



ELISS2023

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Dolní Břežany, Czech Republic

Attosecond pulse generation: strong laser fields and extreme nonlinear optics

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Lund University

2023-08-29

Dolní Břežany, Czech Republic



LUND
UNIVERSITY



IMPULSE



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

10^{18} seconds

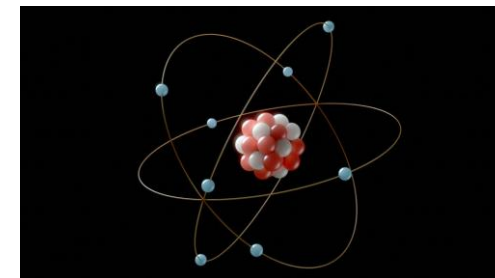


10^0 seconds



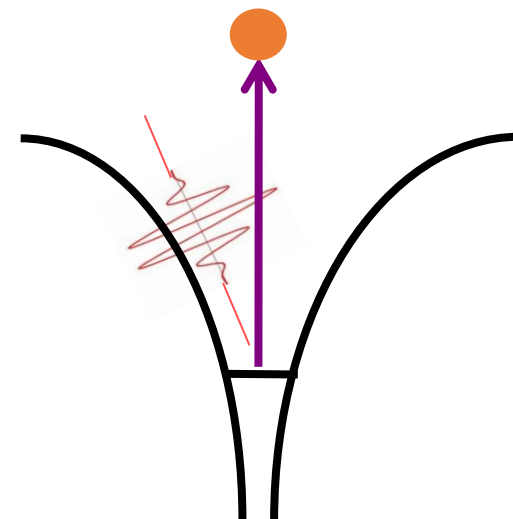
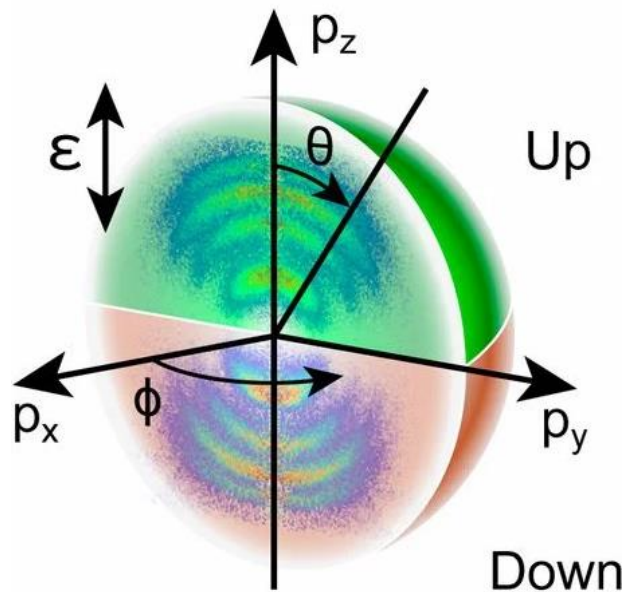
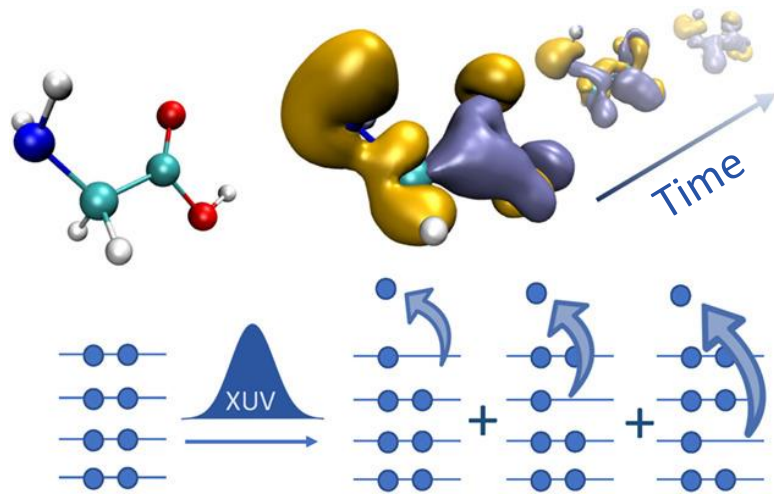
“Attosecond”

10^{-18} seconds

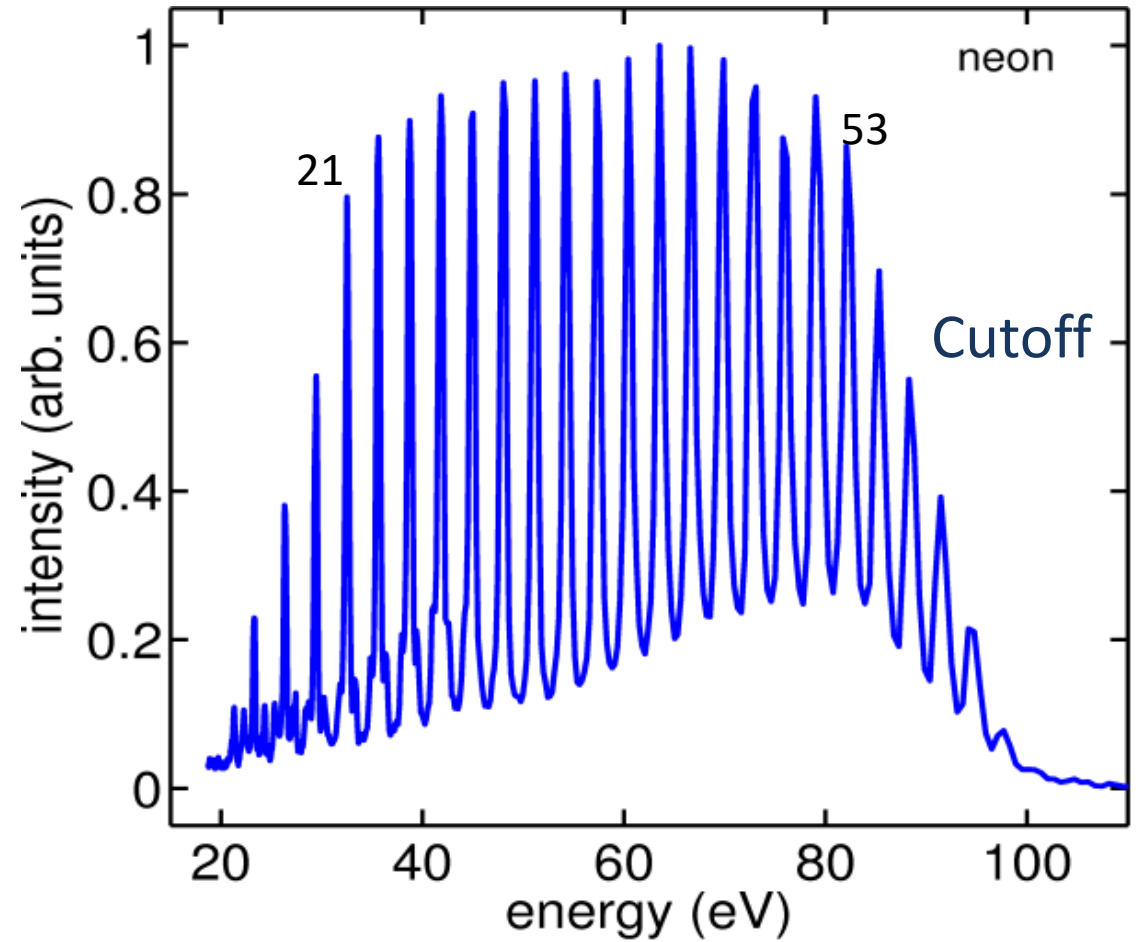
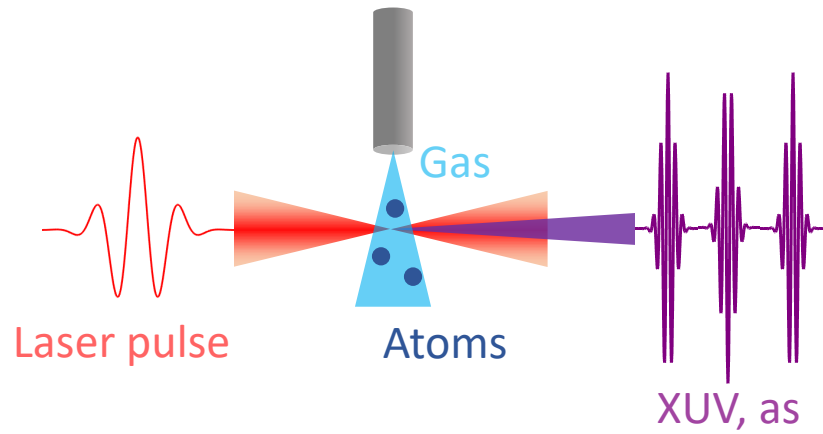


Observables:

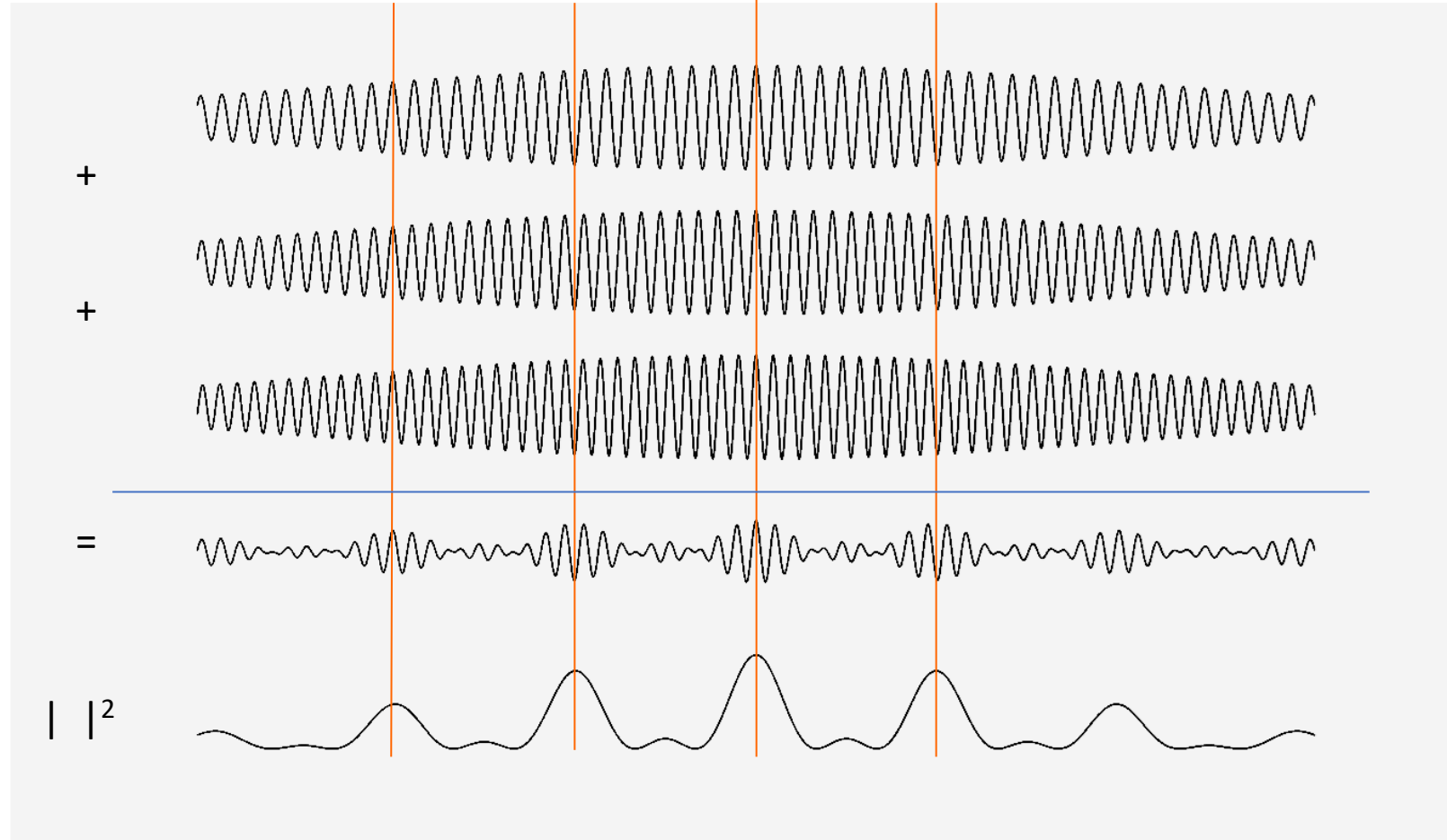
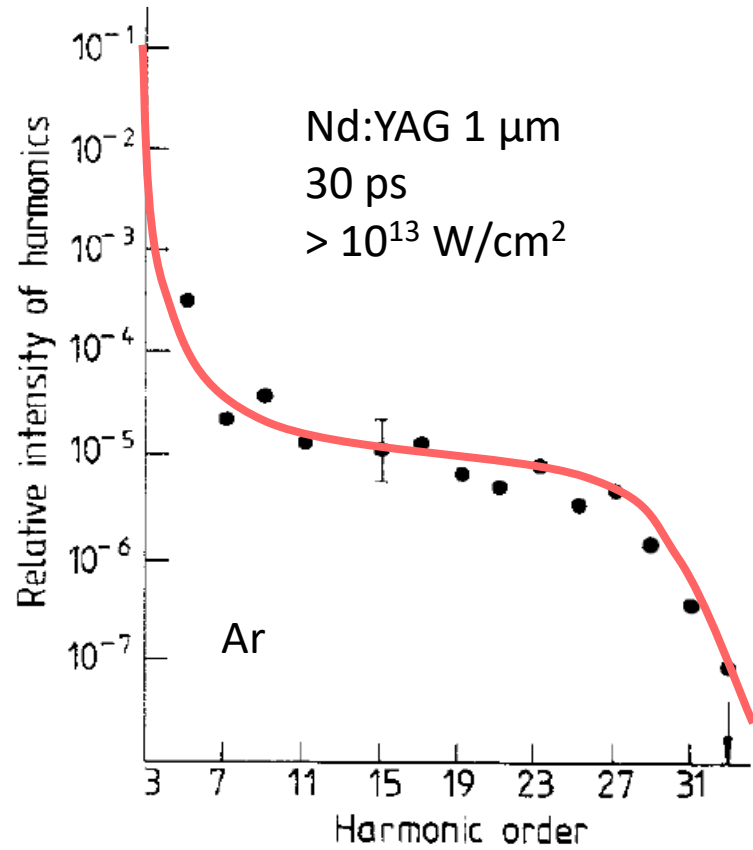
- Photoelectrons
- Charge migration
- Correlations
- Delays
- Fields...



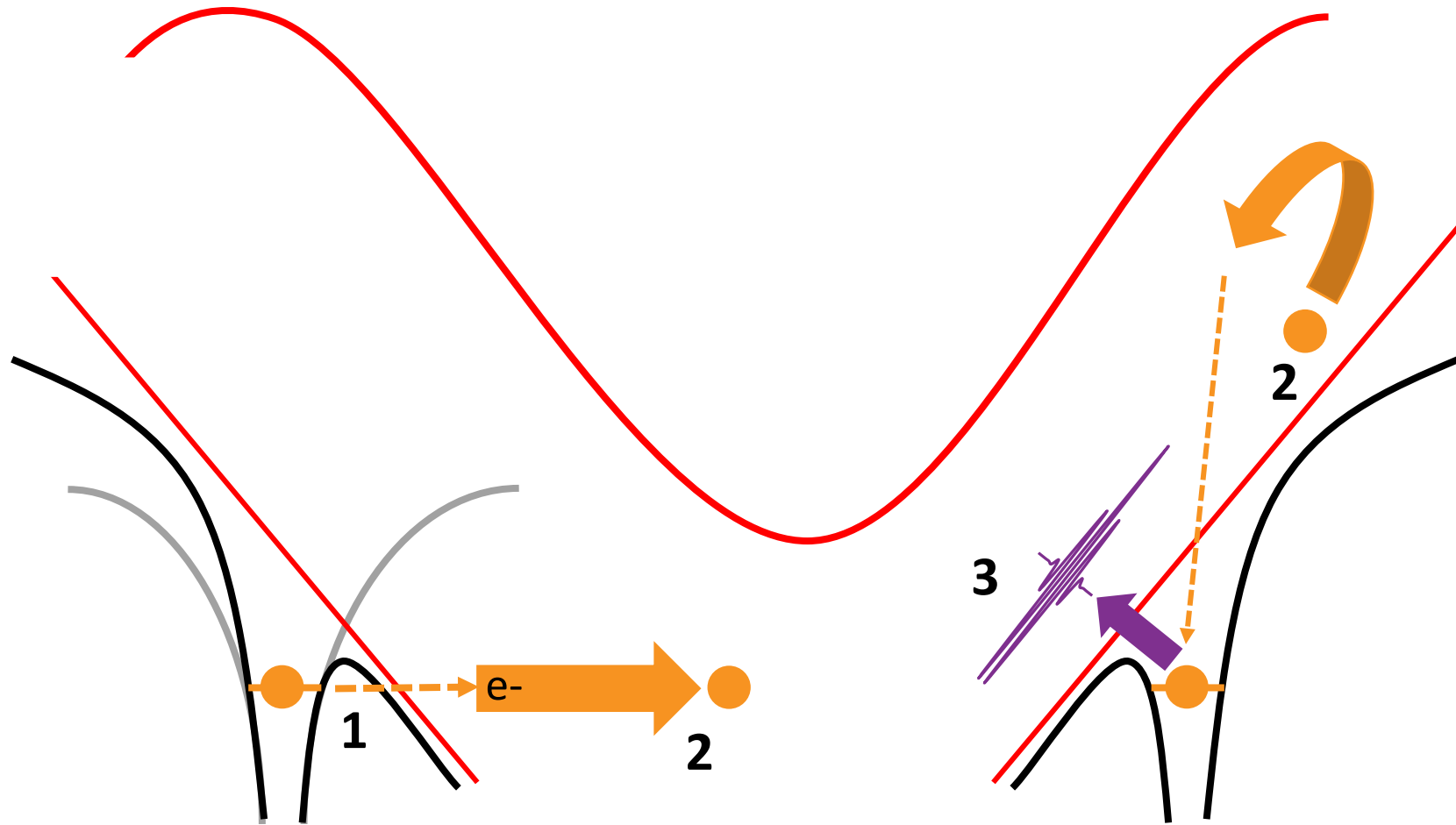
Attosecond pulses by high-order harmonic generation in gases (HHG)



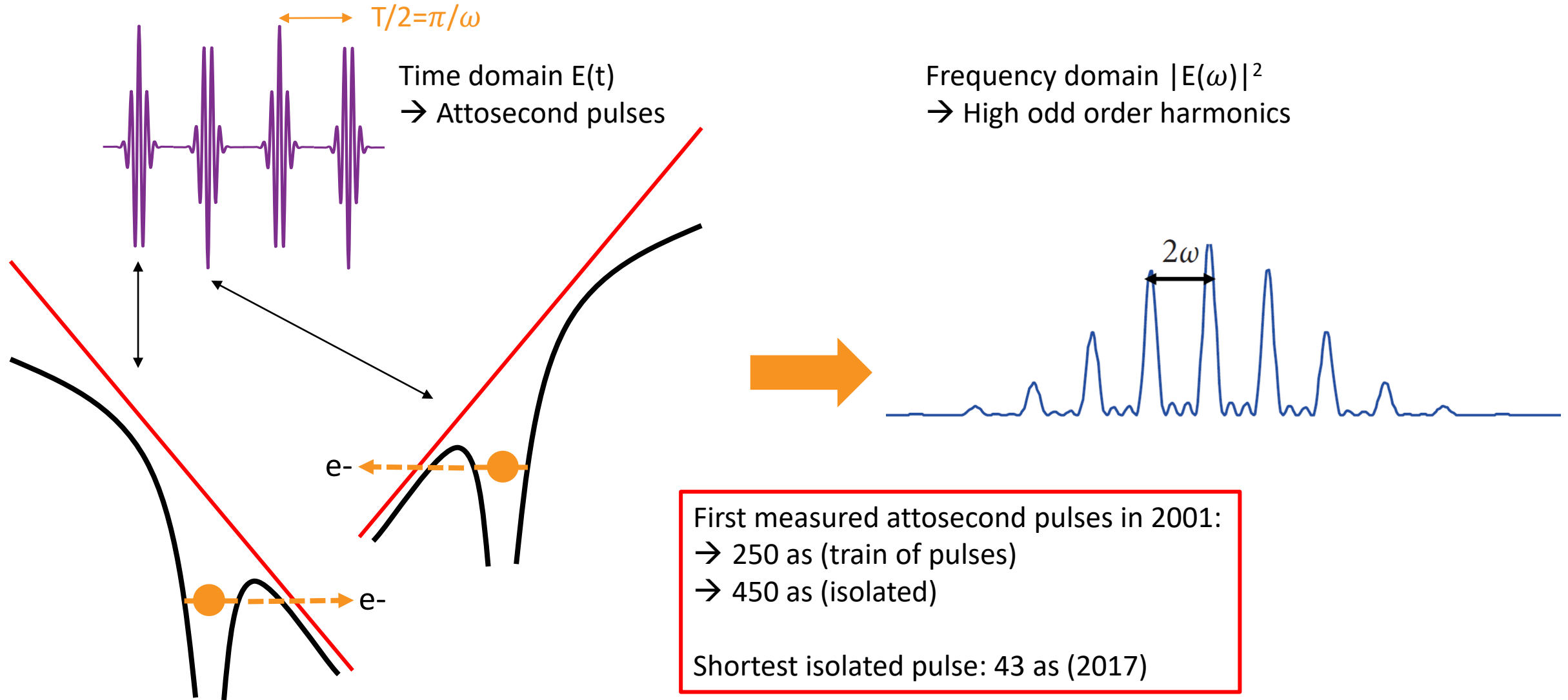
Attosecond pulse generation via HHG



The three step model – a physical picture for HHG

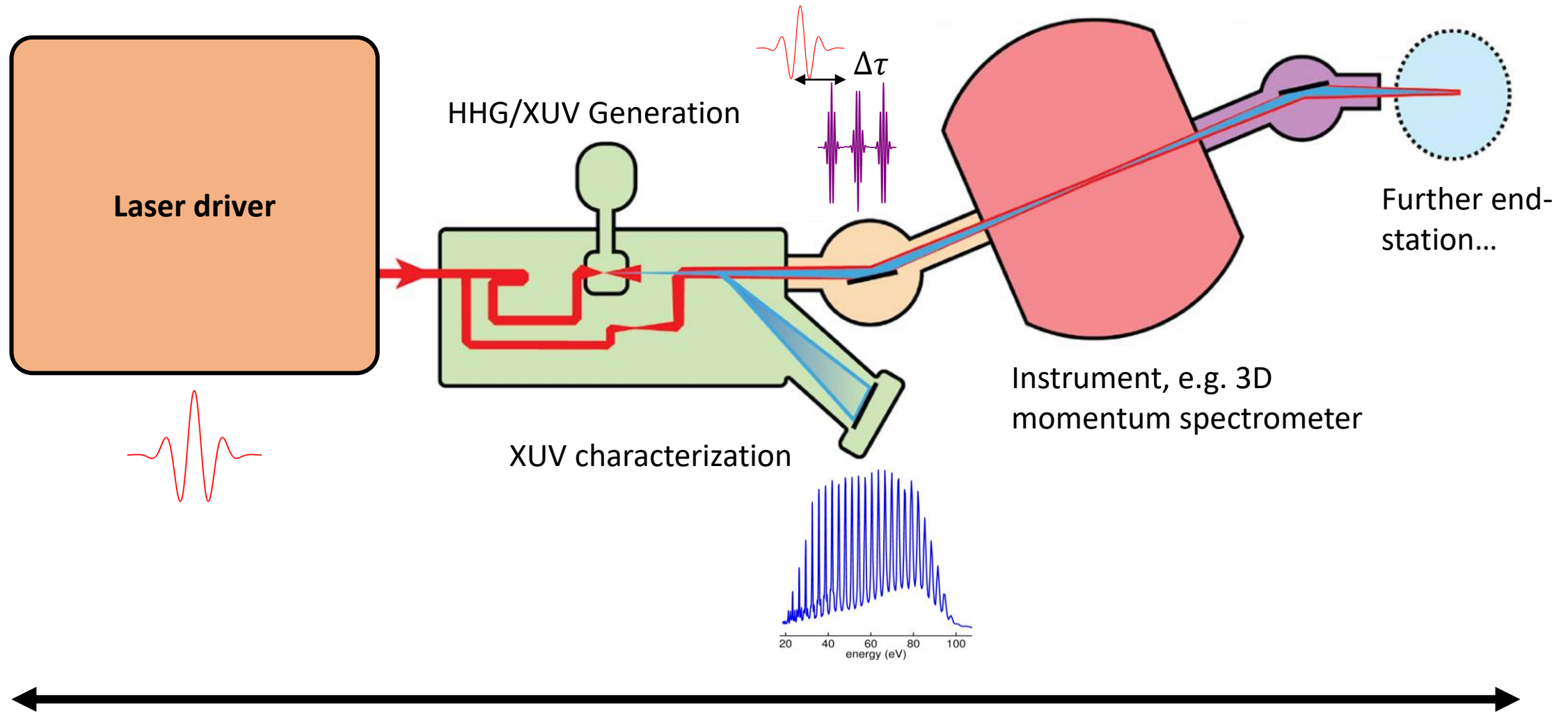


Properties of HHG light

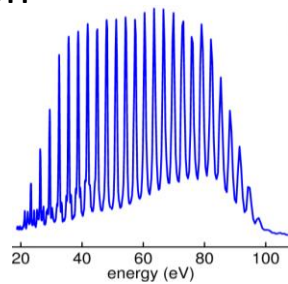


*P. M. Paul et al., Science 292 (2001).
M. Hentschel et al. Nature 414 (2001).
T. Gaumnitz et al., Opt. Express 25 (2017).*

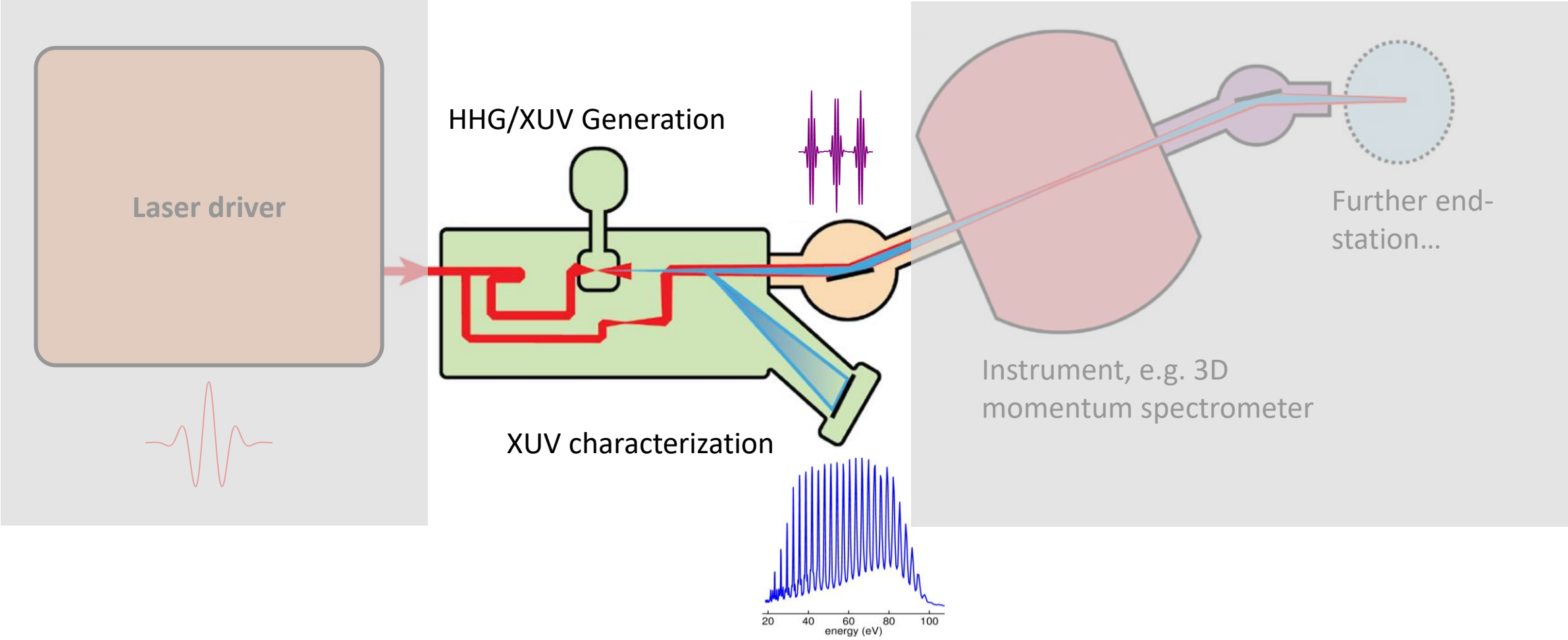
A typical Attosecond beamline



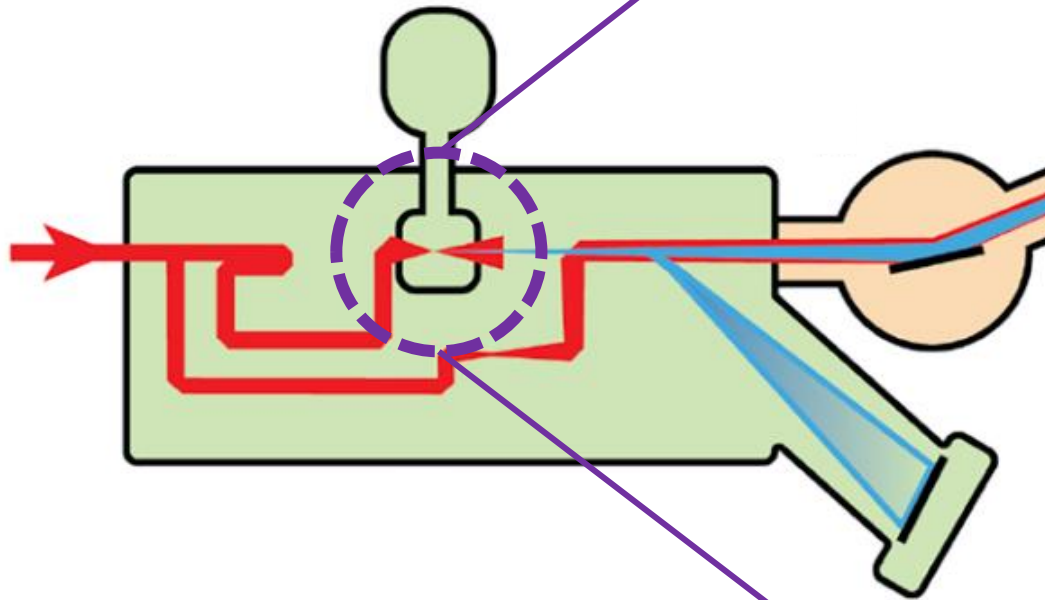
Footprint: ~1 m to > 50 m!



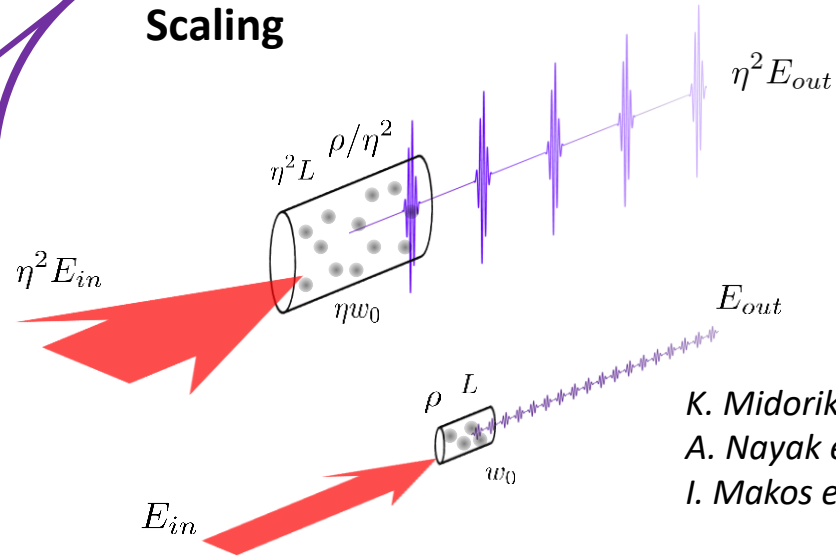
A typical Attosecond beamline



Versatility and challenges of HHG beamlines



Scaling



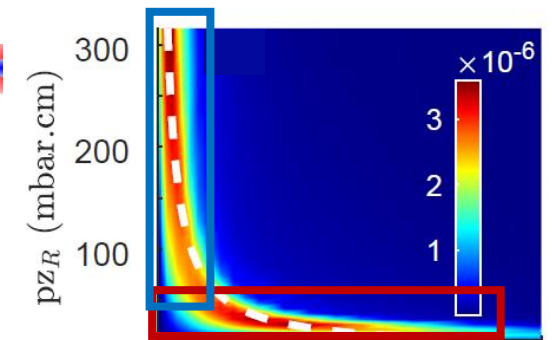
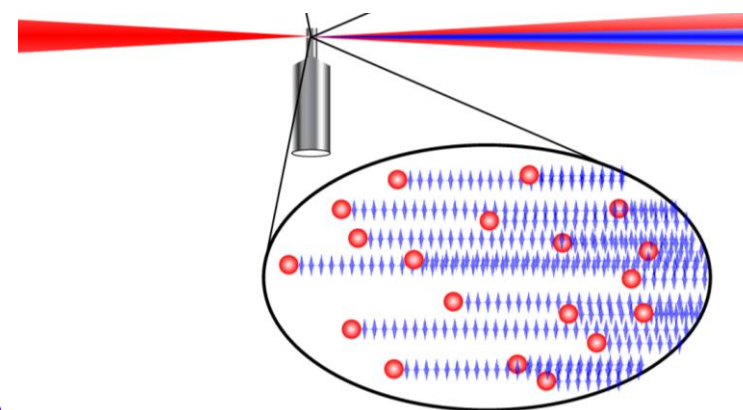
μ J energies

- 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

- C. M. Heyl et al., Optica 3 (2016).*
- R. Klas et al., PhotonIX 2 (2021).*

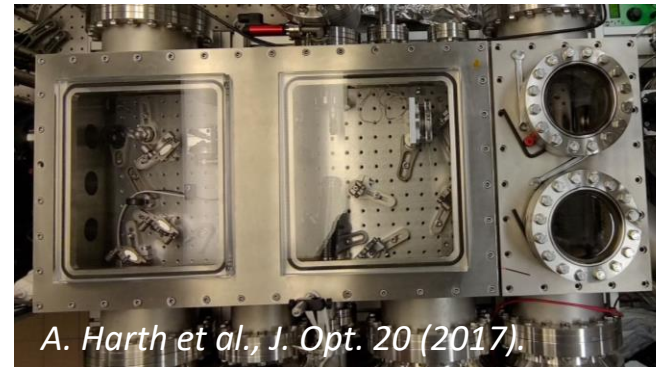
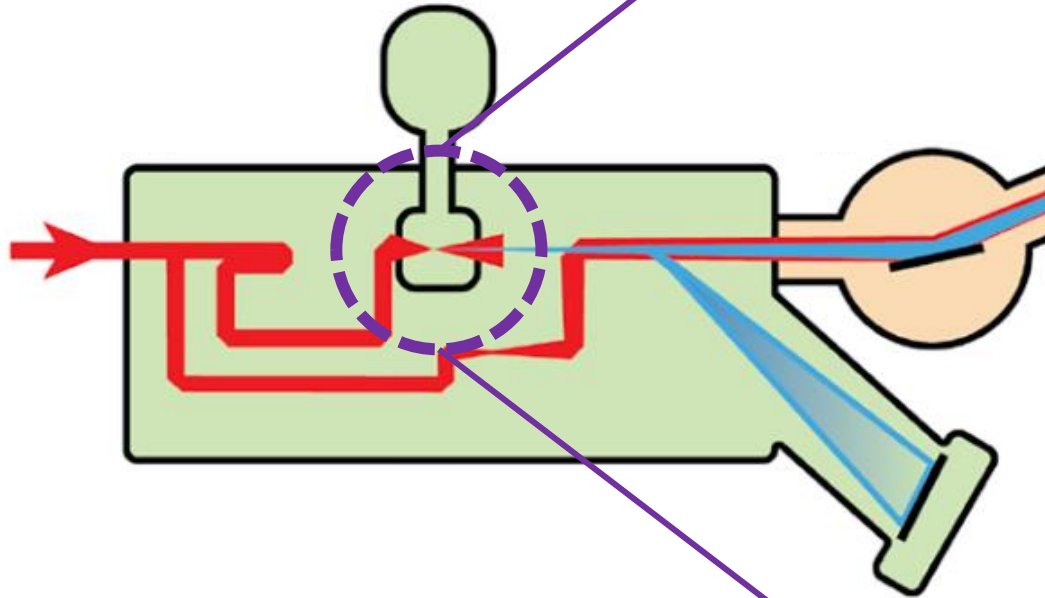
Phase-matching



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

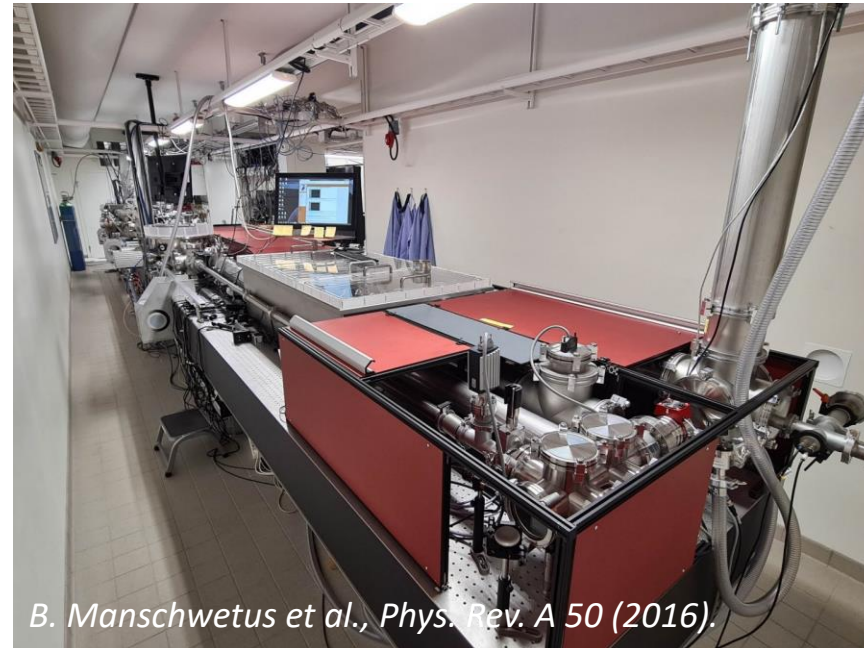
- R. Weissenbilder et al., Nat. Rev. Phys. 4 (2022).*

Versatility and challenges of HHG beamlines



Lund 200 kHz laser
 μJ \rightarrow short focusing,
small target

A. Harth et al., J. Opt. 20 (2017).



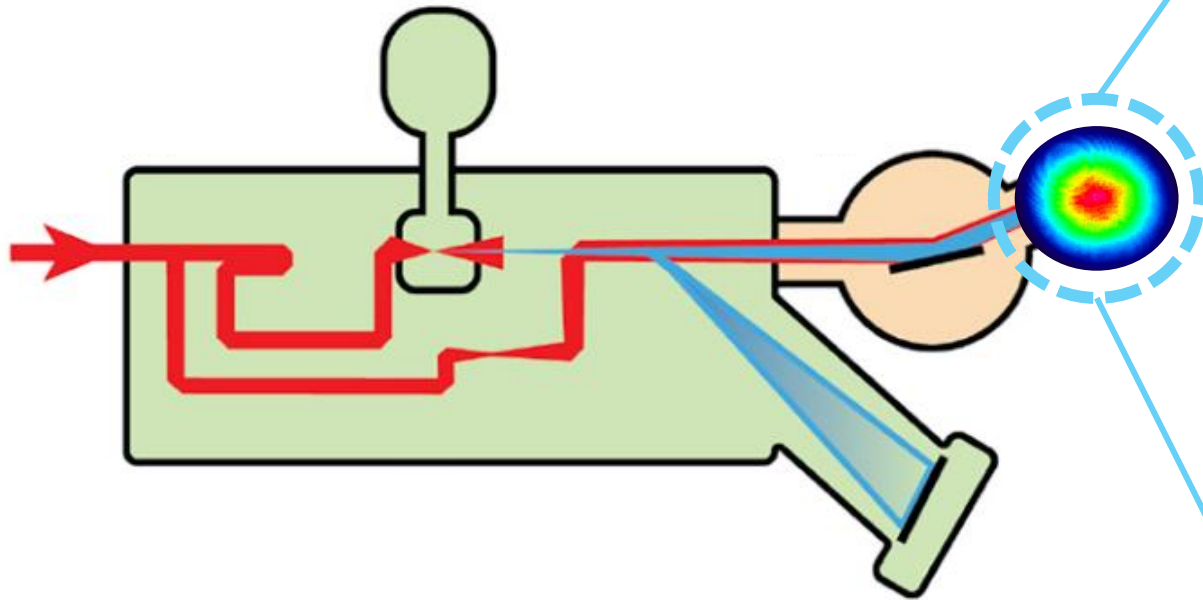
Lund TW laser
mJ \rightarrow long focusing,
longer gas cell

B. Manschwetus et al., Phys. Rev. A 50 (2016).

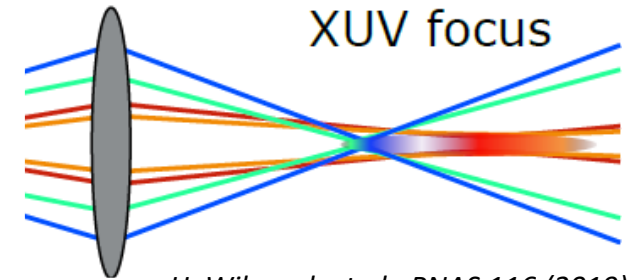
SYLOS long GHHG beamline:

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

Versatility and challenges of HHG beamlines



XUV wavefront

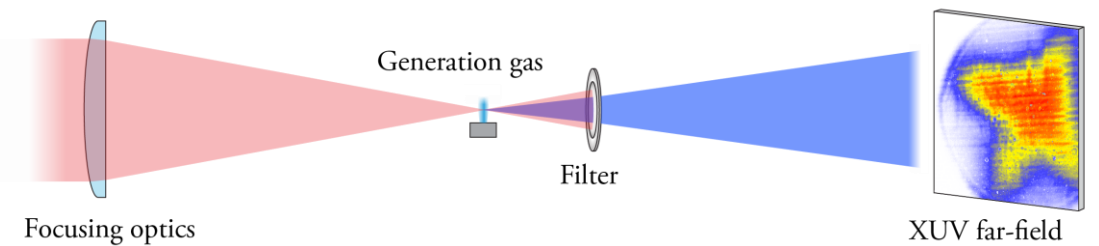


H. Wikmark et al., PNAS 116 (2019).

Chromatic aberrations

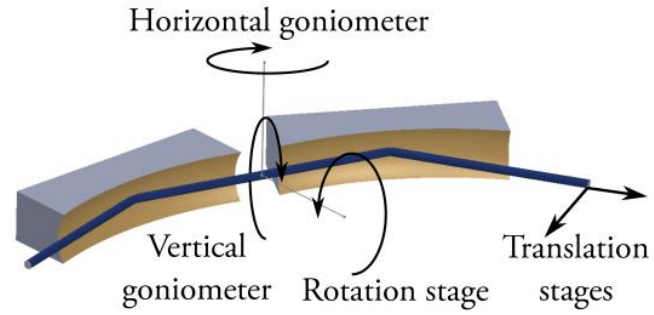
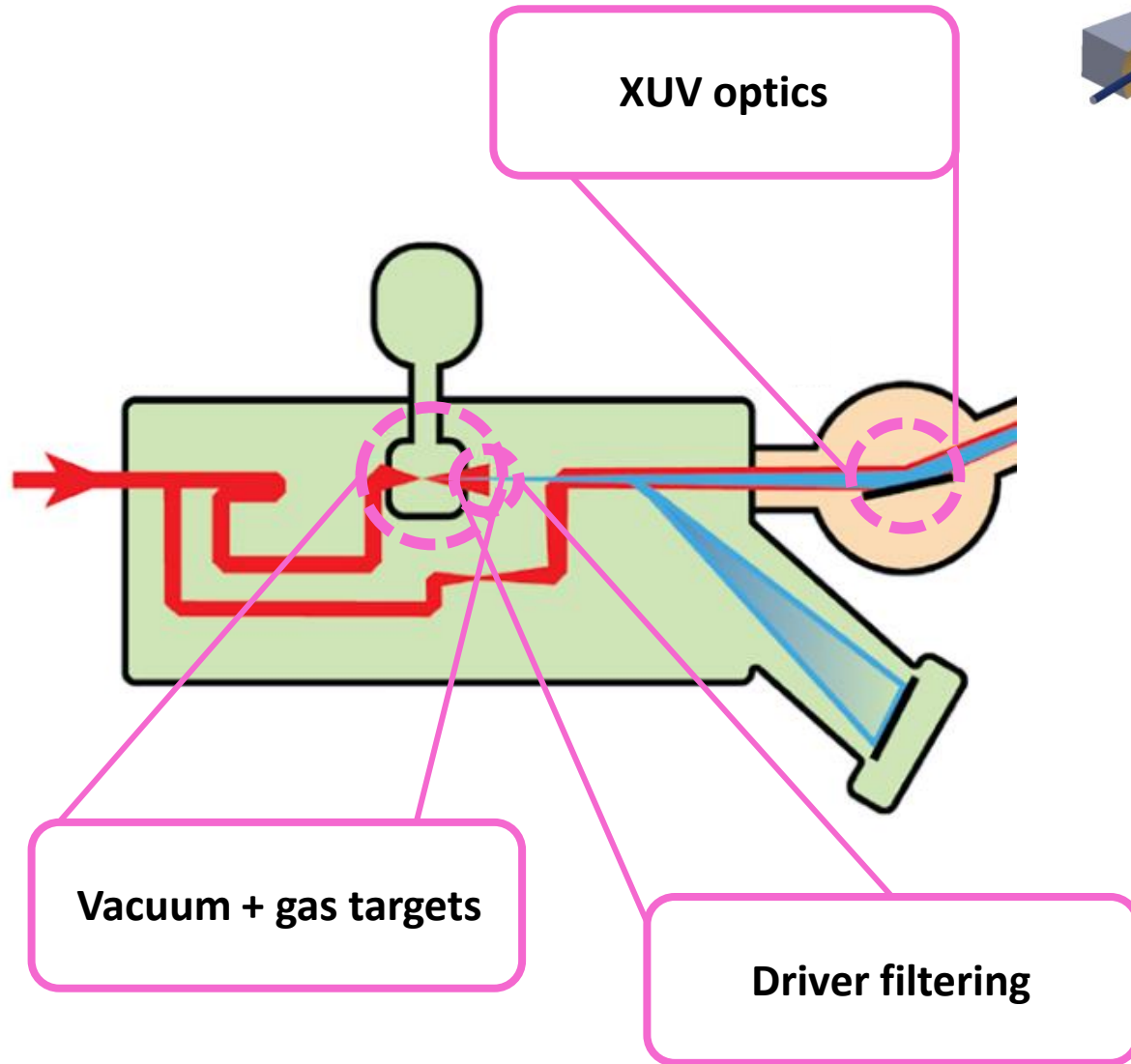
Spatio-temporal couplings

Astigmatism...

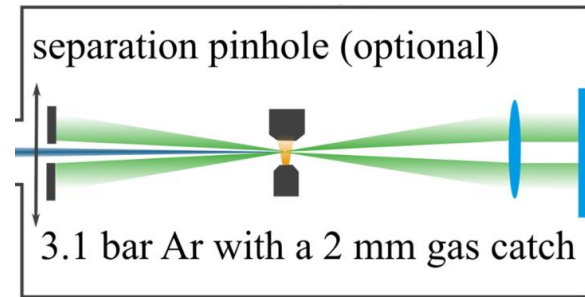


M. Plach et al., arXiv:2308.08018 (2023).

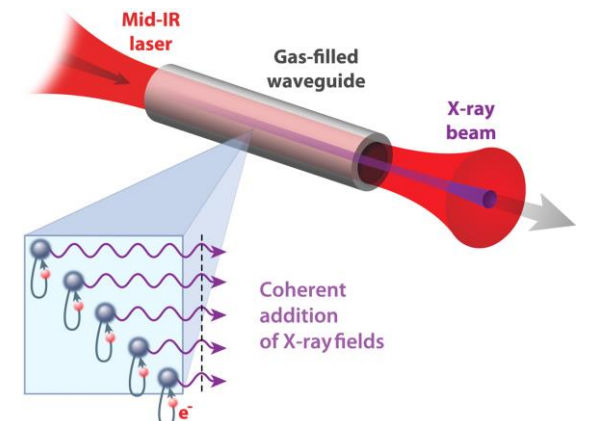
Versatility and challenges of HHG beamlines



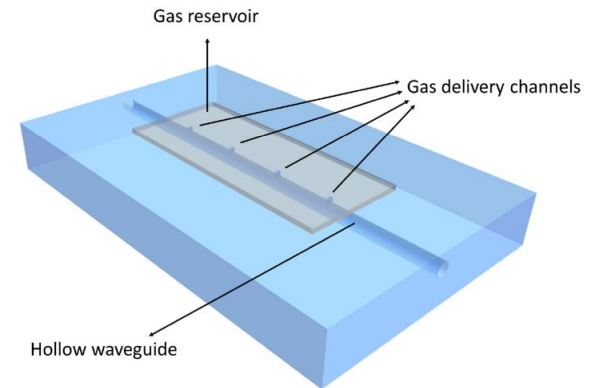
H. Coudert-Alteirac et al., *Appl. Sci.* 7 (2017).



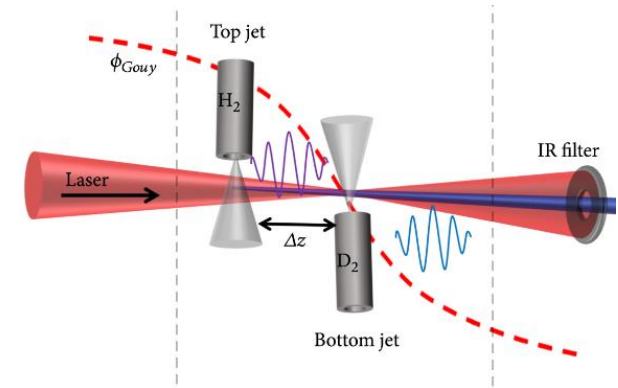
R. Klas et al., *Opt. Express* 26 (2018).



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

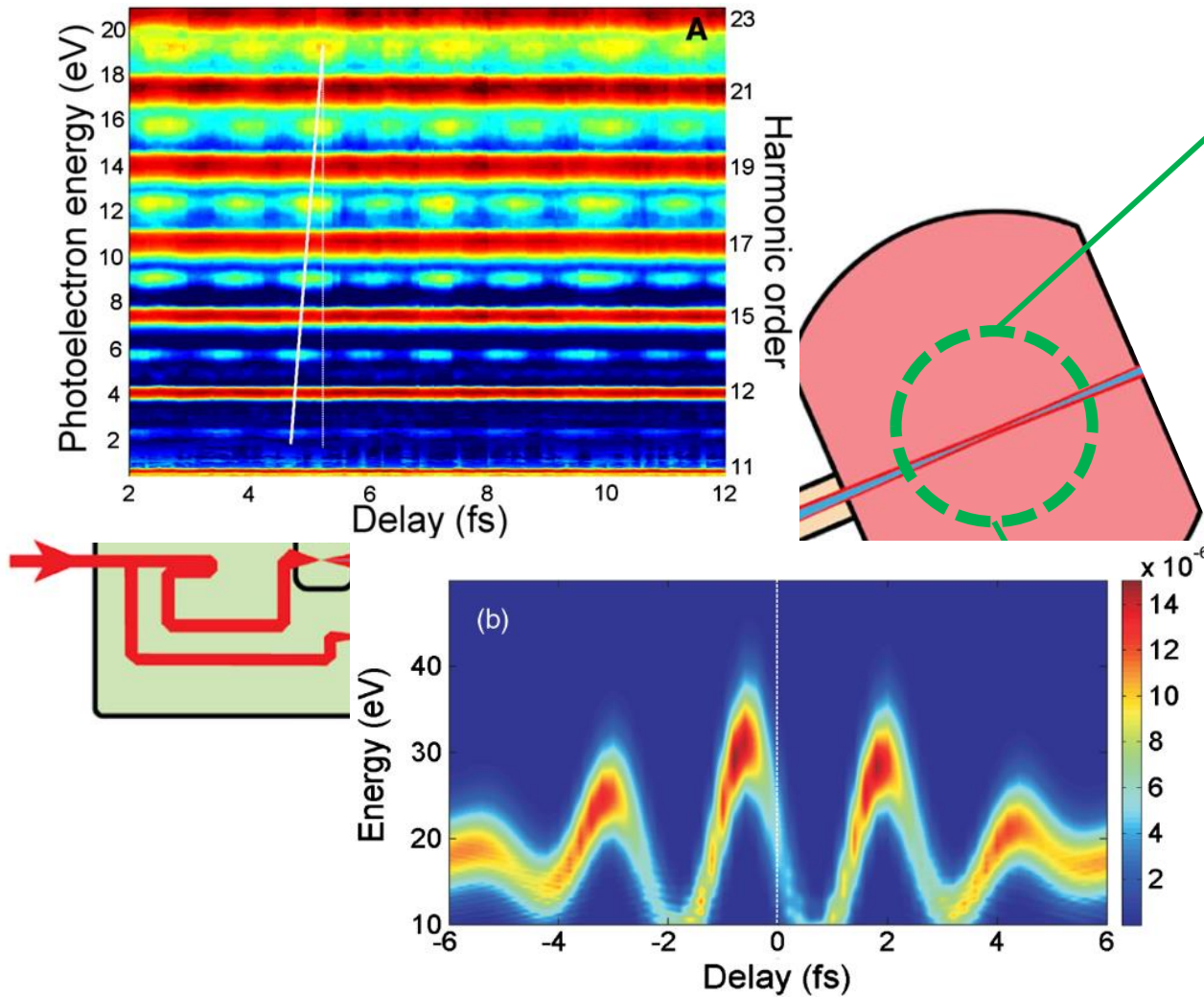


A. G. Ciriolo et al., *J. Phys. Photonics* 2 (2020).



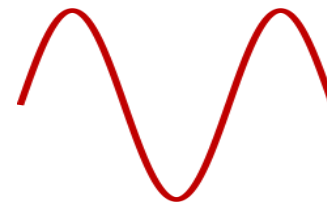
M. H. Mustary et al., *Ultrafast Science* (2022).

Attosecond pulse characterization

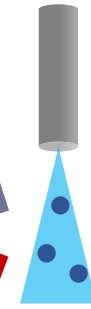


Cross-correlation measurement

Attosecond pulses



Probe field (IR)

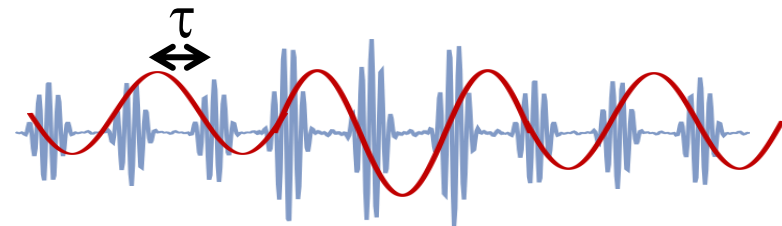


Atom
ionization

Electronic wavepacket:
replica of attosecond pulse



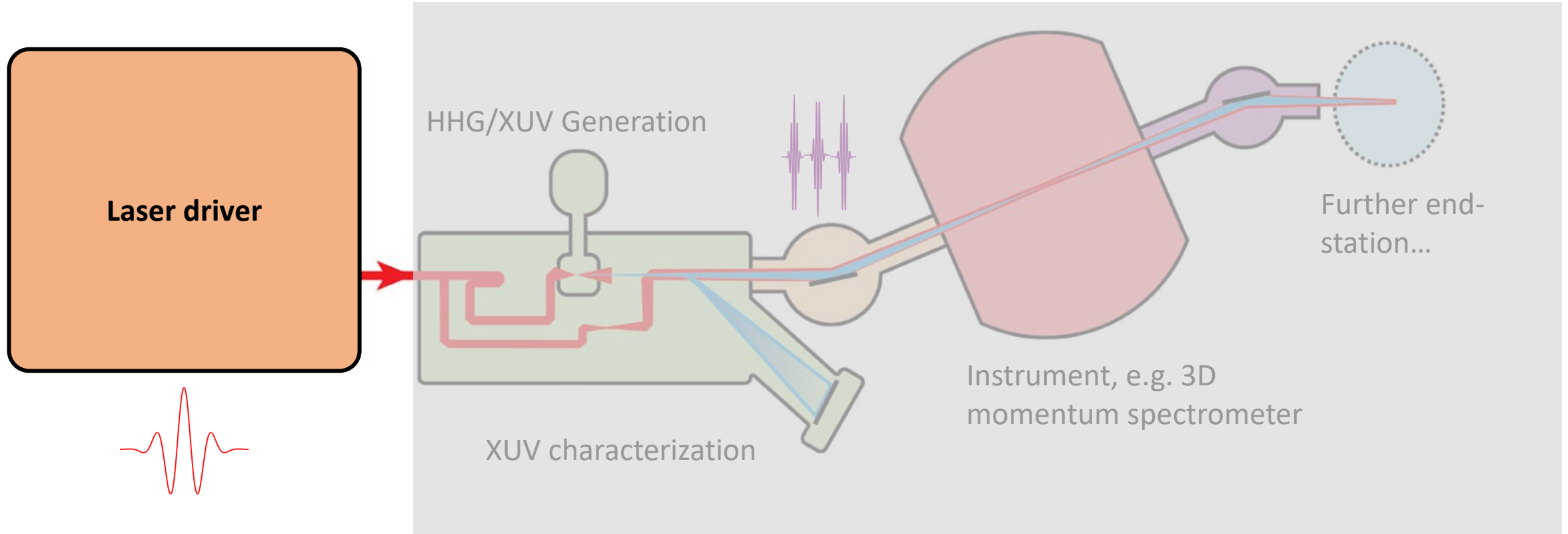
Interferometry technique: RABBIT (APT)



Strong-field technique: Streaking (IAP)

- 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).*

Tailored drivers for HHG



Isolated attosecond pulse vs. Attosecond pulse train

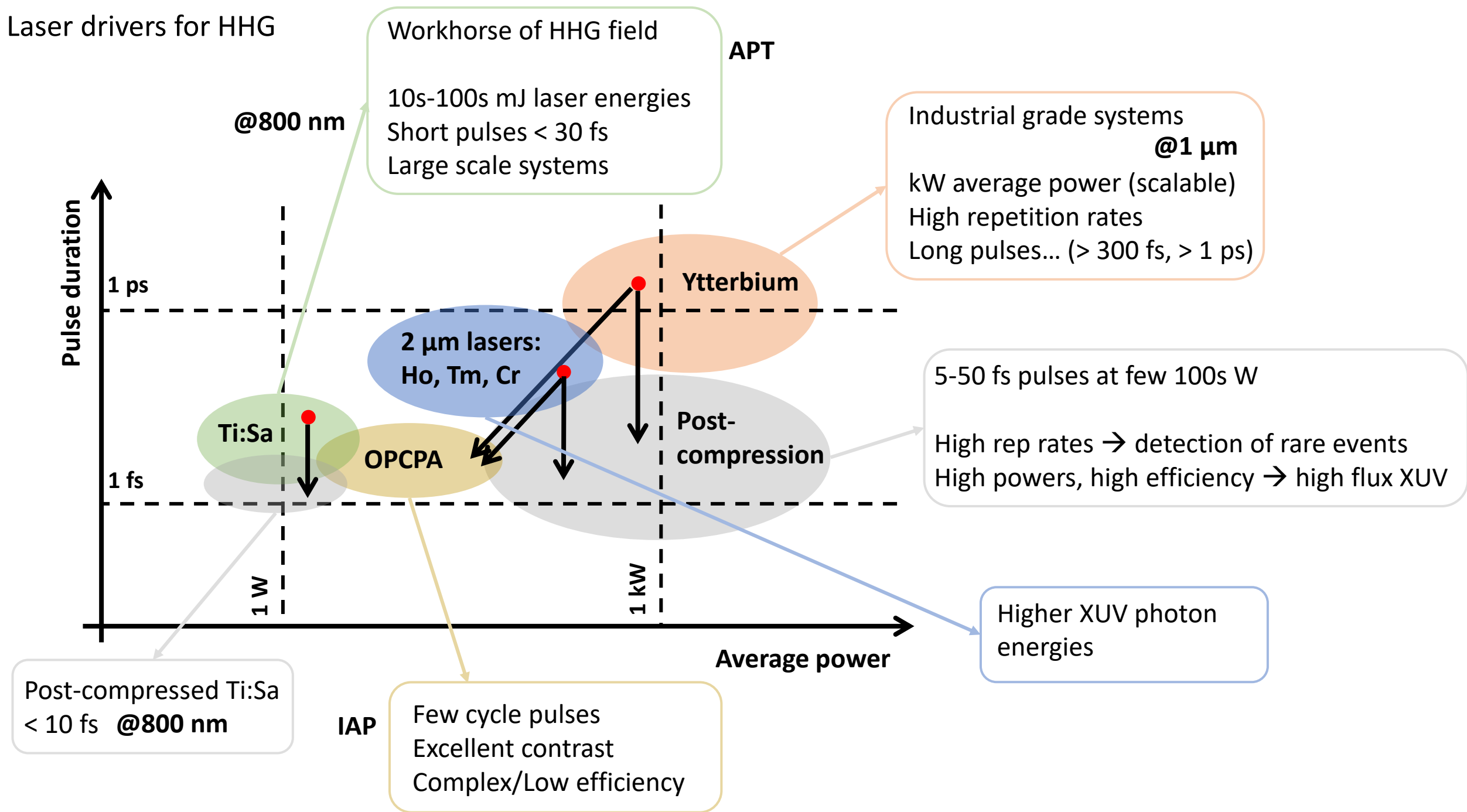
High flux XUV

High photon energies

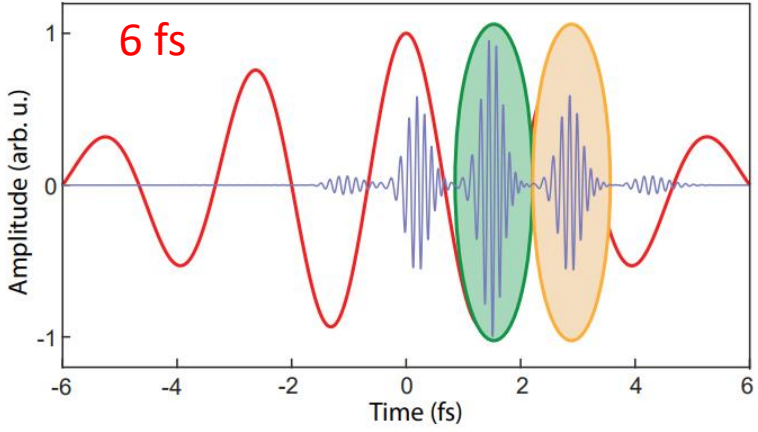
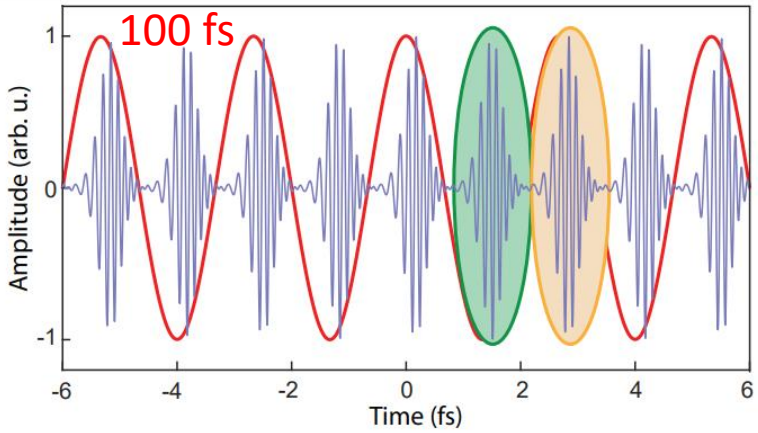
Broadband XUV vs. narrowband XUV

High yield XUV

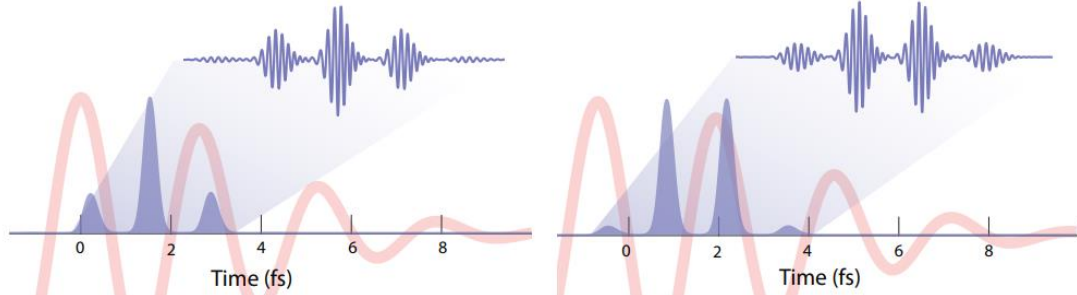
Laser drivers for HHG



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

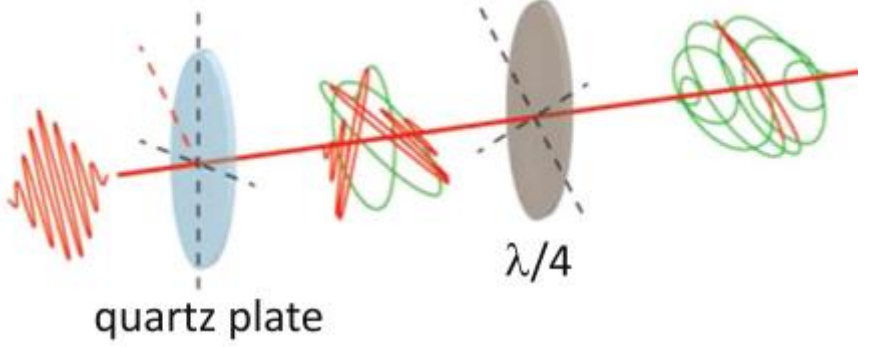


Controlling the carrier-envelope phase is important



CEP = 0 vs. CEP = pi

Polarization gating



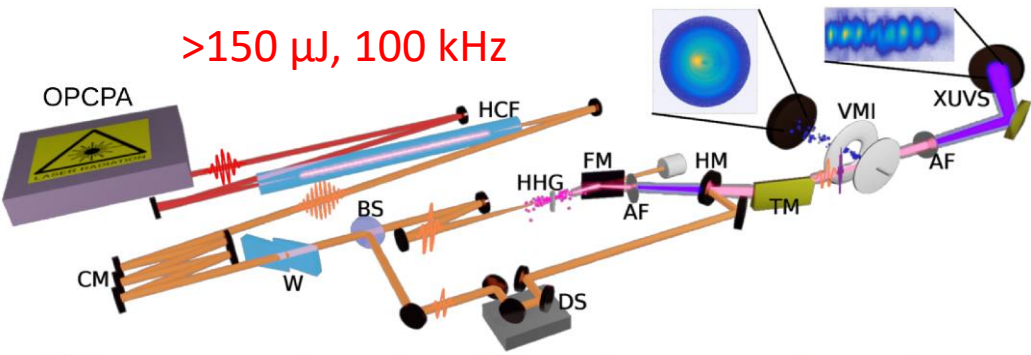
S. Mikielsson, doctoral thesis (2021).
H. R. Telle et al., Appl. Phys. B 69 (1999).

G. Sansone et al., Science 314 (2006).

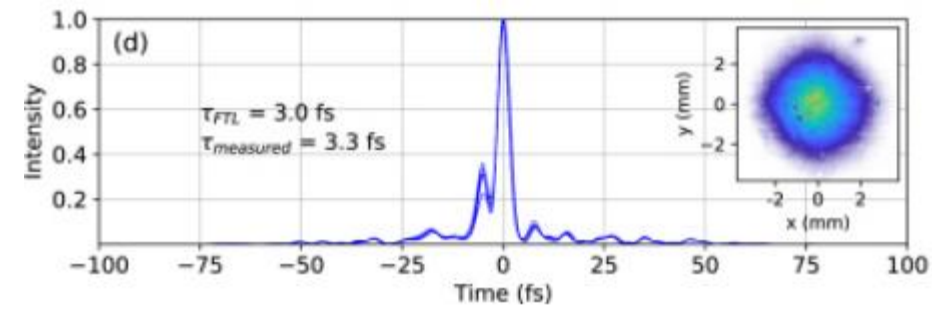
M. Hentshell et al., Nature 414 (2001).

F. Calegari et al., J. Phys. B: At. Mol. Opt. Phys. 49 (2016).

Laser drivers for HHG – OPCPA / Waveform synthesizer

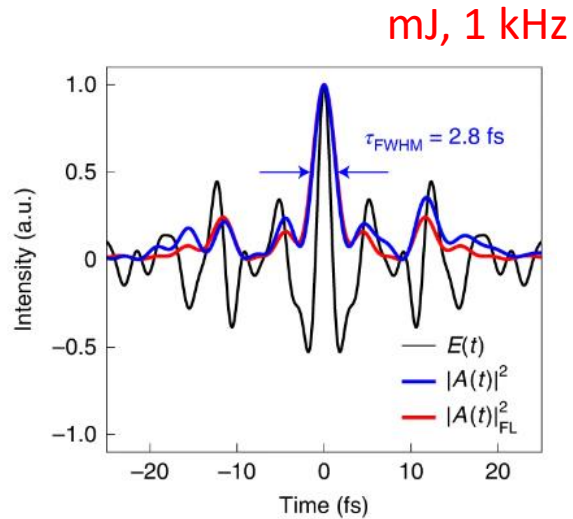


>150 μJ , 100 kHz

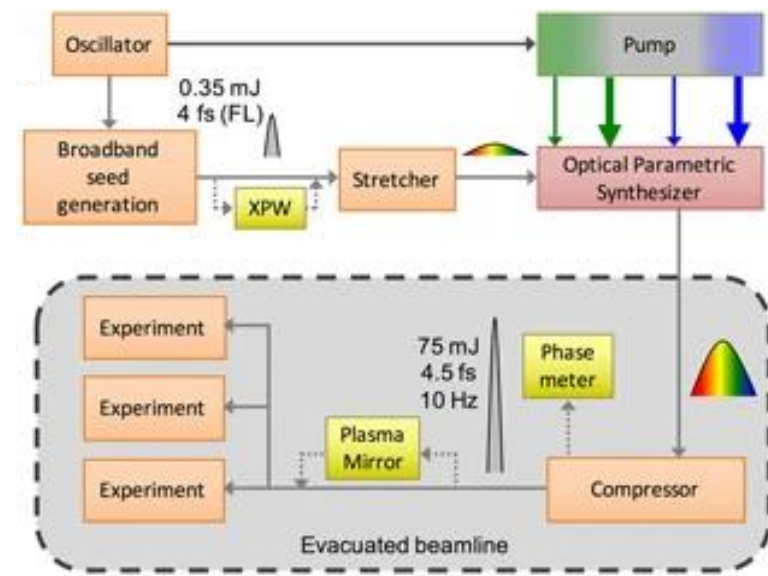
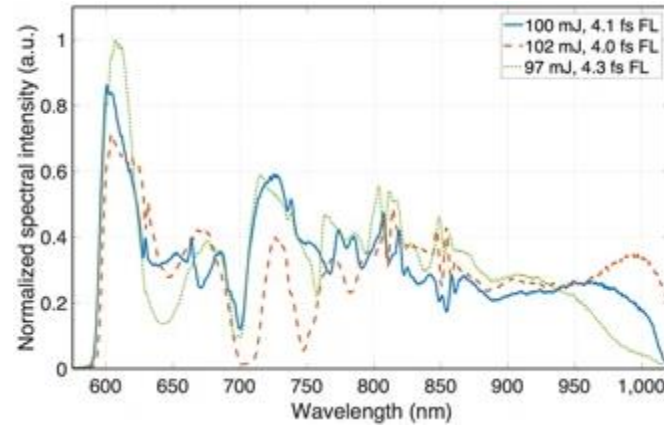


F. Furch et al., *Opt. Lett.* 42 (2017).

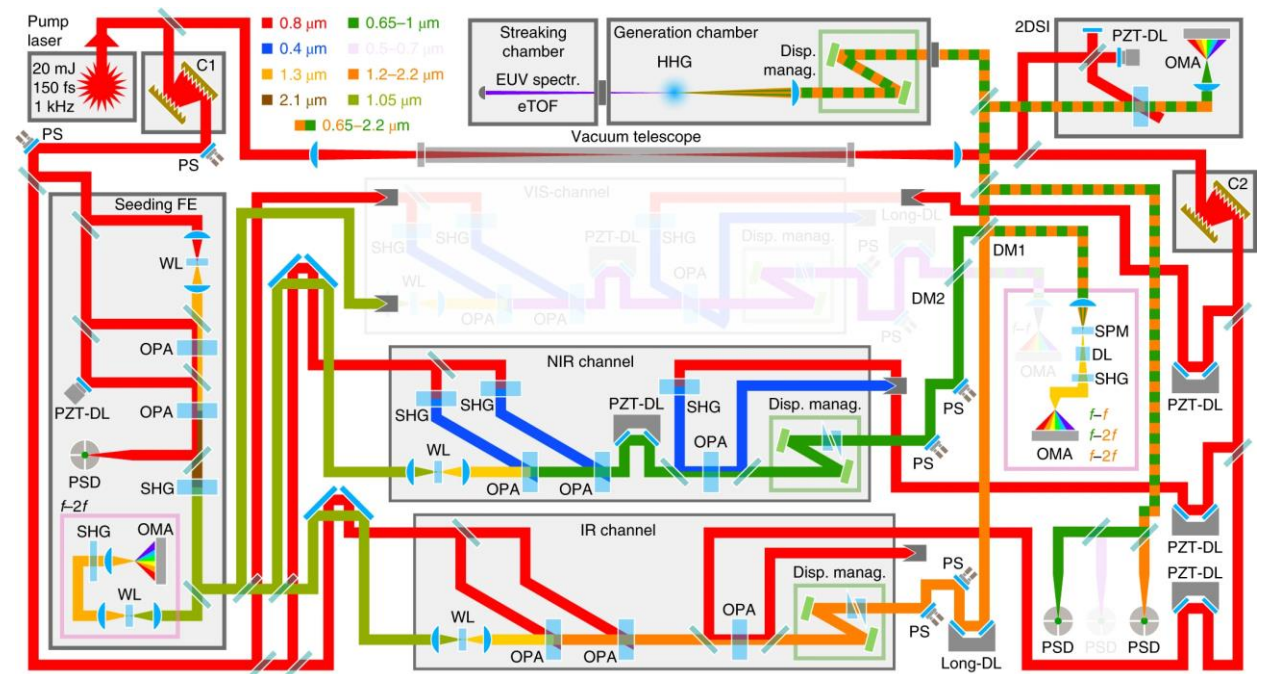
T. Witting et al., *Optica* 9 (2022).



100 mJ, 10 Hz

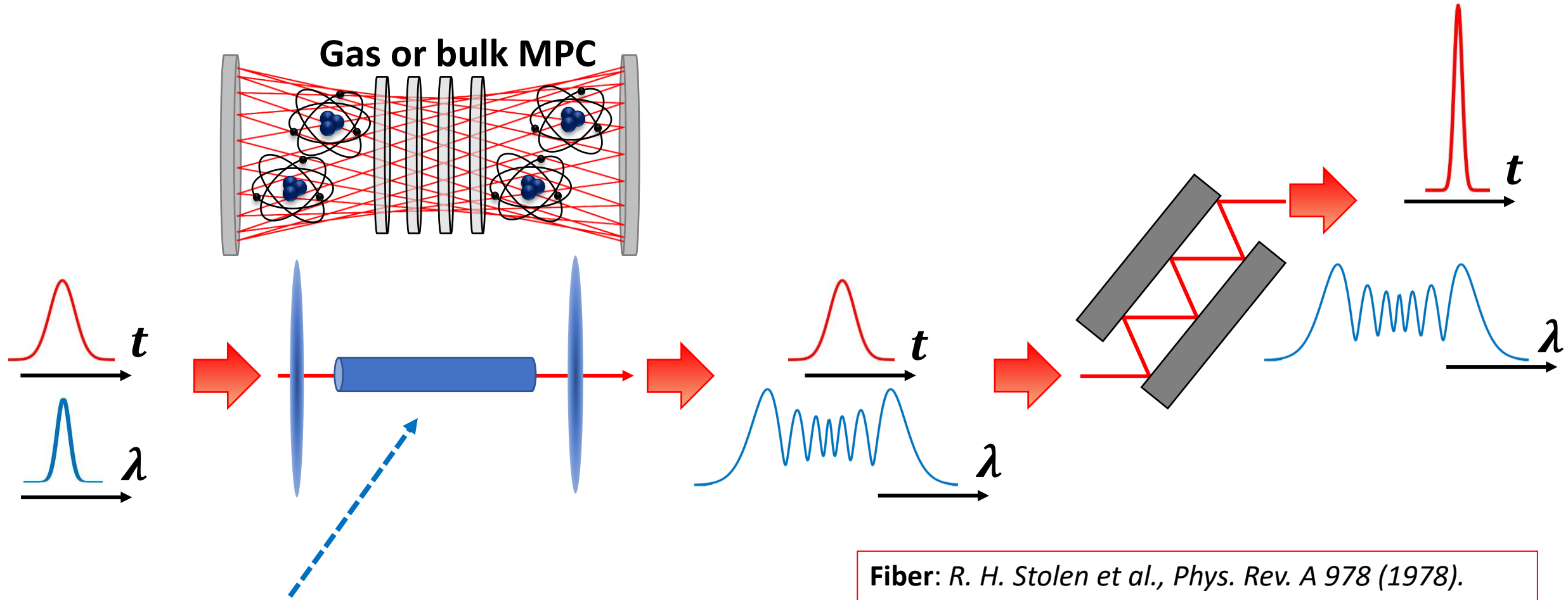


D. E. Rivas et al., *Sci. rep.* 7 (2017).



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

Laser drivers for HHG – Post-compression

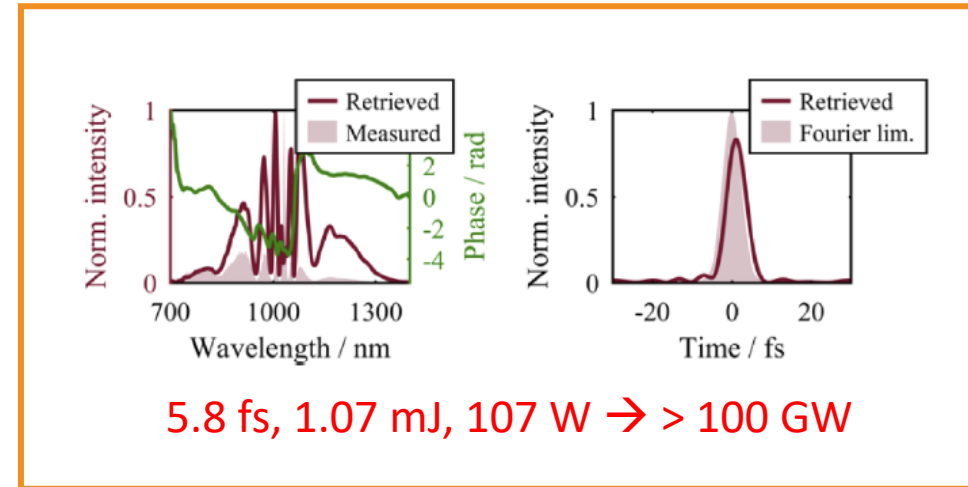
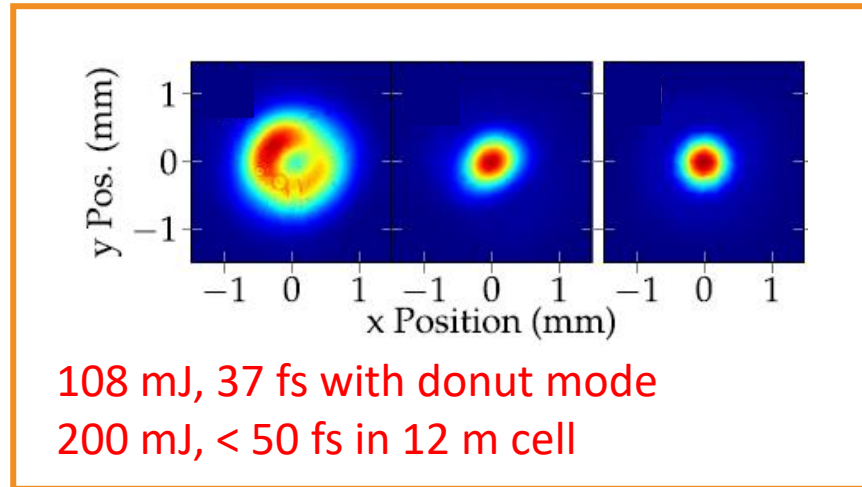
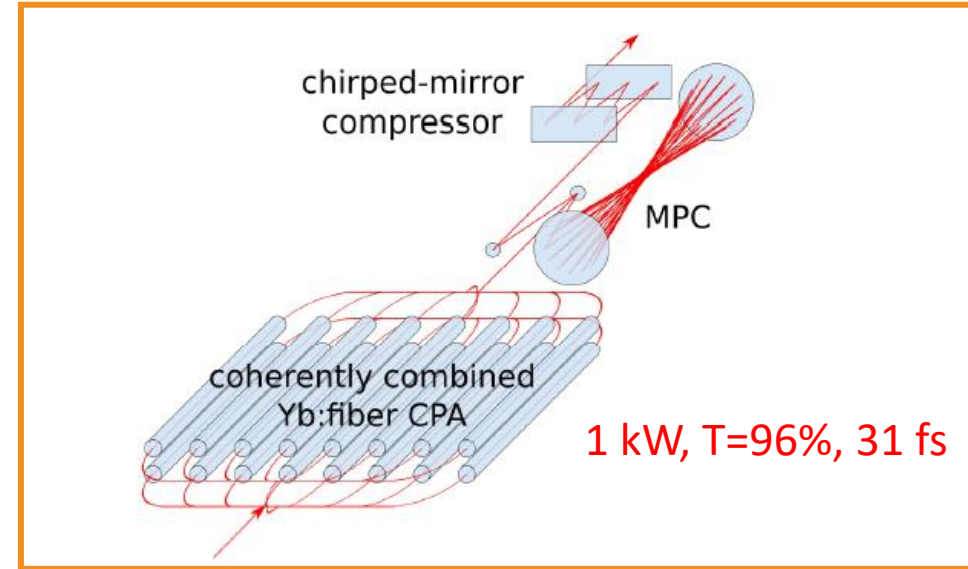
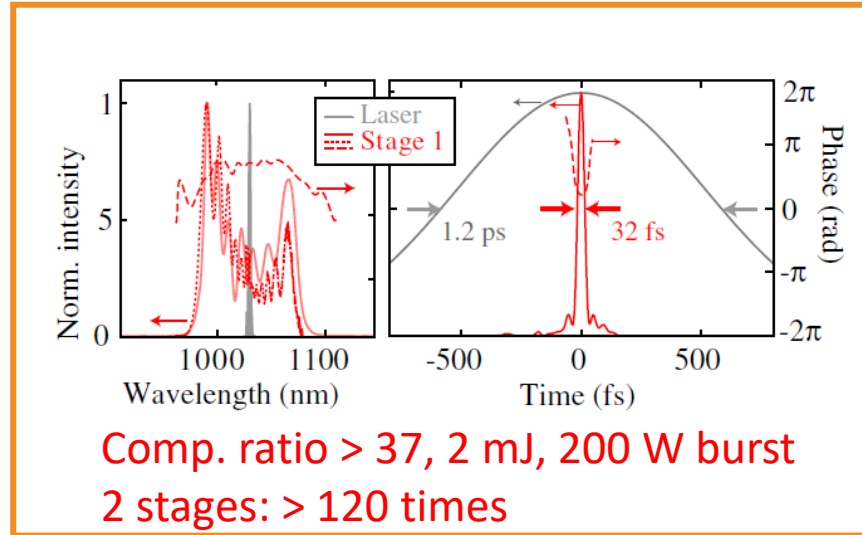


Gas or bulk MPC

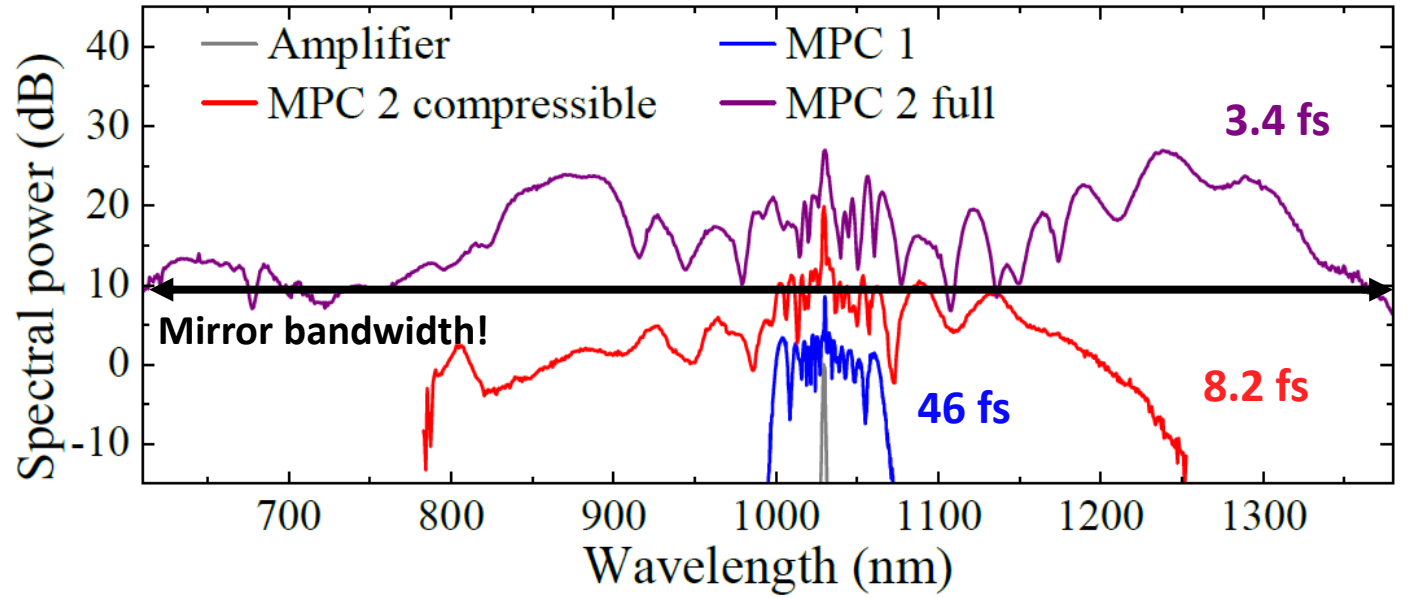
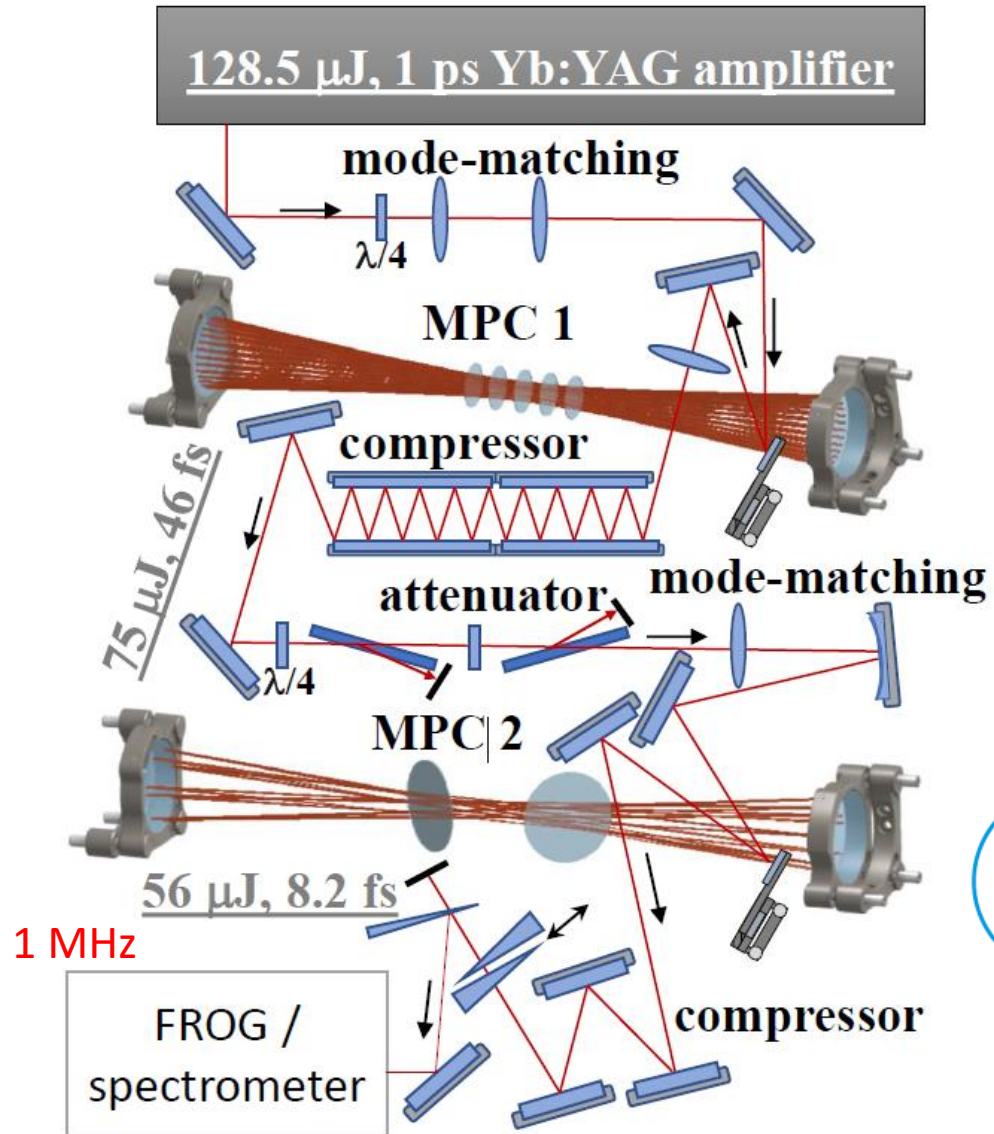
Guiding structure: filament, capillary, fiber...

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).

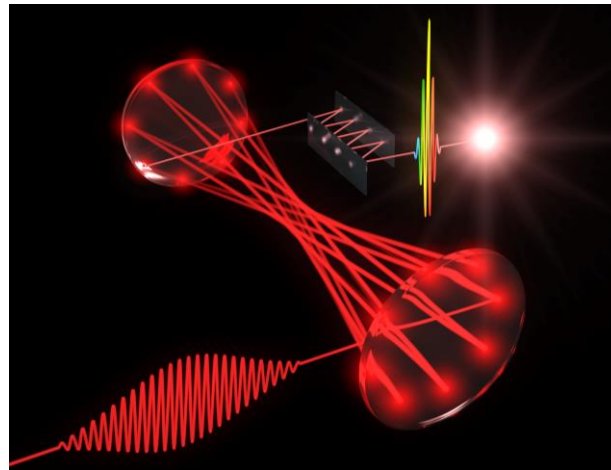
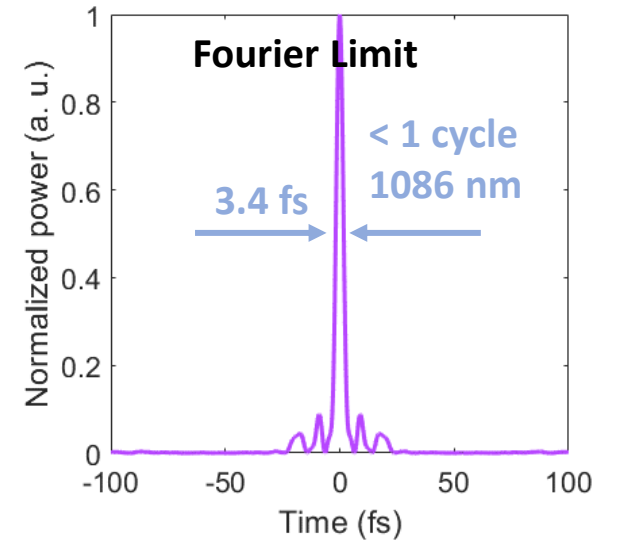
Laser drivers for HHG – Post-compression in multi-pass cells



Laser drivers for HHG – Post-compression



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

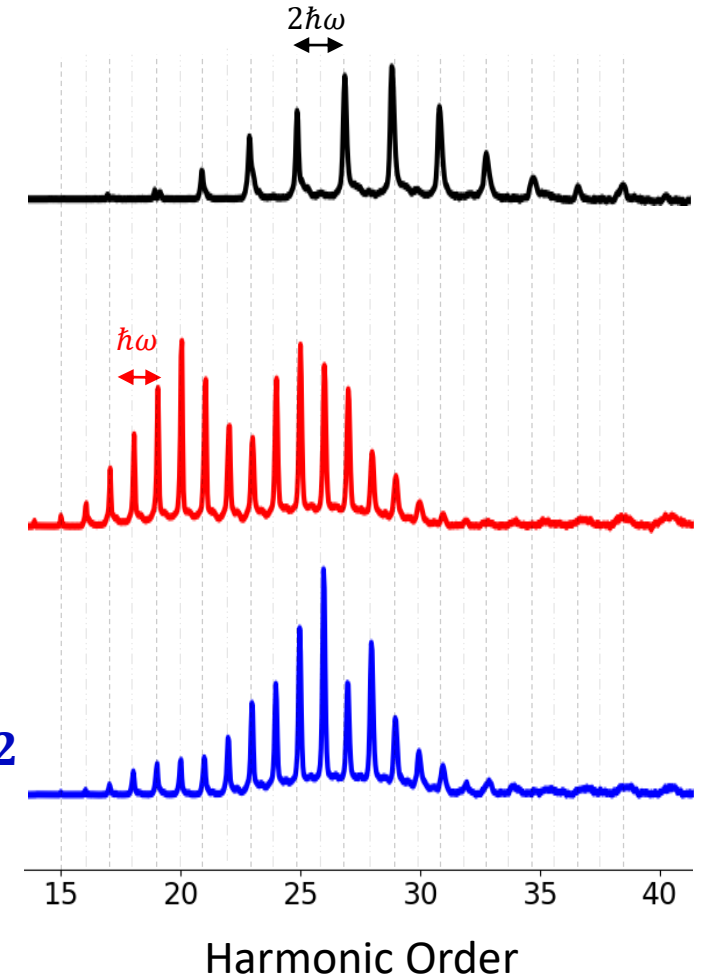
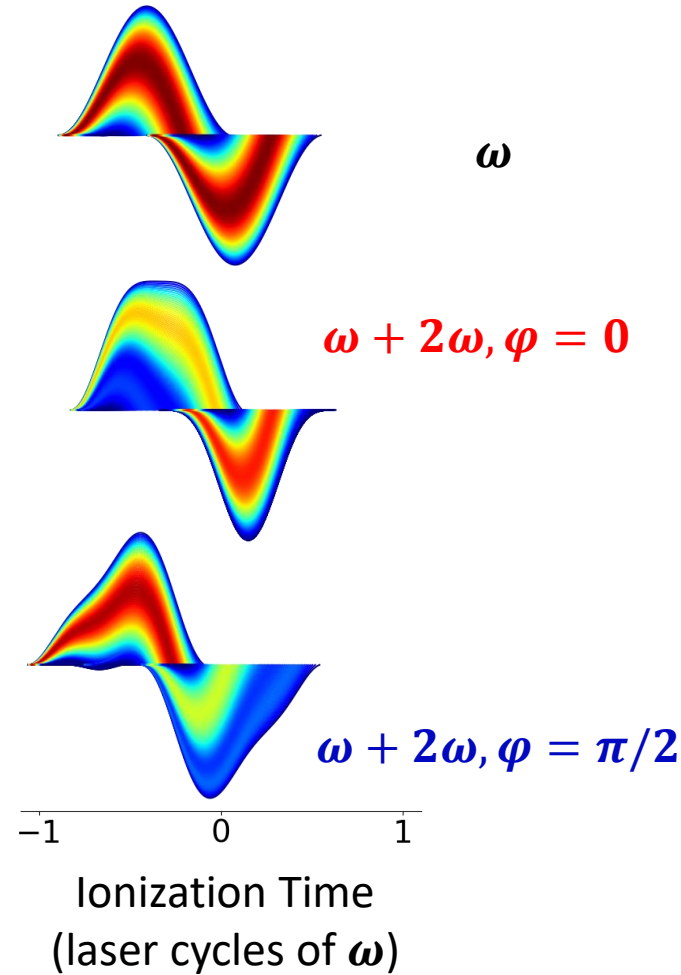
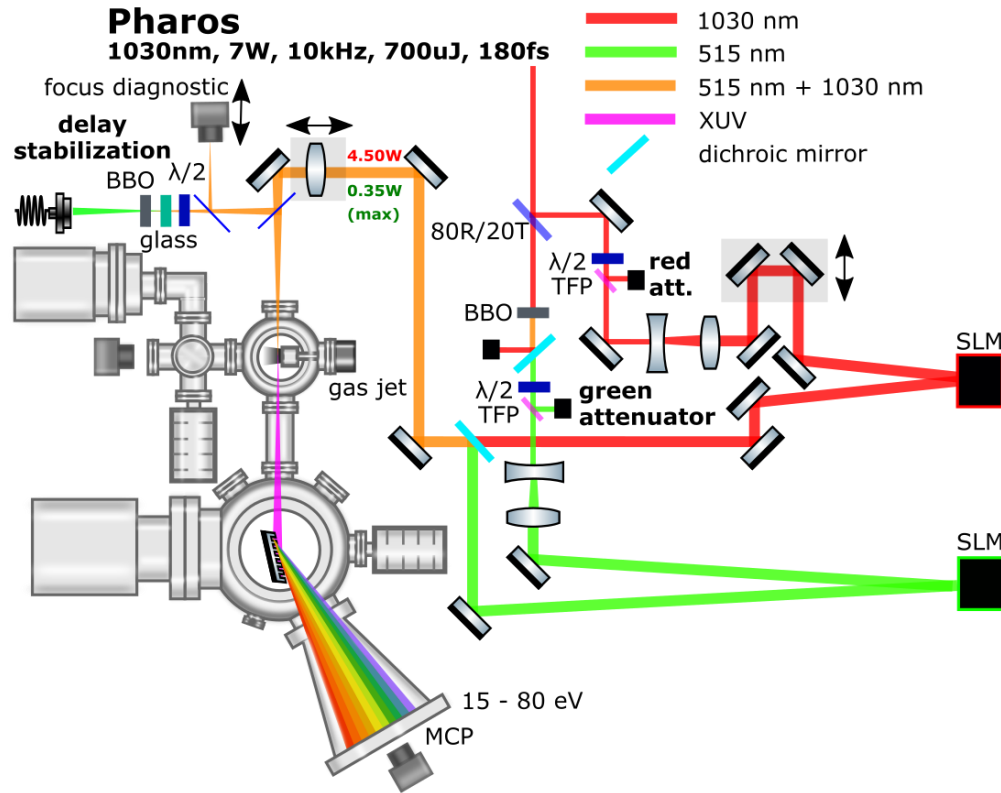


Laser drivers for HHG – Multi-color driver

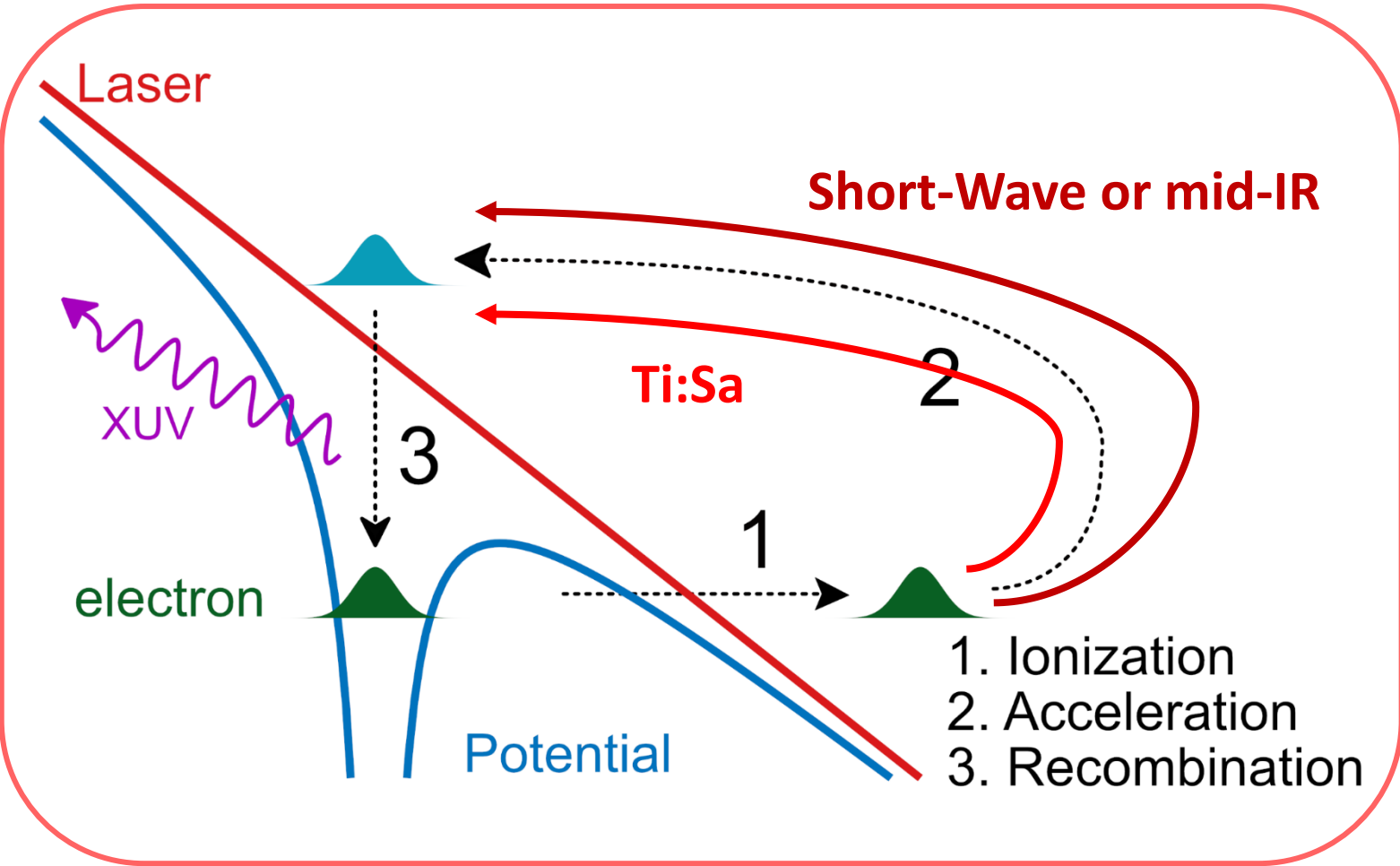
Control in experiment over second harmonic intensity ratio and phase

Classical electron trajectories

Examples for harmonics generated in argon (experiment)



Laser drivers for HHG – Higher photon energies with longer wavelengths



Emitted photon energy

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

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

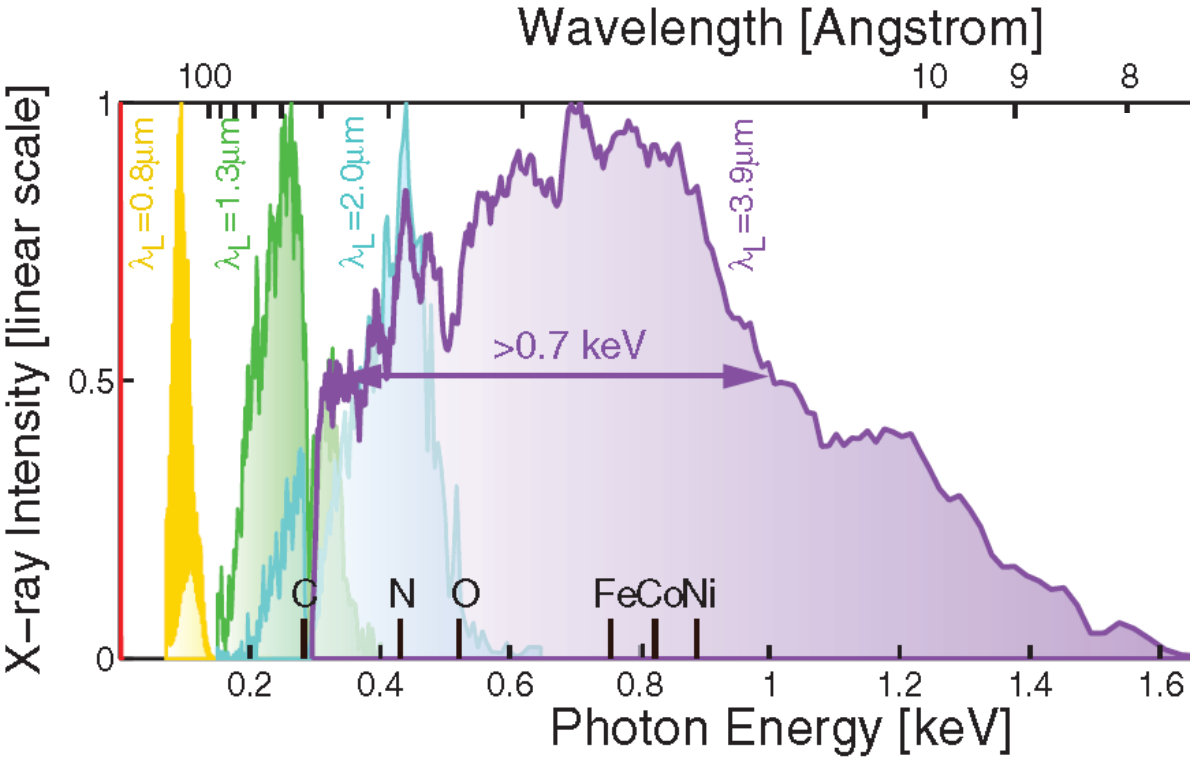
→ Higher XUV photon energies
 $E_{max} \propto I\lambda^2$

But...

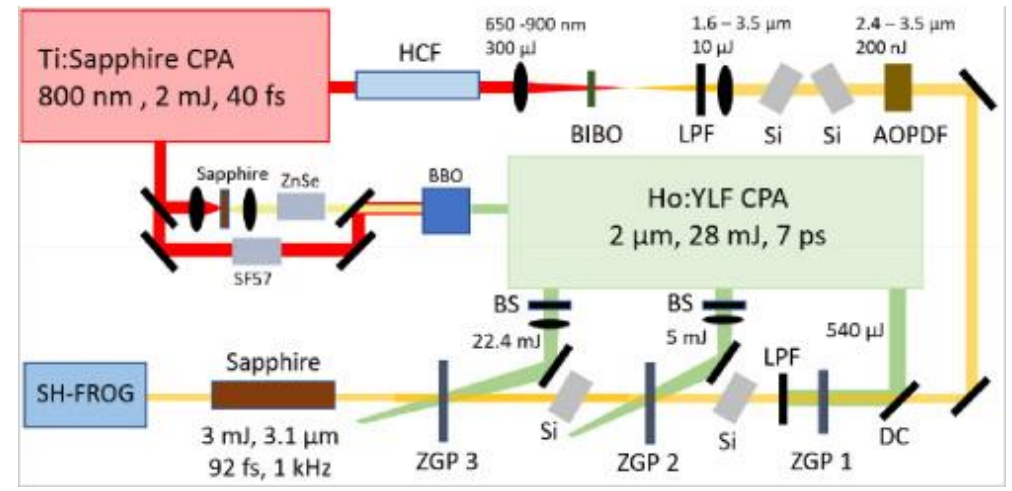
conversion efficiency is lower:

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

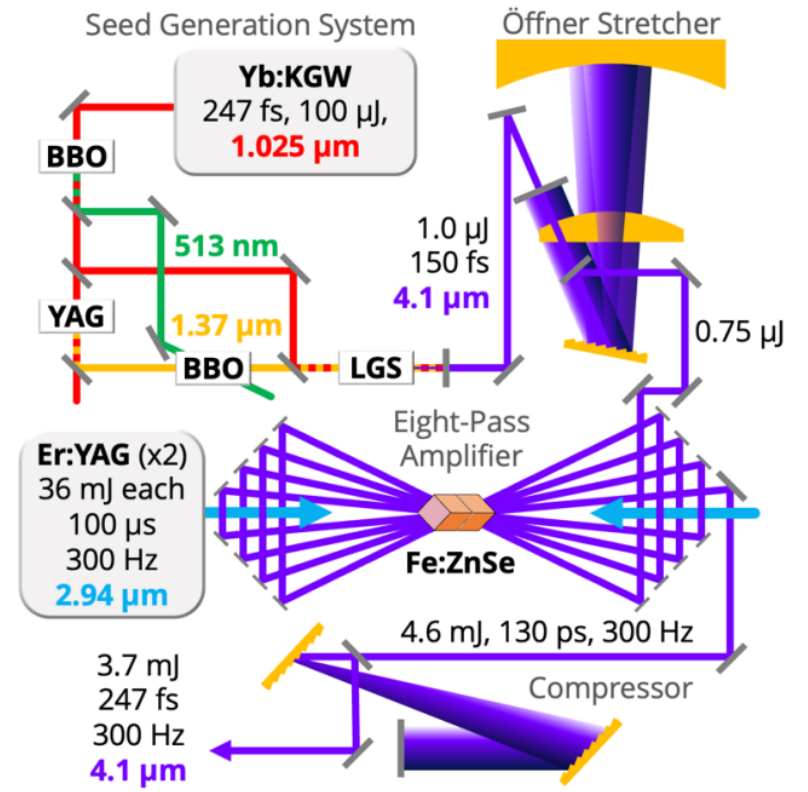
Laser drivers for HHG – Higher photon energies with longer wavelengths



3 μm

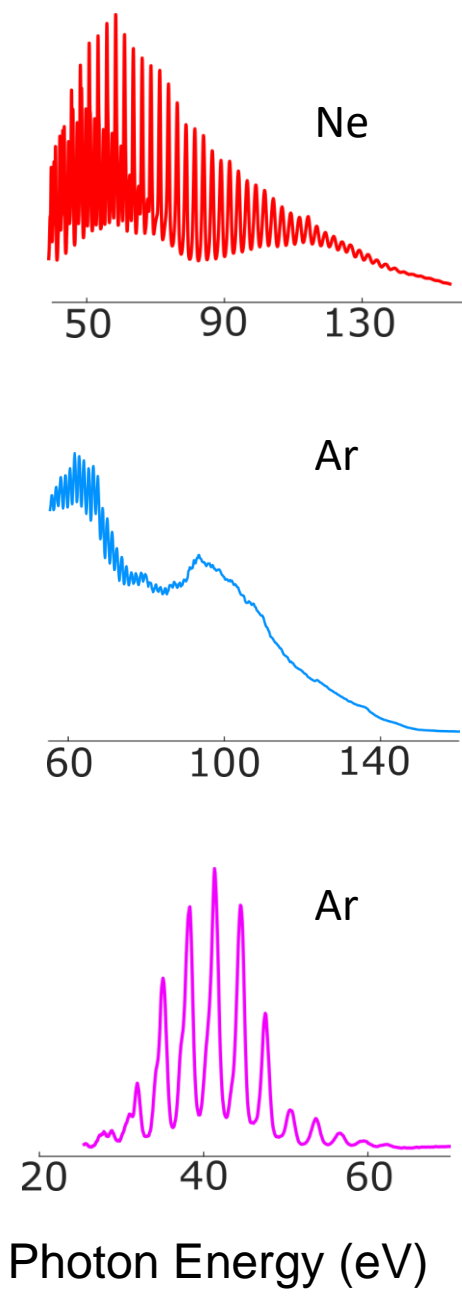
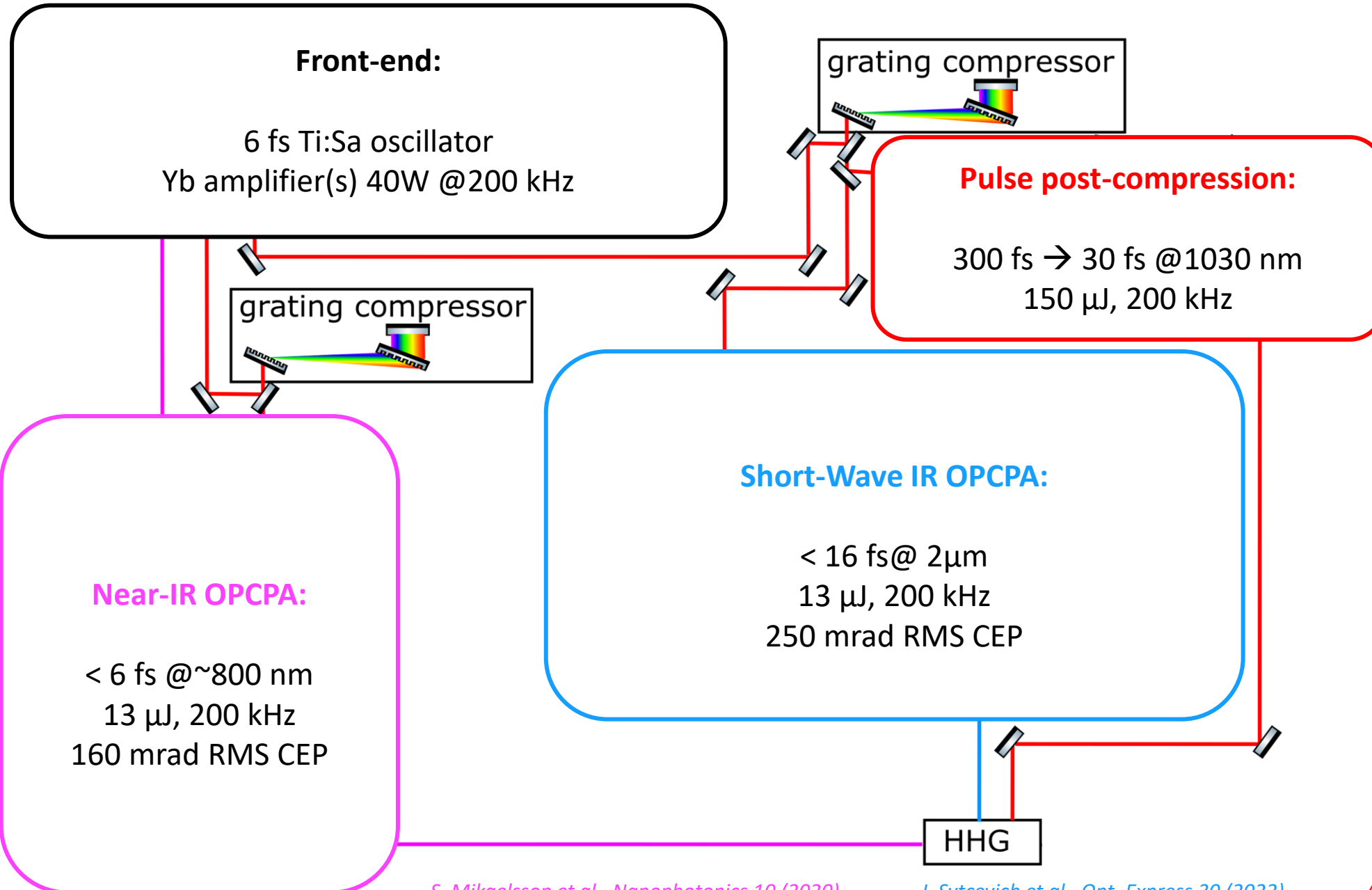


4 μm



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

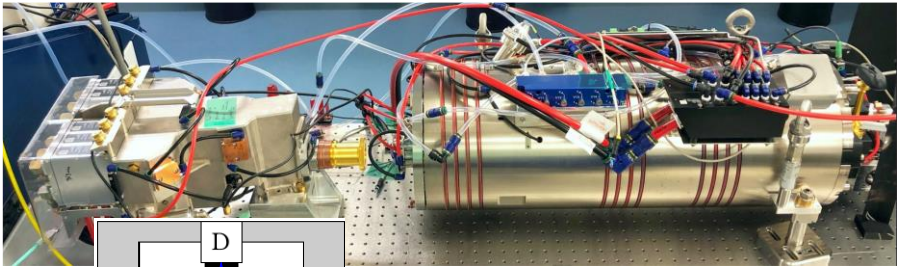


S. Mikaelsson et al., *Nanophotonics* 10 (2020).

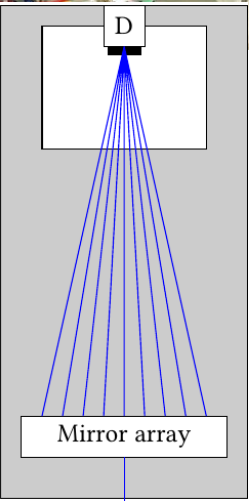
I. Sytceвич et al., *Opt. Express* 30 (2022).

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

Next-generation HHG drivers in Lund



Trumpf Laser Scientific



Thin disk
500W 200 kHz
Yb-CPA pump

Near-IR OPCPA

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

Short-Wave IR OPA

< 16 fs, 200 μ J, \sim 2 μ m, 290 mrad RMS CEP stability

Post-compressed Yb

10-30 fs, 1.5 mJ, 1030 nm

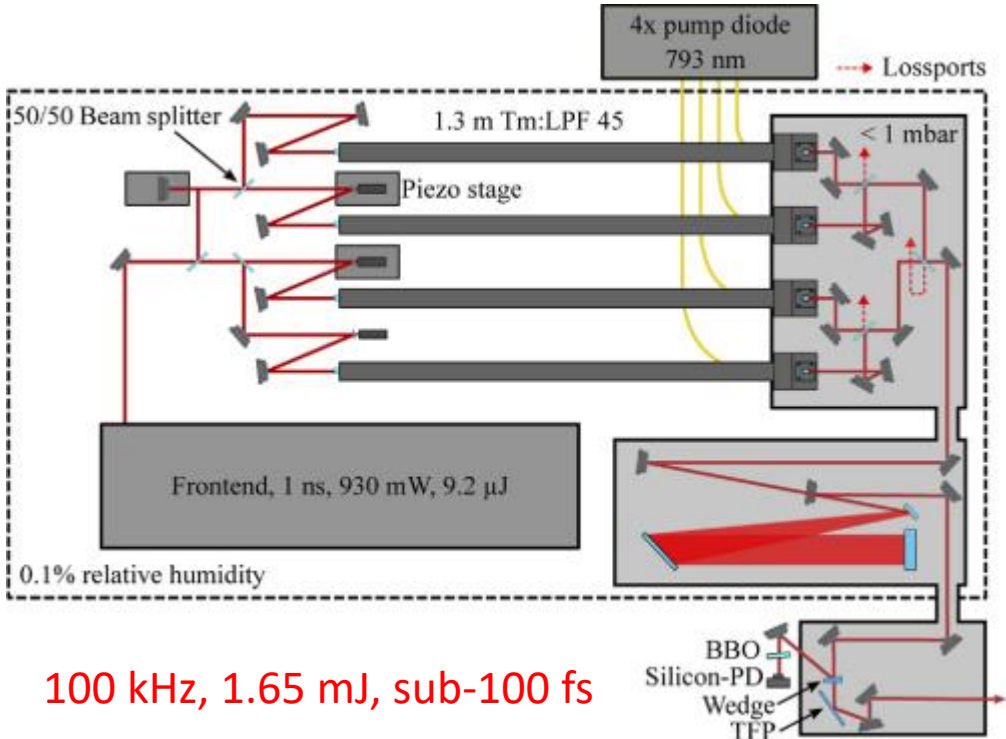


Light Conversion

New TW laser @800nm

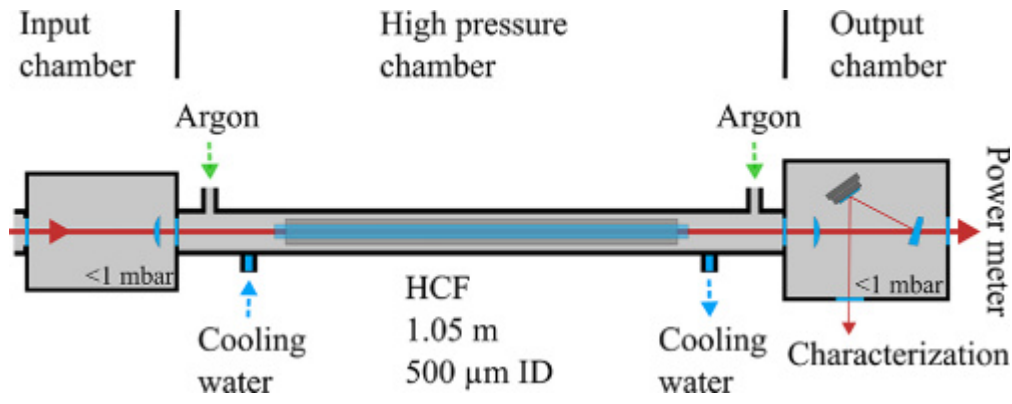
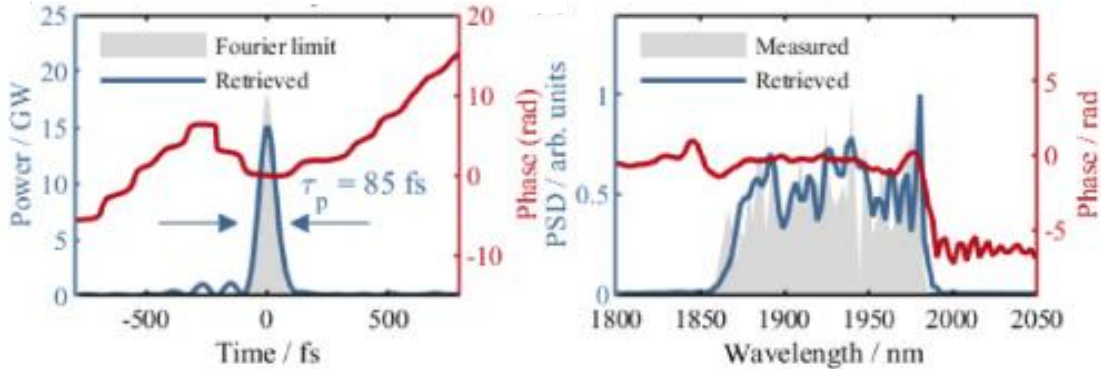
10 fs, 50 mJ, 100 Hz
10 fs, 250 mJ, 10 Hz

New key player for Attoscience?



100 kHz, 1.65 mJ, sub-100 fs

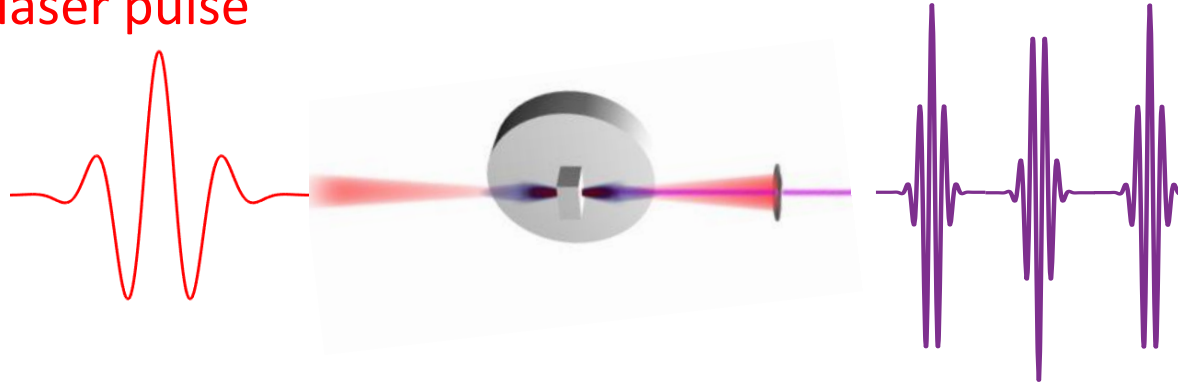
Tm fiber femtosecond laser systems



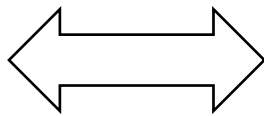
100 kHz, 1.3 mJ, 10 fs

Summary – Take home message: versatility!

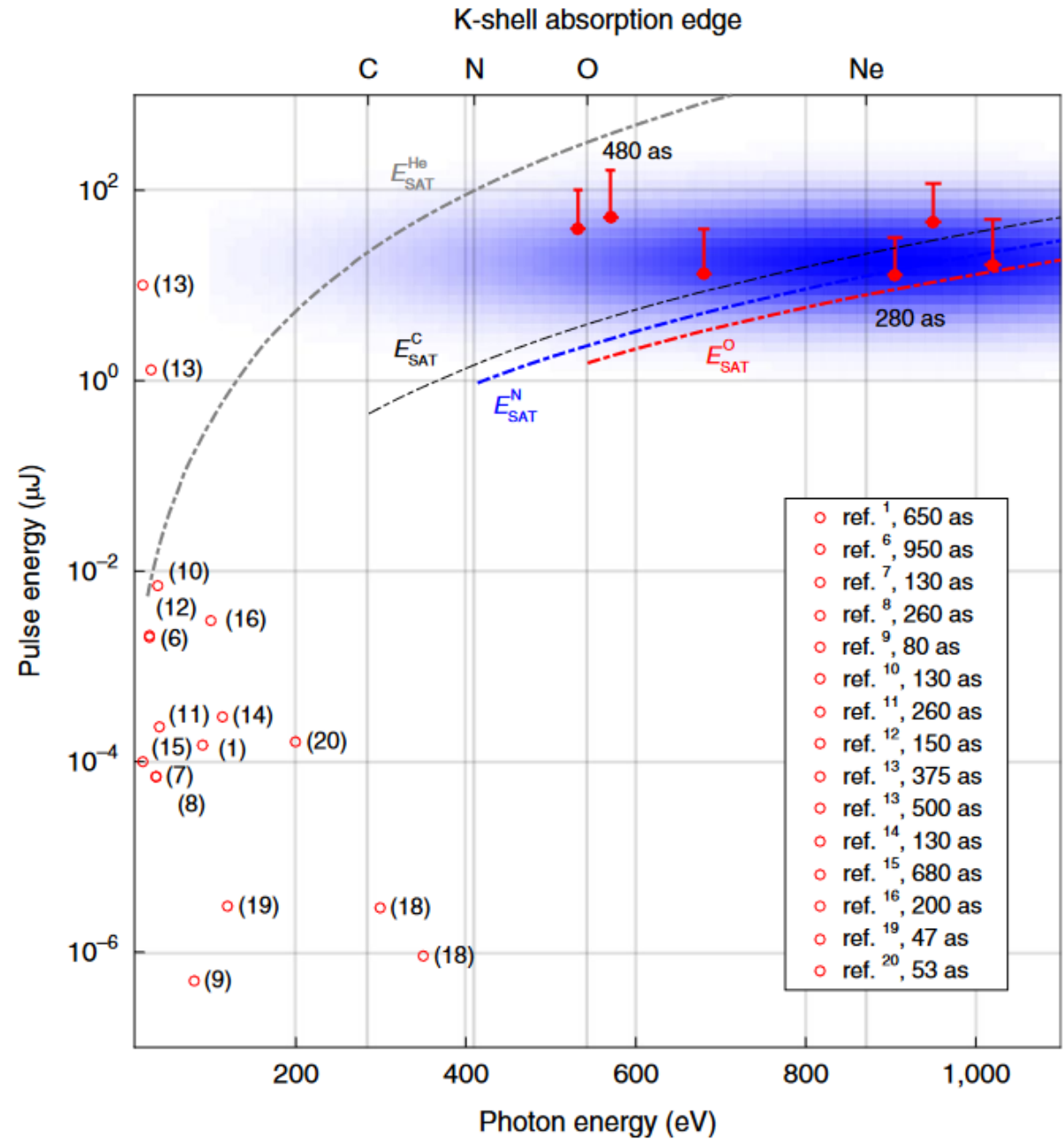
Femtosecond laser pulse



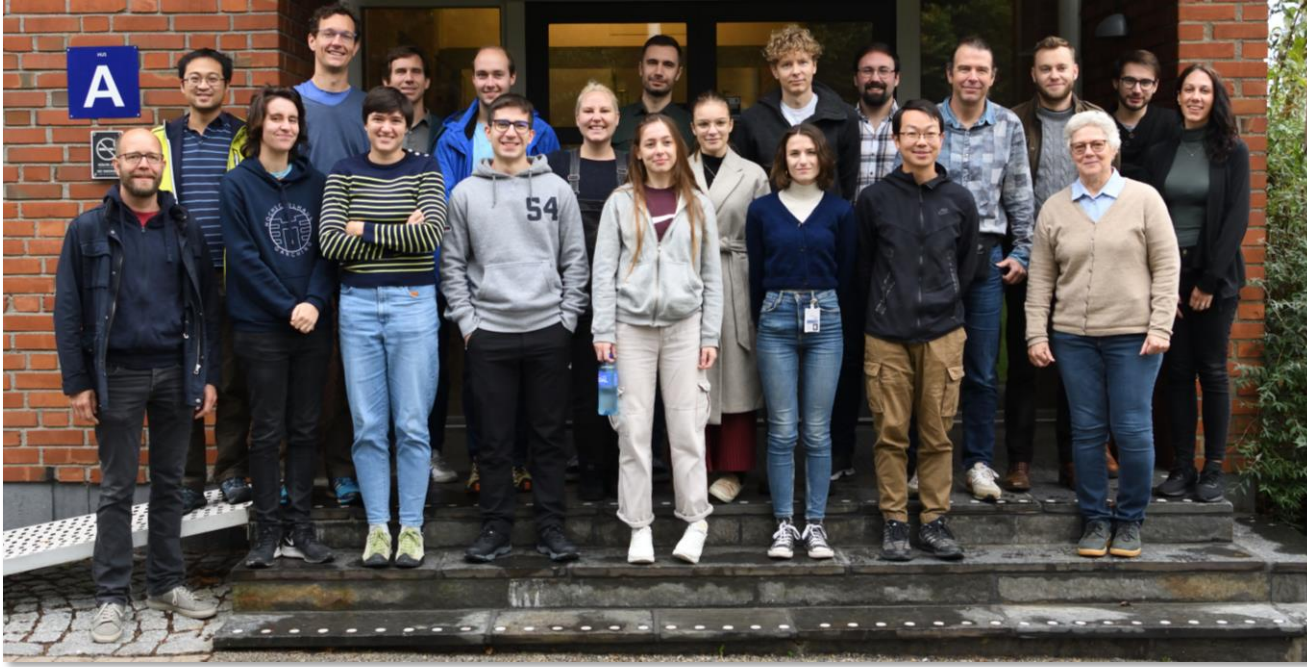
Laser driver



HHG process & XUV light properties



Team work



Attosecond Physics group @Lund University



LUND
UNIVERSITY

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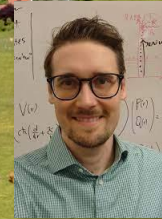
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ATTO X

The 10th International Conference on
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Back-up Slides

RABBIT technique: interferometry

