Extreme Power Photonics:

New Phenomena

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Laser pulse at ELI:

$$I \sim 10^{24} \div 10^{25} W/cm^2, \quad \lambda \sim 1 \mu m, \quad \tau \gtrsim 10^{-15} s$$

$$E_0[\mathrm{V/cm}] = 19\sqrt{I[\mathrm{W/cm^2}]}$$

$$E_0 \approx (2 \div 6) \cdot 10^{13} V/cm$$

$$E_0/E_S \sim (1 \div 4) \cdot 10^{-3}\,, \qquad E_S = m^2c^3/e\hbar = 1.32 \cdot 10^{16} V/cm$$

The characteristic formation length and time for quantum processes in intense fields

$$l_f \sim l_C \frac{E_S}{E}, \quad \tau_f \sim l_f / c$$

A.I. Nikishov, V.I. Ritus, 1964

$$l_C = \frac{\hbar}{mc} = 3.86 \cdot 10^{-11} cm$$ - Compton length

ELI: $l_f \sim 10^{-8} cm, \quad \tau_f \sim 3 \cdot 10^{-19} s$

Relativistic compression

↓

$$\lambda \to \lambda_c \sim 10^{-4} \mu m \quad \tau \to \tau_c \sim 10^{-18} s$$

$$I \to I_c \sim 10^{26} \div 10^{27} W/cm^2$$

$$l_f \lesssim 10^{-9} cm, \quad \tau_f \lesssim 3 \cdot 10^{-20} s$$

$$l_f \ll \lambda\,, \quad \tau_f \ll T = 2\pi c/\lambda$$

Locally the laser pulse is equivalent to a constant field !

Total probability of a process initiated by a single particle in a constant field depends on 3 Lorentz and gauge invariant parameters

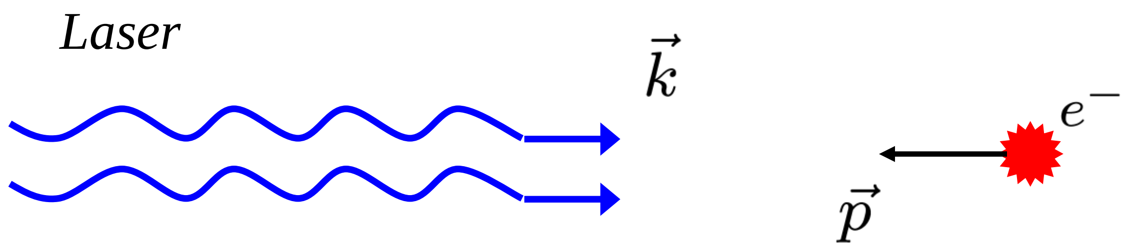
$$f = \frac{\vec{E}^2 - \vec{H}^2}{2E_S^2}\,, \quad g = \frac{(\vec{E}\cdot\vec{H})}{E_S^2}$$

$$\chi^2 = \frac{e^2 (p^\mu F_{\mu\nu})^2}{m^6 c^8}$$

$$(\hbar = c = 1)$$

$$W = W(f, g, \chi^2)$$

For head-on collision at laboratory reference frame:



$$E_R = E_L\sqrt{\frac{1+v/c}{1-v/c}}\,, \qquad v = pc/\varepsilon$$ - electron velocity

for ultrarelativistic particle $1 - v/c \ll 1$, or

$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} = \varepsilon/mc^2 \gg 1 \qquad E_R \approx 2\gamma E_L$$

$$\chi = \frac{E_R}{E_S} \approx 2\gamma\frac{E_L}{E_S}$$

Nonlinear vacuum QED effects at ELI

- ❑ e^+e^-- pair production
- ❑ light-by-light scattering (including harmonics generation in vacuum)
- ❑ crash of a superstrong laser pulse due to electromagnetic cascades induced by a created pair

Pair production by a single focused pulse

N.B. Narozhny, S.S. Bulanov, V.S. Popov, V.D. Mur, PLA **330,** 1 (2004)

$I, W/cm^2$	E_0/E_S	N_e $\Delta=0.1$	N_e $\Delta=0.05$	N_h $\Delta=0.1$
$4\cdot10^{27}$	0.16	$4.0\cdot10^{-11}$	$4.6\cdot10^{-42}$	$9.6\cdot10^{-23}$
$1\cdot10^{28}$	0.25	24 !!	$3.1\cdot10^{-19}$	$2.0\cdot10^{-7}$
$2\cdot10^{28}$	0.35	$3.0\cdot10^{7}$	$1.4\cdot10^{-7}$	16
$6\cdot10^{28}$	0.62	$8.4\cdot10^{13}$	$1.9\cdot10^{5}$	$3.4\cdot10^{9}$

$\lambda \sim 1\mu m\,, \tau \sim 10 fms$

$\Delta = \lambda/2\pi R$

Compare the total energy of produced pairs with the energy of the laser pulse

$$W_{e^-e^+} = 2mc^2 N_e$$

$$W_L \approx 10^{21} \frac{I}{I_S} mc^2$$

$$I_S = \frac{c}{4\pi} E_S^2 = 0.5 \cdot 10^{30} \mathrm{W/cm}^2$$

$$W_{e\_e^+} \sim W_L \sim 10^{21} mc^2 \quad \text{at} \quad I \approx 0.6 I_S$$

COLLAPSE OF THE LASER PULSE !

1. The effect of pair production by a single pulse strongly depends on geometry of the field in the laser focal region

2. The effect becomes observable at $I \ll I_S$

3. Pair production by an intensive field imposes limitation on attainable laser intensity

Pair production by two colliding pulses

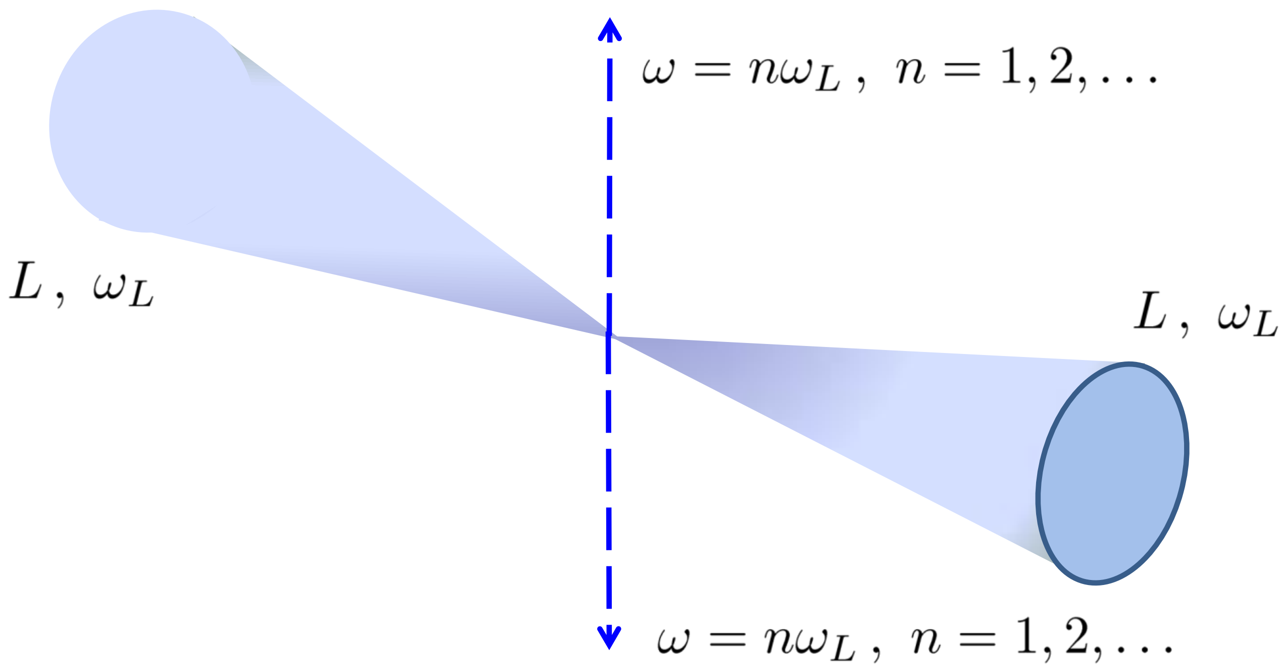
S.S. Bulanov, N.B. Narozhny, V.S. Popov, V.D. Mur, ZhETF **129,** 14 (2006)

$I, W/cm^2$	E_0/E_S	N_e $\Delta=0.1$	N_e $\Delta=0.05$	N_h $\Delta=0.1$
$1.0\cdot10^{26}$	$2.5\cdot10^{-2}$	$4.5\cdot10^{-12}$	$6.0\cdot10^{-9}$	$7.1\cdot10^{-13}$
$2.0\cdot10^{26}$	$3.6\cdot10^{-2}$	$5.1\cdot10^{-2}$	7.2	$1.8\cdot10^{-2}$
$2.5\cdot10^{26}$	$4.0\cdot10^{-2}$	14 !!	$1.2\cdot10^{3}$	6.0
$5.0\cdot10^{26}$	$5.7\cdot10^{-2}$	$2.6\cdot10^{7}$	$5.5\cdot10^{8}$	$1.8\cdot10^{7}$

1. The effect becomes observable at $I \approx 10^{26} W/cm^2$
2. Small difference between e- and h-pulses

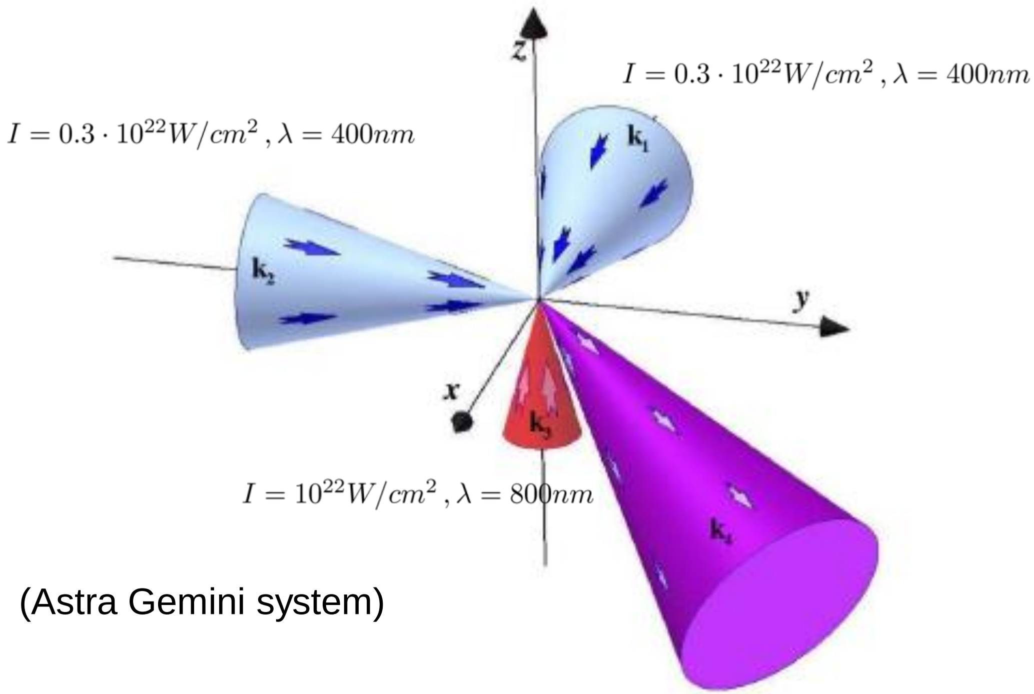
Light-by-light scattering

A. Di Piazza, K. Z. Hatsagortsyan, and C. H. Keitel, Phys. Rev. D **72,** 085005 (2005)



The effect is detectable only at $E_0 \gg E_S$!

E. Lundström, et al., Phys. Rev. Lett. **96**, 083602 (2006)



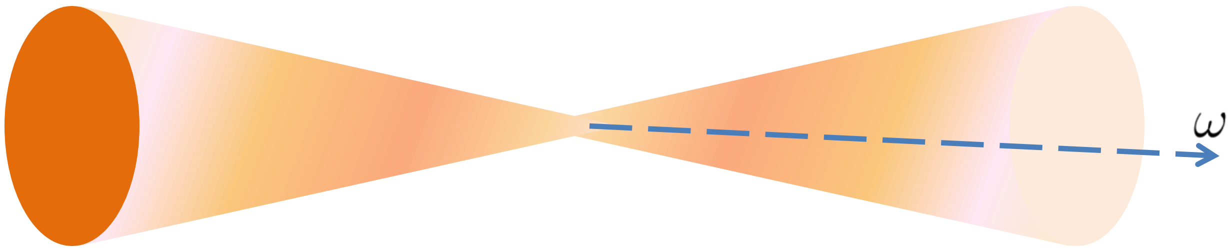
(Astra Gemini system)

$$N_{ph} = 0.07 \text{ per shot}$$

$$\lambda = 267nm$$

Harmonic generation by a single focused laser pulse

A.M.Fedotov, N.B. Narozhny, Phys. Lett. A **362**, 1 (2007)

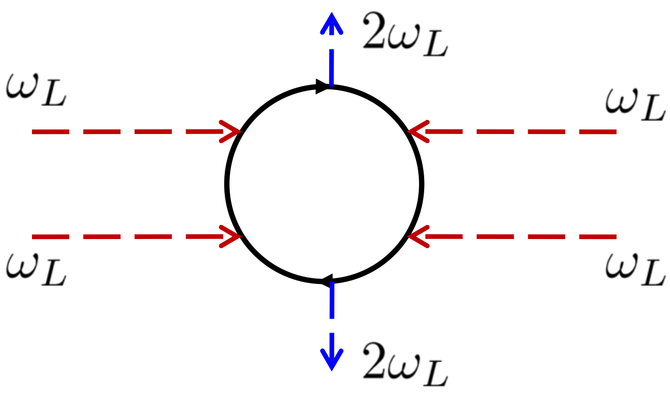


$L\,,\ \omega_L$

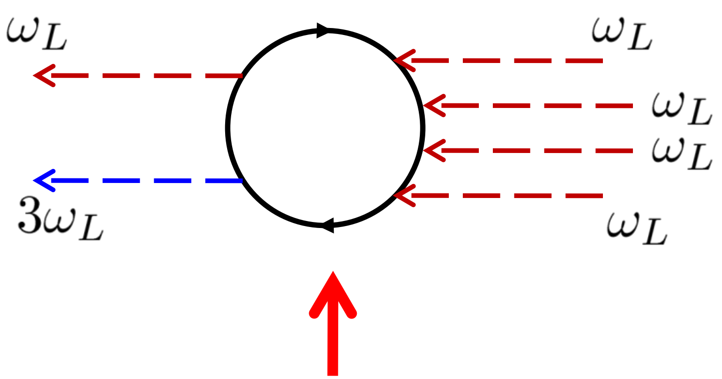
$$\omega = (2n+1)\omega_L\,,\ \ n = 1, 2, \ldots$$

The effect is detectable at $I \approx 10^{27} W/cm^2$!

A. Di Piazza, K. Z. Hatsagortsyan, and C. H. Keitel



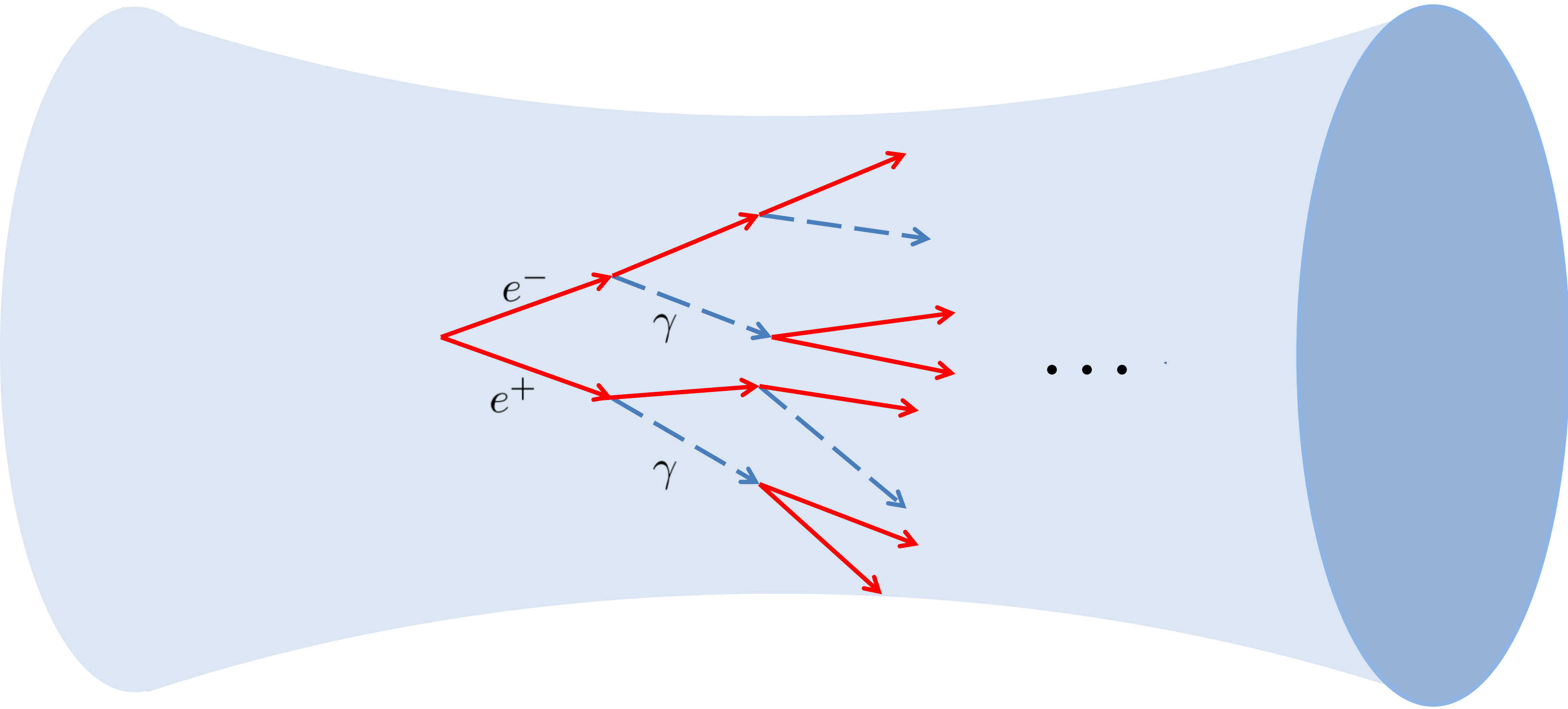
A.M.Fedotov, N.B. Narozhny,



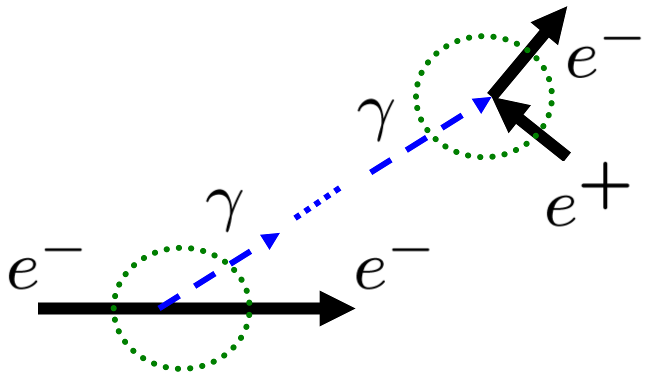
the effect of stimulated emission of a photon

Electromagnetic cascades induced by a created pair

Pair creation can give start to an electromagnetic cascade



The effect was observed at SLAC experiment



D.L.Burke, et al., PRL, **79**, 1626 (1997)

Laser: $\lambda = 0.527\mu\text{m (green)}\,,\ \tau_L = 1.6ps\,,\ I \approx 1.3{\times}10^{18}\text{W/cm}^2\,,\ \eta = \dfrac{eE}{m\omega c} \approx 0.3$

Energy of particles: $\varepsilon_e = 47\text{GeV}\,,\ \varepsilon_\gamma = 29.2\text{GeV}$ $\rightarrow$ $\chi_e \approx 0.3\,,\ \chi_\gamma \approx 0.2$

$$W_\gamma \sim \frac{\alpha}{m\gamma}\eta^2\,,\ \boxed{\tau_e \sim 1/W_\gamma \sim 10^{-13}s}$$

$$W_{e^-e^+} \sim \frac{\alpha}{\varepsilon_\gamma}\eta^{10}\,,\ \boxed{\tau_\gamma \sim 1/W_{e^-e^+} \sim 6\cdot 10^{-11}s}$$

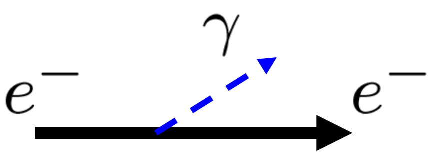
No of steps of the cascade/laser shot $\sim \dfrac{\tau_L}{\tau_\gamma} \sim 2\cdot 10^{-2}$

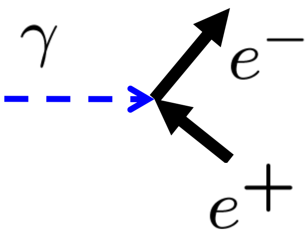
Excellent agreement with experiment!

Two colliding pulses

$$\lambda = 1\mu m\,,\ \tau_L = 10^{-14}s\,,\ I = 2.5\cdot 10^{26} W/cm^2$$ (≈ 1 pair/shot)

$$\eta \approx 10^4\ ,\quad E_0/E_S \approx 10^{-2}\,,\ \text{at}\ \chi \gg E_0/E_S$$ (locally constant crossed field)





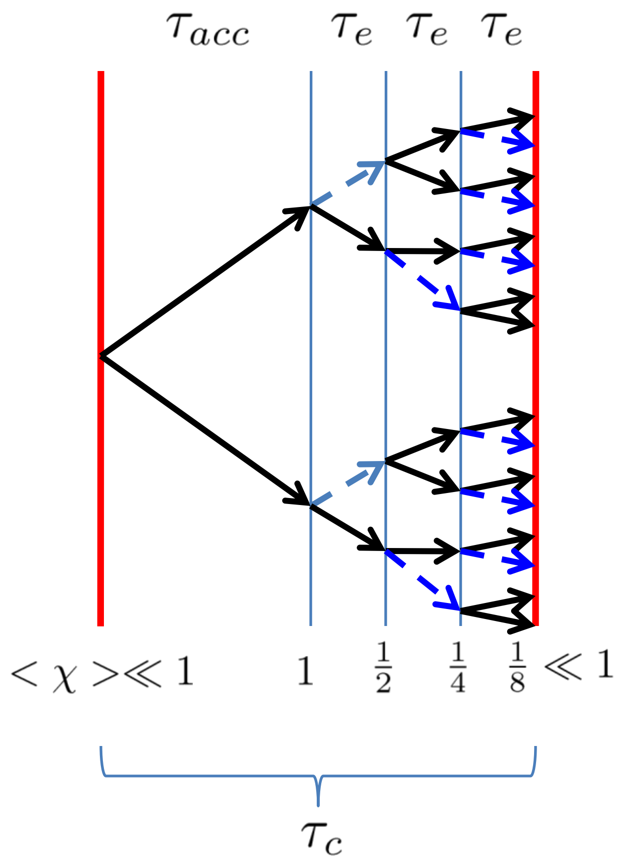
$$W_\gamma \sim \frac{\alpha m}{\varepsilon_e}\ \ \text{at}\ \ (\chi_e \sim 1) \qquad W_{e^-e^+} \sim \frac{\alpha m}{\varepsilon_\gamma}\ \ \text{at}\ \ (\chi_\gamma \sim 1)$$

The first pair is created at rest with $\chi \sim 10^{-2}$

after $\boxed{\tau_{acc} \approx \tau_C \sqrt{\frac{m}{\omega}\frac{E_S}{E_0}} \sim 0.7\cdot 10^{-16}s\,,}$ $\chi \sim 1$

e^-, e^+ irradiate photons, χ of secondary particles ~ 1

$$\boxed{\tau_e \sim \tau_\gamma \sim W_\gamma^{-1} \sim 10^{-17}s}$$



$\cdots$

at $t = \tau_c\,,\;\; N_c = 10$

$$\tau_c = \tau_{acc} + 3\tau_e \approx 10^{16}$$

The charged particles are pushed out of the pulse due to ponderomotive effect

$$\tau_{out} \sim \lambda/c \sim 3 \cdot 10^{-15} < \tau_L$$

The total number of created particles

$$N \sim N_c^{\frac{\tau_{out}}{\tau_c}} \sim 10^{30}$$

BANG !!!

Nonlinear QED effects
initiated by ultrarelativistic particles

- ❑ particle shower produced by a high energy electrons or photons colliding with a superstrong laser pulse

- ❑ self-consistent kinetic description of disintegration of an intense focused laser pulse due to electromagnetic cascades induced by high energy photons and electrons

- ❑ non-perturbative QED with ultrarelativistic particles and the ELI facility

Non-perturbative QED with ultrarelativistic particles and the ELI facility

The coupling constant in QED at $\chi \gg 1$

$$g = \alpha \chi^{2/3}$$

N.B. Narozhny, Phys. Rev. D **20**, 1313 (1979), **21**, 1176 (1980)

QED becomes a strong-coupling theory at $\chi \gtrsim 1.6 \cdot 10^3$ **!**

ELI: $I \sim 10^{26} W/cm^2 \rightarrow E_0/E_S \sim 10^{-2}$

$g \sim 1 \quad \rightarrow \quad \gamma \sim 10^5$ (SLAC)

New non-perturbative methods should be developed

Relativistic nuclear physics in superstrong laser fields

- excitation and fission of relativistic nuclei in a superstrong laser field

- control of beta-decay by a superstrong laser field

Excitation and fission of relativistic nuclei in a superstrong laser field

If the values $\hbar\omega \sim 1eV, \quad E_0 \sim 10^{15}V/cm$ were obtained

Lorentz invariant intensity parameter:

$$\eta_e = \frac{eE_0}{cm_e\omega} \sim 10^5, \qquad \eta_p = \frac{eE_0}{m_p\omega c} \sim 10^2$$

Quantum processes at $\eta \gg 1$ are multiphoton.
The number of involved photons $s_{eff} \sim \eta^3$

$s_{eff}\hbar\omega \sim 1MeV$!!!

~ excitation and binding energies of many nuclei

Methods developed in atomic physics could be successfully applied

Control of beta-decay by a superstrong laser field

The field can efficiently change the probability of β decay if

$$E \gtrsim E_* = E_S \left(\frac{2\mathcal{E}_0}{m}\right)^{3/2}$$

$\mathcal{E}_0$ is the maximal kinetic energy of e^-

A.I. Nikishov, V.I. Ritus, ZhETF, **85**, 1544 (1983)

$$T \rightarrow He^3 + e^- + \tilde{\nu} \quad \longrightarrow \quad \mathcal{E}_0 = 18.65 KeV$$

$$E_* \approx 3 \cdot 10^{-2} E_S$$

THANK YOU

FOR ATTENTION !