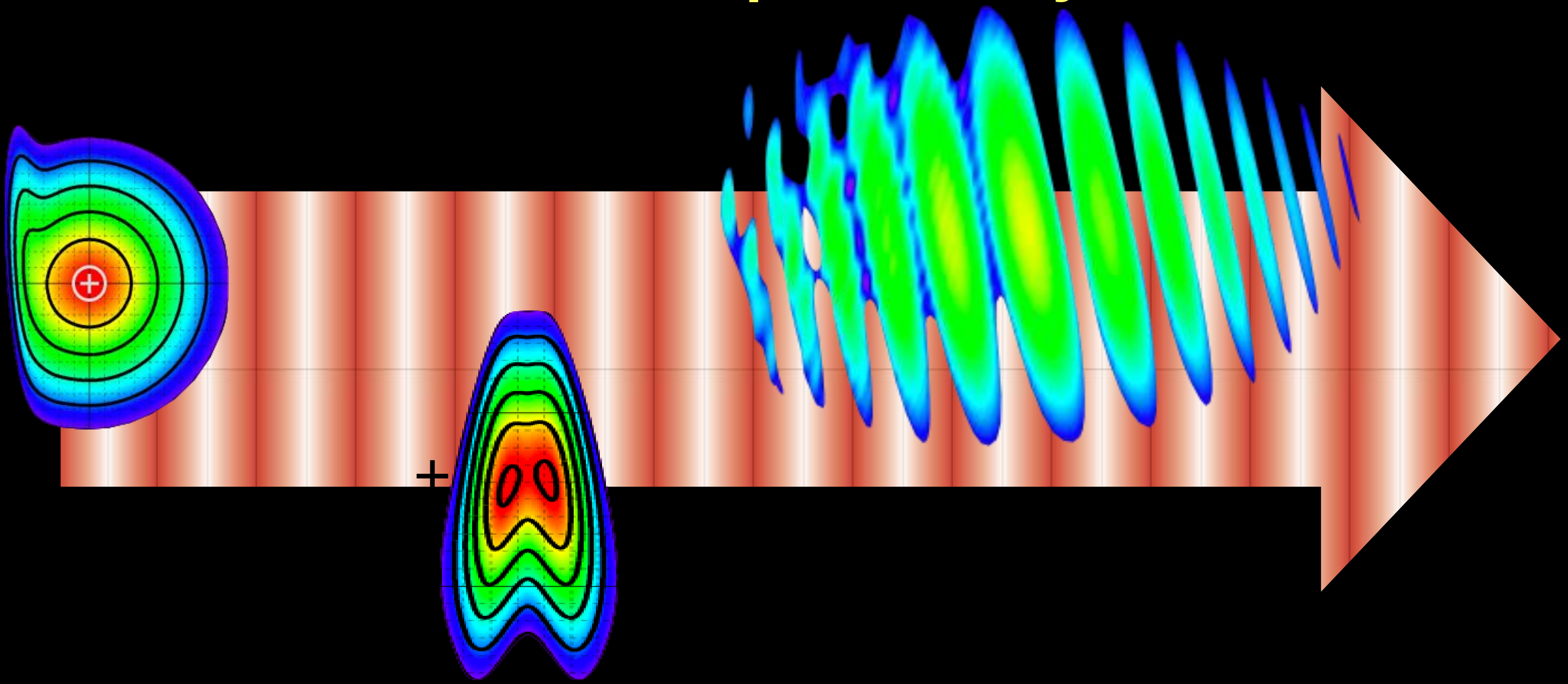
Extremely high-intensity laser interactions with fundamental quantum systems



Christoph H. Keitel, Max Planck Institute for Nuclear Physics

Outline

Laser-Vacuum Interaction:
laser-enhanced vacuum fluctuations and refractivity

Laser-Electron Interaction:
Relat. quantum dynamics, Pair creation & recolliders

Laser-Ion and Nuclei Interaction:
Ionic and Nuclear Quantum Optics via XFEL

Applications: characterising laser pulses, metrology, proton therapy, laser colliders, laboratory astrophysics

see A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, C. H. Keitel, Rev. Mod. Phys. 84, 1177 (2012)
entitled: Extremely high-intensity laser interactions with fundamental quantum systems

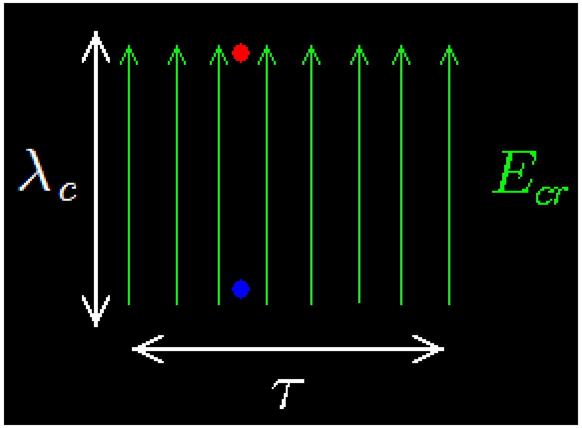
Quantum Vacuum & Critical fields

- Virtual particles are present
- They live for a very short time and cover a very short distance ($\tau = \hbar/mc^2$ and $\lambda_c = \hbar/mc$, respectively). For electrons and positrons: $\lambda_c \approx 10^{-11}$ and $\tau \approx 10^{-21}$s.

critical fields: physical meaning

$$\frac{\hbar}{mc} \times eE_{cr} \sim mc^2$$

$$\frac{e\hbar}{mc} \times B_{cr} \sim mc^2$$

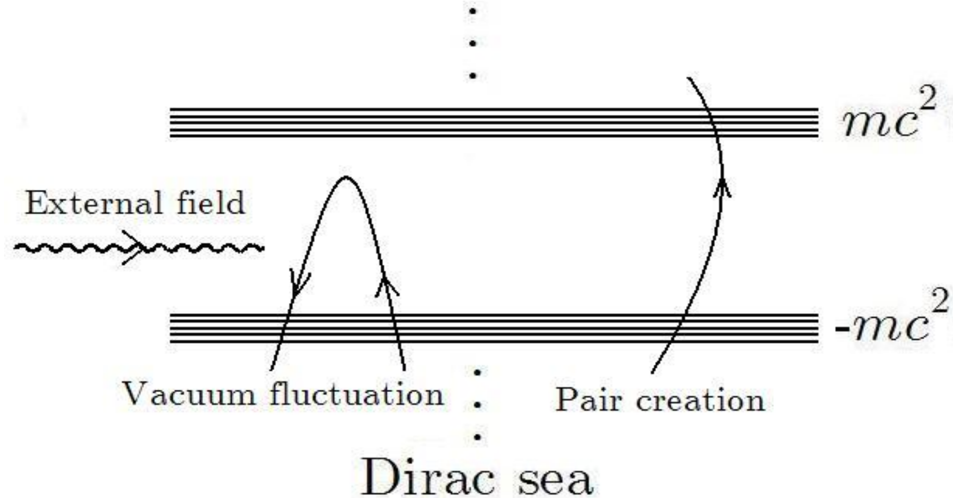


Available in highly charged ions but not feasable in near future with laser

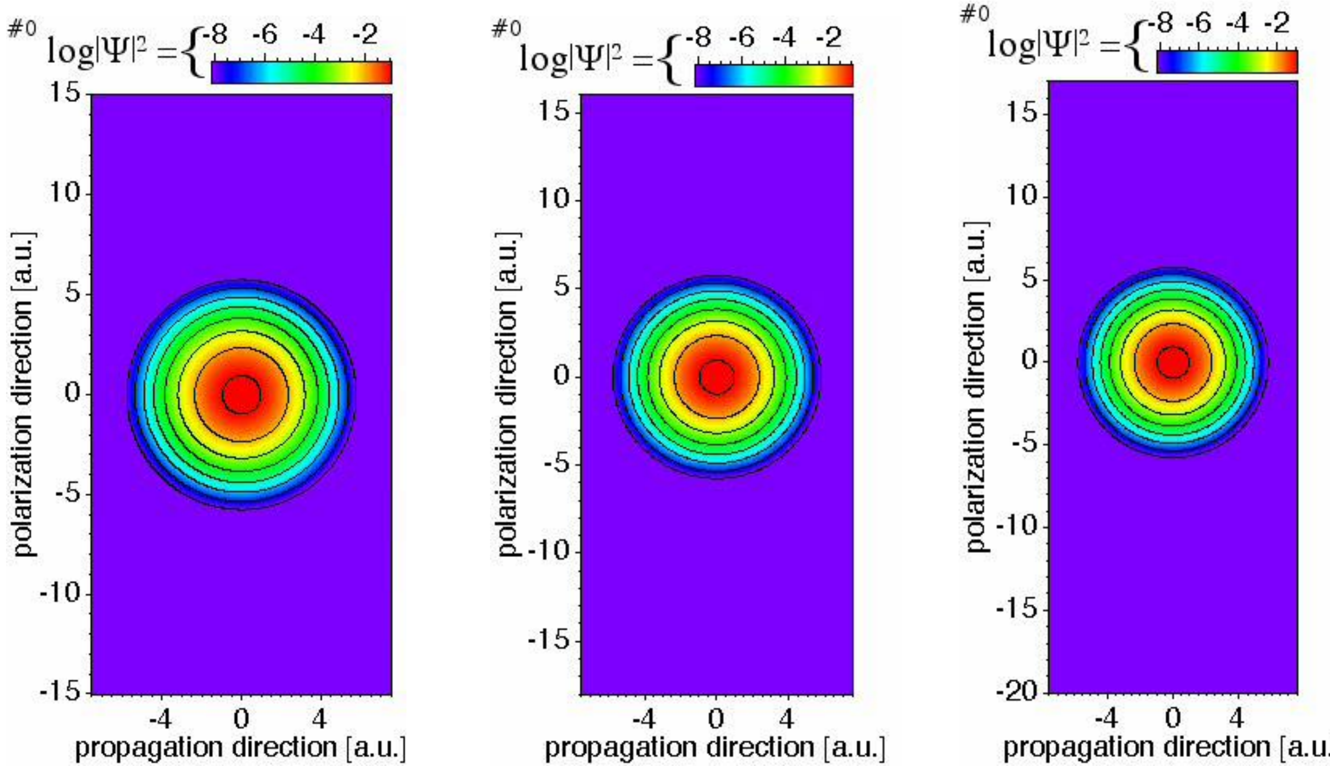
$$I_{cr} = \frac{cE_{cr}^2}{8\pi} = 2.3 \times 10^{29}\, W/mc^2$$

Effects for much smaller fields ?

Quantum Vacuum: Real and Virtual Pairs



Dirac dynamics of an electron with negative energy in crossed laser beams: pairs from 10^{26} W/cm^2 approaching critical el. field $m^2c^3/e\hbar$



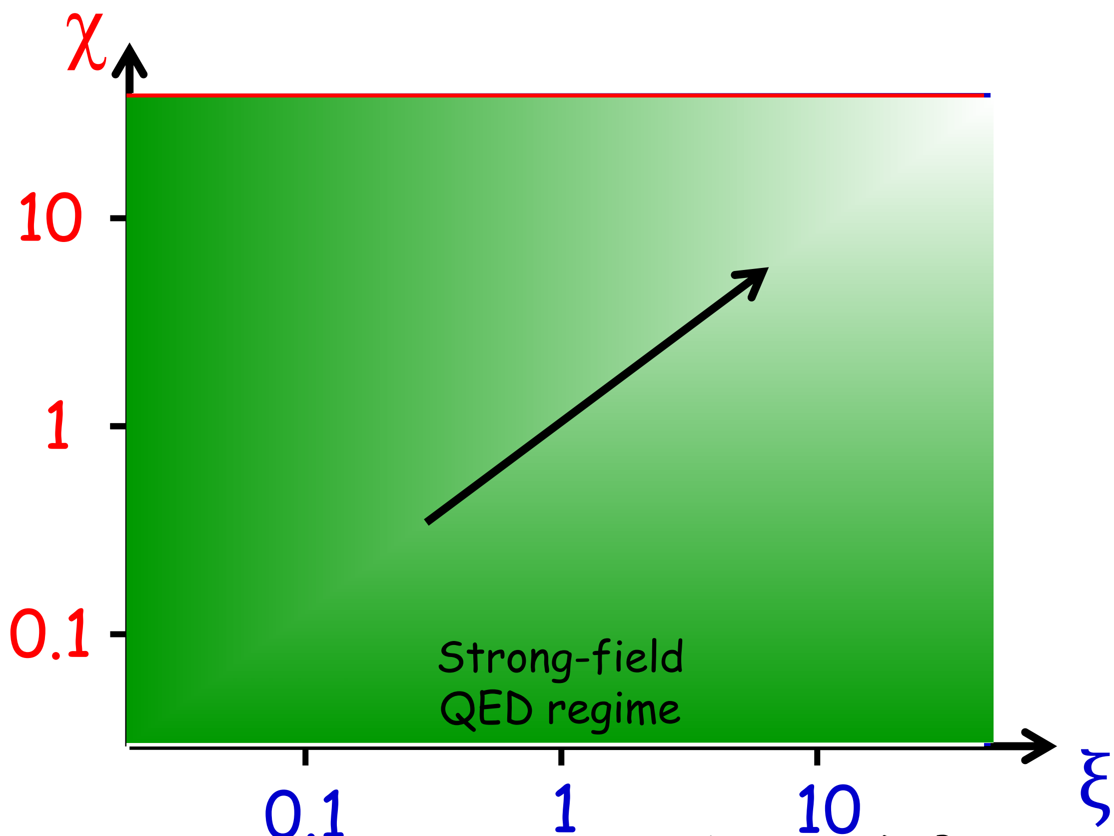
Regimes of QED in a strong laser field

A particle (e^-, e^+ or γ) with energy $\mathcal{E}$ ($\hbar\omega$ for a photon) collides head on with a plane wave with amplitude E_L and angular frequency ω_L (wavelength λ_L)

Relevant parameters (Di Piazza et al., RMP 84, 1177 (2012)):

$$\xi = \frac{1}{2\pi}\frac{|e|E_L\lambda_L}{mc^2} = \frac{|e|E_L\bar{\lambda}_C}{\hbar\omega_L}$$

$$\chi = 2\frac{\hbar\omega}{mc^2}\frac{E_L}{E_{cr}} = \frac{E_L}{E_{cr}}\bigg|_{\text{r. f.}}$$



Courtesy Di Piazza

Optical laser and electron accelerator technology

Optical laser technology ($\hbar\omega_L = 1$ eV)	Energy (J)	Pulse duration (fs)	Spot radius (μm)	Intensity (W/cm^2)
State-of-art (Yanovsky et al., Opt. Express (2008))	10	30	1	2x10^{22}
Soon (APOLLON, Vulcan, Astra-Gemini, BELLA etc…)	10-100	10-100	1	10^{22}-10^{23}
Near future (2020) (ELI, HiPER)	10^4	10	1	10^{25}-10^{26}

Electron accelerator technology	Energy (GeV)	Beam duration (fs)	Spot radius (μm)	Number of electrons
Conventional accelerators (PDG)	10-50	10^3-10^4	10-100	10^{10}-10^{11}
Laser-plasma accelerators (e.g. Leemans et al., PRL 2013)	0.1-5	50	5	10^9-10^{10}

$$\xi = 7.5\frac{\sqrt{I_L[10^{20}\mathrm{W/cm^2}]}}{\hbar\omega_L[\mathrm{eV}]}$$

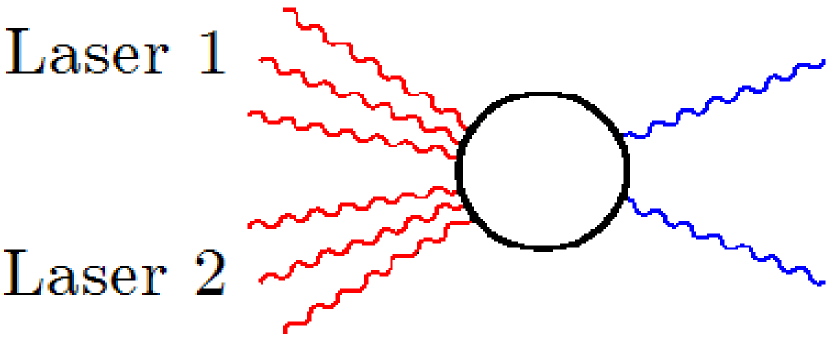
$$\chi = 5.9 \times 10^{-2}\,\mathcal{E}[\mathrm{GeV}]\sqrt{I_L[10^{20}\,\mathrm{W/cm^2}]}$$

Present technology allows in principle the experimental investigation of strong-field QED and laser particle physics

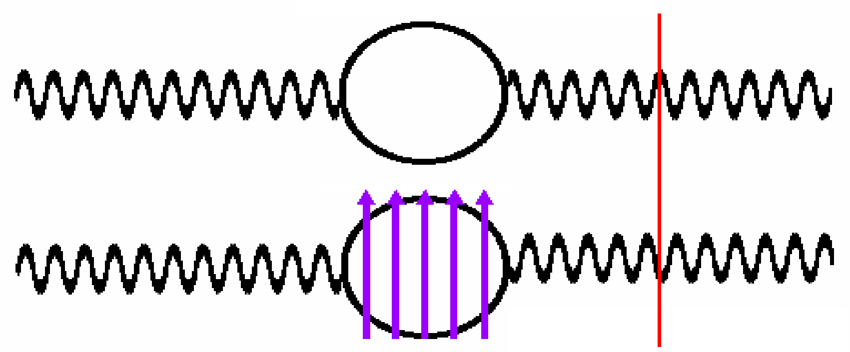
Courtesy Antonino Di Piazza

Effects to think of e.g. …..

- *Harmonic generation* in vacuum in the collision of two strong laser beams

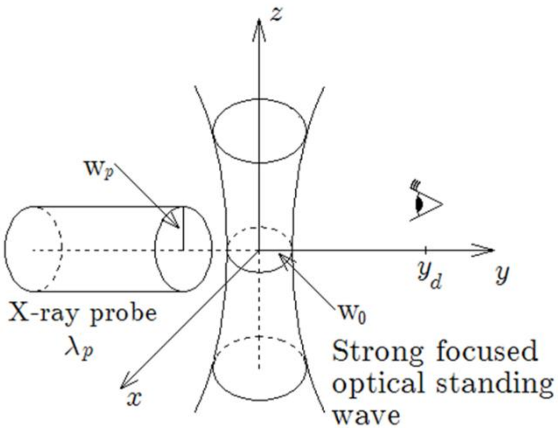


- Vacuum refractive indices with phase shifts in the presence of a strong standing wave



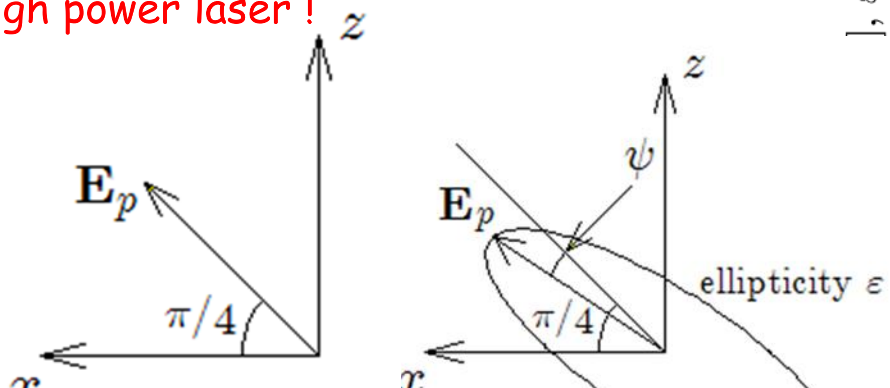
Effects of vacuum fluctuations for realistic laser intensities ?

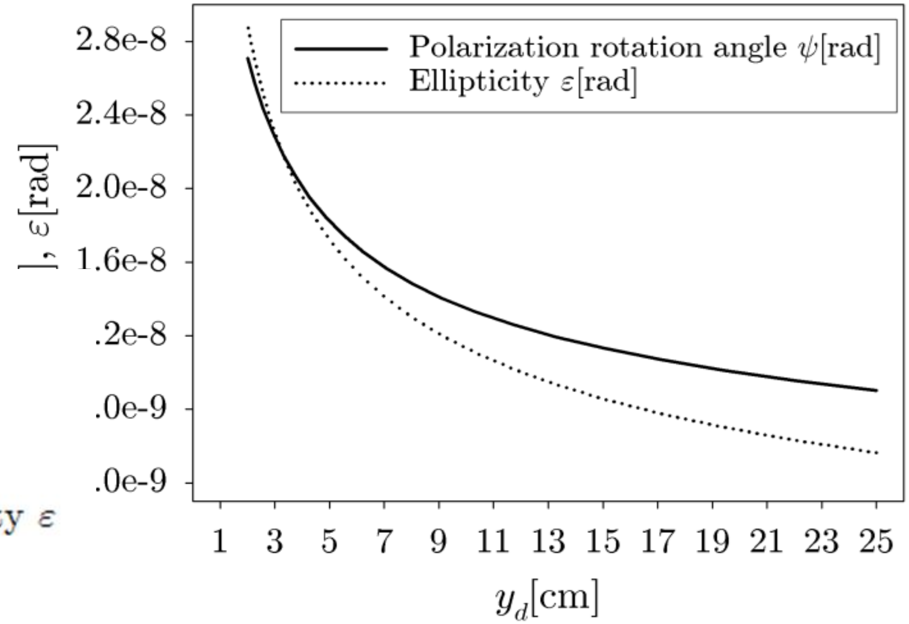
In the presence of strong fields the Maxwell Lagrangian density has to be modified to take into account vacuum fluctuations



$$\mathscr{L} = \frac{1}{2}(E^2 - B^2) + \frac{2\alpha^2}{45m^4}\left[(E^2 - B^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$$

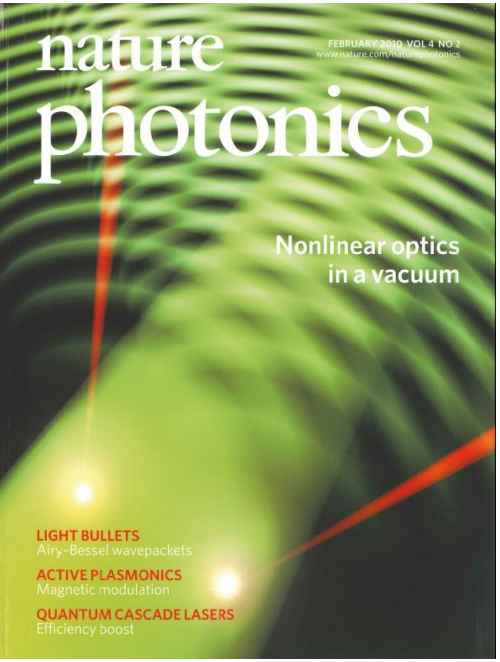
combination XFEL & high power laser !





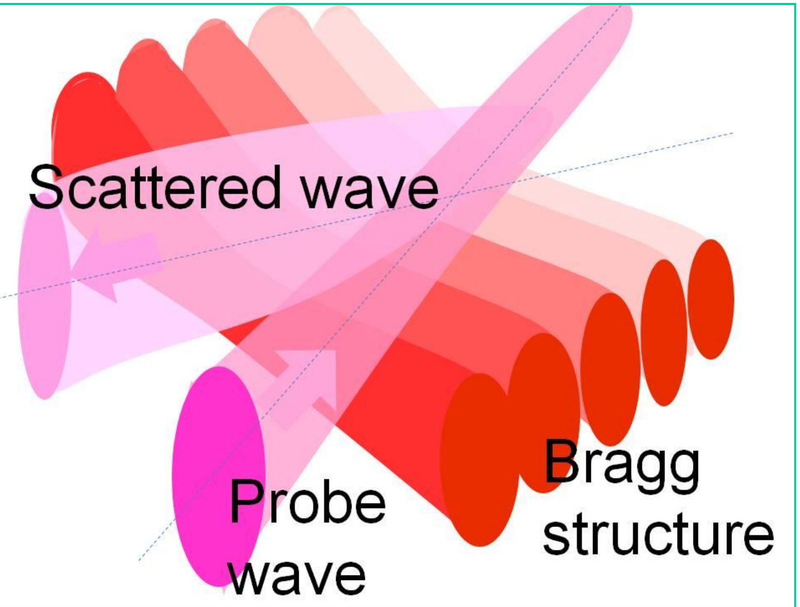
Probe field polarization and elipticity before and after interaction with intense field

A. Di Piazza et al., PRL 97, 083603 (2006) & see also T. Heinzl et al. Opt. Comm. 267, 318 (2006)



- Strong field's parameters: 10 PW, 800 nm, 30 fs, focused to one wavelength (intensity 10^{24} W/cm^2)
- Weak field's parameters: 100 TW, 527 nm, 100 fs focused to 290 μm (intensity $7.5*10^{16}$ W/cm^2)
- Separation between the two strong beams: 64 μm
- The position of the x in the figure corresponds to the classical formula: $(n+1/2)\lambda_p = D \sin\phi$
- With the above parameters one obtains about 6.4 diffracted photons per shot

B. King et al, Nature Photonics **4**, 92 (2010), PRA 2010 and New J. Phys. (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)

Single charged particle quantum dynamics

Dirac Equation $$i\hbar\partial_t\Psi = \left\{c\boldsymbol{\alpha}\cdot\left[\mathbf{p}+\frac{e}{c}\mathbf{A}\right]+\beta mc^2+V\right\}\Psi$$

Laser-Driven Atoms: solved numerically in few groups since 1997

Alternatives: Klein Gordon (W.Becker, Faisal, Reiss), Schrödinger beyond Dipol, Expansions of Dirac Eq., Classical/Semiclassical Approaches;

$$\frac{d}{dt}\vec{p} = m\frac{d}{dt}\frac{\dot{\vec{r}}}{\sqrt{1-(\dot{\vec{r}}/c)^2}} = \vec{F}_{Laser} + \vec{F}_{Coulomb}$$

Nonresonant Laser-Particle/Ion Interaction: Dirac Eq. for laser driven atomic systems

- Problems:

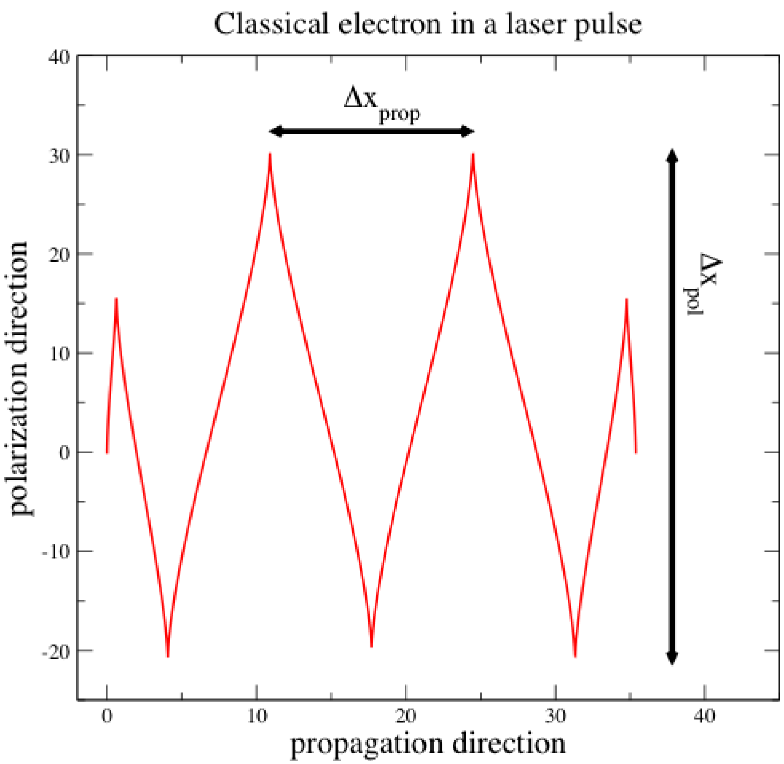
G R Mocken et al., Comp. Phys. Comm. 178, 868 (2008)

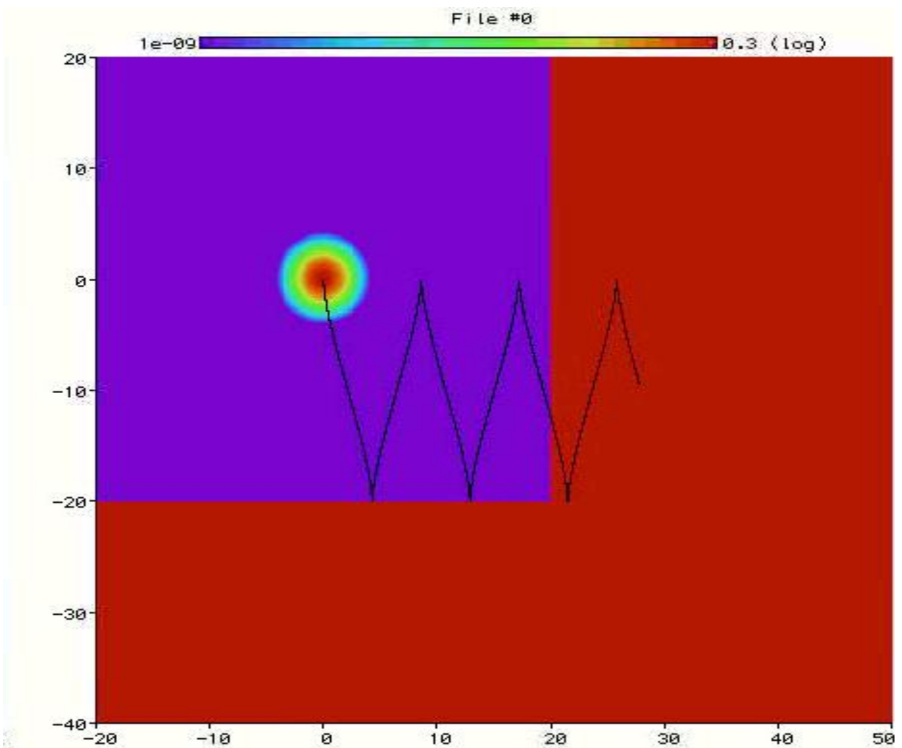
- Dirac very similar to Schrödinger, but

$$\Delta t_{\text{Dirac}} \approx 10^{-5}\text{a.u.} \ll \Delta t_{\text{Schrödinger}} \approx 10^{-3}\text{a.u.}$$

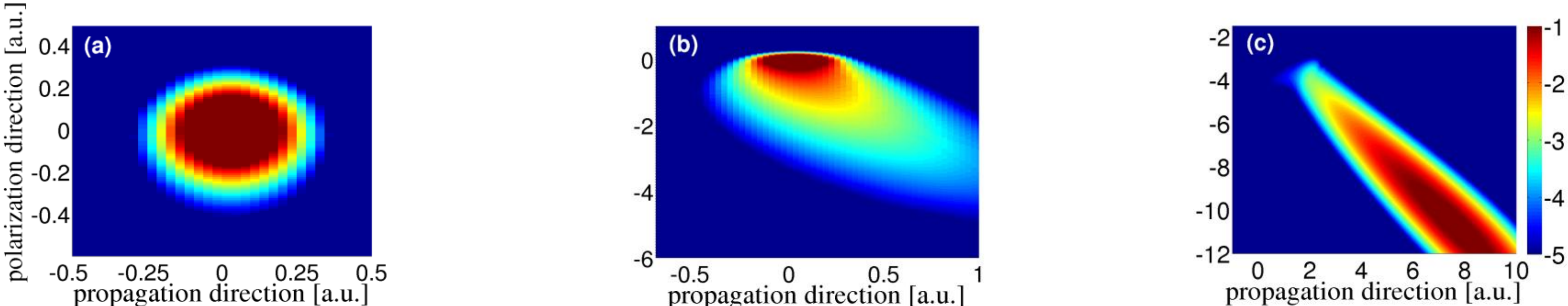
$$\Delta x_{\text{pol}} = \frac{2E_0}{\omega^2}, \quad \Delta x_{\text{prop}} = \frac{\pi}{2c}\frac{E_0^2}{\omega^3}$$

- Solutions:
- “Moving position space grid” to keep the grid size small
- “Moving momentum space grid” to keep the position space grid resolution small
- “Variably-sized position space grid” to dynamically adapt the grid size to requirements





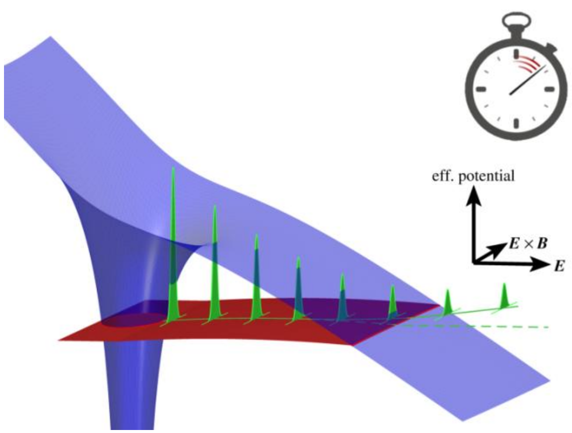
Bound electrons and ionisation from highly charged ions

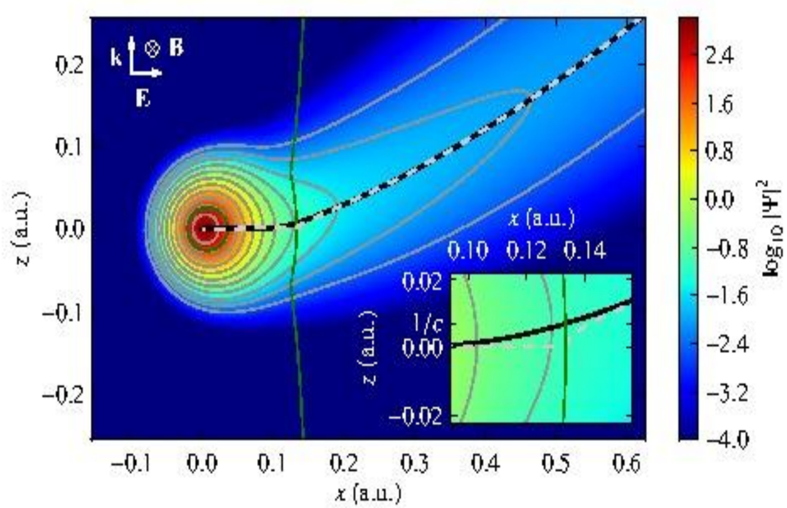


-> increasing laser intensity ->

Directions and yields of ionisation are characteristic for laser intensity and ionic charge
=> Sensitive means of measuring extremely intense laser intensities

Tunneling and the time in the classically forbidden barrier





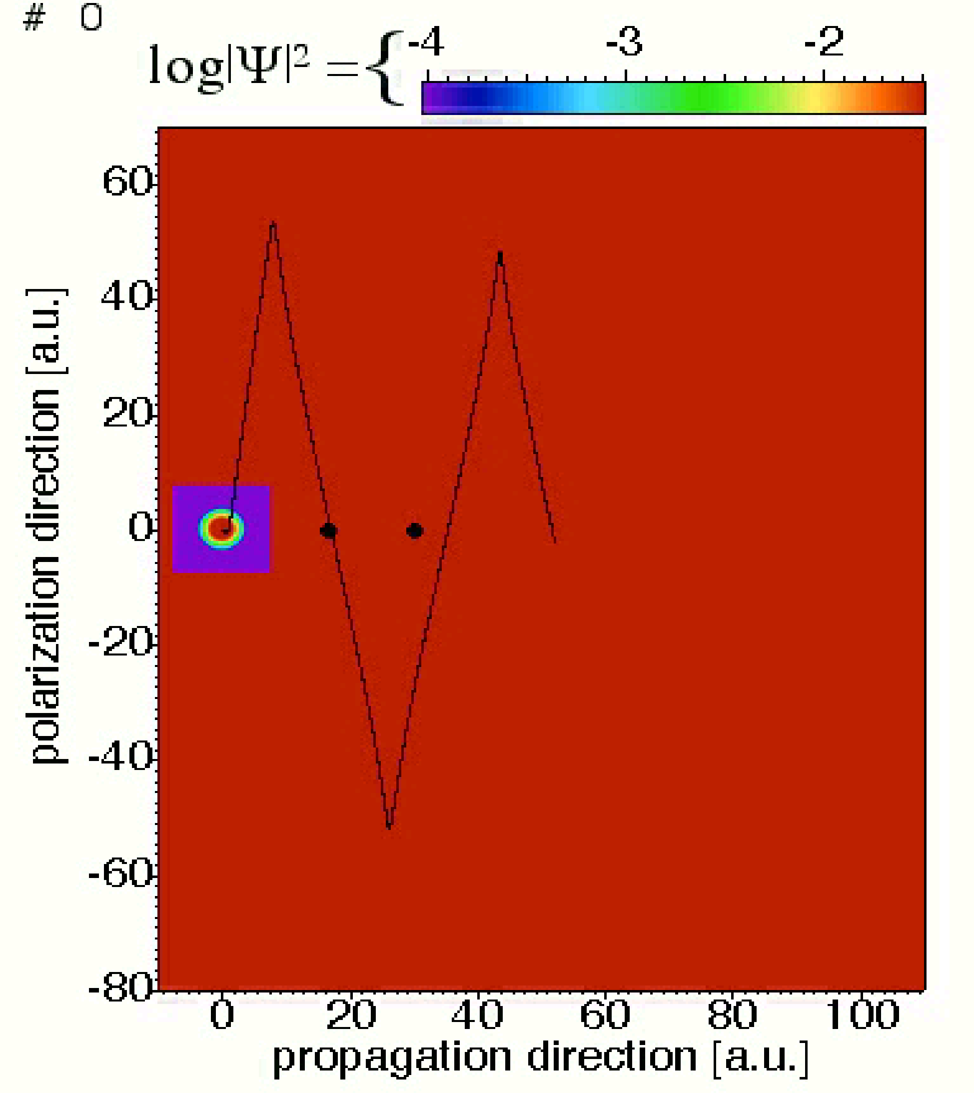
Numerical Dirac Simulation:

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

M. Klaiber, et al, **PRL** 110, 153004 (2013)

Electrons: Dirac dynamics in strong laser pulses

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



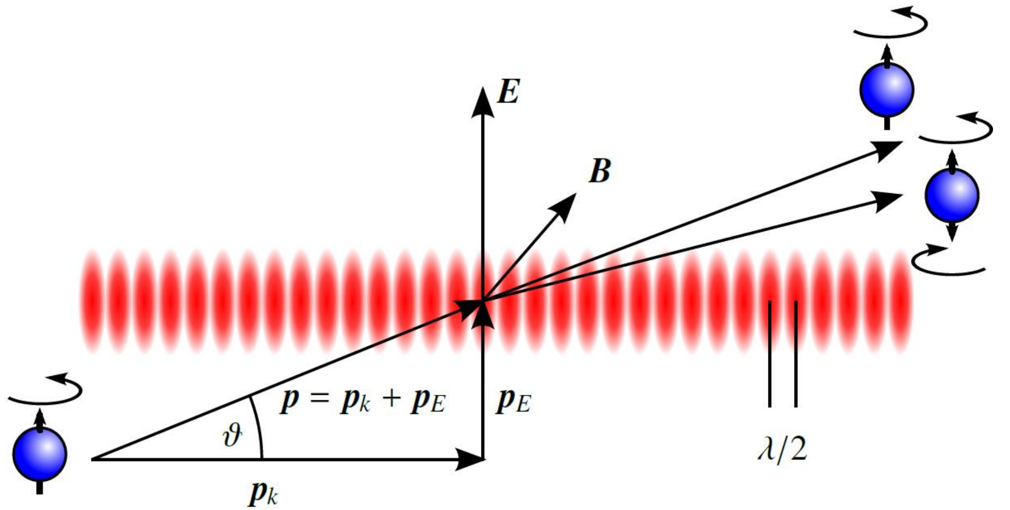
E= 50 a.u., w= 1 a.u., ca. 36% speed of light, Sn^{50+}

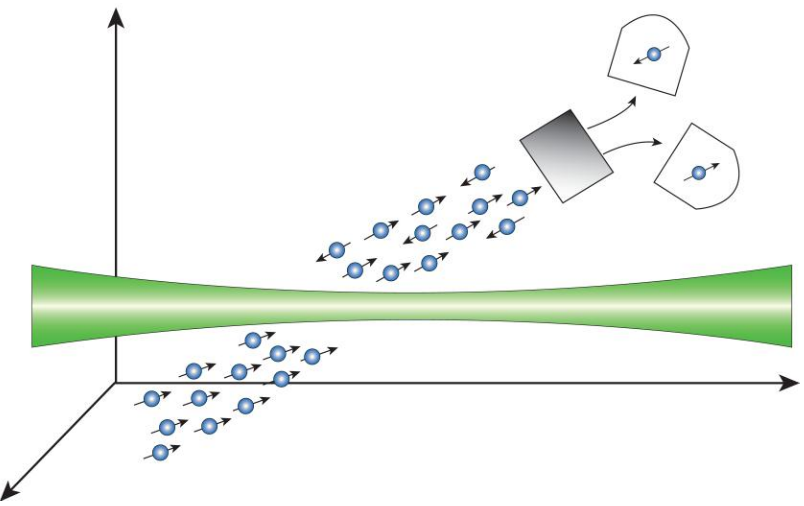
- Drift in laser-propagation direction via magnetic field component
  - problem for recollisions
- Enhanced quantum spreading with increased laser intensity & quantum interference at scattering processes
- Dirac propgation time consuming enhanced via adaptive grids

- Quantum features in various situations of relevance

Intrinsic quantum effects:
Spin dynamics & QED for electron-laser scattering

Scattering of electron at crossed laser fields with spin flip (Kapitza-Dirac effect) via propagation of Dirac equation involving laser fields



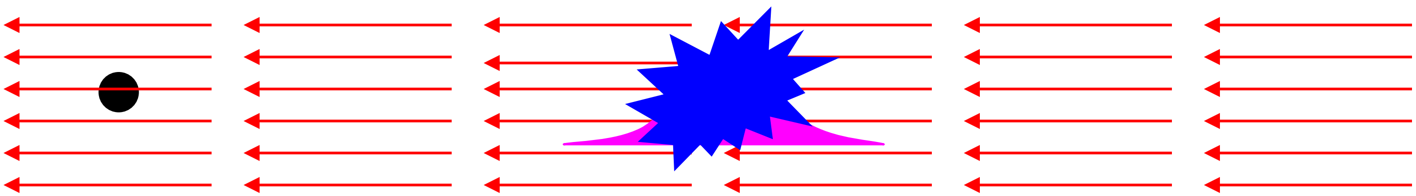


A full QED approach reveals quantum nature of the laser field: collapse and revivals for spin oscillations as magnetic coupling weak even for rather intense laser pulses of about 10^{18} W/cm²

S. Ahrens et al, PRL 109, 043601 (2012) & O. Skoromnik et al, PRA 2013

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)

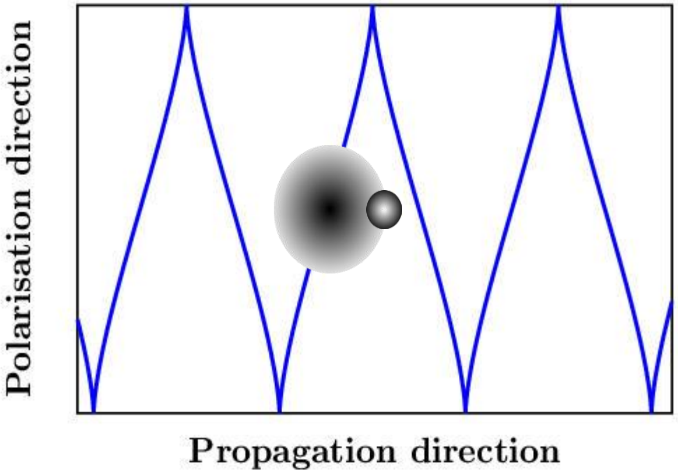
Radiative reaction

$$m_0 \frac{du^\mu}{ds} = -eF_T^{\mu\nu} u_\nu$$

$$\partial_\mu F_T^{\mu\nu} = -e \int ds \delta(x - x(s)) u^\nu \longrightarrow F_T^{\mu\nu}(x) = F^{\mu\nu}(x) + F_S^{\mu\nu}(x)$$

Feed-back of modified fields yields Lorentz-Abraham-Dirac equation.

- In the realm of classical electrodynamics, i.e. if quantum effects are negligible, the Lorentz-Abraham-Dirac equation can be approximated by the so-called Landau-Lifshitz equation (Landau and Lifshitz, 1947; Spohn, Europhys. Lett. 2000; Gralla et al., Phys. Rev. D 2009)



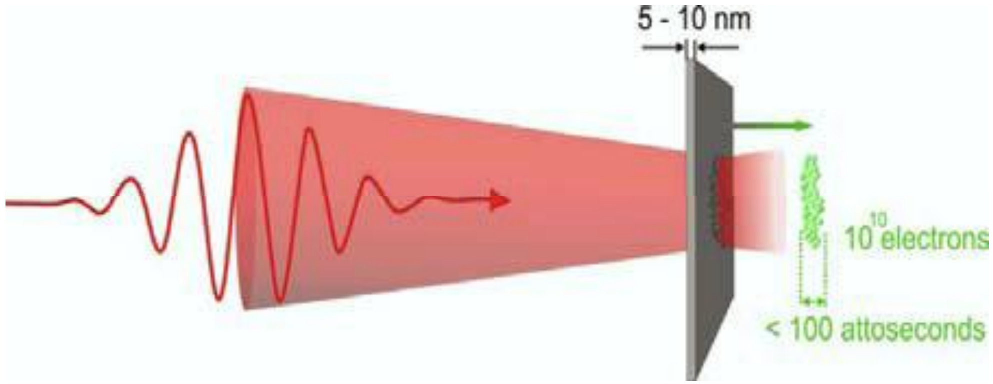
Damping &
Reabsorption
of initially emitted
Light alters Dynamics

first with lasers in JPB 31, L75 (1998)

Radiation reaction effects of electrons in plasma

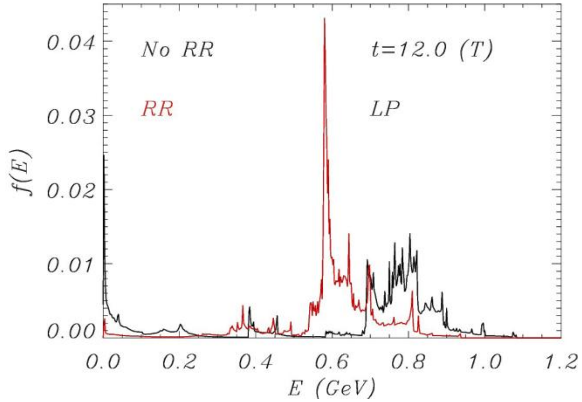
Radiation reaction (RR) is expected to play a relevant role in the interaction between an intense (~10^{23} W/cm^2) laser beam and a plasma

Strong laser beam interacting with a plasma slab: RR effects on the energy spectrum & for generation of forward Raman scattering



The effects of RR have been taken into account by including in the particle in cell code new force terms according to the one-particle Landau-Lifshitz equation

Laser and plasma parameters:
wavelength λ=0.8 μm, intensity I=2.33 x 10^{23} W/cm^2, laser pulse duration 7 cycles, plasma density $n=100n_c$, plasma thickness 1λ.



RR effects for linear polarization strongly narrow the ion spectrum

Instabilities in plasmas may be enhanced via radiative reaction

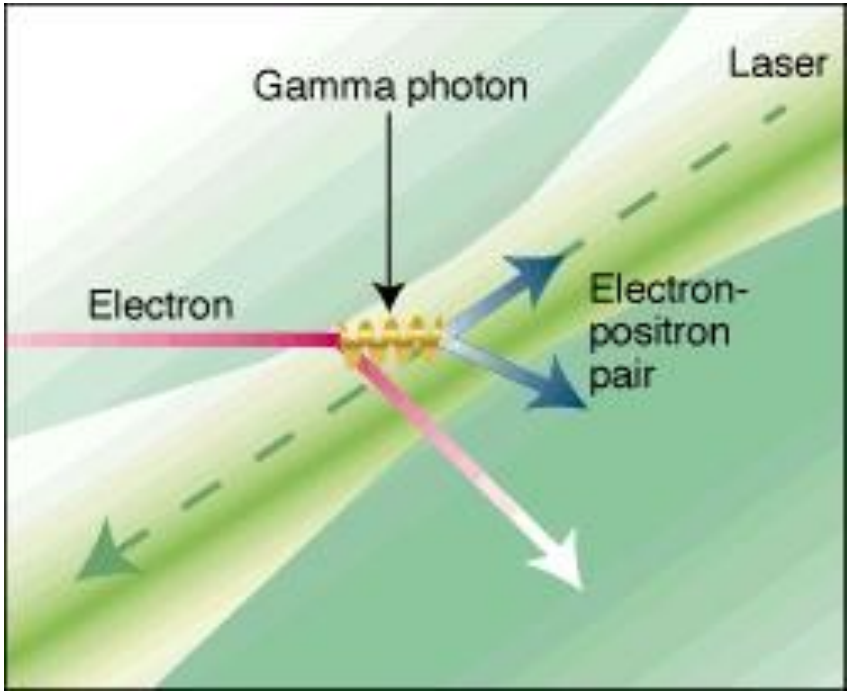
M. Tamburini et al., Nuc. Inst. Meth. 653, 181 (2011)

N Kumar et al., Phys. Rev. Lett. 111, 105001 (2013)

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

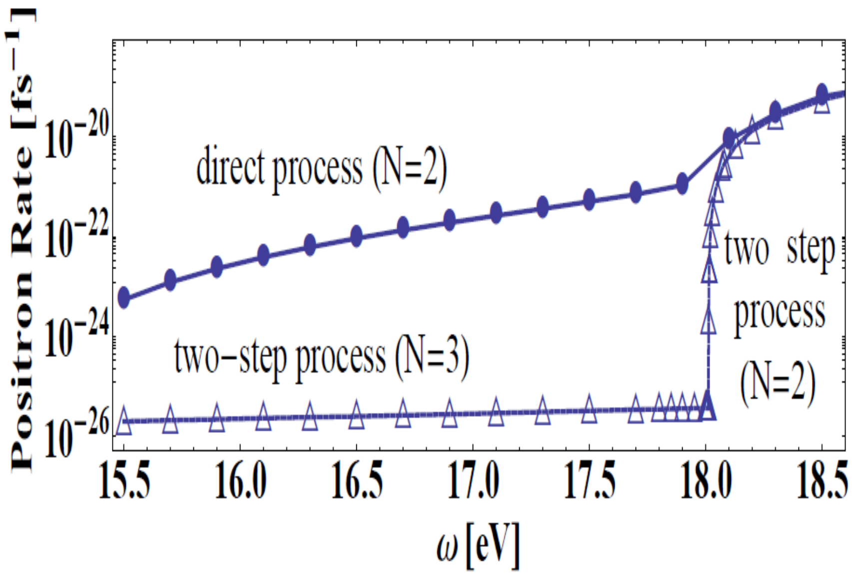
two-step: $e + \omega \rightarrow e' + \gamma$

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

Compton back scattering &

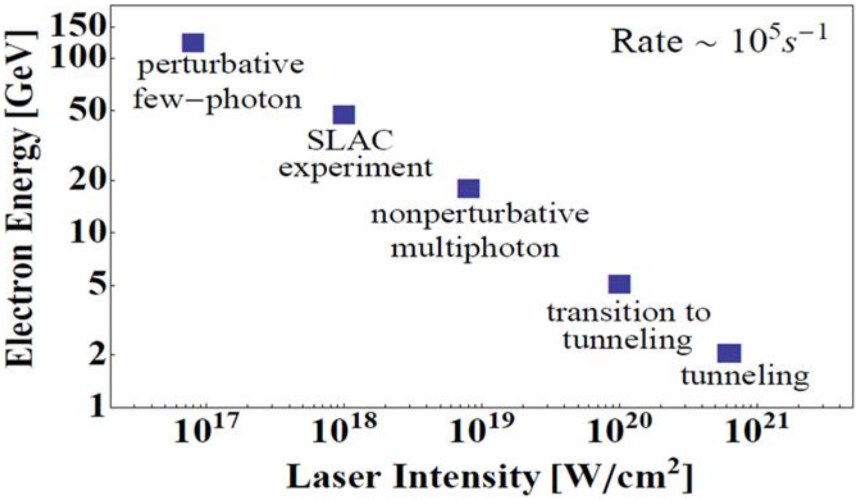
Multiphoton Breit-Wheeler

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

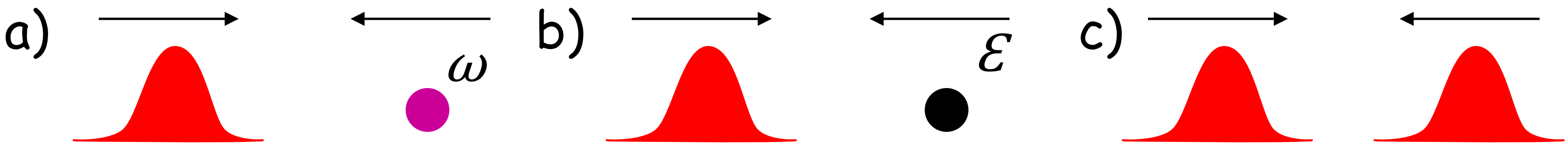
- Substantial pair production rate in various interaction regimes
- Novel usage of DESY beamline (17.5 GeV) for pair production
- The future of pair production: all-optical setup



Huayu Hu et al., Phys. Rev. Lett. 105, 080401 (2010)

Electron-positron pair production: Mechanisms

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

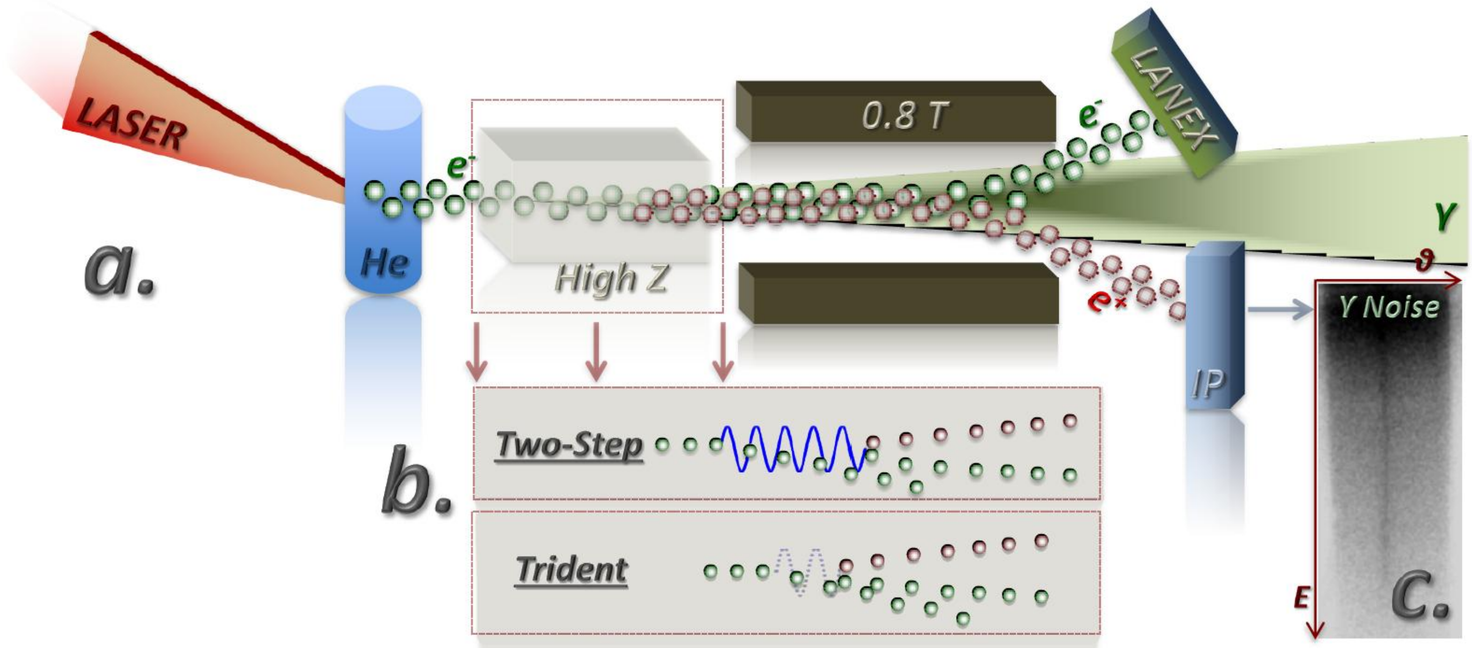


e.g. Schützhold et al PRL 2009 - Hu et al PRL 2010 - Ruf et al PRL 2009 perturbative multiphoton regime at $\xi \gg 1$ and non-perturbative tunneling regime at $\xi \gg 1$– see also Di Piazza et al, RMP 2012 or arXiv 2012

	Parameter (head-on collision)	Rate scaling (tunneling)
Laser-photon collision (a))	$\varkappa=(2\omega/m)(E_L/E_{cr})$	$\sim m\varkappa^{3/2}\exp(-8/3\varkappa)$
Laser-charge collision (b))	$\chi=(2\mathcal{E}/m)(E_L/E_{cr})$	$\sim m(Z\alpha)^2\exp(-3^{0.5}2/\chi)$
Laser-laser collision (c))	$\Upsilon=E_L/E_{cr}$	$\sim m\Upsilon^2\exp(-\pi/\Upsilon)$

Lab. astrophysics: Positron Jets with lasers

Theory support for experimental campaign carried out at the HERCULES laser (CUOS, Michigan) with teams around G. Sarri, K. Krushelnick & M. Zepf



(a) Table-top experimental setup for the production of short, narrow, and ultra-relativistic positron beams. (c) 30 fs positron jets as recorded by the image plate.

(b) Our theoretical analysis revealed that the scaling with the charge number Z and the thickness d is consistent with a two-step process (Bremsstrahlung+Bethe-Heitler)

Parameters & possible astrophysical significance

An ultrashort (30fs), ultra-collimated (3mrad) high energy (E_{MAX} = 150 MeV) positron beam generated.

Overall positron yield: 3×10^{7}

Overall lepton yield: 3×10^{8}

Positron density: 2×10^{14} cm^{-3}

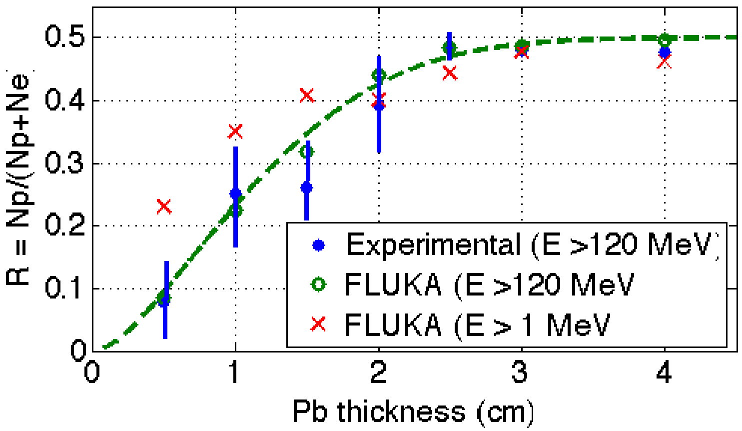
Lepton density: 2×10^{15} cm^{-3}

Intensity: 10^{19} erg s^{-1} cm

Parameter not as in astrophysical jets but with scaling results may become relevant

G. Sarri *et al.*, Phys. Rev. Lett. 110, 255002 (2013)

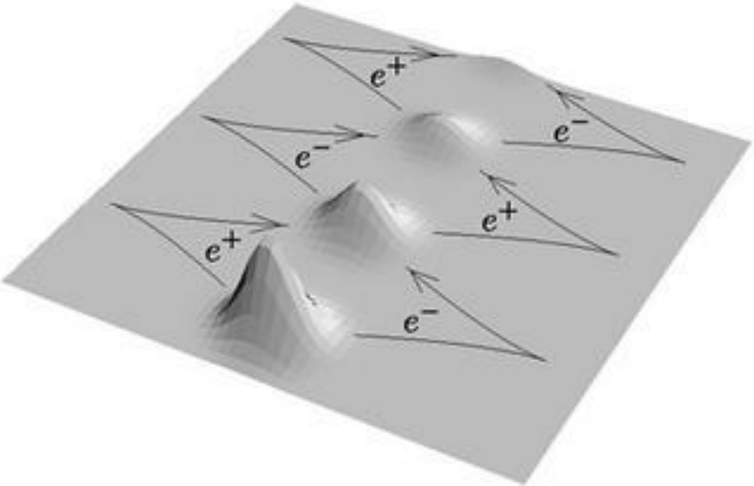
In a subsequent experimental campaign at Astra Gemini (Oxford) with our theory support ultra-relativistic neutral electron-positron beams have been generated (G. Sarri, et al., Nature Comm. 6, 4767 (2015))



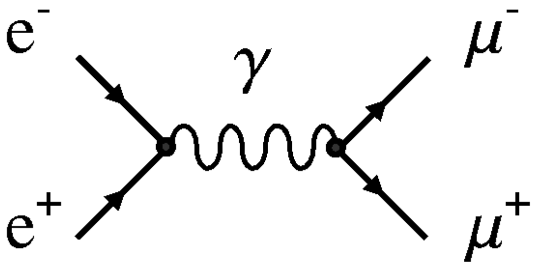
Generation of e^-/e^+ jets with variable % of e^+ from 0 to 50%!
Plasma dynamics of those neutral lepton- antilepton jets yet to be studied

Particle Physics with Strong Lasers

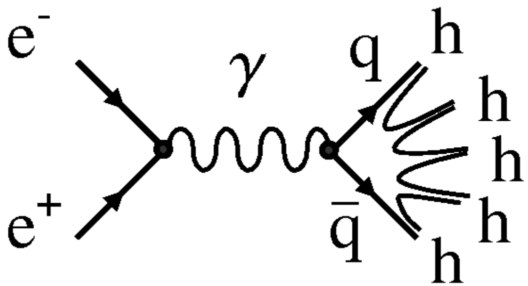
Positronium dynamics in an intense laser field:



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



muon production
$(m_\mu c^2 = 106\ \mathrm{MeV})$



pion production
$(m_\pi c^2 = 140\ \mathrm{MeV})$

energetic threshold for muon:

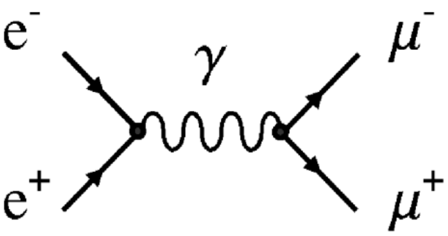
$$2eA \geq 2Mc^2$$

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

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

Theory of laser-driven muon creation

Employ Volkov states in the usual amplitude for $e^+e^- \rightarrow m^+m^-$:

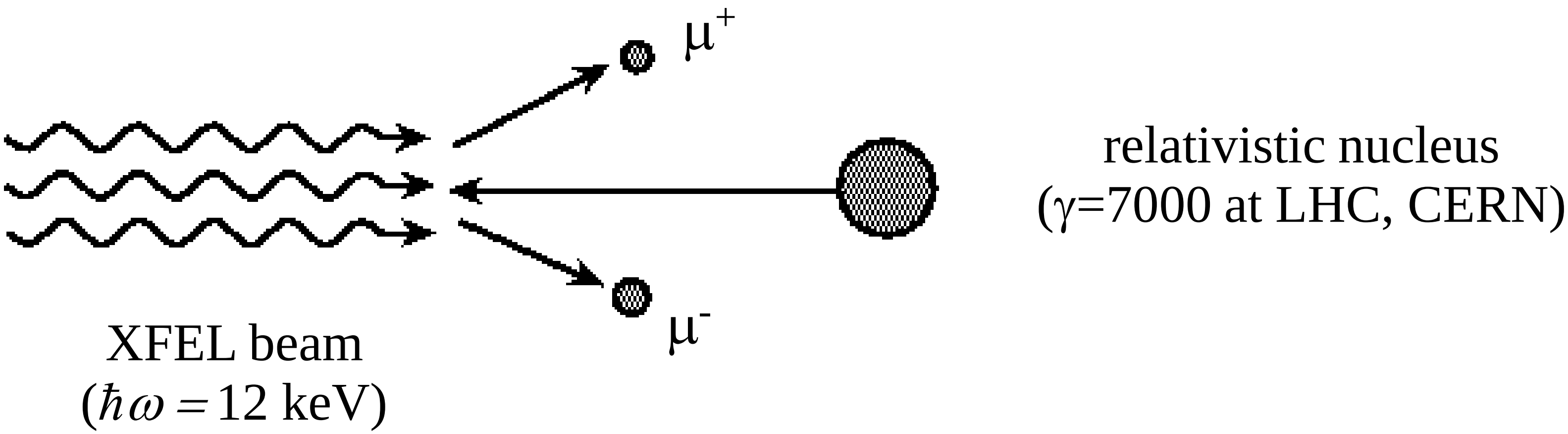


$$S_{e^+e^-\to\mu^+\mu^-} = -\mathrm{i}\alpha \int d^4x\, d^4y\, \overline{\Psi}_{p_+}(x)\gamma^\mu \Psi_{p_-}(x)$$
$$\times D_{\mu\nu}(x-y)\overline{\Psi}_{P\_}(y)\gamma^\nu \Psi_{P_+}(y)$$

Average over the momentum distribution in the Ps ground state:

$$S_{\mathrm{Ps}\to\mu^+\mu^-} = \int \frac{d^3p}{(2\pi)^3}\, \Phi(\boldsymbol{p})\, S_{e^+e^-\to\mu^+\mu^-}$$

Muon pair creation in XFEL-nucleus collisions



- Relativistic Doppler shift leads to

$$\hbar\omega' = (1+\beta)\gamma\hbar\omega = 168 \text{ MeV}$$

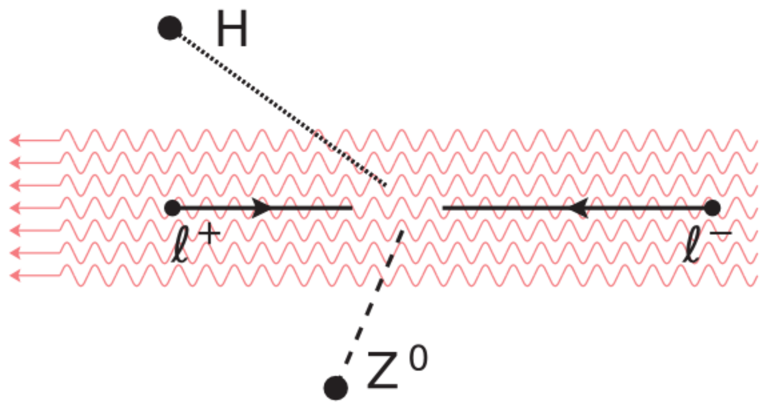
in nuclear rest frame

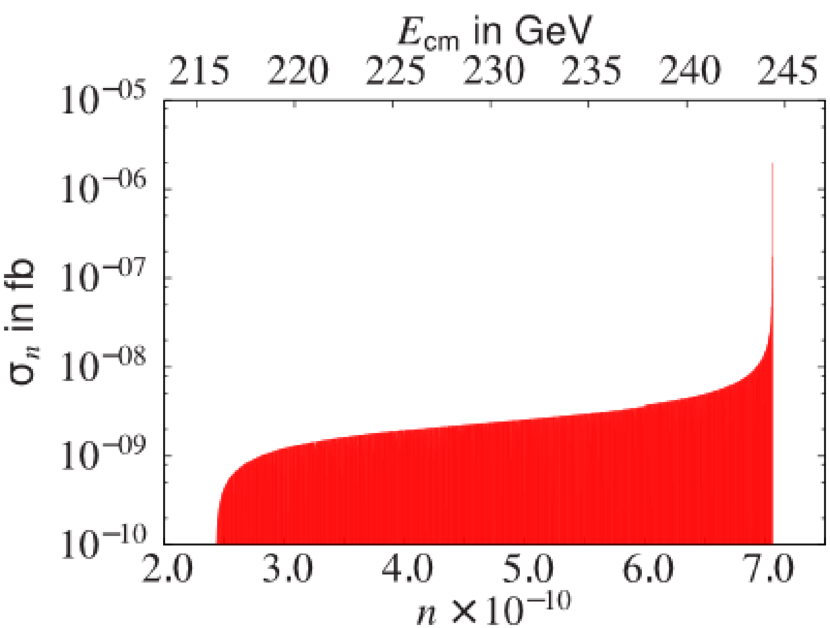
- Energy threshold $\Delta\varepsilon = 2Mc^2 = 211$ MeV for $\mu^+\mu^-$ creation can be overcome by absorption of two x-ray photons

For ion beam with 10^{11} particles and XFEL pulse with 100 fs, 40 kHz and 10^{22} W/ cm ^{2}
=> 1 muon pair per second envisaged

C. Müller et al, PRL 101, 060402 (08) and, Phys. Lett. B 672, 56 (09)

Higgs boson creation in laser-boosted lepton collisions

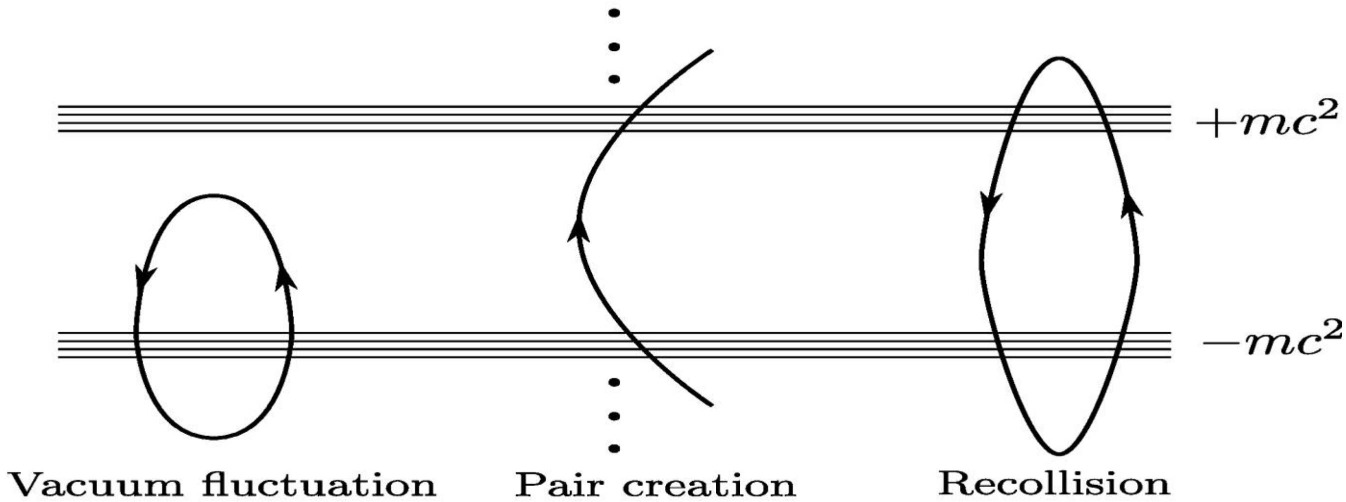




	$\mu^+\mu^-$	e^+e^-
Intensity parameter ξ	1	1
Laser frequency (eV)	1	1
Laser intensity I (W/cm^2)	7.6×10^{22}	1.8×10^{18}
Free lepton energy p^0 (GeV)	71	71
Lorentz factor γ	670	1.4×10^5
Beam waist w_x (mm)	0.8	170
Beam waist w_y (μm)	1.2	1.2
Pulse duration (ns)	11.3	5×10^5
Pulse power (PW)	2.3×10^3	11
Pulse energy (GJ)	26	5.4×10^3
Total cross section (fb)	38	38

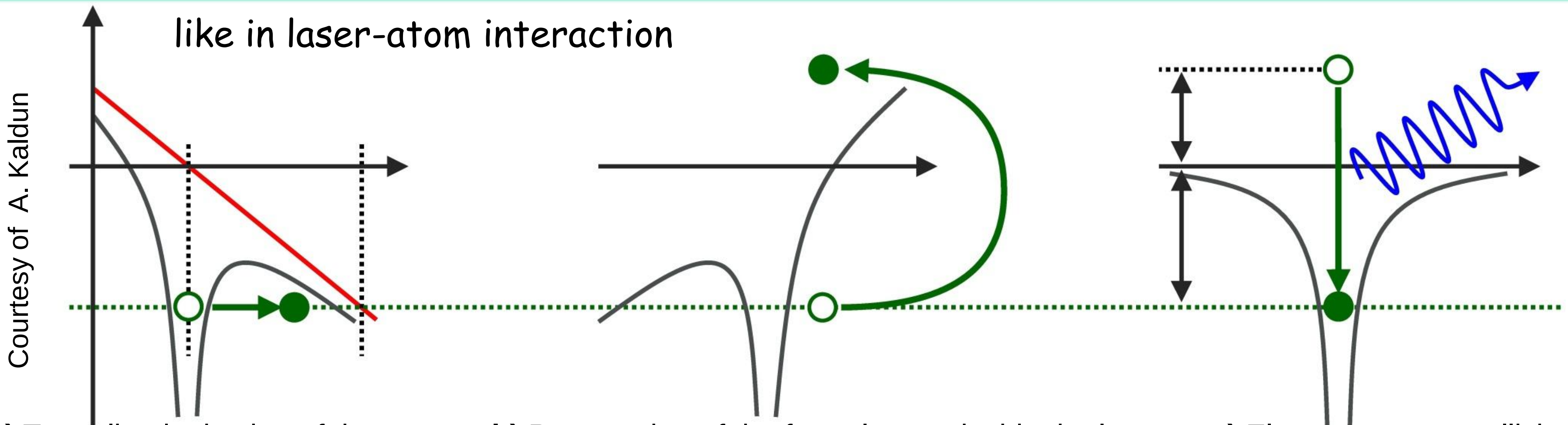
S. J. Müller et al., Phys. Lett. B 730 (2014) 161

From Collisions to Recollisions in Vacuum



Dirac sea

like in laser-atom interaction



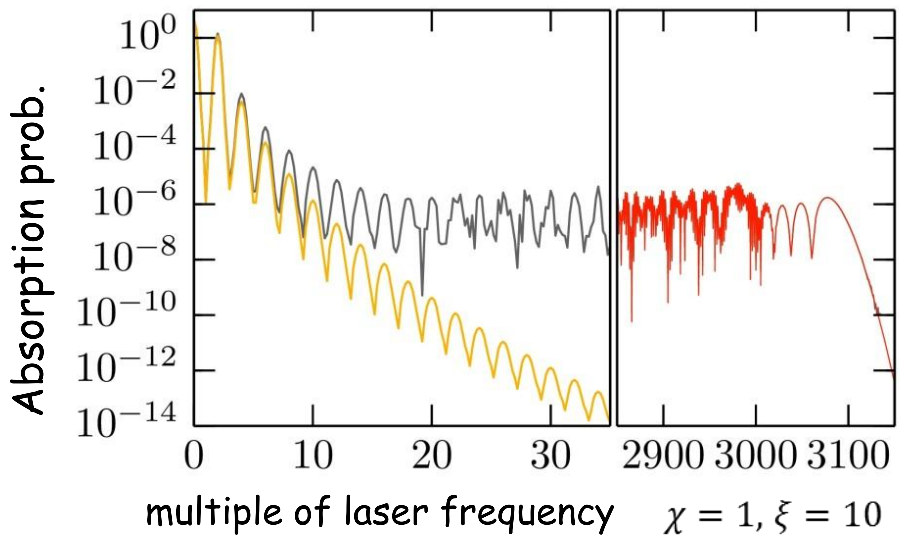
a) Tunneling ionization of the atom **b)** Propagation of the free electron inside the laser **c)** Electron-atom recollision

Recollisions in atomic physics: Semi-classical three-step model for High-harmonics generation (HHG)
As the free electron is accelerated by the laser field, a large amount of energy is released during the recollision.

see e.g. P. Corkum (1993) or M. Protopapas et al, Rep. Prog. Phys. (1997)

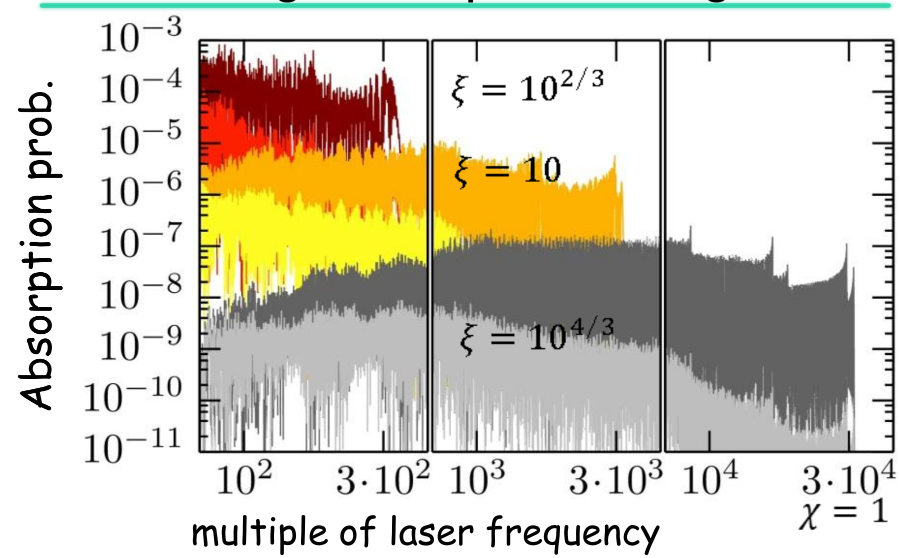
Recollisions of laser-generated electron-positron pairs

Quasistatic vs. recollision contribution



- The Polarization operator mainly describes vacuum fluctuations (annihilation of the pair within one formation length, yellow curve)
- If real pair creation becomes sizable ($\chi = 1$), also recollision processes contribute (red curve)
- They are responsible for the large plateau-region in the photon absorption spectrum

Scaling of the plateau region



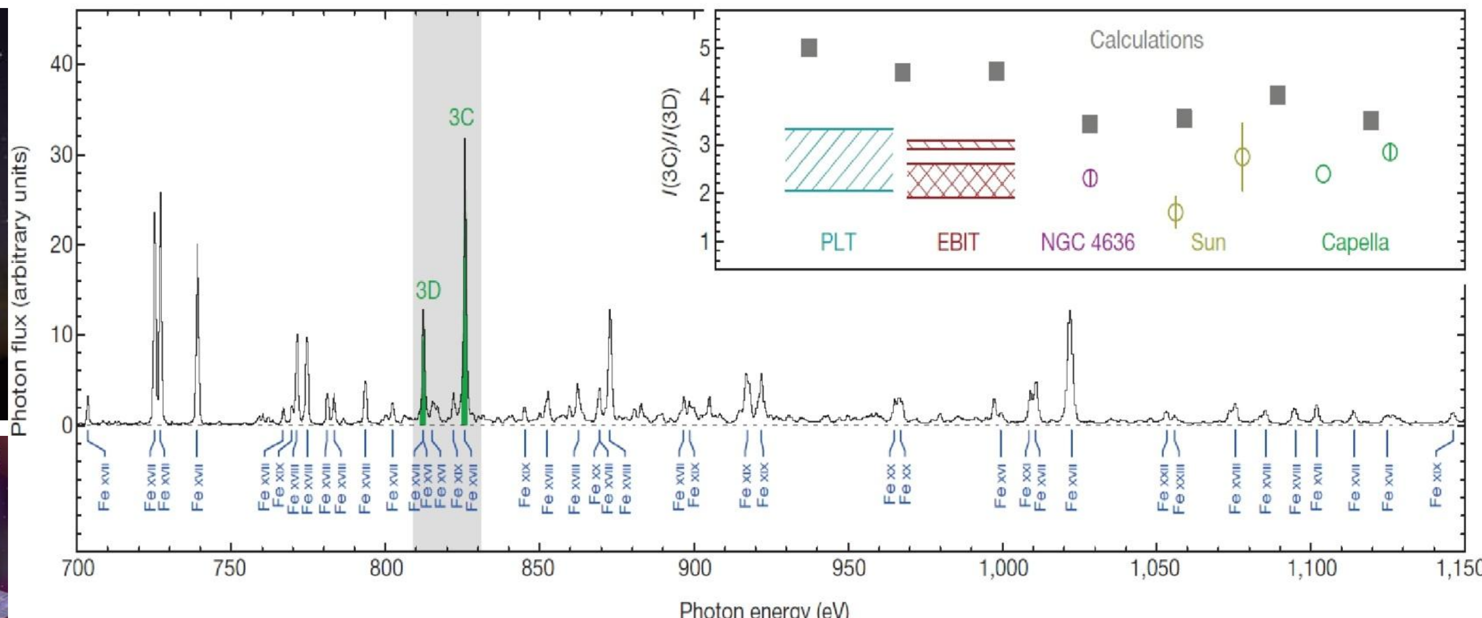
- During a recollision many laser photons can be efficiently absorbed from the laser
- The width of the plateau scales as $3.17\xi^3/\chi$
- The height of $\left|\int P_\perp\right|^2$ scales as $\chi^{10/3}/\xi^6$
- The recollision probability is suppressed for parallel photon polarization (light colors), as the momentum distribution hinders recollisions

arXiv:1407.0188 S. Meuren et al, PRL 2015

Ions interacting with high frequency lasers: laboratory astrophysics

Iron (Fe): the most visible (even if not the most abundant) element of the universe. Fe ions in stars emit x-ray radiation with characteristic frequencies.

E.g. x-ray spectrum of the star system **Capella** (in the constellation Auriga), recorded by the **Chandra X-ray Observatory**:

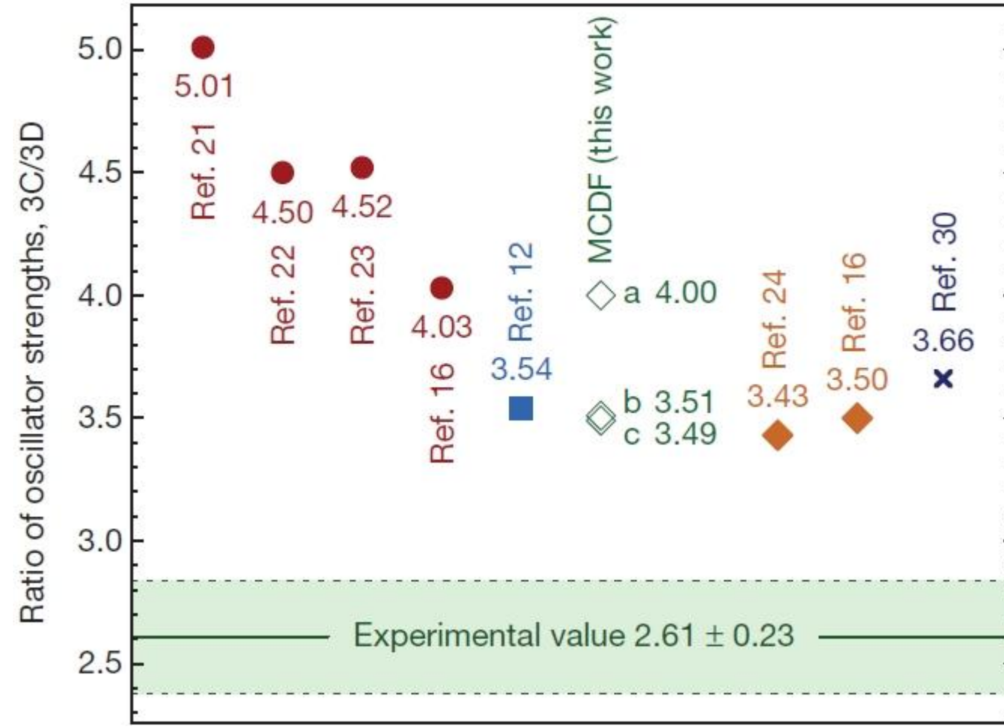


Data: D. P. Huenemoerder *et al.*, Astron. J. **141**, 129 (2011)
Figure: S. Bernitt, *et al.*, Nature **492**, 225 (2012)

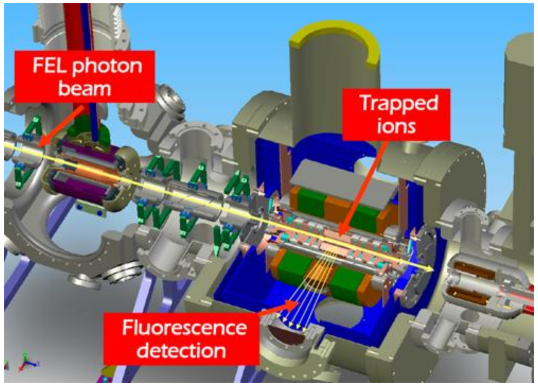
Problem:
observed lines carry information about the plasma and correlated bound electron dynamics

Alternative
x-ray laser spectroscopy with Fe ions trapped in an EBIT by the group Crespo/Ullrich (at LCLS free electron laser facility)
i.e. avoiding plasma influence

Compare with theory:
3C: $1s^2 2s^2 (2p^5)_{1/2} 3d_{3/2}$;
3D: $1s^2 2s^2 (2p^5)_{3/2} 3d_{5/2}$
large-scale multiconfiguration Dirac-Fock



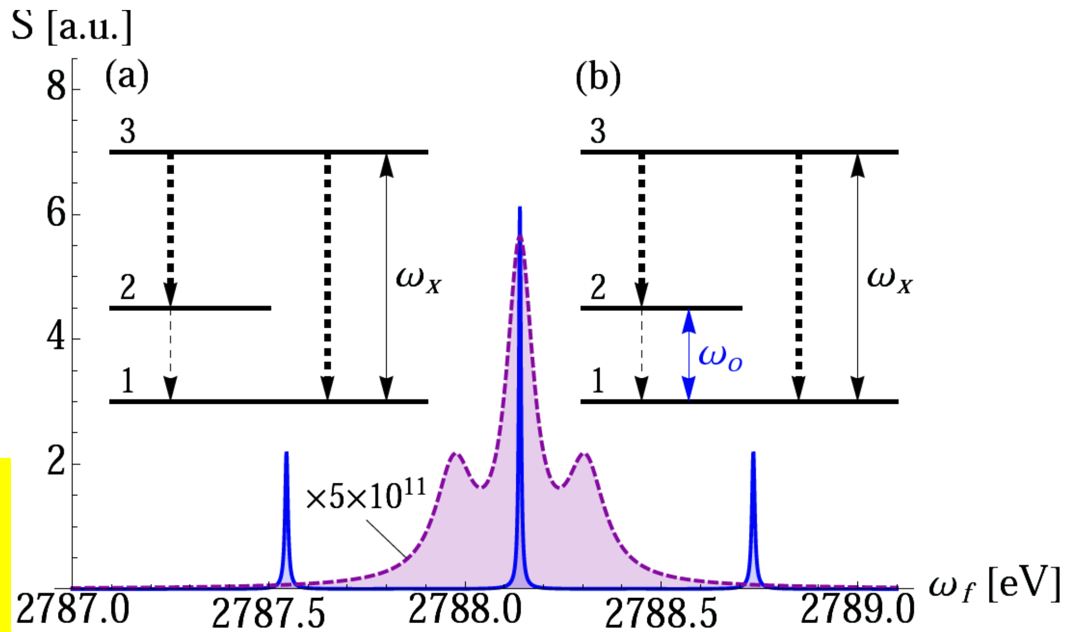
S. Bernitt, *et al.*, Nature **492**, 225 (2012)
N. S. Oreskina et al, PRL 113, 143001 (2014)



Theoretical **prediction** for the brightness of the 3C line **30%** above the measured value by x-ray laser spectroscopy, also ratio still incorrect: i.e. plasma influence in the modelling not only responsible for discrepancy between experiment and theory! PRL 2014 shows that nonlinear interaction need be included in astrophysical models

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

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



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

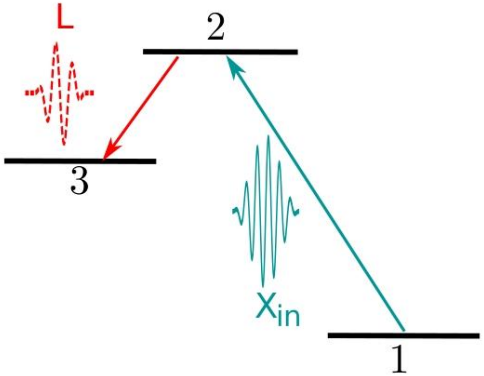
Line widths can be largely decreased by an additional optical driving: a new tool to measure the **transition matrix elements** of HCI via the separation of the spectral lines given by the Rabi frequency

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)

O. Postavaru et al, Phys. Rev. Lett. **106**, 033001 (2011)
see also in atomic systems L.M. Narducci et al., Phys. Rev. A **42**, 1630 (1990)

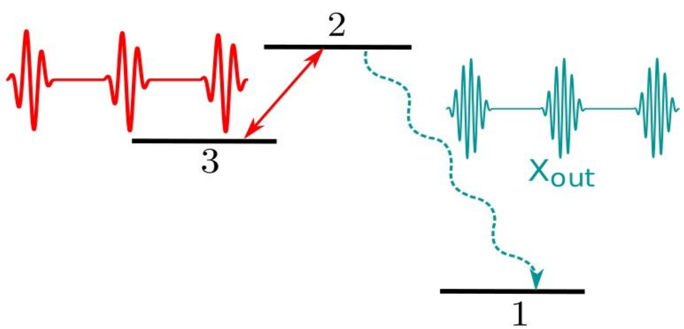
X-ray combs from optical quantum control

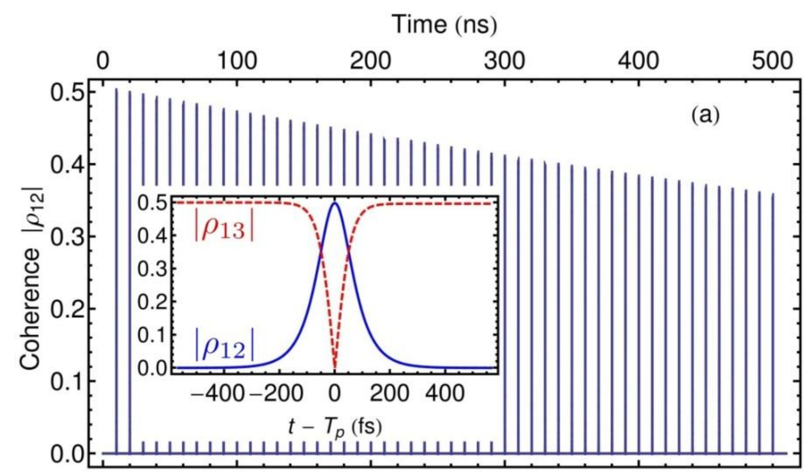
1. Preparation of the system



- An x-ray pulse driving the 1 ↔ 2 transition and a subsequent laser pulse driving the 2 ↔ 3 transition prepare the system in the initial, slowly decaying state
- An optical-frequency-comb laser consisting of a train of 2π pulses imprints a **pulse-like structure** in the x-ray dipole response with increased effective decay time

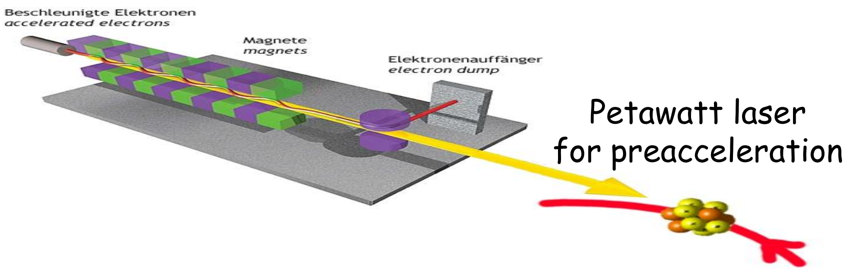
2. Optical-frequency-comb control and resulting x-ray dipole response





S. M. Cavaletto et al, Nature Photonics 8, 520 (2014)

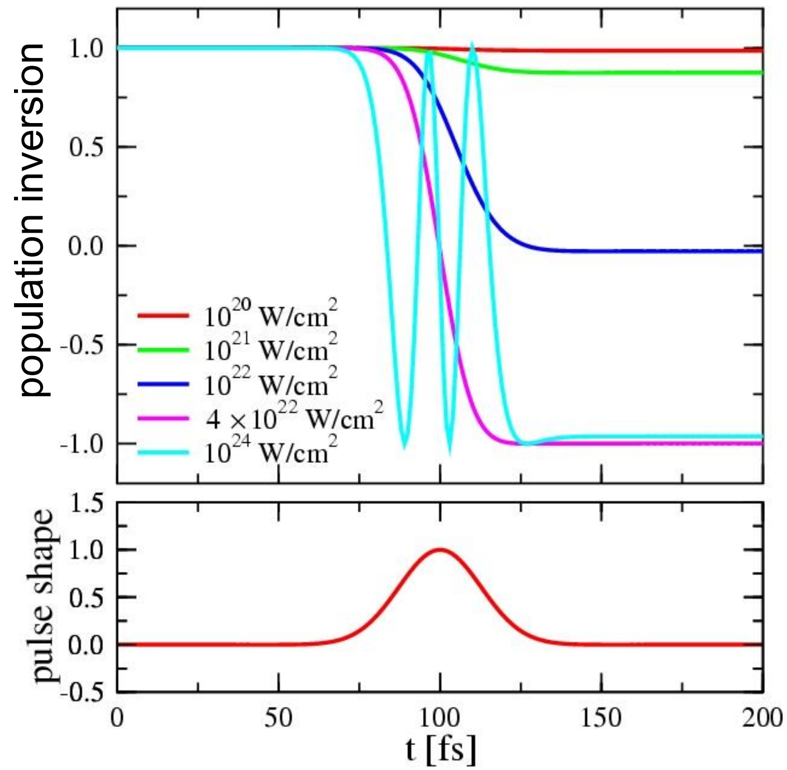
Nuclear Quantum Optics with XFEL: Rabi flopping



- 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

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

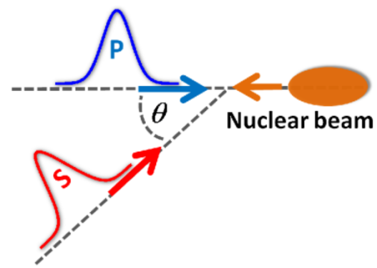


Population inversion in ^{223}Ra for laser parameters as in the DESY TESLA technical design report supplement

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

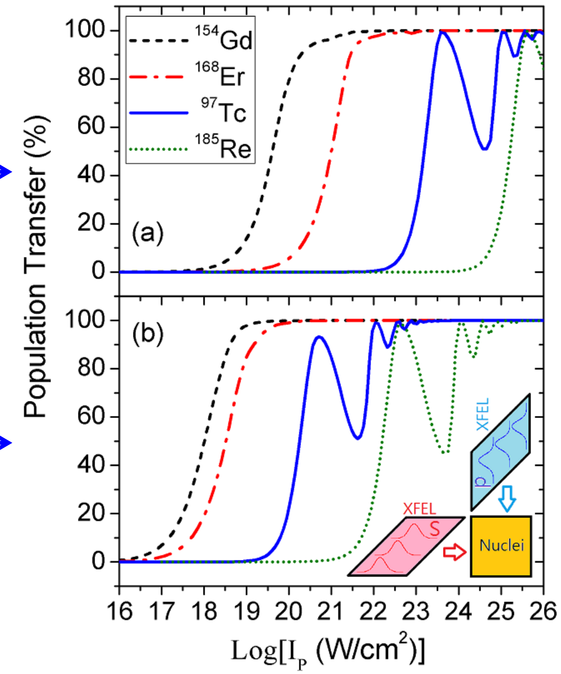
Nuclei: population transfer

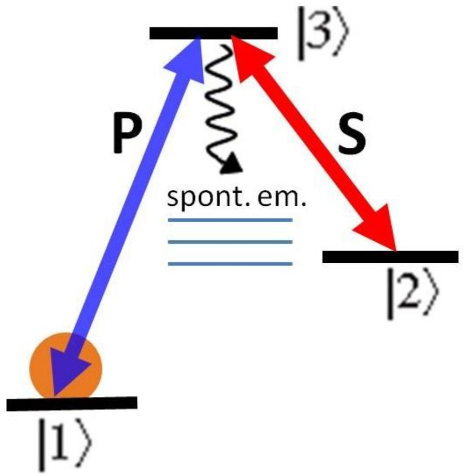
Parameters for XFEL
but alternative via
oscillating mirrors at ELI
(D van der Brugge and A. Pukhov, Phys. Plasmas 17, 033110 (2010), A. M. Sergeev et al., Proc. SPIE 8080, 808017 (2011)))



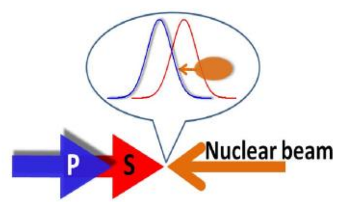
Seeded XFEL →

XFEL O →



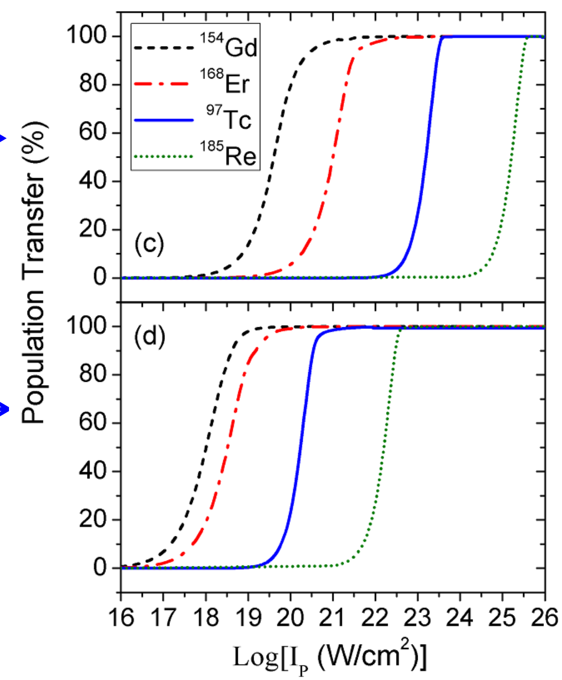


$$|D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2 + \Omega_s^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2 + \Omega_s^2}}|2\rangle$$



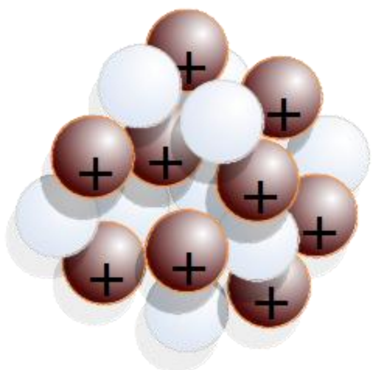
Seeded XFEL →

XFEL O →



W.-T. Liao et al., **Phys. Lett. B 705, 134 (2011) and Phys. Rev. C. 87, 054609 (2013)**

Nuclear quantum dynamics and isomer triggering



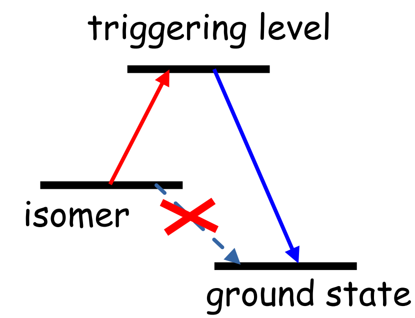
Nuclear system

Nuclear isomer = nucleus in long-lived excited state

- Lifetimes: *ns, μs, ms, s, min, h, years, …*

Triggering = release of stored excitation energy on demand

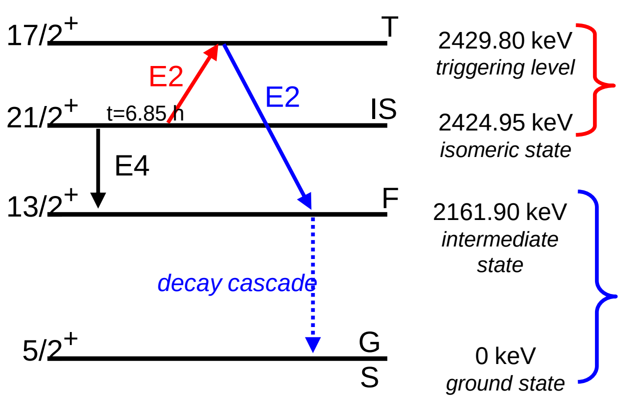
- clean energy source (nuclear battery)
- insight in nuclear structure
- possibly astrophysical significance



References:

- P. Walker and G. Dracoulis, Nature (London) **399**, 35 (1999),
- A. Pálffy *et al.*, Phys. Rev. Lett. **99**, 172502 (2007)

^{93}Mo nucleus

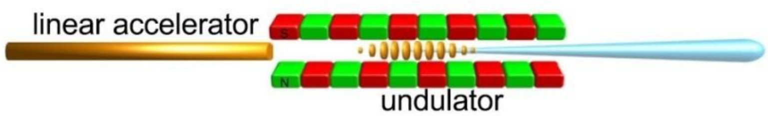


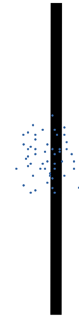
4.85 keV ⟶ accessible by lasers (XFEL)

1 MeV photon = signature for triggering

Mechanisms of laser-nucleus interaction in embedded nuclei

X-ray Free-Electron Laser



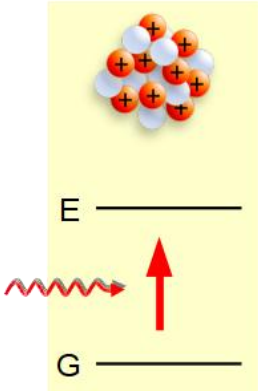


solid-state target

*Driving of **nuclear** transition*

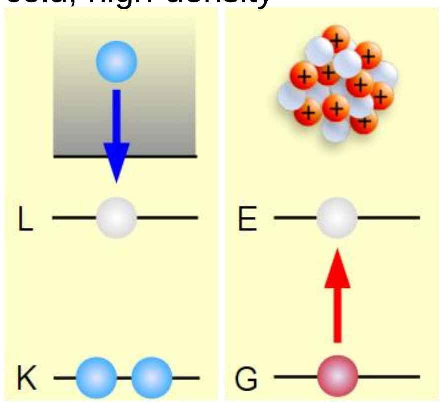
Direct laser-nucleus interaction:

- XFEL provides x-rays (< 25 keV) resonant with nuclear transition
- Obstacles:
  - small nuclear transition widths
  - small size of nuclei
  - screening from electrons



Secondary nuclear processes:

- High intensity XFEL can produce new states of matter, like cold, high-density plasmas
- Processes coupled to the atomic shell, like NEEC become possible
- NEEC is time-reversal of internal conversion



Competition between ***direct photoexcitation*** and ***secondary NEEC***

Results: ^{93m}Mo triggering with the XFEL

Direct photoexcitation:

- XFEL on resonance with triggering transition (4.85 keV)
- Consider realistic laser parameters, e.g.: LCLS at SLAC

Number of triggered isomers per pulse:
~ 1.8 x 10^{-15}

- Spatial coherence can drastically increase nuclear triggering (see XFEL oscillator)

Secondary NEEC:

- NEEC prefers capture into deep vacancies
  - Broad electron distribution present

Number of triggered isomers per pulse:
~ 5.6 x 10^{-9} (T_e = 350 eV)

- NEEC takes place on longer time scale compared to laser pulse
- Many NEEC resonance channels can contribute

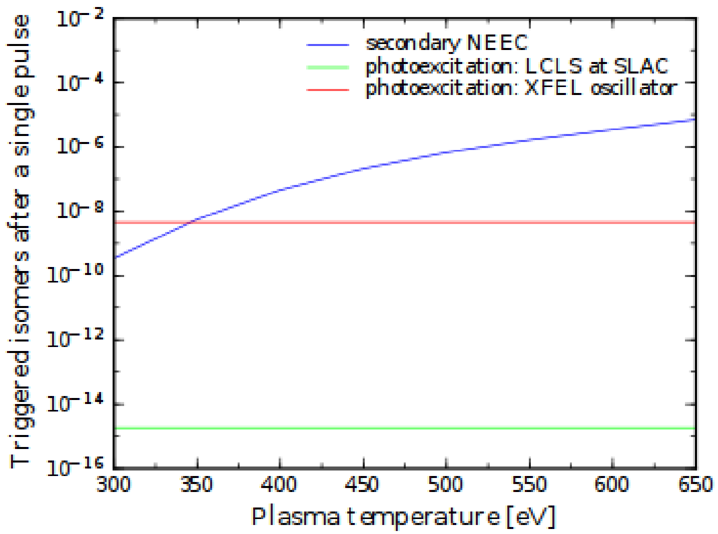
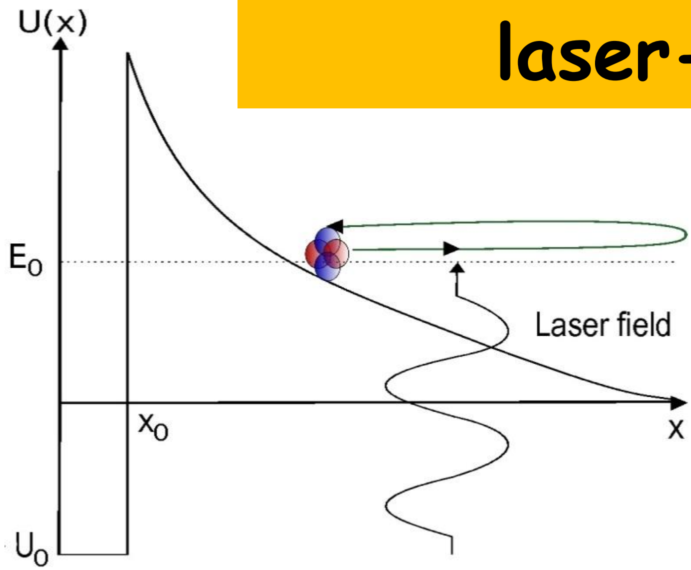


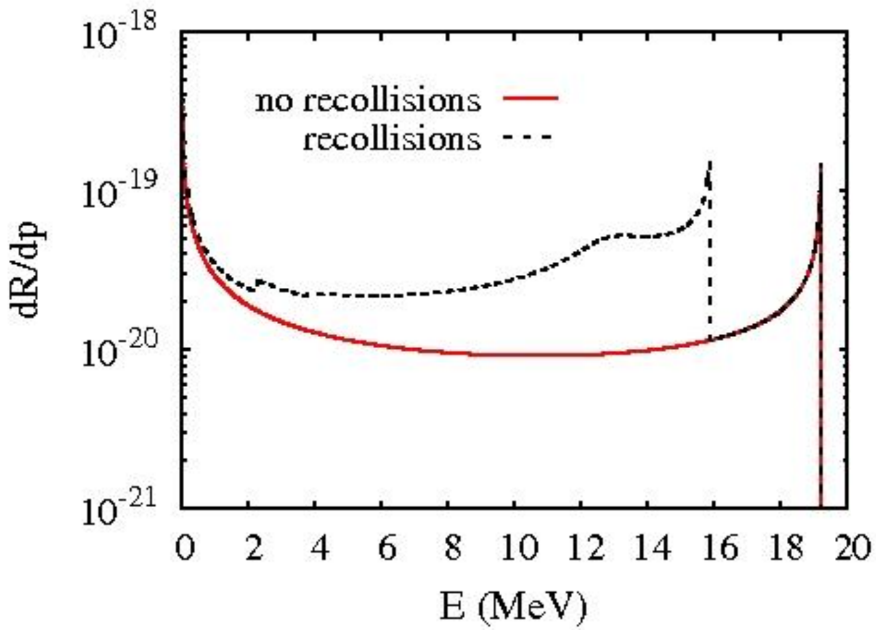
FIG: Number of triggered isomers after a single pulse. Comparison between photoexcitation and secondary NEEC.

J. Gunst et al, Phys. Rev. Lett. **112**, 082501 (2014)

Nuclear tunneling and recollisions in laser-assisted α decay



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



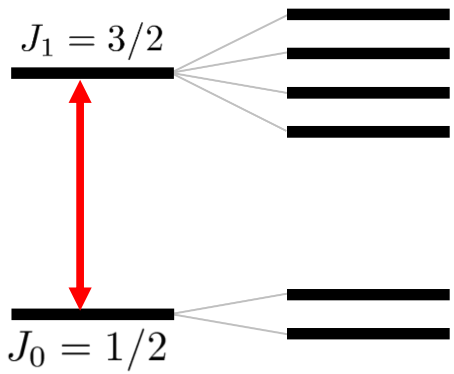
alpha particle spectrum is completely changed by the laser

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

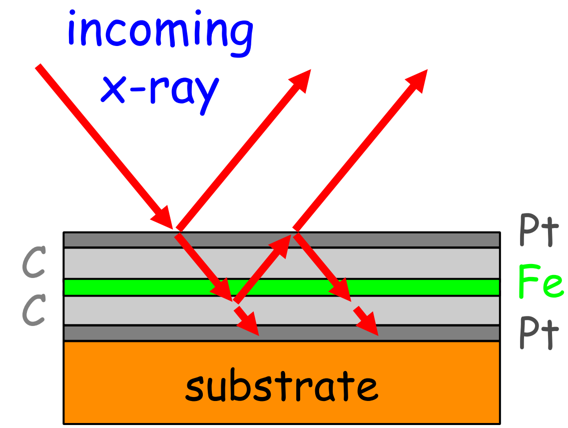
H Castaneda Cortes et al., Phys. Lett B 29409 (2013)

X-ray quantum optics with nuclei in solids

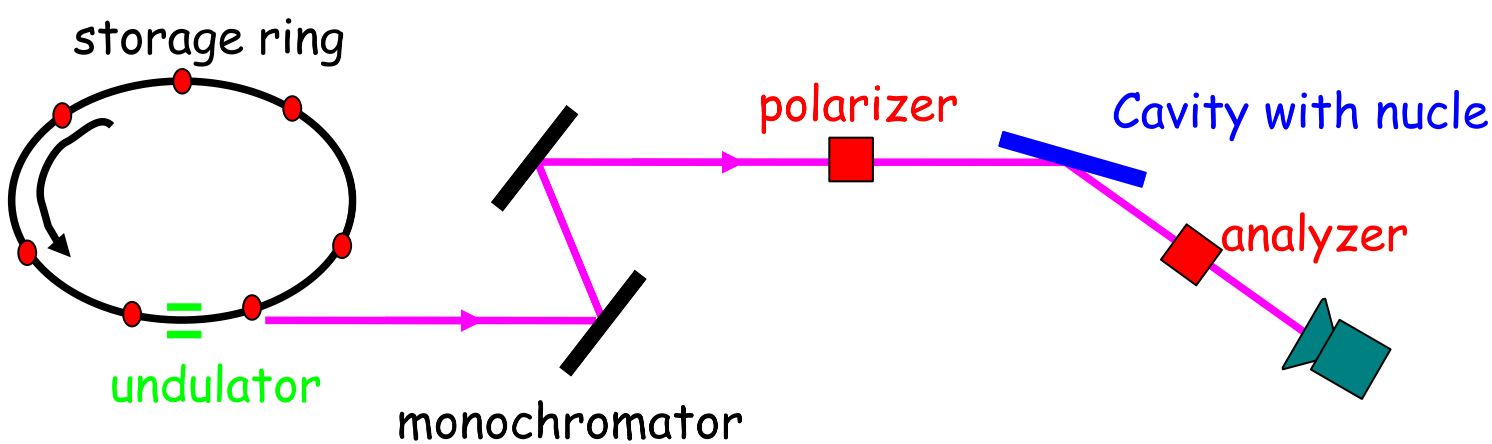
^{57}Fe Mössbauer nucleus in nm-sized planar cavity



$$\lambda = 0.86\ \text{Å}$$
$$\hbar\omega_0 = 14.4\ \text{keV}$$
$$\hbar\Gamma = 4.7 \times 10^{-9}\ \text{eV}$$
$$1/\Gamma = 141\ \text{ns}$$



Typical experimental setup at synchrotron radiation source

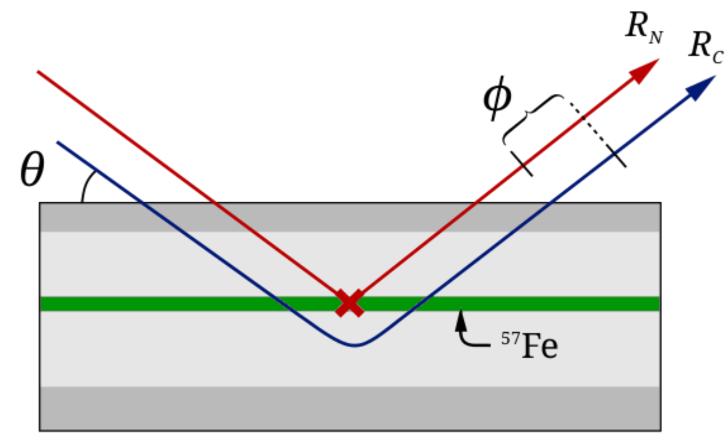


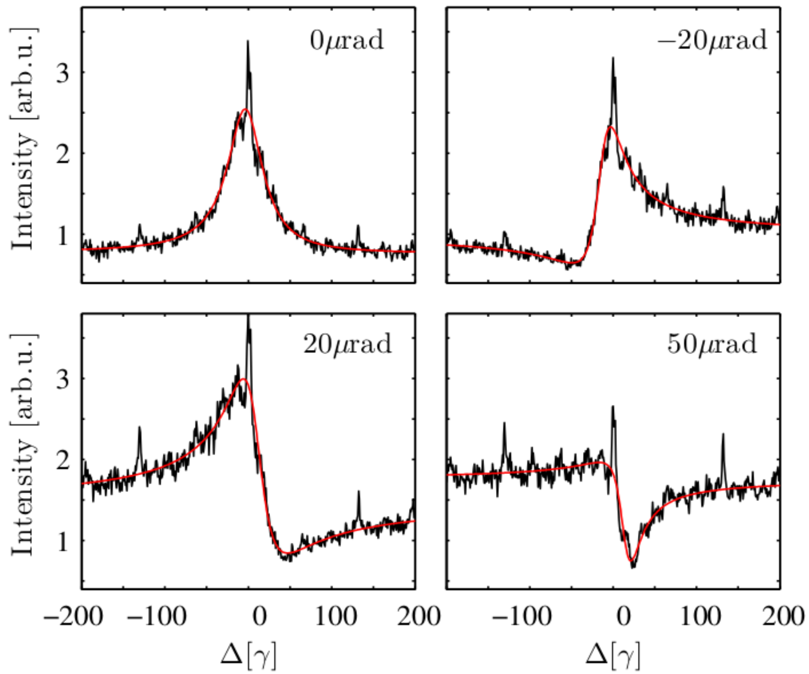
Quantum optical theory: Heeg, Evers, Phys. Rev. A. 88, 043828 (2013)

Spectral control with Mössbauer nuclei

Operate cavity as x-ray interferometry

- Continuum: broadband cavity reflection
- Bound state: narrow nuclear response
- Relative phase controlled by x-ray incidence angle

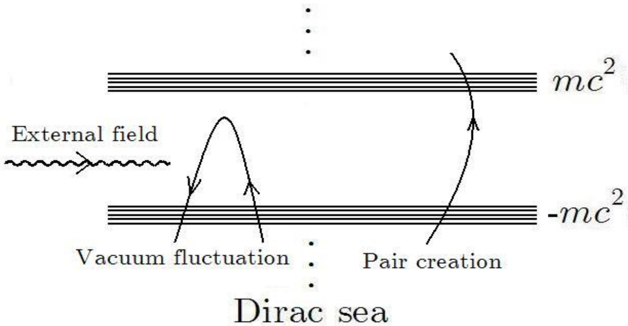




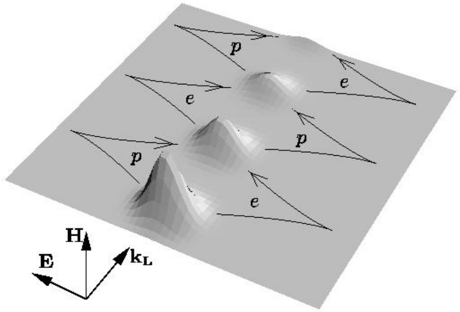
experimental raw data (Petra III, DESY)

fit with theory

Demonstration of nuclear coherences, interferences and enhanced x-ray refractivity
Kilian Heeg et al (Evers group) PRLs 2013 & twice 2015
see also recent Science/ Natures by Röhlsberger & Kocharovskaya groups



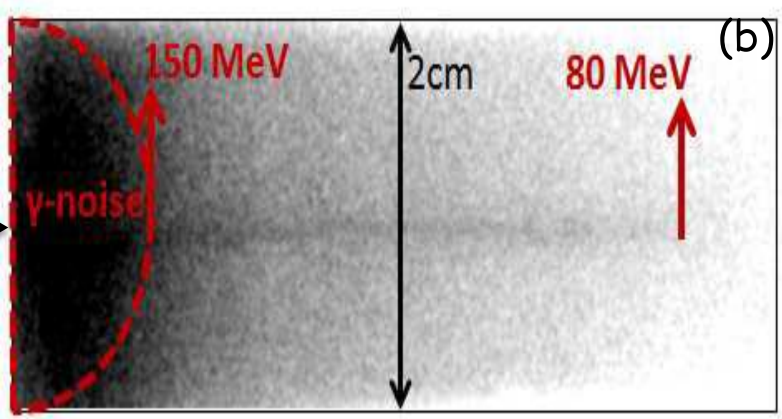
Conclusions

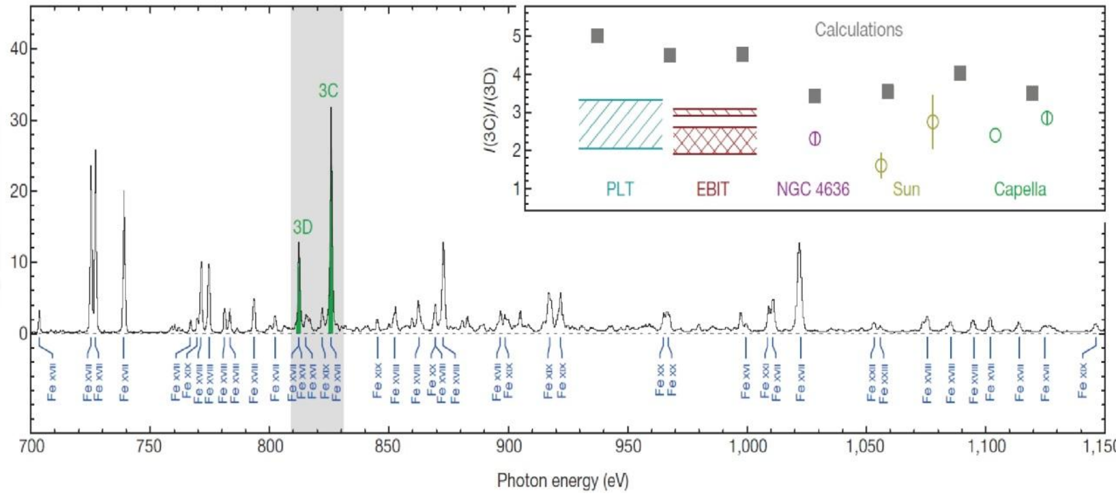


Laser-vacuum interaction: light-light scattering, vacuum refractivity, matterless double slit & multi slits

Laser-electron interaction: Dirac & spin dynamics, pair creation with created jets for astrophysics, particle physics

Laser-ion & nuclei interaction: metrology and tunneling times, nuclear population transfer, astrophys. iron spectra

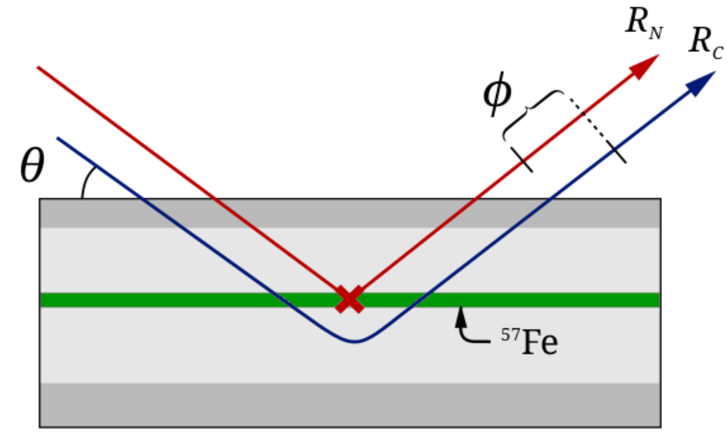


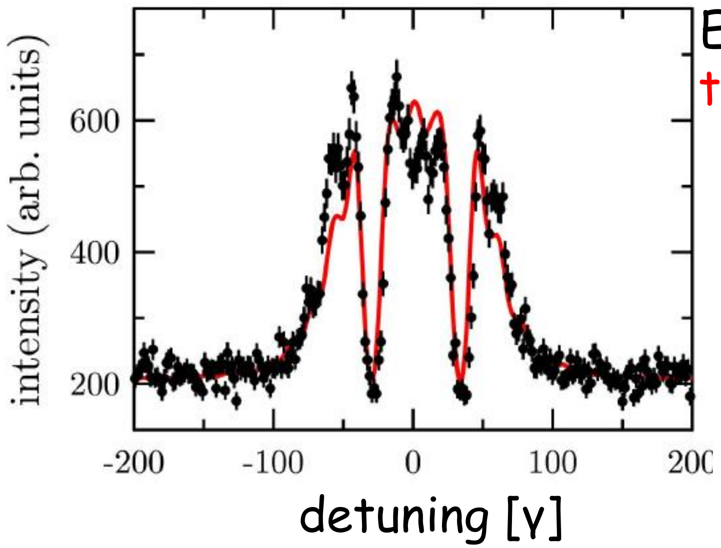


Quantum optics with Mössbauer nuclei

Operate cavity as x-ray interferometry

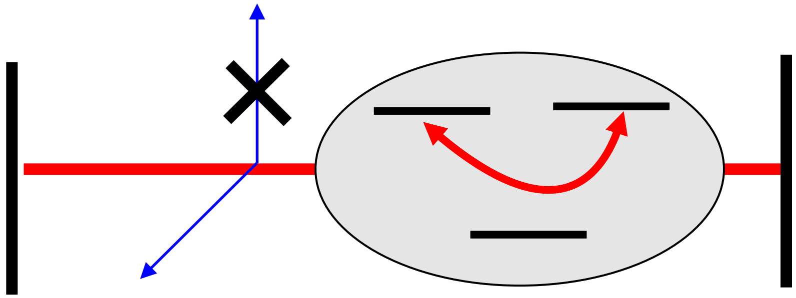
- Continuum: broadband cavity reflection
- Bound state: narrow nuclear response
- Relative phase controlled by x-ray incidence angle





Experiment (Petra III)

theory incl. exp. details

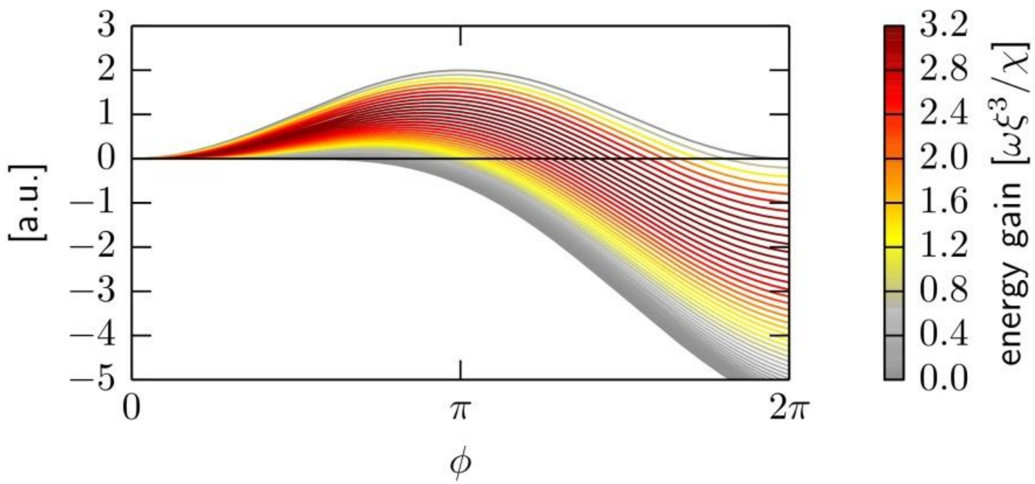


Demonstration of nuclear coherences, interferences and enhanced x-ray refractivity

Kilian Heeg et al (Evers group) PRLS 2013, twice 2015

see also recent Science/ Natures by Röhlsberger & Kocharovskaya groups

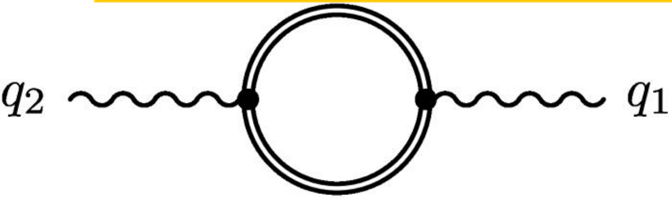
Recollisions of laser-generated electron-positron pairs



Classical trajectories (laser polarization direction) of electrons created shortly after a laser-field peak (positron trajectories have an opposite sign).
Color: energy gain at the recollision point

- Already for existing laser parameters ($\xi = 100$) pair-production probabilities of 10% are reached for a single GeV photon **arXiv:1406.7235** S. Meuren et al PRD 2015

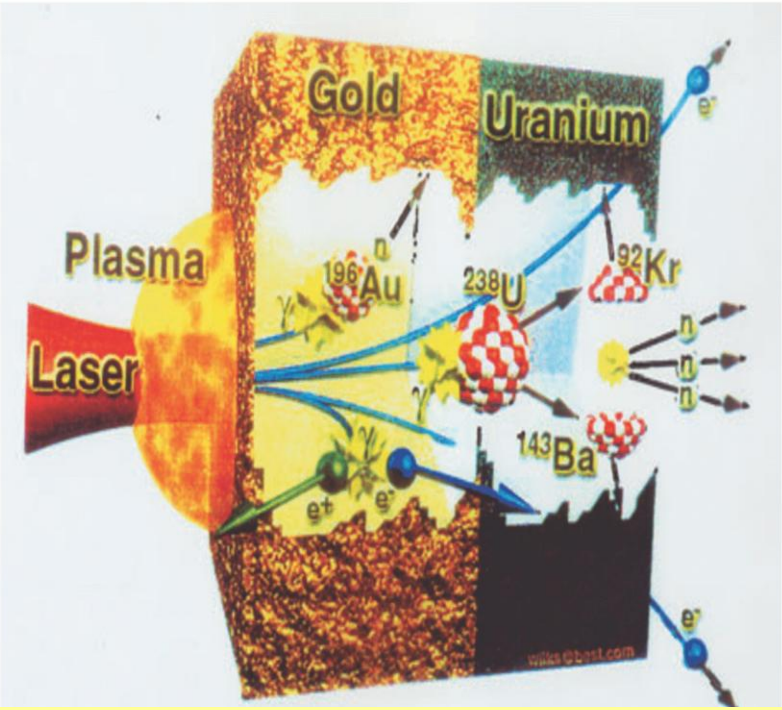
- After its creation the electron-positron pair propagates in the field
- For a linearly polarized laser the two particles may recollide
- We have shown quantum-mechanically that these processes contribute to the polarization operator (photon propagator with electron-positron loop):

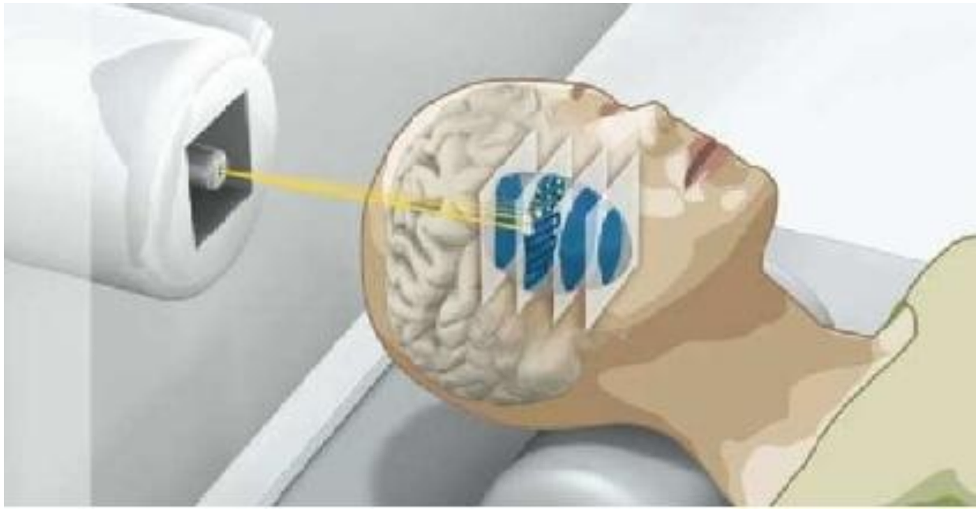


$$q_2^\mu = q_1^\mu + n\, k^\mu$$

arXiv:1407.0188 S. Meuren et al. PRL 2015

MeV Acceleration and Nuclear Physics via Laser-Plasma Interaction





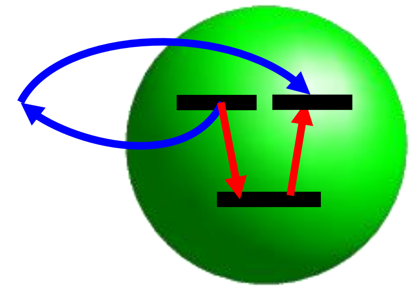
photonuclear neutrons e.g. by G. Pretzler et al., PRE 58, 1165 (1998), T. Ditmire et al Nature (1999), K. Ledingham et al., PRL 2000, N. Izuma PRE (2002), G Grillon et al PRL (2002)

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)

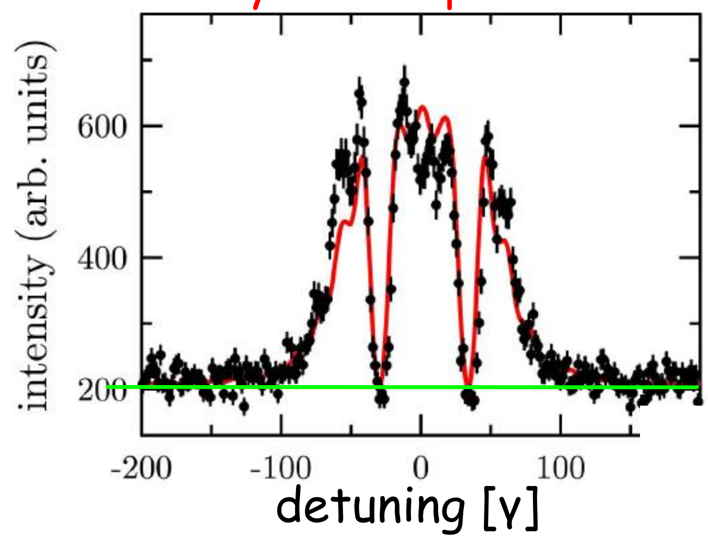
Spontaneously generated x-ray coherences

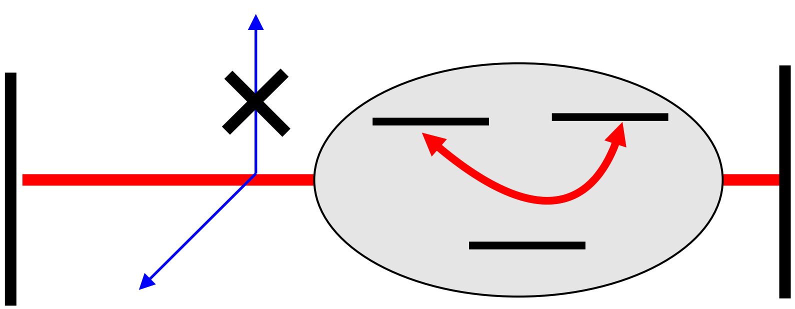
- Interaction with vacuum can "spontaneously" generate coherences
  - SGC usually suppressed, e.g. for atoms in free space → experimentally unexplored
- We observed nuclear SGC by engineering an anisotropic vacuum with only one polarization



- Signature: destructive interference in spectrum
  - Data shows: Essentially no decoherence

Experiment (Petra III)
theory incl. exp. details



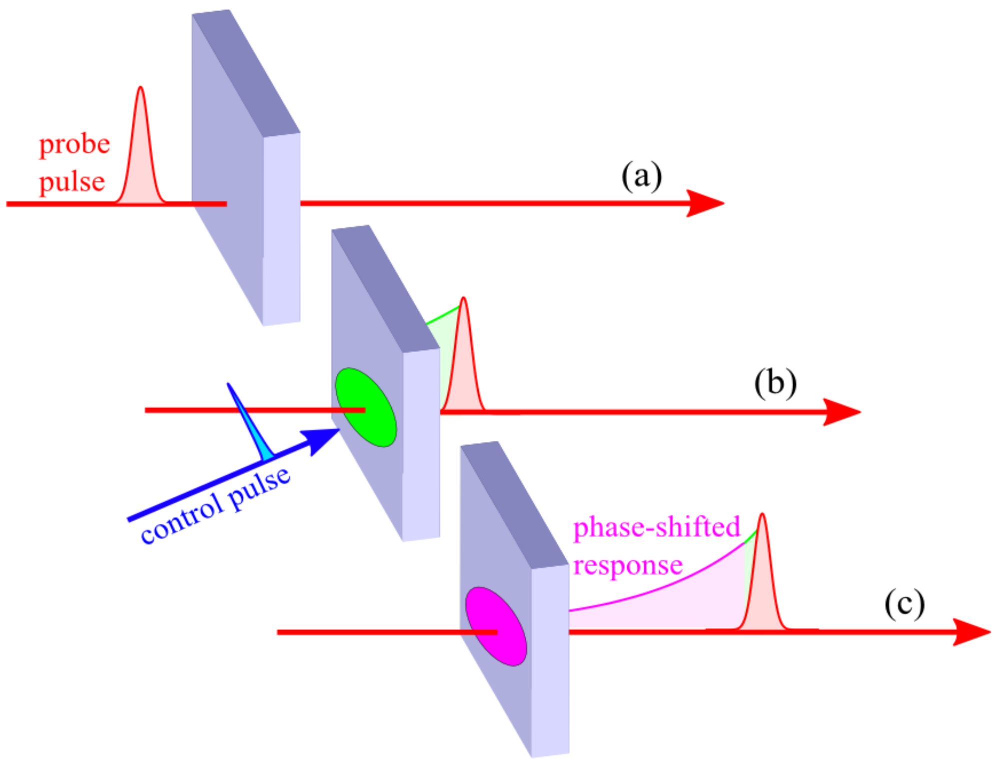


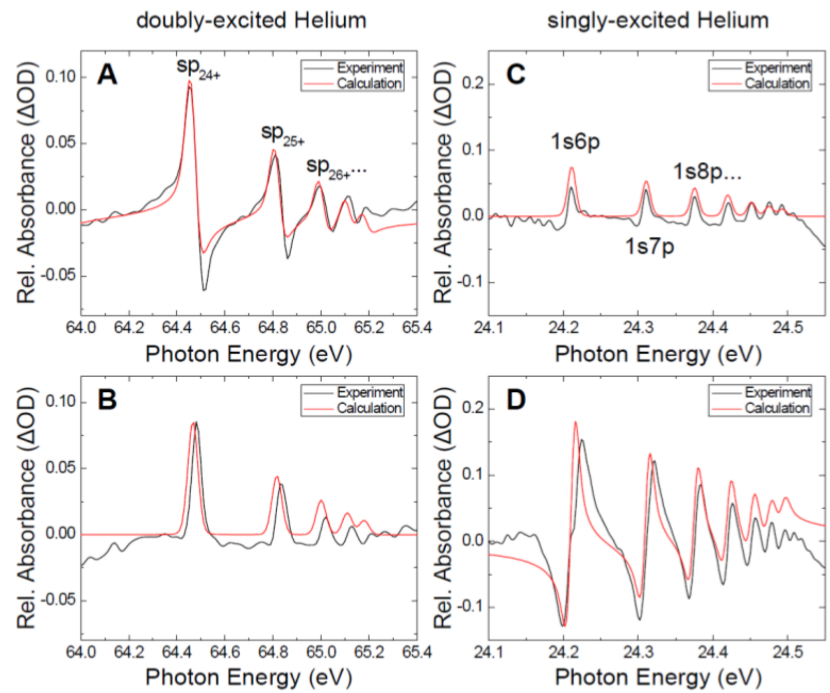
SGC can appear if atoms experience anisotropic environments

Heeg, Wille, Schlage, Guryeva, Schumacher, Uschmann, Schulze, Marx, Kämpfer, Paulus, Röhlsberger, Evers, Phys. Rev. Lett. 111, 073601 (2013)

Nuclear control experimentally ? - first atoms via Fano resonances

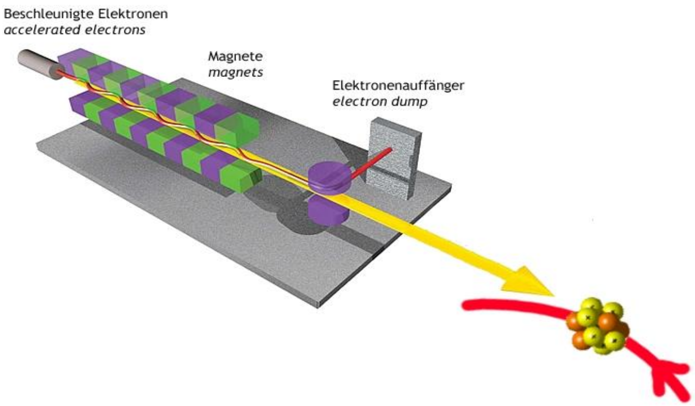
- Recall attosecond spectroscopy experiment in T. Pfeifer's group @ MPIK
- Two pathways for ionisation due to autoionising state in He
- Manipulate interference between "bound state" and "continuum" channel via control laser field which imprints phase shift on atoms
- Control of spectroscopic line shapes

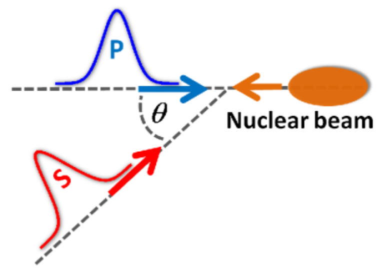


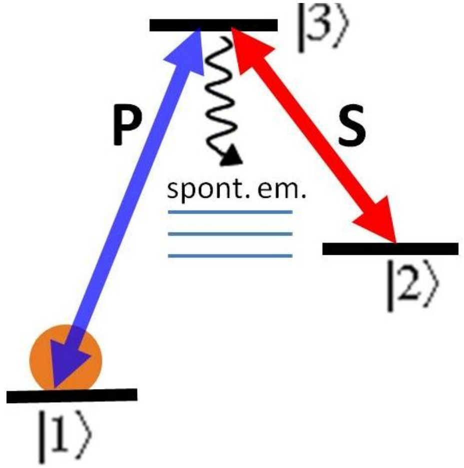


Ott, Kaldun, Raith, Meyer, Laux, Evers, Keitel, Greene, Pfeifer, Science 340, 716 (2013)

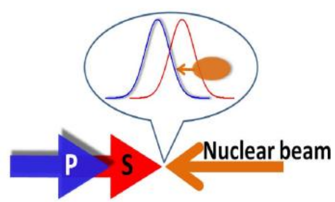
Coherence based population transfer





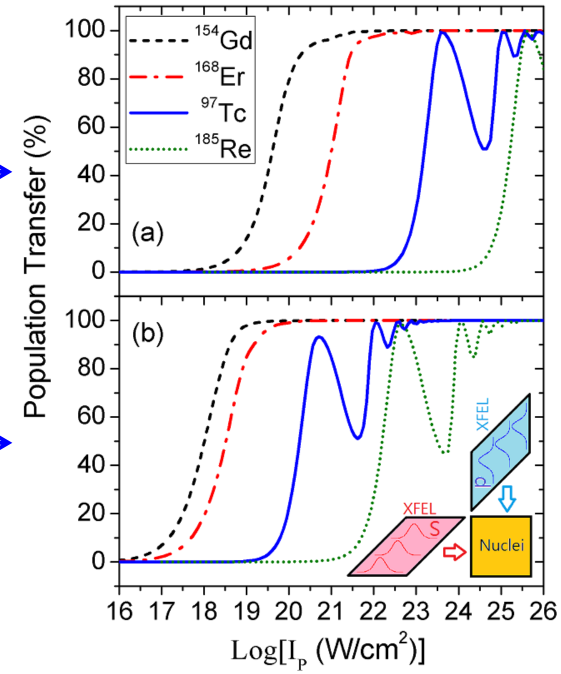


$$|D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2+\Omega_s^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2+\Omega_s^2}}|2\rangle$$



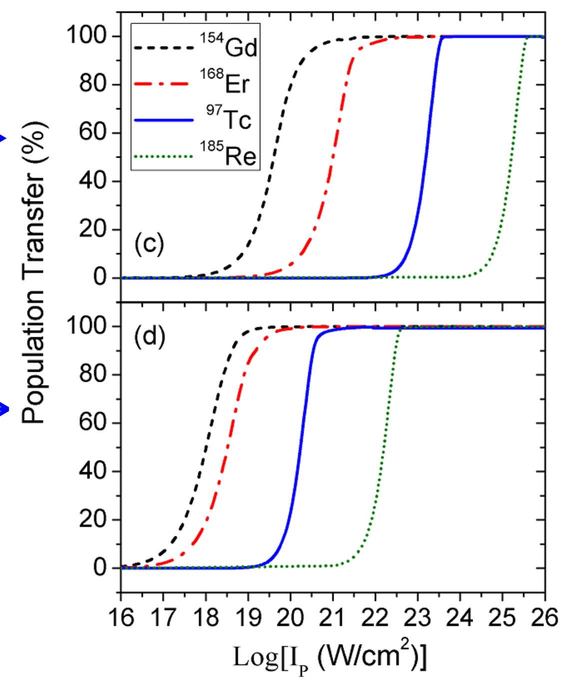
Seeded XFEL →

XFEL O →



Seeded XFEL →

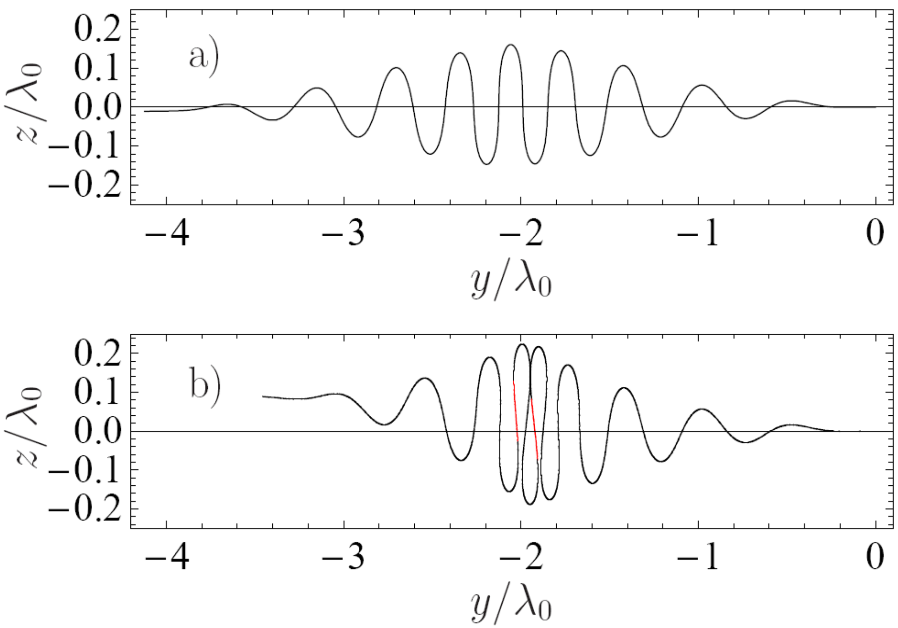
XFEL O →

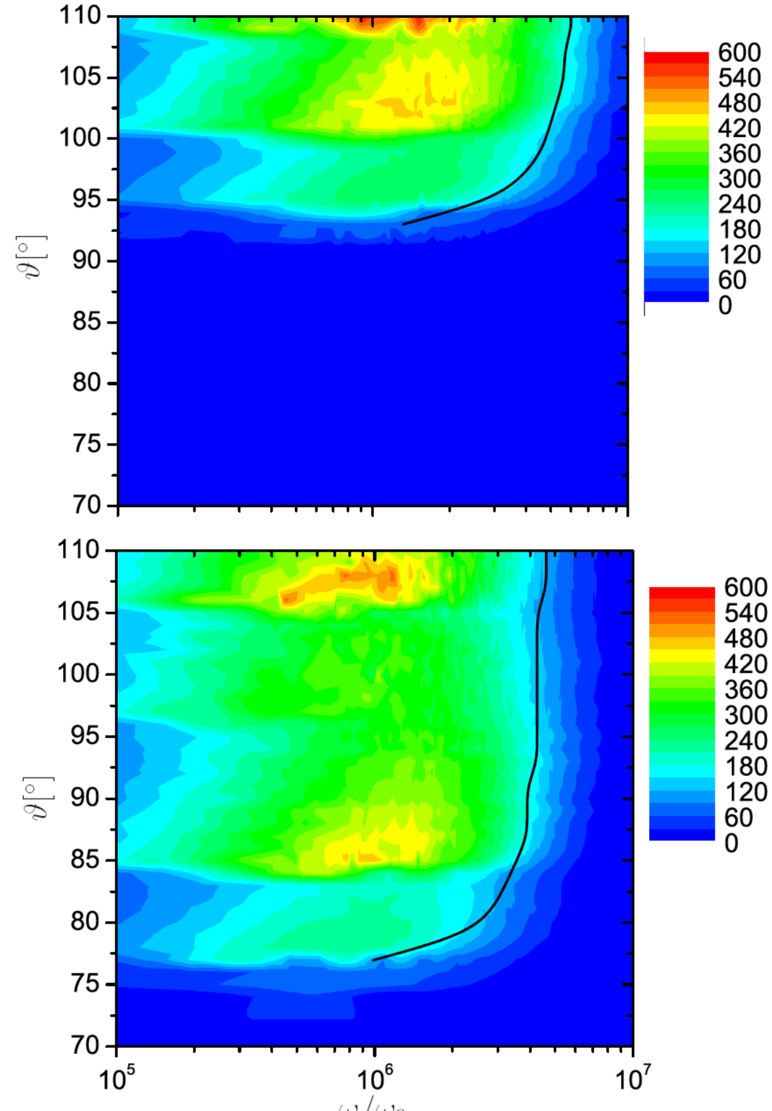


W.-T. Liao, A. Pálffy and C. H. Keitel, Phys. Lett. B 705, 134 (2011) and Phys. Rev. C. 87, 054609 (2013)

- One can see that if the initial longitudinal momentum of the electron is almost compensated by the laser field, the resulting angular distribution of the emitted radiation is very sensitive to radiation reaction

- Numerical parameters: electron energy 40 MeV, laser wavelength 0.8 μm, laser intensity 5*10^{22} W/cm^2, focused to 2.5 μm (10 PW), pulse duration 30 fs

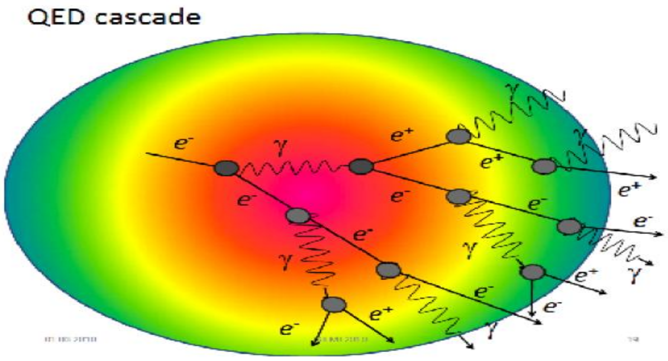




Test of Landau Lifshitz equation envisaged.. A. Di Piazza et al, PRL **102**, 254802 (2009)

QED cascades

By an avalanche or cascade process we mean here a process in which even a single electron in a ¯eld emits high-energy photons, which can interact with the field itself generating electron-positron pairs, which, in turn, emit photons again and so on (a cascade process may also be initiated by a photon rather than by an electron) - Figure courtesy Elkina



- Kirk and Bell, Phys. Rev. Lett. 2008: first prediction of a cascade production if even a single electron is present in the focus of a standing wave with intensity larger than 10^{24} W/cm^2

- Bulanov et al., Phys. Rev. Lett. 2010): no upper limit is envisaged in the case of linear polarization, due to the reduced electromagnetic emission

- Nerush et al. Phys. Rev. Lett. 2011: cascades in laser-laser collision occurs independently of the laser polarization at intensities of the order of 10^{24} W/cm^2

(recall: cascade debate only for counterpropagting laser pulses)