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Strong-field physics with few-cycle pulses in the MIR

eli attosecond

Matthias Kübel

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

Strong-field physics at long wavelengths

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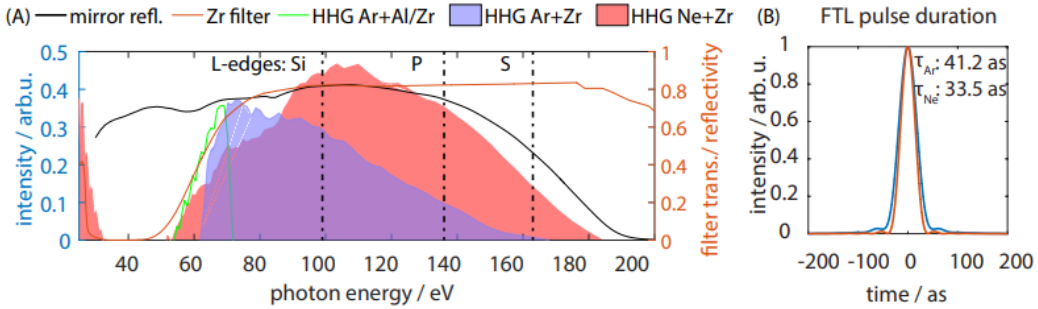
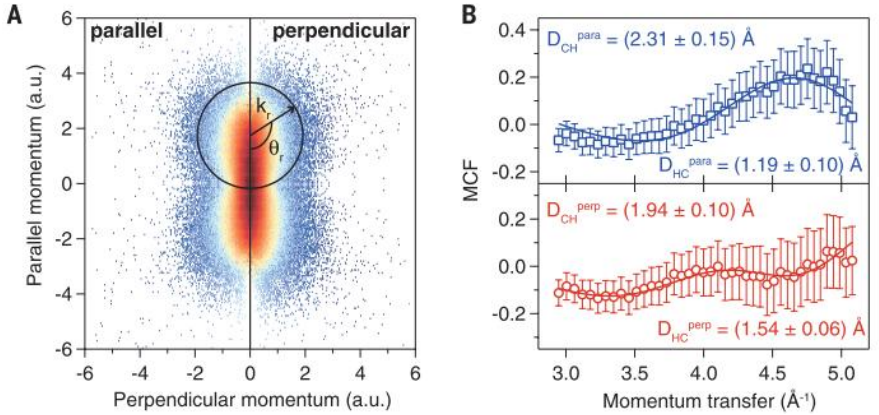
- HHG & attosecond pulses

$$U_P \propto I\lambda^2$$



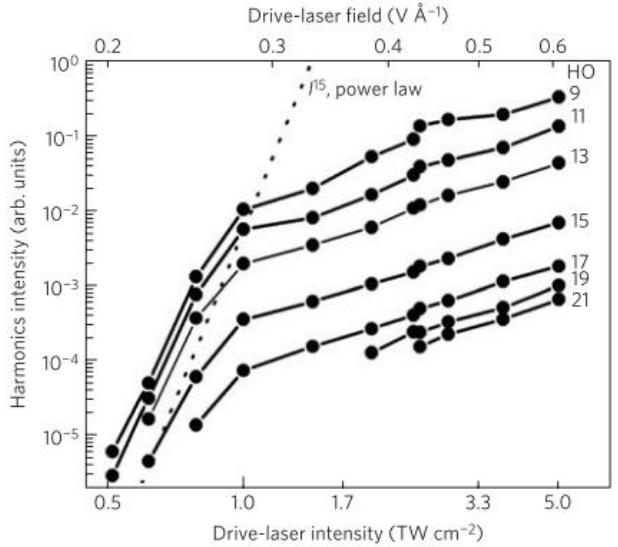
e.g. T. Gaumnitz, *et al.*,
Opt. Express **25**(22), 27506 (2017).

- Molecular imaging (LIED)



e.g., B. Wolter, *et al.*,
Science **354**, 308 (2016).

- HHG from solids (semiconductors)



e.g., S. Ghimire, et al., Nat. Phys. **7**, 138 (2011)

Laser-driven electron scattering from C_{60} – "big atom" or molecule?

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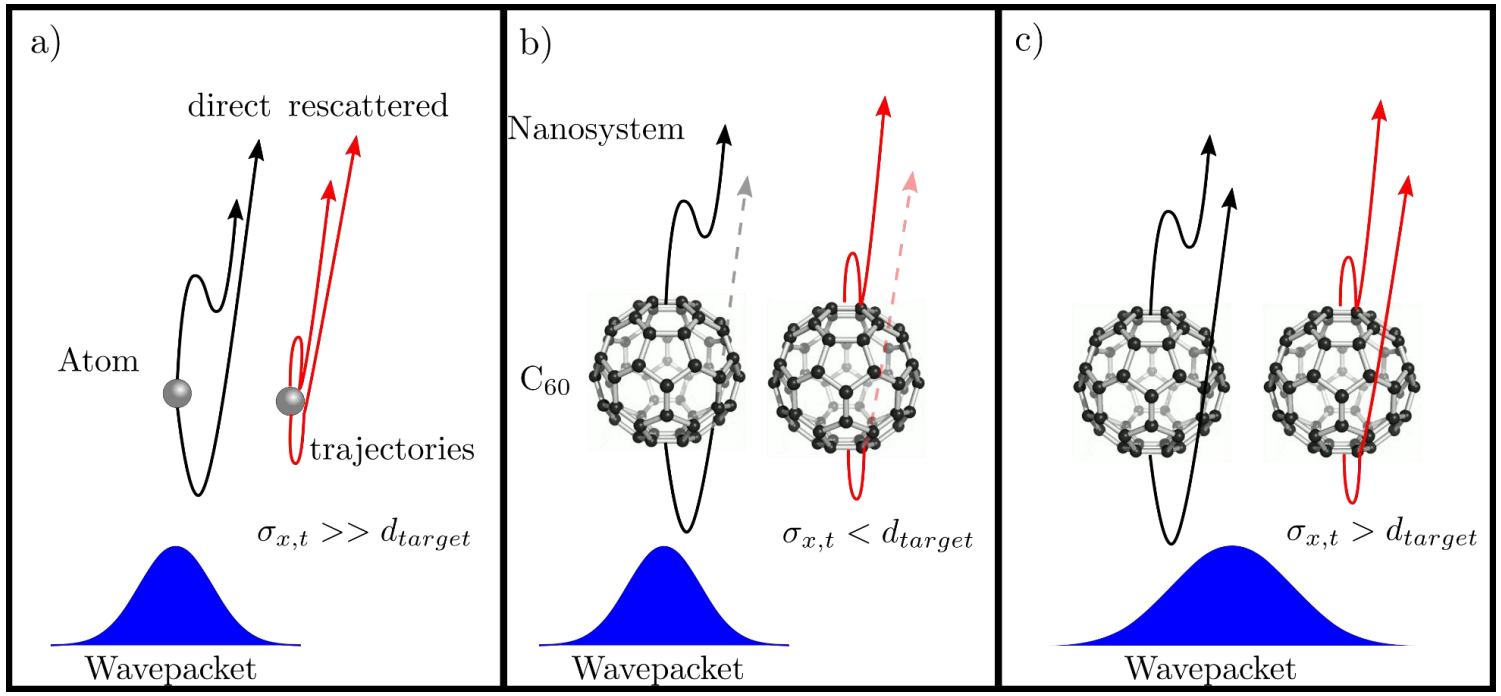
S. Skruszewicz *et al.*
in preparation (2026)



Wavepacket size at the tunnel exit

$$\sigma_{p,0} = \left(\frac{|E(t_0)|}{\sqrt{I_p}}\right)^{1/2} \qquad \sigma_{x,0} = \sigma_{p,0}^{-1}$$

Wavepacket size at the rescattering instance

$$\sigma_{x,t} = \sqrt{\sigma_{x,0}^2 + \left(\frac{\hbar t}{2\sigma_{x,0}}\right)^2}$$

LIED of electron dynamics in Xe

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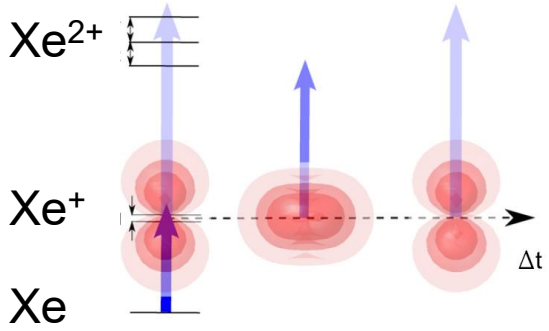
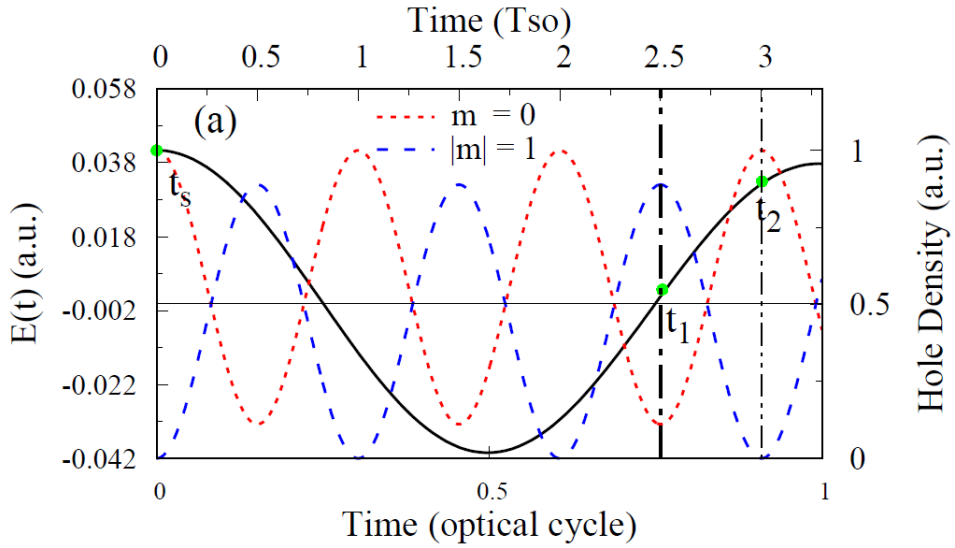


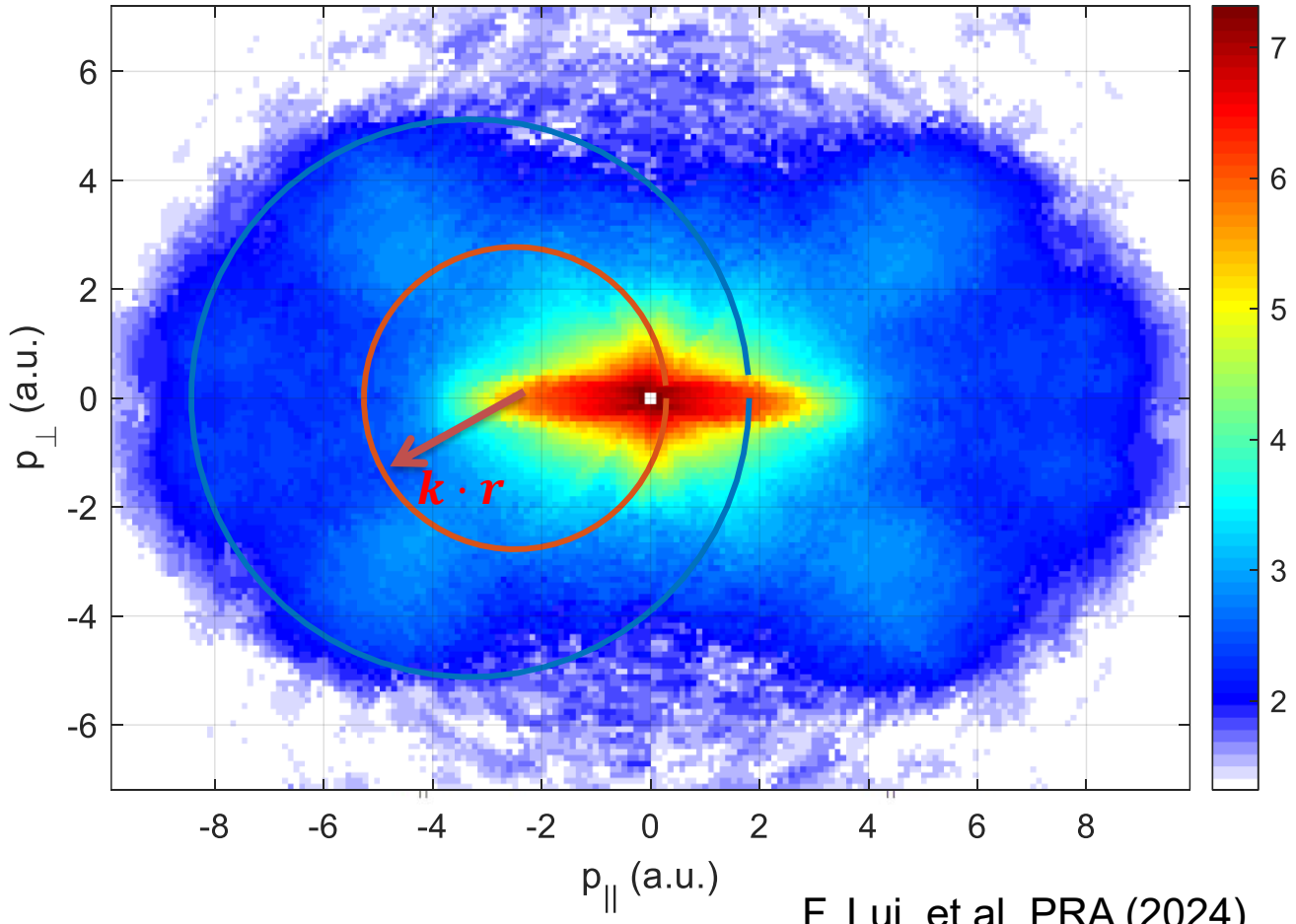
H.J. Wörner & P.B. Corkum,
J. Phys. B **44**, 041001 (2011)

~3 fs



~10 fs

Results for Kr



F. Lui, et al, PRA (2024)

Stereo-ATI measurements at 3.1 µm using Xe

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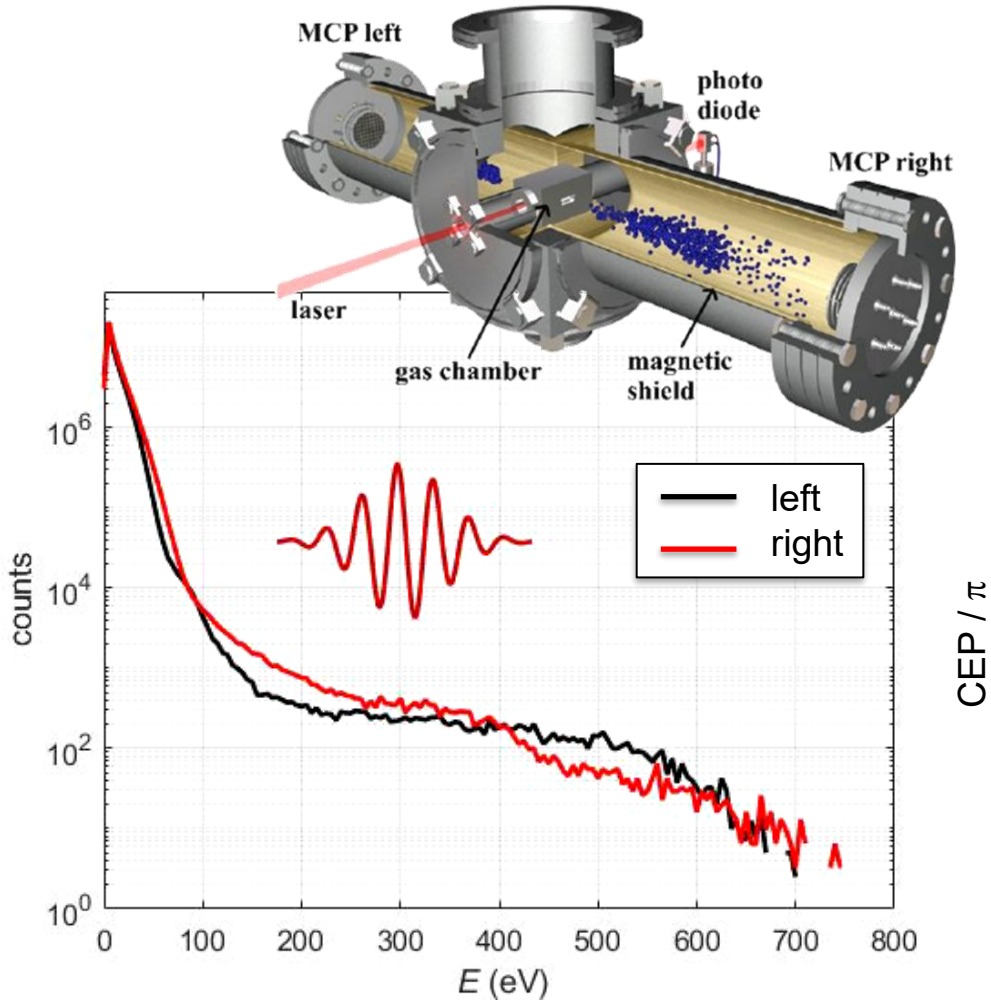
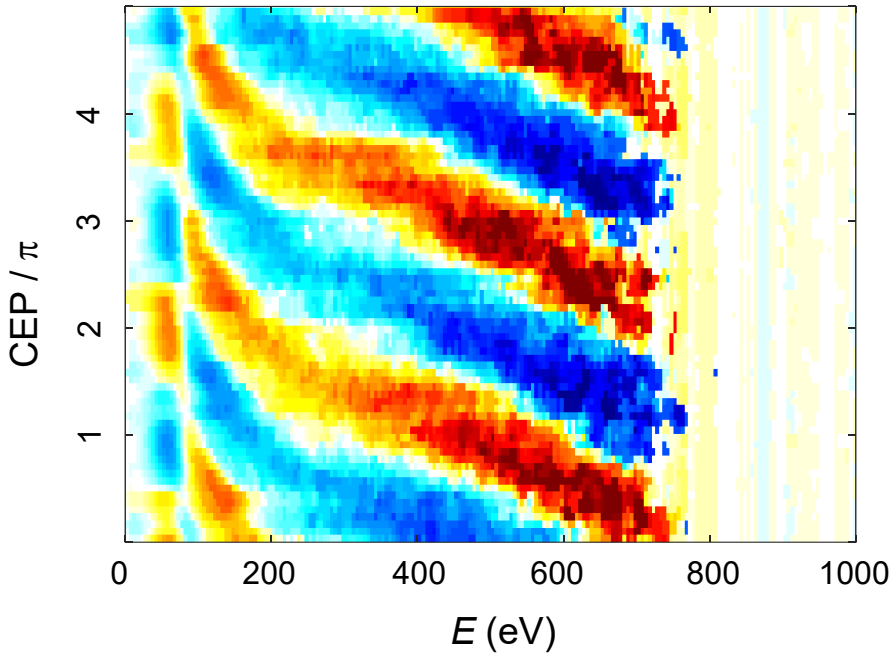
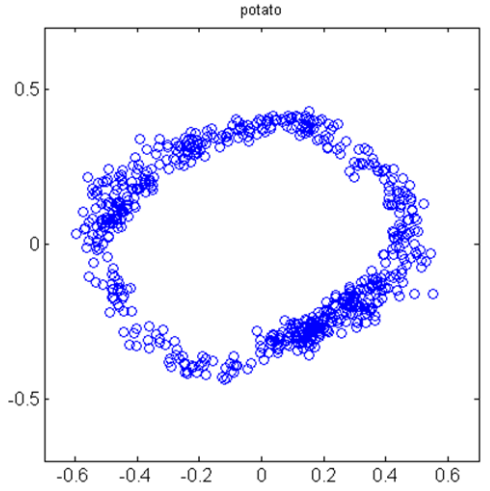
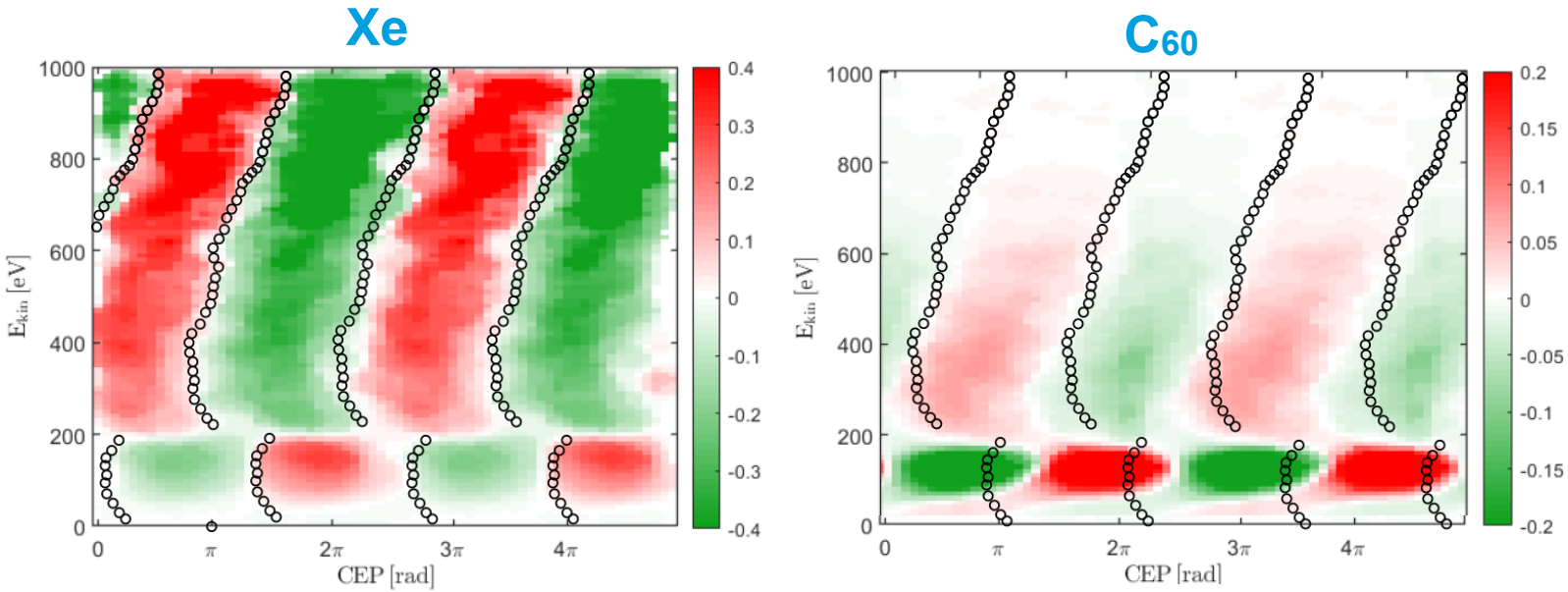






~20k laser shots per dot

Rescattering from C_{60}



Asymmetry:

$$A = \frac{Y_{LEFT}(CEP) - Y_{RIGHT}(CEP)}{Y_{LEFT}(CEP) + Y_{RIGHT}(CEP)}$$

Laser parameters:

3.1 μm, 17 fs (1.7 cycles)
I = $8 \cdot 10^{13}$ W/cm^2

Forward scattered electrons perturbed by the C_{60} cage

S. Skruszewicz *et al.*
in preparation (2026)

CEP dependence, Cesium, 3.1 µm, 30 fs

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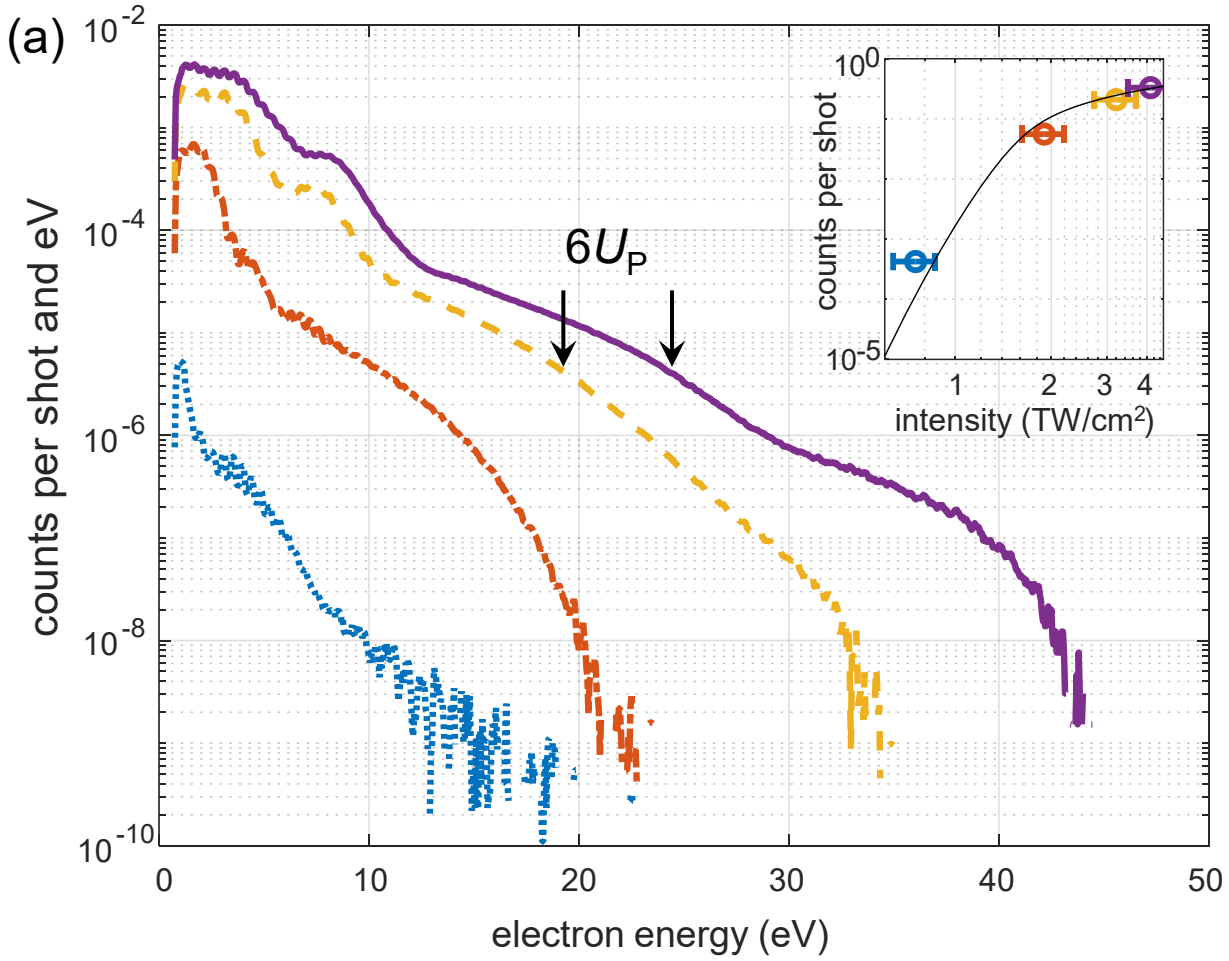

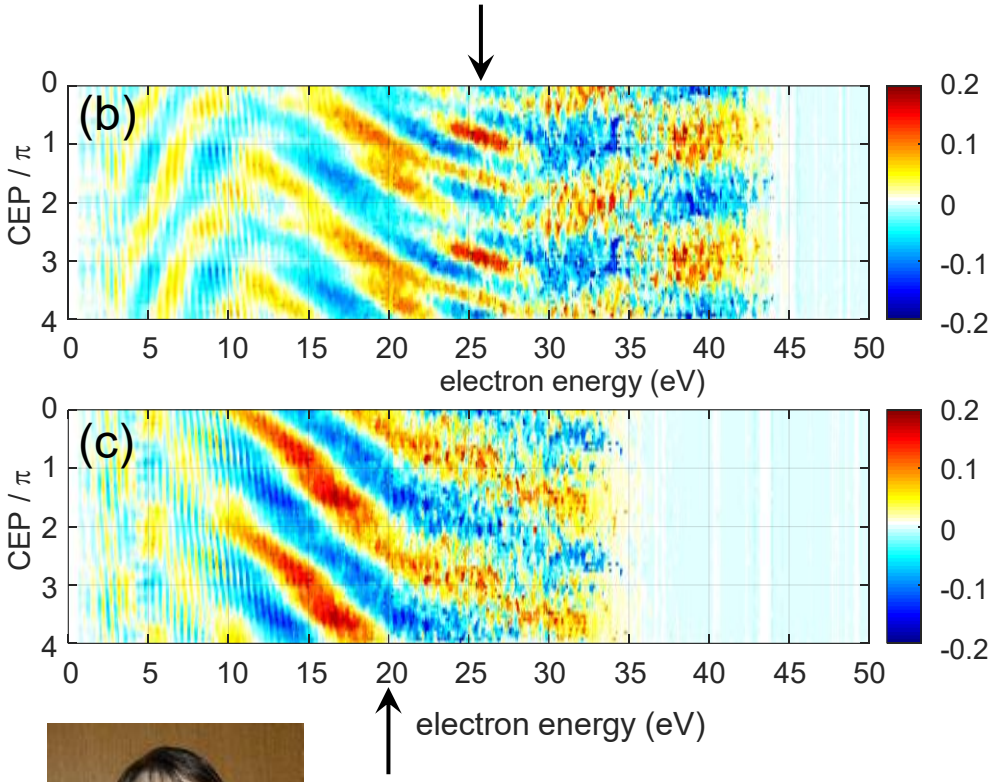

D. Milosevic

MK, et al., PRL (2021)

CEP measurements using HHG from solids

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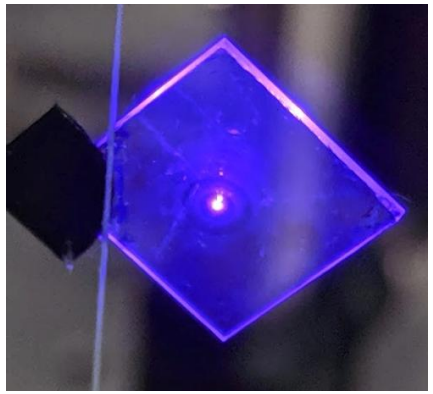
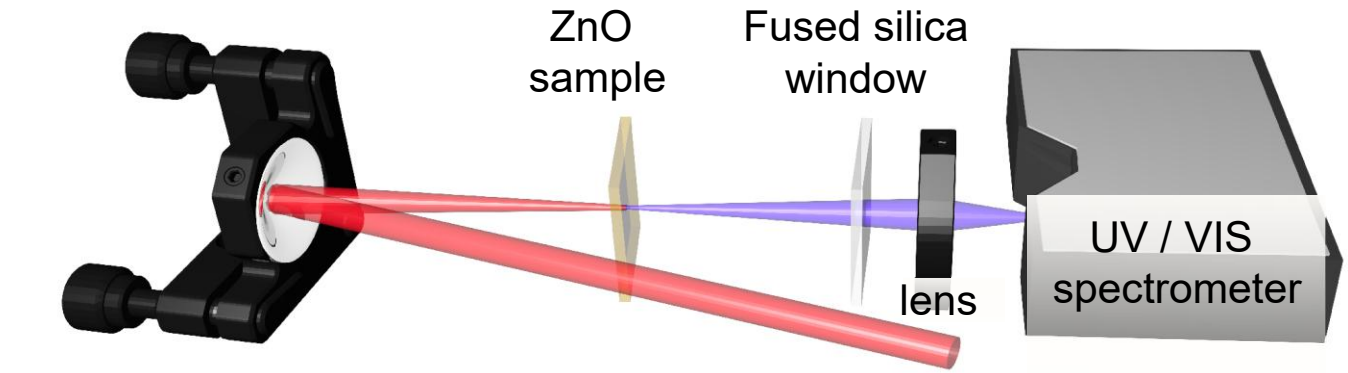
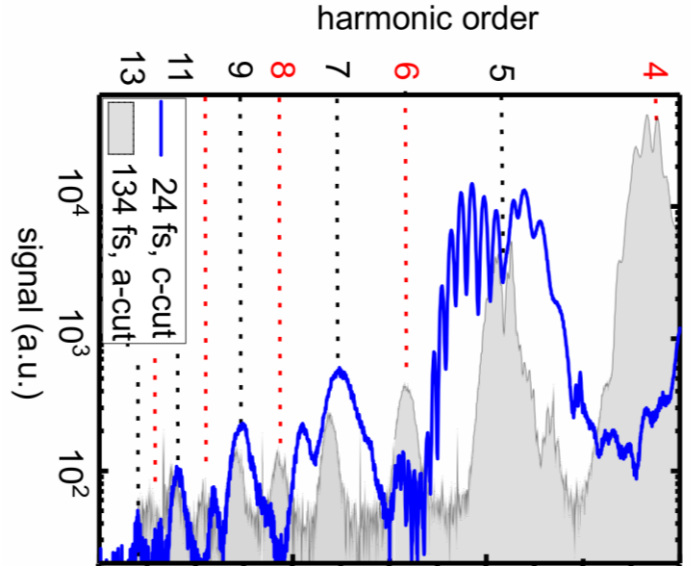
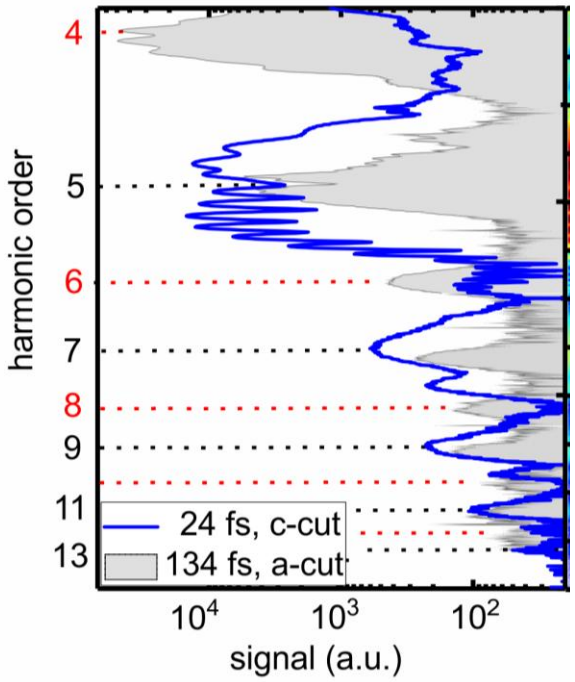




Laser:
3.1 µm, 25 fs, 10 µJ, 100 kHz



Hollinger, R. *et al. Opt Express* **28**, 7314 (2020)



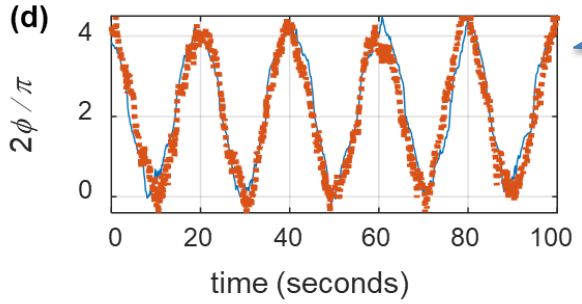
$\Delta\phi = \phi_5 - \phi_3$

$\Delta\phi = \phi_7 - \phi_5$

$\Delta\phi = \phi_9 - \phi_7$

…

$\Delta\phi = \phi_n - \phi_{n-2}$



Relative phase of 7th and 9th harmonic
→ $\Delta\phi = \phi_9 - \phi_7 = 2 \times \mathrm{CEP}$

Hollinger, R. *et al. Opt Express* **28**, 7314 (2020)

On-target pulse characterization in solid-HHG

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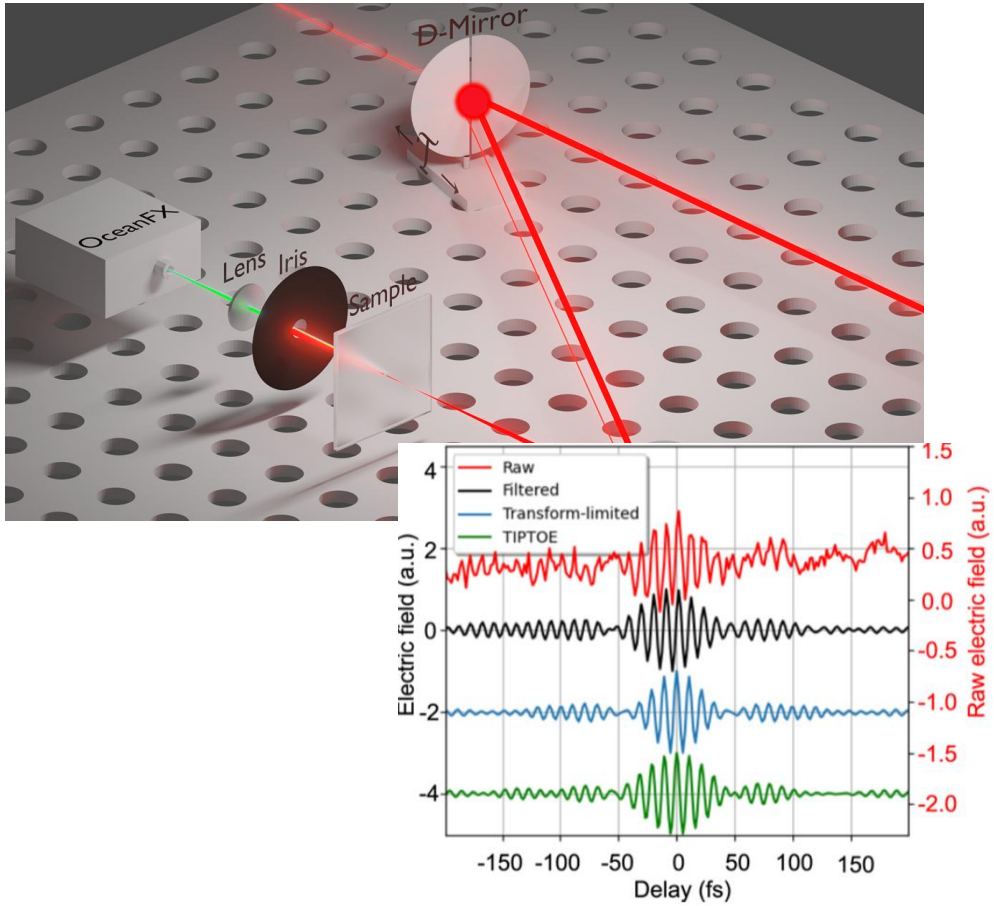

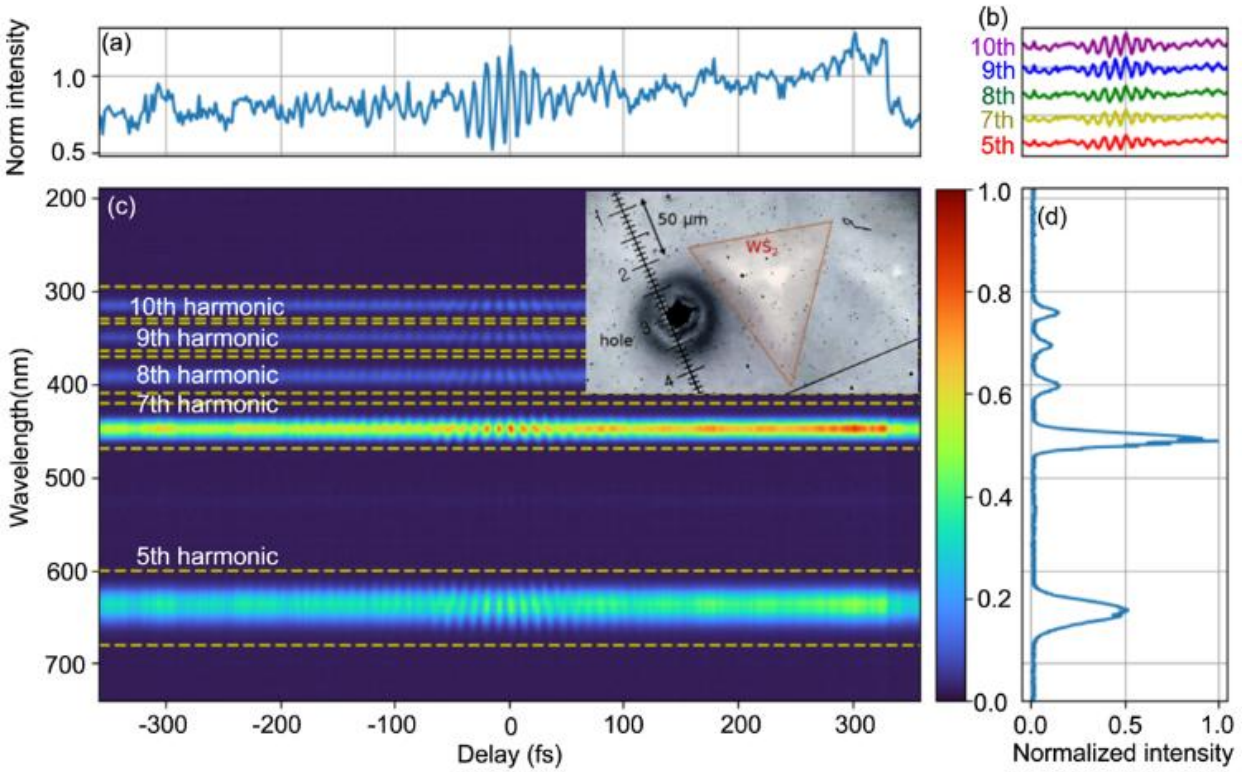

Work in progress: HHG interometery

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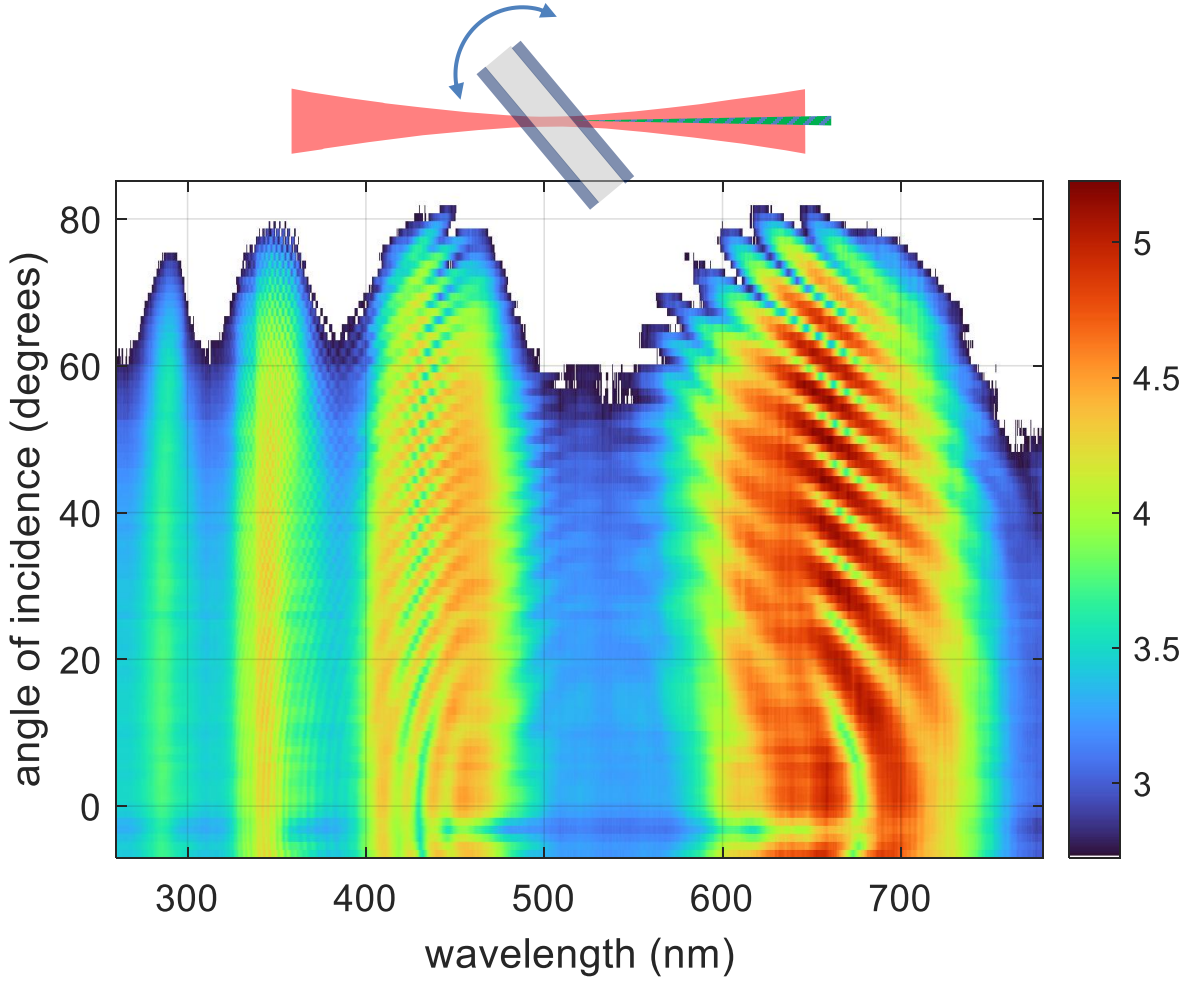

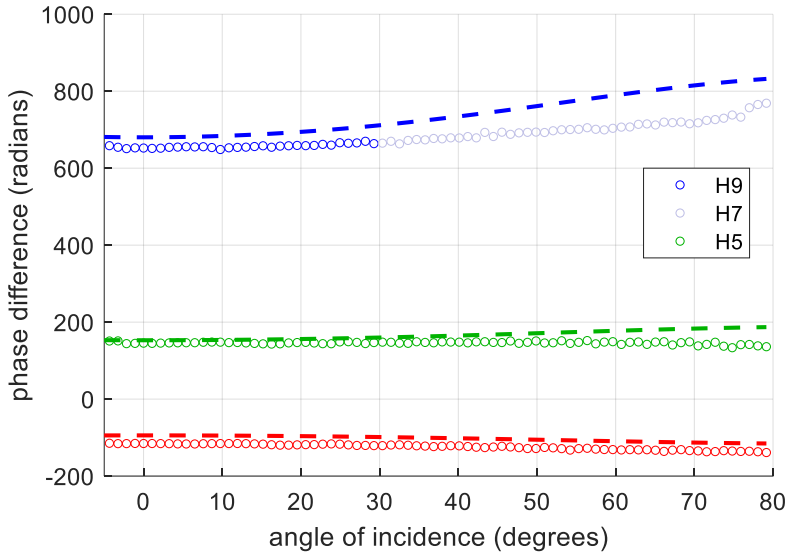

M. Awad, et al. *in preparation*

Thanks to

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Tamás Csizmadia
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Eric Comier

U Sarajevo

Dejan Milosevic
Benjamin Fetic

… and many more

HI JENA HELMHOLTZ

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eli attosecond

Thank you for your attention!

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

DFG

QUTIF

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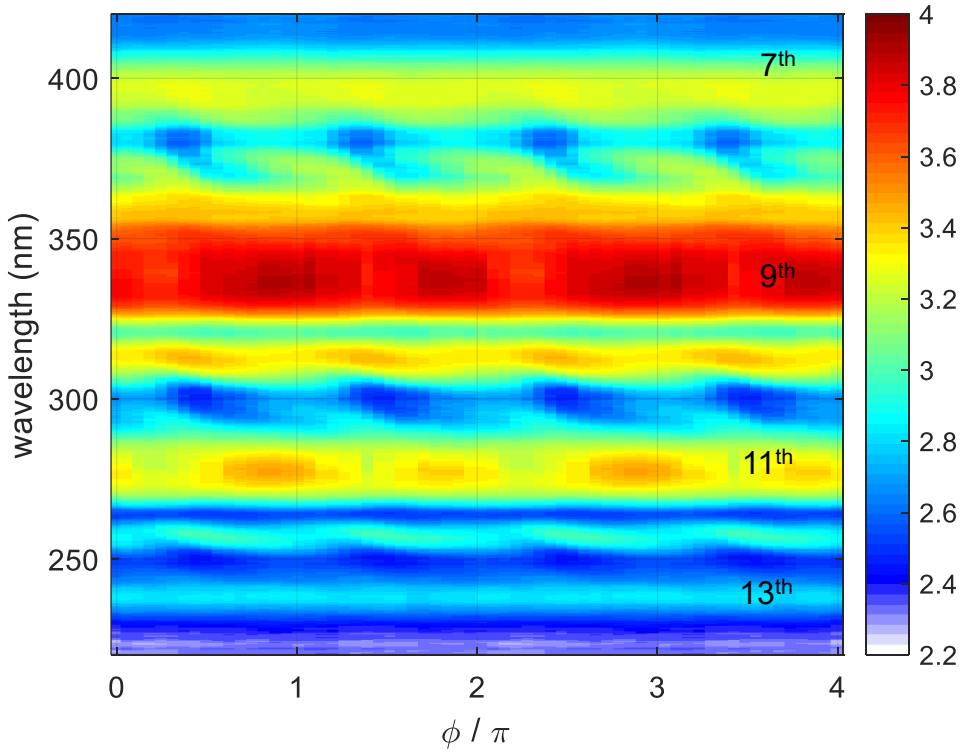
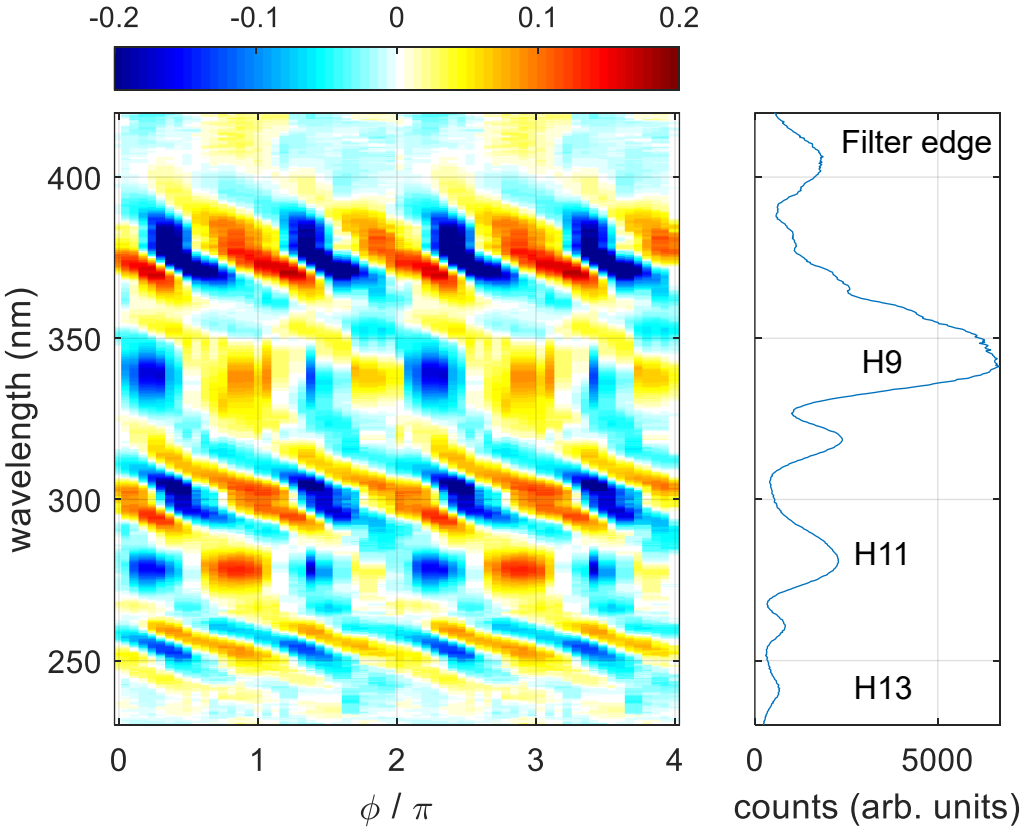
Logarithmic signal



Normalized signal



Scaling strong-field interactions: from Xe to Cs

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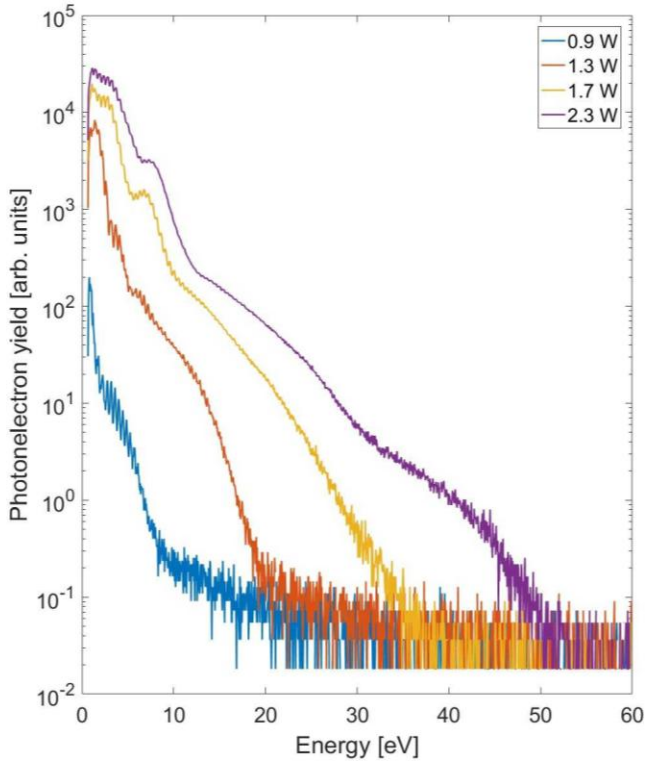
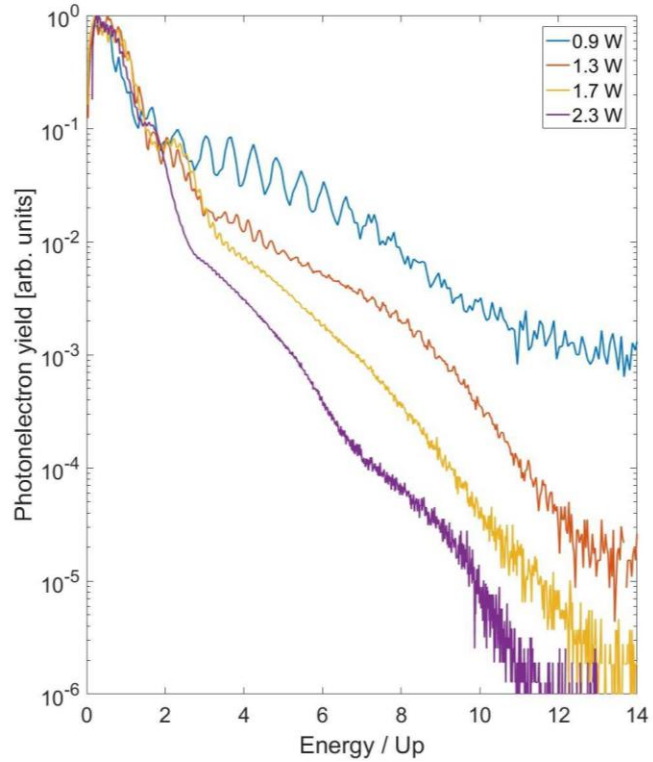
	Xe, 800 nm, 1×10^{14} W/cm²	Cs, 3100 nm 2×10^{12} W/cm²
U_P / eV	6	2
I_P / eV	12.1	3.9
$\gamma = \sqrt{\frac{I_P}{2U_P}}$	1	1
I_{BS} / W/cm²	8.6×10^{13}	9.2×10^{11}
I / I_{BS}	~1	~2





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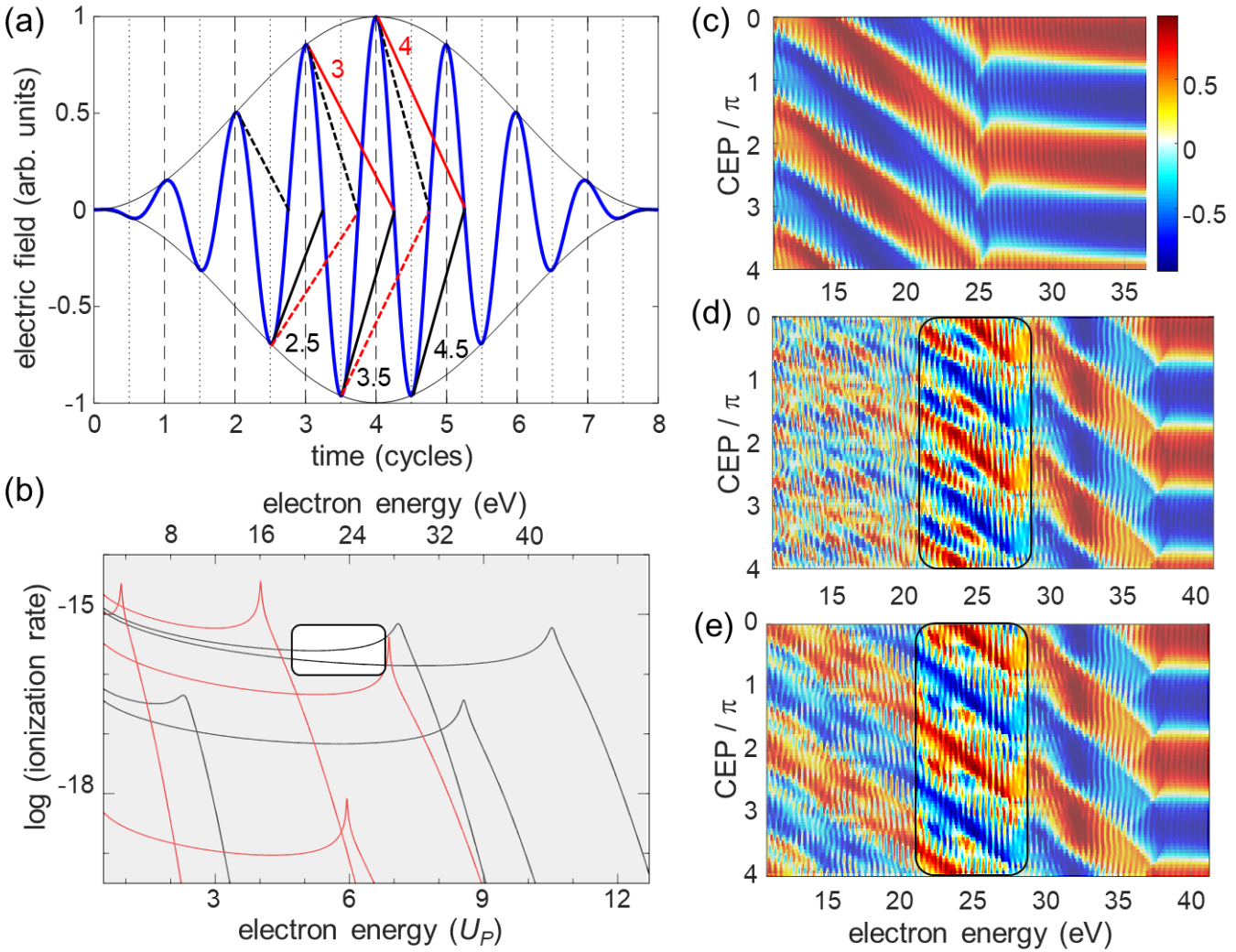

Overview

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Overview:

- Photoelectron spectroscopy:
  - ➢ Stereo-ATI CEP meter experiments — D. Hoff, et al., *unpublished*
  - ➢ CEP-dependent photoionization of C_{60} — S. Skruczewicz, et al., *to be published*
  - ➢ LIED in Xenon — F. Lui, et al, PRA (2024)
  - ➢ High-order CEP-dependent asymmetry in ATI of Cs — MK, et al., PRL (2021)
- HHG from solids
  - ➢ CEP measurements using HHG from ZnO — R. Hollinger, et al., Opt. Exp (2020)
  - ➢ HHG-TOE: Pulse characterization using HHG — M. Awad, et al., Opt. Exp (2024)
  - ➢ HHG interferometry — M. Awad. et al., *in preparation*
- Coincidence experiments using RABBITT — S. Hell, *work in progress*