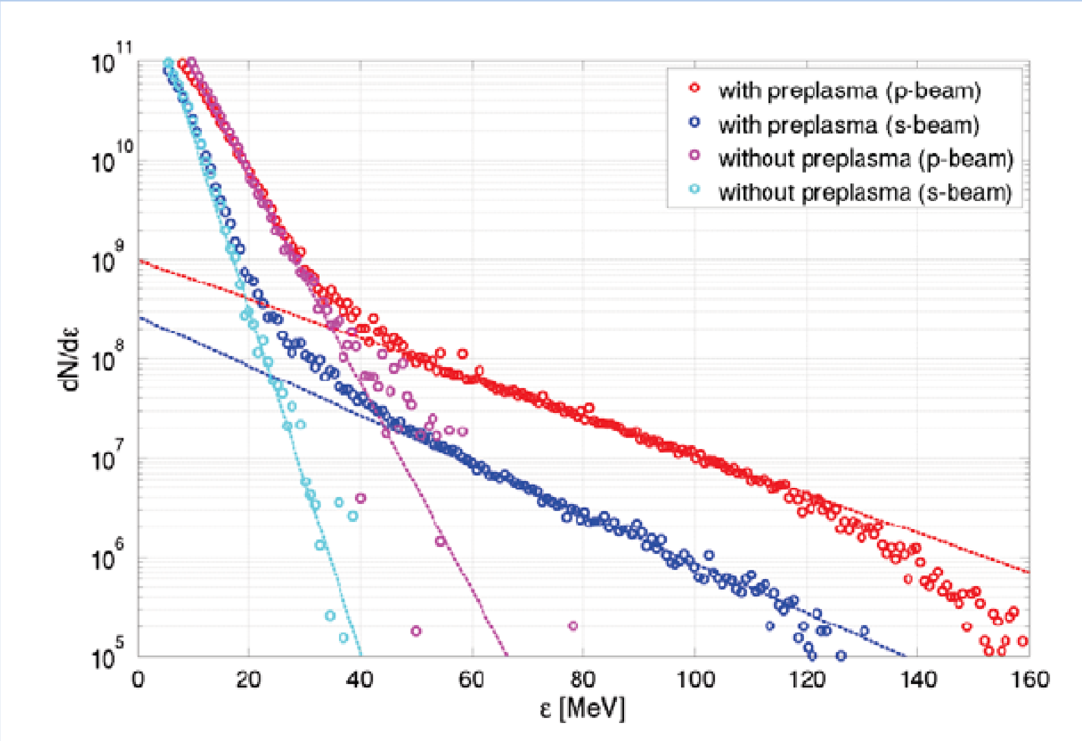
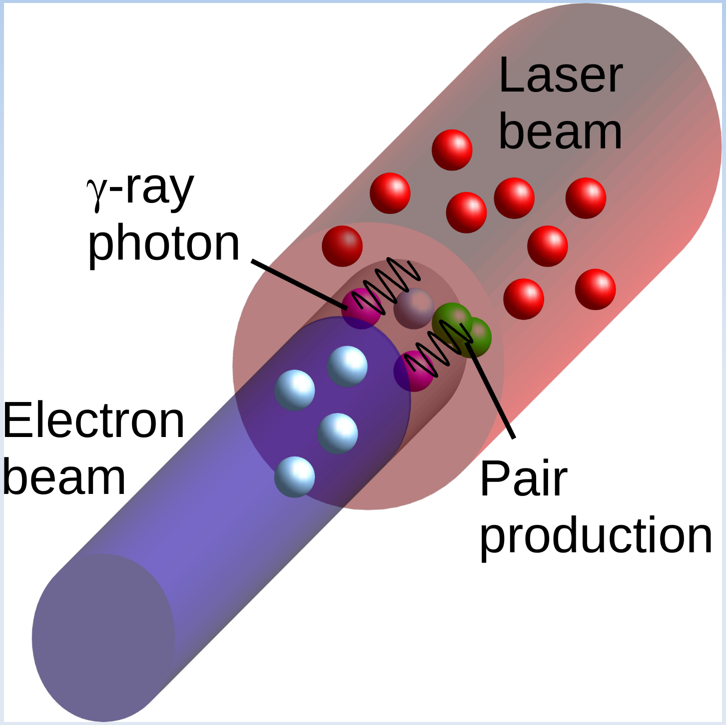
Towards experimental measurements of nonlinear QED effects in ultra-intense laser-matter interactions





<u>C. P. Ridgers</u>[1], C. S. Brady[2], T. Blackburn[3], J.G. Kirk[4], R.Duclous[5], P. Zhang[6], A.G.R. Thomas[6], D.Stark[7], A. Arefiev[7], K. Bennett[2], T.D. Arber[2] & A.R. Bell[3]

1. University of York, 2. University of Warwick, 3. University of Oxford,
4. Max-Planck Institute for Nuclear Physics, 5. CEA, Arpajon 6. University of Michigan
7. University of Texas

Outline

- Introduction
- Modelling the QED processes
- Laser-electron beam collider experiments
- QED+plasma experiments

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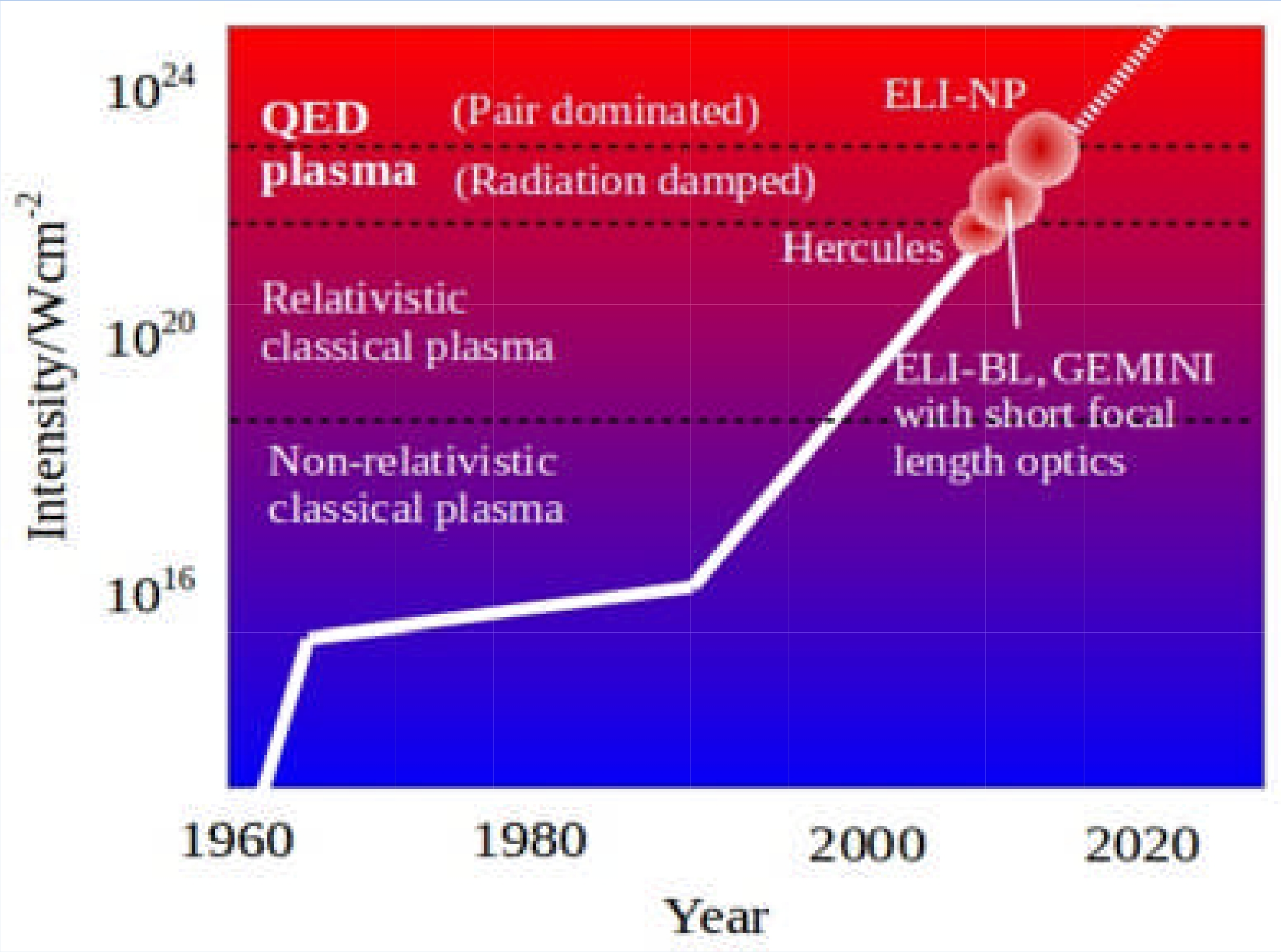
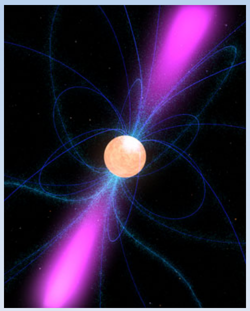
Rapid Increase in Laser Intensity

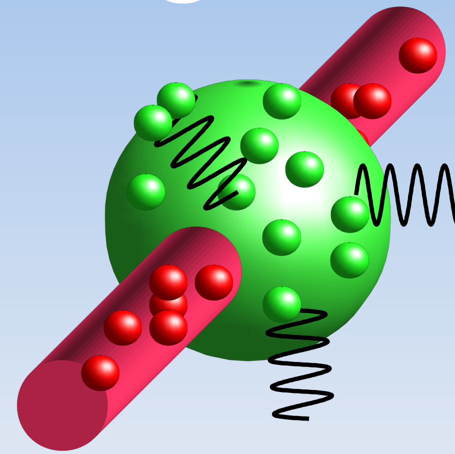


Why is the New Regime Interesting?

Fundamental Physics



Astrophysics: analogue to pulsar atmospheres



Strong-field QED

New Applications

Existing Applications

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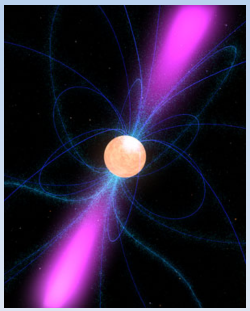

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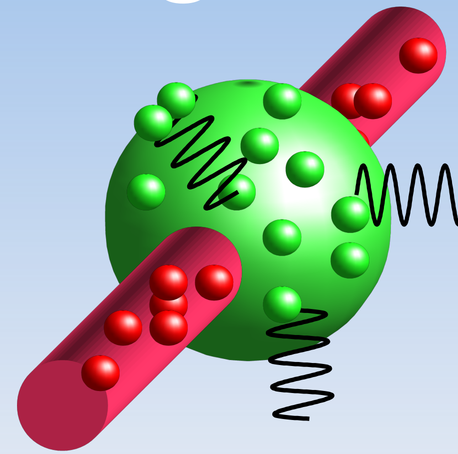

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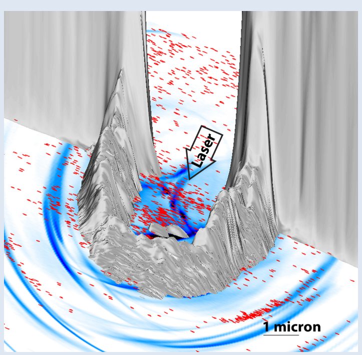
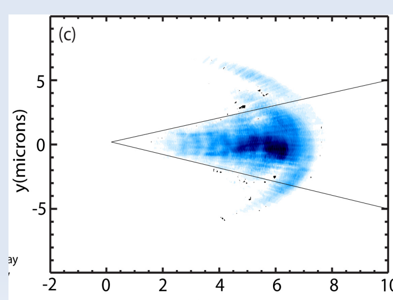


Prolific positron production

Generate ultra-intense bursts of gamma-rays



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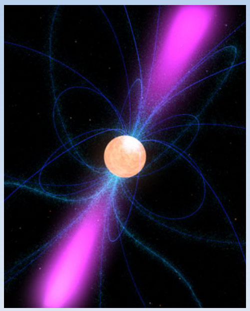

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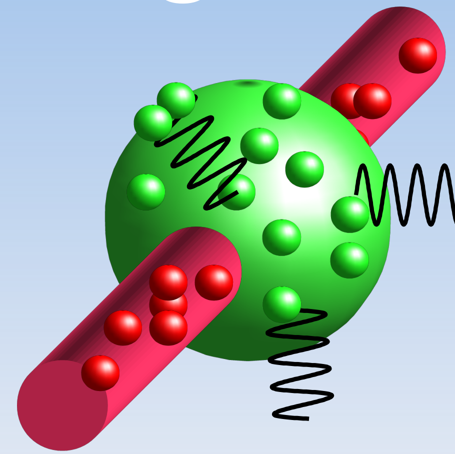

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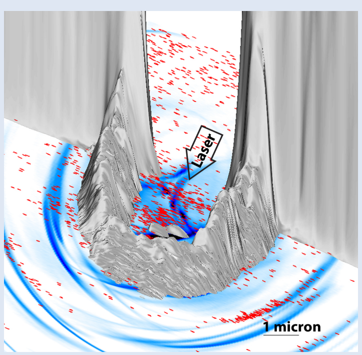

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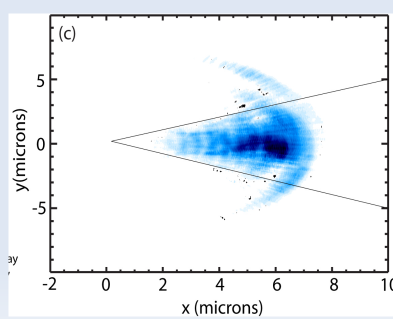
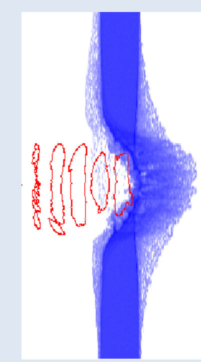


Existing Applications

Accelerate electrons & ions to multi-GeV energies



Critical Field

Field does work ~$m_e c^2$ over λ_c

$$E_s = \frac{2\pi m_e c^2}{e\lambda_c} = 1.3\text{x}10^{18}\ Vm^{-1}$$

$$I_s = 2\text{x}10^{29}\ Wcm^{-2}$$

J. Schwinger, Phys. Rev., **82**, 664 (1951)

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η~E/E_s in rest frame

In lab frame: $\eta \approx \frac{\gamma}{E_s}\left|\boldsymbol{E}_\perp + \boldsymbol{v}\times\boldsymbol{B}\right|$

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Assume $\gamma \sim a$ $\quad a = \frac{e E_{laser}}{m_e c\,\omega_{laser}}$ $\quad \left|\boldsymbol{E}_\perp + \boldsymbol{v}\times\boldsymbol{B}\right| \sim E_{laser}$

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Puting these into formula for η

$$\eta \sim 0.1 \frac{I}{5\times 10^{22}\, Wcm^{-2}}$$

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The QED+Plasma Regime

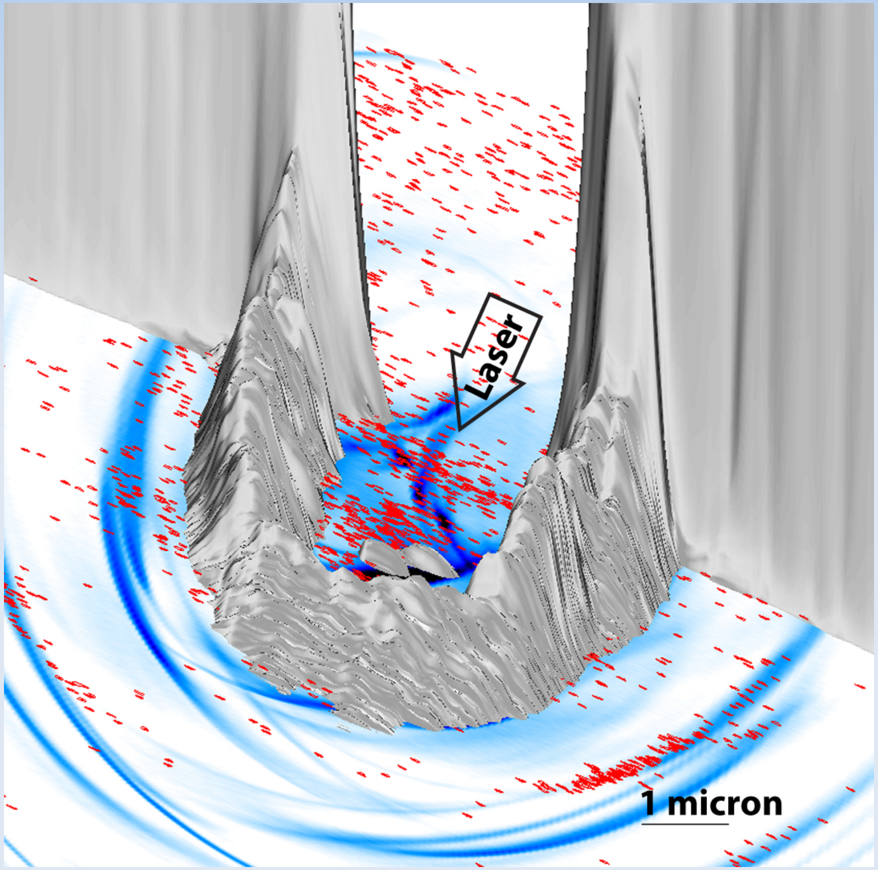
$$\eta \sim 0.1 \frac{I}{5\times 10^{22}\, Wcm^{-2}}$$

FEEDBACK

QED processes

⬇ ⬆

Classical Plasma Physics



C.P. Ridgers, *et al*, PRL, 108, 165006 (2012)

Critical Field

What can we do with PW-class lasers (I~10^{21}Wcm^{-2})?

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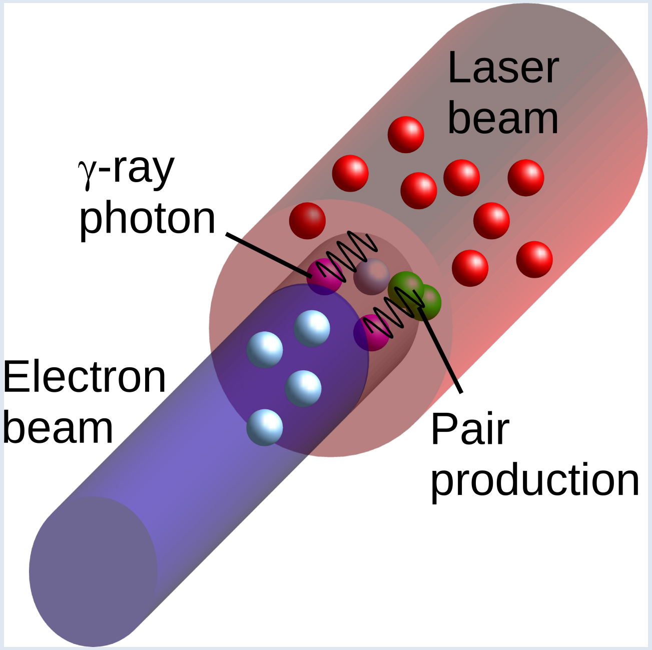

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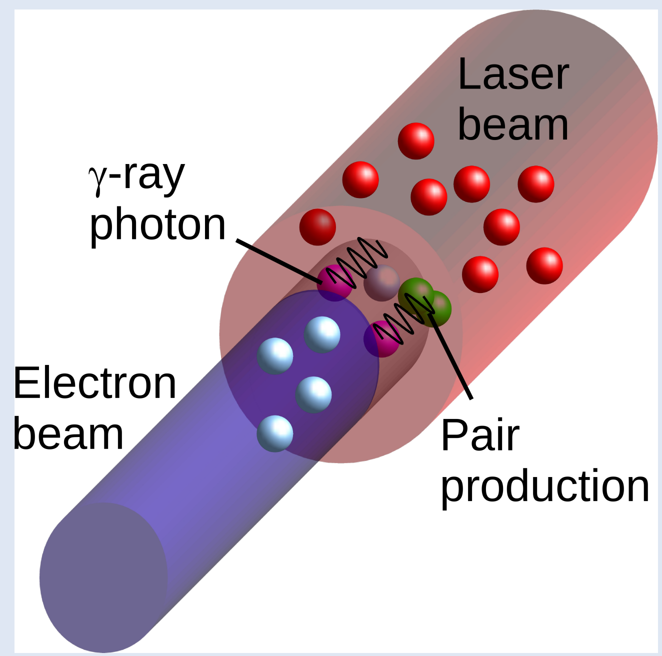
$$\eta \sim 0.1\frac{\gamma}{1000}\sqrt{\frac{I}{10^{21}Wcm^{-2}}}$$



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Modelling the emission processes

1. Split EM field into 'low frequency' (laser-fields) & 'high frequency' (gamma-rays) components

C.P. Ridgers *et al*, J Comp Phys, 260, 273 (2014)

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C.P. Ridgers *et al*, J Comp Phys, 260, 273 (2014)

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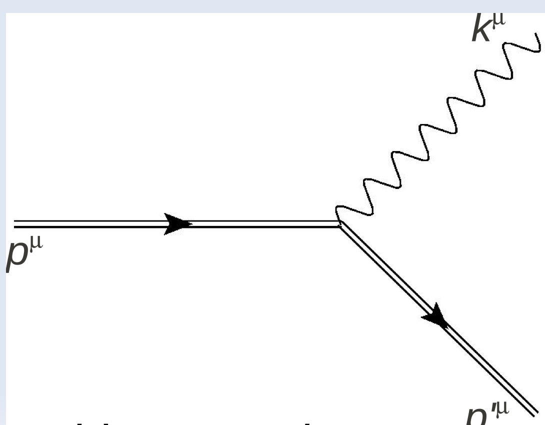
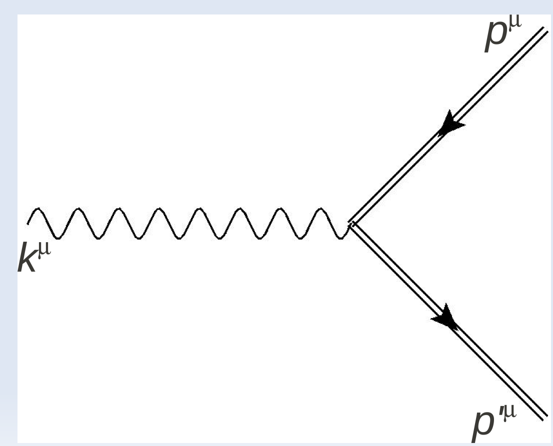
Modelling the emission processes

1. Split EM field into 'low frequency' (laser-fields) & 'high frequency' (gamma-rays) components
2. 'Low frequency' fields are treated classically
3. Use strong-field QED – basis states dressed by fields
4. Keep lowest order interactions between electrons, positrons, gamma-rays with classical low frequency fields

Photon emission



Pair production



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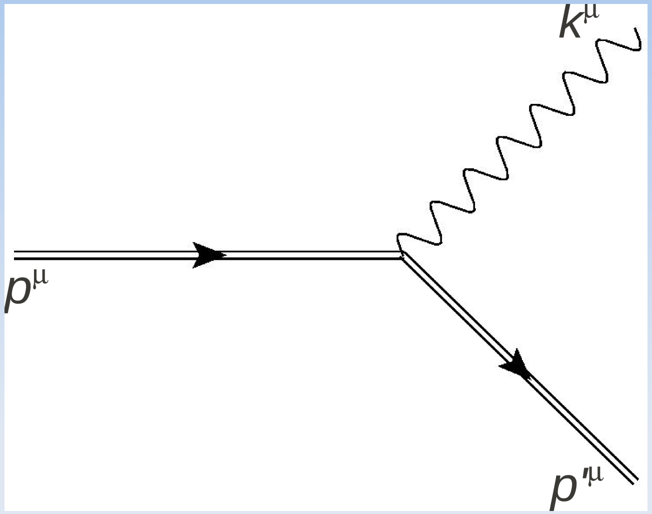
Photon emission

1. $\dfrac{\text{Formation length}}{\text{Laser wavelength}} = 1/a \ll 1$

Quasi-static=> emission pointlike



J.G. Kirk *et al*, PPCF, 51, 085008 (2009)
V.N. Baier, 'High Energy Processes in Aligned Single Crystals'

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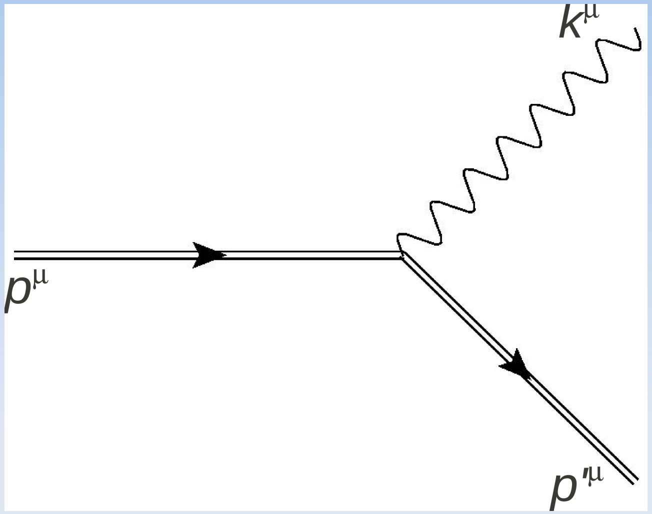
2. $E \ll E_s$ **"Weak"-field**



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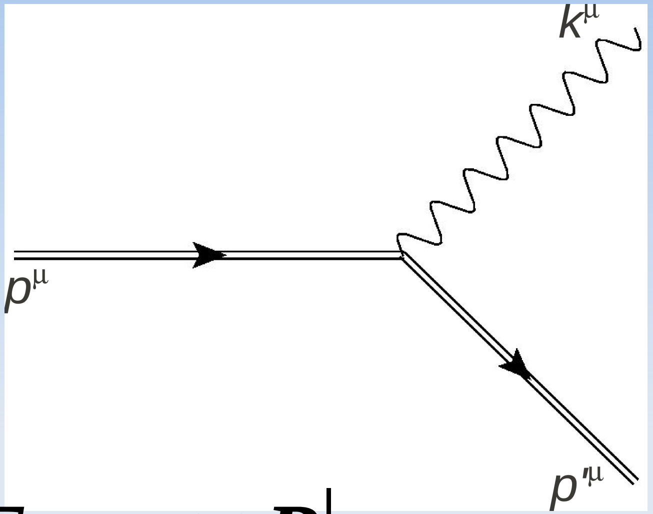

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Photon emission depends on $\eta \approx \frac{\gamma}{E_s} \left| \boldsymbol{E}_\perp + \boldsymbol{v} \times \boldsymbol{B} \right|$

Calculate emission rates in any convenient configuration with $E, cB \ll E_s$.

Constant crossed-field – synchrotron emission

Plane EM wave – nonlinear Compton scattering

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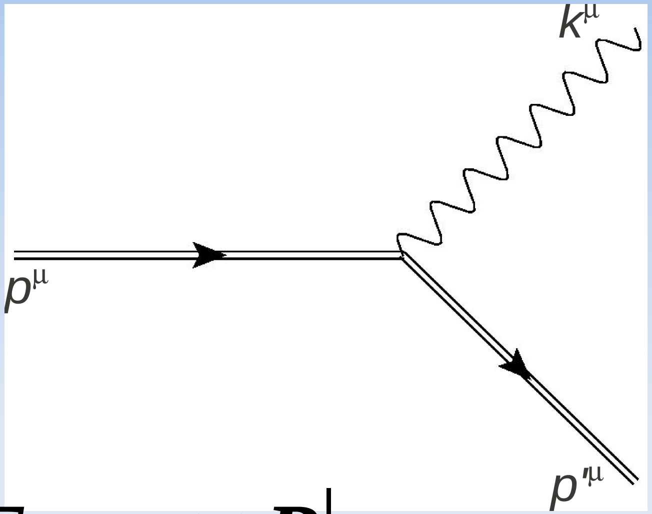

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Constant crossed-field – synchrotron emission

Plane EM wave – nonlinear Compton scattering

Motion of electrons, positrons is classical between emission events

J.G. Kirk *et al*, PPCF, 51, 085008 (2009); V.N. Baier, 'High Energy Processes in Aligned Single Crystals'

Model Validity

INTENSITY/Wcm^{-2}

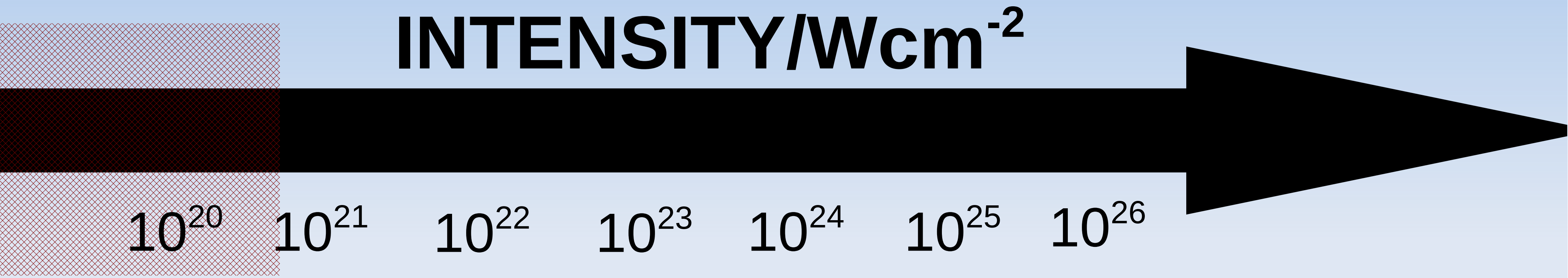
10^{20} 10^{21} 10^{22} 10^{23} 10^{24} 10^{25} 10^{26}

Two assumptions:

1. Quasi-static => $a \gg 1$

2. Weak-field => $I \ll 10^{29} Wcm^{-2}$

Model Validity



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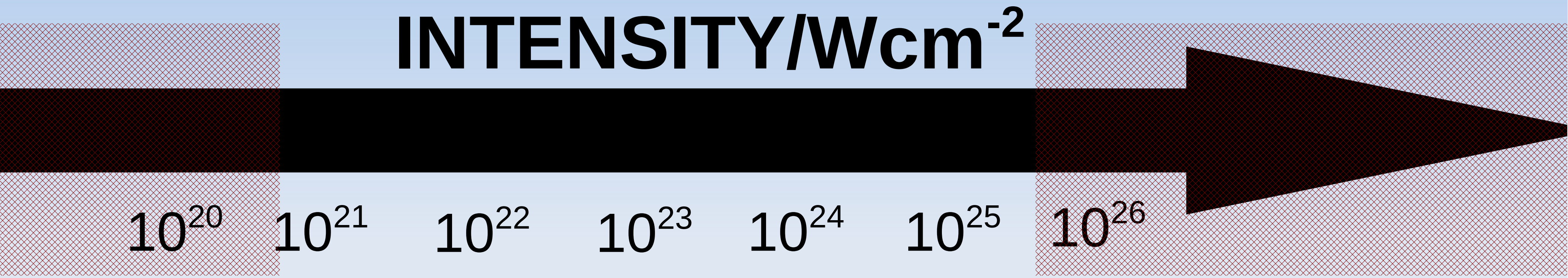

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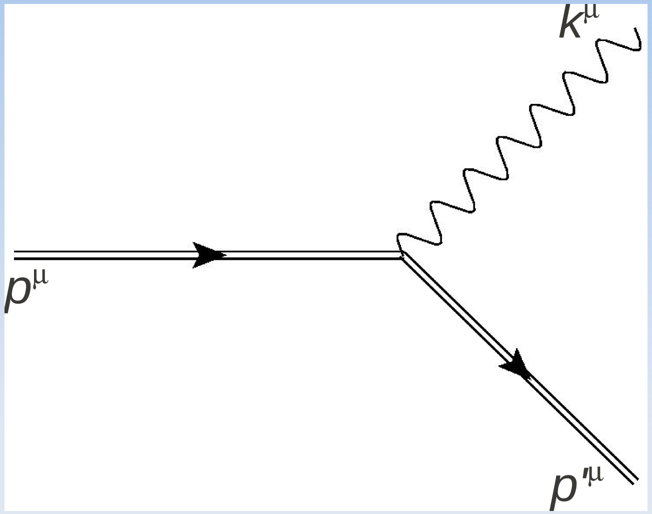
$$\frac{Energy\ emitted}{\gamma_{osc} m_e c^2} \sim \left(\frac{\eta}{0.1}\right)^{1.5}$$



η>0.1 radiation reaction important

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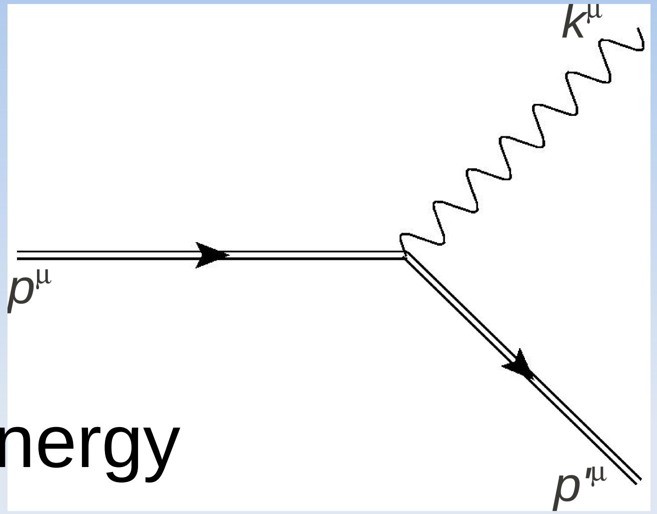

Photon energy $= 0.44\eta$ X Electron energy

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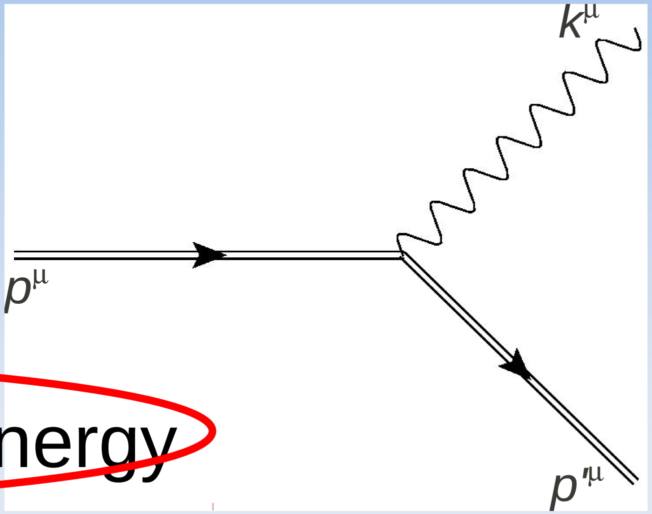

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>> laser photon energy (1eV for 1 micron)

=> emission INCOHERENT

η>0.1

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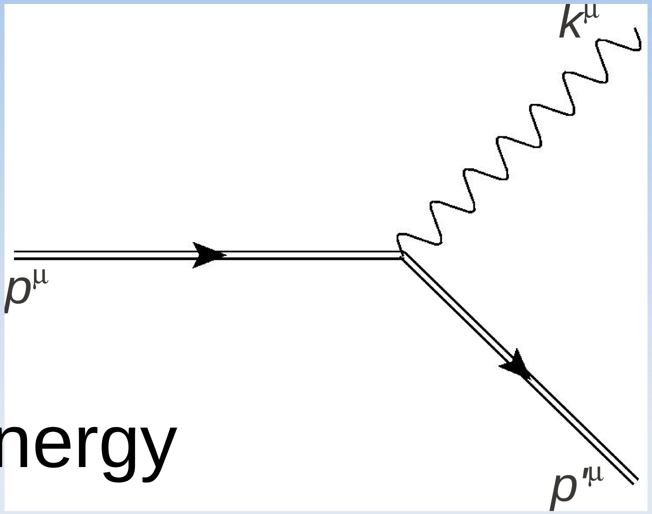

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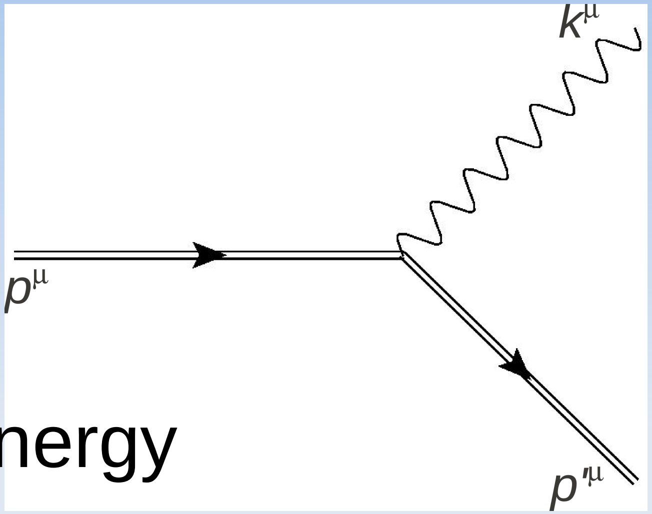

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Classical

$$\frac{d\boldsymbol{p}}{dt} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) - \frac{\boldsymbol{p}}{\tau_{RD}}$$

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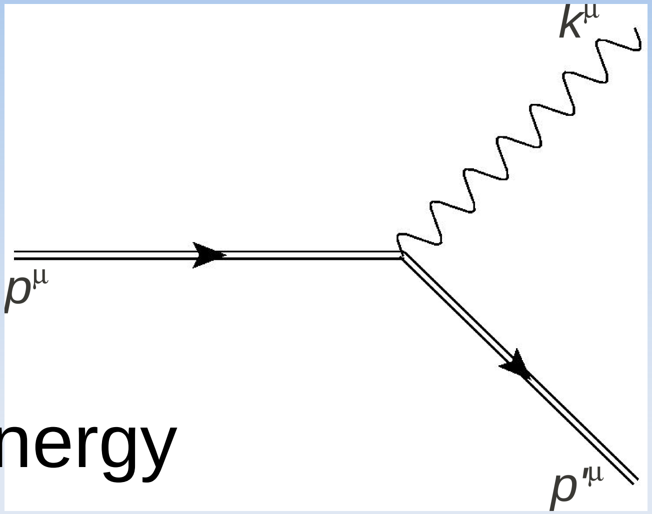

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Lorentz force **Radiation reaction**

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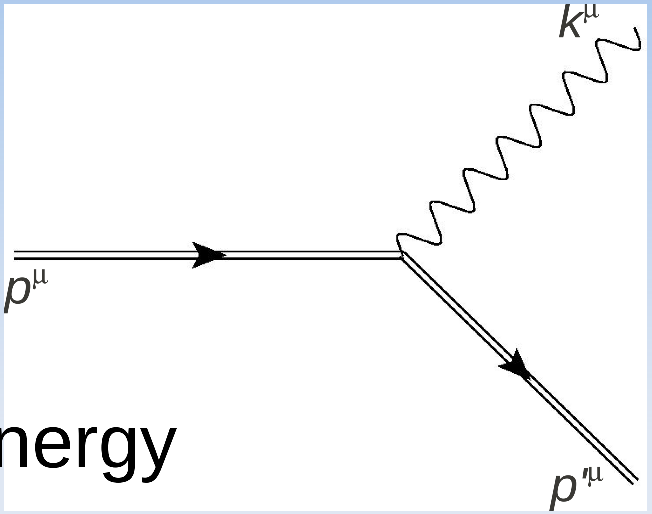

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Quantum

$$\Delta \boldsymbol{p} = -\sum \hbar \boldsymbol{k}$$

A. DiPiazza *et al*, Phys Rev Lett, 105, 220403 (2010)

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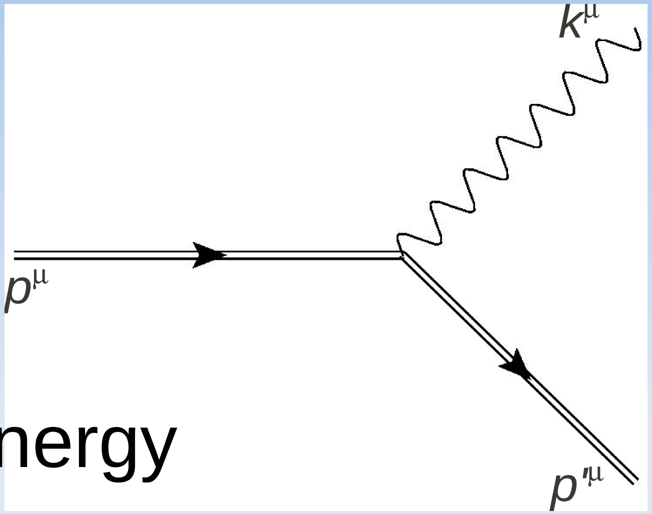

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Quantum effects

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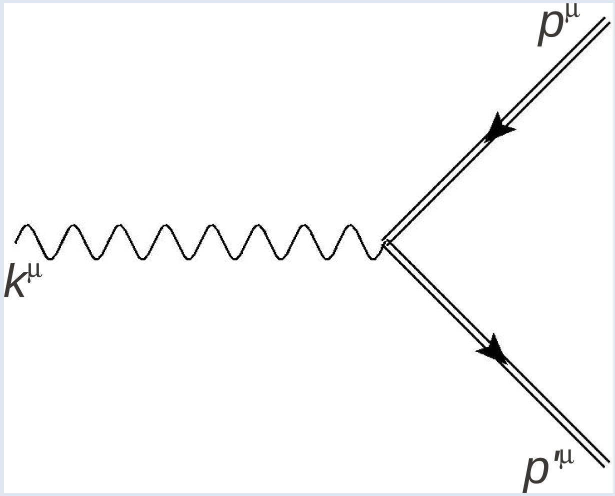
(3) Pair production



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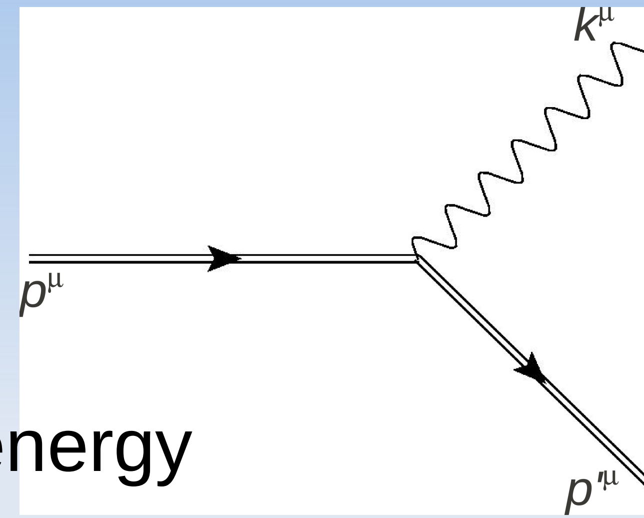

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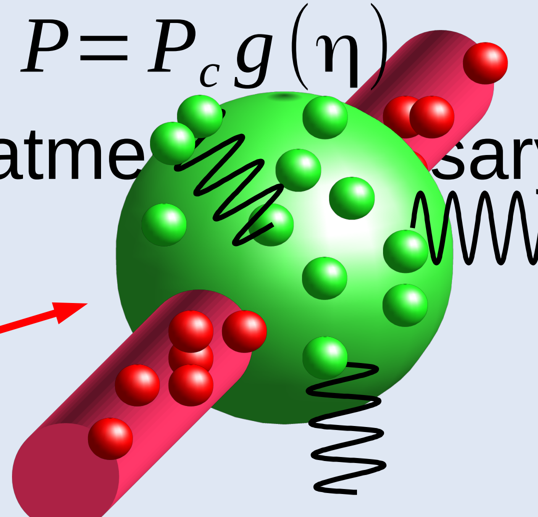
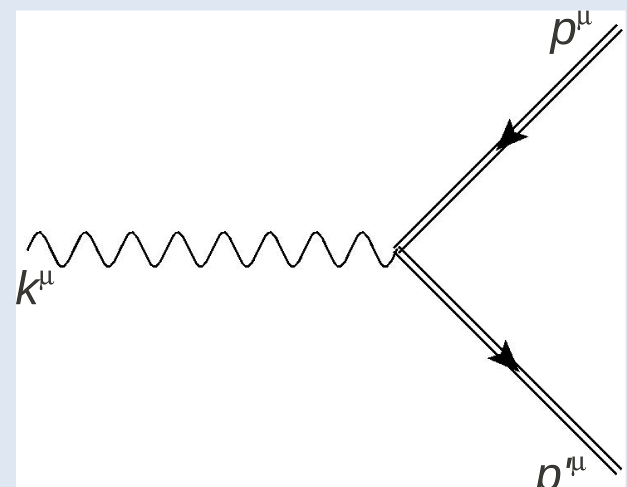


$\eta \sim 1$



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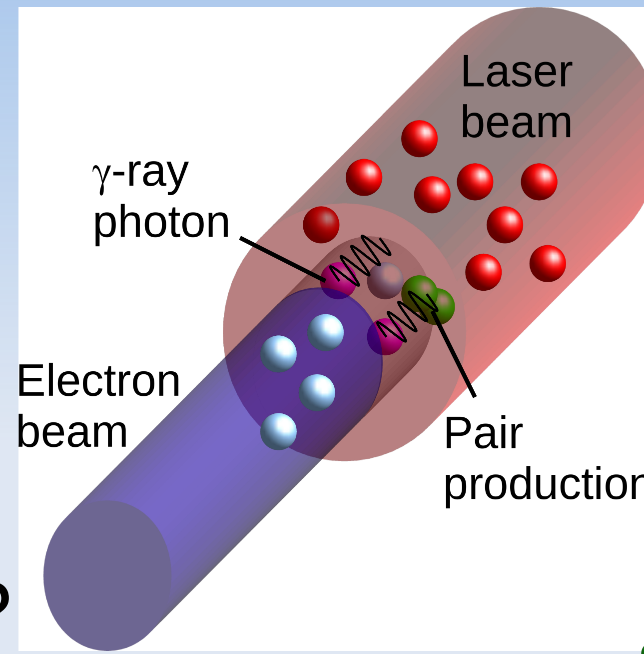
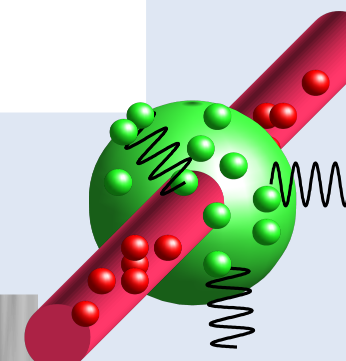
Electron Beam – Laser Pulse Collisions

$$\eta \sim 0.1 \frac{\gamma}{1000}\sqrt{\frac{I}{10^{21}\, Wcm^{-2}}}$$

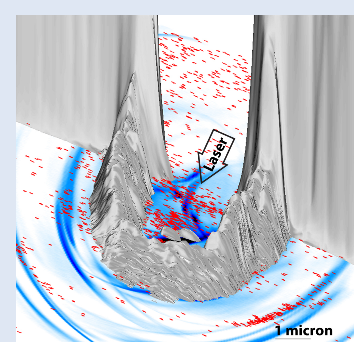


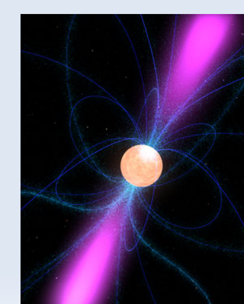
What can we learn from this?



1. Probe strong-field QED

2. Physics underpinning 10PW and pulsar magnetospheres





A. Timhokin, MNRAS, 408, 2092 (2010)

Previous experiments

1. SLAC E-144

>40GeV electron beam from 'standard' particle accelerator

Collides with laser intensity 10^{18}-10^{19}Wcm^{-2}

Saw Compton scattering and Breit-Wheeler pair production in weakly non-linear (NOT quasi-static) regime

C. Bula *et al*, Phys Rev Lett, 76, 3116 (1996)
D. Burke *et al*, Phys Rev Lett, 79, 1626 (1998)

Previous experiments

1. SLAC E-144 → weakly non-linear

2. CERN SPS

100GeV electron beam from 'standard' particle accelerator
Collides with crystal → electric fields $10^{13}Vm^{-1}$

Saw synchrotron radiation in strongly non-linear (quasi-static) regime → measured $g(\eta)$

K. Andersen, *et al*, Phys Rev D, 86, 072001 (2012)

Previous experiments

1. SLAC E-144 → weakly non-linear
2. CERN SPS → strongly non-linear synchrotron radiation
3. **'All-optical'**

~hundreds of MeV electron beam from laser wakefield accelerator

Collides with laser intensity 10^{18}-10^{19} Wcm^{-2}

Evidence of Compton scattering in the weakly non-linear regime

K. TaPhouc *et al*, Nat. Photonics, 6, 308 (2012)
N. Powers *et al*, Phys Rev Lett, 8. 28 (2014)
G. Sarri *et al*, Phys Rev Lett, 113, 224801 (2015)

Previous experiments

1. SLAC E-144 → weakly non-linear
2. CERN SPS → strongly non-linear synchrotron radiation
3. 'All-optical' → weakly non-linear

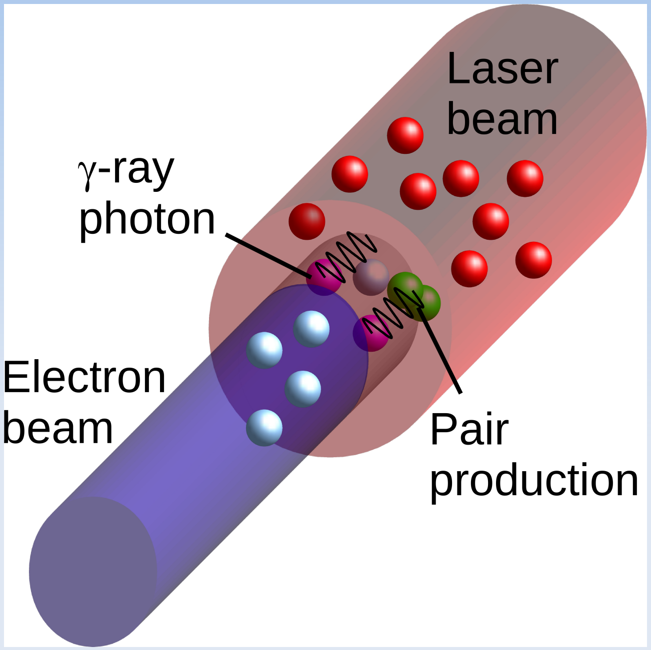
What next?

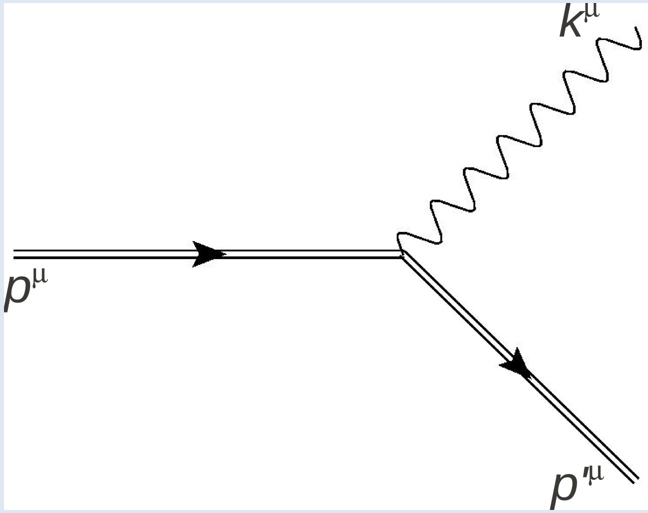
Quantum radiation reaction in very non-linear regime

Pair production?

Electron Beam – Laser Pulse Collisions

$$\eta \sim 0.1 \frac{\gamma}{1000} \sqrt{\frac{I}{10^{21}\, Wcm^{-2}}}$$

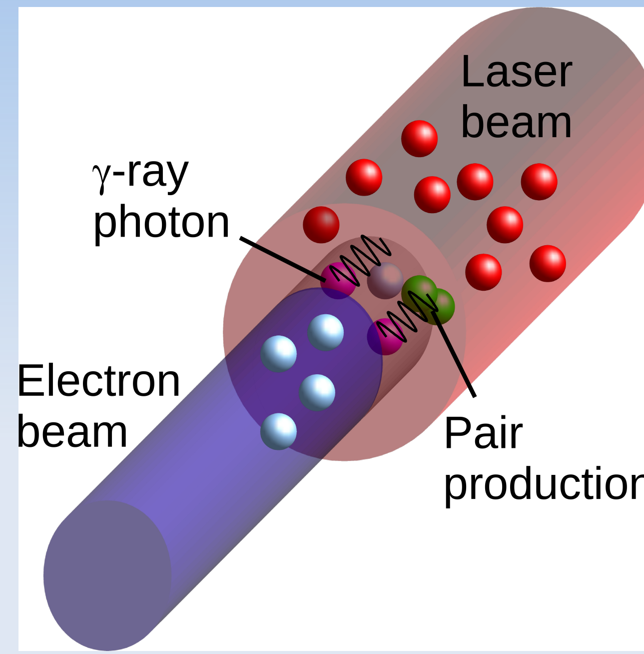


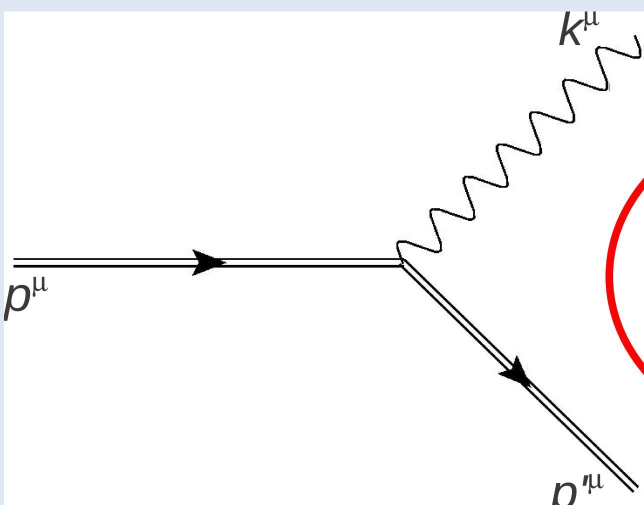


$$\eta \sim 0.1$$
$$I \sim 10^{21}\, Wcm^{-2}$$
$$\gamma \sim 1000$$

Electron Beam – Laser Pulse Collisions

$$\eta \sim 0.1 \frac{\gamma}{1000}\sqrt{\frac{I}{10^{21}\,Wcm^{-2}}}$$





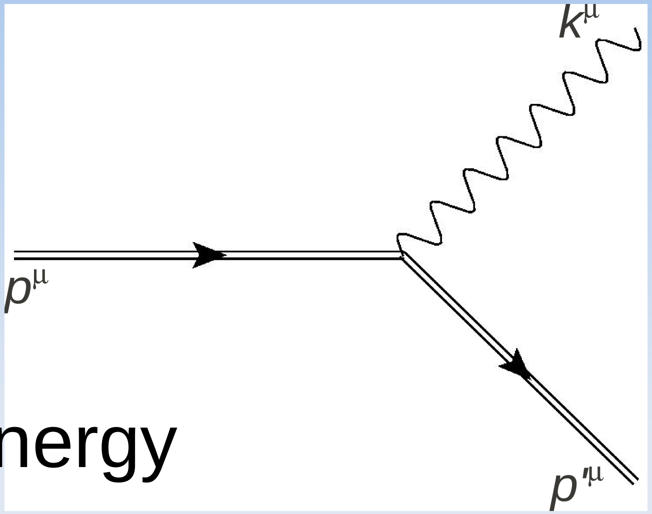
$$\eta \sim 0.1$$
$$I \sim 10^{21}\,Wcm^{-2}$$
$$\gamma \sim 1000$$

PW (Gemini)

Photon emission

$$\frac{Energy\ emitted}{\gamma_{osc} m_e c^2} \sim \left(\frac{\eta}{0.1}\right)^{1.5}$$

$\eta > 0.1$ radiation reaction important



Photon energy $= 0.44\eta$ X Electron energy

Quantum effects

(1) Include electron recoil $P = P_c\, g(\eta)$

(2) Probabilistic treatment necessary

Classical

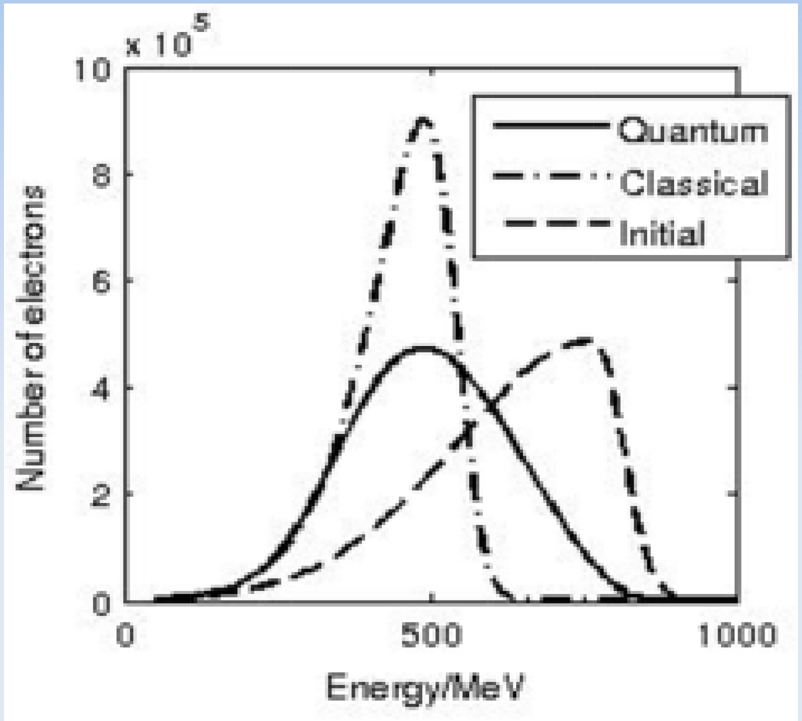
$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{\mathbf{p}}{\tau_{RD}}$$

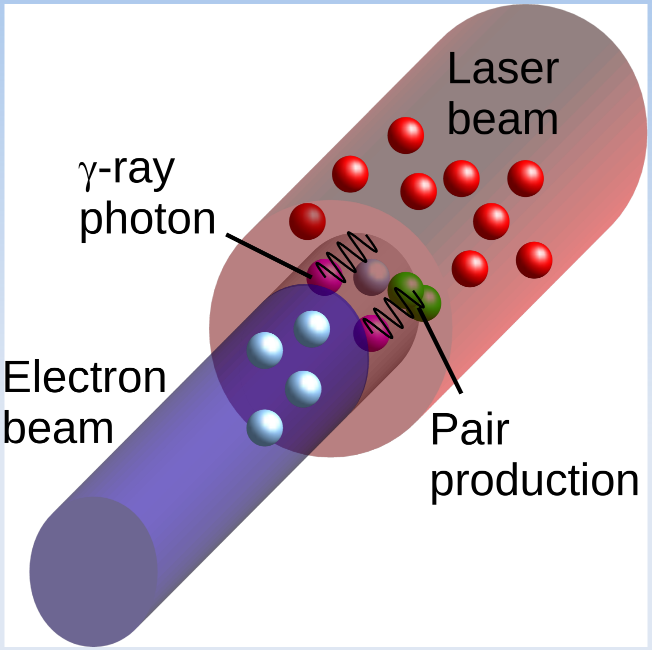
Lorentz force Radiation reaction

Quantum

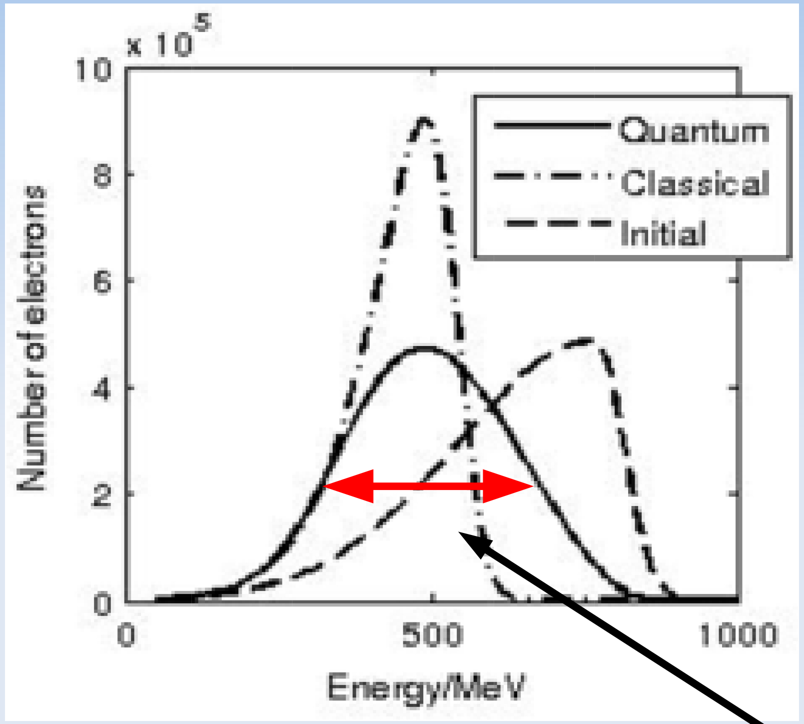
$$\Delta \mathbf{p} = -\sum \hbar \mathbf{k}$$

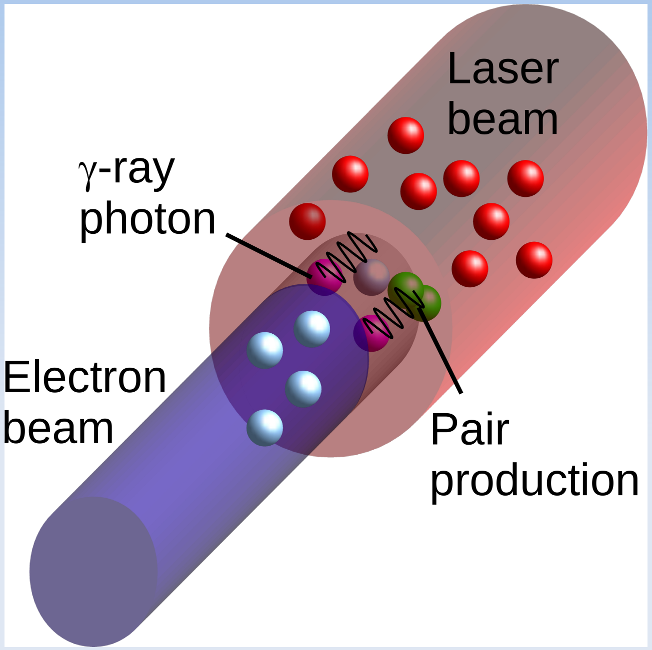
Future Experiments





Future Experiments

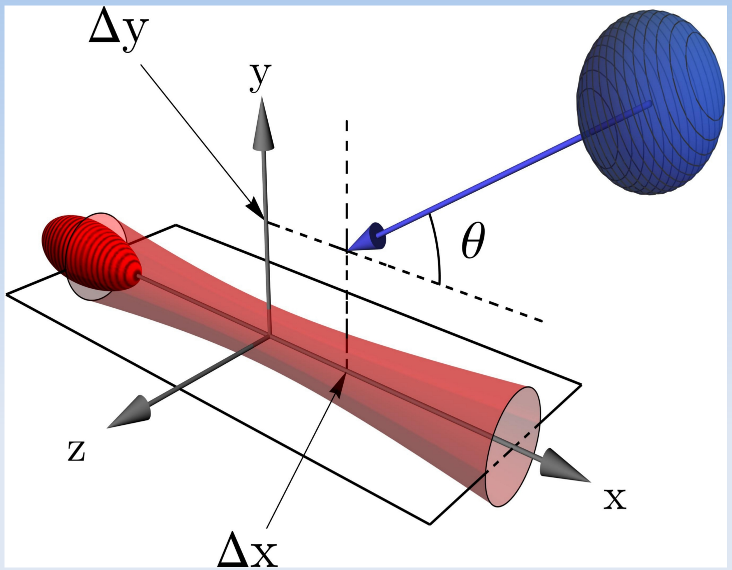




Quatum model predicts larger energy spread

Future Experiments

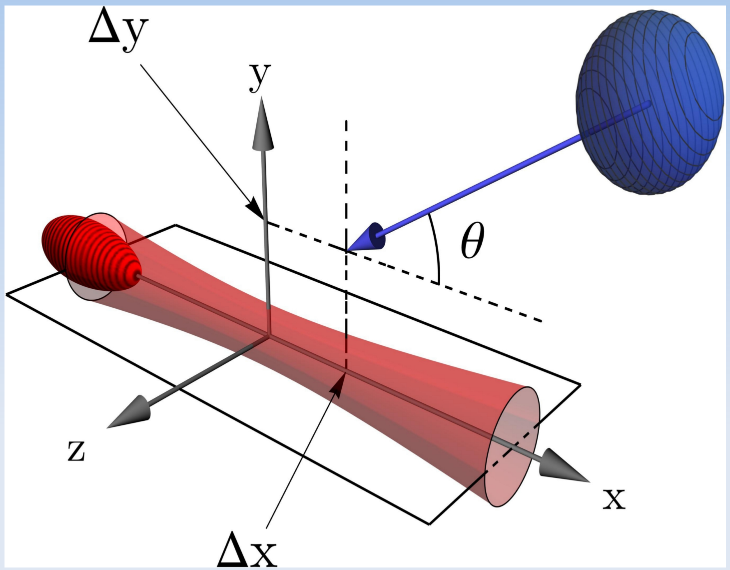
Problem → alignment of electron beam and laser pulse

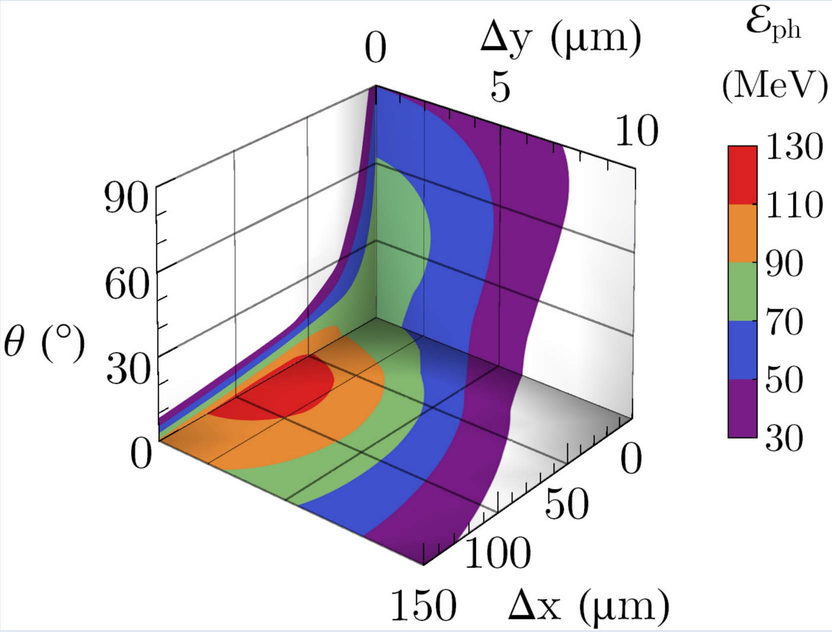


T.G. Blackburn *et al*, PPCF,57, 075012 (2015)

Future Experiments

Problem → alignment of electron beam and laser pulse



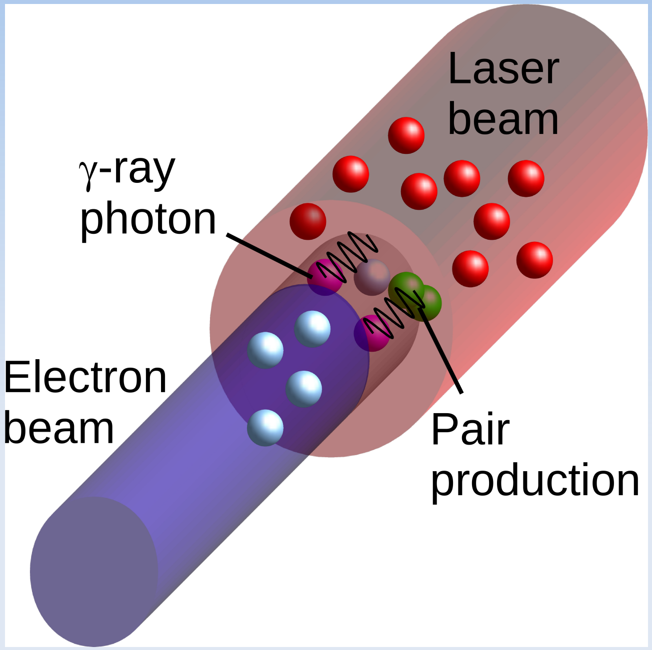


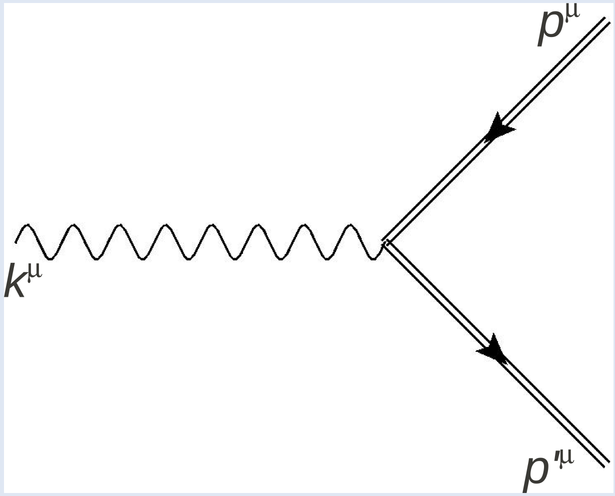
Misalignment strongly reduces emitted power

T.G. Blackburn *et al*, PPCF,57, 075012 (2015)

Electron Beam – Laser Pulse Collisions

$$\eta \sim 0.1\,\frac{\gamma}{1000}\sqrt{\frac{I}{10^{21}\,Wcm^{-2}}}$$





$$\eta \sim 1$$

$$I \sim 10^{22}\,Wcm^{-2}$$

$$\gamma \sim 4000$$

Electron Beam – Laser Pulse Collisions

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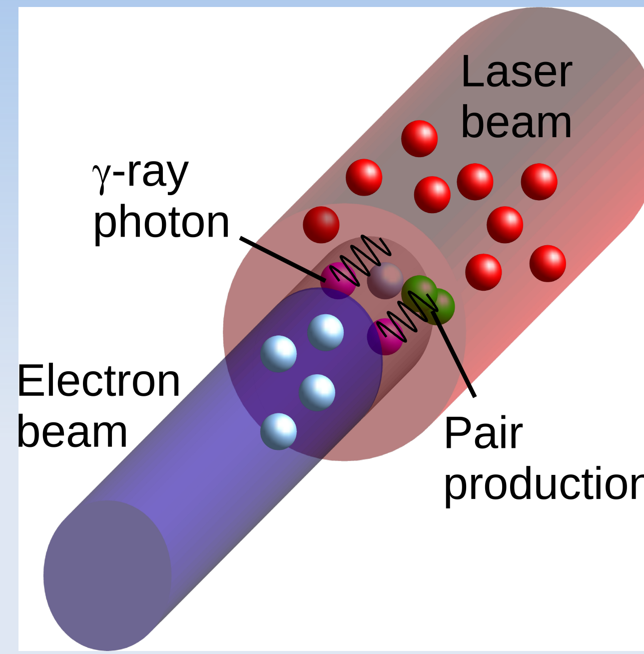
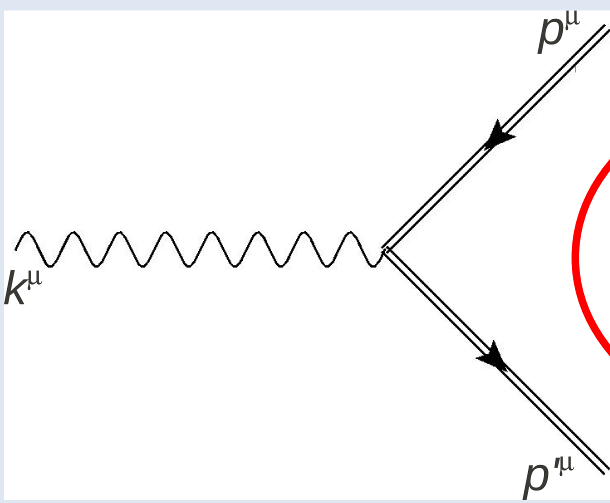




$$\eta \sim 1$$
$$I \sim 10^{22}\, Wcm^{-2}$$
$$\gamma \sim 4000$$

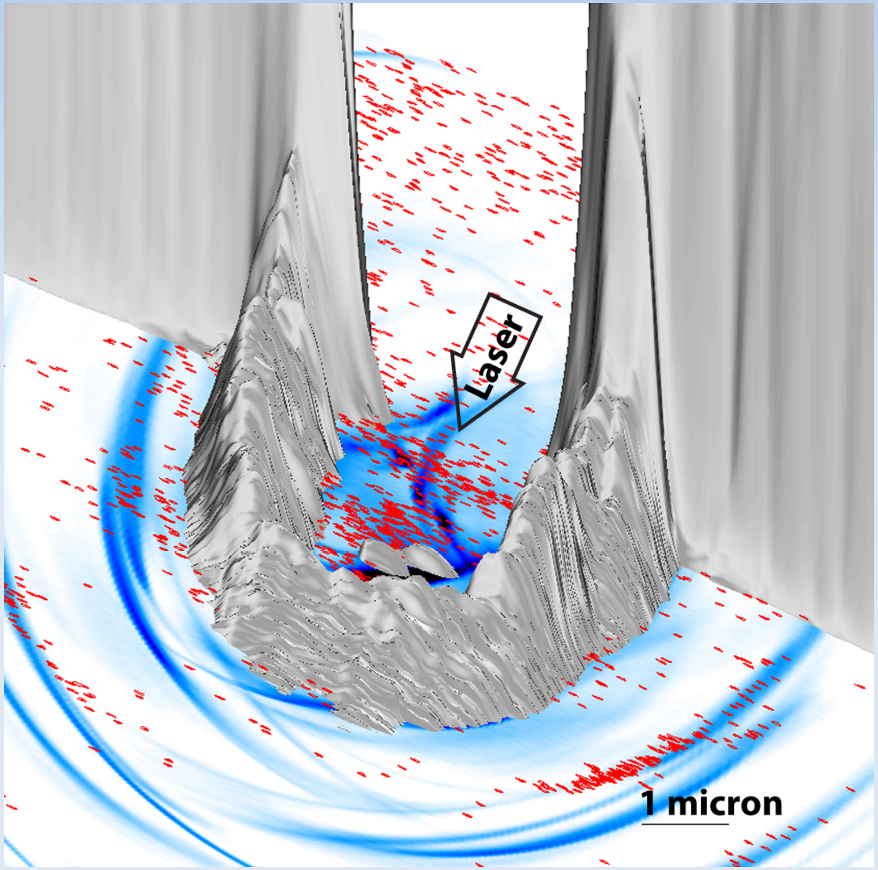
10PW (ELI-BL)

Outline

- Introduction
- Modelling the QED processes
- Laser-electron beam collider experiments
- **QED+plasma experiments**

The QED+Plasma Regime

$$\eta \sim 0.1 \frac{I}{5 \times 10^{22} Wcm^{-2}}$$



FEEDBACK

QED processes

⬇ ⬆

Classical Plasma Physics

C.P. Ridgers, *et al*, PRL, 108, 165006 (2012)

Feedback: Plasma Physics → QED

Rates

Photon production:

$$\frac{dN_\gamma}{dt} = \frac{\sqrt{3}\,\alpha_f}{2\pi\tau_C}\frac{\eta}{\gamma} h(\eta)$$

$$\eta = \frac{\gamma}{E_s}\left(\boldsymbol{E}_\perp + \boldsymbol{v} \times \boldsymbol{B}\right)$$

Pair production:

$$\frac{dN_\pm}{dt} = \frac{\alpha_f}{\tau_C}\frac{m_e c^2}{h\nu}\chi T_\pm(\chi)$$

$$\chi = \frac{h\nu}{2\mathrm{m}_e c^2 E_s}\left(\boldsymbol{E}_\perp + \hat{\boldsymbol{k}} \times \boldsymbol{B}\right)$$

T. Erber, Rev. Mod. Phys., **38**, 626 (1966)

Feedback: Plasma Physics → QED

Rates

$$\frac{dN_\gamma}{dt} = \frac{\sqrt{3}\alpha_f}{2\pi\tau_C}\frac{\eta}{\gamma}h(\eta)$$

Determined by
parameters that depend on...

$$\eta = \frac{\gamma}{E_s}\left(\boldsymbol{E}_\perp + \boldsymbol{v}\times\boldsymbol{B}\right)$$

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…electron motion &
local fields

$$\frac{dN_\pm}{dt} = \frac{\alpha_f}{\tau_C}\frac{m_e c^2}{h\nu}\chi\,T_\pm(\chi)$$

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Determined by
plasma physics

T. Erber, Rev. Mod. Phys., **38**, 626 (1966)

Feedback: QED → Plasma Physics

(1) Radiation reaction

$$\frac{d\boldsymbol{p}}{dt} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) + \text{PHOTON EMISSION}$$

Lorentz force — $-e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$

Radiation reaction force — PHOTON EMISSION

Equation of motion modified →

Plasma physics modified

Feedback: QED → Plasma Physics

(1) Radiation reaction

$$\frac{d\boldsymbol{p}}{dt} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) + \text{PHOTON EMISSION}$$

Lorentz force

Radiation reaction force

Equation of motion modified →

Plasma physics modified

(2) Prolific pair production: 1 pair per electron per laser period

Summary: Physics of the New Regime

FEEDBACK

QED processes

↓ ↑

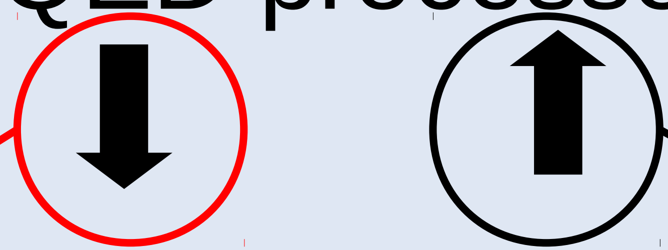
Classical Plasma Physics

Fields alter QED rates

Summary: Physics of the New Regime

FEEDBACK

QED processes

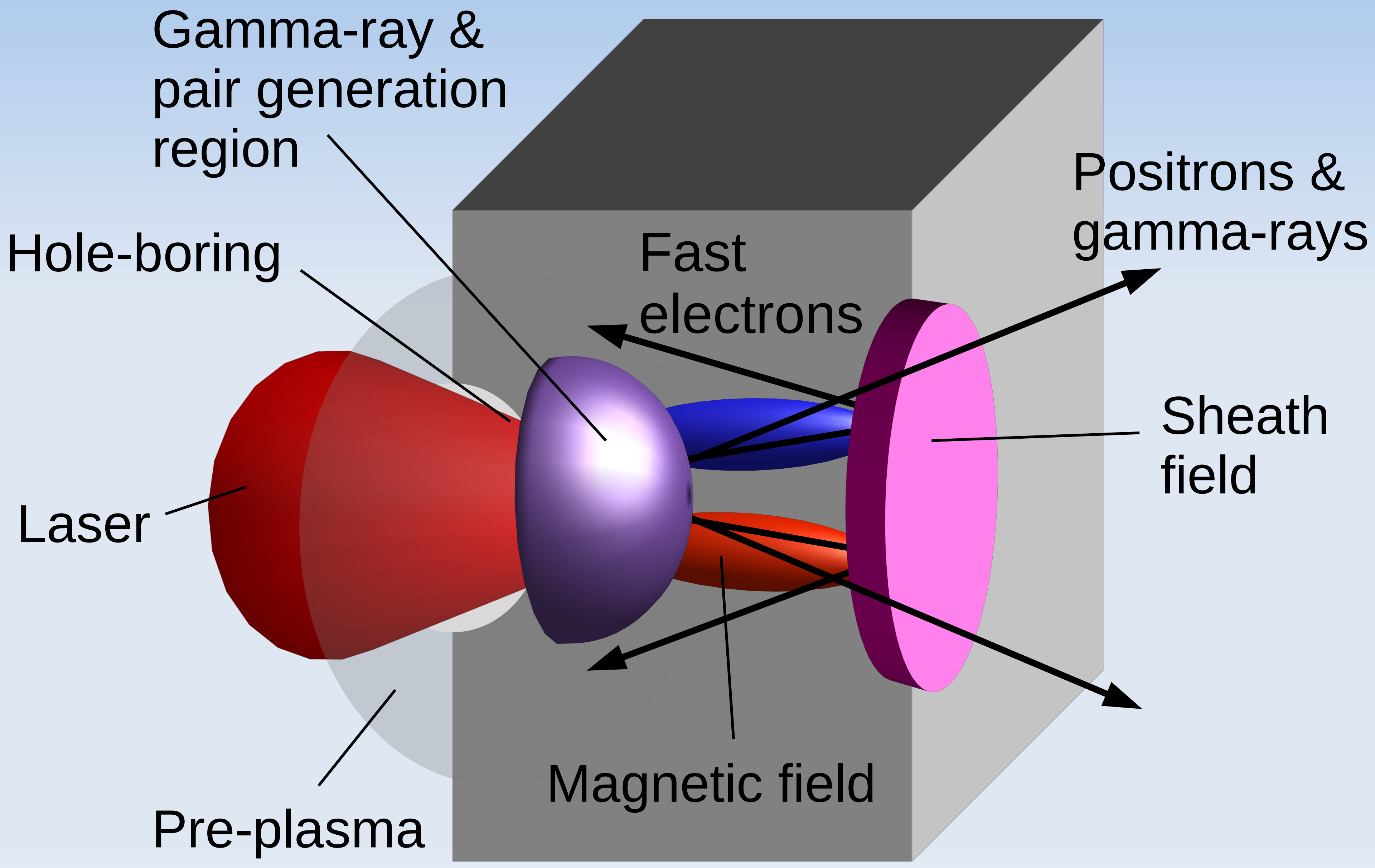


Classical Plasma Physics

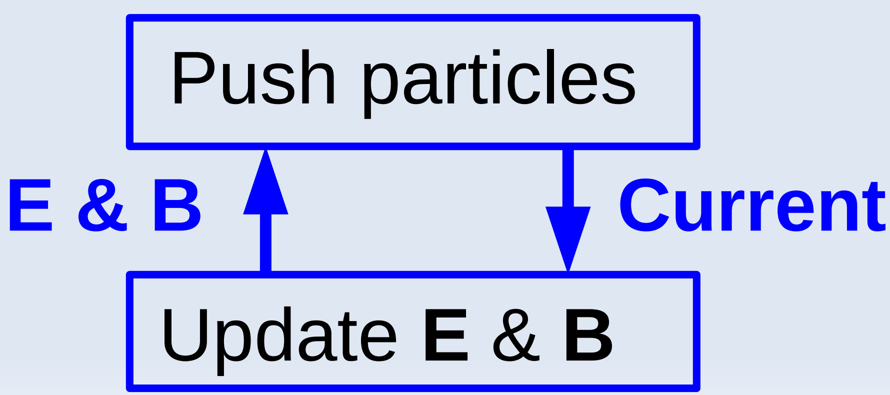
Radiation reaction & sources modify currents

Fields alter QED rates

Laser-Plasma Interactions are Complicated



QED-PIC Codes



'Standard' PIC code

Adding QED Emission Processes to PIC

(1) Laser fields may be treated classically

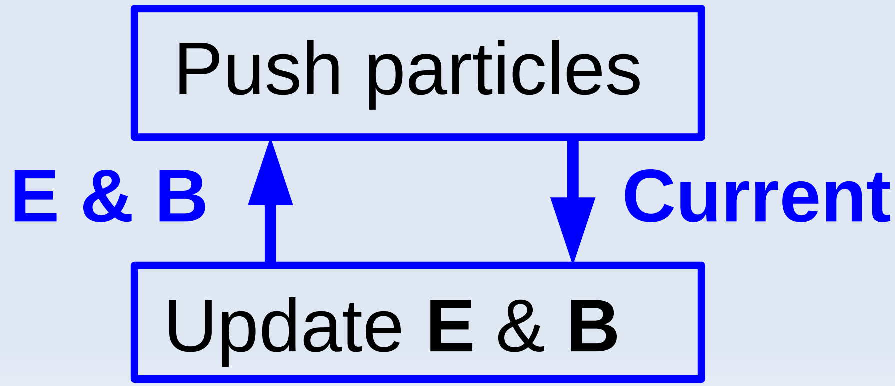
(2) Quasi-static (a>>1) => pointlike emission

(3) ”Weak” field ($E<<E_s$) => rates in arbitrary fields = rates in const B-field & motion classical

(4) Emitted photon energy >> laser photon energy => incoherent

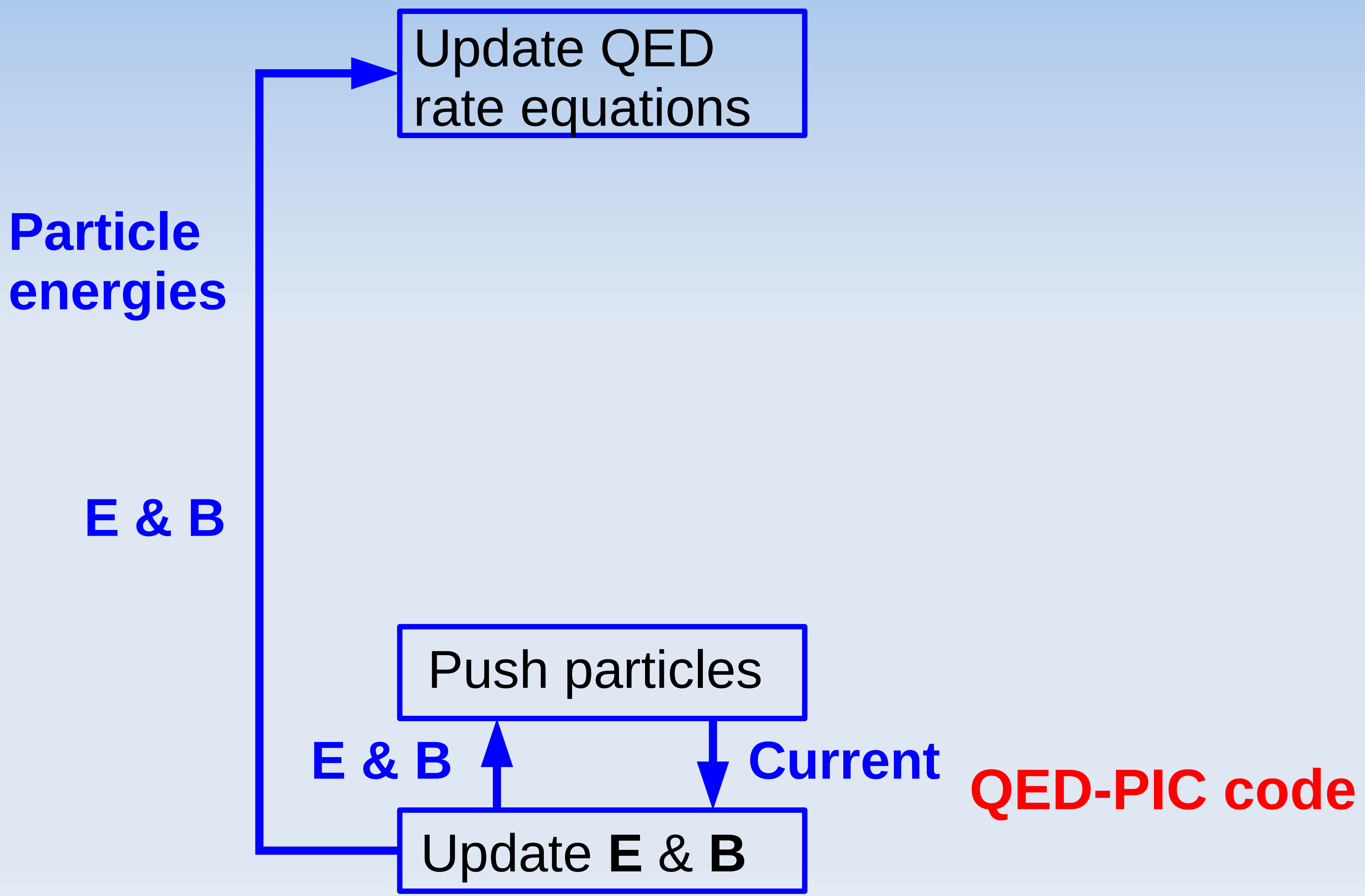
C.P. Ridgers *et al*, J Comp Phys, 260, 273 (2014)

QED-PIC Codes

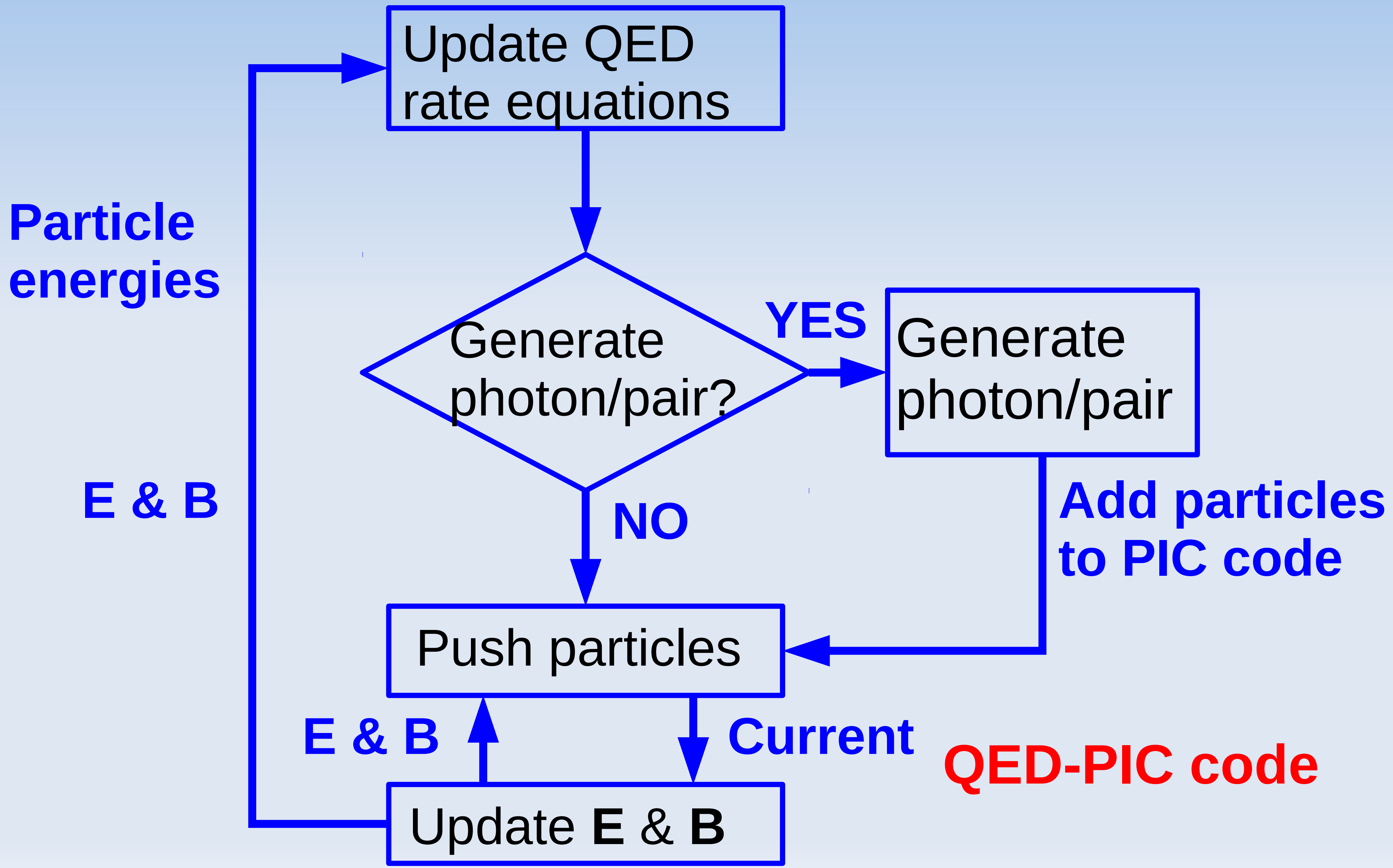


'Standard' PIC code

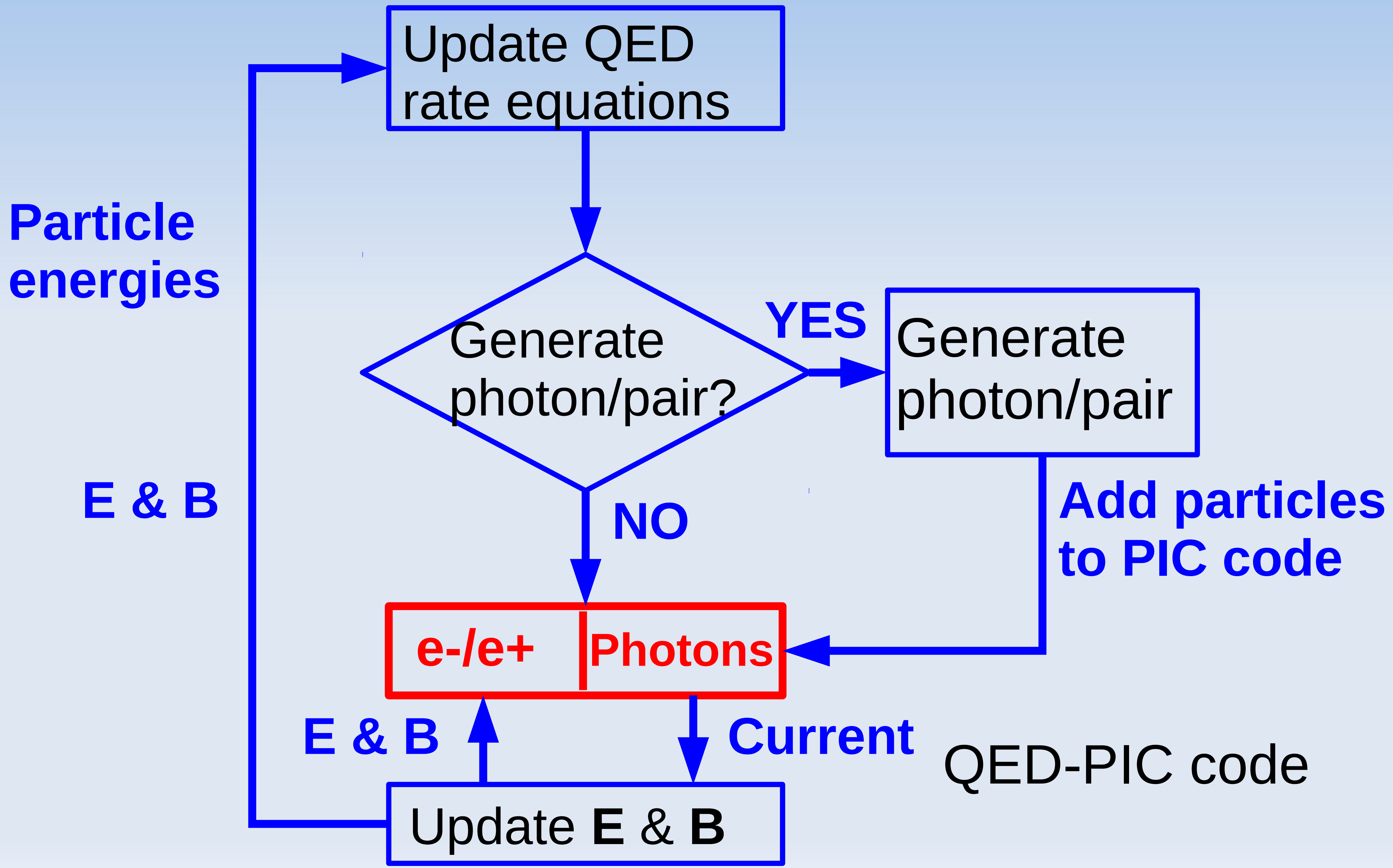
QED-PIC Codes



QED-PIC Codes



QED-PIC Codes



QED-PIC code

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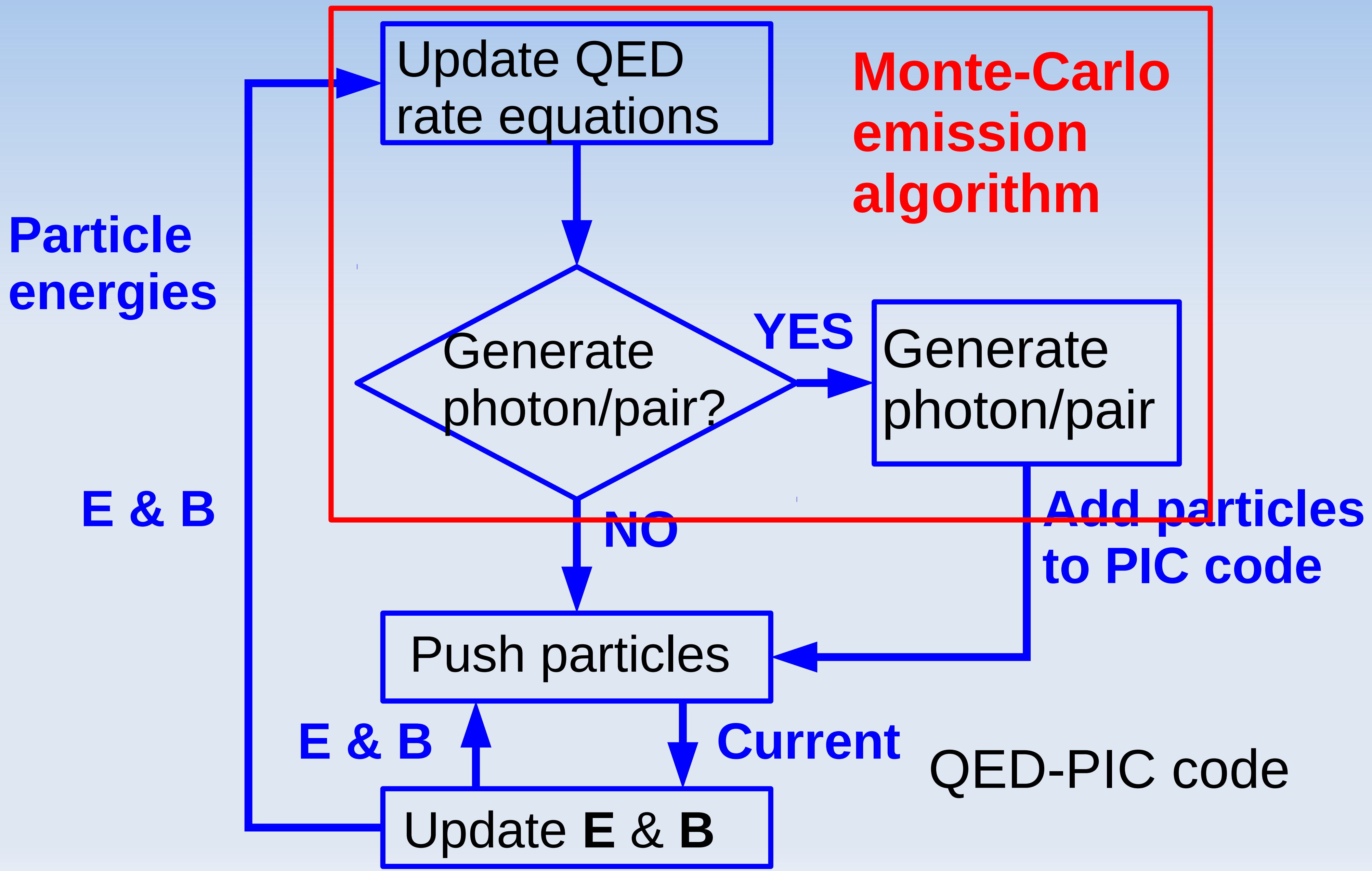
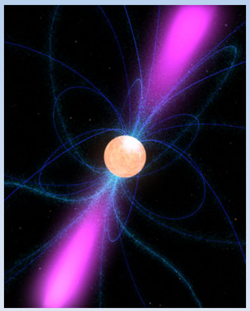


Why is the New Regime Interesting?

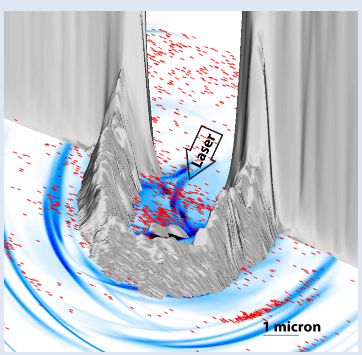
Fundamental Physics

Depend on plasma physics



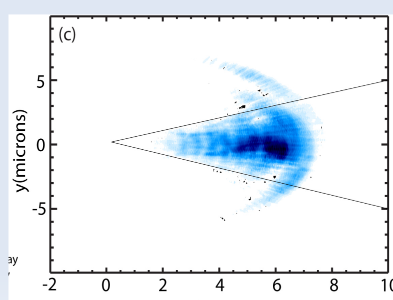
Astrophysics: analofue to pulsar atmospheres

New Applications



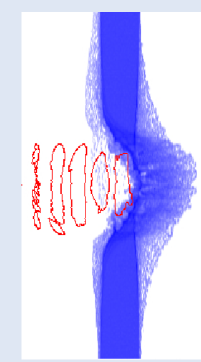
Prolific positron production

Generate ultra-intense bursts of gamma-rays

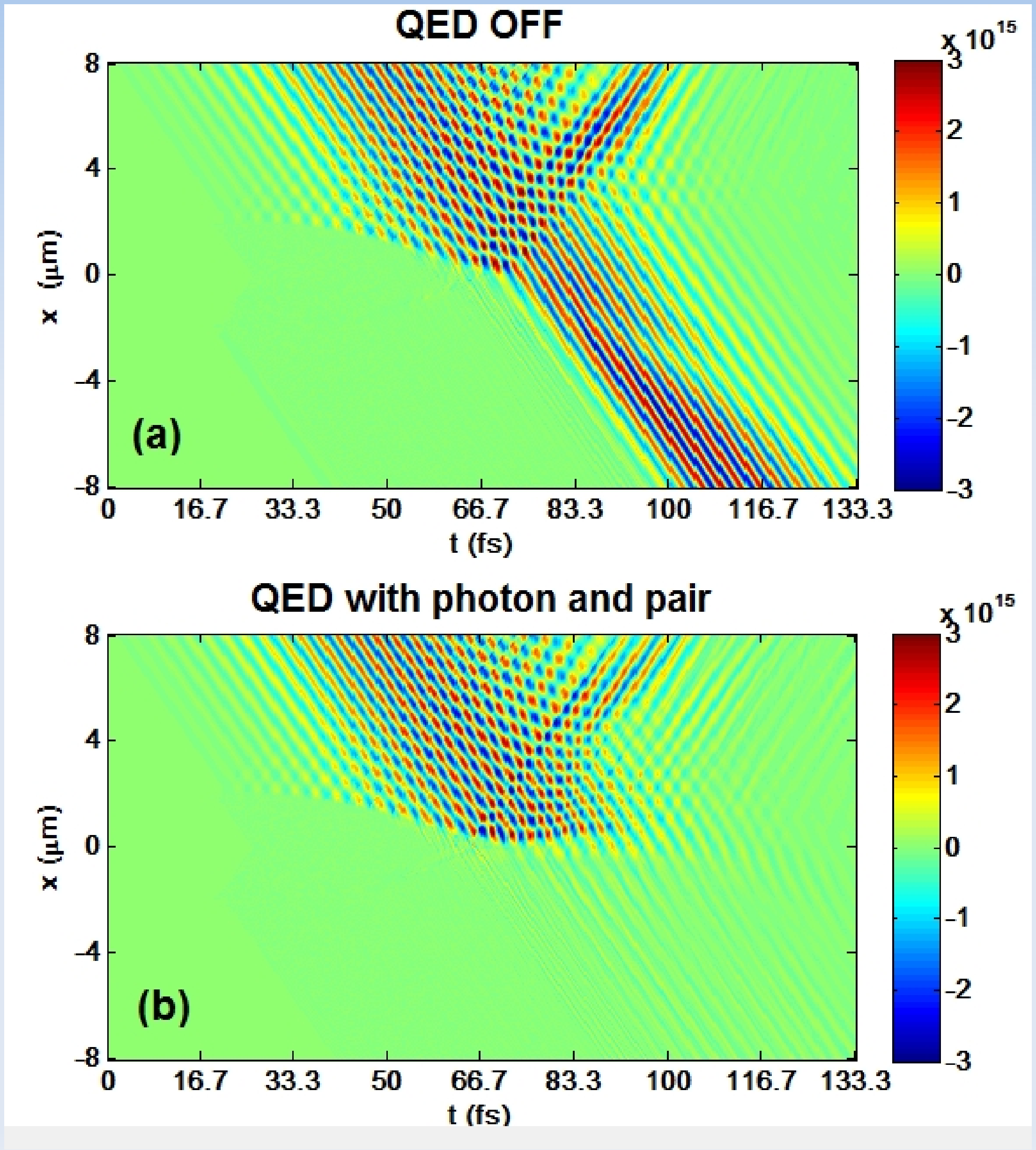


Existing Applications

Accelerate electrons & ions to multi-GeV energies

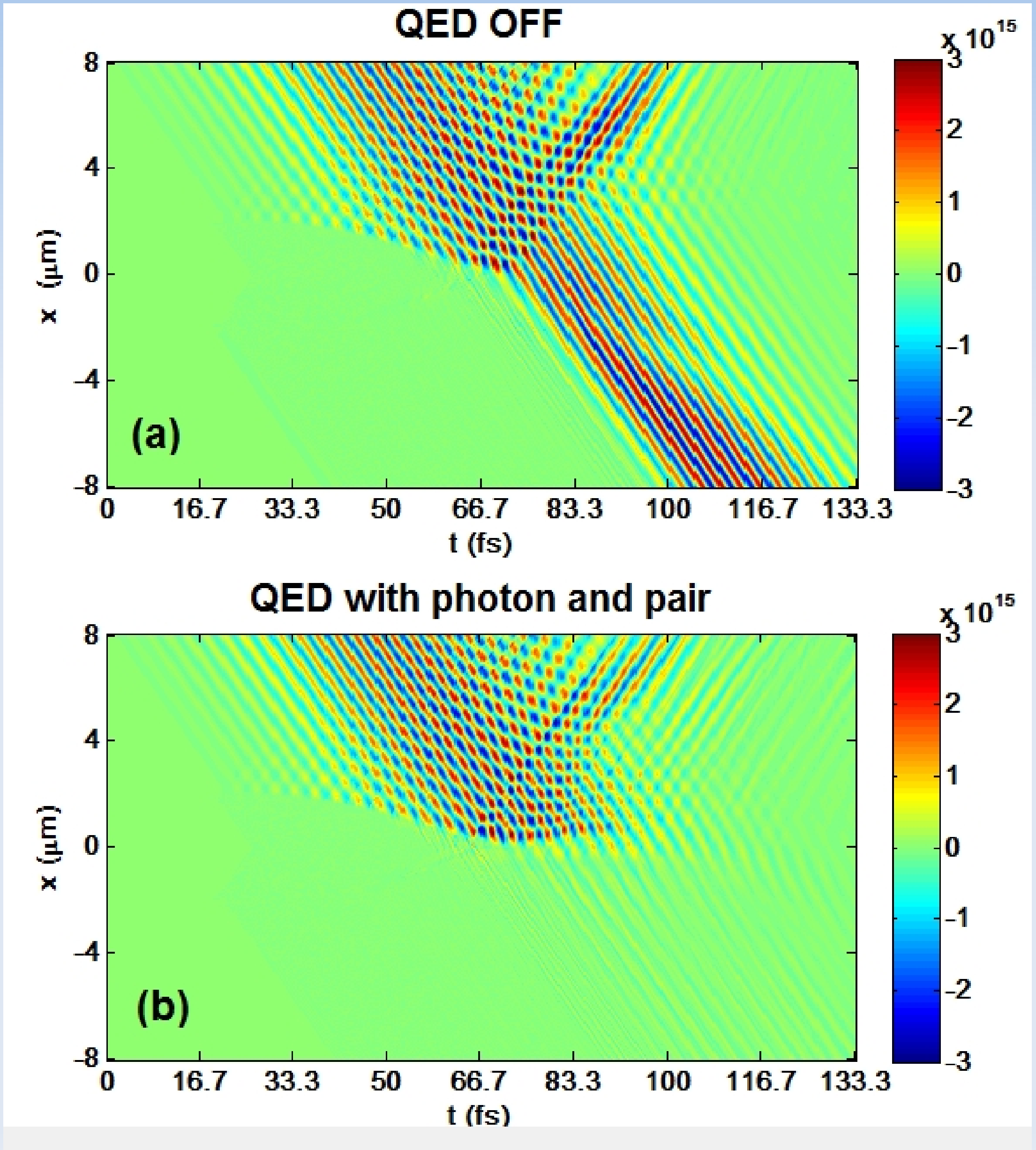


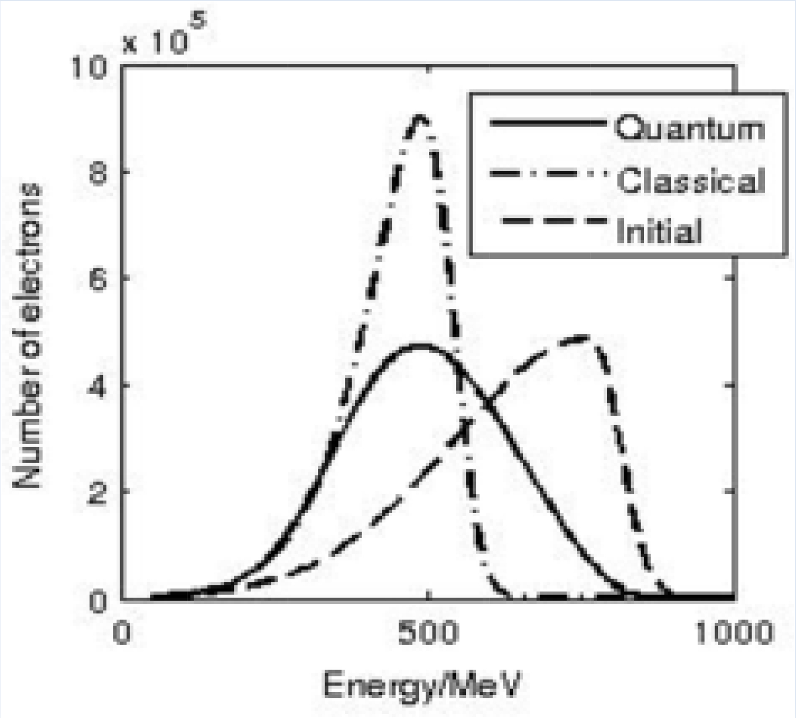
Example effect on relativistic transparency



P. Zhang *et al*, New J Phys, 17, 043051 (2015)

Example effect on relativistic transparency





P. Zhang *et al*, New J Phys, 17, 043051 (2015)

QED+plasma at ~10^{22}Wcm^{-2}

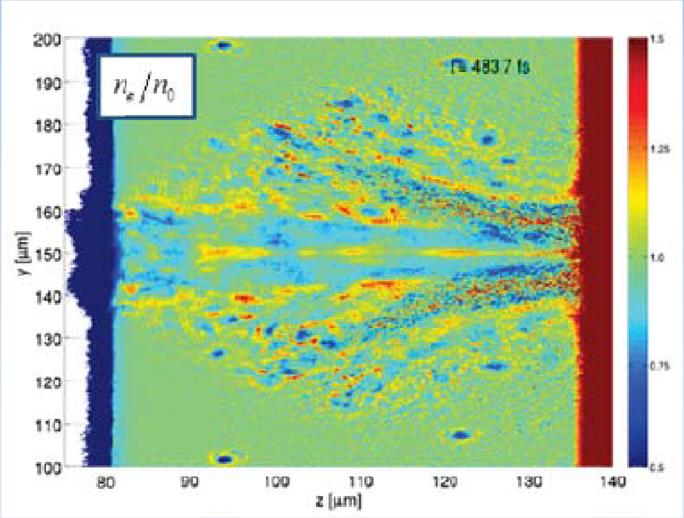
$$\eta \sim 0.1 \frac{I}{5\times 10^{22}\,Wcm^{-2}}$$

-

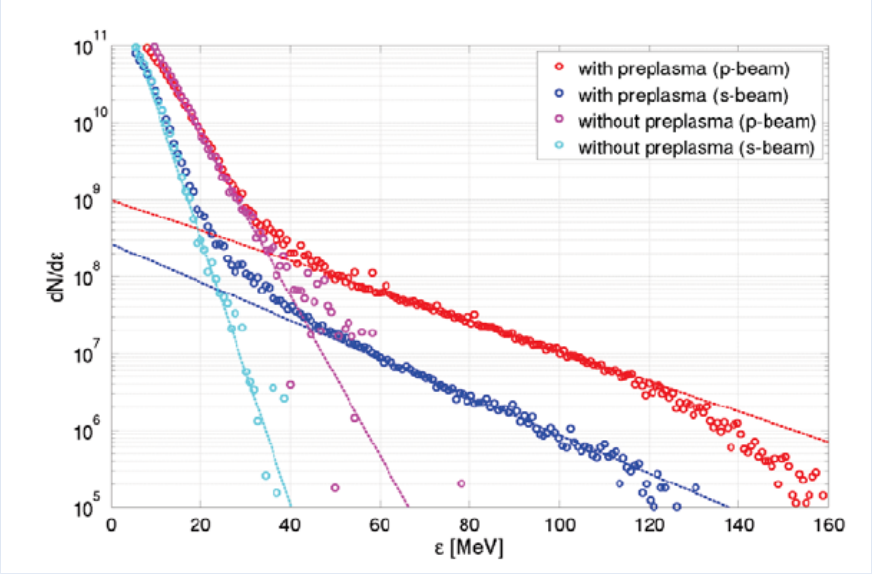
QED+plasma at $\sim 10^{22} Wcm^{-2}$

$$\eta \sim 0.1 \frac{I}{5\times 10^{22}\, Wcm^{-2}}$$

$$\eta \sim 0.1 \frac{\gamma}{1000} \sqrt{\frac{I}{10^{21}\, Wcm^{-2}}}$$



Plasma processes in extended pre-plasma accelerate electrons to γ>>a



A. Arefiev, AIP Conf Proc, 1507, 363 (2012)

Conclusions

1. QED processes will play a major role in plasmas created by next generation lasers

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2. By accelerating electrons to high energy these processes can be studied using today's PW lasers

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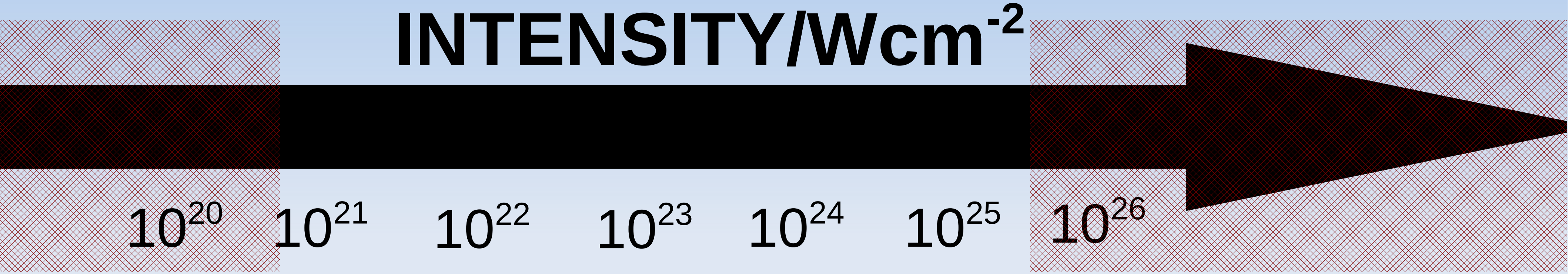
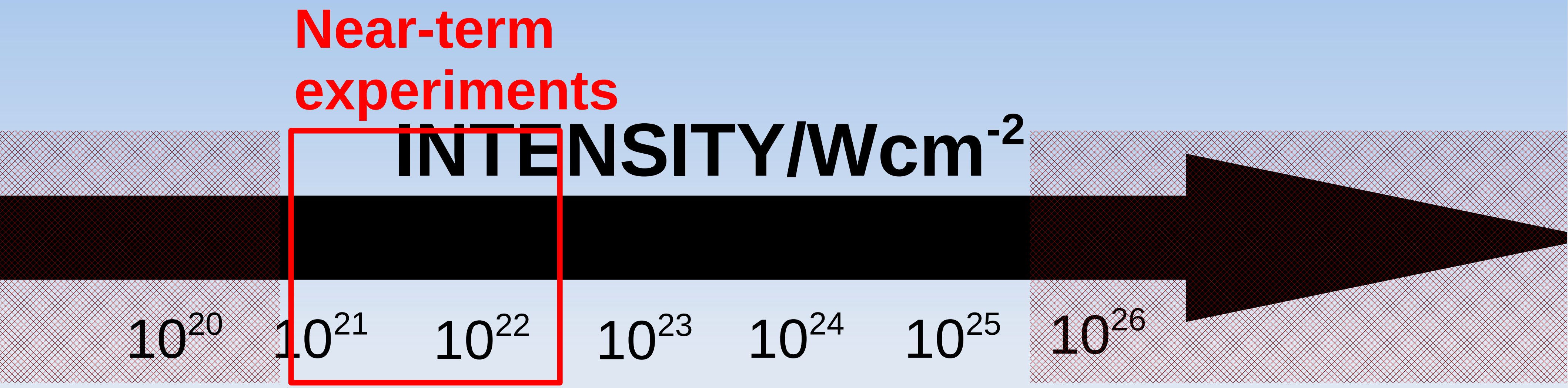
2. By accelerating electrons to high energy these processes can be studied using today's PW lasers

3. Plasma processes can potentially be used to study the interaction between QED and plasma processes with PW-class lasers

Outlook

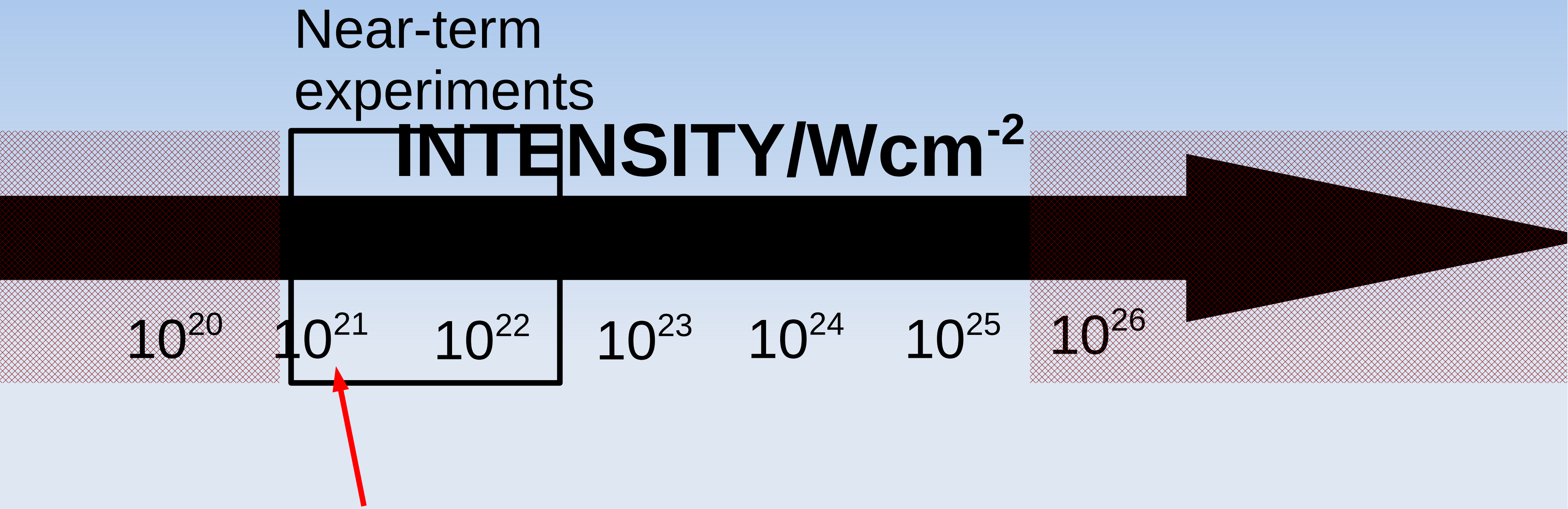


Outlook



Near-term experiments
INTENSITY/Wcm-2
10^20
10^21
10^22
10^23
10^24
10^25
10^26

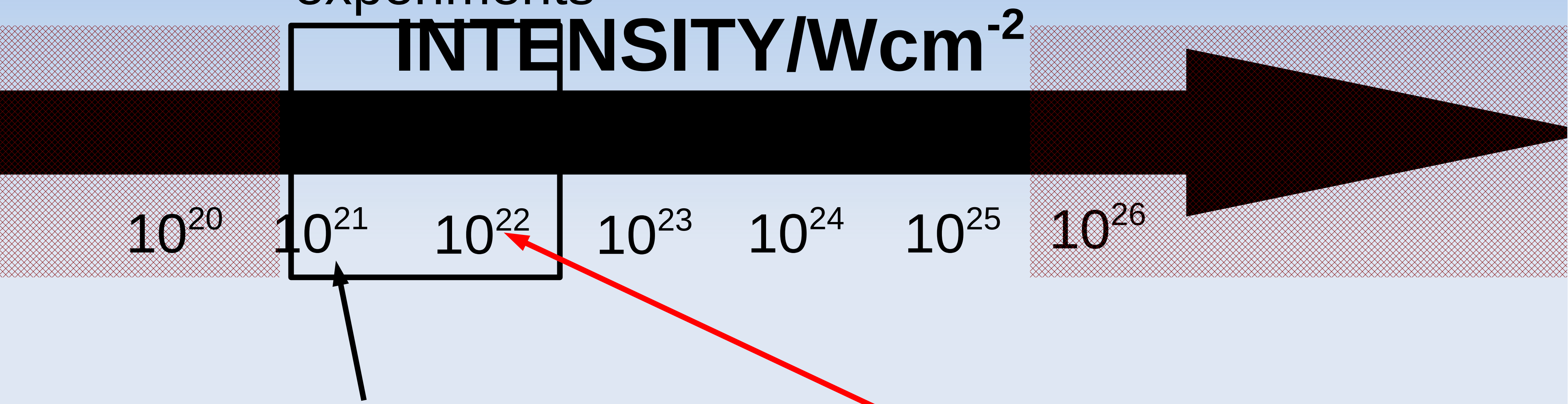
Outlook



1. Benchmark QED model → measure quantum effects on radiation reaction

Outlook

Near-term experiments



1. Benchmark QED model → measure quantum effects on radiation reaction

2. First hints of 'QED+plasma' regime