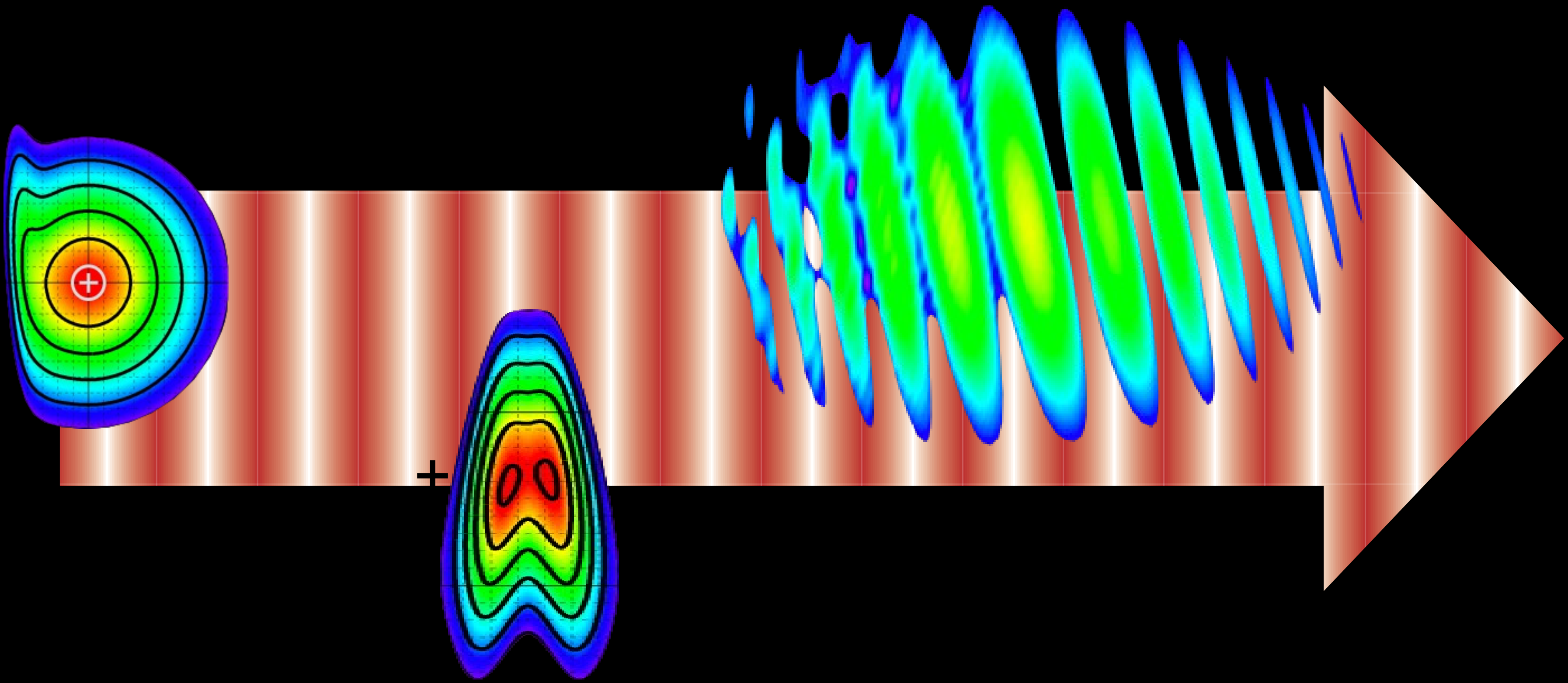
Electrons, Ions and Nuclei in Extremely Intense Laser Pulses



Christoph H. Keitel, Max-Planck-Institute for Nuclear Physics

involved key group members in presented projects:
A. Di Piazza, J. Evers, Z Harman, K. Z. Hatsagortsyan, M. Klaiber, A Palffy
plus former members C Müller, B King and A Ipp

Outline

Laser-Electron Interaction:

Quantum Effects, Spin-induced Dynamics, Laser-enhanced Fluctuations & Pair Creation, Laser Colliders

Laser-Ion Interaction:

Relativistic Ionisation, Picture of Relatistic Tunneling, Resonant Interaction & Ion Acceleration

Laser-Nuclei Interaction:

Nuclear Quantum Optics, Nuclear Population Transfer, Laser-assisted Alpha Decay and Recollisions

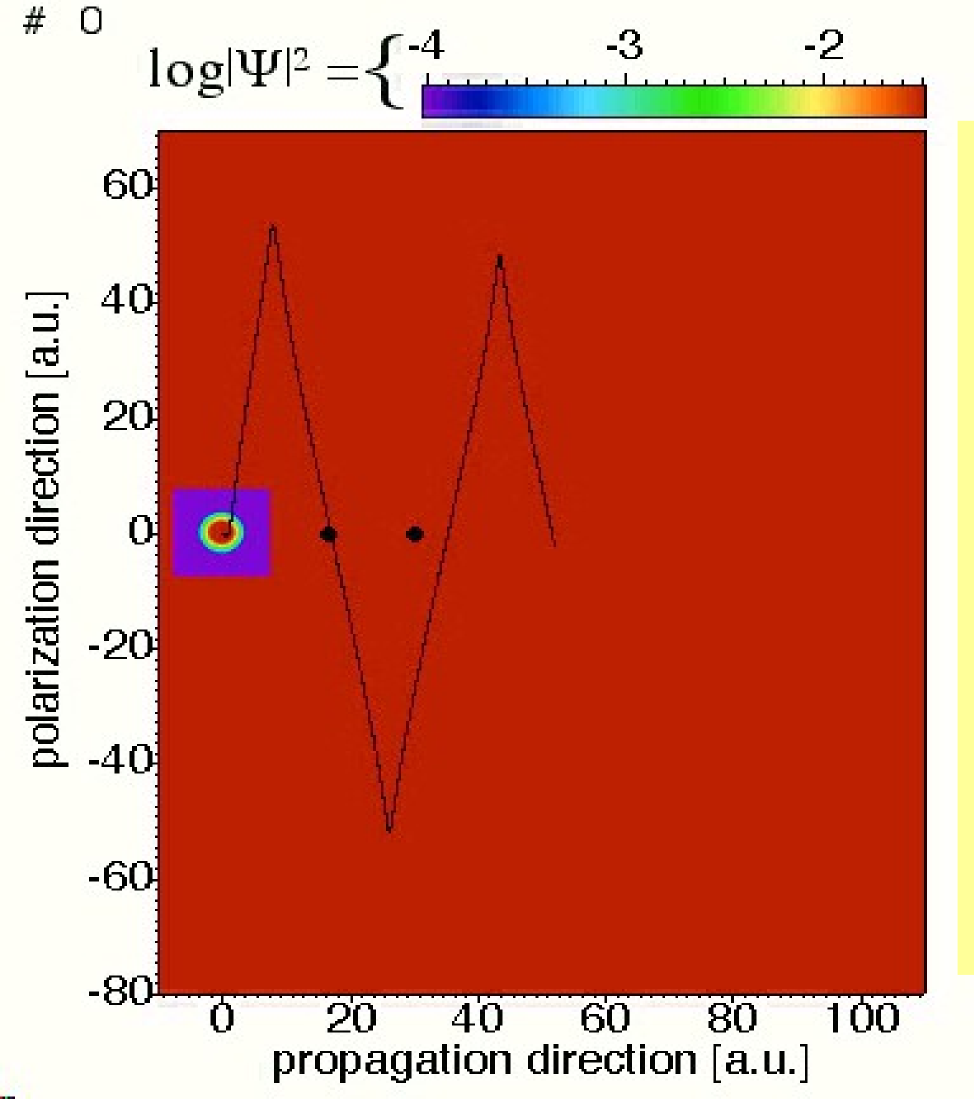
Current high-power laser technology

Optical laser technology (ħ $_L$=1 eV)	Energy (J)	Pulse duration (fs)	Spot radius (m)	Intensity (W/cm^2)
State-of-art (Yanovsky et al. (2008))	10	30	1	2 10^{22}
Soon (Polaris, Astra-Gemini, Phelix, etc…)	10-100	10-100	1	10^{22}-10^{23}
Soon (PFS)	5	5	1	10^{22}-10^{23}
Vulcan 10 PW(CLF)	300	30	1	10^{23}
Near future (2020) (ELI, HiPER)	10^4	10	1	10^{24}-10^{26}

- GeV electron acceleration (Leemans et al 2006)
- Laser induced pair creation demonstrated Burke et al 1996
- High-energy processes feasible

Electrons: Dirac dynamics in strong laser pulses

Example: electron double scattering via 2D solution of Dirac equation



- Drift in laser-propagation direction via magnetic field component
  - problem for recollisions

- Enhanced quantum spreading with increased laser intensity & quantum interference at scattering processes

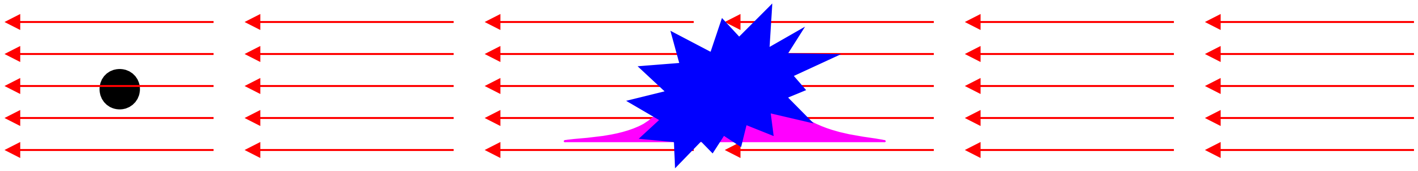
- Dirac propgation time consuming enhanced via adaptive grids

- Quantum features in various situations of relevance

E= 50 a.u., w= 1 a.u., ca. 36% speed of light, Sn^{50+}

Multiphoton Compton scattering

- Multiphoton Compton scattering is one of the most fundamental processes in electrodynamics



the electron exchanges many photons with the laser field and emits a high-energy photon

the quantum photon-energy spectrum with sharp cut-off reduces to the classical one at `¿1 (see also Seipt and Kaempfer, PRA 2011, Boca and Oprea, Phys Scr. 2011)

Quantum corrections to the dressed mass have been found (see, e.g., Ritus, 1985; Meuren and Di Piazza, PRL 2011)

$$m^{*2} = m^2\left(1+\frac{\xi^2}{2}\right) + \Delta m^2(\chi)$$

- alterations of multiphoton Compton scattering photon spectra by the finite extension of the laser pulse (Heinzl et al., Phys. Rev. A 2010): emission line broadening and appearance of subpeaks

Spin dynamics in the Kapitza-Dirac effect

Spinflip for odd photon numbers

➡ 3-photon Kapitza-Dirac effect
(2 absorbed , 1 emitted)

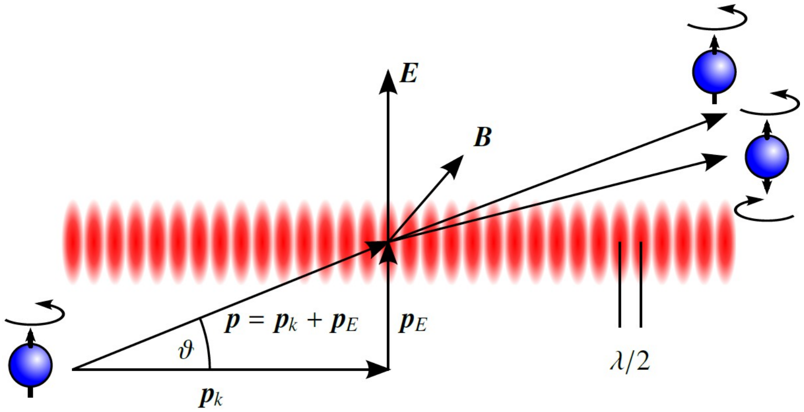
Bragg condition must be fulfilled

➡ k or p_E must be relativistic

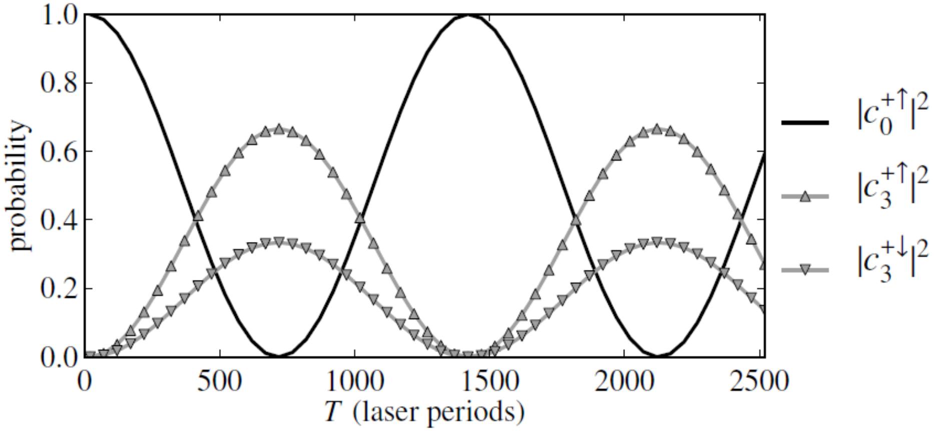
Counterpropagating laser beams:
Peak intensity: $2\ 10^{23}$ W/cm² (each beam)
Wave length: 0.4 nm (photons)

Electron beam:
Momentum: 176 keV/c
Inclination: $\vartheta = 0.4°$

Time of half Rabi cycle: 1 fs



Experimental setup



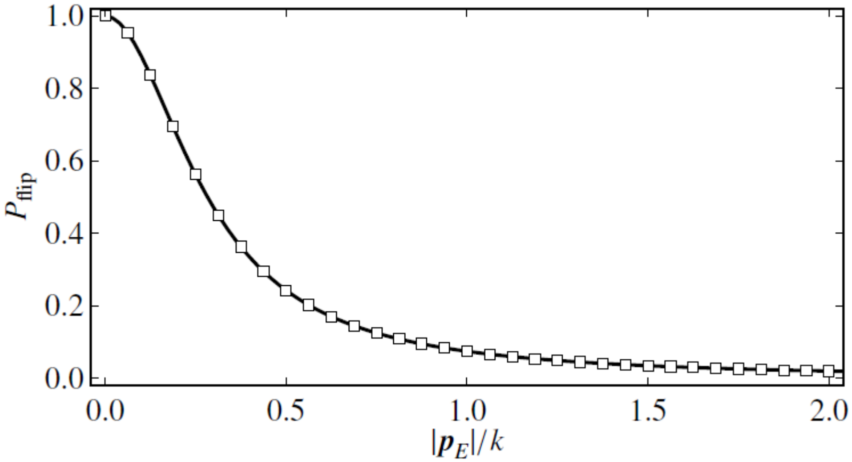
Spin resolved diffraction probability

S. Ahrens, H. Bauke, C.H. Keitel, C. Müller, Phys. Rev. Lett. 109, 043601 (2012).

Spin dynamics in the Kapitza-Dirac effect

Spinflip probability tunable by electron momentum p_E

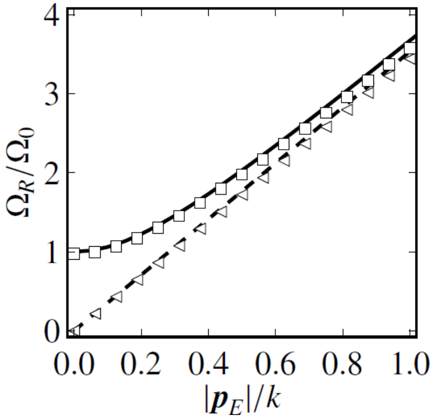
$$P_{flip} \qquad 1 \qquad \frac{25 p_E^2}{3k^2} \qquad ^{1}$$



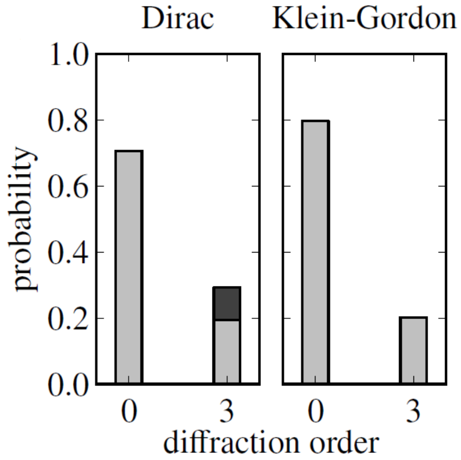
Spinflip probability

Spin degree of freedom mediates diffraction

Big differences between Dirac and Klein-Gordon possible



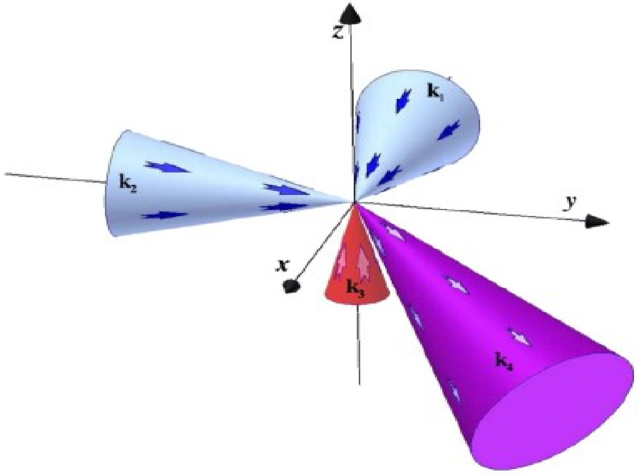
Rabifrequency



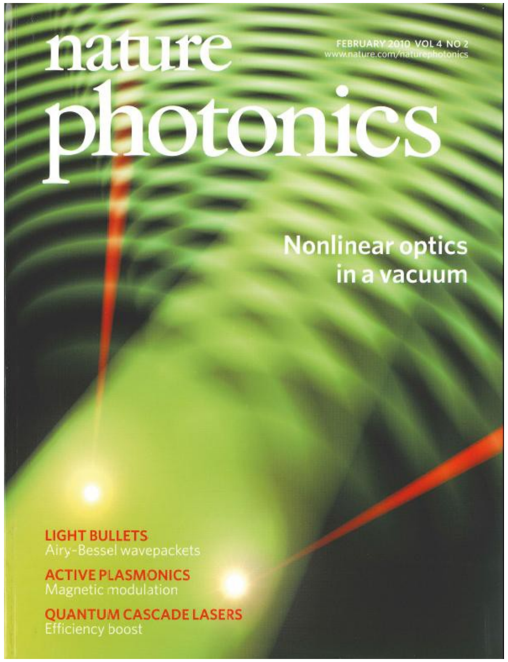
Diffraction pattern

Reference: Phys. Rev. Lett. 109, 043601 (2012).

Laser-enhanced Electron-Positron Vacuum Fluctuations: mediate Light-Light Scattering



Stimulated Photon-Photon Scattering and Matterless Double Slits (new: with focussed pulses)


nature photonics

FEBRUARY 2010 VOL 4 NO 2
www.nature.com/naturephotonics

Nonlinear optics in a vacuum

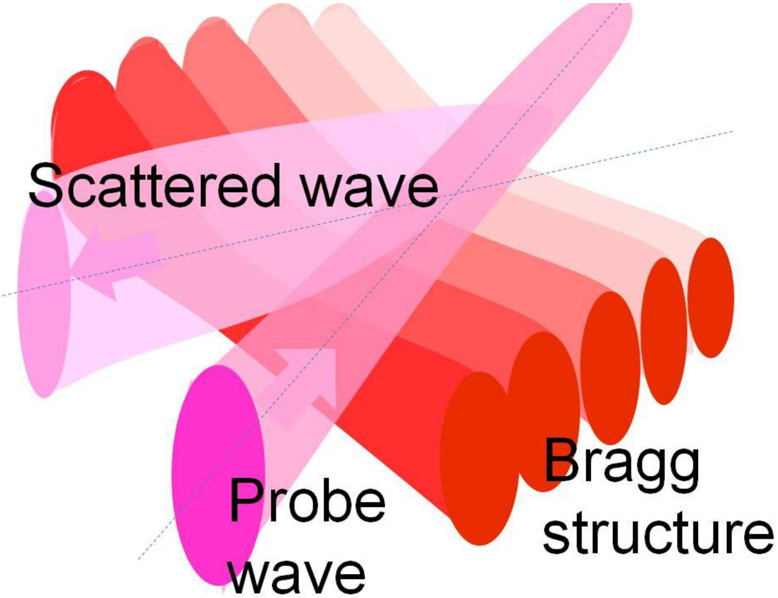
LIGHT BULLETS
Airy-Bessel wavepackets

ACTIVE PLASMONICS
Magnetic modulation

QUANTUM CASCADE LASERS
Efficiency boost

E. Lundstroem et al, PRL 96, 083602 (2006)

B. King et al, Nature Photonics **4**, 92 (2010), PRA (2010) & New J. Phys. in press (2012)



Bragg scattering of light in vacuum structured by strong periodic fields

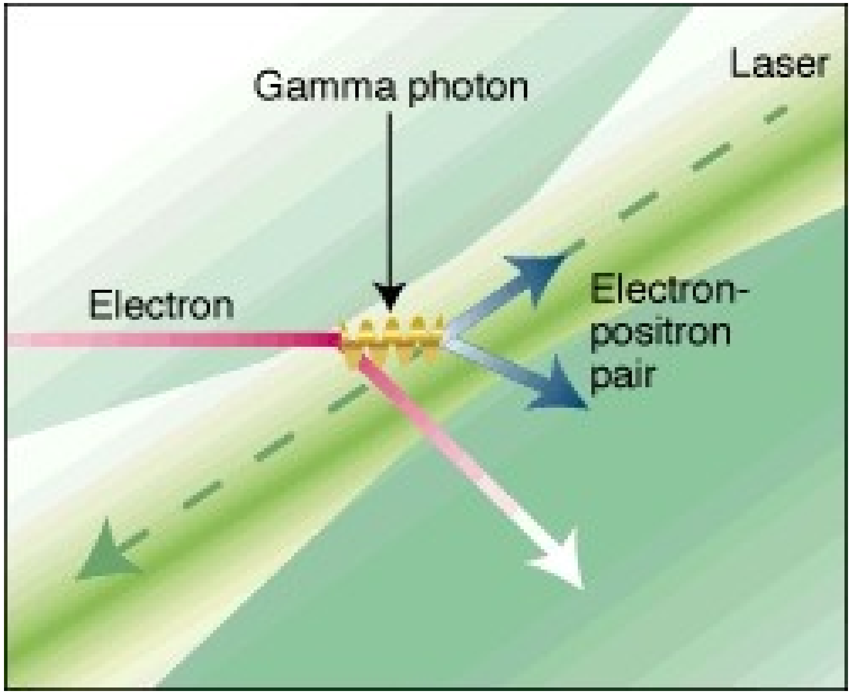
At a fixed total power: 2 times enhancement of the photon scattering probability over the stimulated photon-photon scattering

G. Yu. Kryuchkyan & K. Z. Hatsagortsyan, PRL 107, 053604 (2011)

Pair production in strong laser pulses

Historical Remark: SLAC Experiment

The first laboratory evidence of multiphoton pair production.



D. Burke et al., Phys. Rev. Lett. 79, 1626 (1997)

- $3.6\times 10^{18}\, W/cm^2$ optical laser (2.35 eV)
- Electron accelerated to 46.6 GeV
- Energy threshold reached (in center of inertial frame)

Theory: combined treatment of two processes

direct: $e + N\omega \rightarrow e' + e^+e^-$

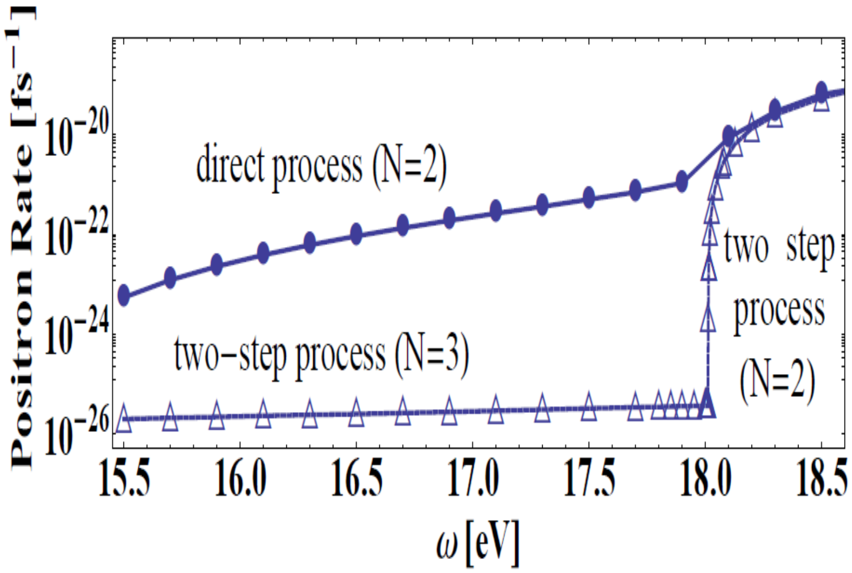
Bethe-Heitler type

two-step: $e + \omega \rightarrow e' + \gamma$

$\gamma + N\omega \rightarrow e^+e^-$

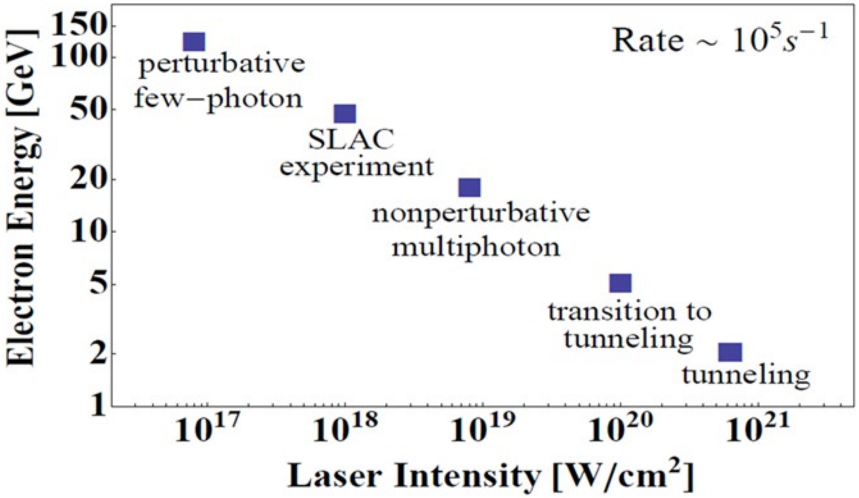
Compton back scattering &
Multiphoton Breit-Wheeler

Separate Direct and Two-Step Processes



Direct process and two-step process can be separated by kinematic requirements at VUV intensities $10^{13}\,W/cm^2$, with a 17.5 GeV electron from DESY beamline

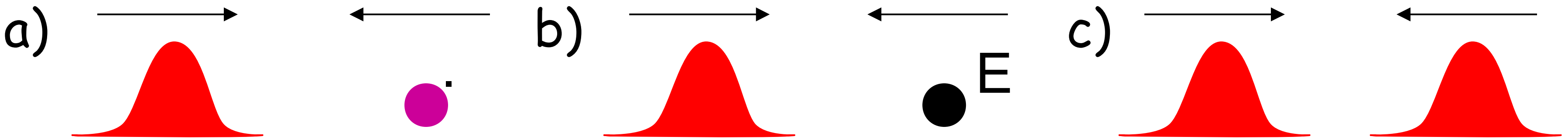
- Substantial pair production rate in various interaction regimes
- Novel usage of DESY beamline (17.5 GeV) for pair production
- The future of pair production: all-optical setup



Huayu Hu, Carsten Müller, C. H. Keitel, Phys. Rev. Lett. 105, 080401 (2010)

Electron-positron pair production: Mechanisms

Three main classes of pair-production processes have been investigated, including laser fields

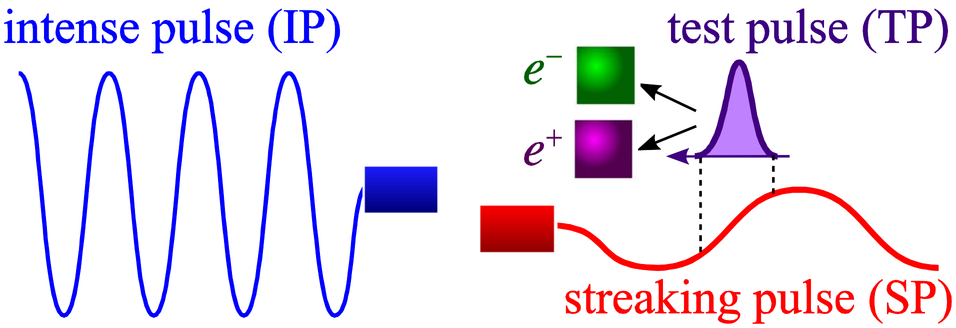


eg Schützhold et al PRL 2009 - Hu et al PRL 2010 - Ruf et al PRL 2009

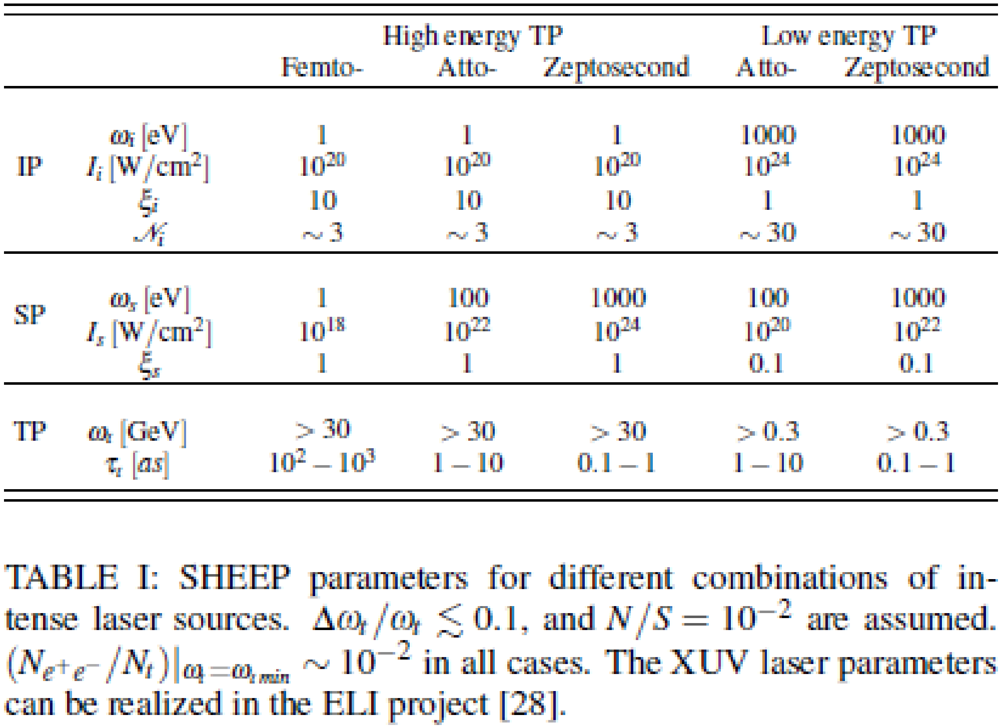
perturbative multiphoton regime at $\xi \ll 1$ and non-perturbative tunneling regime at $\xi \gg 1$ – see also Di Piazza et al, RMP 84, 1177 (2012)

	Parameter (head-on collision)	Rate scaling (tunneling)
Laser-photon collision (a))	$\chi=(2\omega/m)(\mathcal{E}/\mathcal{E}_{cr})$	$\propto m\chi^{3/2}\exp(-8/3\chi)$
Laser-charge collision (b))	$\nu=(2E/m)(\mathcal{E}/\mathcal{E}_{cr})$	$\propto m(Z\alpha)^2\exp(-3^{0.5}2/\nu)$
Laser-laser collision (c))	$\epsilon=\mathcal{E}/\mathcal{E}_c$	$\propto m\epsilon^2\exp(-\pi/\epsilon)$

Streaking at high energies with electrons and positrons (SHEEP)



Characterization of ultra-short pulses of γ-rays of GeV energies employing streaking method based on strong field pair production: from femtosecond time-scale up to zeptosecond.



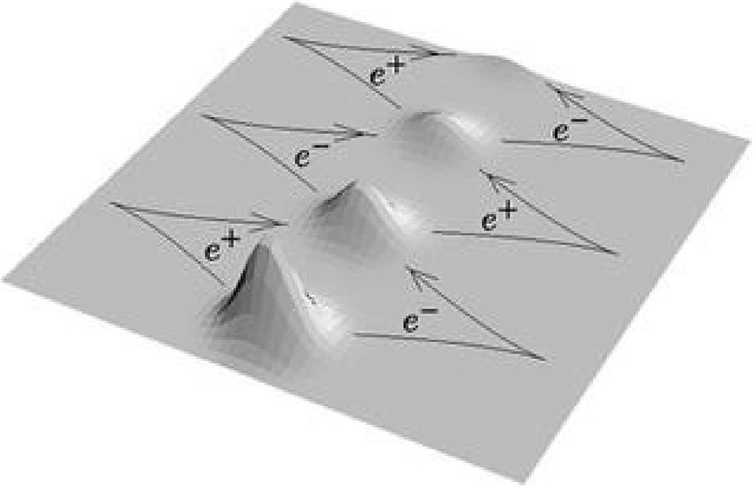
		High energy TP			Low energy TP	
		Femto-	Atto-	Zeptosecond	Atto-	Zeptosecond
IP	ω_i [eV]	1	1	1	1000	1000
	I_i [W/cm^2]	10^{20}	10^{20}	10^{20}	10^{24}	10^{24}
	ξ_i	10	10	10	1	1
	$\mathcal{N}_i$	~ 3	~ 3	~ 3	~ 30	~ 30
SP	ω_s [eV]	1	100	1000	100	1000
	I_s [W/cm^2]	10^{18}	10^{22}	10^{24}	10^{20}	10^{22}
	ξ_s	1	1	1	0.1	0.1
TP	ω_t [GeV]	> 30	> 30	> 30	> 0.3	> 0.3
	τ_t [as]	$10^2 - 10^3$	$1 - 10$	$0.1 - 1$	$1 - 10$	$0.1 - 1$

TABLE I: SHEEP parameters for different combinations of intense laser sources. $\Delta\omega_t/\omega_t \lesssim 0.1$, and $N/S = 10^{-2}$ are assumed. $(N_{e^+e^-}/N_t)|_{\omega_t=\omega_{t\,min}} \sim 10^{-2}$ in all cases. The XUV laser parameters can be realized in the ELI project [28].

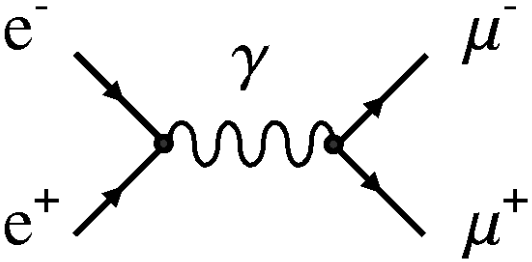
A. Ipp, J. Evers, C. H. Keitel, and K. Z. Hatsagortsyan, Phys. Lett B 702, 383 (2011)

Particle Physics with Strong Lasers

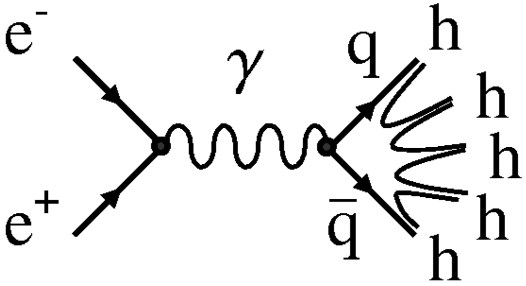
Positronium dynamics
in an intense laser field:



Particle reactions by laser-driven
e^+e^- collisions



muon production
$(m\ c^2 = 106$ MeV)



pion production
$(m\ c^2 = 140$ MeV)

energetic threshold for muon:

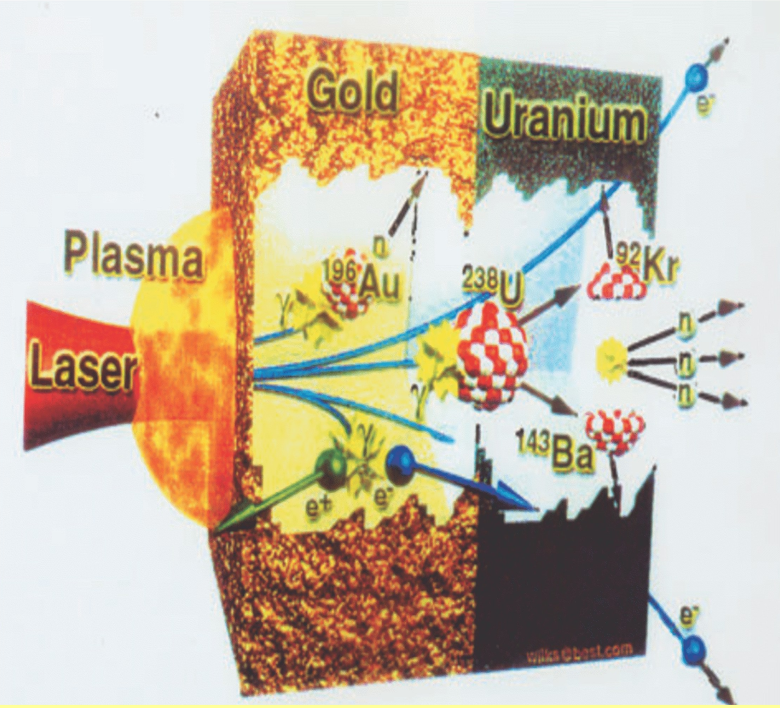
$$2eA \geq 2Mc^2$$

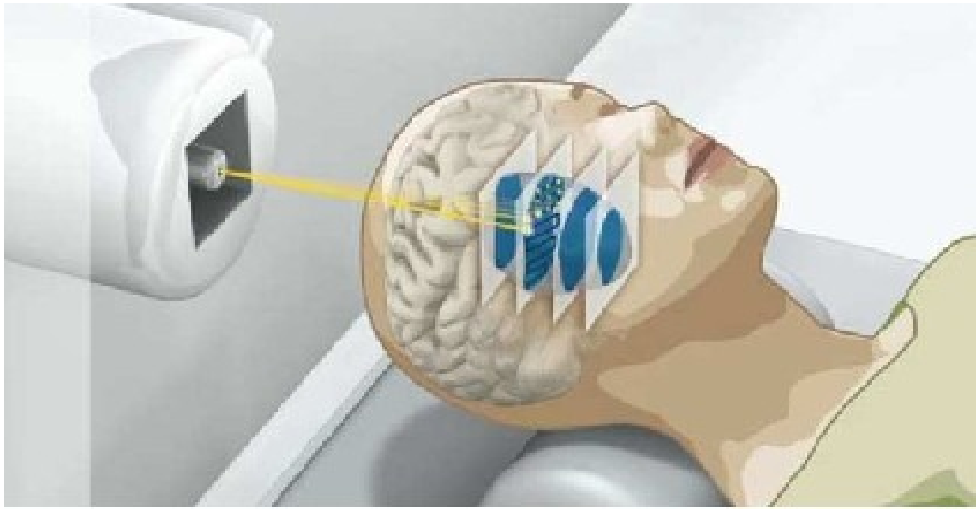
$(I \geq 5\times10^{22}$ W/cm^2 at $= 1$ m)

B. Henrich et al. PRL 93, 013601 (2004) & K. Z Hatsagortsyan et al., EPL (2006), Obserservation of GeV electrons: W. Leemans et al., Nat. Phys. 2, 696 (2006); Small muon rates: C. Müller et al., Phys. Lett. B 669, 209 (2008);

Also Pion Production via Proton Laser Collision: A Dadi & C Müller, Phys Lett B 697, 142(2011)

MeV Acceleration and Nuclear Physics via Laser-Plasma Interaction



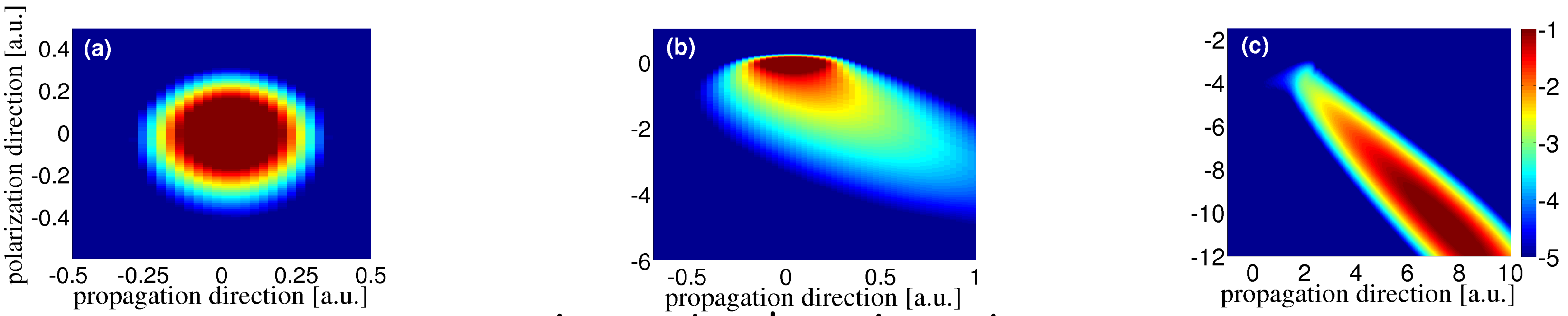


photonuclear neutrons e.g. by G. Pretzler et al., PRE 58, 1165 (1998), T. Ditmire et al Nature (1999), K. Ledingham et al., PRL 2000, N. Izuma PRE (2002), G Grillon et al PRL (2002)

quasi-monoenergetic protons for cancer therapy: H. Schwoerer, S. Pfotenhauer, O. Jäckel, K. Amthor, W. Ziegler, R, Sauerbrey, K. Ledingham, T. Esirkepov, Nature 439, 445 (2006)

ultra-fast proton sources: Peter V Nickles … W. Sandner … O. Willi.., JOSA B 25 (2008) & ion acceleration T. Sokollok, .. W. Sandner, ..O. Willi.., Phys. Rev. Lett. 103, 135003 (2009)

IONS: Ionisation & Characterising intense pulses with highly charged ions

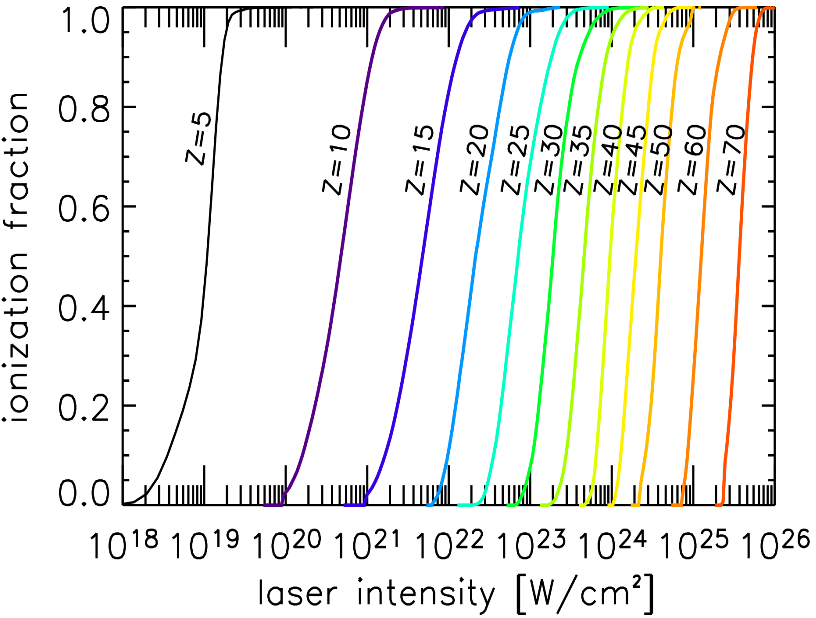


-> increasing laser intensity ->

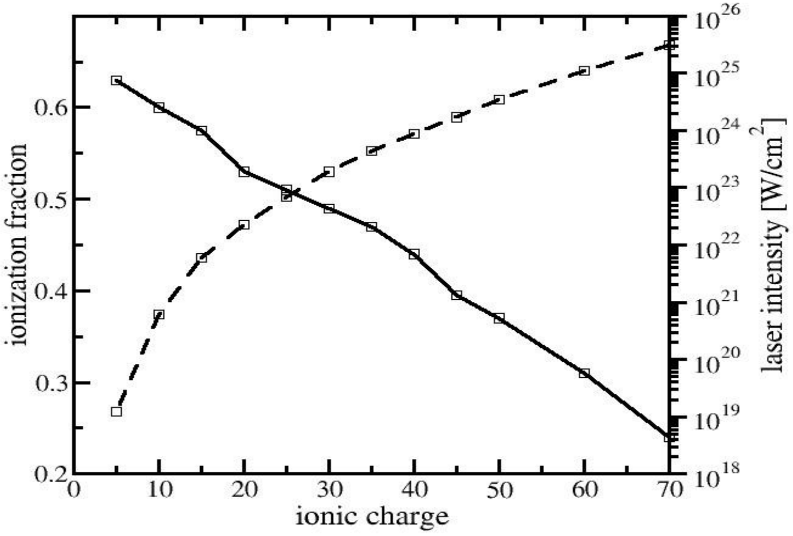
Directions and yields of ionisation are characteristic for laser intensity and ionic charge

=> Sensitive means of measuring extremely intense laser intensities

H G Hetzheim and C H Keitel, Phys. Rev. Lett. 102, 083003 (2009)

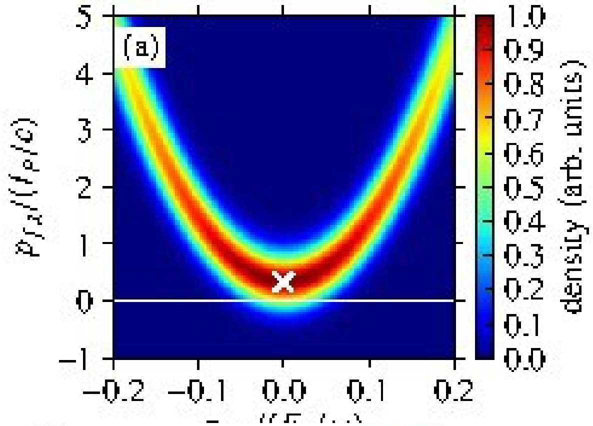


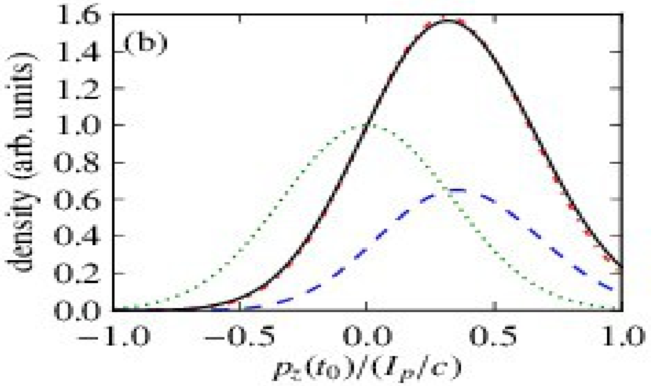
Ionization fraction for several different hydrogen-like ions Z as a function of the maximal laser intensity for single-cycle square-shaped laser pulse; wavelength 1054 nm.

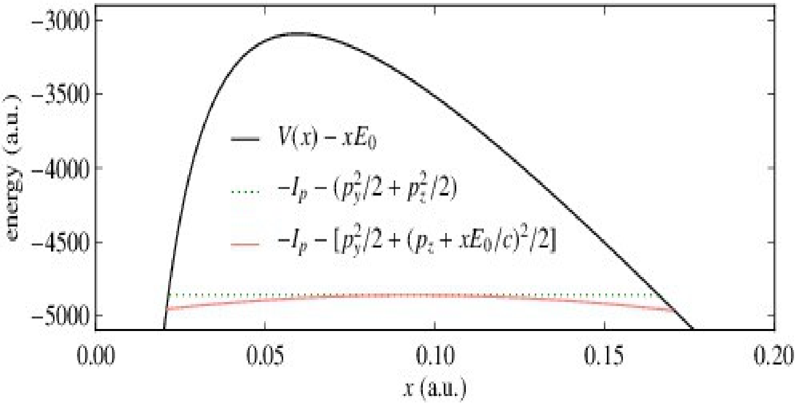


The solid line defines the most sensitively measured ionization fraction (left axis), whereas the dashed line shows the corresponding laser intensity (right axis) as a function of the respective optimal ionic charge Z.

Laser-induced relativistic Tunneling





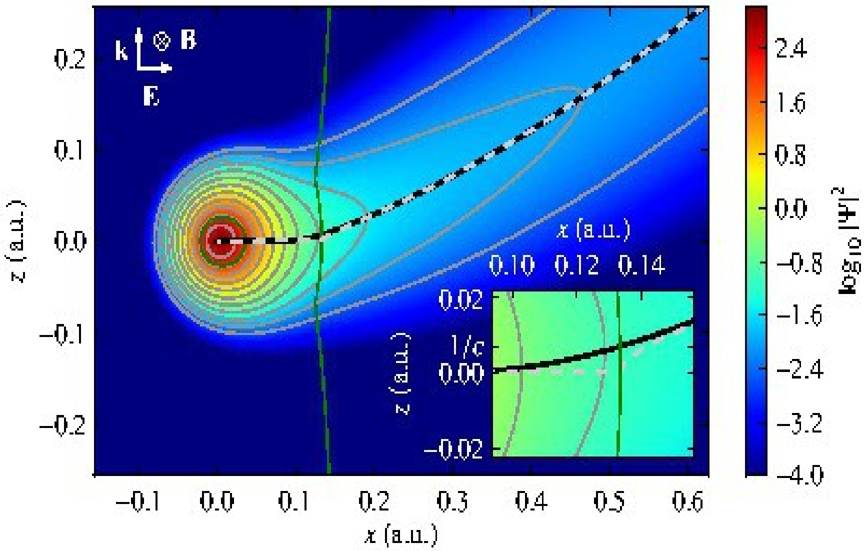


***Tunnel ionisation yield**:*
Asymptotic momentum distribution:
➢messurable momentum shift (Ip/c)
due to relativistic tunneling

***Tunnel-exit distribution**:*
➢Only magnetic-dipole (blue) and mass-correction (red) relevant
➢momentum shift (Ip/c) compared to the n-r distribution (green)

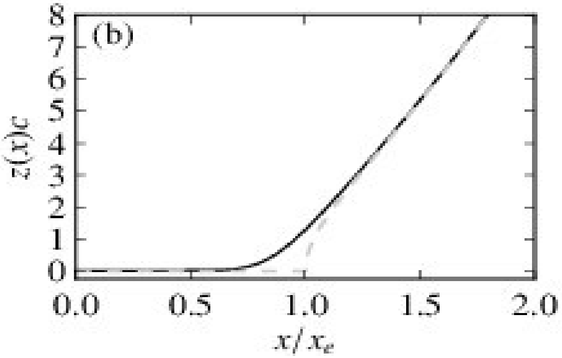
***Relativistic Tunneling picture**:*
➢non-relativistic potential
➢position-dependent energy-levels
due to the laser magnetic field

M. Klaiber, E. Yakoboylu, H. Bauke, K Z Hatsagortsyan,
C H Keitel, arXiv 1205,2004 (2012)



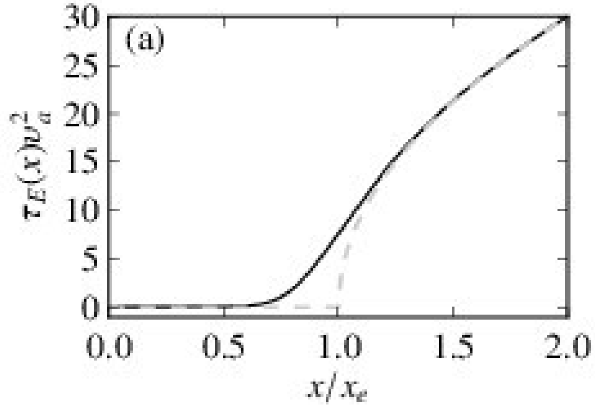
***Numerical Dirac Simulation**:*

- ion with Z=90 in the tunneling regime
- momentum shift and coordinate drift at the tunneling exit **yielding a tunneling time**



Analytical quantum-mechanical model (black):

- maximum of the wavefunction shifted compared to the quasi-classical description (grey)
- only visible near the tunneling-exit

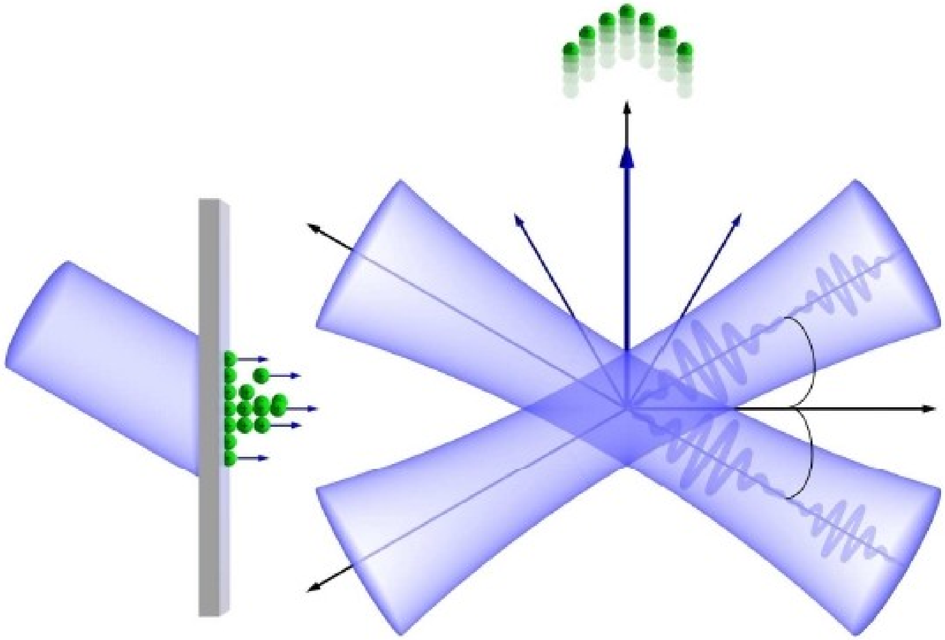


Reason:

- Quasi-classical: instantaneous tunneling, no drift
- quantum-mechanical: non-zero tunneling time, Lorentz-force induced drift under the barrier
- but: only messurable near the tunneling-exit

Ion acceleration: Intense high-quality medical ion beams via laser fields

Particle acceleration by **laser fields**:



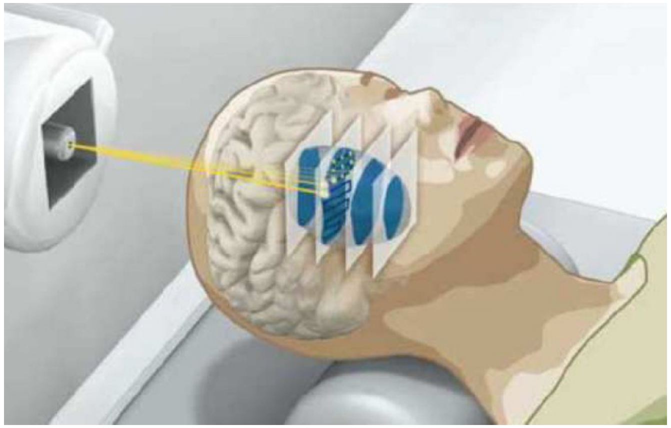
(1) abundant ion generation
in a laser-plasma interaction

(2) post-acceleration by a powerful PW-scale laser beam

e.g. simulation results for a tightly focused 40 PW laser pulse:

kinetic energy: 233 MeV +/- 1%
number of ions: 10^6/shot

in the range of **medical applicability**:
laser acceleration may be an economic future alternative to conventional accelerators (such as e.g. the HIT facility of the Heidelberg University Hospital)



B. J. Galow, Z. Harman, and C. H. Keitel, Opt. Express **18**, 25950 (2010)

Dense monoenergetic proton beams from chirped laser-plasma interaction

- Introduce linear frequency chirp: $f = f_0 + b_0 (t – z/c)$
- Relativistic proton energies already at moderate laser intensities of 10^{21} W/cm^2
- Dense monoenergetic proton beams (1 % energy spread and 10^7 particles per bunch)
- Multi-GeV proton beams at future facilities like ELI, HiPER
- Analytical model agrees with 2D-PIC calculations

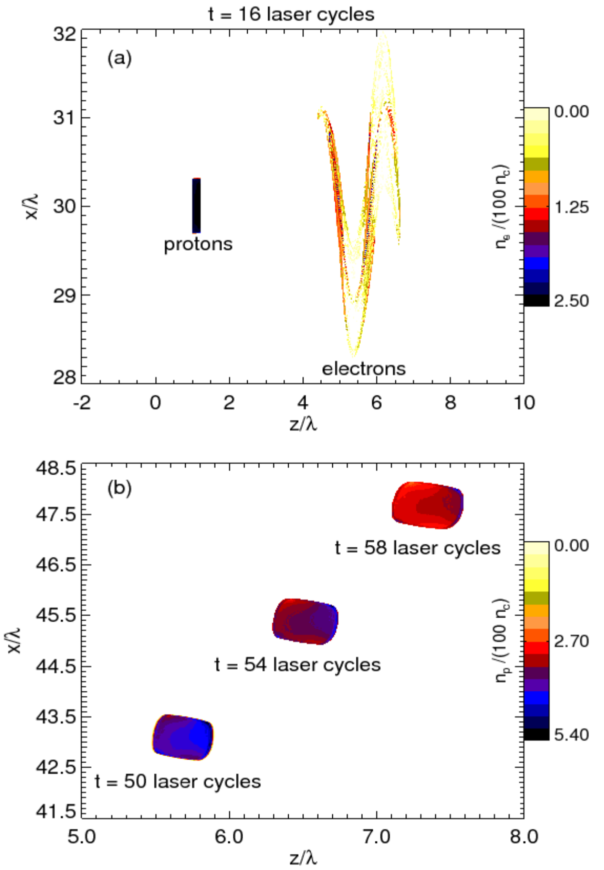
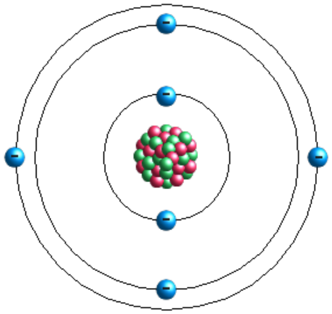


Figure: Snap-shots (a) of the electron and proton density distribution during laser-plasma interaction and (b) of the proton density distribution after laser-plasma interaction.

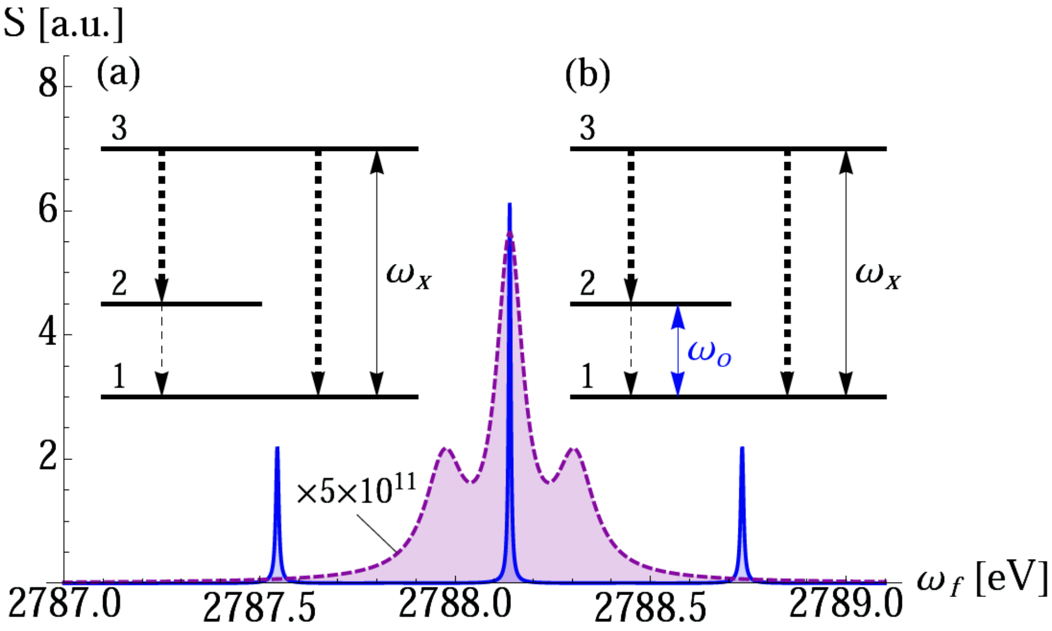
B Galow, Y I Salamin, T Liseykina, Z Harman, C H Keitel, PRL 107, 185002 (2011)
Y I Salamin et al, PRA 85, 063831 (2012) & J X Li et al, PRA 85, 063832 (2012)

Highly charged ions in high-frequency light (XFEL or via ELI): population transfer and application in high-precision metrology

Highly char
(HCI): rela
Atomic syste
a strong nucl



Transition data – transition energies and matrix elements - for such ions are required for the modeling of astrophysical or thermonuclear fusion plasmas



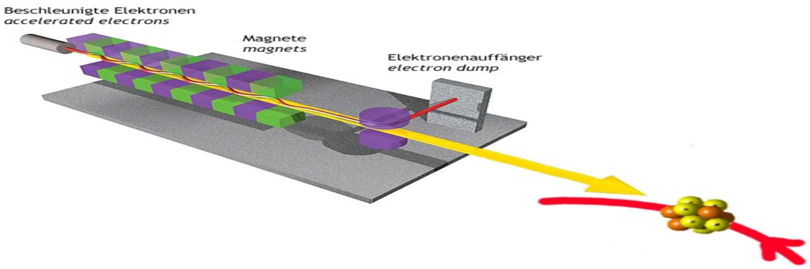
Resonance fluorescene: excitation by a resonant laser field (XFEL)
+ spontaneous decay

Fluorescence photon spectrum for the 2s-2p$_{3/2}$ transition in lithiumlike ^{209}Bi (Z=83). Red dashed line: the broad spectrum with x-ray driving between levels 1 and 3 (panel a). Blue line: the narrowed spectrum when an optical laser driving between the hyperfine-split levels 1 and 2 is switched on in addition (panel b)

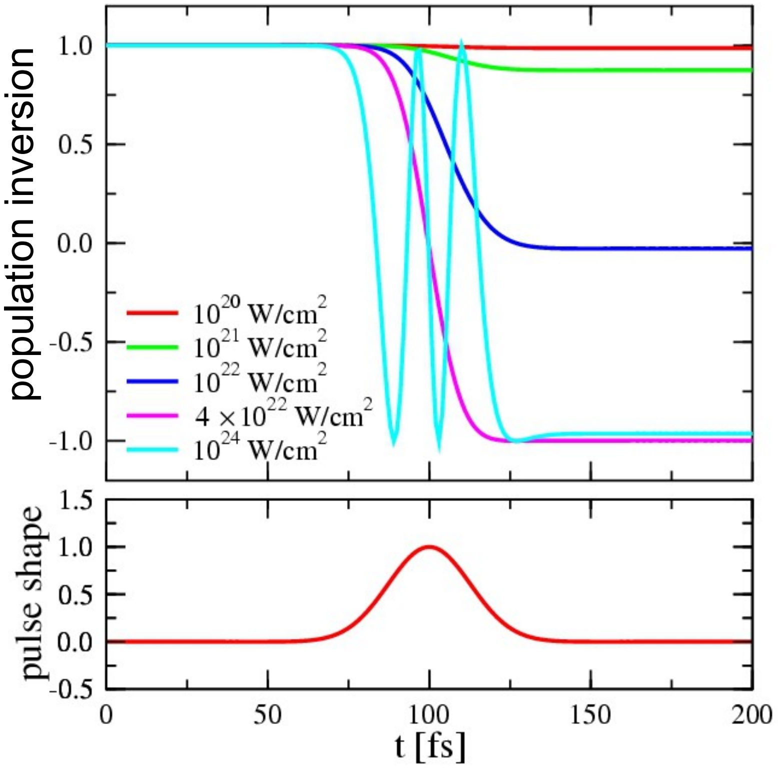
Line widths can be largely decreased by an additional optical driving:
a new tool to measure the **transition matrix elements** of HCI

O. Postavaru, Z. Harman, and C. H. Keitel, Phys. Rev. Lett. **106**, 033001 (2011)

Nuclear Quantum Optics with XFEL: Rabi flopping



- resonant laser-nucleus interaction allows to induce Rabi flopping of nuclear population
- detection e.g. via scattered light, state-selective measurements
- potential application: model-free determination of nuclear parameters



Population inversion in ^{223}Ra for laser parameters as in the DESY TESLA technical design report supplement

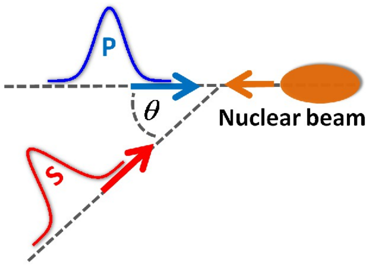
example nuclei:

nucleus	transition	ΔE [keV]	μ [e fm]	$\tau(g)$	$\tau(e)$ [ps]
^{153}Sm	$3/2^- \to 3/2^+$	35.8	$>0.75^{(1)}$	47 h	<100
^{181}Ta	$9/2^- \to 7/2^+$	6.2	$0.04^{(1)}$	stable	$6 \cdot 10^6$
^{225}Ac	$3/2^+ \to 3/2^-$	40.1	$0.24^{(1)}$	10.0 d	720
^{223}Ra	$3/2^- \to 3/2^+$	50.1	0.12	11.435 d	730
^{227}Th	$3/2^- \to 1/2^+$	37.9	$\ldots^{(2)}$	18.68 d	$\ldots^{(2)}$
^{231}Th	$5/2^- \to 5/2^+$	186	0.017	25.52 h	1030

T. Bürvenich, J. Evers and C. H. Keitel, Phys. Rev. Lett. 96, 142501 (2006)
See also Adriana Palffy et al., Phys. Rev C (2007)

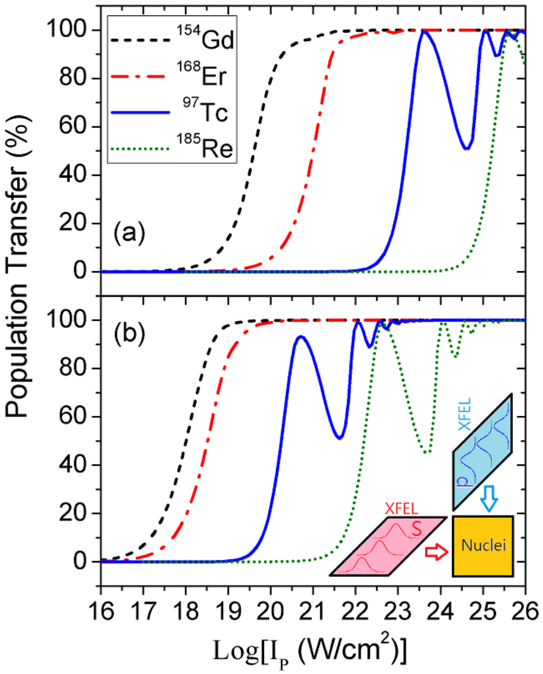
Nuclei: population transfer

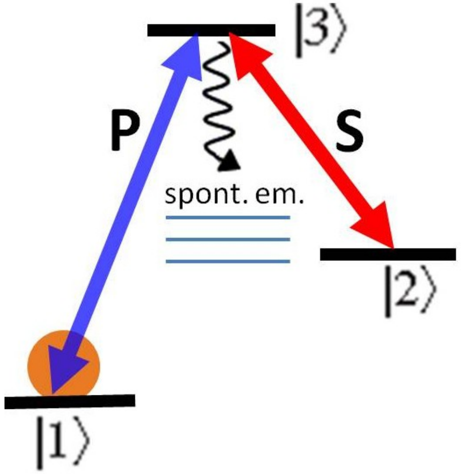
Parameters for XFEL
but alternative via
oscillating mirrors at ELI
(D van der Brugge and A. Pukhov,
Phys. Plasmas 17, 033110 (2010),
A.M. Sergeev et al., Proc. SPIE
8080, 808017 (2011)))



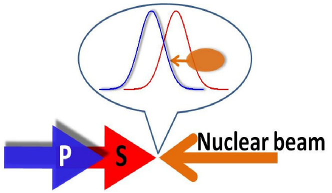
Seeded XFEL →

XFEL → O



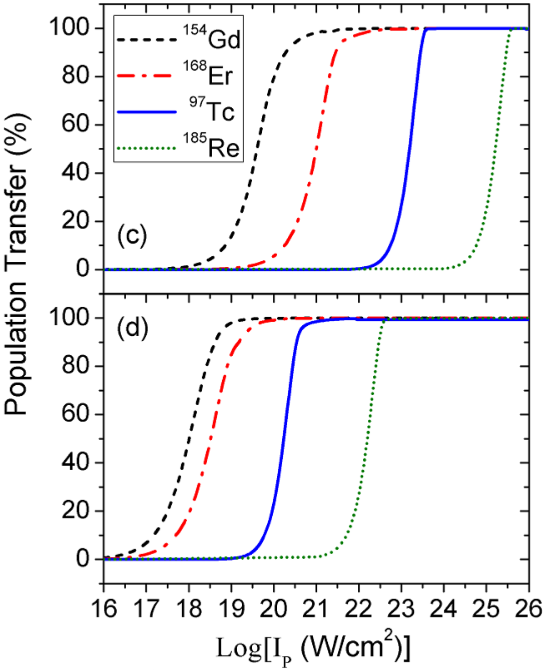


$$|D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2+\Omega_s^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2+\Omega_s^2}}|2\rangle$$



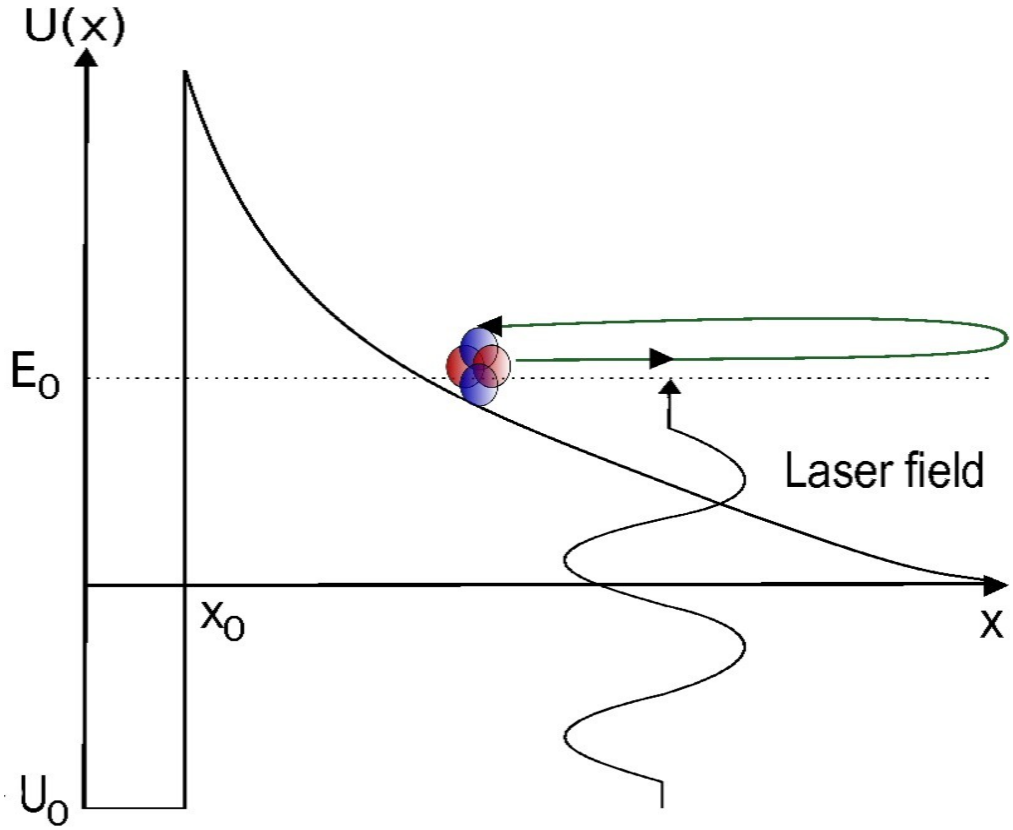
Seeded XFEL →

XFEL → O

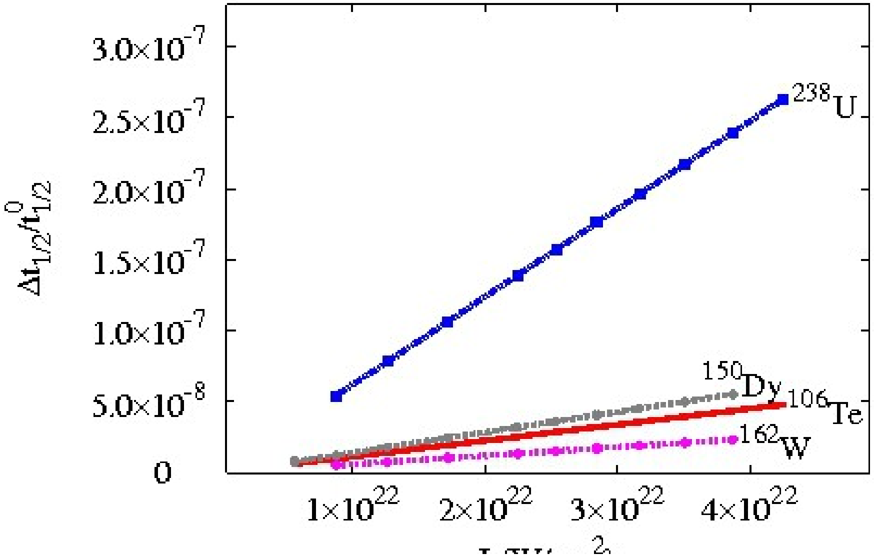


W.-T. Liao, A. Palffy and C. H. Keitel, **Phys. Lett. B 705, 134 (2011)**

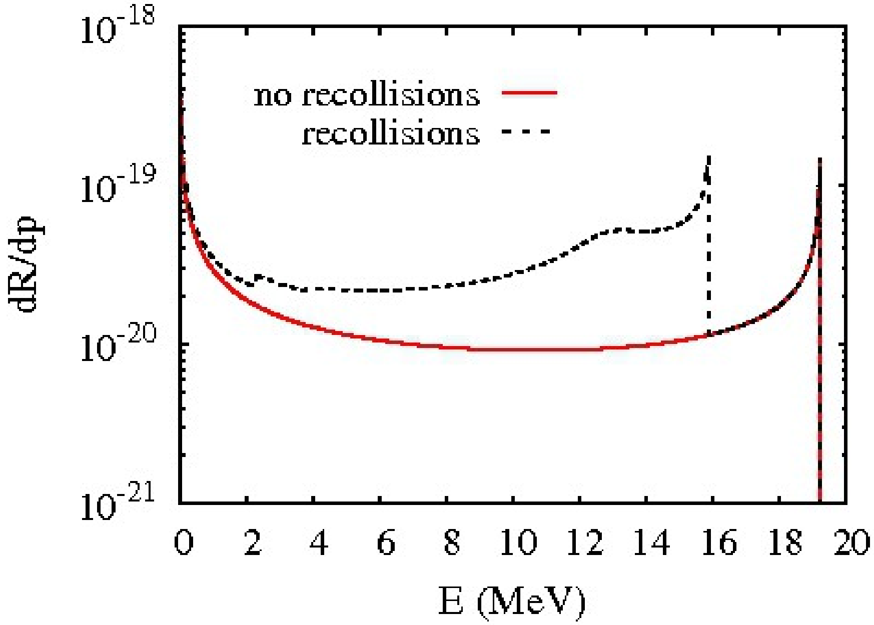
Nuclear tunneling and recollisions in laser-assisted α decay



Non-relativistic process
Semi-classical parameter regime



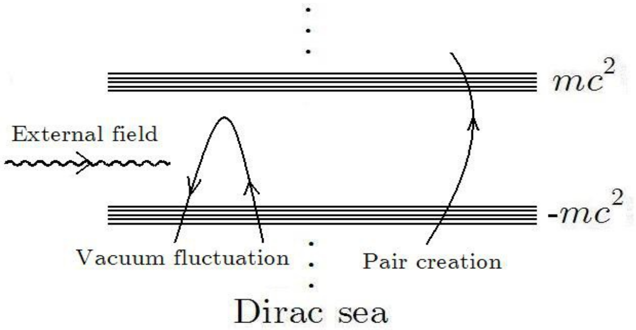
Tunneling rate is barely influenced by a strong optical laser (800 nm)



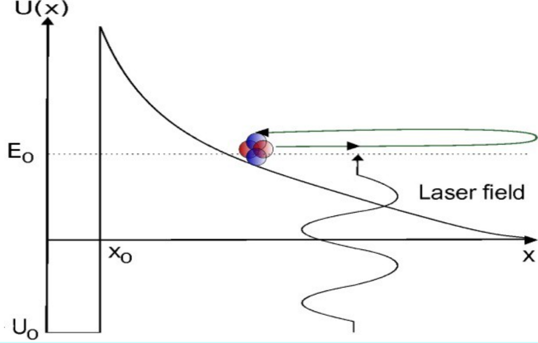
alpha particle spectrum is completely changed by the laser

Recollisions with the daughter nucleus occur at intensities of 10^{22}-10^{23} W/cm^2

H Castaneda Cortes, C Müller, C H Keitel, A Palffy, arXiv 1207.2395 (2012)



Conclusions



Laser-electron interaction: Relativistic Quantum Dynamics, Kapitza-Dirac Scattering, Pair creation & Laser Colliders

Laser-ion interaction: Relativistic Ionisation and Tunneling, Resonant Interaction & QED Metrology, Ion Acceleration

Laser-nuclei interaction: Nuclear Excitation & Coherent Population transfer, Laser-assisted alpha decay&recollisions