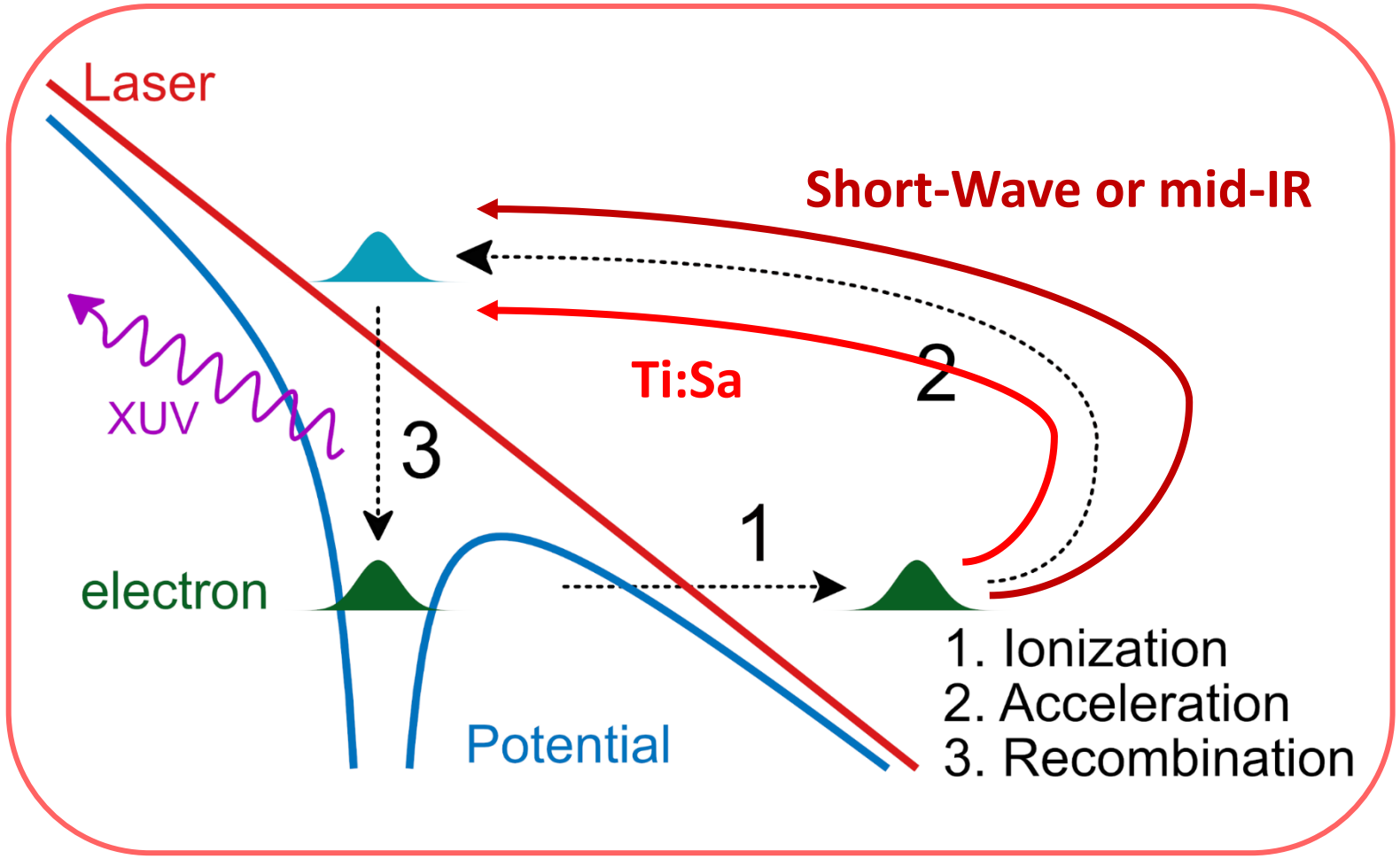


Examples for harmonics generated in argon (experiment)



H. Merdji et al., Opt. Lett. 32 (2007). *S. Haessler et al., Phys. Rev. X 4 (2014).* *A.-K. Raab et al., in preparation.*

Laser drivers for HHG – Higher photon energies with longer wavelengths



Emitted photon energy

$$E_{XUV} = I_p + 3.17U_p$$

$$U_p = \frac{e^2 E_0^2}{4m\omega^2} \propto \lambda^2$$

→ Higher XUV photon energies

$E_{max} \propto I\lambda^2$

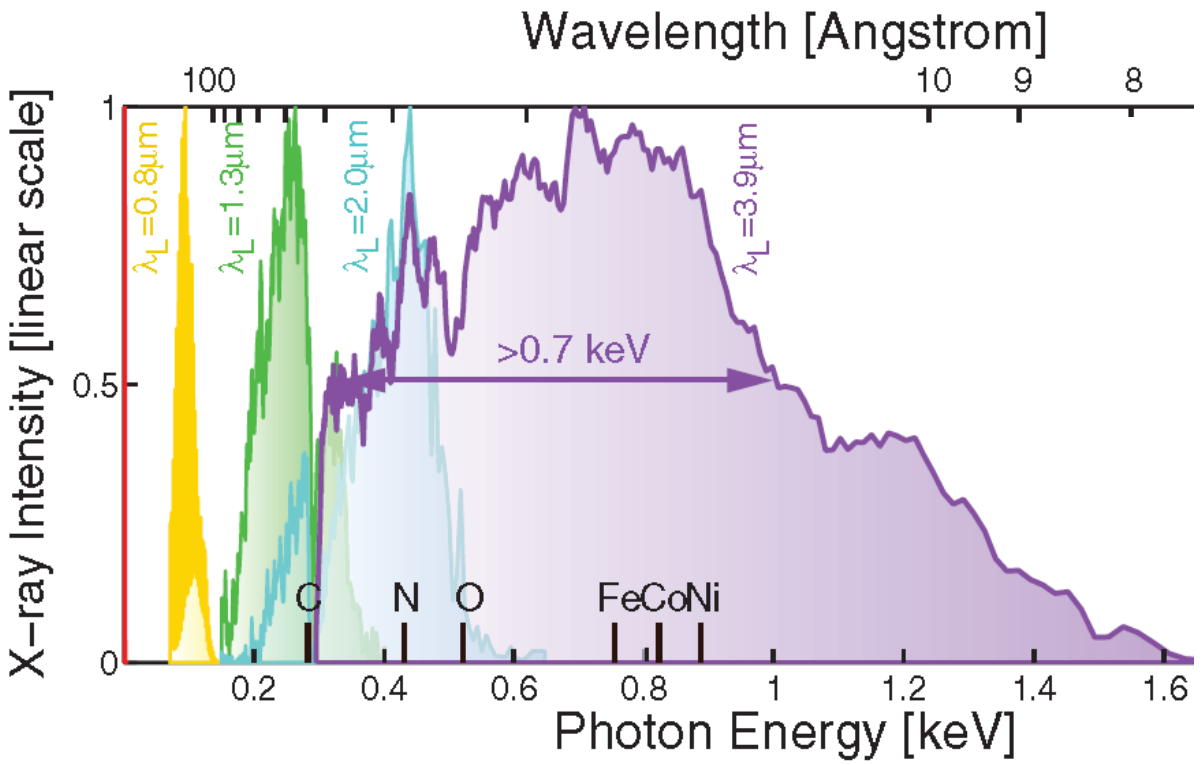
But…

conversion efficiency is lower:

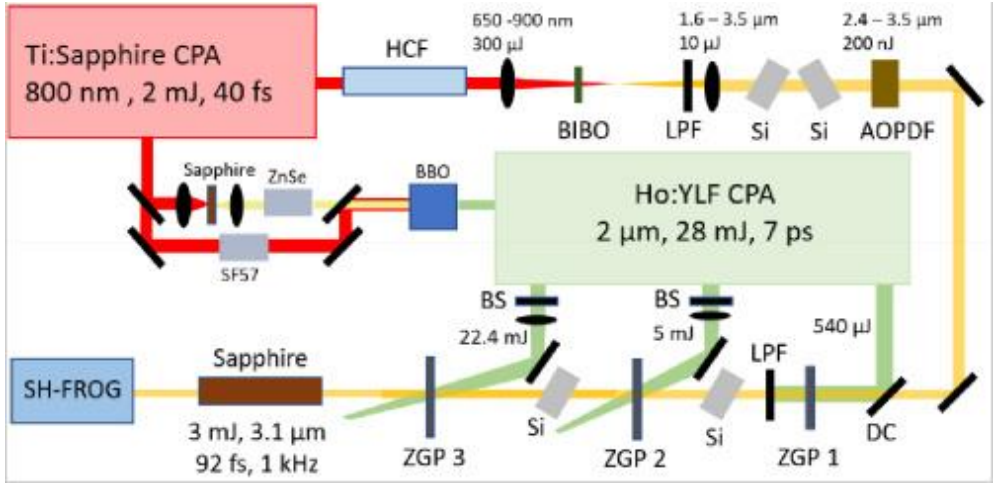
$$CE \propto \lambda^{-5-6}$$

J. Tate et al., Phys. Rev. Lett 98 (2007). *A.D.Shiner et al., Phys. Rev. Lett 103 (2009).*

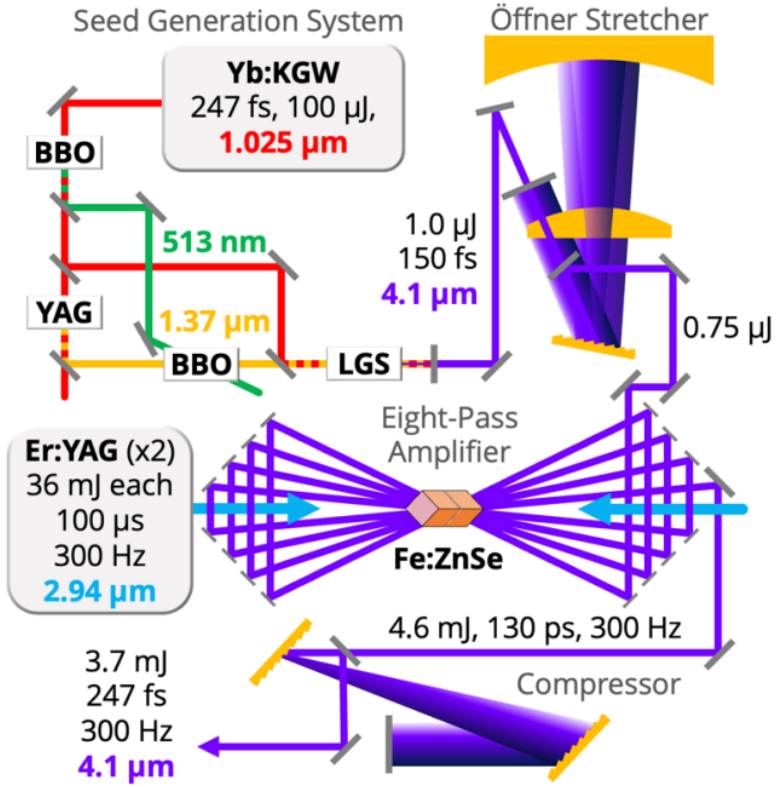
Laser drivers for HHG – Higher photon energies with longer wavelengths



3 μm



4 μm



B. Sheehy et al., Phys. Rev. Lett. 83 (1999).
T. Popmintchev et al., Science 336 (2012).
F. Zhou et al., Opt. Lett. 47 (2022).
Z. Alphonse Marra et al., CLEO paper FW3M.3 (2023).

A triple beamline in Lund

Front-end:

6 fs Ti:Sa oscillator
Yb amplifier(s) 40W @200 kHz

grating compressor

grating compressor

Pulse post-compression:

300 fs → 30 fs @1030 nm
150 µJ, 200 kHz

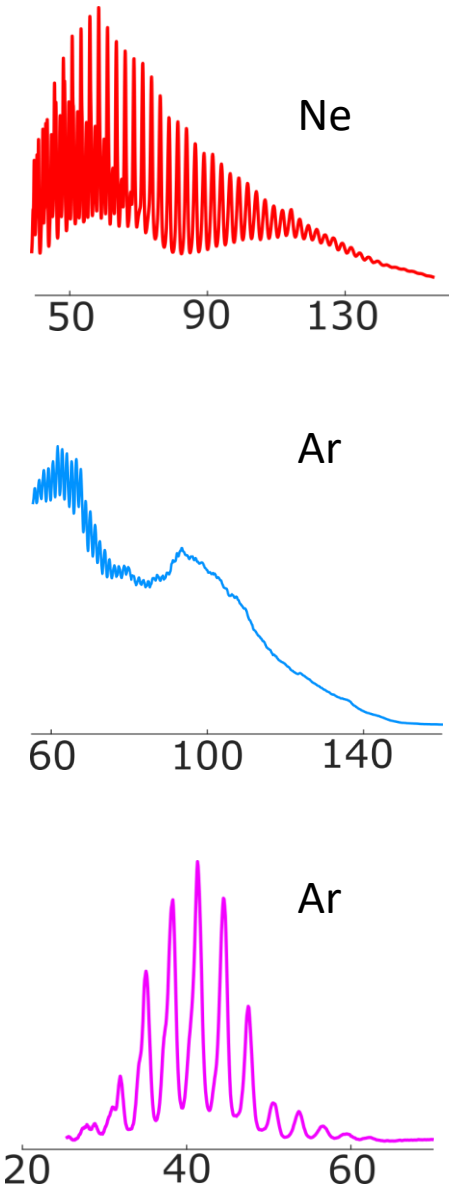
Short-Wave IR OPCPA:

< 16 fs@ 2µm
13 µJ, 200 kHz
250 mrad RMS CEP

Near-IR OPCPA:

< 6 fs @~800 nm
13 µJ, 200 kHz
160 mrad RMS CEP

HHG

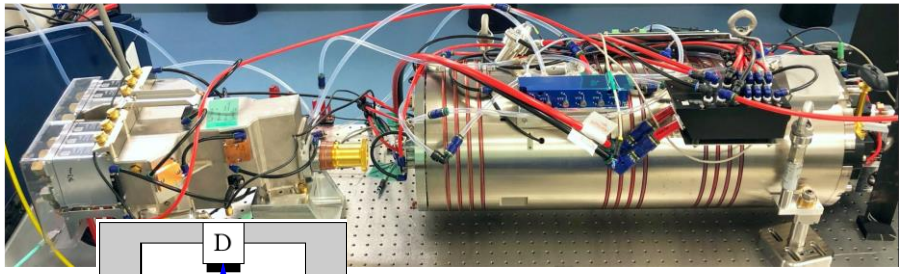


S. Mikaelsson et al., Nanophotonics 10 (2020).

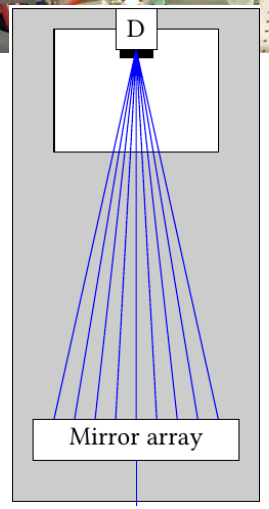
I. Sytcevich et al., Opt. Express 30 (2022).

A.-K. Raab et al., Opt. Lett. 47 (2022).

Next-generation HHG drivers in Lund



Trumpf Laser Scientific



Light Conversion

Thin disk
500W 200 kHz
Yb-CPA pump

Near-IR OPCPA

< 6 fs, 250 µJ, 850 nm, 160 mrad RMS CEP stability

Short-Wave IR OPA

< 16 fs, 200 µJ, ~2 µm, 290 mrad RMS CEP stability

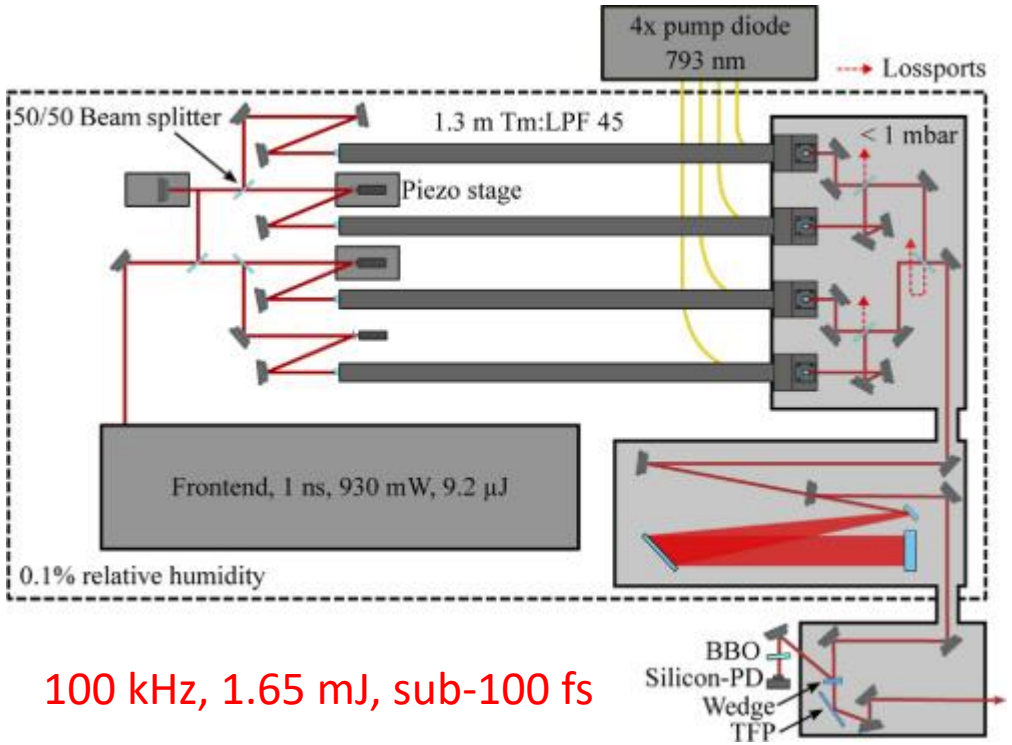
Post-compressed Yb

10-30 fs, 1.5 mJ, 1030 nm

New TW laser @800nm

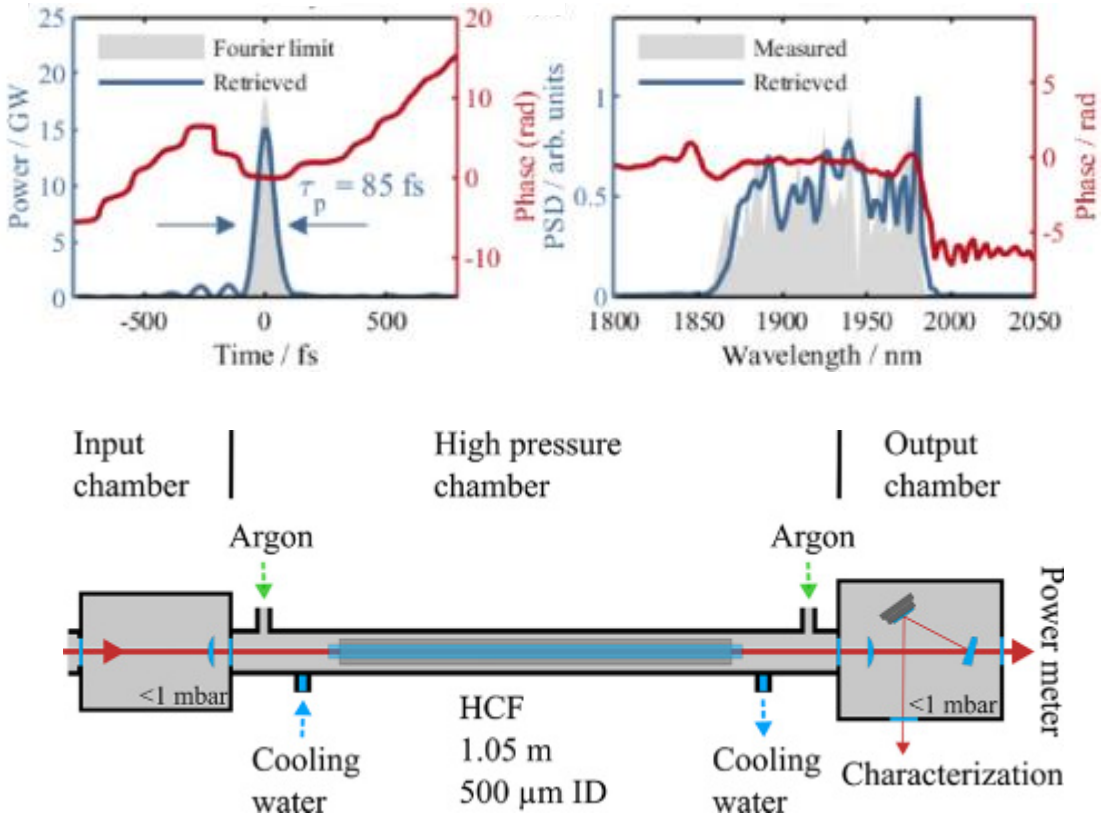
10 fs, 50 mJ, 100 Hz
10 fs, 250 mJ, 10 Hz

New key player for Attoscience?



100 kHz, 1.65 mJ, sub-100 fs

Tm fiber femtosecond laser systems

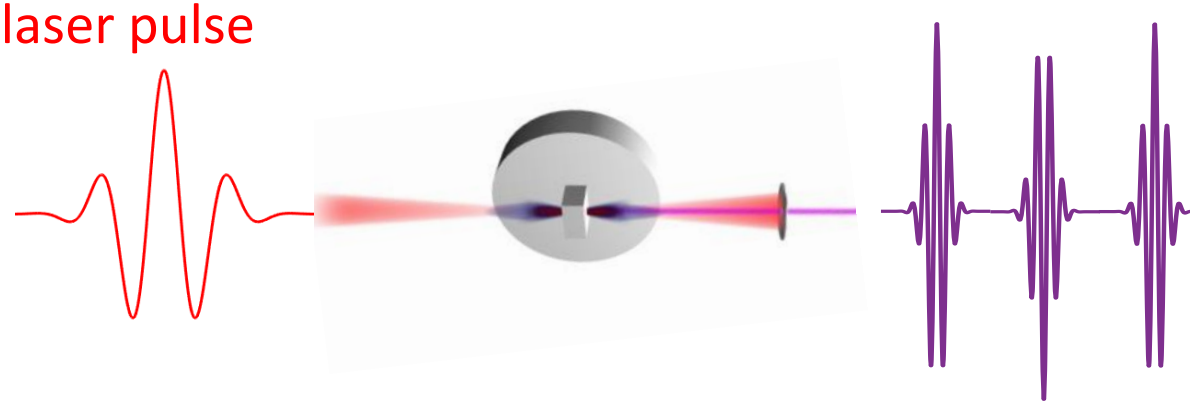


100 kHz, 1.3 mJ, 10 fs

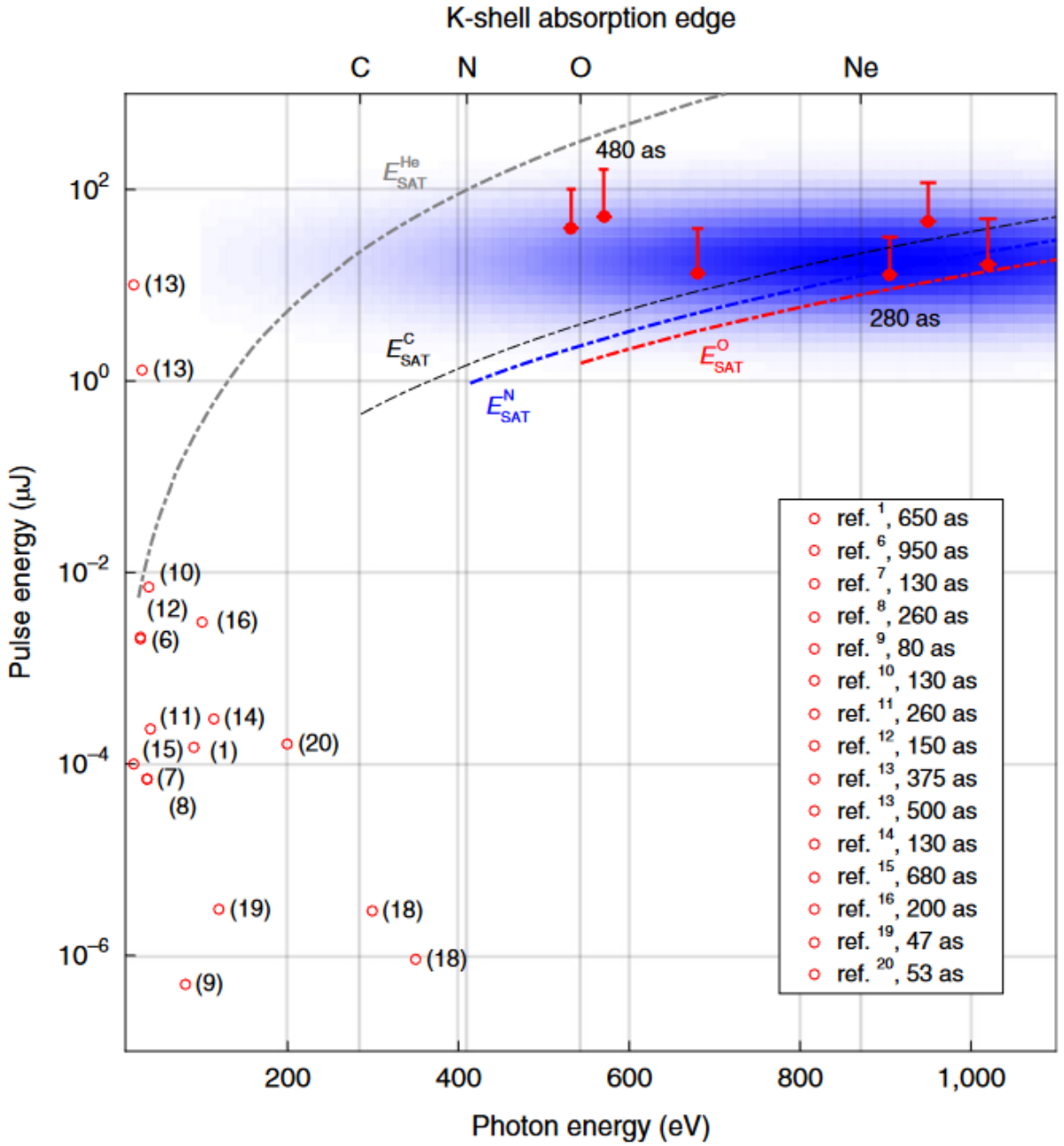
T. Heuermann et al., Opt. Lett. 47 (2022). *Z. Wang et al., Opt. Lett. 48 (2023).*

Summary – Take home message: versatility!

Femtosecond
laser pulse

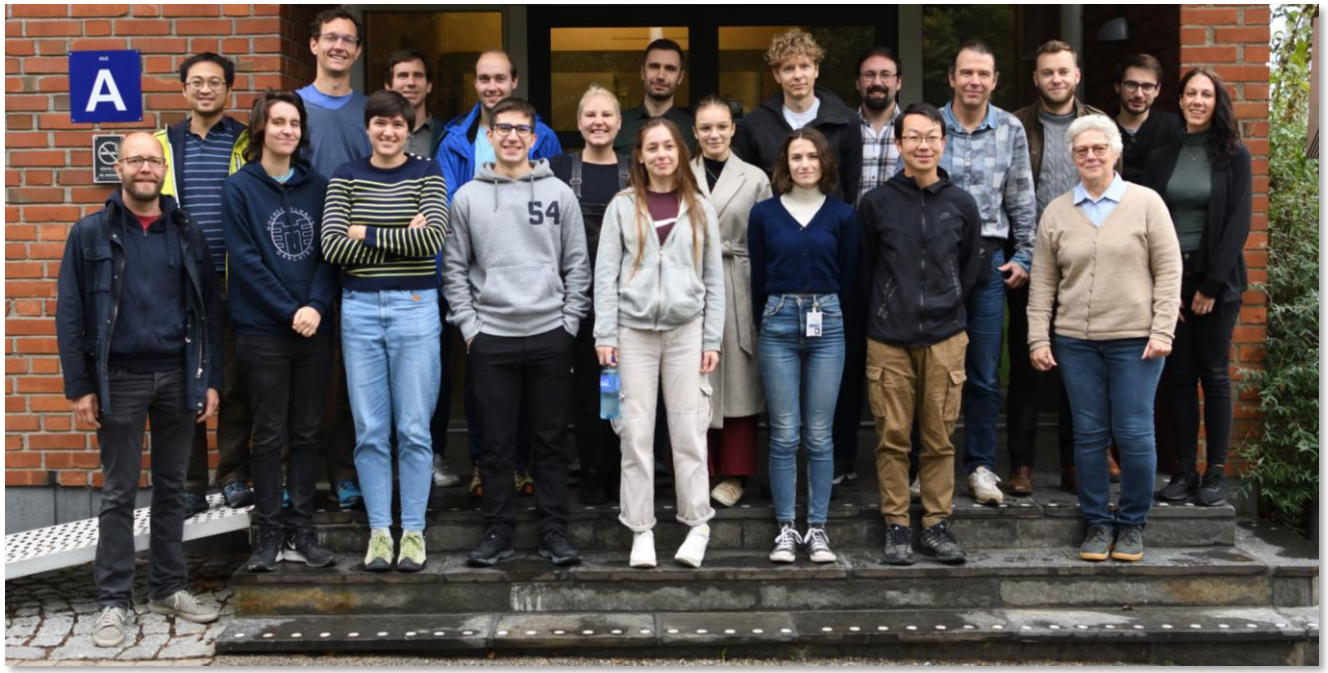


Laser driver ⟺ HHG process & XUV light properties



J. Duris et al., Nat. Photon. 14 (2020).

Team work



Attosecond Physics group @Lund University

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Anne L'Huillier

Cord Arnold

Marcus Dahlström

Anne-Lise Viotti

Mathieu Gisselbrecht

Johan Mauritsson

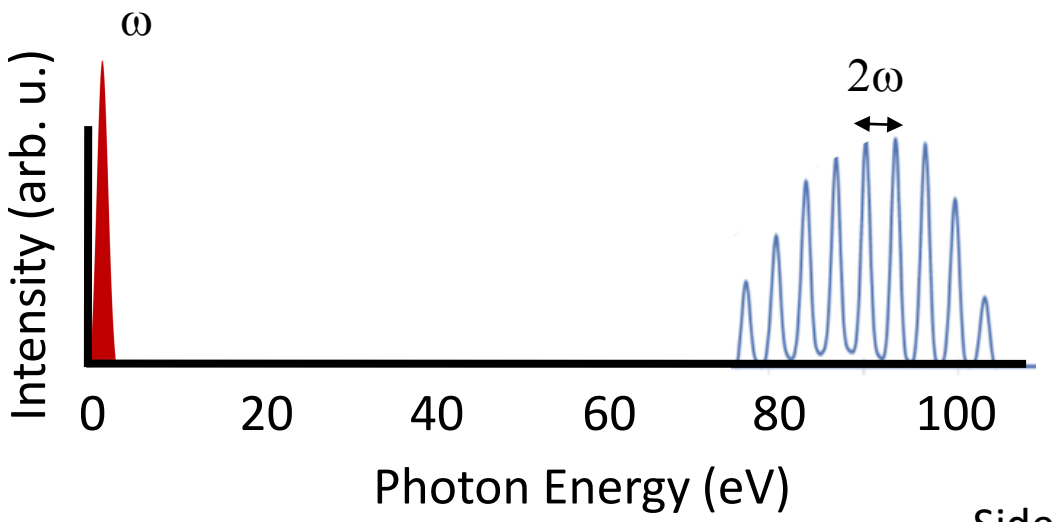
ATTO X

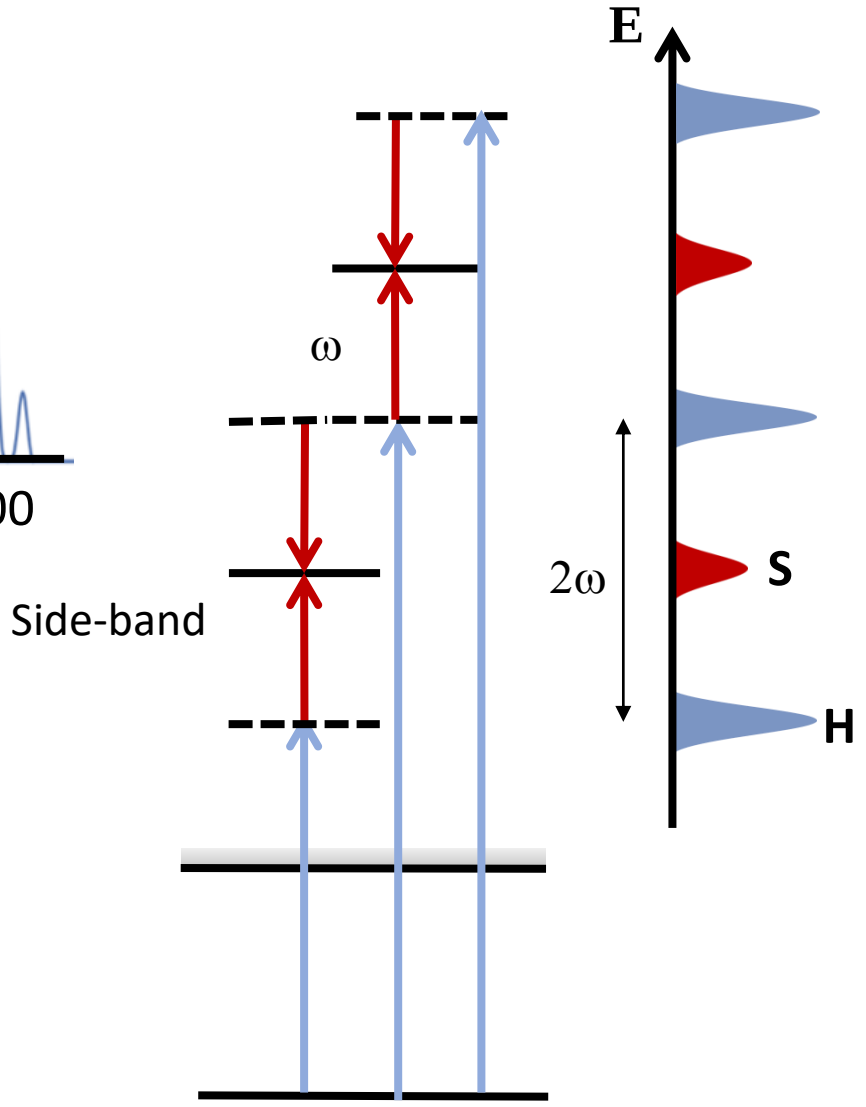
The 10th International Conference on Attosecond Science and Technology

July 6-11, 2025 in Lund, Sweden

Back-up Slides

RABBIT technique: interferometry





Paul et al., Science, 2001, Véniard et al., Phys. Rev. A 1996