# Radiation dominated nonlinear Compton scattering: signatures of quantum dynamics and attosecond gamma-ray bursts

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LNPC17, April 21, 2017
Yokohama, Japan

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Max-Planck-Institut
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# Outline

- Radiation reaction. Radiation Dominated Regime
- Signatures of a photon stochastic emission
- Ultrashort gamma-ray pulses via nonlinear Compton scattering
- Signatures of quantum radiation reaction
- Conclusion

# Radiation Dominated Regime

nonrelativistic

relativistic

$$m\dot{\mathbf{v}} = e\mathbf{E} + \frac{e}{c}[\mathbf{vH}] + \frac{2e^2}{3c^3}\ddot{\mathbf{v}} \longrightarrow mc\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i \qquad g^i = \frac{2e^2}{3c}\frac{d^2u^i}{ds^2}$$

$$\mathbf{f} = \frac{2e^3}{3mc^3}\dot{\mathbf{E}} + \frac{2e^4}{3m^2c^4}[\mathbf{EH}] \longrightarrow g^i = \frac{2e^3}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l - \frac{2e^4}{3m^2c^5}F^{il}F_{kl}u^k + \frac{2e^4}{3m^2c^5}(F_{kl}u^l)(F^{km}u_m)u^i$$

$$\lambda \gg r_0 \qquad r_0 = \frac{e^2}{mc^2}$$

$$\alpha\chi \ll 1 \qquad \chi = \frac{E}{E_{cr}}$$

$$E_{cr} = \frac{m^2}{e}$$

$$\alpha\chi \ll 1 \qquad \chi = \frac{E'}{E_{cr}} = \frac{\gamma E}{E_{cr}}$$

$$f_x = -\frac{2e^4}{3m^2c^4}\frac{(E_y - H_z)^2 + (E_z + H_y)^2}{1 - v^2/c^2}$$

$$\frac{F_R}{F_L} = \frac{\alpha\gamma^2 E}{E_{cr}} = \alpha\chi\gamma \qquad F_R \sim F_L$$

**THE CLASSICAL THEORY OF FIELDS**

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L. D. LANDAU AND E. M. LIFSHITZ

Institute for Physical Problems, Academy of Sciences of the U.S.S.R.

In the relativistic domain a regime is possible when radiation reaction force is not perturbation in the Lab frame

# Radiation Dominated Regime

The characteristic emitted photon energy: $\omega_c \sim \chi\varepsilon$

The probability of a photon emission on a coherence length: $\alpha$

Phase interval for a coherence length: $1/\xi$

Number of coherence lengths on a laser period : $\xi = eE/m\omega = a_0$

Number of emitted photons during a laser period : $N_{ph} \sim \alpha\xi$

The electron radiative energy loss during a laser period: $\Delta\varepsilon^{(T)}{}_{rad} \sim \alpha\xi\chi\varepsilon$

Radiation Dominated Regime (RDR):

$$R \equiv \frac{\Delta\varepsilon^{(T)}{}_{rad}}{\varepsilon} \sim \alpha\xi\chi \gtrsim 1$$

RDR is significant in quantum domain

$$\chi \ll 1,\ R \gtrsim 1 \quad \rightarrow \quad \xi \gtrsim 10^3$$

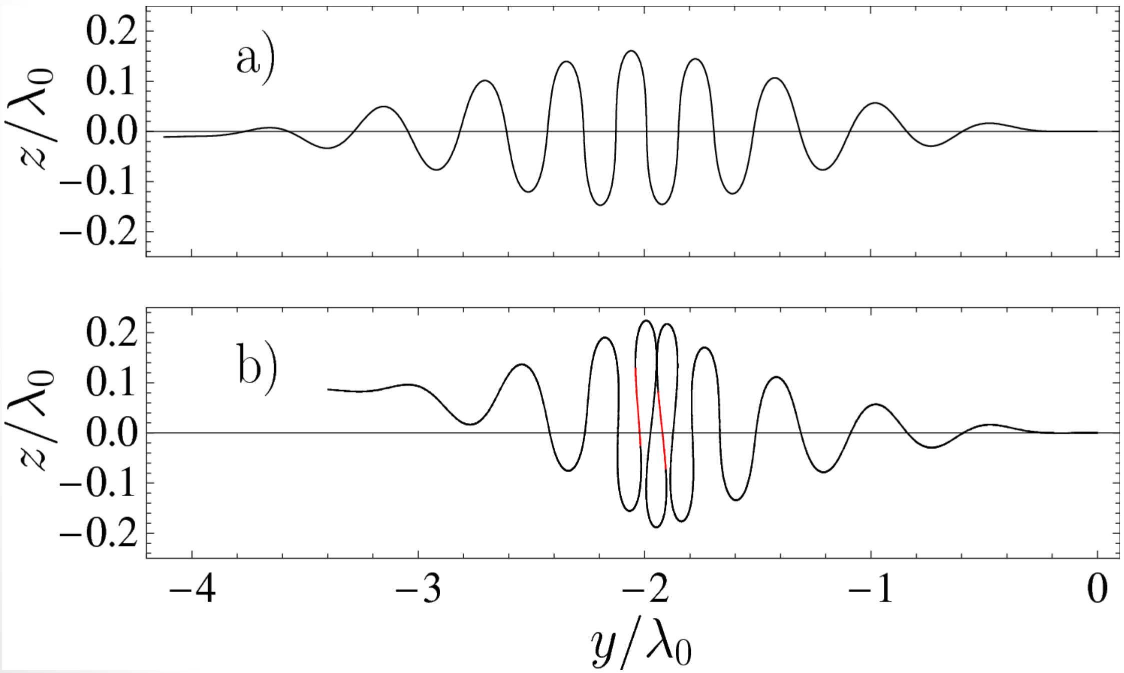
Classical RDR: $I \gtrsim 10^{24}\ \mathrm{W/cm^2}$

# Reflection regime

Electron reflection regime: $\gamma \sim \frac{\xi}{2}$ $\theta \sim \frac{\xi}{\gamma} < 1$ $\beta_d = \frac{\xi^2/2}{1+\xi^2/2}$ $\gamma_d \sim \frac{\xi}{2}$

Laser electron

Electron trajectory




$\gamma \lesssim \frac{\xi}{2}$ most of electrons initially fulfill the reflection condition. In the near reflection direction, a very broad gamma-photon peak is formed with specific properties.

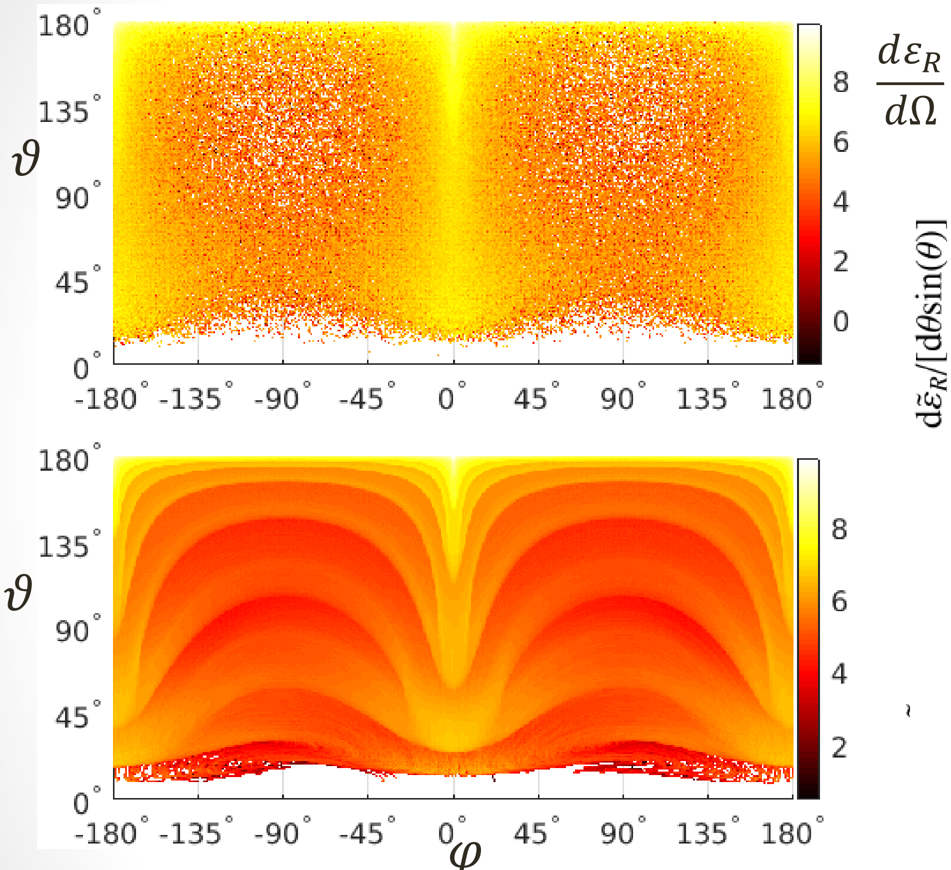
$\gamma \gtrsim \frac{\xi}{2}$ only few front electrons in the electron beam can be reflected due to the combined effects of the radiation reaction and the laser focusing: ultrashort gamma-ray emission in the backward direction.

$\gamma \gg \frac{\xi}{2}$ the radiation concentrates mainly in the forward direction. The peak of angular BW vs laser pulse length as a QRR signature.

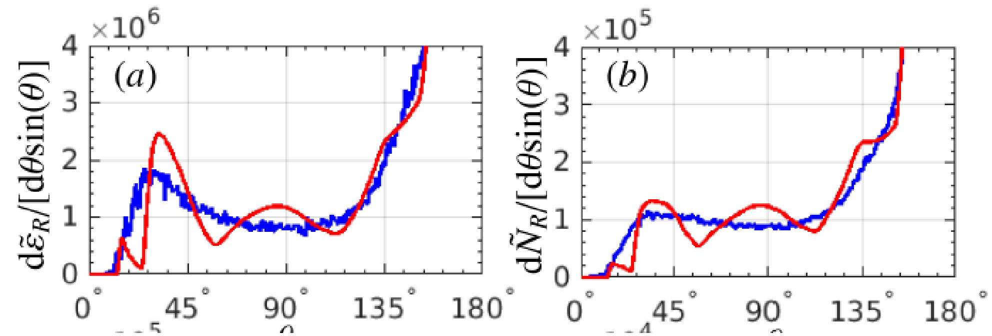
# Signatures of stochastic effects in photon emission

$$\gamma \lesssim \xi/2$$

with stochastic effects




without stochastic effects




$\varepsilon > 1\text{MeV}$

the electron straggling effect is not significant

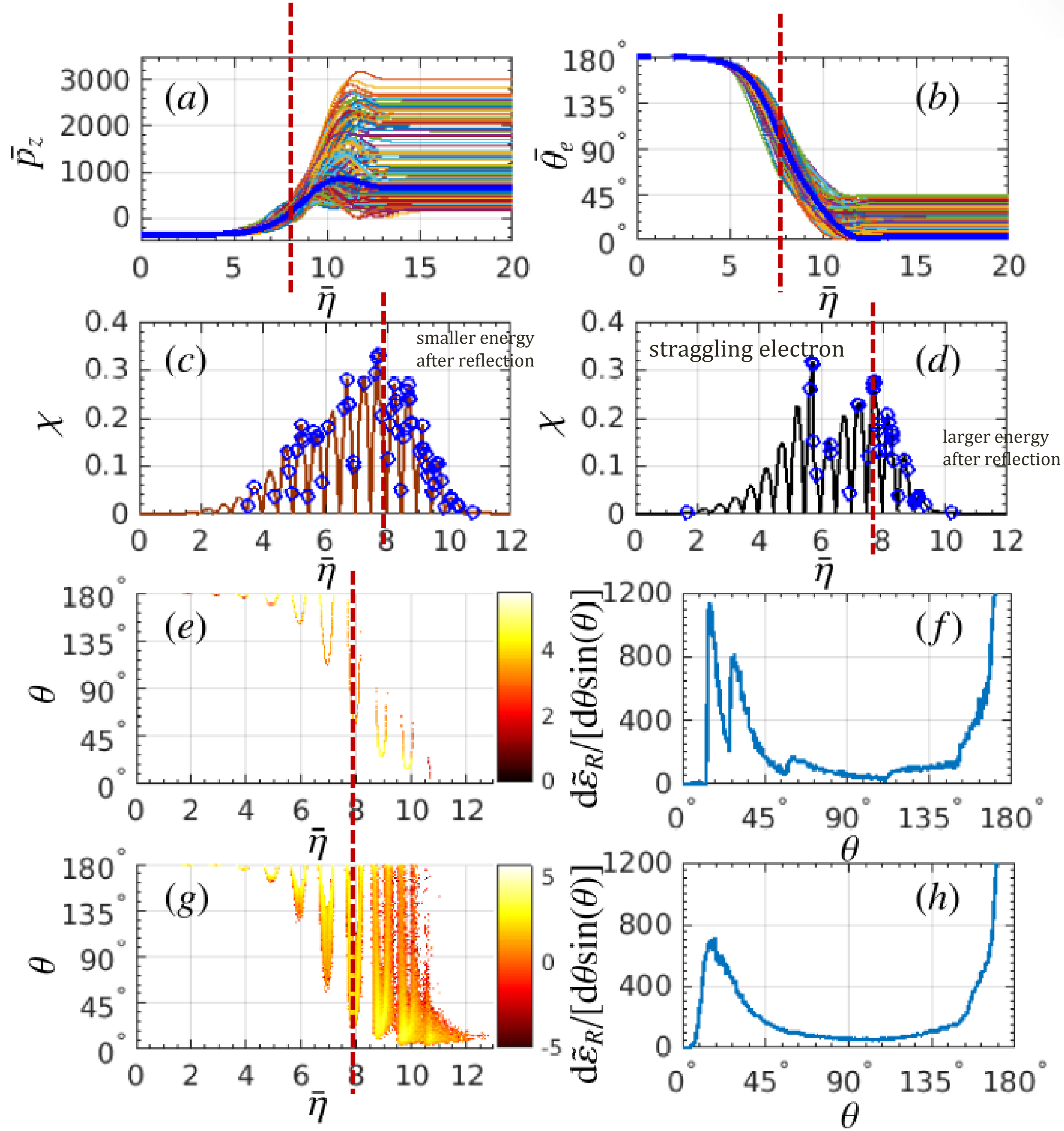
$$I = 4.9 \cdot 10^{23} \frac{W}{cm^2}$$
$$\lambda = 1\ \mu m$$
$$\xi = 600$$
$$\varepsilon = 180\ MeV$$

Jian-Xing Li, Chen, KZH, Keitel, arXiv:1612.06796

# Signatures of stochastic effects in photon emission

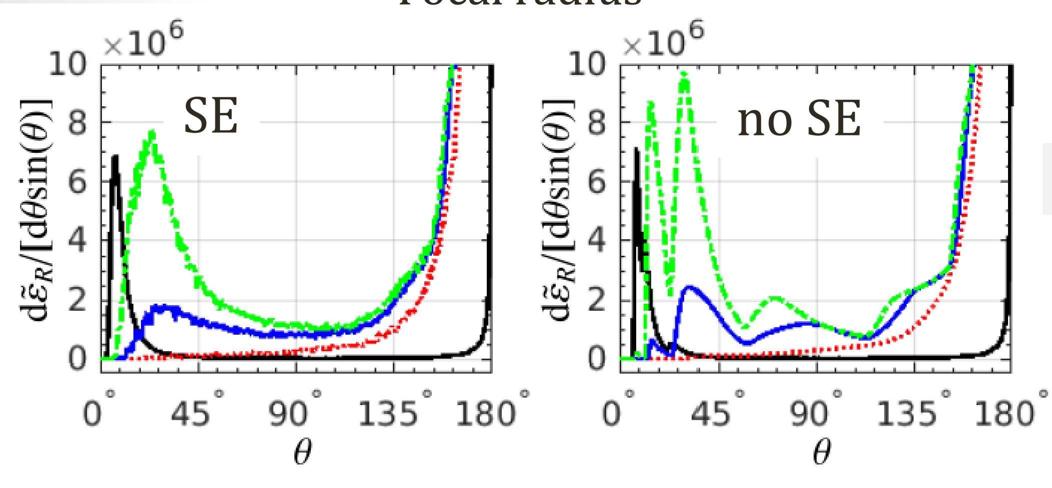
$$\theta_e = arctan\frac{m\xi}{|p_z|}$$

$$\bar{\eta} = \omega t - kz$$



# Signatures of stochastic effects in photon emission

Focal radius



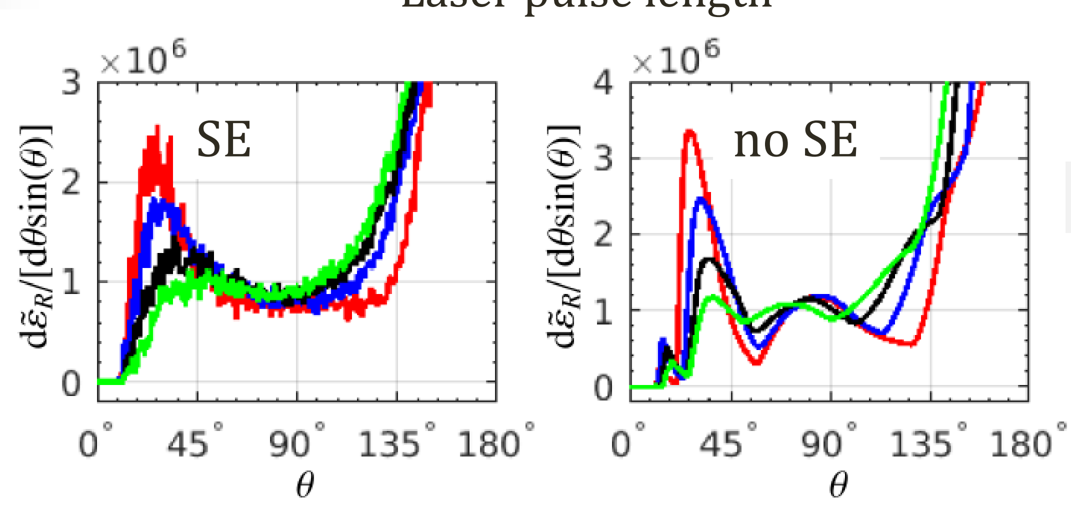

$w_0 = \lambda$

$w_0 = 2\lambda$

$w_0 = 3\lambda$

$w_0 = \infty$

Laser pulse length

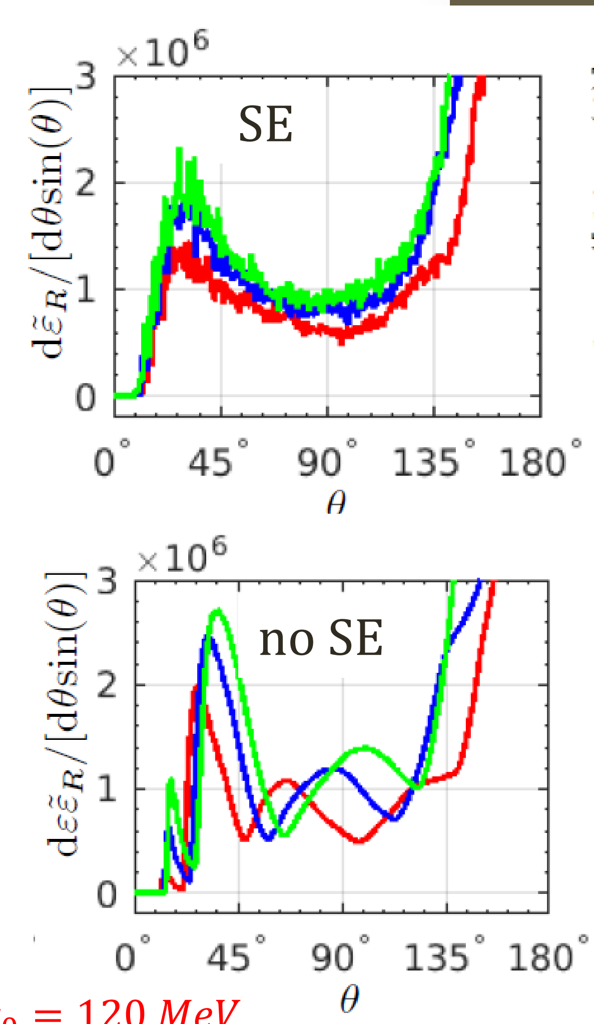



$L = 3\lambda$

$L = 6\lambda$

$L = 8\lambda$

$L = 10\lambda$




$\varepsilon_0 = 120\ MeV$

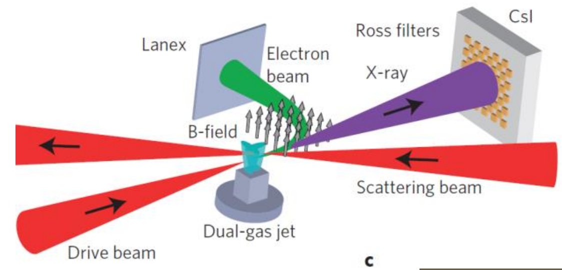
$\varepsilon_0 = 180\ MeV$

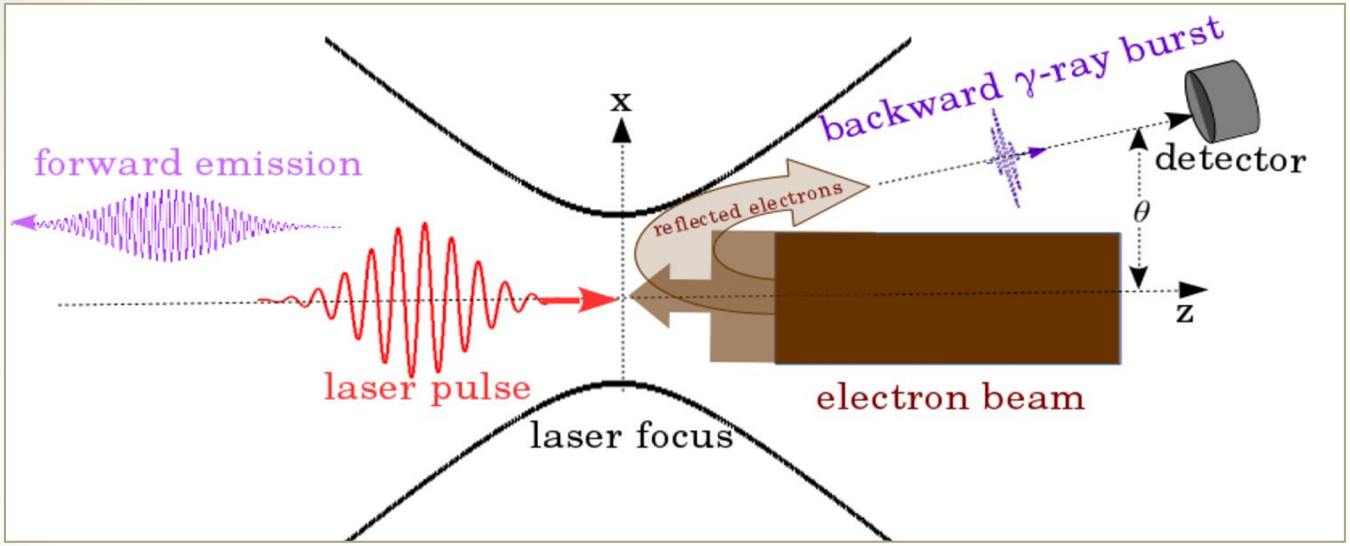
$\varepsilon_0 = 240$ MeV

Jian-Xing Li, Chen, KZH, Keitel, arXiv:1612.06796

# How to obtain short pulses in Compton scattering

$\gamma \gtrsim \xi/2$



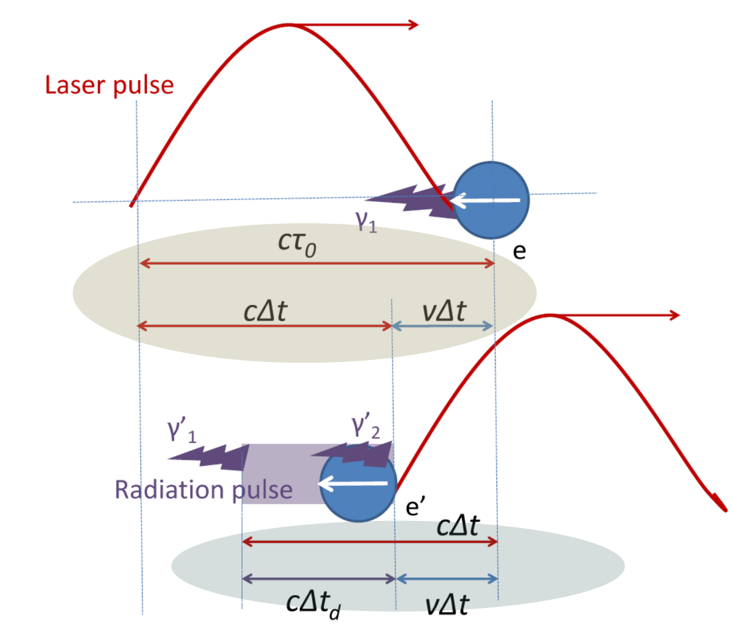

- a small front part of the electron beam is reflected
- the strong emission at the reflection is in near-backwards direction

- Nonlinear regime $\xi \gg 1$ $\quad \xi = \frac{eE}{mc\omega} \quad n \sim \xi^3$
- Radiation dominated regime $R = \alpha\xi\chi \quad \chi = \gamma\xi(\omega/m)\,(1 - \beta\cos\vartheta) \gtrsim 1$
- Reflection regime $\gamma \sim \xi/2$
- Focusing $w_0 \sim \lambda \qquad \gamma \sim \xi \quad \sim 10^3$

J.-X. Li, KZH, C. H. Keitel, PRL, 115, 204801 (2015)

# Radiation pulse duration

## Single electron

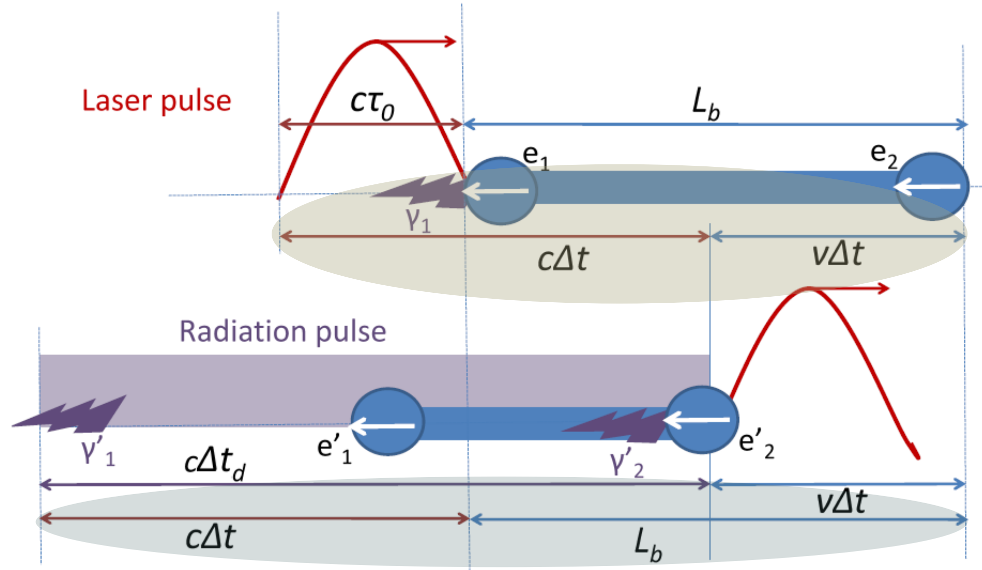



$$c\Delta t + v\Delta t = c\tau_0 \qquad \Delta t = \frac{\tau_0}{1+\beta}$$

$$c\Delta t_d = c\Delta t - v\Delta t$$

$$\Delta t_d = (1-\beta)\Delta t \approx \frac{\Delta t}{2\gamma^2} \approx \frac{\tau_0}{4\gamma^2}$$

## Electron bunch



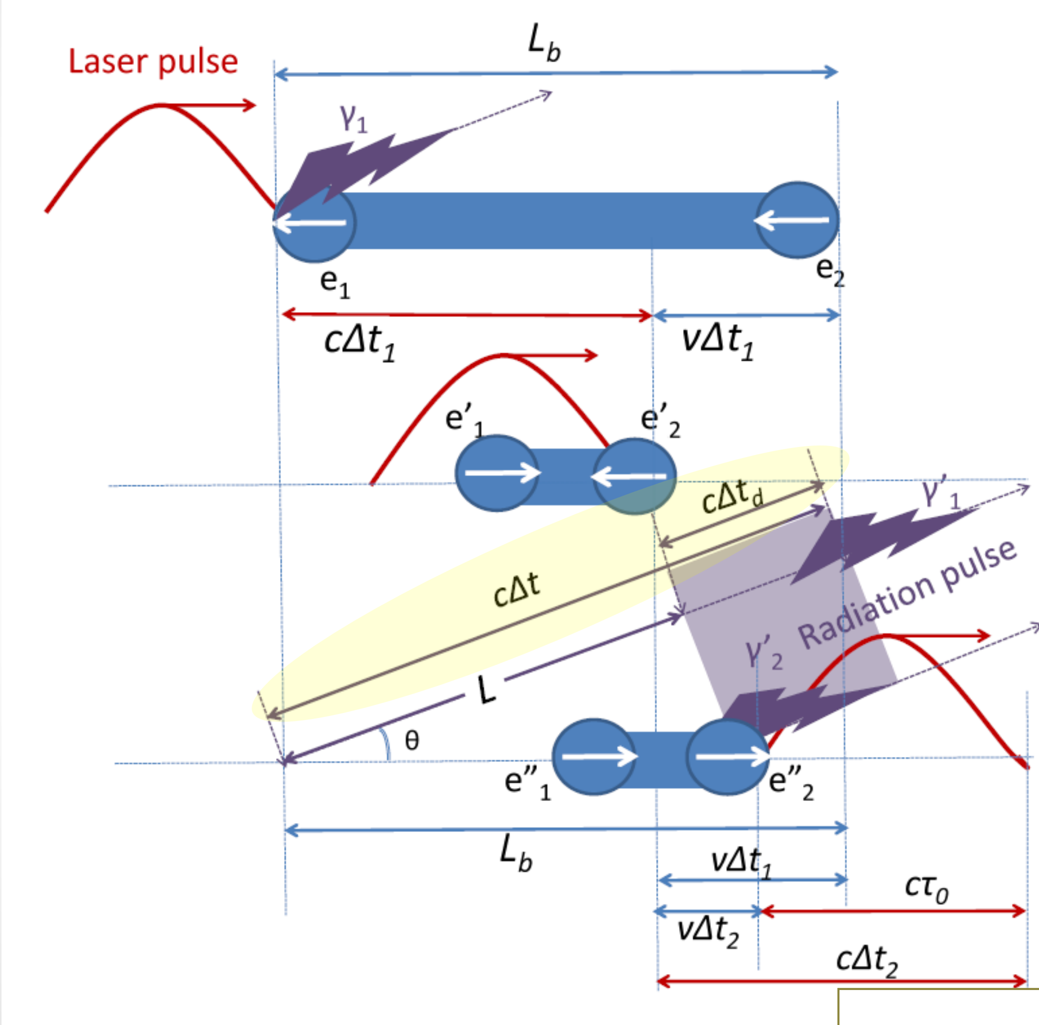

$$(c+v)\Delta t = c\tau_0 + L_b \qquad \Delta t = \frac{\tau_0 + L_b/c}{1+\beta}$$

$$c\Delta t_d + v\Delta t = c\Delta t + L_b$$

$$\Delta t_d = \frac{\tau_0}{4\gamma^2} + \frac{2L_b/c}{1+\beta}.$$

# Radiation pulse duration

Pulse duration when the electron bunch is reflected from the laser pulse




$$\Delta t_2 \to \frac{L_R}{c} \qquad L_b \to L_b{}^{eff}$$

$$\Delta t = \Delta t_1 + \Delta t_2$$

$$c\Delta t_1 + v\Delta t_1 = L_b$$

$$\Delta t_1 = \frac{L_b/c}{1+\beta}$$

$$c\Delta t_2 - v\Delta t_2 = c\tau_0$$

$$\Delta t_2 = \frac{\tau_0}{1-\beta}$$

$$c\Delta t_d = c\Delta t - L$$

$$L \equiv [L_b - v(\Delta t_1 - \Delta t_2)]\cos\theta$$

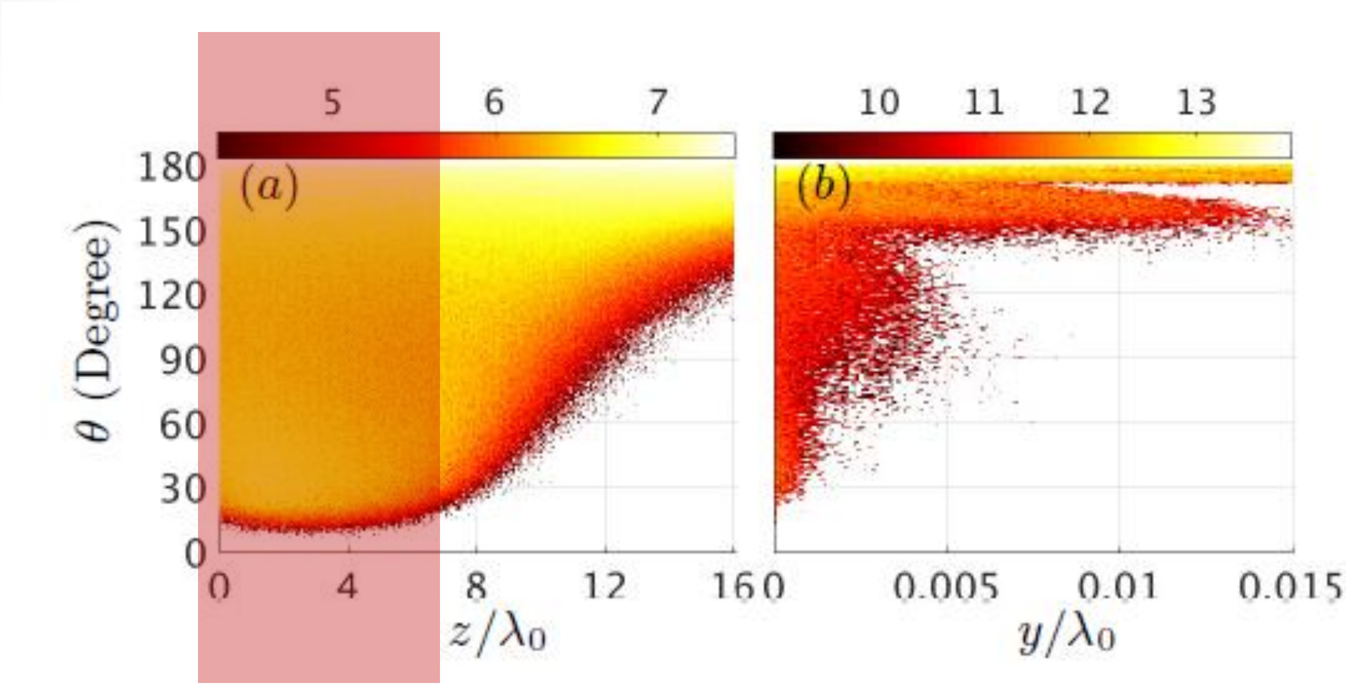
$$\Delta t_d = \tau_0 \frac{1-\beta\cos\theta}{1-\beta} + \frac{L_b}{c}\frac{1-\cos\theta}{1+\beta}$$

Focused laser pulse:

$$\Delta t = \frac{L_R}{c} + \frac{L_b/c}{1+\beta}$$

$$\Delta t_d \sim \pi T_0 \left(\frac{w_0}{\lambda_0}\right)^2 (1-\beta\cos\theta) + \frac{L_b}{c}\frac{1-\cos\theta}{1+\beta}$$

# Effective length of the electron bunch




$z \lesssim 5\lambda_0$

Angle-resolved radiation intensity vs initial coordinate of the electron in the bunch

Only front electrons in the bunch contributes into the radiation.

# Radiation angular distribution

Time-resolved

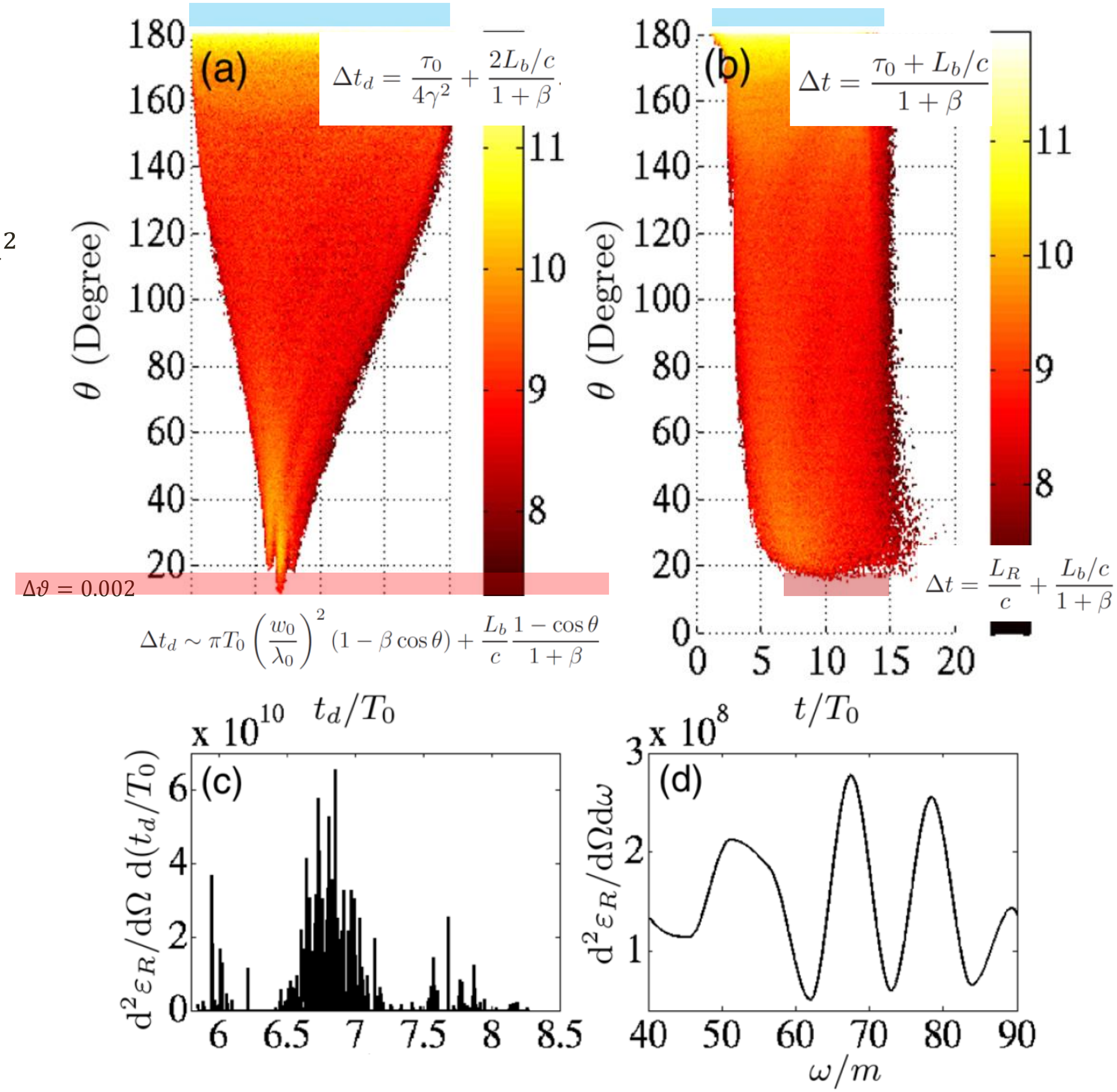
Lab-frame

Electron-frame

$\Delta t_d / \Delta t$

$$I = 4.9 \cdot 10^{23}\ W/cm^2$$
$$\lambda = 1\ \mu m$$
$$a_0 = 600$$
$$\varepsilon = 200\ MeV$$
$$\gamma \gtrsim a_0/2$$

$$\chi_{max} \approx 0.8$$
$$L_b = 10\lambda$$
$$w_b = w_0$$
$$N_e = 3 \cdot 10^8$$
$$\frac{\Delta\gamma}{\gamma} = \Delta\vartheta = 10^{-3}$$



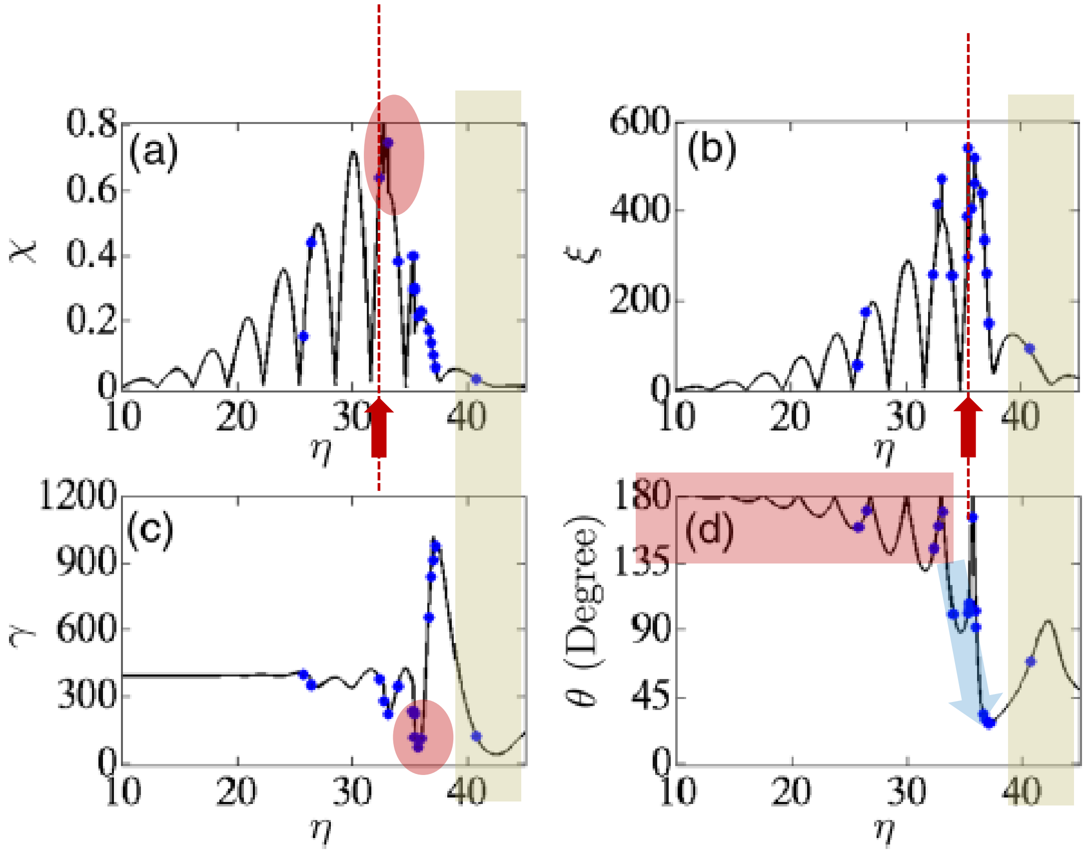

Spectrum

$$\tau_\gamma \approx 800\ as$$
$$\Omega \approx 35\ MeV$$

$$\tau_L \approx 13\ fs$$
$$\tau_e \approx 33\ fs$$

Due to shortness:
Flux ~$10^{14}$ photons/s/0.1%BW,
Brilliance~$10^{20}$ photons/s/mrad2/mm2/0.1%BW

# Dynamics of a single electron




$$\theta \sim \frac{\xi}{\gamma}$$

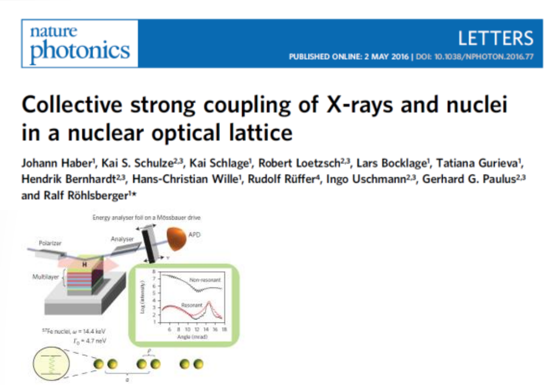
$$\eta = \omega\left(t - \frac{z}{c}\right)$$

$I = 4.9 \cdot 10^{23}\ W/cm^2$
$\lambda = 1\ \mu m$
$\varepsilon = 200\ MeV$

almost no radiation after reflection

# Why ultrashort gamma-ray pulses are important?

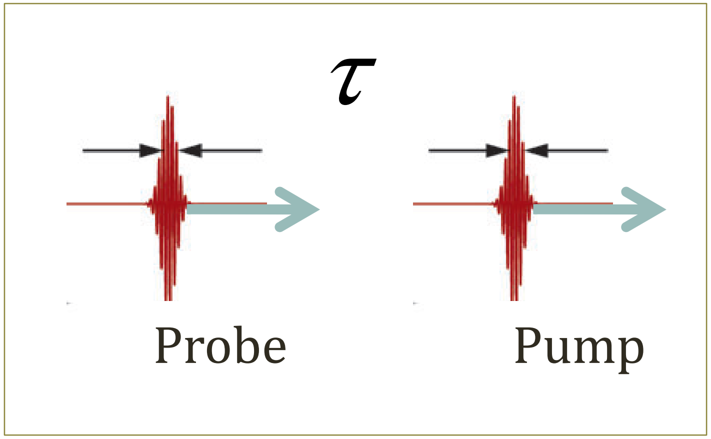
Quantum optics in the hard X-ray regime
with quantum transition of nucleus


nature photonics | LETTERS
PUBLISHED ONLINE: 2 MAY 2016 | DOI: 10.1038/NPHOTON.2016.77

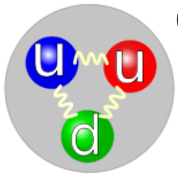
**Collective strong coupling of X-rays and nuclei in a nuclear optical lattice**

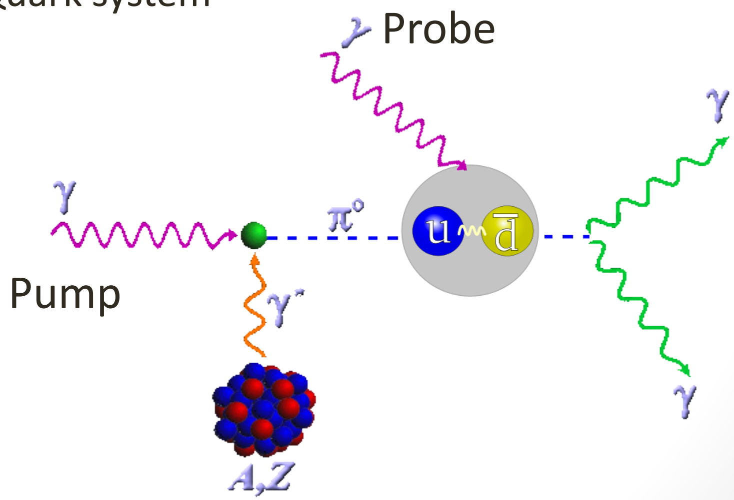
Johann Haber[1], Kai S. Schulze[2,3], Kai Schlage[1], Robert Loetzsch[2,3], Lars Bocklage[1], Tatiana Gurieva[1], Hendrik Bernhardt[2,3], Hans-Christian Wille[1], Rudolf Rüffer[4], Ingo Uschmann[2,3], Gerhard G. Paulus[2,3] and Ralf Röhlsberger[1]*

Time-resolved
intra-nuclear dynamics



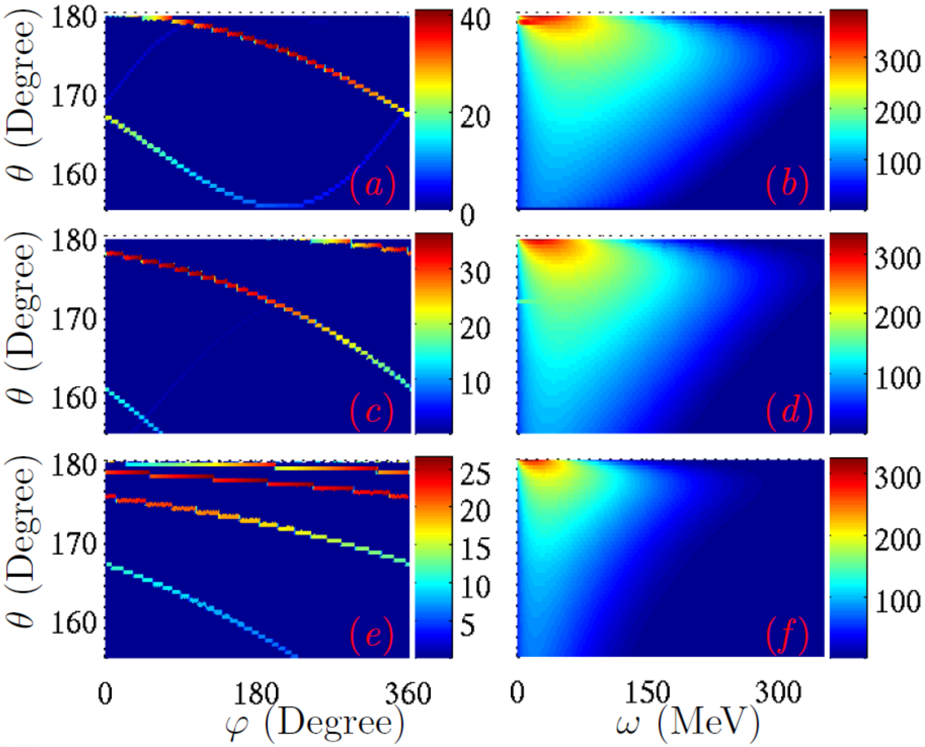

Quark system



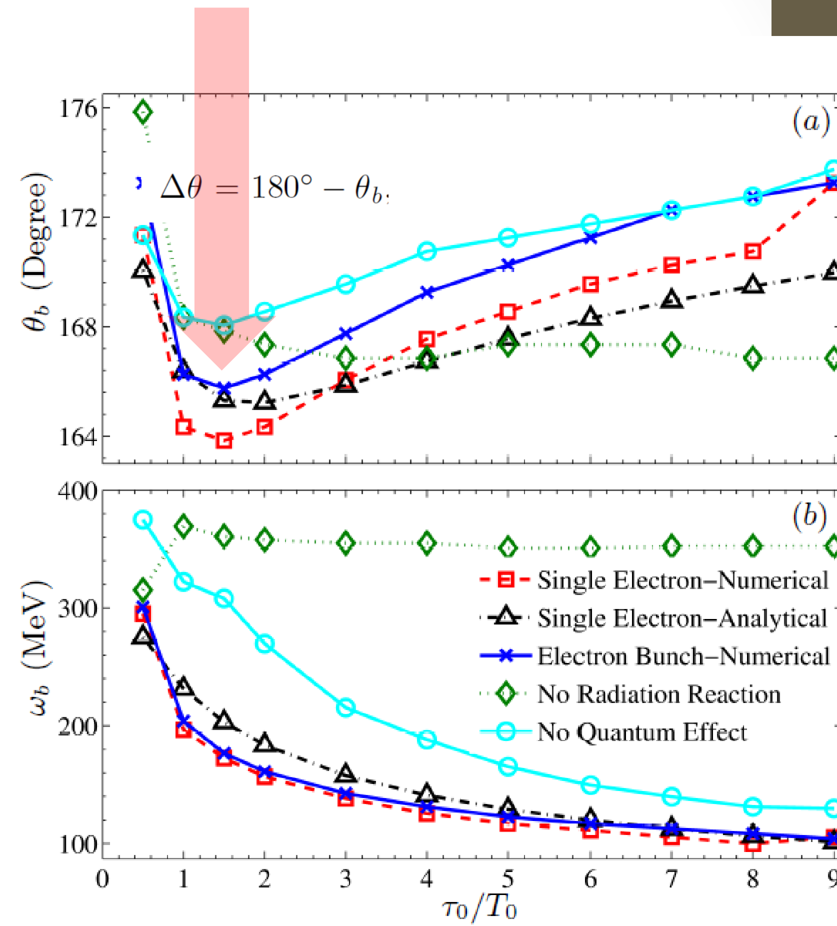



# Robust signatures of quantum radiation reaction for nonlinear Compton scattering in focused ultrashort laser pulses

$$\gamma \lesssim \xi/2$$




$d\varepsilon/d\Omega$ [GeV/sr]    $\varepsilon/d\Omega d\omega$ [1/sr]




Quantum regime:

$$R = \alpha\xi\chi \geq 1$$

$$\chi \approx 2\gamma\xi\omega/m \sim 1$$

$$\xi \leq \gamma \leq 20\xi \quad \Longrightarrow \quad R \sim 1 \Rightarrow \chi \sim 1$$

$$\chi \ll 1 \Rightarrow R \ll 1$$

Jian-Xing Li, KZH, Keitel, PRL, 113, 044501 (2014)

# Explanation of spectral features in RDR

$$\frac{d\varepsilon}{d\phi} \sim \frac{\Delta\varepsilon}{\Delta\phi_{coh}}$$

$$\Delta\varepsilon \sim \alpha\omega_c \qquad \omega_c \sim \frac{m\chi\gamma}{1+\chi}$$

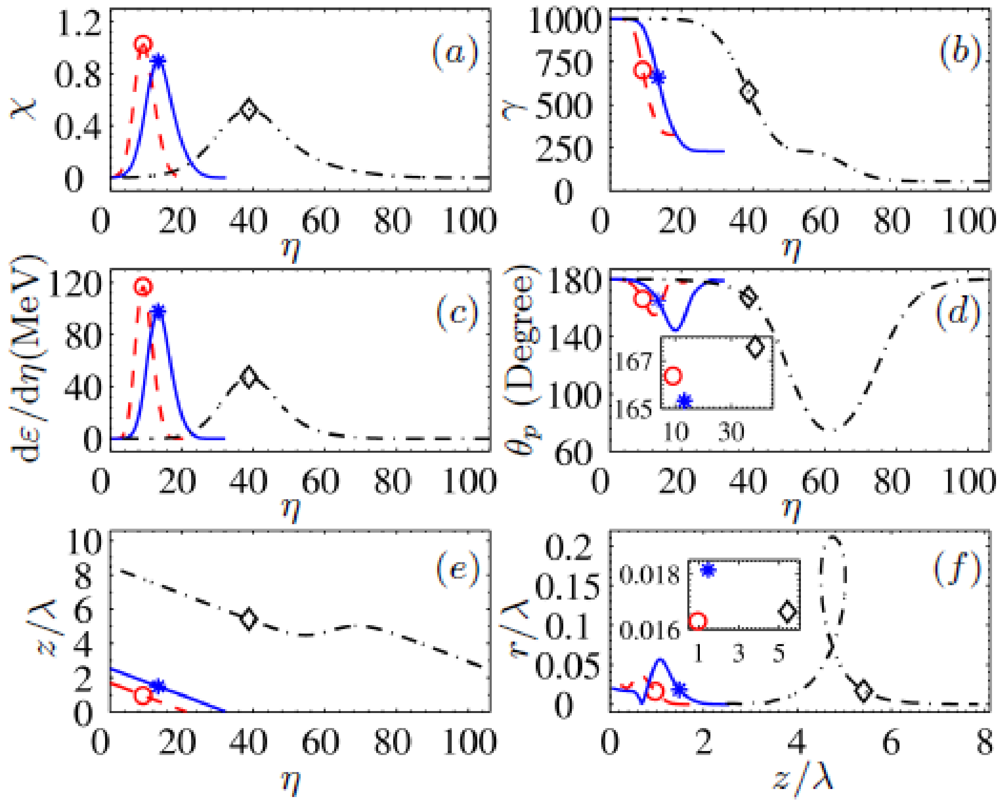
$$\Delta\phi_{coh} \sim \frac{2\pi}{\xi} \qquad \chi \approx 2\frac{\omega_L}{m}\xi\gamma$$

$$\boxed{\frac{d\varepsilon}{d\phi} \sim \frac{\alpha\omega_c\xi}{2\pi} \propto \chi^2}$$

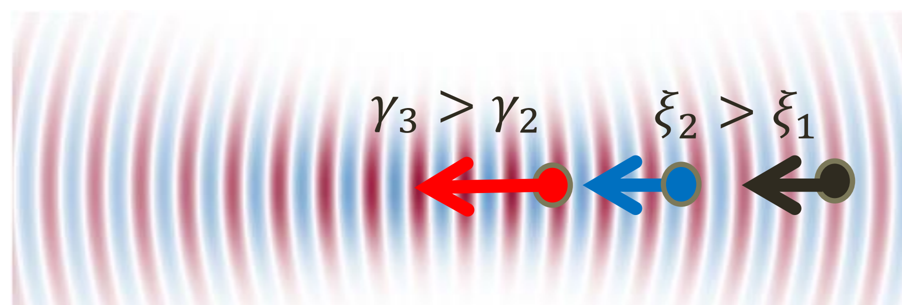
$$\chi \propto \xi\gamma$$

$$p_{\perp m} \sim m\xi(\phi_m)$$

$$\theta_e \sim \xi/\gamma$$




The single electron's dynamics in a counterpropagating laser pulse.
Red, blue, black correspond to 1, 1.5 and 5 laser cycles pulse duration.




Competing of radiation loss and focusing

# Conlcusion

- We offers a way to demonstrate the effect of stochastic emission of photons in the radiation angular distribution. The signatures are robust and are enhanced with tightly focused and short laser pulses.

- Brilliant attosecond gamma-ray bursts can be produced by the combined effect of laser focusing and the radiation reaction in nonlinear Compton scattering in the radiation-dominated regime. The radiation pulse duration is independent on the laser and electron beam durations.

- We have identified signatures of quantum RDR in dependence of both the angular spread and the spectral bandwidth of the Compton radiation spectra on the laser pulse duration. They are robust and observable in a broad range of electron and laser beam parameters.

*Thank you for your attention!*

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# Classical equation of motion with quantum radiation

Electron dynamics in the laser field is classical, but radiation is quantum mechanical.

$\xi \gg 1, \ell_{coh} \ll \lambda_L$ Radiation is determined by the electron local characteristics

The emitted radiation is calculated quantum mechanically, and the differential probability per unit phase interval is [1]

$$\frac{dW_{fi}}{d\eta d\tilde{\omega}} = \frac{\alpha\chi m^2[\int_{\tilde{\omega}_r}^{\infty} K_{5/3}(x)dx + \tilde{\omega}\tilde{\omega}_r\chi^2 K_{2/3}(\omega_r)]}{\sqrt{3}\pi(k_0 \cdot p_i)},$$

$\tilde{\omega}_r = \tilde{\omega}/\rho_0$, with the recoil parameter $\rho_0 = 1 - \chi\tilde{\omega}$ and $\tilde{\omega} = \omega'/(\gamma\chi)$. If $\tilde{\omega}_r \gtrsim 1$, $\frac{dW_{fi}}{d\eta d\tilde{\omega}}$ is very small. Thus, $\tilde{\omega}_r = \tilde{\omega}/\rho_0 = 1$, the cut-off frequency

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

$$\frac{dp^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} p_\nu + \frac{dp_R}{d\tau}^{\mu}$$

$$\frac{dp^\mu}{d\tau} = eF^{\mu\nu}\frac{dx_\nu}{d\tau} - \frac{I}{m} p^\mu$$

$$\frac{dx_\nu}{d\tau} = \frac{p_\nu}{m} + \frac{2r_0}{3}\frac{I}{I_c}\frac{eF_{\nu\sigma}p^\sigma}{m^2}$$

LNPC17, April 21, 2017
Yokohama, Japan

# Radiation Dominated Regime

nonrelativistic — relativistic

$$m\dot{\mathbf{v}} = e\mathbf{E} + \frac{e}{c}[\mathbf{vH}] + \frac{2e^2}{3c^3}\ddot{\mathbf{v}} \longrightarrow mc\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i \qquad g^i = \frac{2e^2}{3c}\frac{d^2u^i}{ds^2}$$

$$\mathbf{f} = \frac{2e^3}{3mc^3}\dot{\mathbf{E}} + \frac{2e^4}{3m^2c^4}[\mathbf{EH}] \longrightarrow g^i = \frac{2e^3}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l - \frac{2e^4}{3m^2c^5}F^{il}F_{kl}u^k + \frac{2e^4}{3m^2c^5}(F_{kl}u^l)(F^{km}u_m)u^i$$

$$\lambda \gg r_0 \qquad r_0 = \frac{e^2}{mc^2}$$

$$\alpha\chi \ll 1 \qquad \chi = \frac{E}{E_{cr}}$$

$$E_{cr} = \frac{m^2}{e}$$

$$\alpha\chi \ll 1 \qquad \chi = \frac{E'}{E_{cr}} = \frac{\gamma E}{E_{cr}}$$

$$f_x = -\frac{2e^4}{3m^2c^4}\frac{(E_y - H_z)^2 + (E_z + H_y)^2}{1 - v^2/c^2}$$

$$\frac{F_R}{F_L} = \frac{\alpha\gamma^2 E}{E_{cr}} = \alpha\chi\gamma \qquad F_R \sim F_L$$

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In the relativistic domain a regime is possible when radiation reaction force is not perturbation in the Lab frame

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# Comment: Channel coupling in radiation reaction

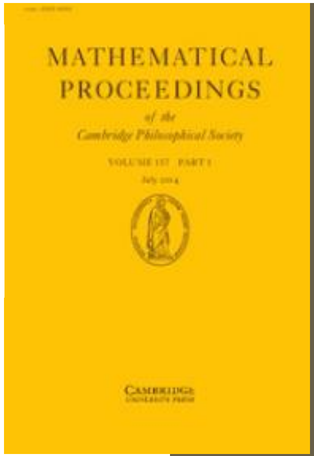
$$\boxed{\begin{gathered}\Delta\varepsilon^{(coh)}{}_{rad} \sim \varepsilon \\ \alpha\chi \sim 1\end{gathered}}$$

THE INFLUENCE OF RADIATION DAMPING ON THE SCATTERING OF LIGHT AND MESONS BY FREE PARTICLES. I

BY W. HEITLER

Communicated by A. H. WILSON

*Received* 16 February 1941




$$-i\dot{b}_A = H_{AI}\, b' e^{i(E'-E_A)t} + \sum_{\nu} H_{AII}\, b''_\nu e^{i(E''_\nu - E_A)t},$$

$$i\dot{b}' = H_{IA}\, b_A e^{i(E_A - E')t} + \sum_{\lambda} H_{IF_\lambda} b_\lambda e^{i(E_\lambda - E')t},$$

$$-i\dot{b}''_\nu = H_{IIA}\, b_A e^{i(E_A - E''_\nu)t} + H_{IIF_\nu} b_\nu e^{i(E_\nu - E''_\nu)t},$$

$$-i\dot{b}_\nu = H_{F_\nu I}\, b' e^{i(E'-E_\nu)t} + H_{F_\nu II}\, b''_\nu e^{i(E''_\nu - E_\nu)t} + \sum_{\lambda} H_{F_\nu III}\, b'''_{\nu\lambda} e^{i(E'''_{\nu\lambda} - E_\nu)t},$$

$$-i\dot{b}'''_{\nu\lambda} = H_{III\,F_\lambda} b_\nu e^{i(E_\nu - E'''_{\nu\lambda})t} + H_{III\,F_\lambda} b_\lambda e^{i(E_\lambda - E'''_{\nu\lambda})t}.$$

$(A) - \nu_0$
$(I) -$
$(II) - \nu_0\nu$
$(III) - \nu\lambda$
$(F) - \nu$

$$\boxed{\nu_0} \to \boxed{\phantom{\nu_0}} \to \boxed{\nu}$$

$$\boxed{\nu_0} \to \boxed{\nu_0\nu} \to \boxed{\nu}$$

$$\boxed{\nu_0} \to \boxed{\phantom{\nu_0}} \to \boxed{\lambda} \to \boxed{\lambda\nu} \to \boxed{\nu}$$

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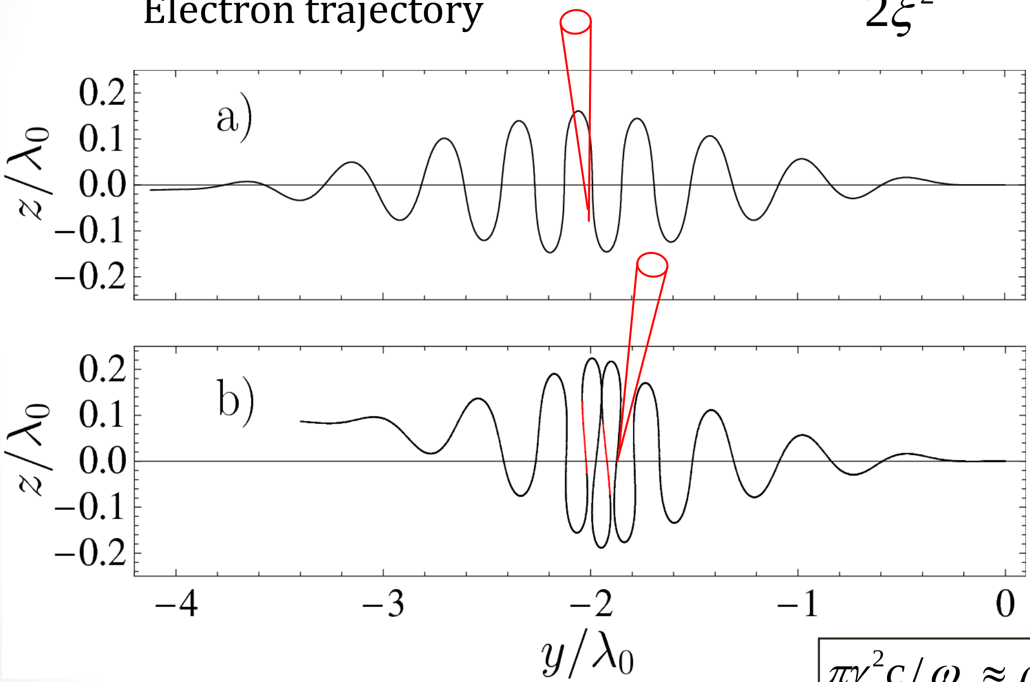
# Radiation dominated dynamics in Thomson scattering

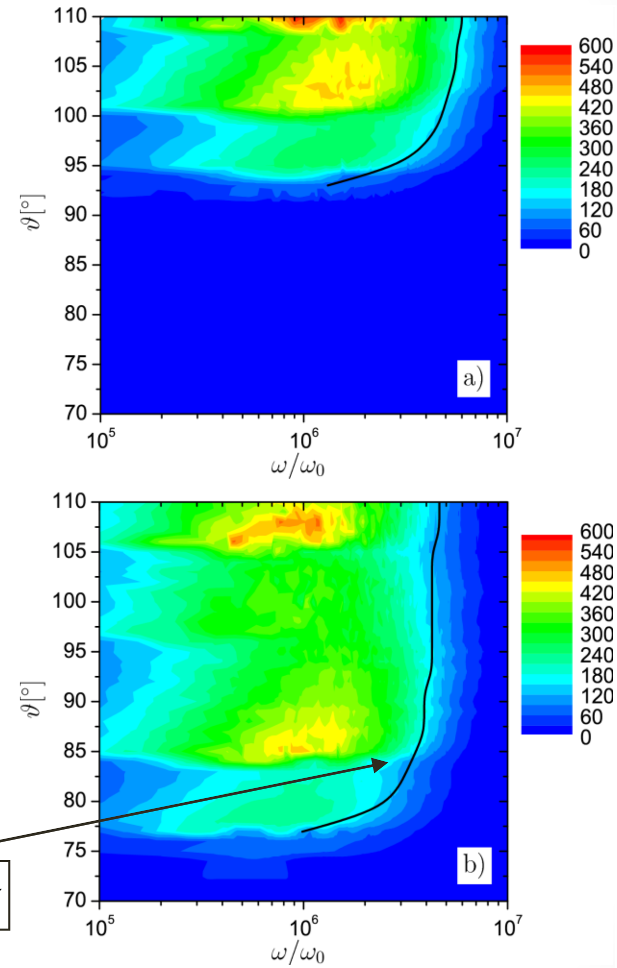
Electron reflection regime: $\gamma \sim \gamma_d \sim \dfrac{\xi}{2}$

$$R \geq \frac{4\gamma_0^2 - \xi^2}{2\xi^2}$$

Electron trajectory




Angle resolved radiation spectra




$\boxed{\pi\gamma^2 c/\omega_c \approx \rho/\gamma}$

Di Piazza, KZH, Keitel, PRL 102, 254802 (2009)

$\gamma$=80 $a_0$=150 I~5x$10^{22}$ W/cm$^2$

$10^9$ electrons in beam
$10^4$ photons per pulse below 90°
1% of electrons contribute

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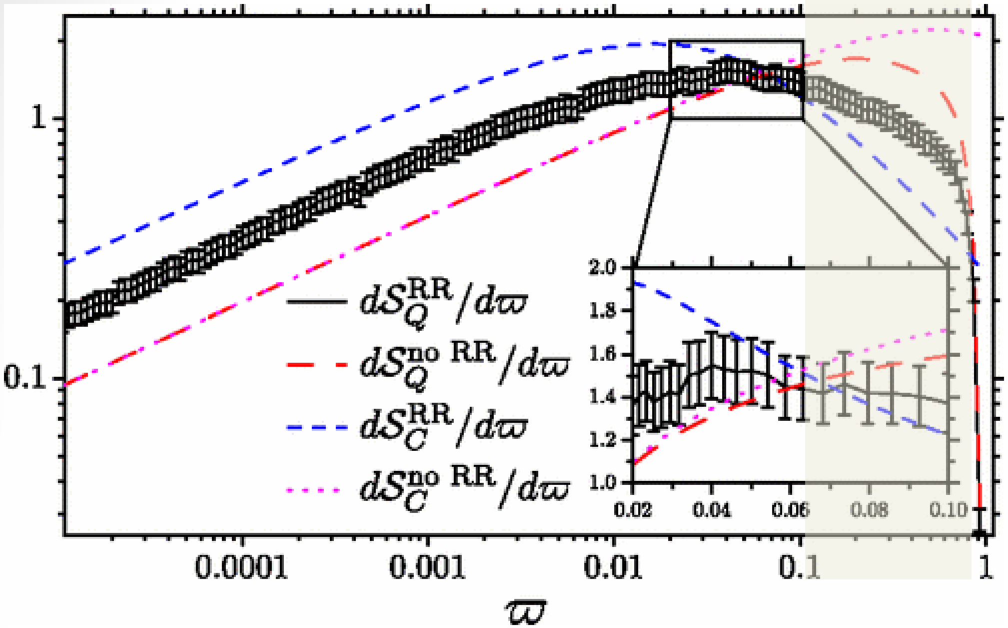
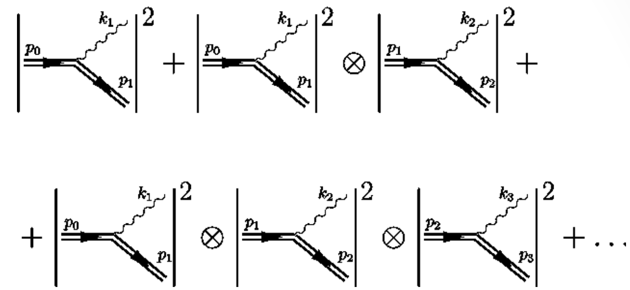
# Quantum radiation dominated regime in Compton scattering



Number of photons 10 keV-1MeV: $(N_0\text{-}N_{RR})/N_0 \sim 40\%$

Typical modification of spectrum in the quantum regime

$\varepsilon$=1 GeV
$\omega$=1.5 eV
I=$5\times10^{22}$ W/cm$^2$
$\xi$=154; $\chi\sim1$; R$\sim$1

Emission of 16 photons
Contribution of more photons 2%

Qualitative signatures of quantum radiation reaction

Radiation reaction for short $\gamma$-ray pulses

Di Piazza, KZH, Keitel PRL 105, 220403 (2010)



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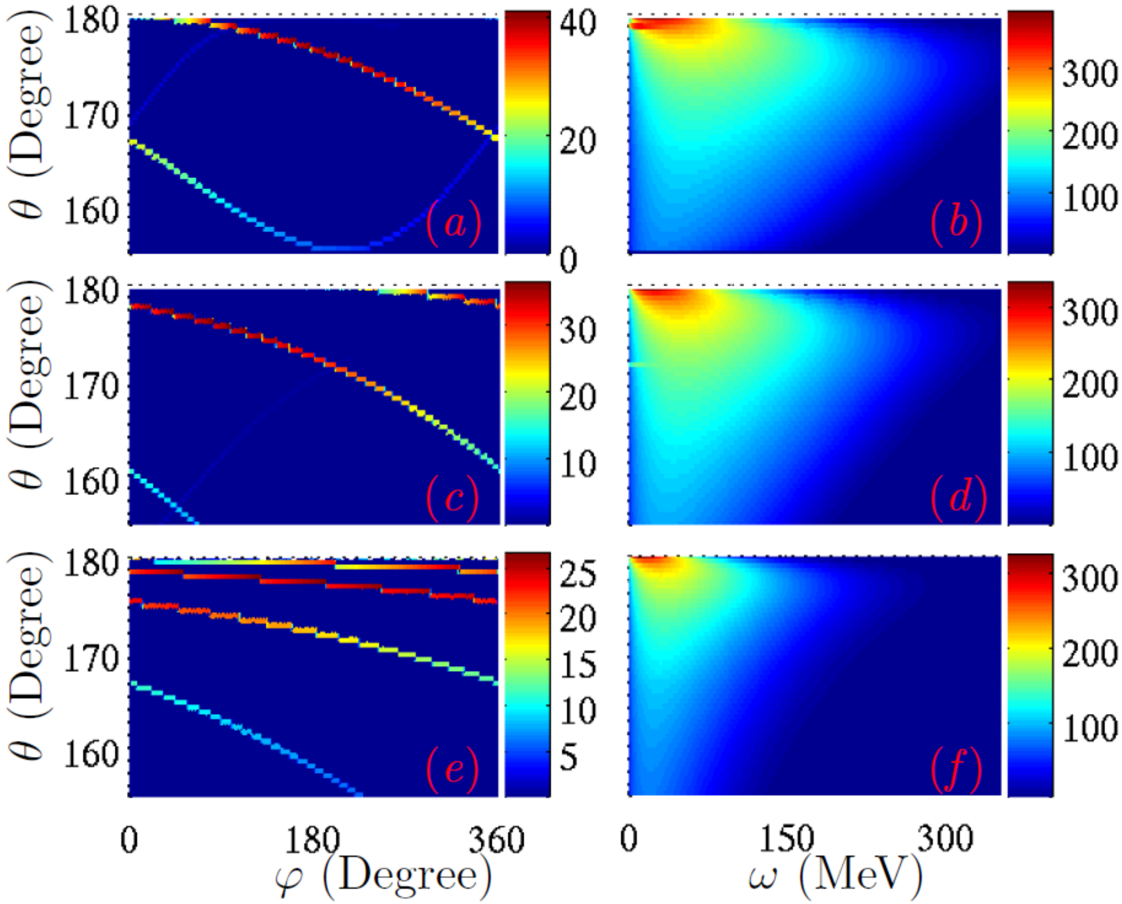
# Qualitative sugnatures of quantum radiation reaction

Quantum RDR:
$$R = \alpha\chi\xi \geq 1$$
$$\chi \approx 2\gamma\xi\omega/m \sim 1$$

$\lambda = 1\ \mu m$,
$w_0 = 10\lambda$
$\xi = 230$,
$\gamma = 10^3$

For each ϑ there is φ, where the radiation energy is maximal.

Radiation angle resolved spectra




Laser pulses of various durations

N=1

N=2

N=5

$d\varepsilon/d\Omega$ [GeV/sr]  $d\varepsilon/d\Omega d\omega$ [1/sr]

J.-X. Li, KZH, Keitel, PRL, 113, 044501 (2014)

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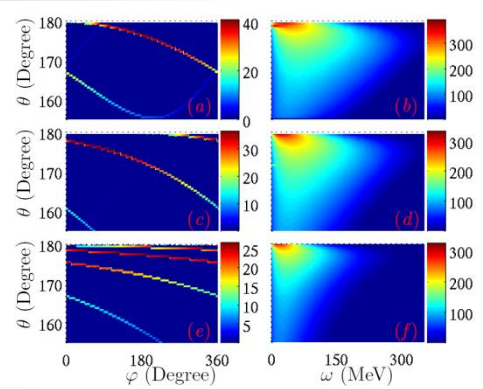
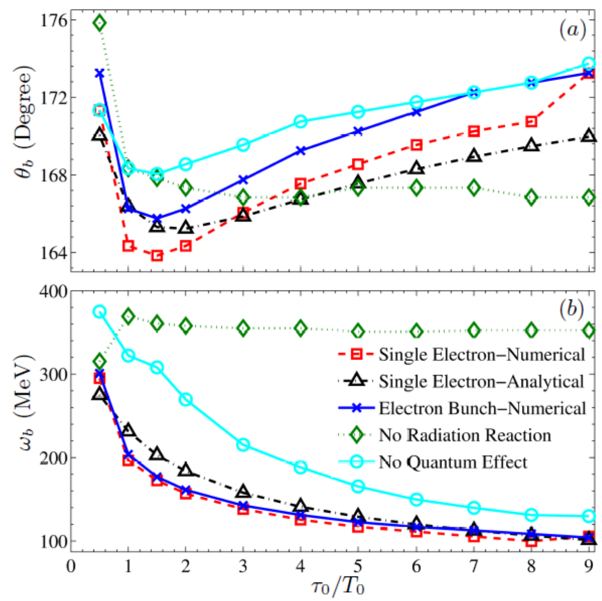
# Robust signatures of quantum radiation reaction for nonlinear Compton scattering in focused ultrashort laser pulses



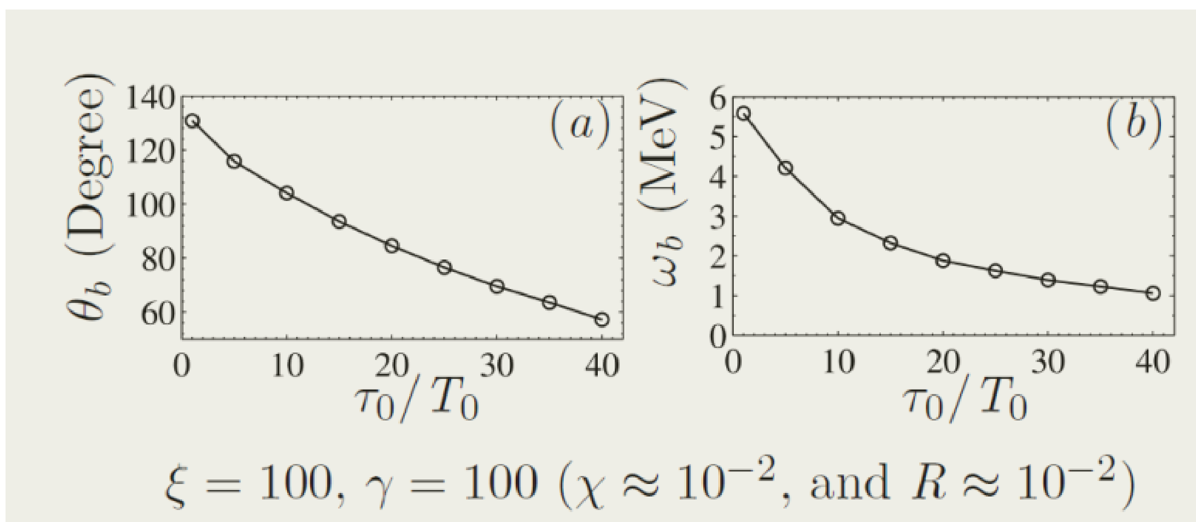



Quantum regime

$$R = \alpha\xi\chi \geq 1$$
$$\chi \approx 2\gamma\xi\omega/m \sim 1$$

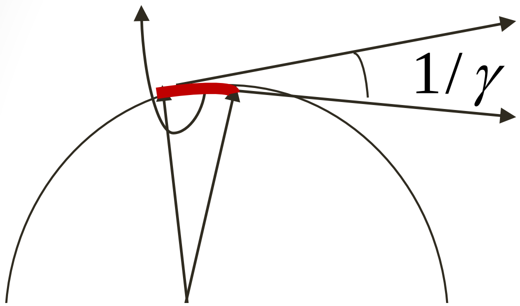
The RR signatures in the classical RR regime:

$$R \ll 1$$
$$\chi \ll 1$$



# Classical equation of motion with quantum radiation

$a_0 \gg 1 \quad \ell_{coh} \ll \lambda_L$




Electron dynamics in the laser field is classical, but radiation is quantum mechanical

Radiation is determined by the electron local characteristics

The emitted radiation is calculated quantum mechanically, and the differential probability per unit phase interval is [1]

$$\frac{dW_{fi}}{d\eta d\tilde{\omega}} = \frac{\alpha\chi m^2[\int_{\tilde{\omega}_r}^{\infty} K_{5/3}(x)dx + \tilde{\omega}\tilde{\omega}_r\chi^2 K_{2/3}(\omega_r)]}{\sqrt{3}\pi(k_0 \cdot p_i)},$$

$\tilde{\omega}_r = \tilde{\omega}/\rho_0$, with the recoil parameter $\rho_0 = 1 - \chi\tilde{\omega}$ and $\tilde{\omega} = \omega'/(\gamma\chi)$. If $\tilde{\omega}_r \gtrsim 1$, $\frac{dW_{fi}}{d\eta d\tilde{\omega}}$ is very small. Thus, $\tilde{\omega}_r = \tilde{\omega}/\rho_0 = 1$, the cut-off frequency


NV Elkina, et al. PRST AB 14, 054401 (2011)
CP Ridgers et al. J. Comput. Phys. 260, 273 (2014)
DG Green, C Harvey, Comput. Phys. Commun. 192, 313 (2015)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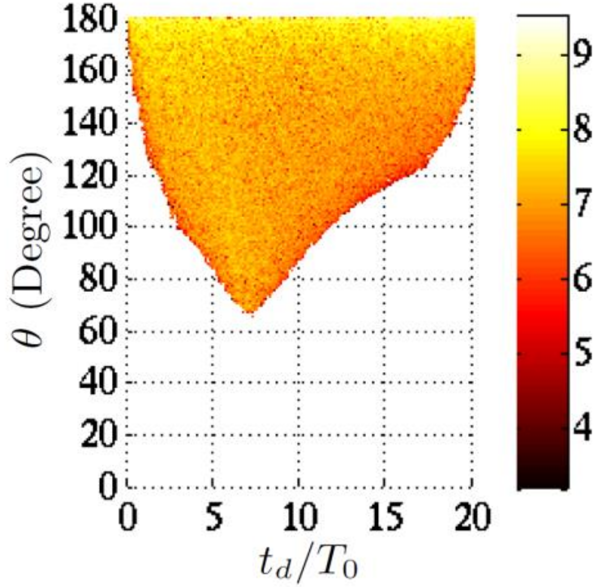
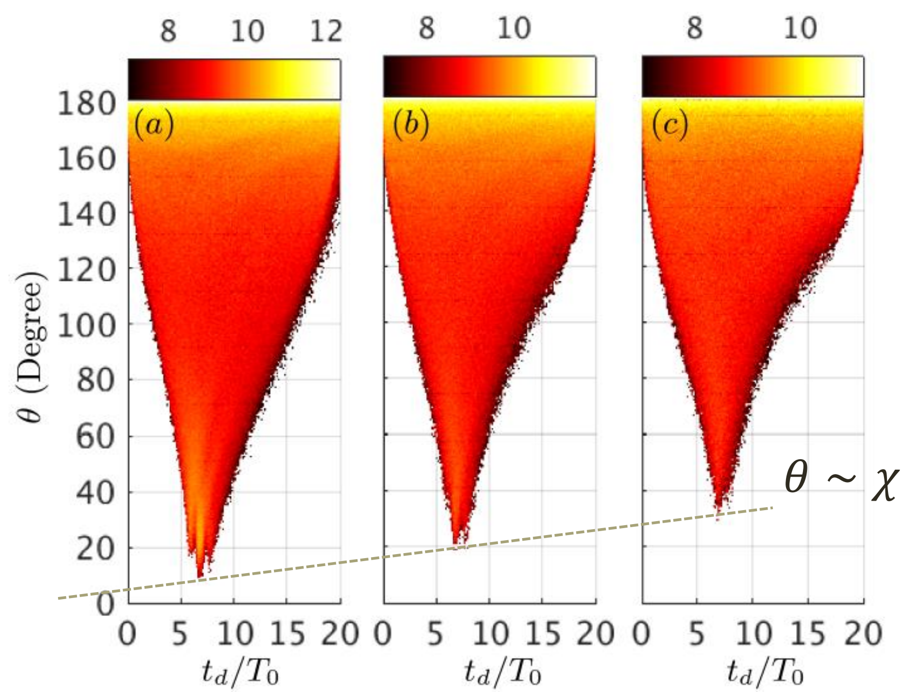
# The role of the radiation dominated regime

# Robustness




$a_0 = 100$

$\varepsilon = 20\ MeV$

$a_0 \sim 2\gamma$

$\chi \approx 0.01$

The radiation loss is small and the reflection condition is assumed to hold for the initial electron energy. Therefore, the reflection can take place in any cycle of the laser pulse. The emission duration is then large and is determined mostly by the total laser pulse duration.

$\boxed{a_0 = 400,\ \varepsilon = 300\ \text{MeV}}$

$a_0 = 600$
$\varepsilon = 300$ MeV

Number of reflected electron is smaller as energy is large.

$a_0 = 400$
$\varepsilon = 200$ MeV

The average gamma-photon energy is lower as $\chi$ is smaller.

$a_0 = 300$
$\varepsilon = 100$ MeV

Number of emitted photons and the average photon energy are lower since chi is much smaller

Variation of $a_0/\gamma$

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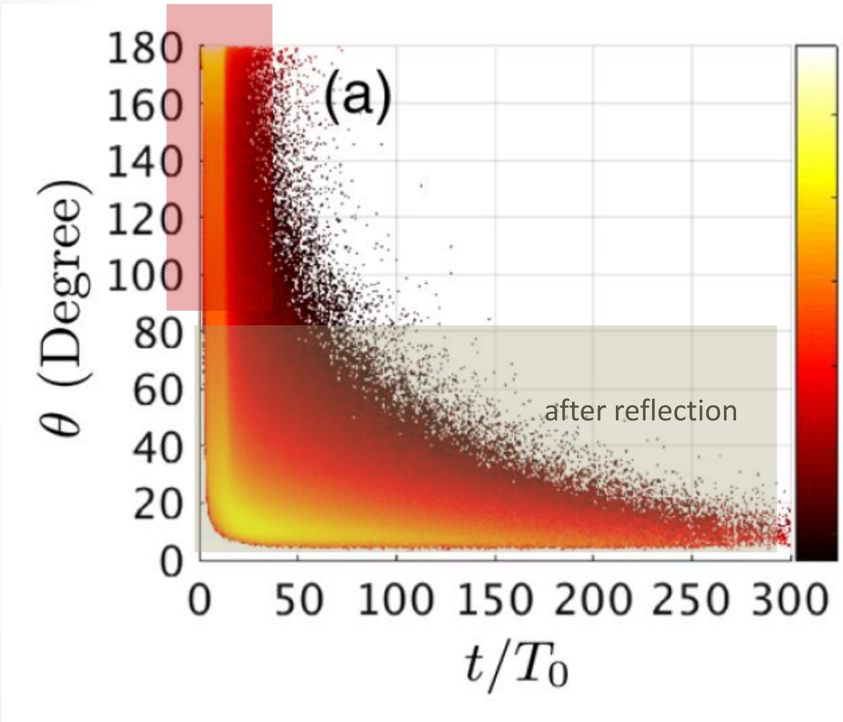
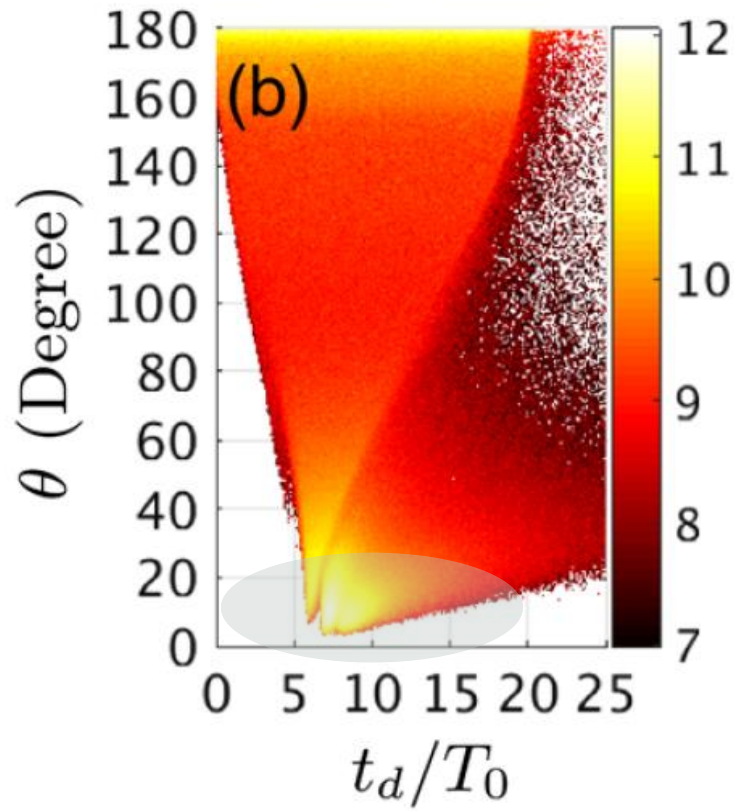
# The role of focusing

In a plane laser field

Time-resolved radiation angular distribution

before reflection




Electron time

$$\Delta t \sim \tau_0/(1-\beta) \gg L_b/c$$

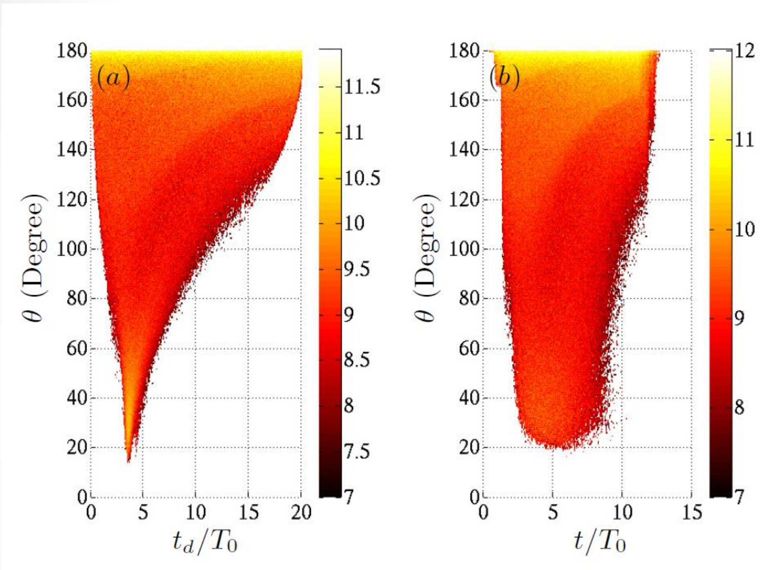
Detector time

$$\Delta t_d \sim \tau_0(1-\beta\cos\theta)/(1-\beta)$$

$$\Delta t_d = \tau_0 \frac{1-\beta\cos\theta}{1-\beta} + \frac{L_b}{c}\frac{1-\cos\theta}{1+\beta}$$

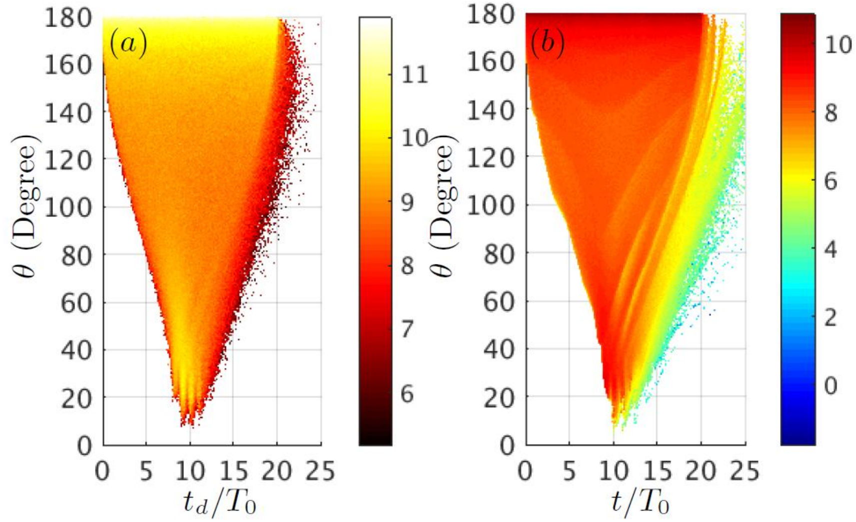
# Multiple gamma-ray bursts and the stochasticity effect

2-cycle pulse




with
stochastic effect

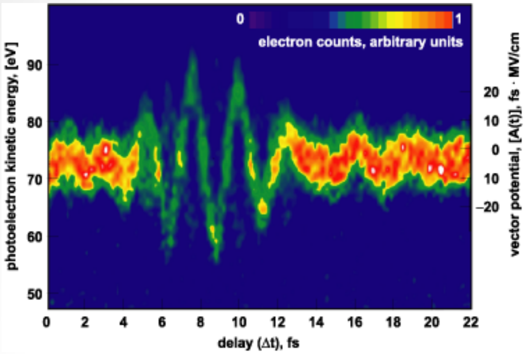
6-cycle pulse

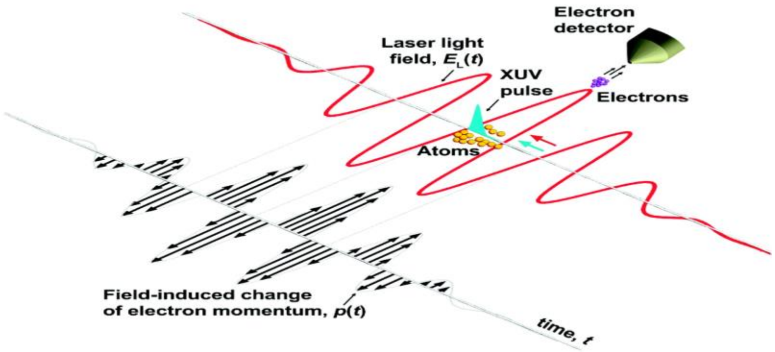



with
stochastic effect

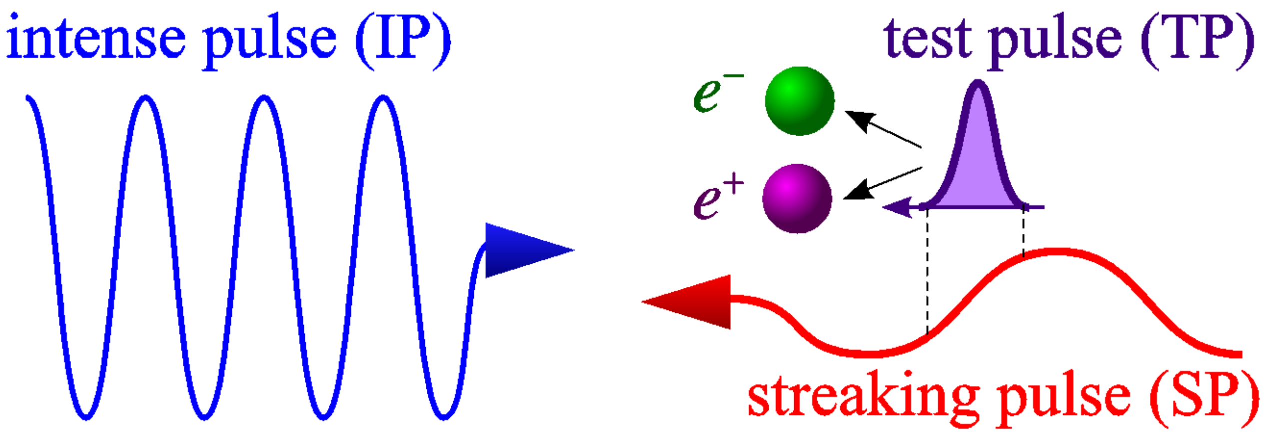
without
stochastic effect

# Streak-camera for γ-rays via strong field e+e- pair production



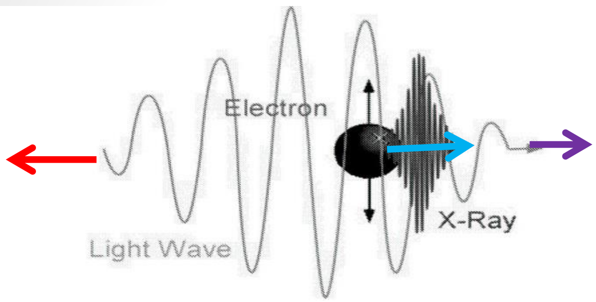




Goulielmakis et al. Science 305,1267 (2004)




Ipp, Evers, Keitel, KZH, PLB 702, 383 (2011)

# Multiphoton Compton scattering



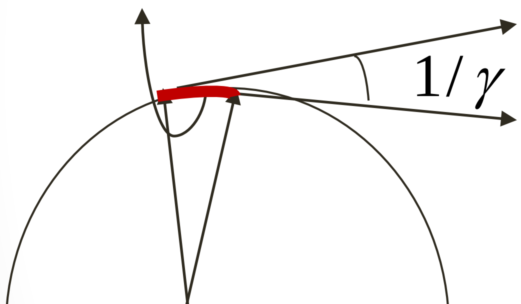

$$F \sim \frac{v}{c} \times BA$$

$$\omega' = n\omega_L'$$

$$\xi = \frac{eE_0}{mc\omega_L}$$

$$n \sim \xi^3$$

$$\ell_f = R\vartheta \sim \lambda_L/\gamma$$



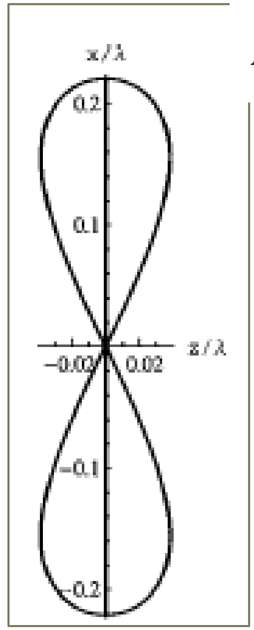

$$\gamma \sim \xi$$

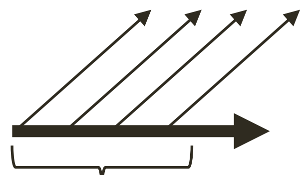
$$\mathrm{R} \sim \lambda_L$$

$$\boldsymbol{p}_\perp + e\boldsymbol{A} = const$$

$$p_\perp = m\xi$$

$$\gamma = \sqrt{1 + {p_\perp}^2/m^2} \sim \xi$$



$\ell_{coh}$

$$|\omega t - \boldsymbol{kr}| < \pi$$

$$\boldsymbol{r} \approx \boldsymbol{v}t;\ t \approx \frac{l}{v}$$

$$\ell_{coh} = \frac{\pi v}{\omega - \boldsymbol{kv}} \sim \frac{2\pi v}{\omega}\gamma^2$$

$$\ell_f \sim \ell_{coh}$$

$$\frac{\lambda_L}{\gamma} \sim \frac{2\pi v}{\omega}\gamma^2$$

$$\omega \sim \gamma^3 \omega_L \sim \xi^3 \omega_L$$

$$\frac{\omega}{\varepsilon} \sim \frac{\omega_L \xi^2}{m} \sim \frac{\omega_L}{m}\xi\gamma \approx \chi$$

$\sim 10^{22} W/cm^2$

MeV $\gamma$ - rays

# Quantum effects in multiphoton Compton scattering

$$\chi \sim \frac{\omega}{m}$$

$$\chi = \frac{e}{m^3}\sqrt{(F_{\mu\nu}p^{\nu})^2} = \frac{E'}{E_S}$$

$$E_{cr} = \frac{m^2c^3}{e\hbar}$$

$$I_{cr} = 2.3 \cdot 10^{29}\frac{W}{cm^2}$$

$\chi \geq 1$ Quantum regime: emitted photon recoil is significant

$\chi \ll 1$ Classical regime

$$E' \approx 2\gamma E$$

$$\chi \sim 2\frac{\omega_L}{m}\xi\gamma \sim 4 \cdot 10^{-6}\xi\gamma$$

$$\xi = \frac{eE_0}{mc\omega_L}$$

$$\chi \sim 1: \quad \xi \sim 100, \gamma \sim 10^3$$

# Classical equation of motion with quantum radiation

Electron dynamics in the laser field is classical, the radiation is quantum mechanical.

$$\frac{dp^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} p_\nu + \frac{d{p_R}^\mu}{d\tau}$$

$$p + nk = p' + k' \qquad n = \frac{p\cdot k'}{p\cdot k - k\cdot k'}$$

$$\Delta p = nk - k'$$

$$\frac{d{p_R}^\mu}{d\tau} \approx \frac{\Delta {p_R}^\mu}{\Delta\tau}$$

$$\frac{k'}{d\tau} \to \int k' \frac{k\cdot p}{d\phi} \frac{dW}{d^3\boldsymbol{k}'} d^3\boldsymbol{k}' \approx \int \frac{d\wp}{d\omega'}(\phi)\, d\omega' \qquad \phi = \omega t - kz$$

$$\frac{nk}{d\tau} \to k \int \frac{p\cdot p}{p\cdot k - k\cdot k'} \frac{d\wp}{d\omega'} d\omega' = \frac{2r_0}{3} \frac{\wp}{\wp_c} F^{\mu\nu} F_{\nu\sigma} p^\sigma$$

$$\boxed{\frac{dp^\mu}{d\tau} = \frac{e}{m} F^{\mu\nu} p_\nu - \frac{p}{m}\wp + \frac{2r_0}{3}\frac{\wp}{\wp_c} F^{\mu\nu} F_{\nu\sigma} p^\sigma}$$

$$\wp_c = 2\alpha\omega^2\xi^2$$

I. V. Sokolov et al. PRE 85, 036412 (2010)

The emitted radiation is calculated quantum mechanically, and the differential probability per unit phase interval is [1]

$$\frac{dW_{fi}}{d\eta d\tilde{\omega}} = \frac{\alpha\chi m^2[\int_{\tilde{\omega}_r}^{\infty} K_{5/3}(x)dx + \tilde{\omega}\tilde{\omega}_r\chi^2 K_{2/3}(\omega_r)]}{\sqrt{3}\pi(k_0 \cdot p_i)},$$

$\tilde{\omega}_r = \tilde{\omega}/\rho_0$, with the recoil parameter $\rho_0 = 1 - \chi\tilde{\omega}$ and $\tilde{\omega} = \omega'/(\gamma\chi)$. If $\tilde{\omega}_r \gtrsim 1$, $\frac{dW_{fi}}{d\eta d\tilde{\omega}}$ is very small. Thus, $\tilde{\omega}_r = \tilde{\omega}/\rho_0 = 1$, the cut-off frequency

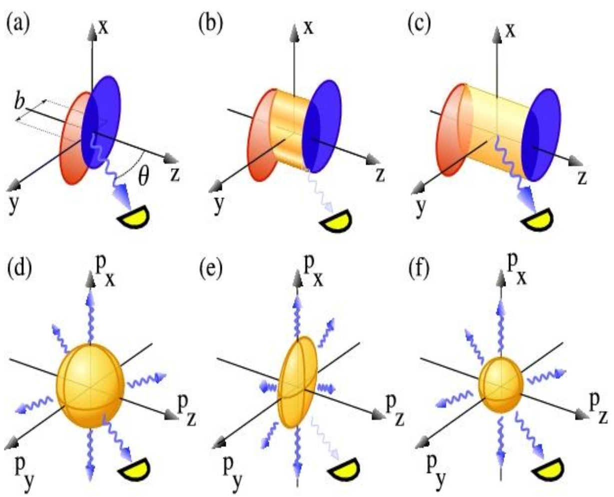
While electron dynamics can be classically calculated (because the electron de-Broglie wavelength is much smaller than the laser wavelength) [2]:

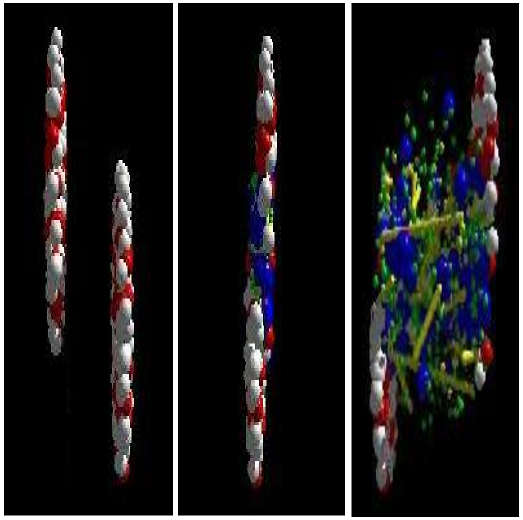
$$\frac{dp^\alpha}{d\tau} = \frac{e}{m}F^{\alpha\beta}p_\beta - \frac{\mathcal{I}}{m}p^\alpha + \tau_c\frac{\mathcal{I}}{\mathcal{I}_c}F^{\alpha\beta}F_{\beta\gamma}p^\gamma,$$

The rate of the electron radiation loss is: $\mathcal{I} = \int d\tilde{\omega}(k_0 \cdot k)dW_{fi}/(d\eta d\tilde{\omega})$, and $\mathcal{I}_c = 2\alpha\omega^2\xi^2$ is the classical radiation loss rate.

I. V. Sokolov, *et al.*, Phys. Rev. E **85**, 036412 (2010)

## Yoctosecond double pulses of γ-rays at heavy ions collision



A Ipp, C. H. Keitel, J. Evers, PRL 103, 152301 (2009)