Strong-field ionization beyond the long-wavelength limit of the dipole approximation

Jochen Maurer[1], André Ludwig[1], Benedikt W. Mayer[1], Christopher R. Phillips[1],
Lukas Gallmann[2] and Ursula Keller[1]

[1]Department of Physics, Institute for Quantum Electronics, ETH Zurich, Switzerland

[2]Institute of Applied Physics, University of Bern, Switzerland

Conference on Extremely High Intensity Laser Physics, Heidelberg, July 22nd 2015

The electric dipole approximation

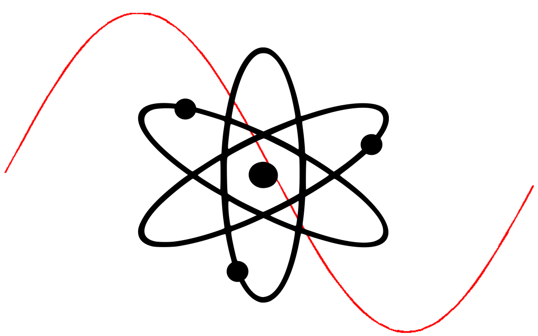
Dipole approximation: the spatial variation of the radiation field can be neglected over the target:

→ vector potential $\vec{A}$ spatially uniform

→ consequence for magnetic field: $\vec{B}(t) = \nabla \times \vec{A}(t) = 0$

<u>Short wavelength limit:</u>

- The spatial variation of the electric field over the target becomes relevant



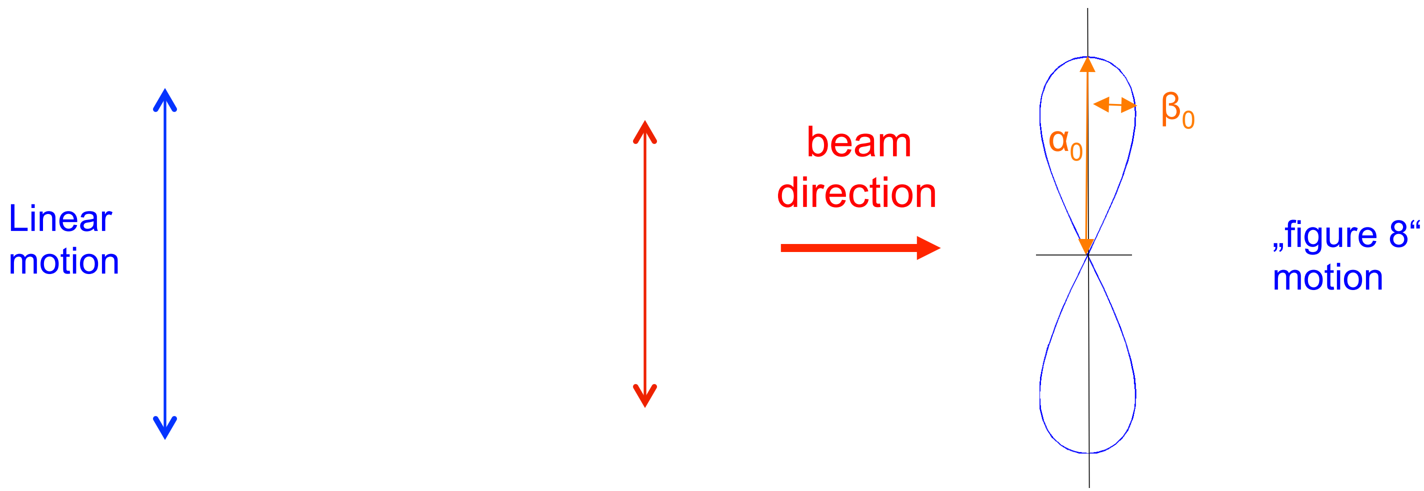
<u>Long wavelength limit</u>

- In strong field ionization: electron dynamics mainly governed by EM field of ionizing laser
- Lower frequency → higher kinetic energy of electron
- Onset of magnetic field effects due to Lorentz force $\vec{F} \propto \vec{v}/c \times \vec{B}$

Dipole approximation in strong field ionization

Strong field ionization: the electron dynamics during the ionization process mainly governed by radiation field → characterization by the case of a free electron

Schematic of the classical motion of a free electron in a linearly polarized laser field in the frame of reference where the electron is on average at rest:



Dipole approximation

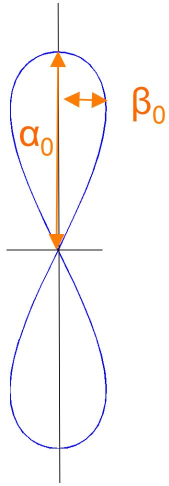
Polarization of the laser field

Beyond dipole approximation including the magnetic field component

Dipole approximation valid for most experiments at 800 nm

→Study of the ionization at longer wavelengths with 3.4 μm

Dipole approximation in strong field ionization



Parameters for the quantification of the effect of the magnetic field and special relativity:

$$z_f = \frac{2U_p}{mc^2}$$

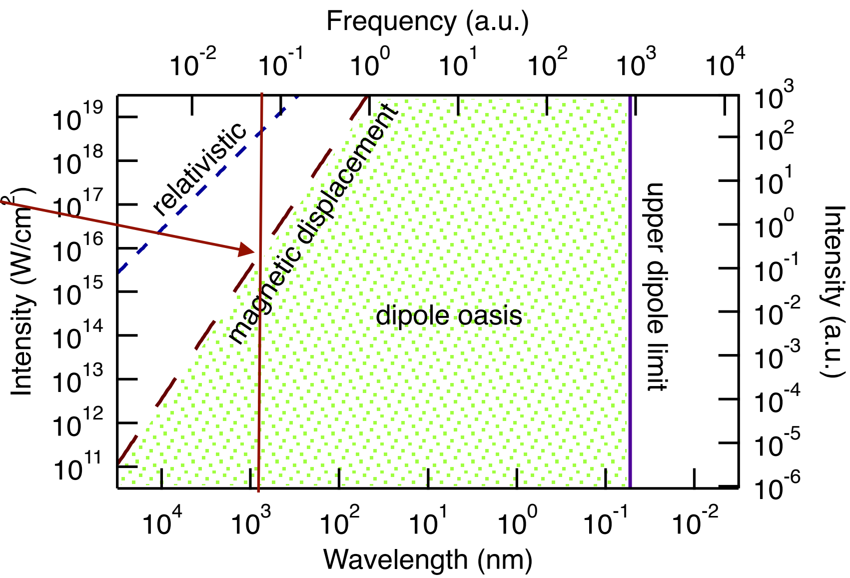
Measure for the onset of relativistic behaviour

$$\beta_0 = \frac{U_p}{2\omega c(1+z_f)} \approx \frac{U_p}{2\omega c} \propto \frac{I}{\omega^3}$$

Measure for influence of magnetic field component

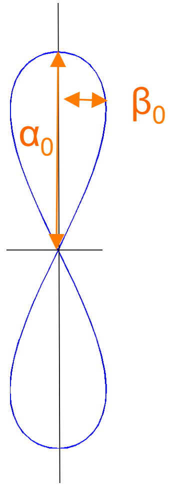
Most experiments are performed at 800 nm,

→ well below the line of $\beta_0 = 1$



H. R. Reiss, PRL **101,** 043002 (2008)

Dipole approximation in strong field ionization



Parameters for the quantification of the effect of the magnetic field and special relativity:

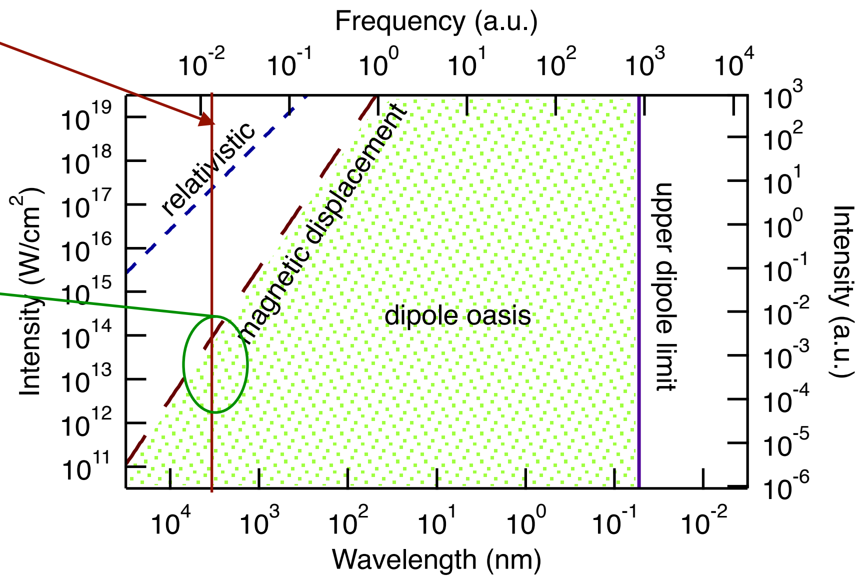
$$z_f = \frac{2U_p}{mc^2}$$

Measure for the onset of relativistic behaviour

$$\beta_0 = \frac{U_p}{2\omega c(1+z_f)} \approx \frac{U_p}{2\omega c} \propto \frac{I}{\omega^3}$$

Measure for influence of magnetic field component

3.4 µm



For $\beta_0 = 1$: I =9x10^{13} W/cm^2 for 3.4 µm

→We want to study this intensity range to observe the onset of magnetic field effects

H. R. Reiss, PRL **101,** 043002 (2008)

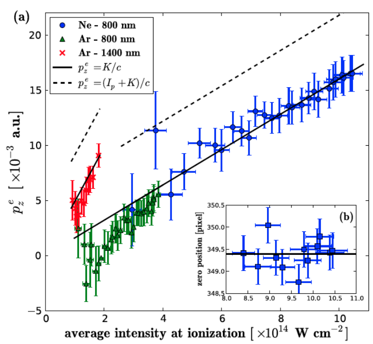
ETH zürich

A selection of recent studies

PRL **106**, 193002 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

Partitioning of the Linear Photon Momentum in Multiphoton Ionization

C. T. L. Smeenk,[1] L. Arissian,[1,2,*] B. Zhou,[3] A. Mysyrowicz,[3] D. M. Villeneuve,[1] A. Staudte,[1] and P. B. Corkum[1]
[1]*JASLab, University of Ottawa and National Research Council, 100 Sussex Drive, Ottawa, Canada*
[2]*Department of Physics, Texas A&M University, College Station, Texas, USA*
[3]*Laboratoire d'Optique Appliqué, ENSTA ParisTech–École Polytechnique, 91761 Palaiseau, France*
(Received 2 February 2011; published 10 May 2011)



- Circularly polarized light ⟷ Linearly polarized light
- λ = 800 nm, 1400 nm ⟷ λ = 3400 nm
- Influence of radiation pressure ⟷ Full electron dynamics in electromagnetic field + Coulomb interaction

Our experiment:
Linearly polarized light
λ = 3400 nm
Full electron dynamics in electromagnetic field + Coulomb interaction

Related theoretical work:

PHYSICAL REVIEW A **87**, 033421 (2013)

Relativistic effects in nonrelativistic ionization

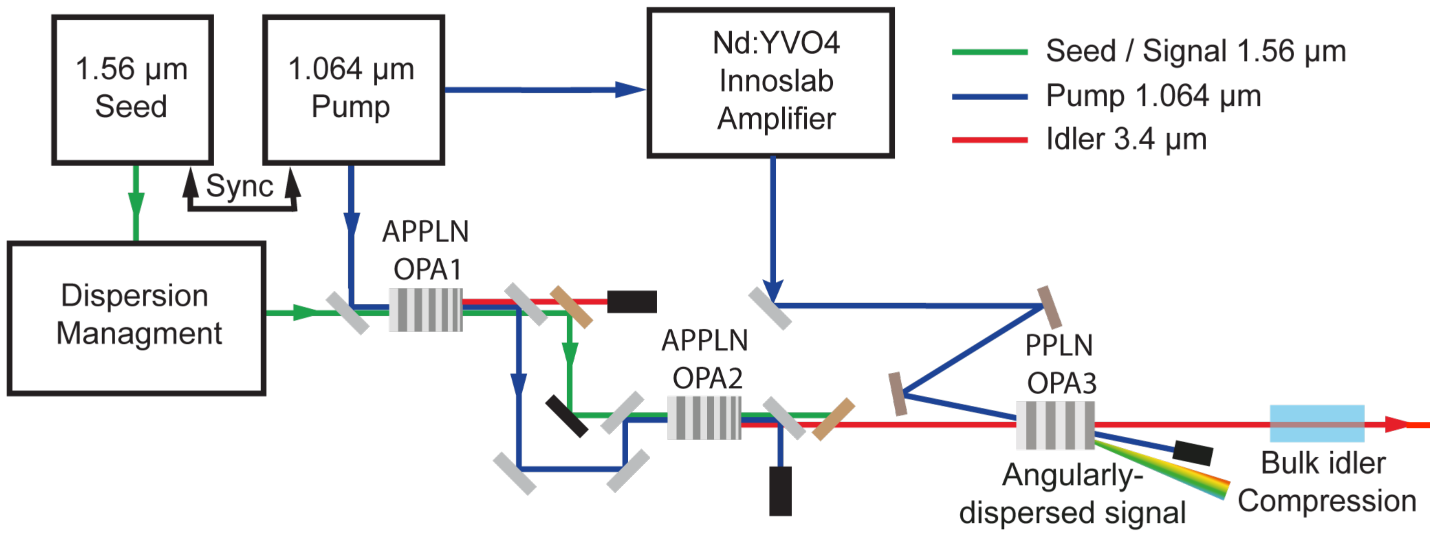
H. R. Reiss
Max Born Institute, 12489 Berlin, Germany, and American University, Washington, D.C. 20016-8058, USA
(Received 11 December 2012; published 27 March 2013)

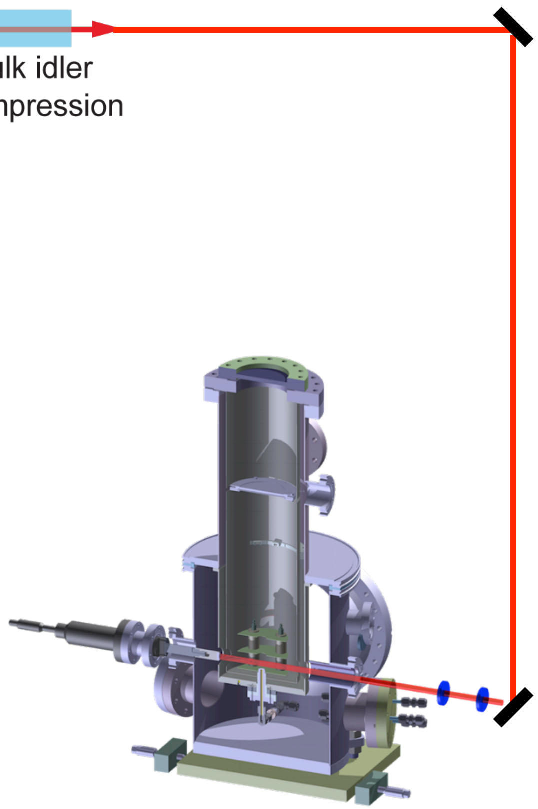
PHYSICAL REVIEW A **85**, 041404(R) (2012)

Quantum theory of longitudinal momentum transfer in above-threshold ionization

A. S. Titi* and G. W. F. Drake†
Department of Physics, University of Windsor, Windsor, Ontario, Canada N9B 3P4
(Received 29 January 2012; published 23 April 2012)

Laser System



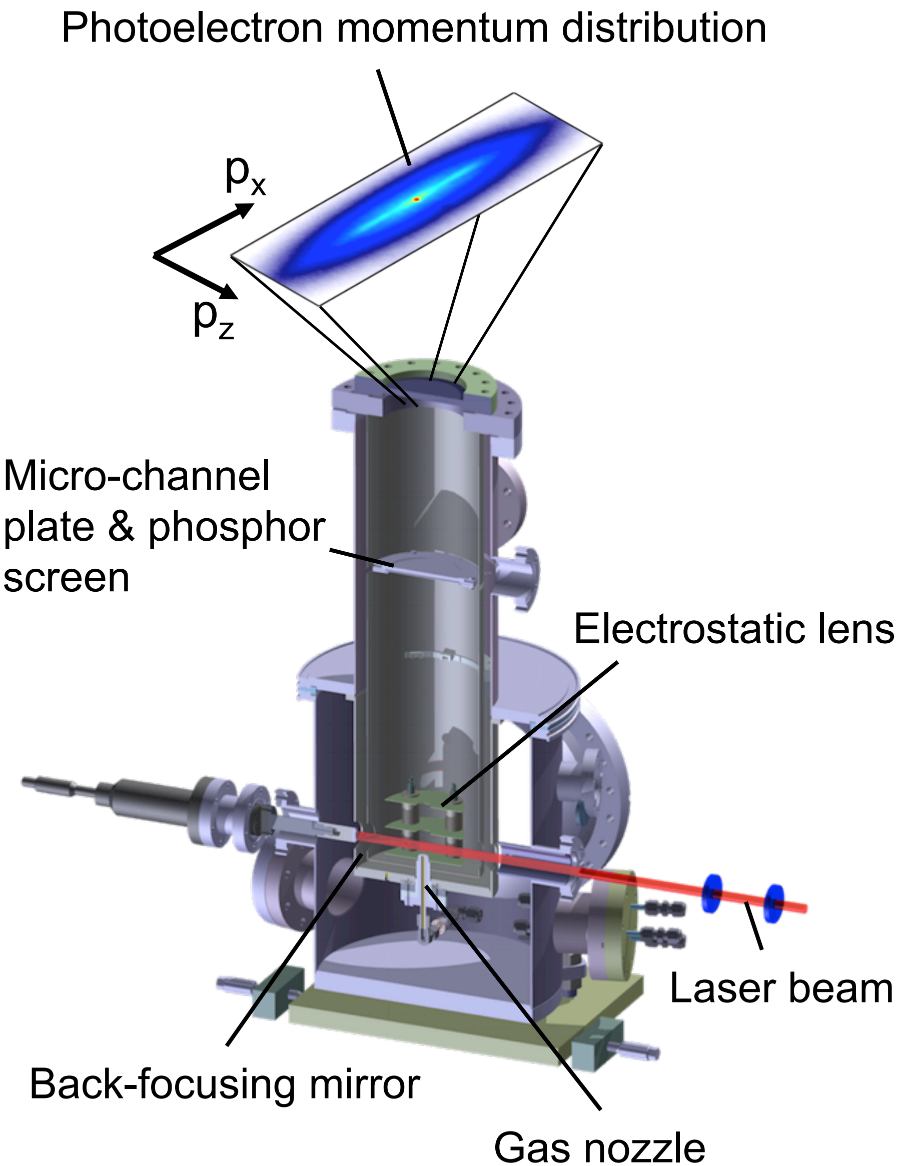


State-of-the-art **mid-IR OPCPA** source

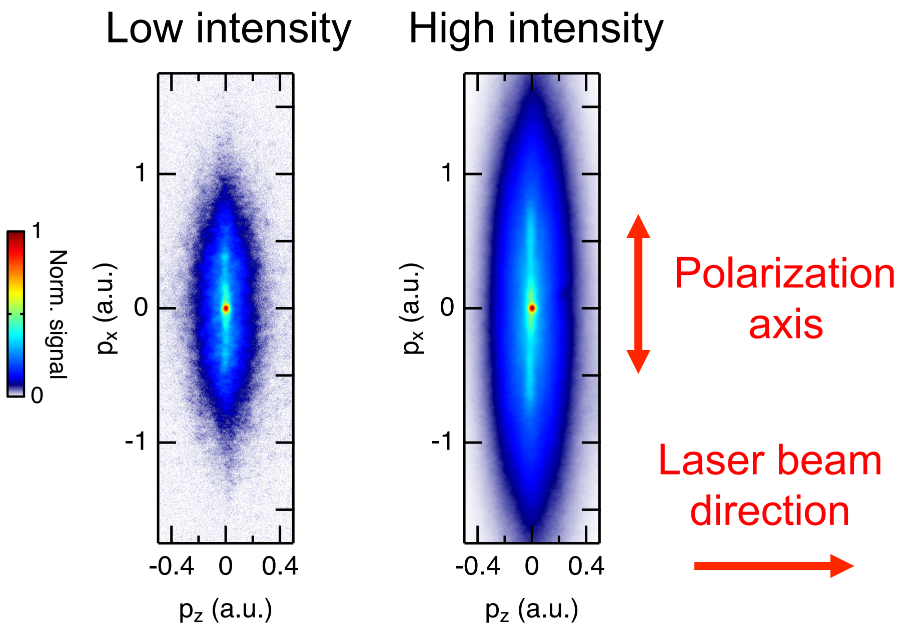
- **3.4 μm** wavelength
- **44 fs** pulse duration
- **21.8 μJ** pulse energy
- **50 kHz** repetition rate

B.W. Mayer, C. R. Phillips, L. Gallmann, and U. Keller, Opt. Express 22, 20798 (2014)
B.W. Mayer, C. R. Phillips, L. Gallmann, M. M. Fejer, and U. Keller, Opt. Lett. 38, 4265 (2013)

Experimental Setup



- Velocity Map Imaging Spectrometer (VMIS)
- Ionization of noble gases
- Acquisition of photoelectron momentum distributions:

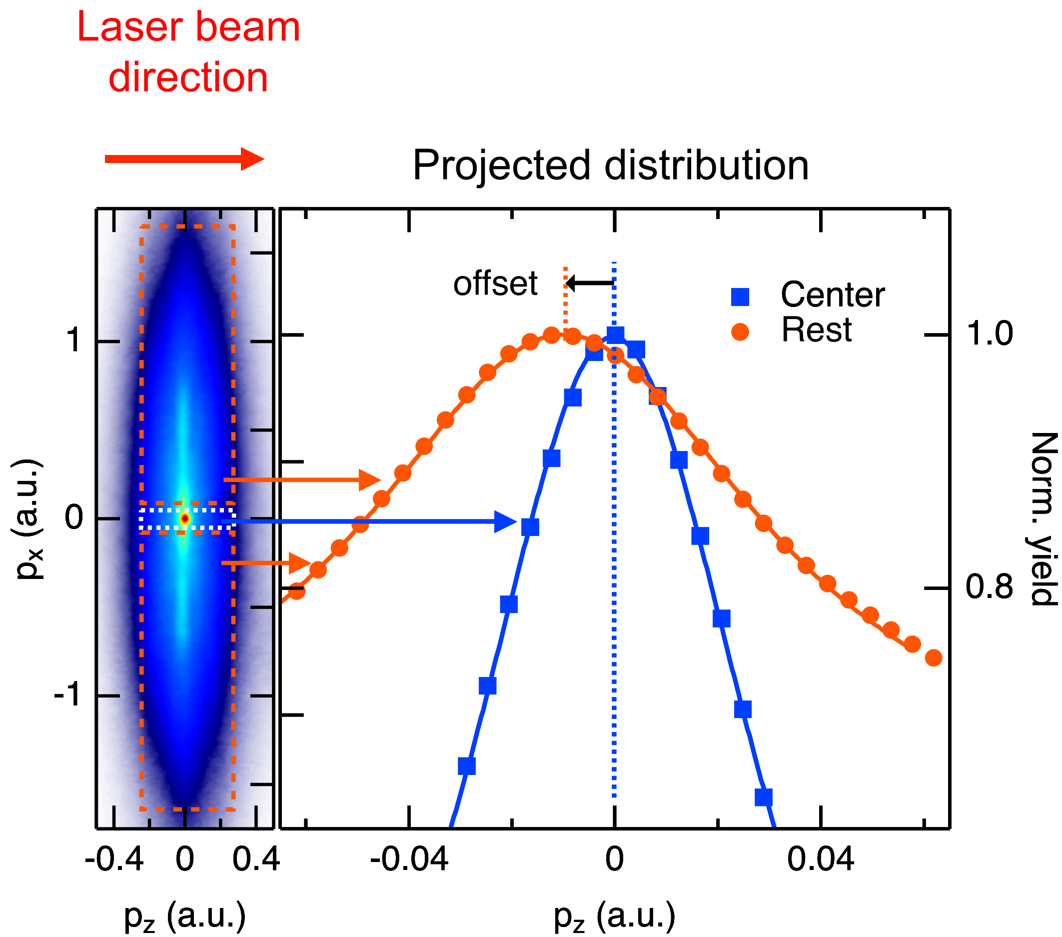


Offset Extraction

- Photoelectron momentum distribution

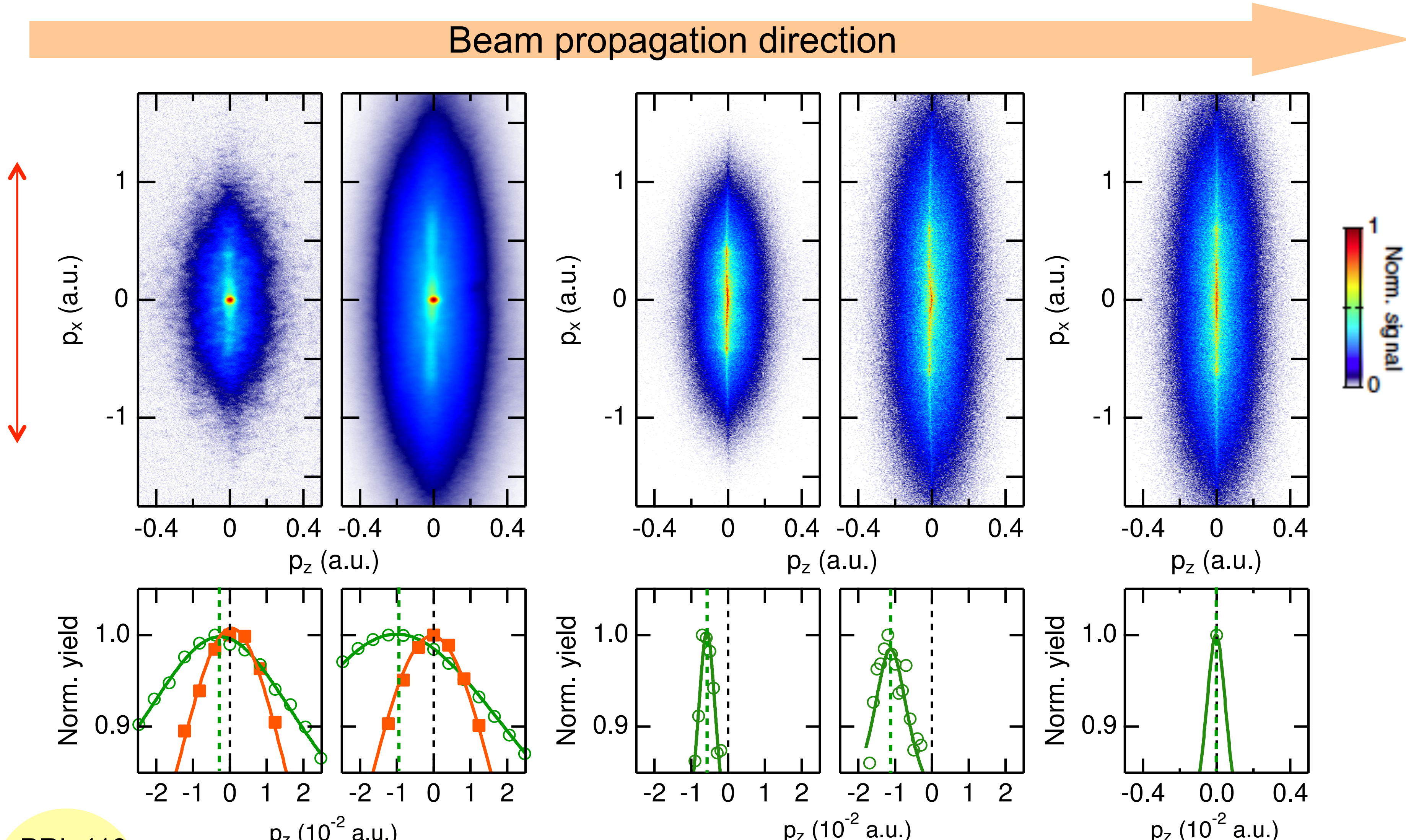
- **Central part**
  - Ionization after pulse
  - Origin highly excited states
  - Zero momentum
  - Serves as calibration

- **Outer part**
  - Ionization during pulse
  - Peak offset opposite to beam propagation direction



Nubbemeyer et al., PRL 101, 233001 (2008)

Data and simulations for xenon



PRL 113, 243001 (2014)

Experiment	Experiment	Simulation	Simulation	Simulation (B-field off)
3×10^{13}W/cm^2	6×10^{13}W/cm^2	3×10^{13}W/cm^2	6×10^{13}W/cm^2	6×10^{13}W/cm^2

CTMC simulations

- Classical Trajectory Monte-Carlo simulations using the two step model of strong field ionization (H.B. van Linden van den Heuvell and H.G. Muller, in Multiphoton Processes (1988))

- Initial step tunneling using the Ammosov-Delone-Krainov ionization rate
  - M. V. Ammosov, N. B. Delone, and V. P. Krainov, Zh. Eksp. Teor. Fiz. 91, 2008 (1986)[Sov. Phys. JETP 64, 1191(1986)]
  - XM Tong and CD Lin, J. Phys. B: At. Mol. Opt. Phys. **38** (2005) 2593–2600

- Subsequent solution of the non-relativistic Newton equations of the motion including the the magnetic field and Coulomb potential

- For each intensity, 1 million trajectories were calculated and subsequently binned in the momentum space

CTMC simulations – initial conditions justified

- The initial conditions for the classical propagation based on the tunnel ionization model

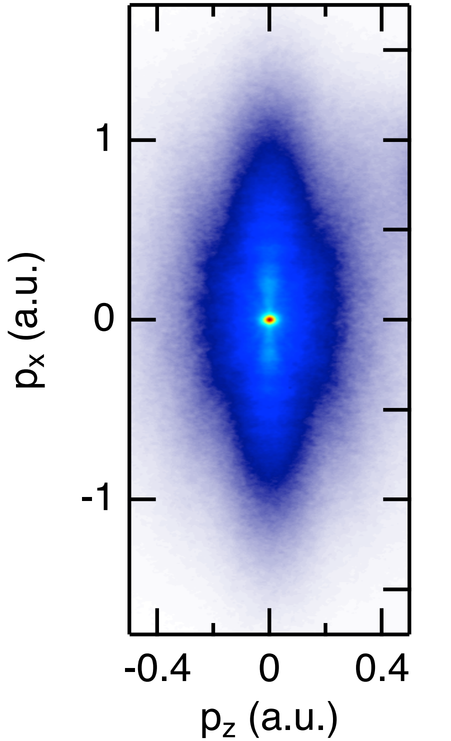
- The usage of the tunneling model beyond dipole approximation has been debated (e.g. H. R. Reiss, PRL **101,** 043002 (2008))

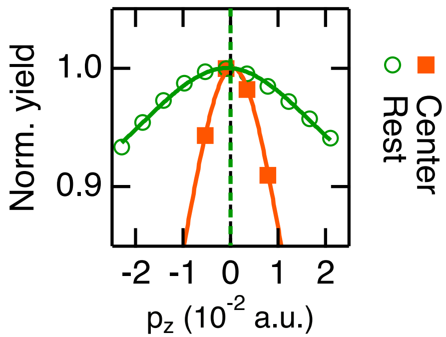
- Despite theoretical description of tunnel ionization beyond the dipole approximation (Klaiber *et al.*, PRL **110**, 153004 (2013)): Check of validity of initial conditions:
  - Variation of the tunnel exit by between 60% and 300%
  - Variation of the ionization rate by at least 5 orders of magnitude

- No significant influence on the shift of the maximum

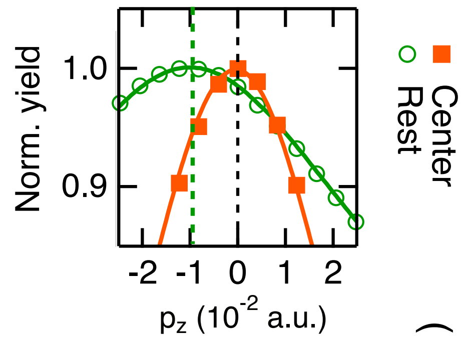
→ Observed shift mainly caused by propagation in continuum – supported by robustness of the experimental results against the different species

800 nm vs 3400 nm

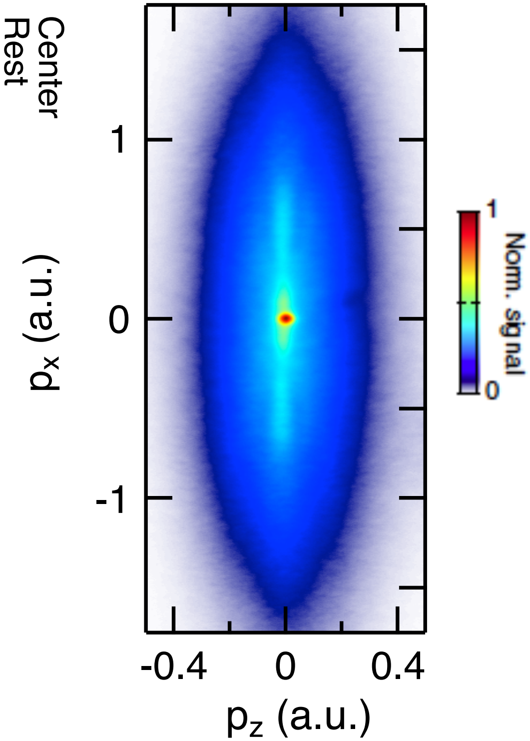




symmetric photoelectron image



asymmetric photoelectron image



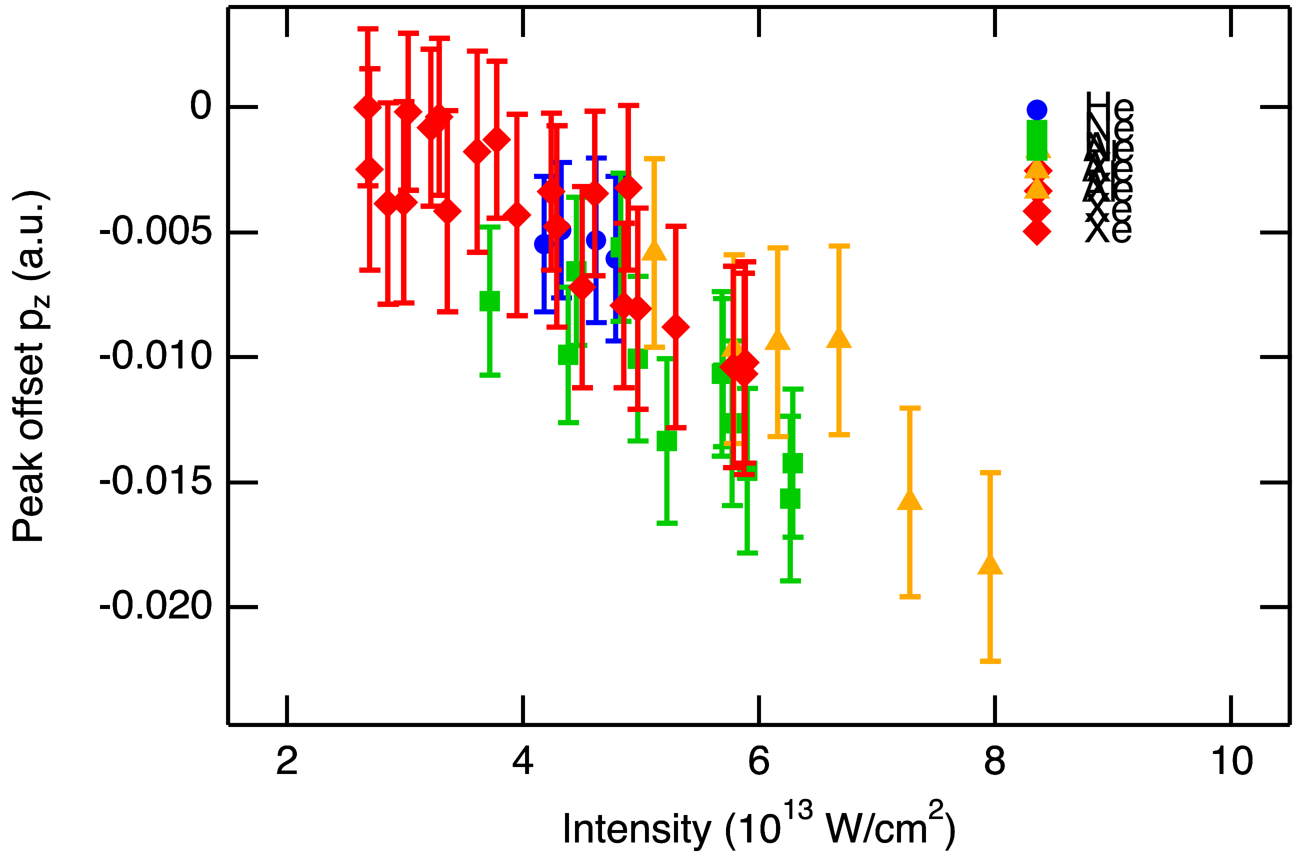
beam propagation direction

- Data were recorded with in the same geometry
- Intensity at 800 nm higher than for 3400 nm

He 800 nm, 1.2×10^{14} W/cm^2

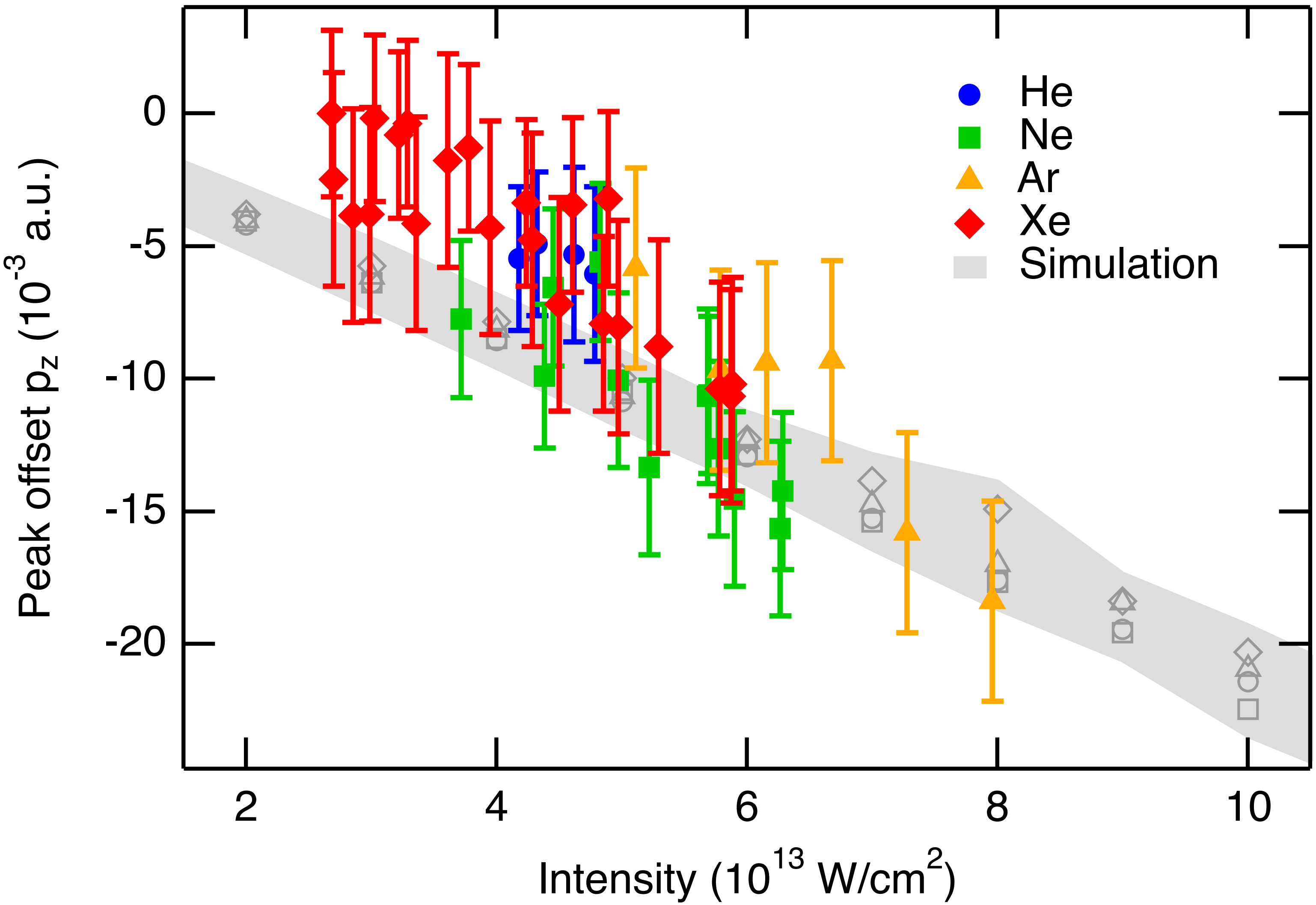
Xe 3400 nm, 6×10^{13} W/cm^2

Results different gases



- Clear trend towards bigger offsets with increasing intensity
- Independent of gas species

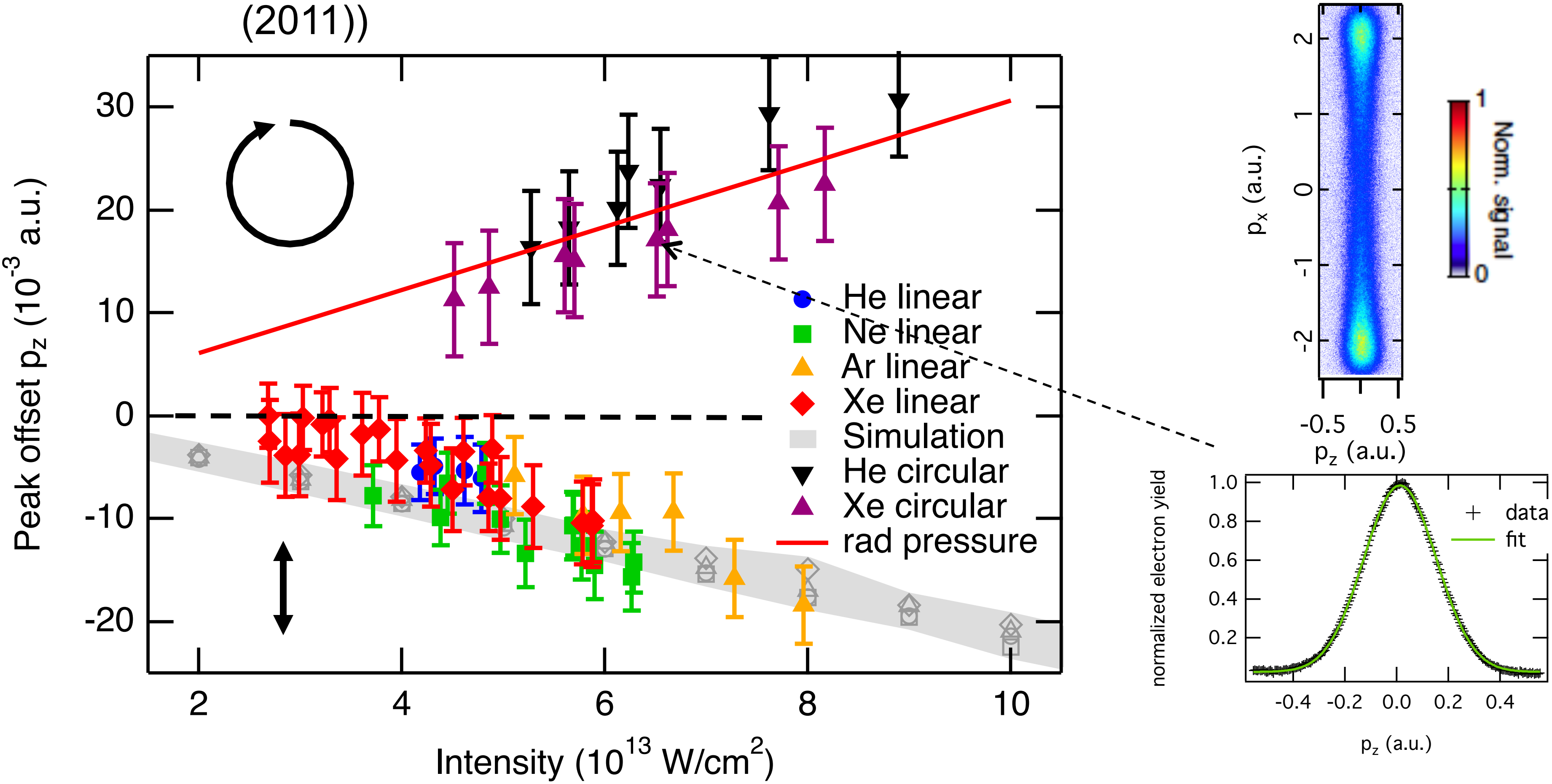
Offset of the maximum of the distribution



Comparison with circular polarization

Comparison with radiation pressure analysis:

- Peak of gaussian fit of projection of the circularly polarized data on beam propagation direction
- Comparison with radiation pressure on a free electron (PRL **106**, 193002 (2011))



Rescattering - cutoffs

unpublished
material

Rescattering - different channels

unpublished
material

Rescattering - atom vs molecule

unpublished
material

Conclusions

- Breakdown of the dipole approximation in the long wavelength limit for strong field ionization observed for $6\text{x}10^{13}$ W/cm^2 at λ = 3.4 µm
- Magnetic field effects from the laser field:
  - Asymmetric electron momentum distribution along the beam propagation direction
  - Peak offsets opposite to beam propagation direction due multiple revisits of the electron
  - Not sensitive to the exact shape of the scattering potential
- Consequences for the recollision process in e.g. high-order harmonic generation