Dense pair plasma generation and nonlinear QED physics with 10PW scale lasers

The second international conference on Nuclear Photonics, June 24th-29th, Brasov, Romania

<u>Wen Luo（罗文）</u>[1], Wei-Yuan Liu[1, 3, 4], Tao Yuan[3, 4], Min Chen[3, 4], Ji-Ye Yu[3, 4], Fei-Yu Li[2], D. Del Sorbo[5], C. P. Ridgers[5], Zheng-Ming Sheng[2, 3, 4]

[1]*School of Nuclear Science and Technology, University of South China, Hengyang 421001, China*

[2]*SUPA, Department of Physics, University of Strathclyde, Glasgow G40NG, United Kingdom*

[3]*Key Laboratory for Laser Plasmas (Ministry of Education), School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

[4]*IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China*

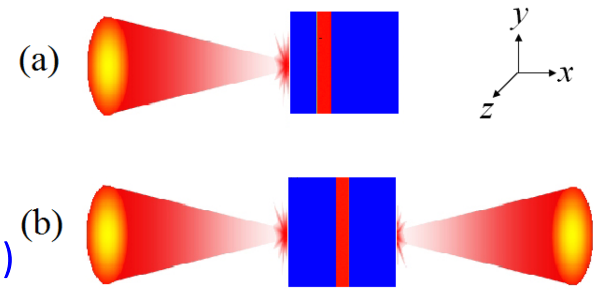
[5]*York Plasma Institute, Physics Department, University of York, York YO10 5DQ, United Kingdom*

Email address: wen.luo@usc.edu.cn

Outline

- 1. Background and Motivation
- 2. Dense electron-positron pair plasma and γ-ray burst generation
    - a) One-side irradiation
    - b) Two-side irradiation

  W. Luo *et al.* Phys. Plasmas 22, 063112 (2015)



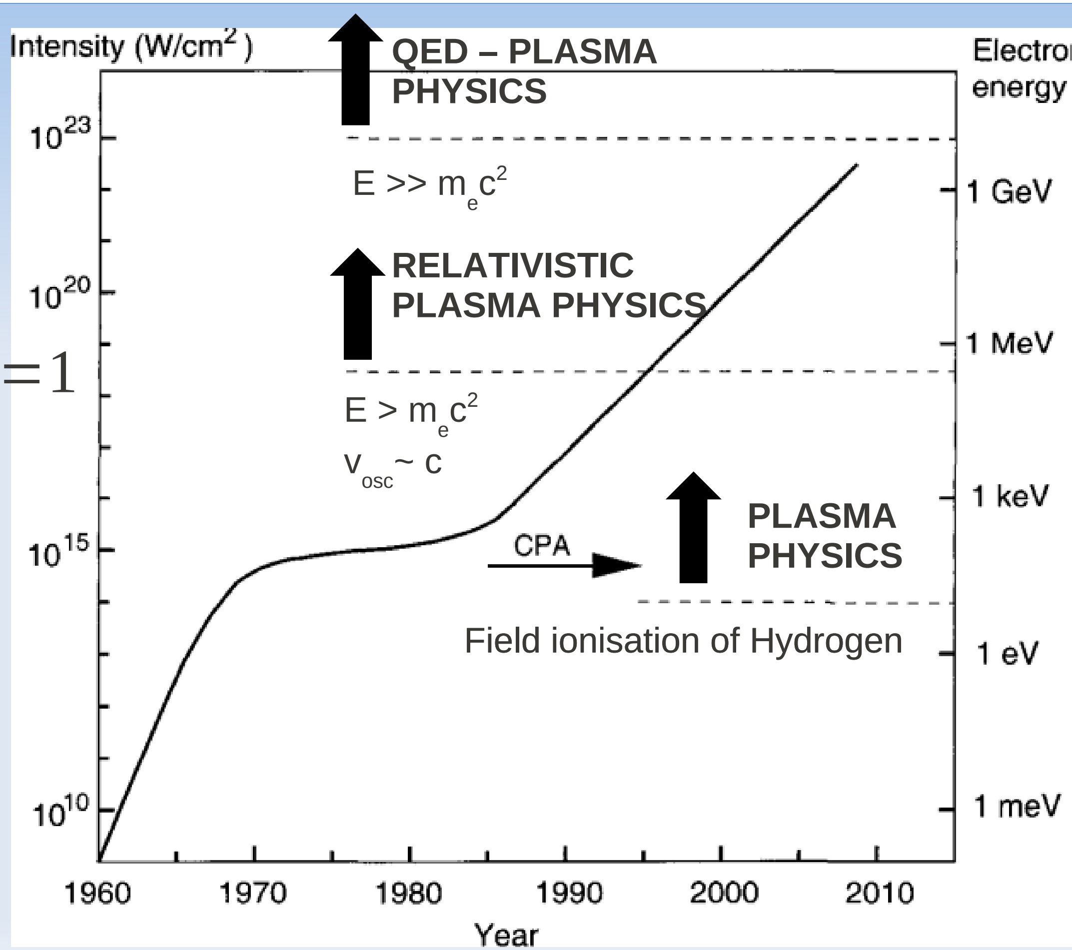
- 3. Enhanced pair plasma production in the relativistic transparency regime   W. Y. Liu, W. Luo *et al.* Phys. Plasmas 24, 103130 (2017)
- 4. Nonlinear QED physics with 10PW scale lasers
    - a) QED cascade saturation   W. Luo *et al*. Scientific Reports 8, 8400 (2018)
    - b) Pair plasma compression and jet formation
    - c) Harmonic generation (HG)   J. Y. Yu,---, W. Luo *et al.* PPCF 60, 044011 (2018)
- 5. Conclusion

Rapid increase in laser intensity

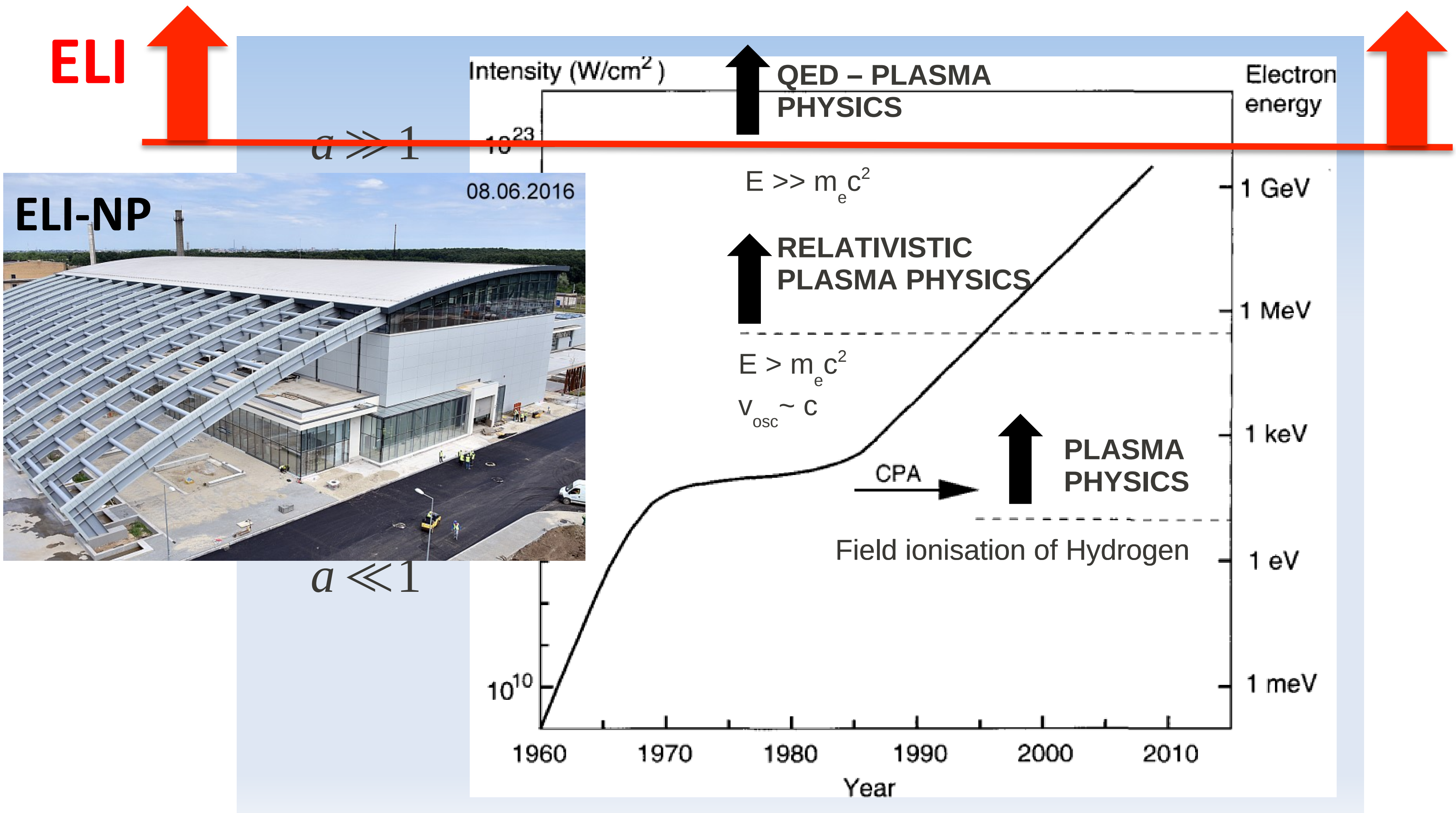
$$a \gg 1$$

$$a = \frac{eE_l}{m_e c\,\omega_l} = 1$$

$$a \ll 1$$



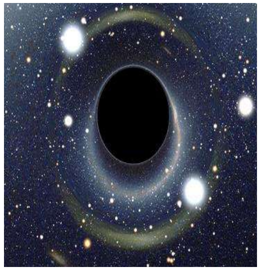
Rapid increase in laser intensity

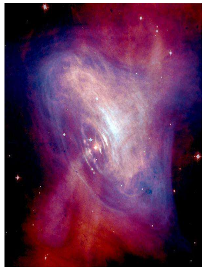


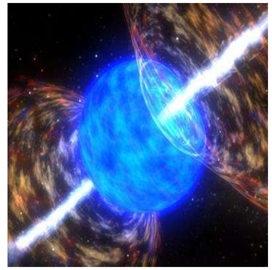
The XCELS, the CLF Vulcan 10 PW project, the Shanghai Super-intense Ultrafast Laser Facility, and so on

Why is the new regime interesting?

Fundamental physics

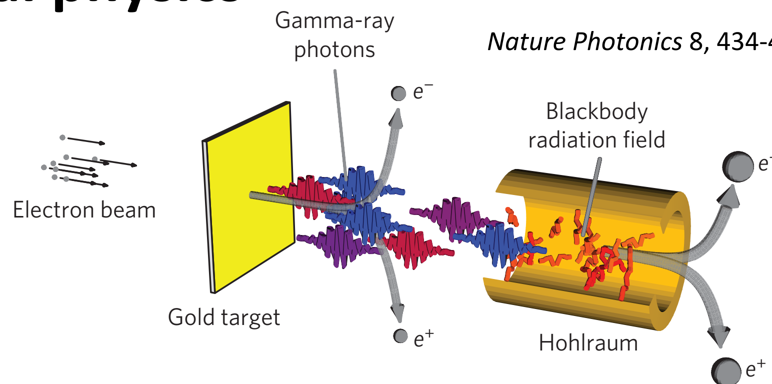

Black holes


Pulsars


Gamma-ray bursts

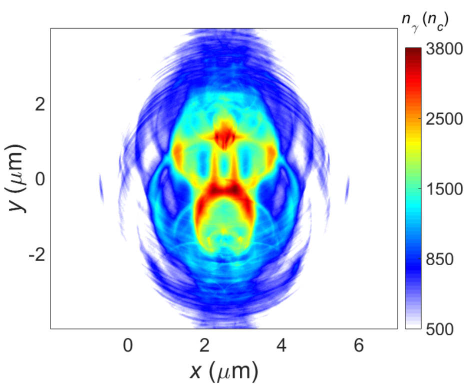
Astrophysics: create an electron-positron plasma by similar mechanisms to that in pulsar atmospheres

Nature Photonics 8, 434-436 (2014)



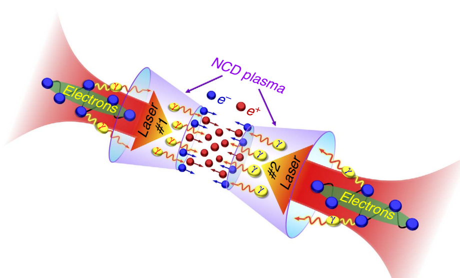
Particle physics: explore strong-field QED – examine the vacuum *PPCF* 60, 044002 (2018)

New Applications



Prolific positron and gamma-ray production

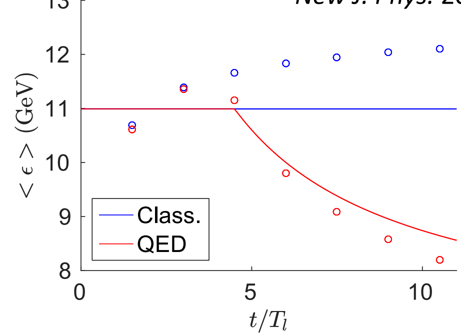
Compact electron-positron collider



Nature Communications 7, 13686 (2016)

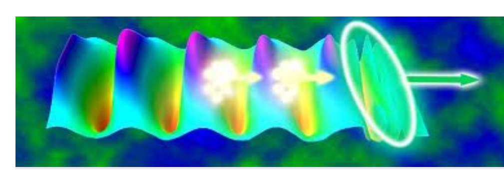
Existing Applications

New J. Phys. 20, 033014 (2018)



Accelerate ions to multi-GeV energies

Next-generation laser wakefield acceleration



Why is the new regime interesting?

Radiation dominated particle dynamics

L. L. Ji *et al.* Phys. Rev. Lett. 112, 145003 (2014).
A. Gonoskov *et al*. Phys. Rev. Lett. 113, 014801 (2014).
M. Jirka *et al*. Phys. Rev. E 93, 023207 (2016).
E. S. Efimenko *et al.,* Scientific Reports 8, 2329 (2018).

Copious $e^{-}e^{+}$ pair production

C. P. Ridgers *et al.* Phys. Rev. Lett. 108, 165006 (2012).
G. Sarri *et al.* Nature Communications 6, 6747 (2015).
W. Luo *et al.* Phys. Plasmas 22, 063112 (2015).
H. X. Chang *et al.* Phys. Rev. E 92, 053107 (2015).
X. L. Zhu *et al.* Nature Communications 7, 13686 (2016).
J. J. Liu *et al.* Optics Express 24, 15978 (2016).
T. Yuan *et al.,* Physics of Plasmas 24, 063104 (2017).
Marija Vranic *et al.,* Scientific Reports 8, 4702 (2018).

QED cascade development

A. R. Bell and J. G. Kirk. Phys. Rev. Lett. 101, 200403 (2008).
A. M. Fedotov *et al.* Phys. Rev. Lett. 105, 080402 (2010).
E. N. Nerush *et al.* Phys. Rev. Lett. 106, 035001 (2011).
N. V. Elkina *et al.* Phys. Rev. Special Topics-AB 14, 054401 (2011).
S. Tang *et al.* Phys. Rev. A 89, 022105 (2014).
S. S. Bulanov *et al.* Phys. Rev. A 87, 062110 (2013).
E. G. Gelfer *et al.* Phys. Rev. A 92, 022113 (2015).
T. Grismayer *et al.* Phys. Rev. E 95, 023210 (2017).

How to produce $e^{-}e^{+}$ pairs from PW laser interaction with ultrathin foil and then initiate pair cascades?

$$\text{foil } e^{-} \xrightarrow{\chi_e} \gamma_{\text{photon}} \underset{\chi_e'}{\overset{\chi_\gamma}{\rightleftarrows}} e^{-} + e^{+}$$

$$\chi_{e,\gamma} = \frac{e\hbar\left|F_{\mu\nu}p^{\nu}\right|}{m_e^3 c^4} \cong \left(\frac{\gamma_{e,\gamma}}{E_s}\right)\left|E_{\perp} + \beta \times c\boldsymbol{B}\right|$$

(i) acceleration of foil electrons by an intense laser field to high Lorentz factors;

(ii) gamma-ray emission by the accelerated electrons quivering in the laser fields; (nonlinear Compton scattering and electron recoil process)

(iii) field-assisted photon decay into electron–positron pairs via Breit-Wheeler process; (multi- or single-photon Breit-Wheeler (BW) process)

(iv) gamma-ray emission by the newly created particles as they lose their transverse energy through synchrotron emission;

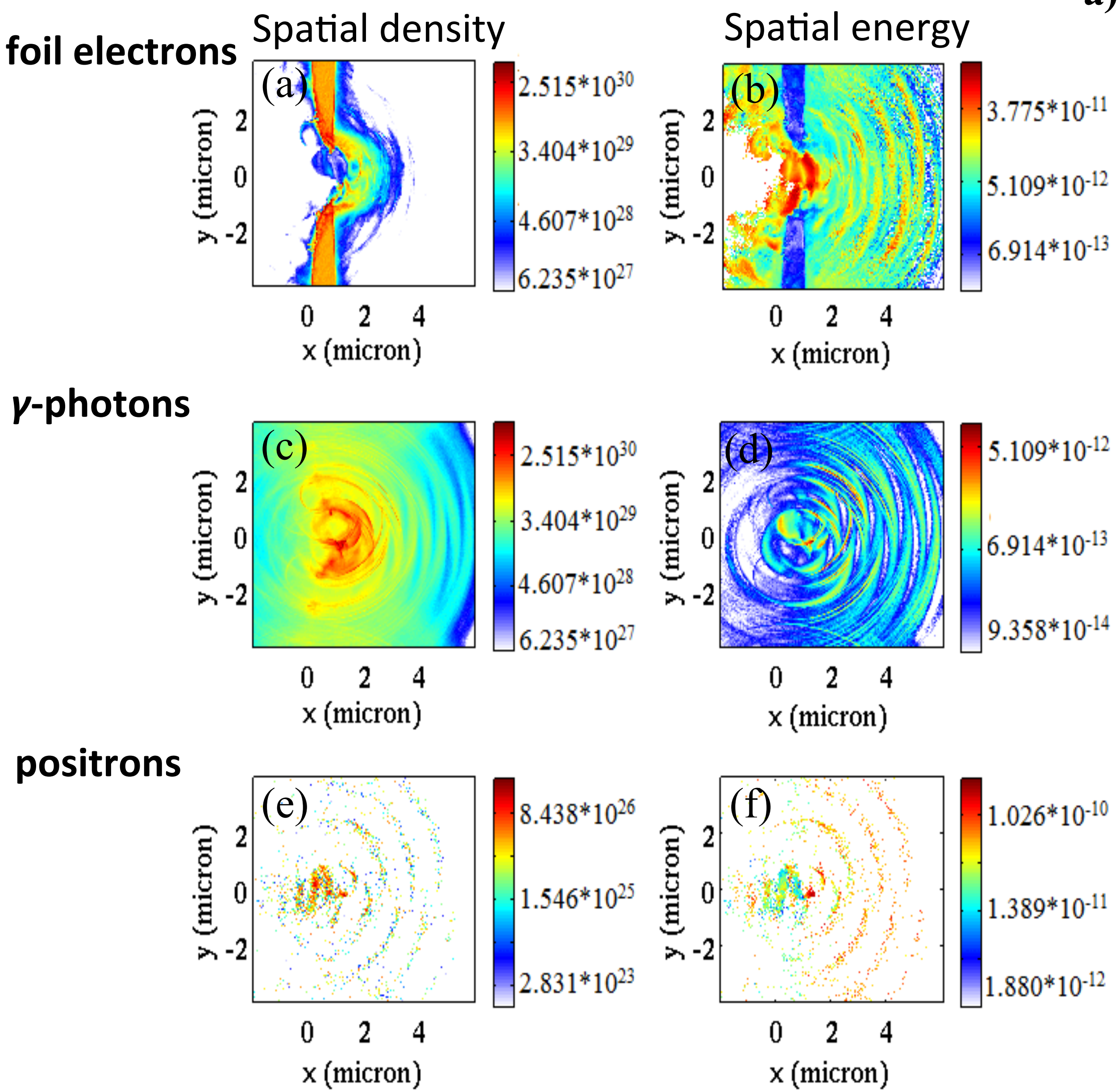
(v) further pair production and gamma-ray emission via steps (iii) and (iv).

QED effects become important when the quantum dynamical parameter $\chi_{e,\gamma}$ approaches or becomes larger than unity.

Multi-dimensional simulations were performed with the QED-PIC code EPOCH to study this work.

Dense pair plasma and γ-ray burst generation

---a) singe laser foil interaction



- **Aluminum with thickness of L = 1 μm and initial density profile of $710n_c$**
- **Linearly p-polarized lasers at intensity of 4×10^{23} W/cm^2 with focused spot size of 1 μm (peak power 12.5 PW).**
- **Transversely super-Gaussian spatial profile and constant temporally profile.**
- **The data are recorded at the moment of t = 30 fs.**
- **The units of density and energy are m^{-3} and Joule, respectively.**

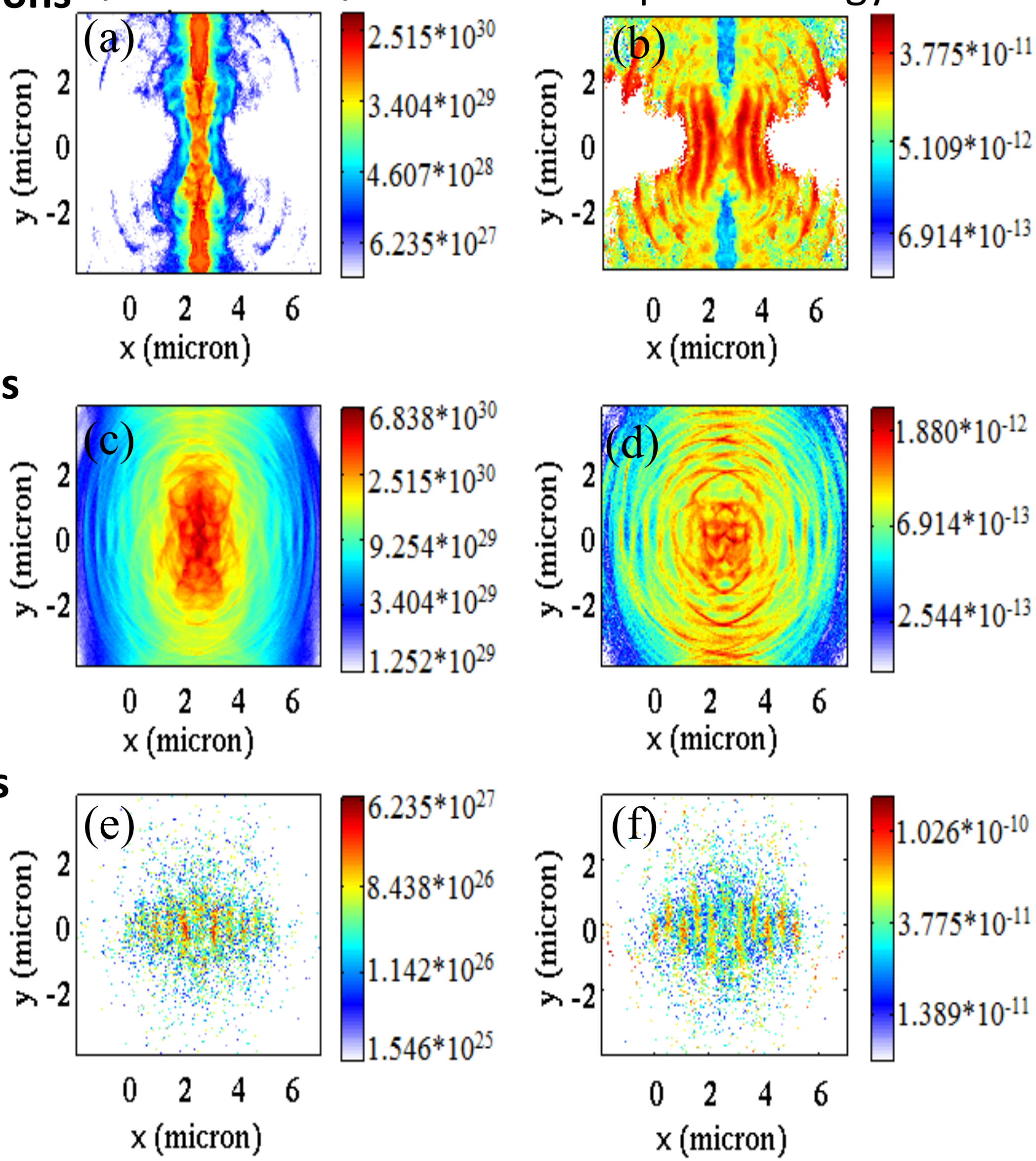
Dense pair plasma and γ-ray burst generation

---b) counter-propagating laser foil interaction

foil electrons Spatial density Spatial energy

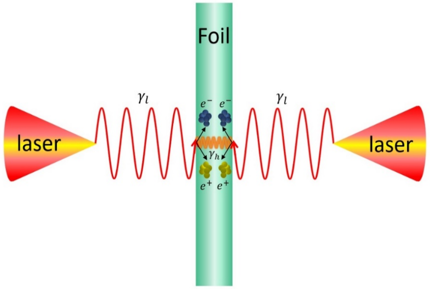
γ-photons

positrons



- **About 20% of the laser energy is converted into γ-rays and it is three times higher than that in the case of one-side irradiation.**
- **Dense electron-positron plasmas are simultaneously generated with a maximum density of 6×10^{27} /m^3, which is eightfold denser compared to the one-side irradiation.**
- **Such enhancement is due to the symmetrical compression of the foil target, and the formation of electric potential and standing wave around the target.**

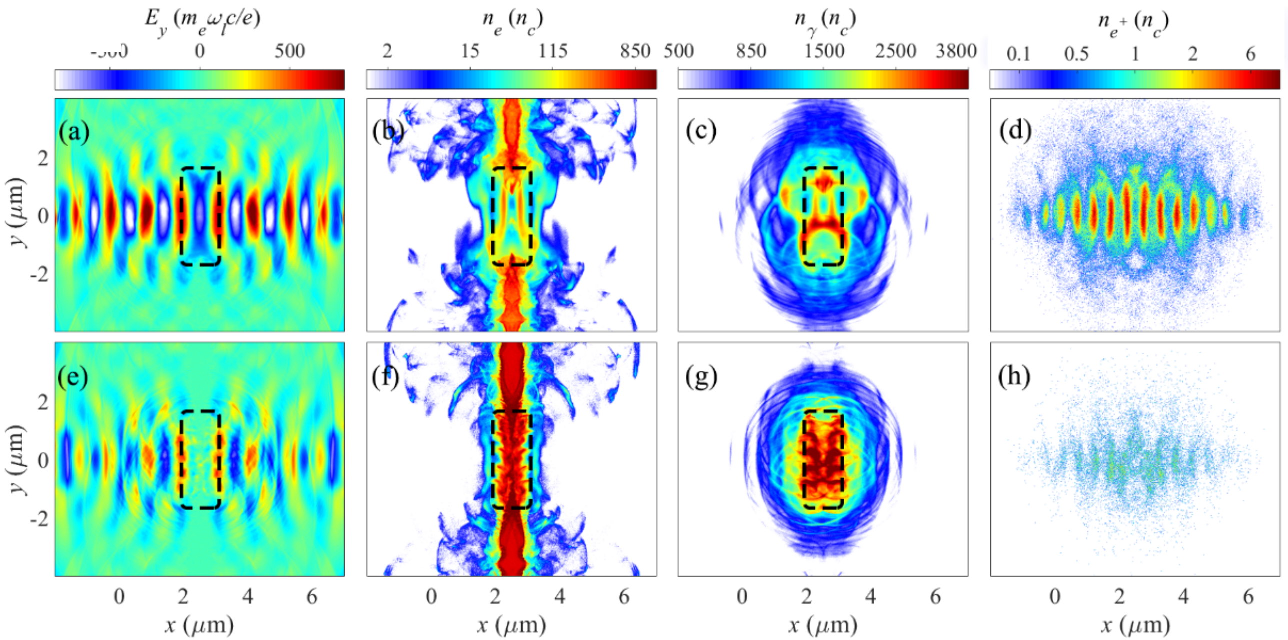
Enhanced pair plasma production in the relativistic transparency regime



A CH foil (fixed thickness of $1\mu m$) illuminated by two counter-propagating, p-polarized laser pulses ($I = 4\times10^{23}$ W/cm^2, i.e. 12.5 PW, a_0=540) from both sides

n_e=280n_c

n_e=710n_c



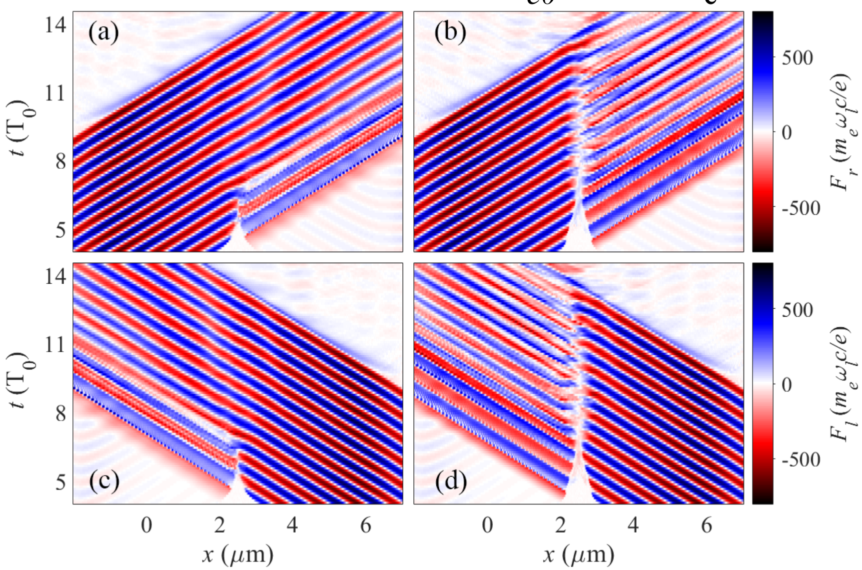
n_e=280n_c	n_e=710n_c
➢ The foil is transparent to the incident lasers	➢ The foil is opaque to the incident lasers
➢ Stable standing wave (SW) is directly formed by the counter-propagating laser pulses	➢ No stable SW is formed
➢ Lower photon density but higher positron density	➢ Higher photon density but lower positron density
➢ Bunched positrons in space due to the SW fields	➢ Positrons dispersed in space

Enhanced pair plasma production in the relativistic transparency regime

$F_{r,l} = (E_y \pm B_z)/2$ $\qquad$ $n_{e0} = 280n_c$ $\qquad$ $n_{e0} = 710n_c$

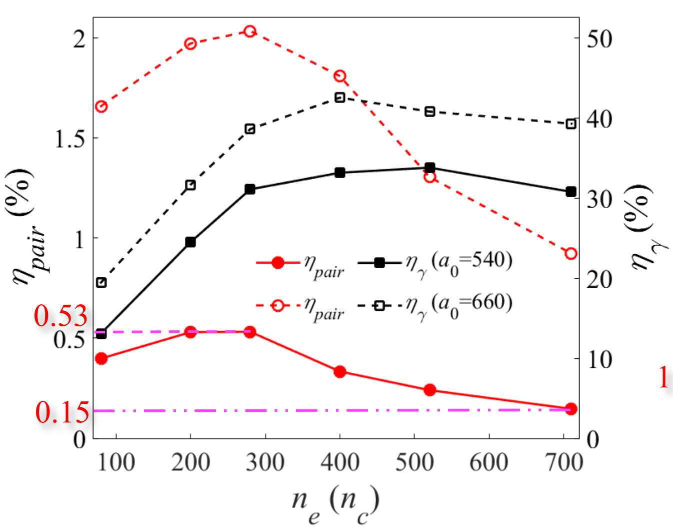
Right-propagating components

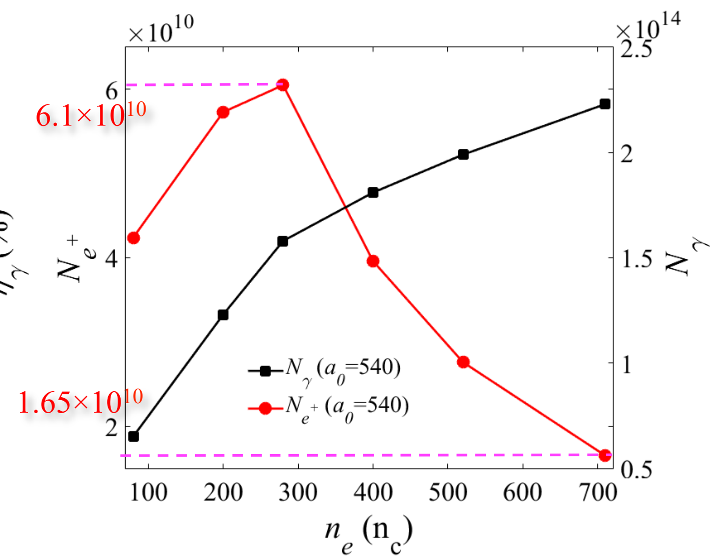
Left-propagating components



- The hole-boring stage terminates at $5.7T_0$ and the onset of transparency begins at $6T_0$, which leads to a transient SW
- A visible interruption of laser propagation occurs until $12T_0$, the plasma remains opaque during the interaction stage

$t = 13.25T_0$





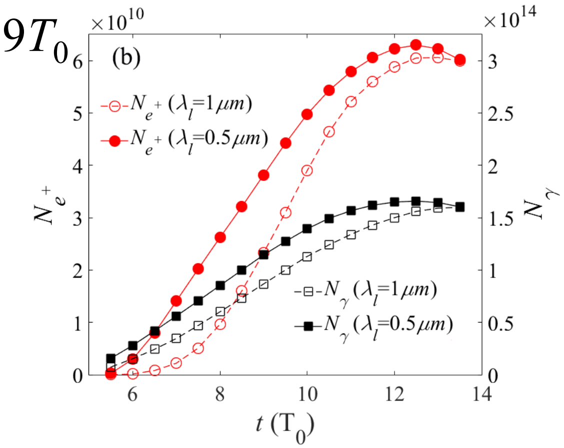
The laser energy conversion to e^-e^+ pairs in the relativistic transparency regime can increase four times compared to that in the opaque regime

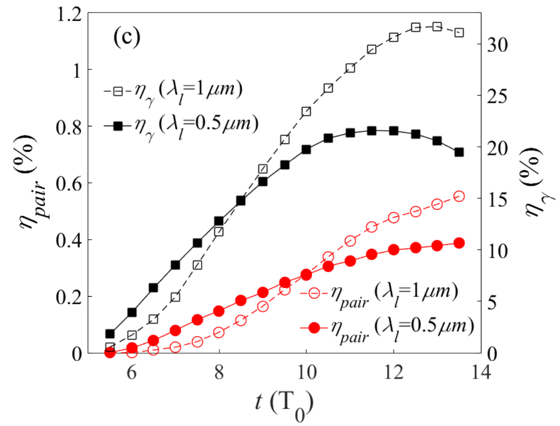
Enhanced pair plasma production in the relativistic transparency regime

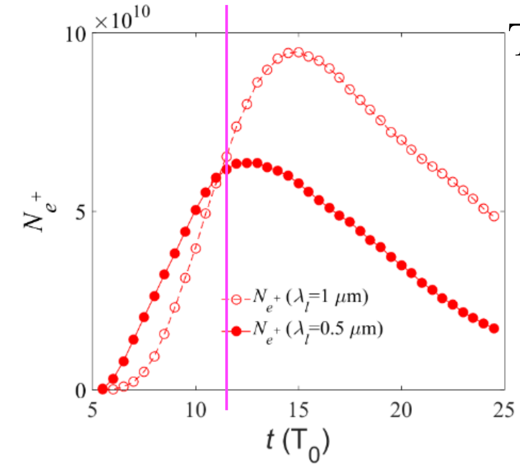
dashed line: $a = 540, \lambda_l = 1\mu m, \omega_l = \omega_0, n_{e1} = 280n_{c1} = 3.08 \times 10^{29}\mathrm{m}^{-3}, T_l = T_0 = 3.33fs$

solid line: $a = 270, \lambda_l = 0.5\mu m, \omega_l = 2\omega_0, n_{e2} = 70n_{c2} = 280n_{c1} = 3.08 \times 10^{29}\mathrm{m}^{-3}, T_l = 2T_0 = 6.66fs$

$\mathrm{T} = 9T_0$

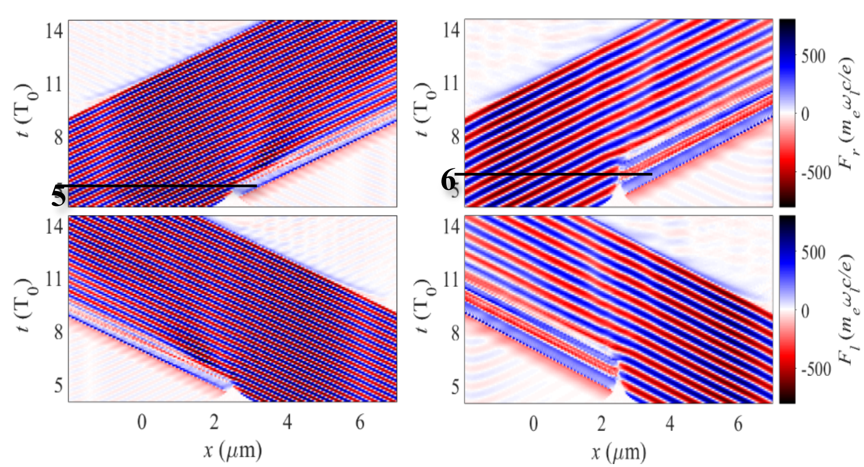






$\mathrm{T} = 30T_0$

Double-frequency   single-frequency

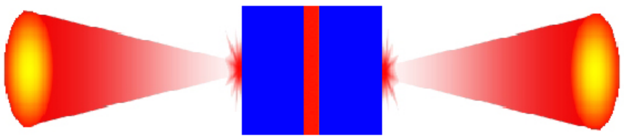


The plasma becomes relativistic transparency approximately **one laser cycle earlier** at double-frequency

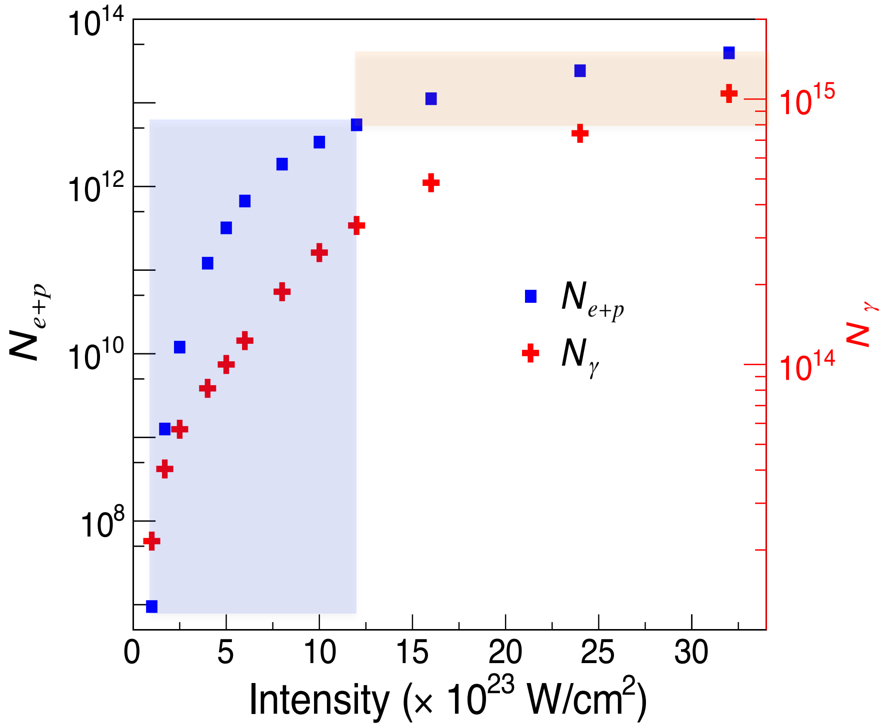
- **The early formation of SW fields** enhances the following photon emission and e^-e^+ pair production;
- The efficient acceleration of charged particles by fundamental frequency lasers will enlarges the pair production probability;

With relatively short durations, such as $9T_0$, the double frequency lasers are more suitable for pair production. For longer durations, such as $30T_0$, the fundamental frequency lasers are more beneficial.

The development of QED cascades



A CH foil with $n_e = 280n_c$ illuminated by two counter-propagating, *p*-polarized laser pulses from both sides



✧ **The number of electron-positron pairs and gamma-photons grows rapidly as the laser intensity reaches a few 10^{23} W/cm^2.**

✧ **However, the rapid increase is replaced by much slower growth when the laser intensity is higher than 10^{24} W/cm^2.**

An analytical model to describe QED cascade development in foils irradiated with intense lasers

$$\text{foil } e^- \xrightarrow{\chi_e} \gamma_{\text{photon}} \underset{\chi_e'}{\overset{\chi_\gamma}{\rightleftarrows}} e^- + e^+$$

$$\chi_{e,\gamma} = \frac{e\hbar|F_{\mu\nu}p^\nu|}{m_e^3 c^4} \cong \left(\frac{\gamma_{e,\gamma}}{E_s}\right)|E_\perp + \beta \times c\boldsymbol{B}|$$

Analytical model (multi-dimensional cases)

Based on cascade particle dynamics

A. M. Fedotov *et al.*, PRL. **105**, 080402 (2010).

V. F. Bashmakov *et al.*, POP **21**, 013105 (2014).

Assumption: No particle leakage **Due to radiative trapping and pair plasma compression**

N_{e0}: the number of foil electrons in the laser focus;
N_{e+p}: the number of produced electrons and positrons;
N_γ: the number of produced energetic photons;
Γ_+: the cascade growth rate;
W_{pair}: pair production probability;
W_γ: photon emission probability;
$\overline{\Gamma_+}$: temporally averaged cascade growth rate.

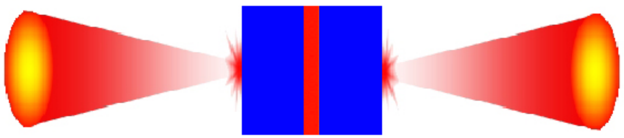
$$\frac{dN_{e+p}}{dt} = 2W_{pair}N_\gamma$$
$$\frac{dN_\gamma}{dt} = W_\gamma(N_{e+p} + N_{e0}) - W_{pair}N_\gamma$$

$$N_{e+p} \simeq 0.5\, N_{e0}[exp(\Gamma_+ t) + exp(-\Gamma_+ t)] - N_{e0}$$
$$N_\gamma \simeq \frac{N_{e0}\Gamma_+}{4W_{pair}}[exp(\Gamma_+ t) - exp(-\Gamma_+ t)]$$
$$\Gamma_+ = 0.5W_{pair}\left(\sqrt{\frac{8W_\gamma}{W_{pair}} + 1} - 1\right)$$

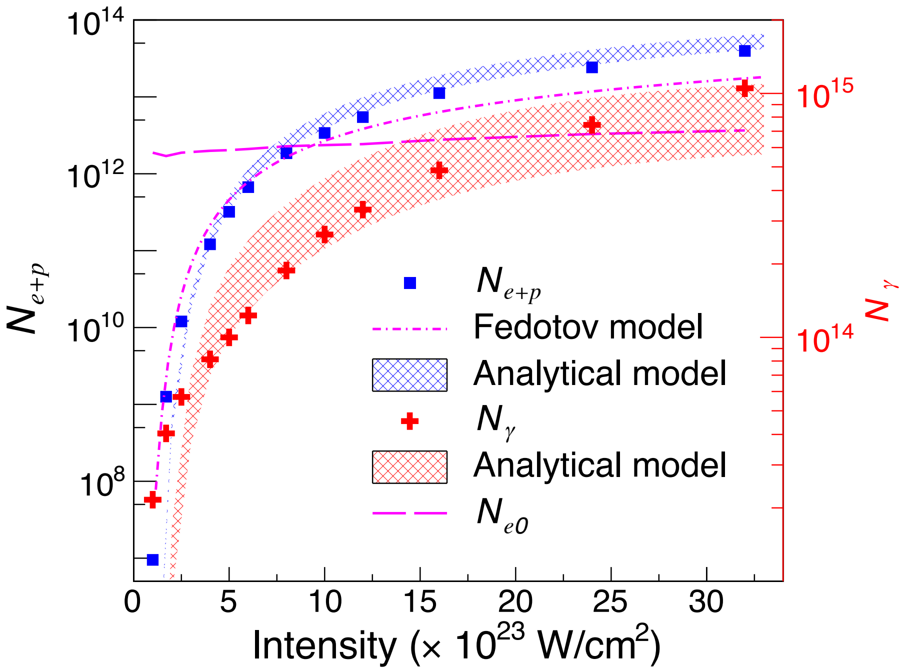
QED-PIC simulation

$$W_{pair}^i = \frac{\delta N_{e+p}^i}{2N_\gamma^i}$$
$$W_\gamma^i = \left(\delta N_\gamma^i + \frac{\delta N_{e+p}^i}{2}\right)/(N_{e+p}^i + N_{e0})$$
$$\overline{\Gamma_+} = 0.5\overline{W_{pair}}\left(\sqrt{\frac{8\overline{W_\gamma}}{\overline{W_{pair}}} + 1} - 1\right)$$

QED cascade saturation



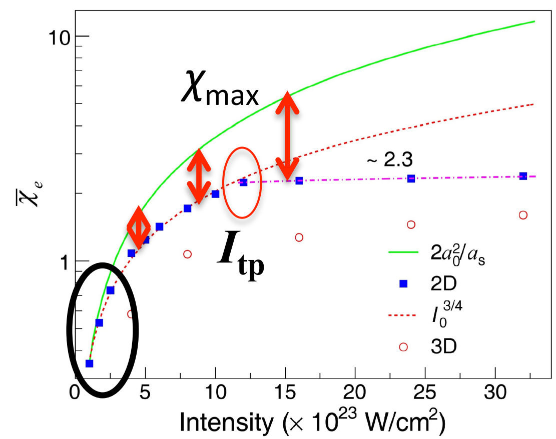
A foil illuminated by two counter-propagating QED-strong laser pulses from both sides



- ✧ **The analytical model works well when describing QED cascades in foils.**
- ✧ **The simulation results also valid the prediction from A. M. Fedotov *et al.* Phys. Rev. Lett. 105, 080402 (2010).**

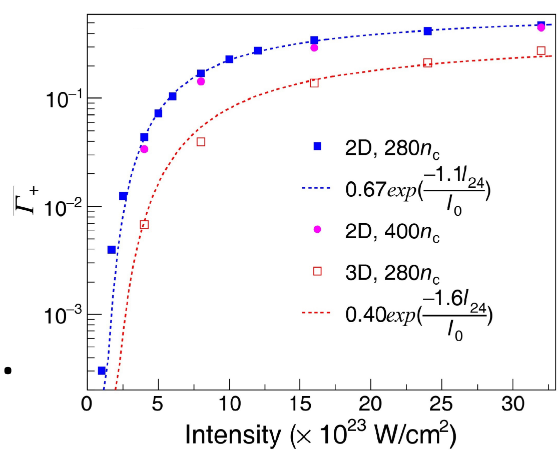
How does QED cascade get saturated?

- **Efficient laser energy absorption and then rapid depletion of the incoming laser pulses**
- **Overdense pair plasma generation which in turn impedes the laser energy absorption**



Weak-field regime: insignificant QED cascades effect.

Transition point:
I_{tp} ~ $1.1I_{24}$, where $I_{24} = 10^{24}$ W/cm^2



Scaling law:
$\Gamma_+ \sim exp(-1.1I_{24}/I_0)$

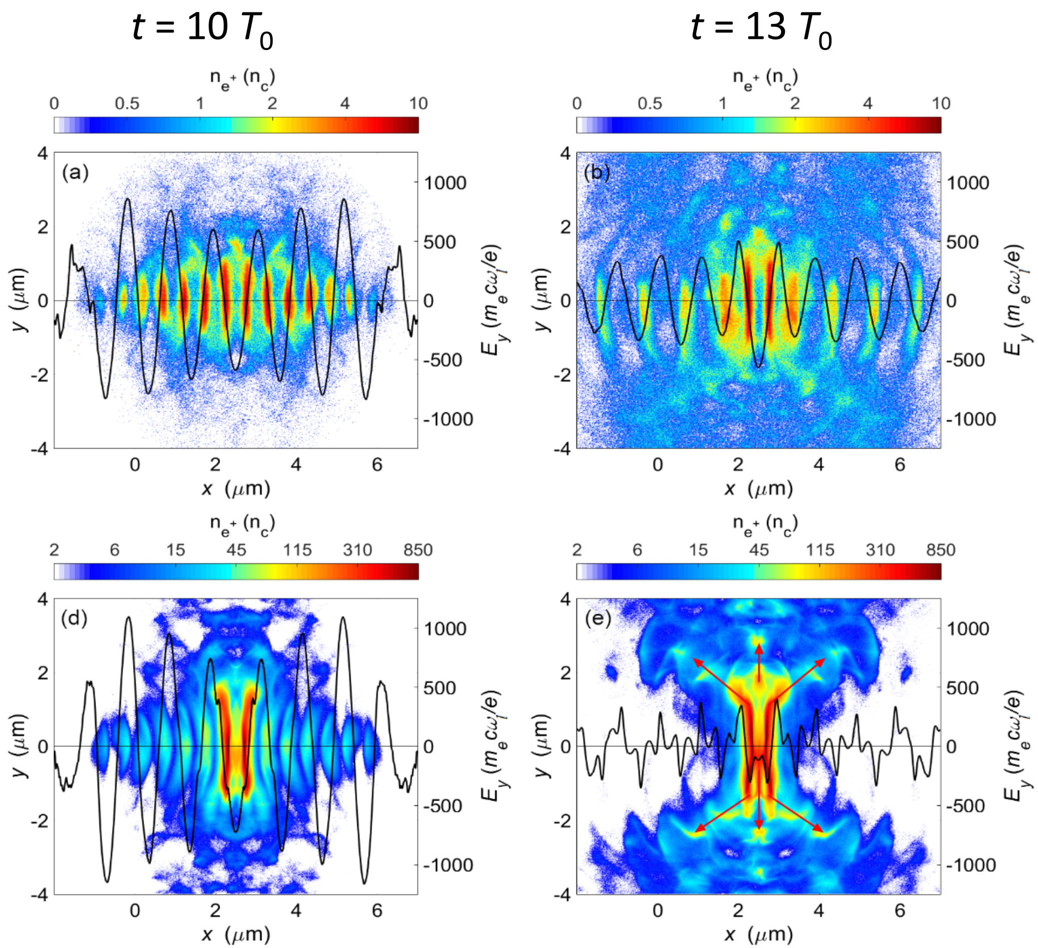
Plasma compression and dense jet formation

$I_0 = 4 \times 10^{23}$ W/cm^2

Radiation-dominated regime:
Radiation trapping

$I_0 = 1.2 \times 10^{24}$ W/cm^2

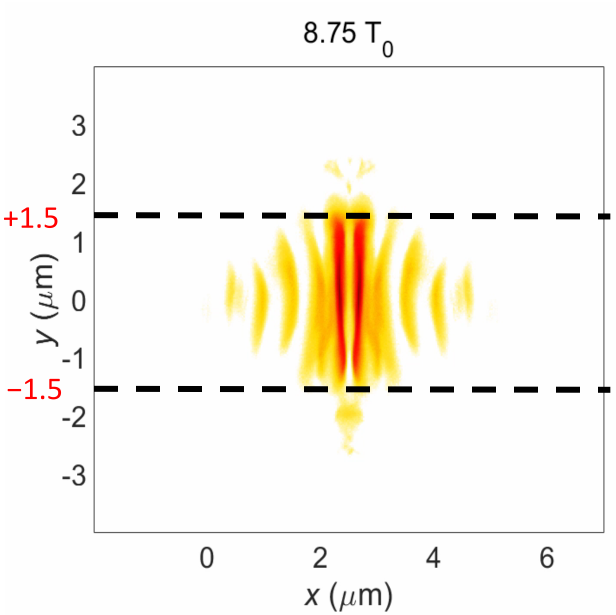
QED plasma-dominated regime:
Plasma compression towards the center

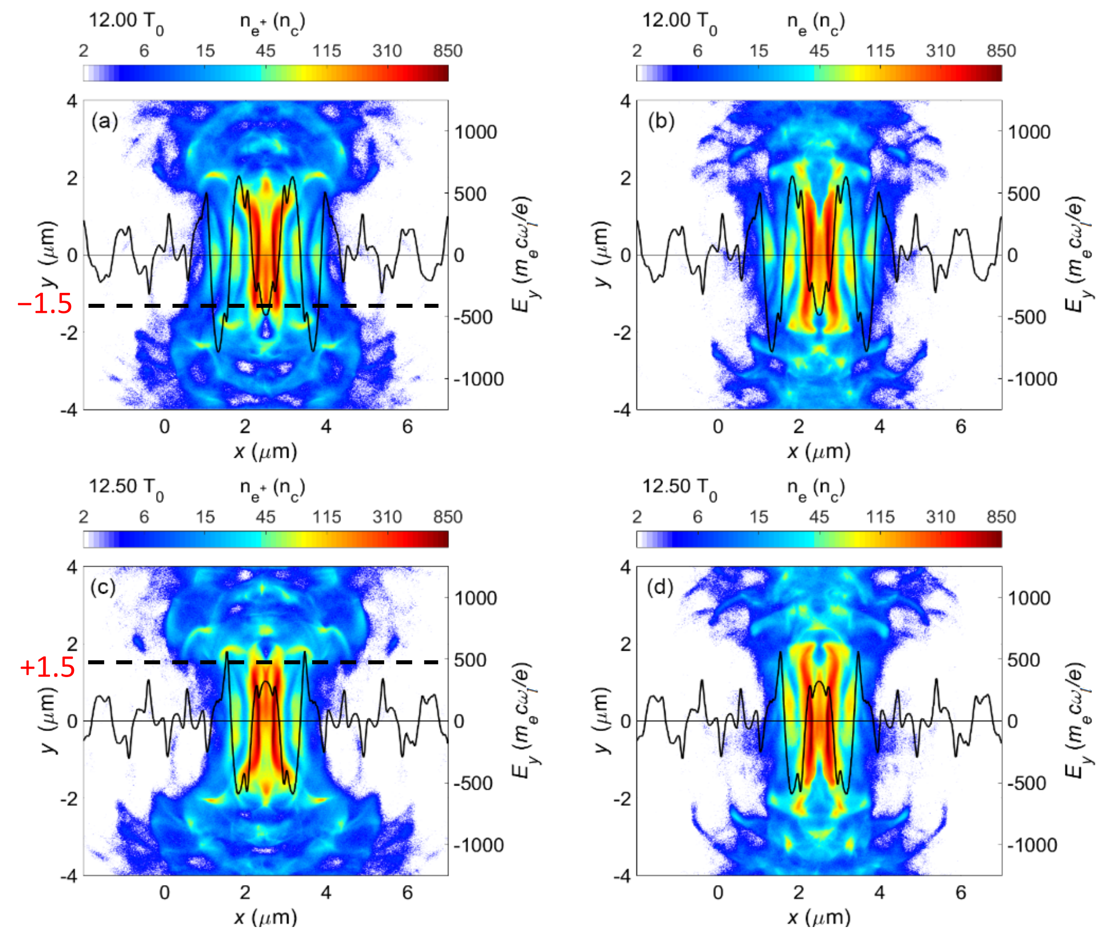


Density maps of the created positrons (contour profile) and longitudinal profiles of the normalized electric fields E_y at $y = 0$ (solid line) at $t = 10T_0$ [(a), (d)] and $t = 13T_0$ [(b), (e)].

Plasma compression and dense jet formation

$I_0 = 1.2 \times 10^{24}$ W/cm^2



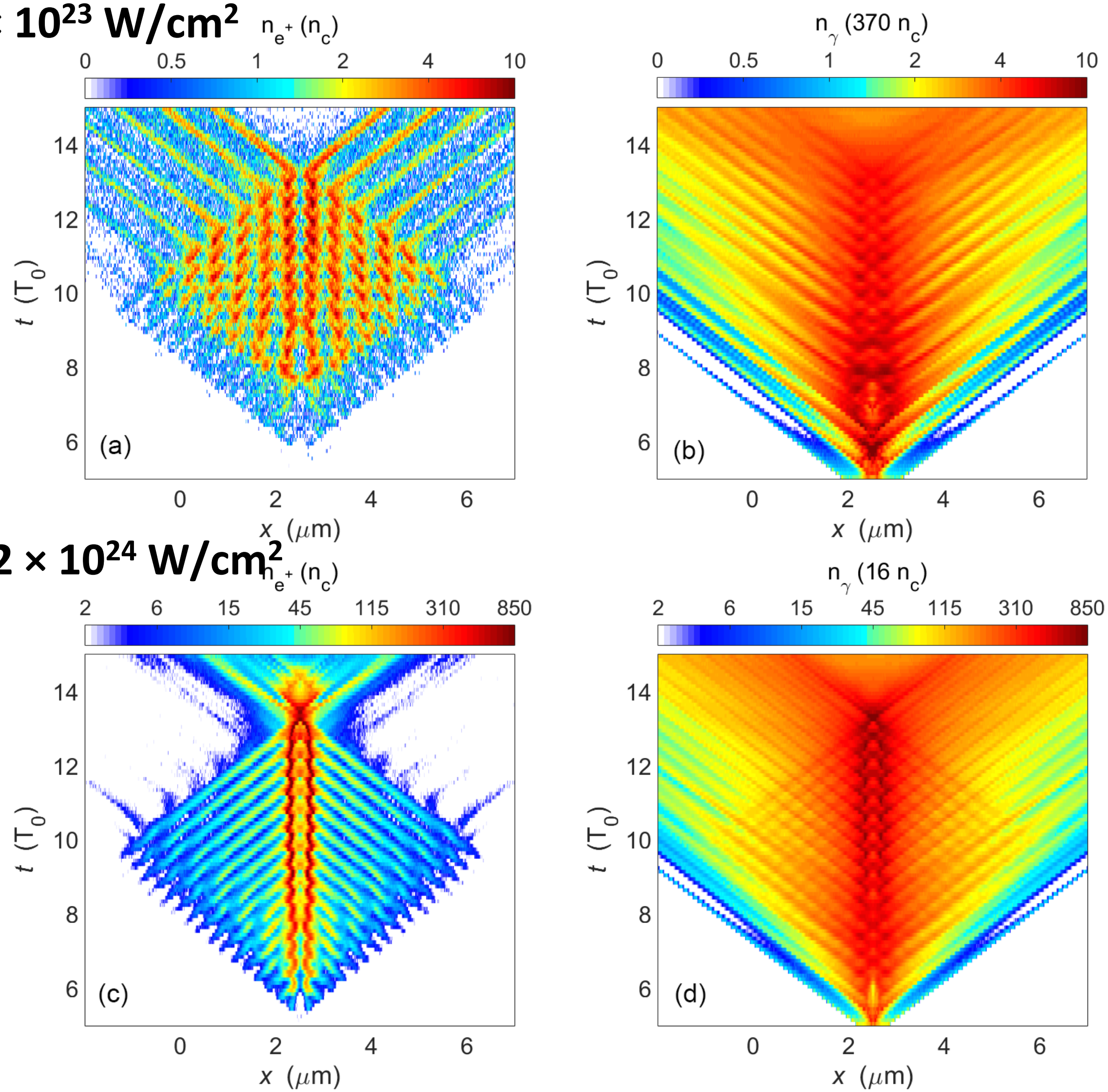


Plasma compression and dense jet formation

Spatiotemporal density evolutions at $y = 0$

I_0 = 4 × 10^{23} W/cm^2

I_0 = 1.2 × 10^{24} W/cm^2



Lower intensities:

1. Pairs are collected in the vicinity of the electric nodes;
2. Photons propagates outward from the initial thin-foil location.

Higher intensities:

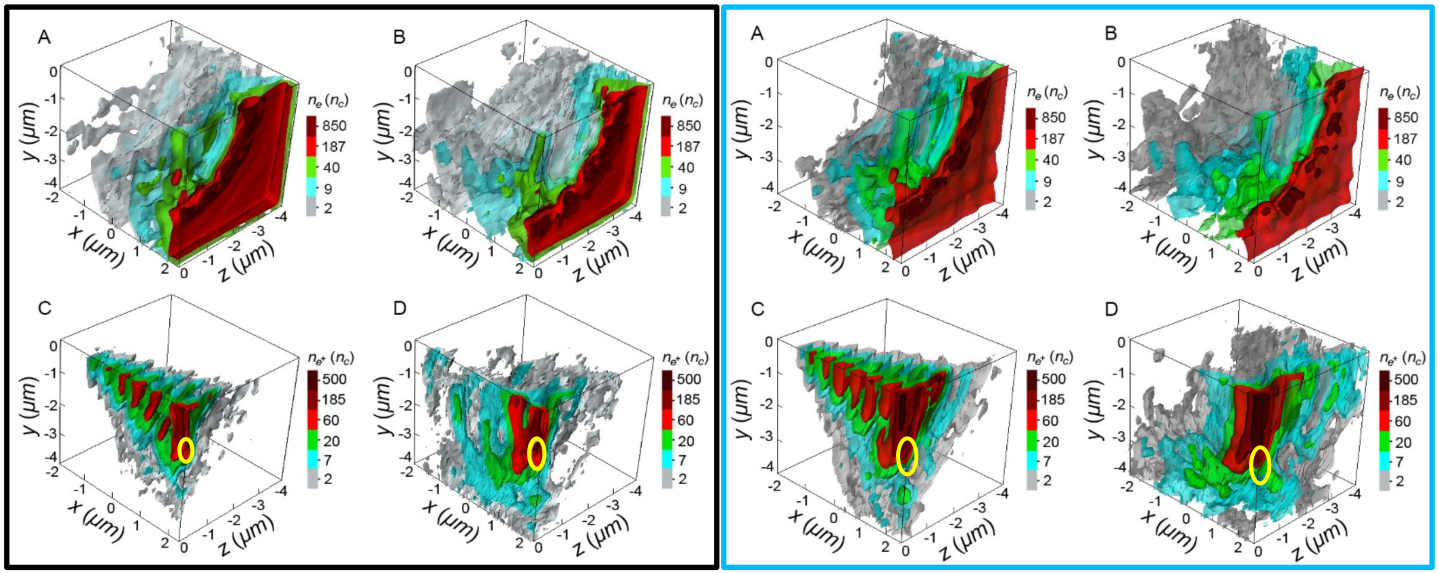
1. The bunches from outer region are compressed towards the center
2. They collide with reflected laser pulses and and then initiate QED cascades once again.

Plasma compression and dense jet formation

$t = 10\ T_0$ | $t = 13\ T_0$ | $t = 10\ T_0$ | $t = 13\ T_0$

Foil electrons

Positrons



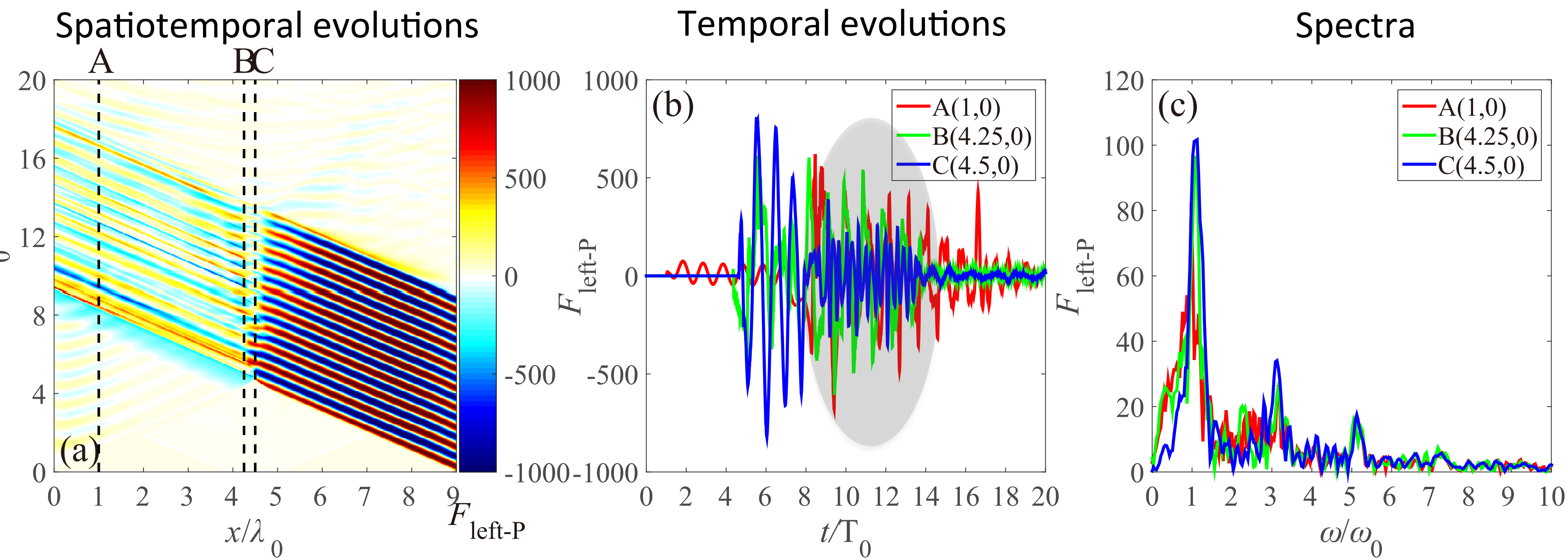
I_0 = 1.6 × 10^{24} W/cm^2 | I_0 = 2.4 × 10^{24} W/cm^2

- **High-field phenomena such as pair plasma compression and the consequent e^-e^+ jet formation have also been observed in more realistic 3D simulations.**

- **Due to an additional plasma expansion along the *z* dimension the density of the compressed electron and positron bunches does not rise as fast as in the 2D case**

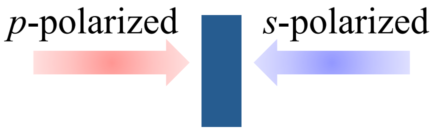
HG in the QED plasma dominated regime

I_0 = 1.6 × 10^{24} W/cm^2

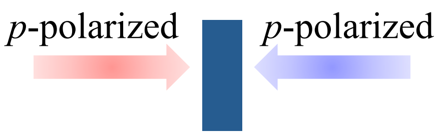


- **The 3rd and 5th harmonic components are visibly observed.**
- **The high order component appears at a later interaction stage, which implies that the HG happens as the QED process is fully excited.**

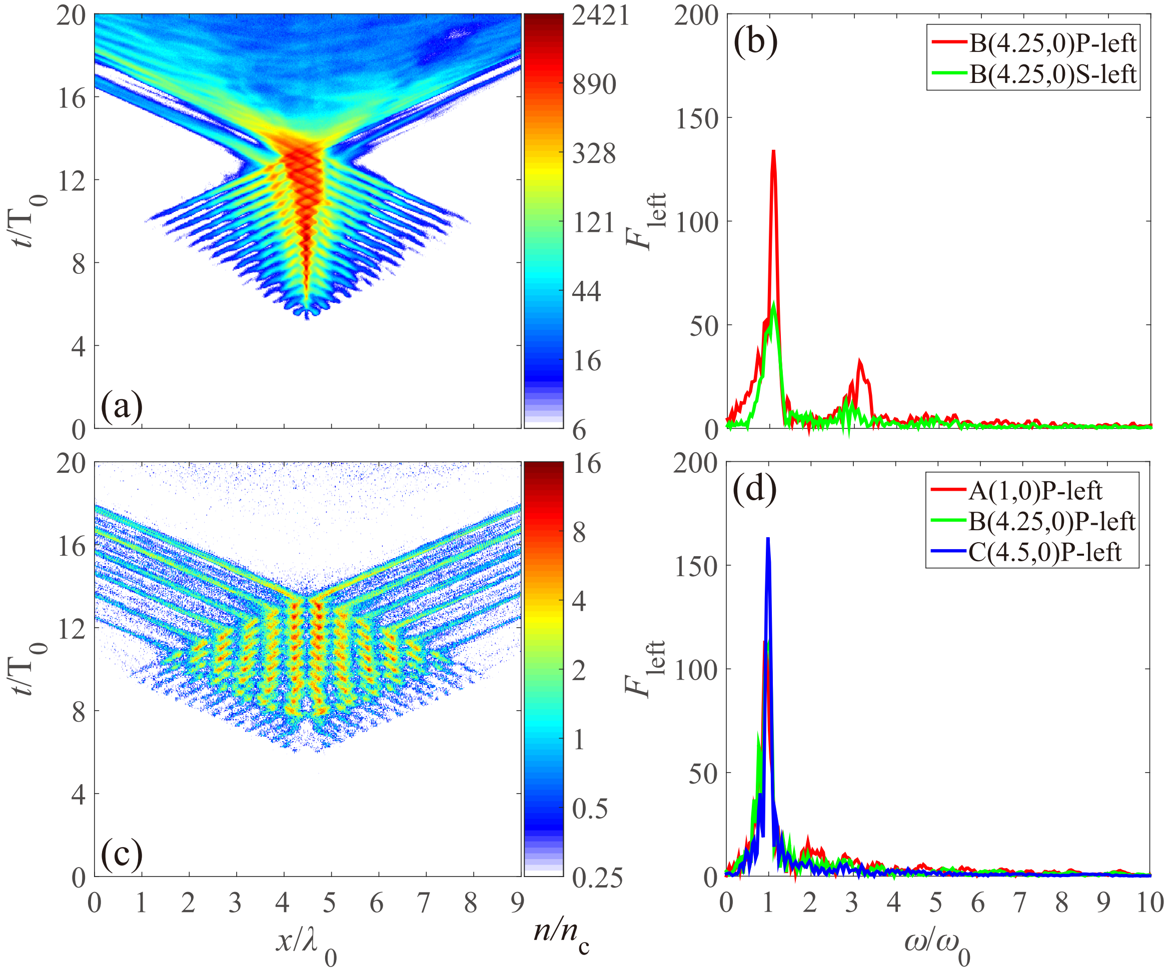
HG in the QED plasma dominated regime



I_0 = 1.6 × 10^{24} W/cm^2

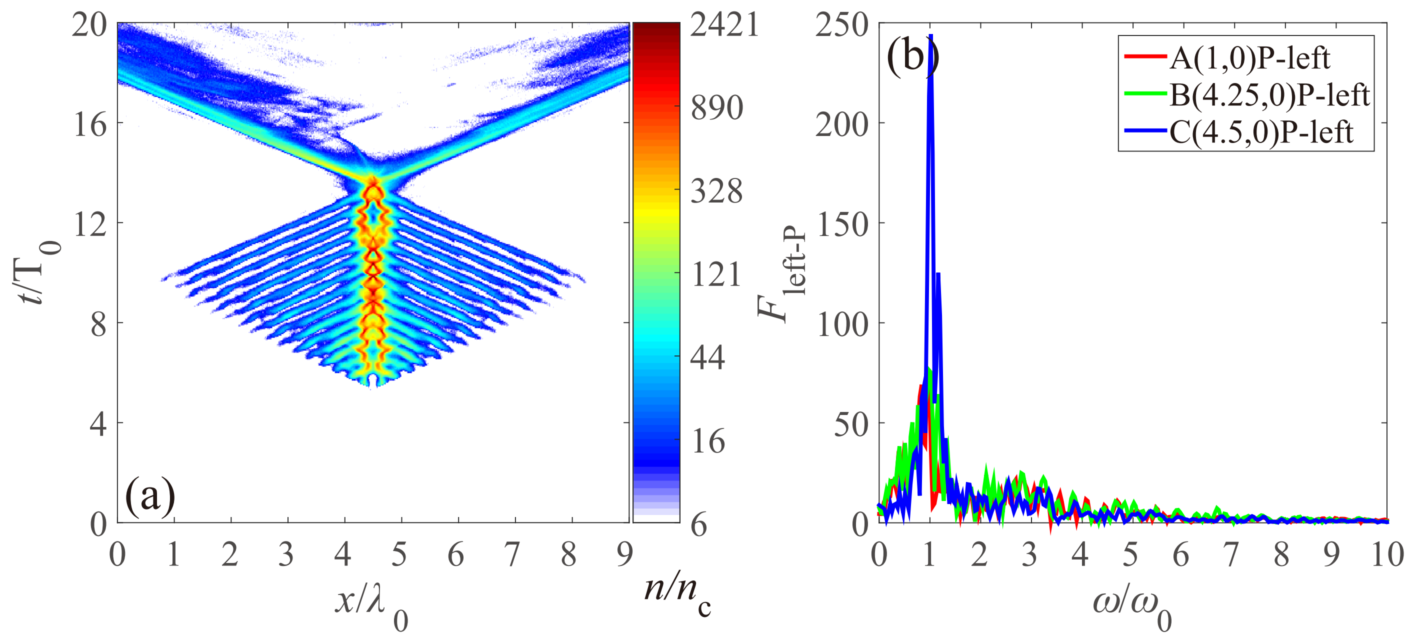


I_0 = 4.0 × 10^{23} W/cm^2



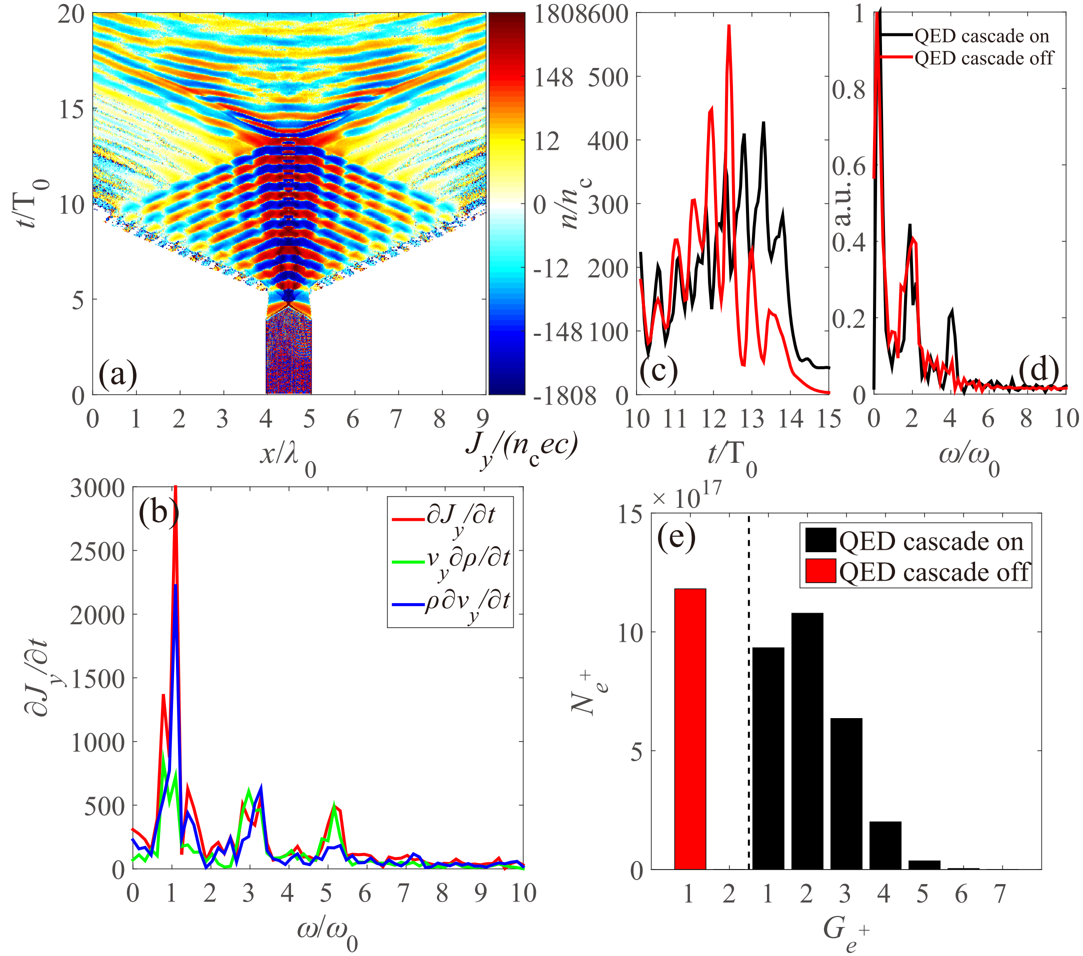
- **The *p* component is larger than the *s* component, which means the harmonics mainly come from the reflected EM waves.**
- **The 3rd and 5th harmonics components no longer exist at the low laser intensity case.-----> QED cascades effect on the HG???**

HG in the QED plasma dominated regime



- **As the QED cascade process was artificially switched off, all the harmonics components are vanished and only some high frequency noise remains in the spectra.**

HG in the QED plasma dominated regime



- **From about t = 8T_0 harmonics components begin to appear in the central area**
- **In the QED cascade on case, the $v_y \partial\rho / \partial t$ term has a dominated contribution to the 5th harmonic component**

Conclusion

- **High-field QED plasma generation and its dynamics has been attracting great interest due to fundamental physics studies and potential applications.**

- **Enhanced dense pair plasma production has been investigated through EPOCH simulations.**

- **A scaling of QED cascade growth with laser intensity is found, which shows clear cascade saturation above threshold intensity of ~ 10^{24} W/cm^2, which is reachable by upcoming 10PW laser facilities.**

- **Nonlinear plasma dynamics, including pair plasma compression and harmonics generation, is demonstrated in the cascade saturation regime.**

Thanks for your attention!