Extreme Plasma Physics

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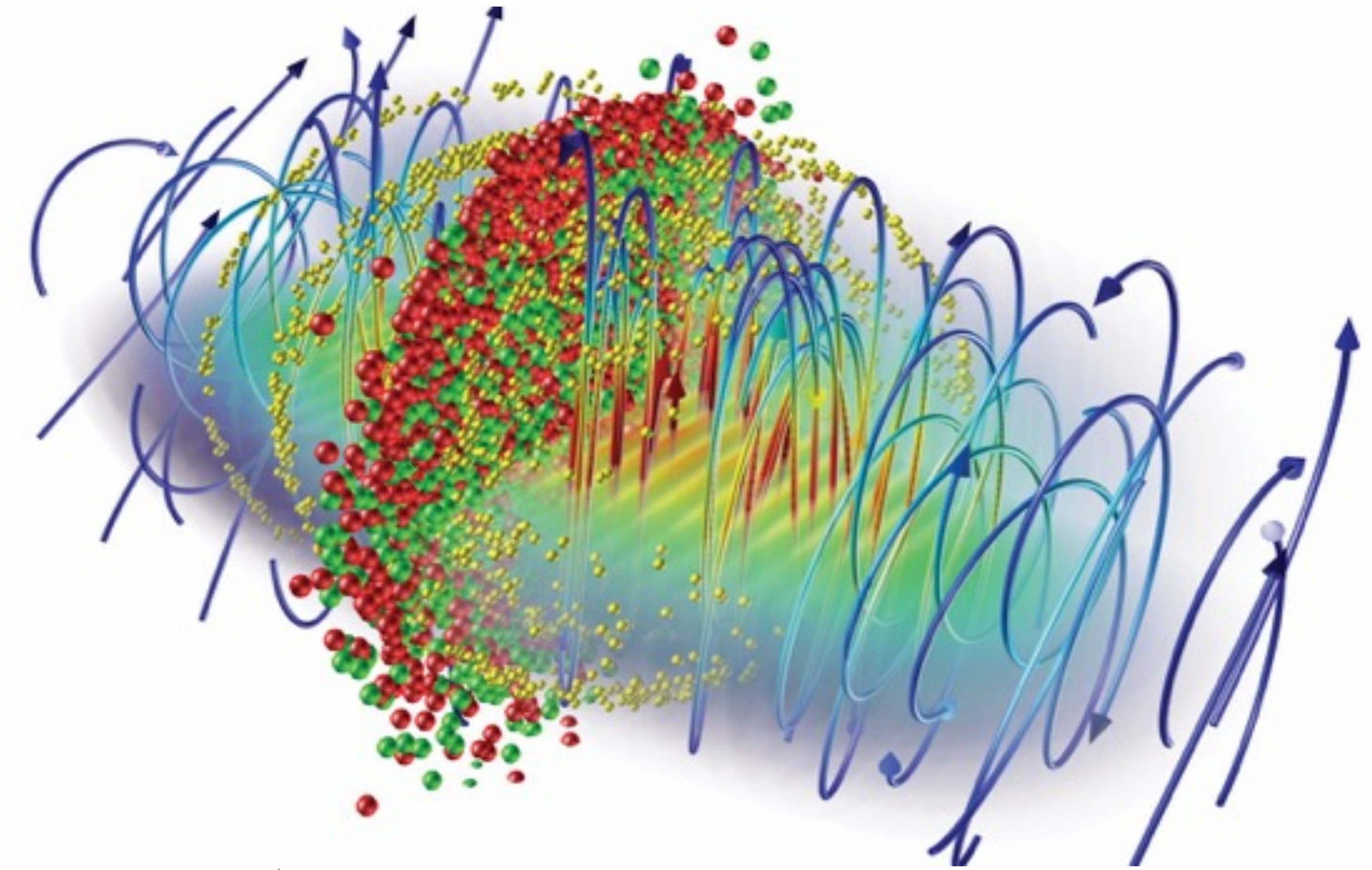

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Typical scales of CED and QED

	CED	QED
Energy scale	Electron rest energy	$\mathcal{E} = mc^2 = 0.5\ \mathrm{MeV}$
Momentum scale	$p = \mathcal{E}/c = 0.5\ \mathrm{MeV/c}$	
Length scale	Classical electron radius $r_0 = e^2/mc^2 = 2.8 \times 10^{-13}\mathrm{cm}$ (Thomson cross section)	Compton length $\lambda_C = \hbar/p = 3.9 \times 10^{-11}\mathrm{cm}$ (Heisenberg uncertainty principle)
Time scale	$r_0/c = 10^{-23}\ \mathrm{s}$	$\lambda_C/c = 1.3 \times 10^{-21}\ \mathrm{s}$
Field scale	Critical field CED $E_0 = \mathcal{E}/er_0 = 1.8 \times 10^{18}\mathrm{V/cm}$	Critical field QED $E_S = \mathcal{E}/e\lambda_C = 1.3 \times 10^{16}\mathrm{V/cm}$
Intensity scale	$I_0 = cE_0^2/4\pi = 8.6 \times 10^{33}\mathrm{W/cm^2}$	$I_S = cE_S^2/4\pi = 4.6 \times 10^{29}\mathrm{W/cm^2}$

Incoherent and coherent QED processes

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Incoherent QED processes

Pair production $\gamma\gamma \to e^+e^-$

$\gamma e \to ee^+e^-$

$ee \to eee^+e^-$

Photon production $ee \to ee\gamma$

$e\gamma \to e\gamma\gamma$

Annihilation $e^+e^- \to \gamma\gamma$

Comptonization $e\gamma \to e\gamma$

Cross section

$$\sigma \sim \alpha^n \sigma_T \times f(\mathcal{E})$$

Coherent QED processes

Non-linear Breit Wheeler, trident, non linear Compton

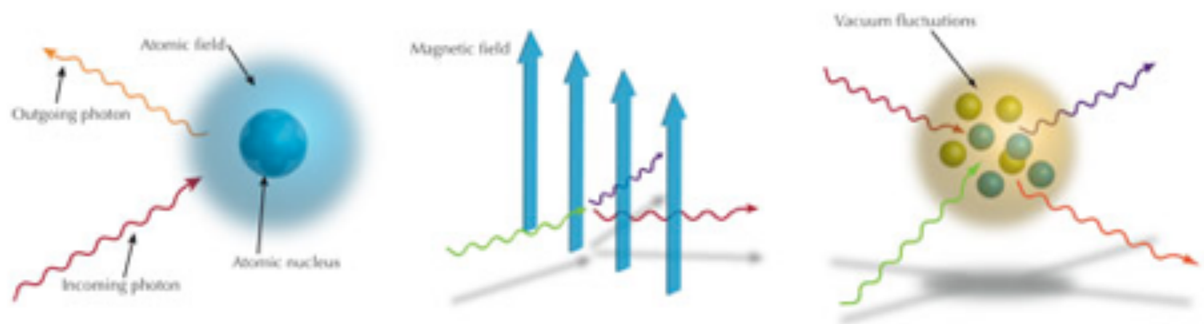
Schwinger mechanism, vacuum polarisation

Photon splitting

Probability rate

$$d\mathcal{P}/dt \sim (\alpha c/\lambda_C) f(E/E_S, \mathcal{E})$$

Orders of magnitude…



ELI

QED Photons interaction

Near-future facilities

- Pulse duration : 30-150 fs
- Focal width ~ µm
- Intensity ~10^{21} - 10^{25} W/cm^2
- Extreme acceleration regime

New facilities open possibilities to explore exotic physics.

Normalised vector potential a_0

- non relativistic
  $a_0 \ll 1$ $\quad I \ll 10^{18}$ W/cm^2
- weakly nonlinear, relativistic
  $a_0 \sim 1$ $\quad I \sim 10^{18}$ W/cm^2
- relativistic, nonlinear
  $a_0 \sim 10$ $\quad I \sim 10^{20}$ W/cm^2
- QED
  $a_0 \sim 1000$ $\quad I \sim 10^{24}$ W/cm^2

$$a_0 = \frac{eA}{mc^2}$$

$$a_0 \approx 0.8 \times 10^{-9} \sqrt{I \left[\frac{\mathrm{W}}{\mathrm{cm}^2}\right]} \, \lambda[\mu\mathrm{m}]$$

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Radiation Reaction in CED

Larmor's formula: instantaneous emitted power for non relativistic particle

$$P = \frac{2}{3}\frac{e^2}{c^3}a^2$$

Thomson scattering: dipole approximation

$$E = E_0 \sin \omega t$$

incident wave

$$\langle P \rangle = \frac{1}{3}\frac{e^4}{mc^3}E_0^2$$

averaged power

$$\langle S \rangle = c\frac{E_0^2}{8\pi}$$

averaged Poynting flux

$$\sigma_T = \frac{\langle P \rangle}{\langle S \rangle} = \frac{8\pi}{3}r_e^2$$

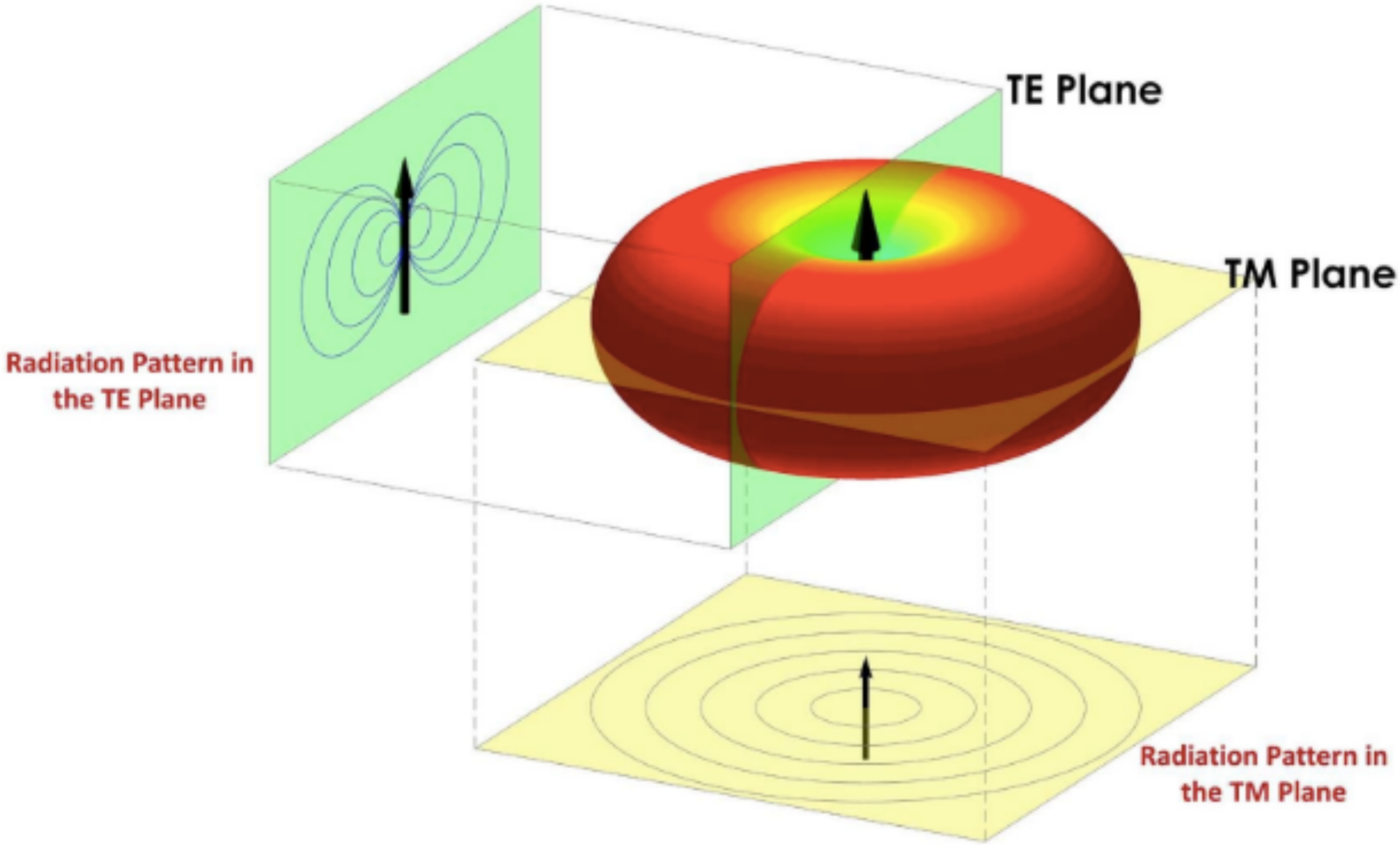
Radiation reaction: the force acting on a particle by virtue of the radiation it produces ?

$$\begin{aligned} \int F_{rad} \cdot v dt &= -\frac{2}{3}\frac{e^2}{c^3}\int a^2 dt \\ &= -\frac{2}{3}\frac{e^2}{c^3}\left([a \cdot u] - \int \dot{a} \cdot v dt\right) \end{aligned}$$

$$F_{rad} = \frac{2}{3}\frac{e^2}{c^3}\dot{a}$$

Radiation Reaction in CED

Dipole radiation pattern



Radiation reaction models

Different approaches of calculating the damping force

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L \boxed{+ \mathbf{F}_{rad}}$$

1	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} - \frac{2}{3}\frac{e^4\gamma}{m^3c^5}\mathbf{p}\left(\mathbf{E}_\perp + \frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2$	[Bell 2008]
2	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} + \frac{2e^3}{3mc^3}\left\{\gamma\left(\left(\frac{\partial}{\partial t}+\frac{\mathbf{p}}{\gamma m}\cdot\nabla\right)\mathbf{E} + \frac{\mathbf{p}}{\gamma mc}\times\left(\frac{\partial}{\partial t}+\frac{\mathbf{p}}{\gamma m}\cdot\nabla\right)\mathbf{B}\right) + \frac{e}{mc}\left(\mathbf{E}\times\mathbf{B} + \frac{1}{\gamma mc}\mathbf{B}\times(\mathbf{B}\times\mathbf{p}) + \frac{1}{\gamma mc}\mathbf{E}(\mathbf{p}\cdot\mathbf{E})\right) - \frac{e\gamma}{m^2c^2}\mathbf{p}\left(\left(\mathbf{E}+\frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2 - \frac{1}{\gamma^2m^2c^2}(\mathbf{E}\cdot\mathbf{p})^2\right)\right\}$	[Landau & Lifshitz 1951]
3	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} + \frac{2e^3}{3m^2c^4}\frac{\mathbf{F_L} - \frac{1}{\gamma^2m^2c^2}\mathbf{p}(\mathbf{p}\cdot\mathbf{F_L})}{1+\frac{2e^2}{3\gamma m^3c^5}(\mathbf{p}\cdot\mathbf{F_L})}\times\mathbf{B} - \frac{2\gamma e^2\mathbf{p}}{3m^3c^5}\left(\frac{\mathbf{F_L} - \frac{1}{\gamma^2m^2c^2}\mathbf{p}(\mathbf{p}\cdot\mathbf{F_L})}{1+\frac{2e^2}{3\gamma m^3c^5}(\mathbf{p}\cdot\mathbf{F_L})}\cdot\mathbf{F_L}\right)$	[Sokolov 2009]
4	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} - \frac{2}{3}\frac{e^4\gamma^5}{mc^3}\left(\left(\mathbf{E}+\frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2 - \frac{1}{\gamma^2m^2c^2}\lvert\mathbf{p}\cdot\mathbf{E}\rvert^2\right)\frac{\mathbf{p}}{p^2}$	[Hededal 2008]
5	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} + \frac{2}{3}\frac{e^2}{mc^3}\left\{\gamma\frac{d\mathbf{F_L}}{dt} - \frac{\gamma}{m^2c^2}\frac{d\mathbf{p}}{dt}\times(\mathbf{p}\times\mathbf{F_L}) + \frac{1}{\gamma m^4c^4}\left(\mathbf{p}\cdot\frac{d\mathbf{p}}{dt}\right)\left(\mathbf{p}\times(\mathbf{p}\times\mathbf{F_L})\right)\right\}$	[Ford 1993]
6	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} + \frac{2e^3}{3mc^3}\left\{\frac{e}{mc}\left(\mathbf{E}\times\mathbf{B} + \frac{1}{\gamma mc}\mathbf{B}\times(\mathbf{B}\times\mathbf{p}) + \frac{1}{\gamma mc}\mathbf{E}(\mathbf{p}\cdot\mathbf{E})\right) - \frac{e\gamma}{m^2c^2}\mathbf{p}\left(\left(\mathbf{E}+\frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2 - \frac{1}{\gamma^2m^2c^2}(\mathbf{E}\cdot\mathbf{p})^2\right)\right\}$	

Reduced L&L is best for PIC

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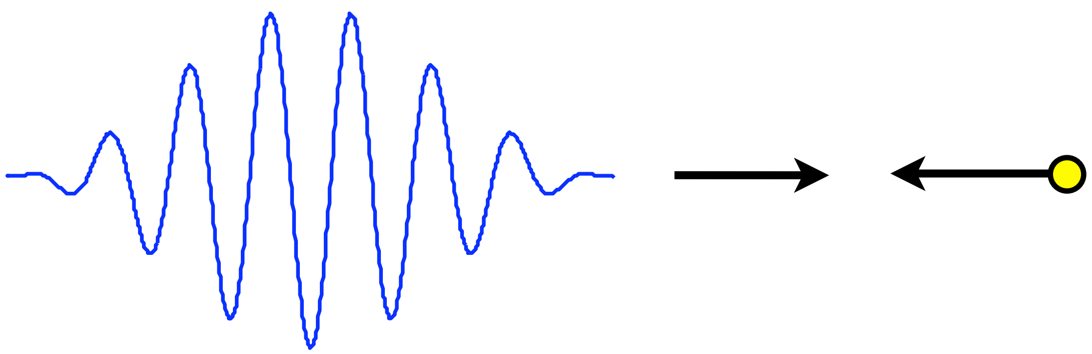
L&L captures physically relevant solutions of LAD equation



Without radiation reaction

$$\frac{d\mathbf{p}}{dt} = e\left(\mathbf{E} + \frac{\mathbf{p}}{\gamma mc} \times \mathbf{B}\right)$$

With radiation reaction

A

$$\frac{d\mathbf{p}}{dt} = e\left(\mathbf{E} + \frac{\mathbf{p}}{\gamma mc} \times \mathbf{B}\right) + \frac{2e^3}{3mc^3}\left\{\cancel{\boxed{\gamma\left(\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{\gamma m}\cdot\nabla\right)\mathbf{E} + \frac{\mathbf{p}}{\gamma mc} \times \left(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{\gamma m}\cdot\nabla\right)\mathbf{B}\right)}}\right.$$
$$\left. + \frac{e}{mc}\left(\mathbf{E}\times\mathbf{B} + \frac{1}{\gamma mc}\mathbf{B}\times(\mathbf{B}\times\mathbf{p}) + \frac{1}{\gamma mc}\mathbf{E}(\mathbf{p}\cdot\mathbf{E})\right) - \boxed{\frac{e\gamma}{m^2c^2}\mathbf{p}\left(\left(\mathbf{E} + \frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2 - \frac{1}{\gamma^2m^2c^2}(\mathbf{E}\cdot\mathbf{p})^2\right)}\right\}$$

B

L&L reduced

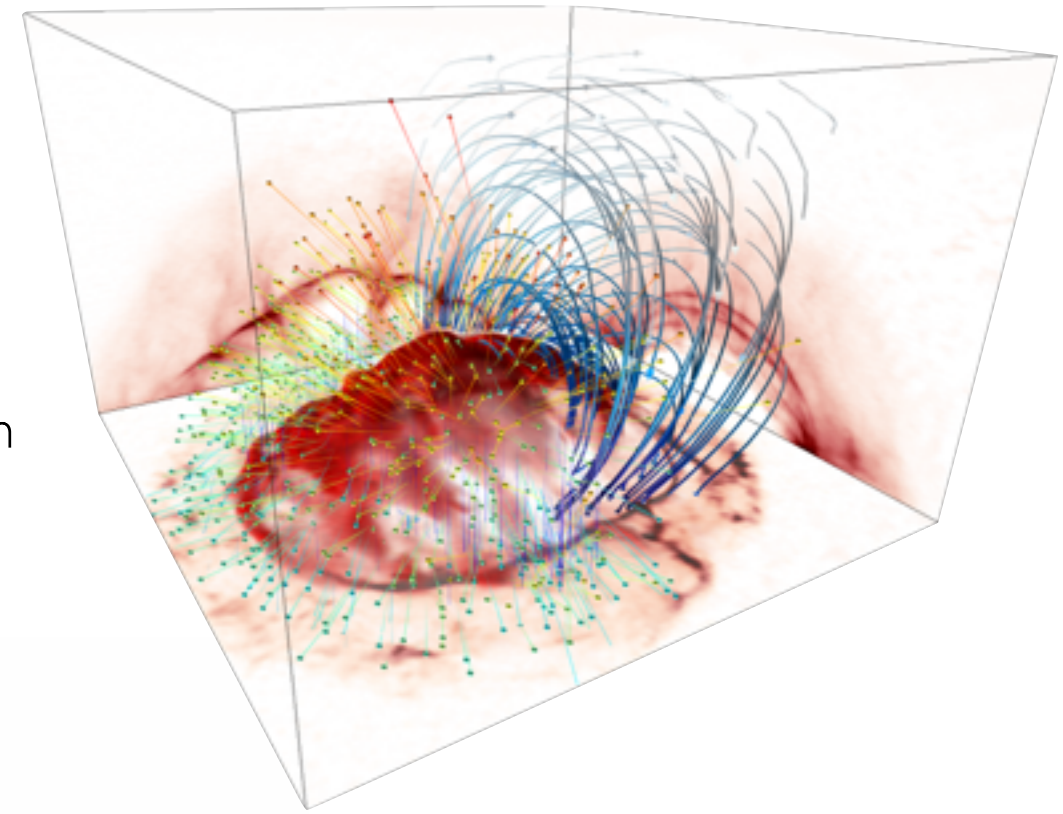
$$\frac{\mathrm{A}}{\mathrm{B}} \sim \frac{1}{2\pi\gamma a_0}$$

OSIRIS 4.0

Osiris

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  $\Rightarrow$ UCLA + IST



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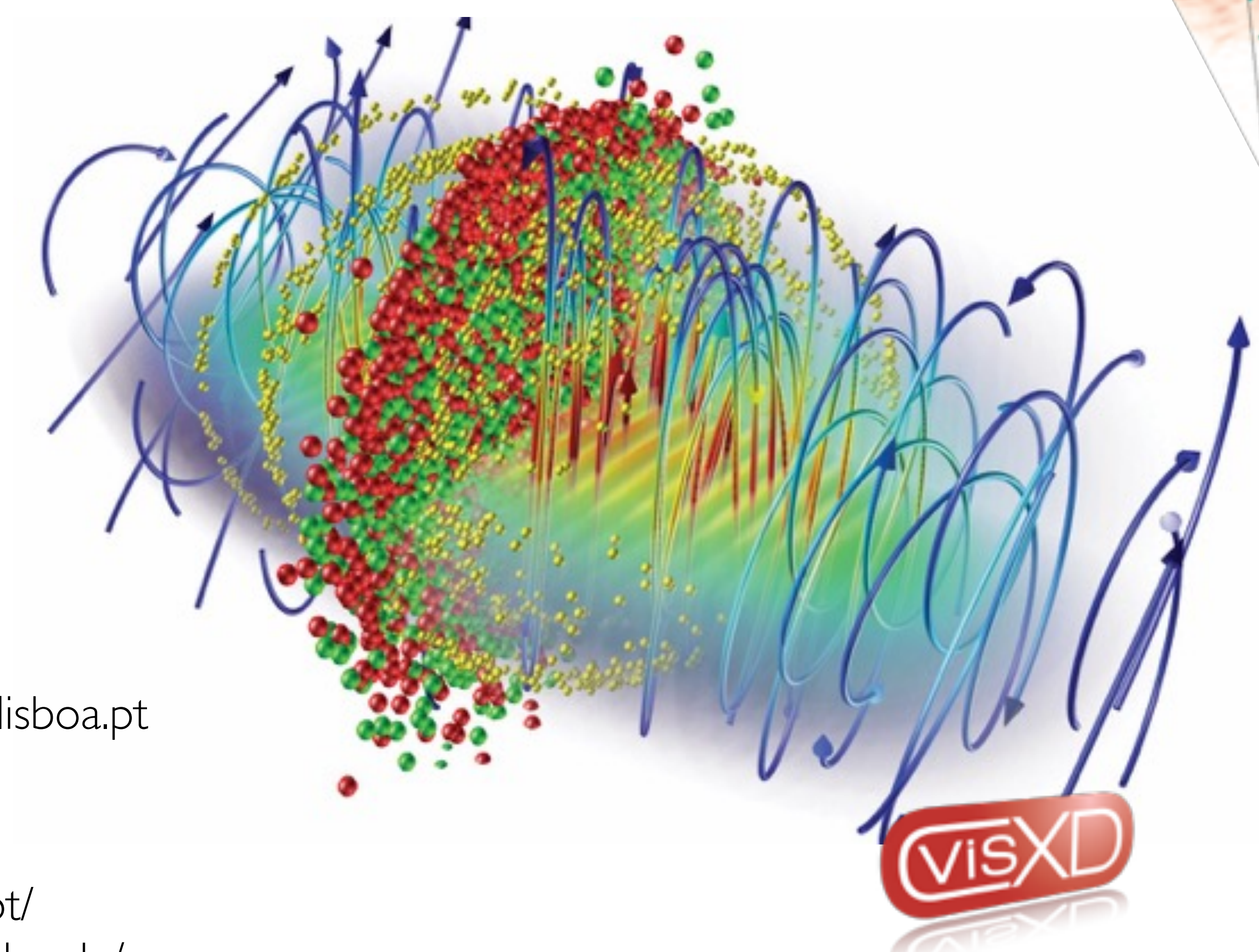
UCLA



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- **Classical radiation reaction**
- **Particle merging**
- GPGPU support
- Xeon Phi support
- **QED Module**

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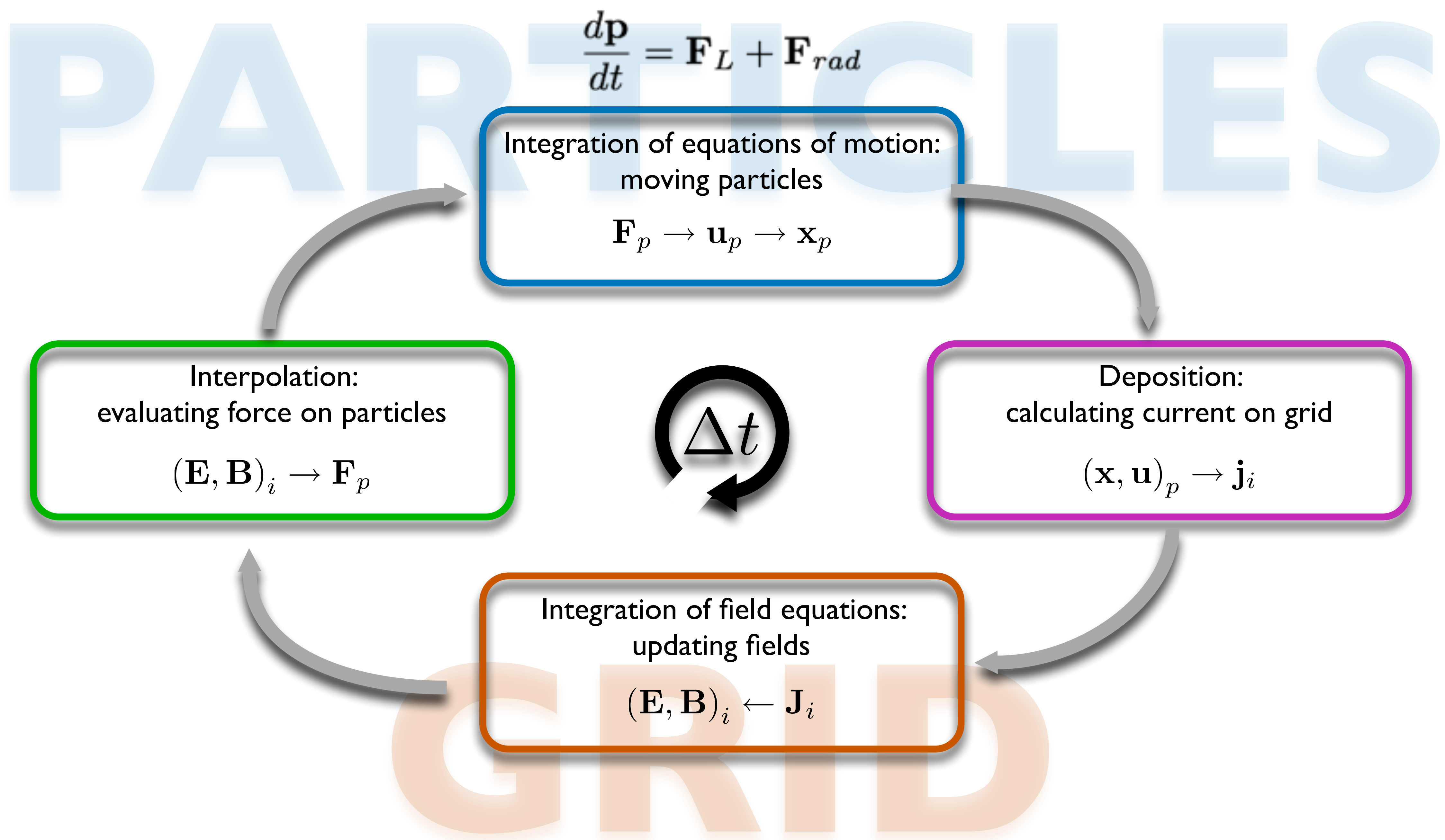
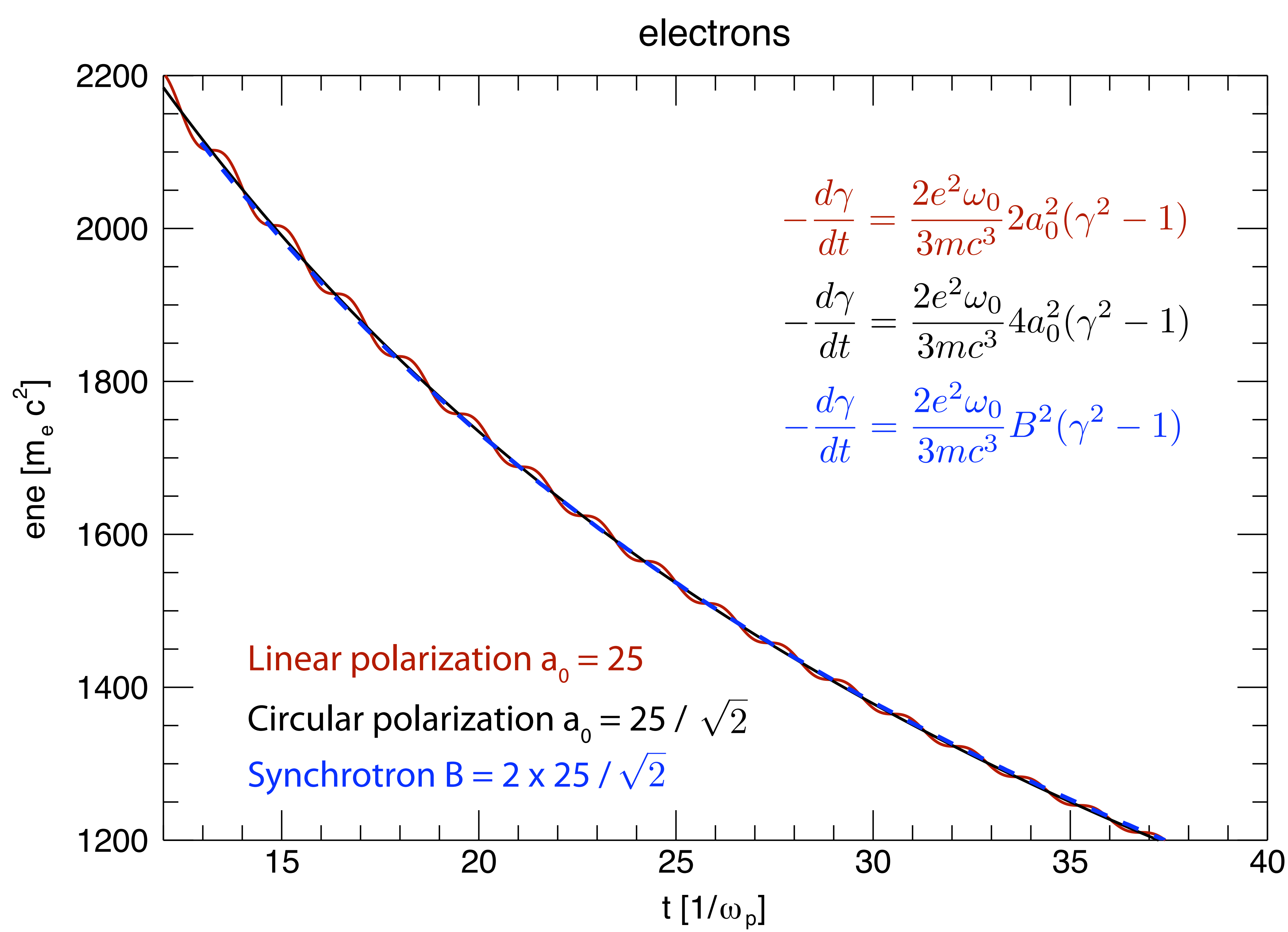
PIC loop with classical radiation reaction

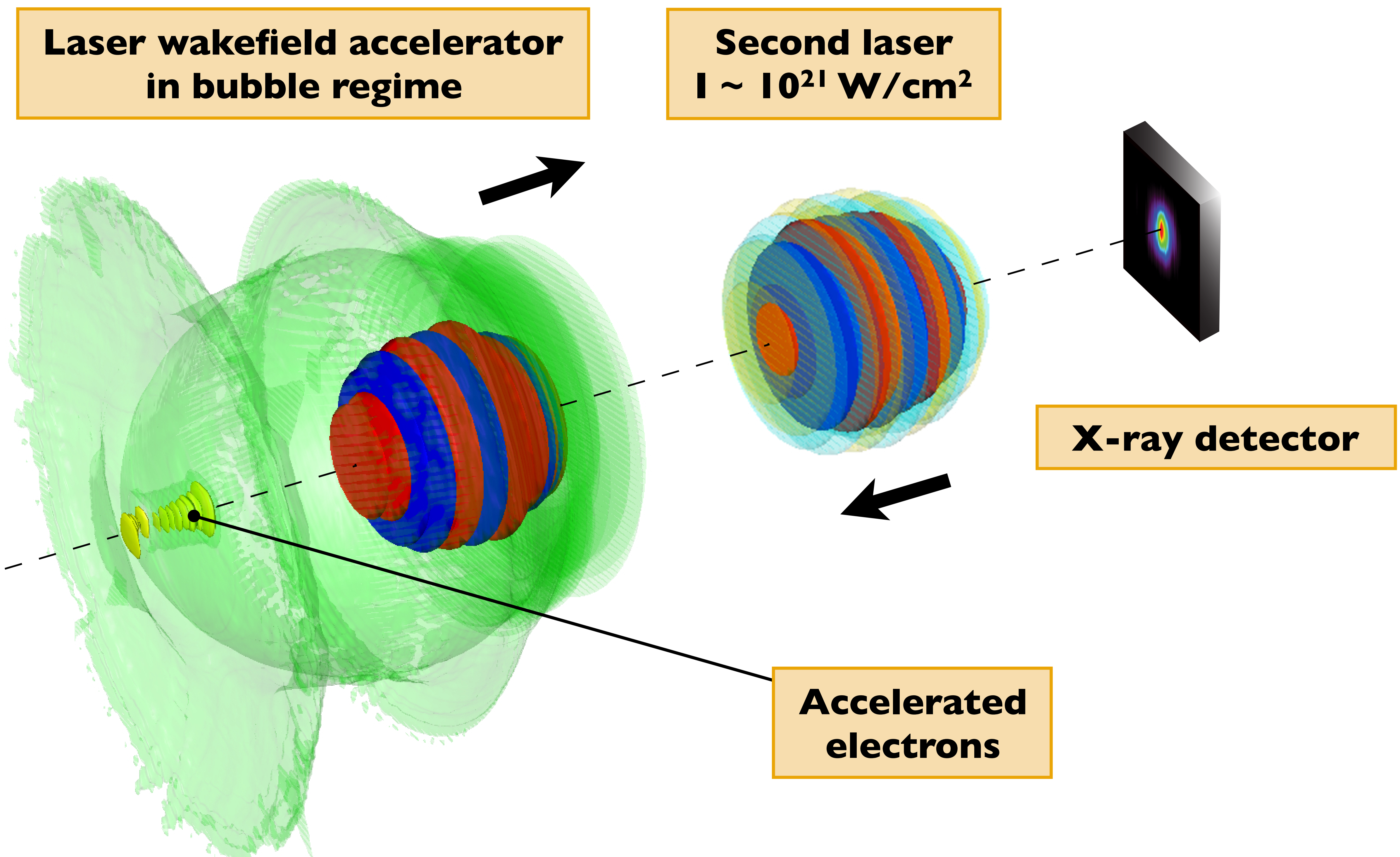


Energy loss in simple setup



Full-scale 3D classical radiation reaction

~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm^2



M. Vranic et al., PRL 113, 134801 (2014)

Classical RR shrinks beam energy spectrum*

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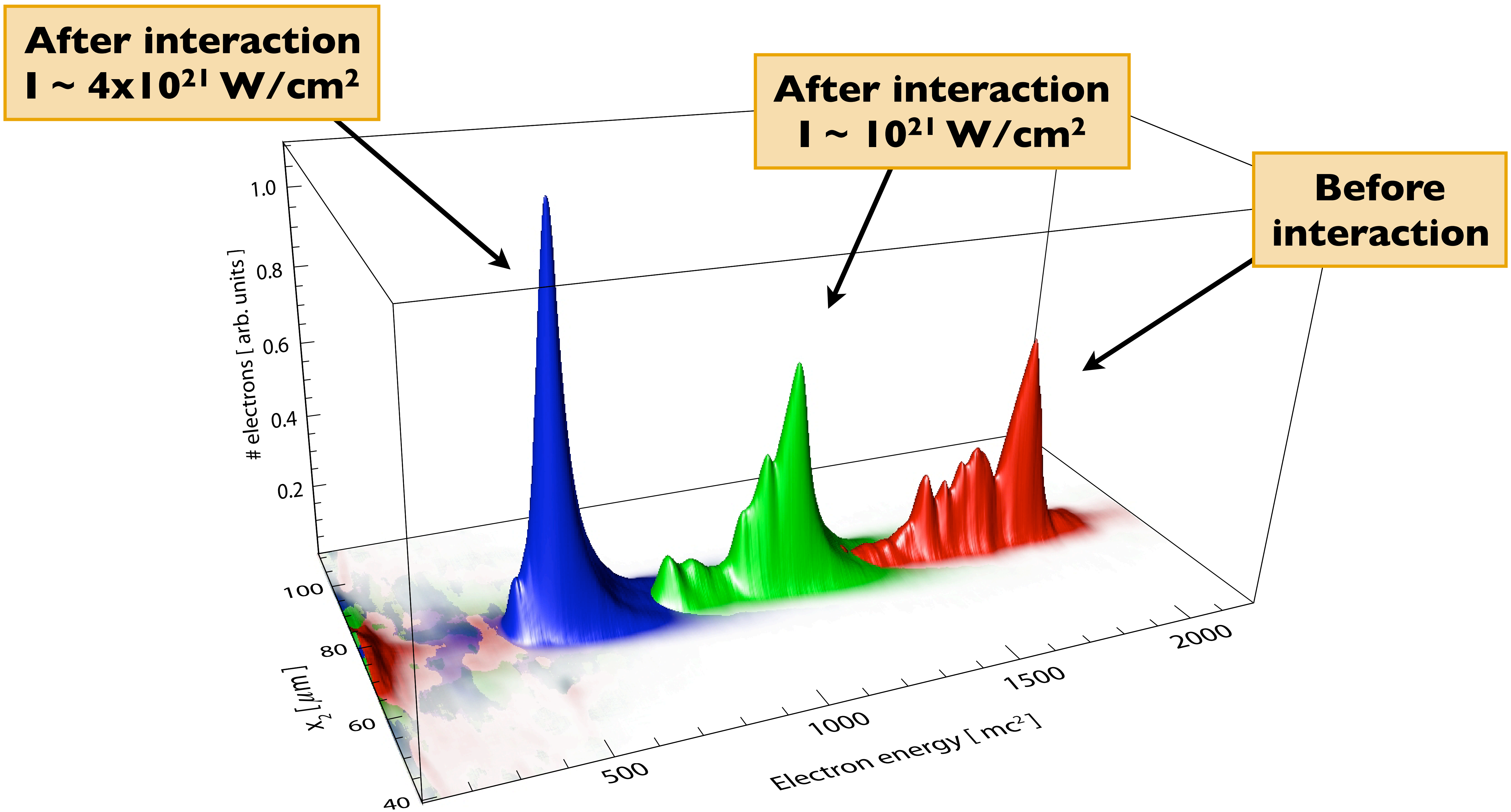
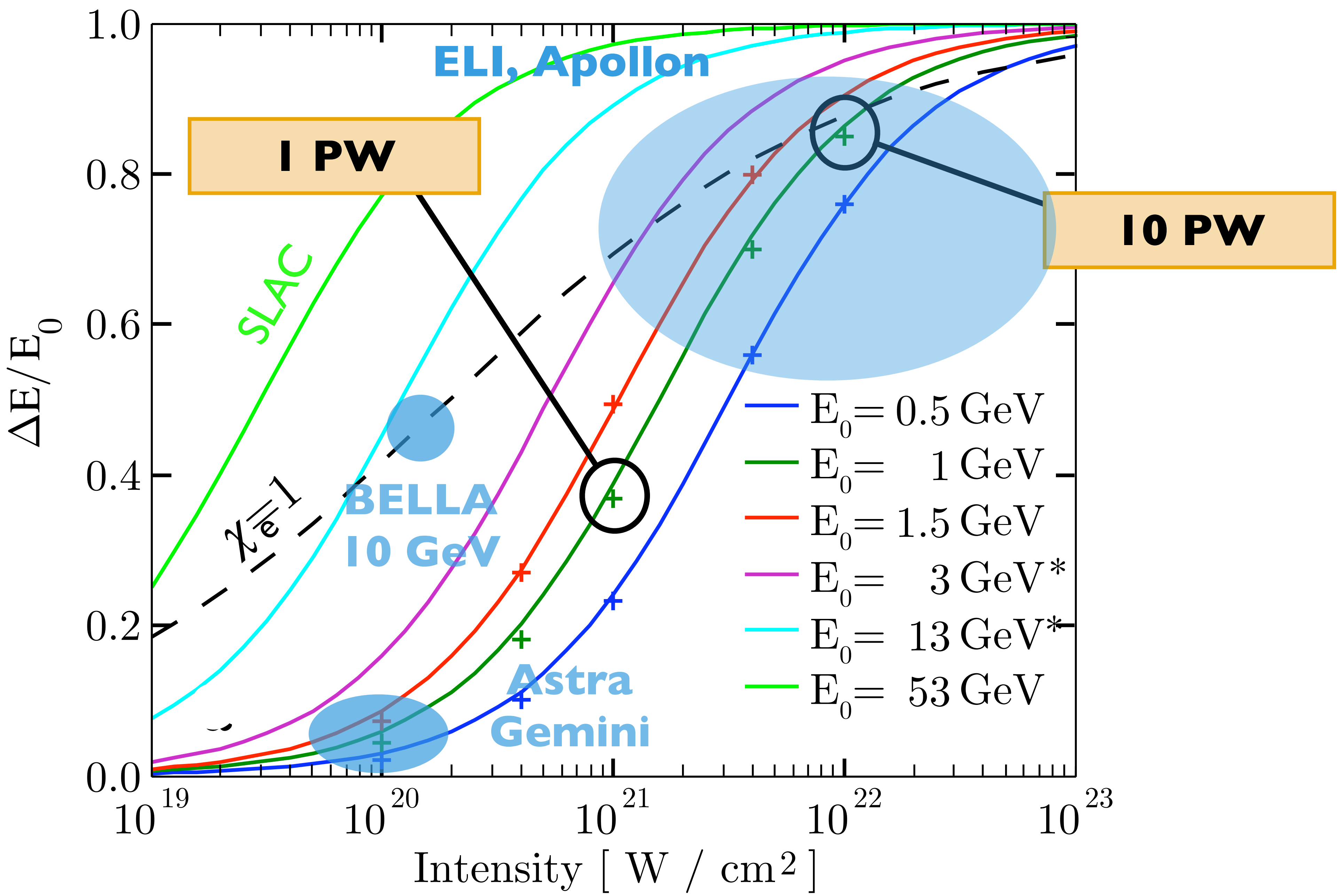
In quantum interaction we expect energy spread and divergence to grow**



* M. Vranic et al., PRL (2014), S. Yoffe et al., NJP (2015), E. Esarey NIMPR (2000), M. Tamburini NIMPR (2010)

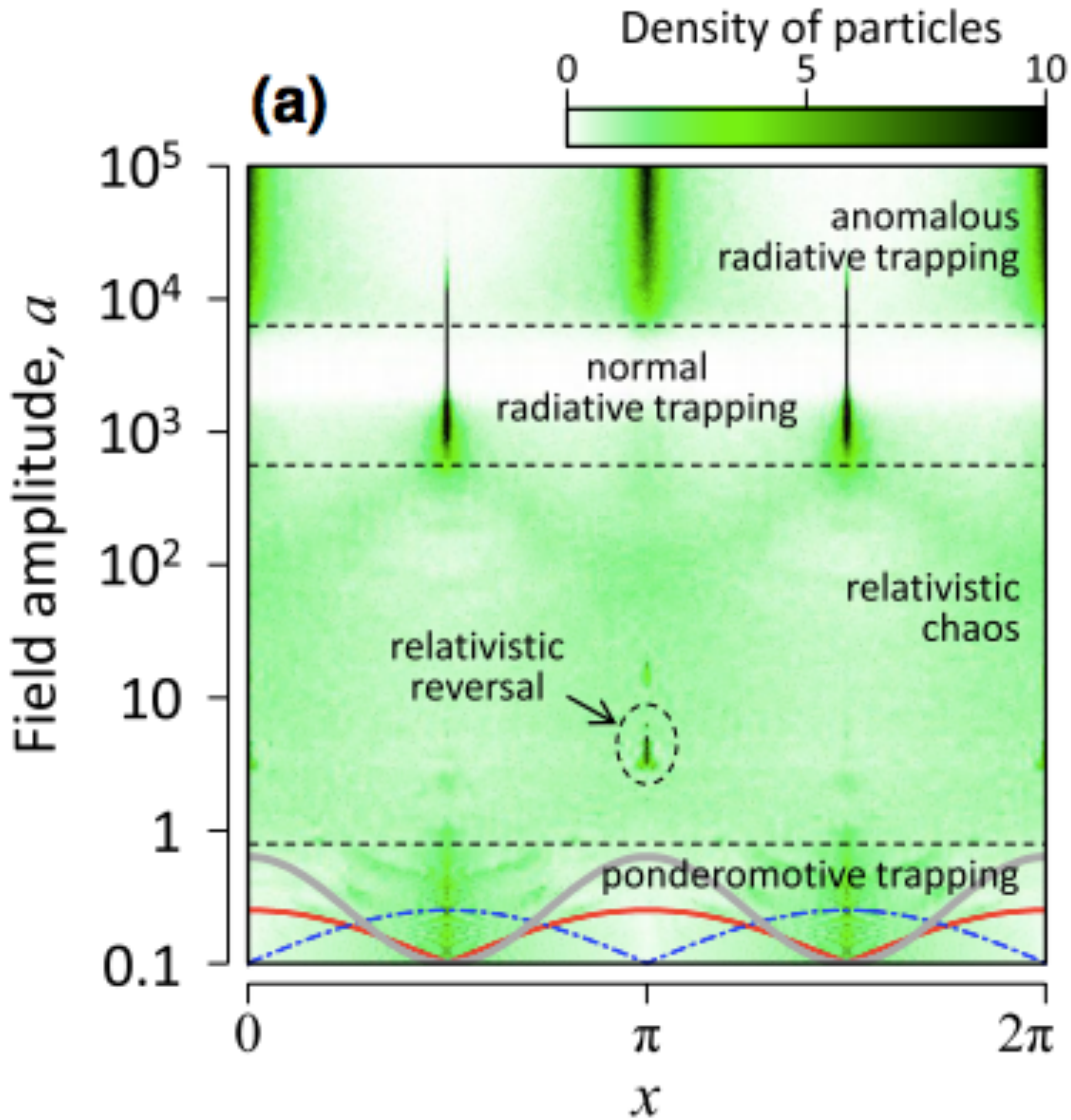
** T. G. Blackburn et al, PRL (2014) D. G. Green et al, PRL (2014), N. Neitz et al, PRL 111, 054802 (2013)

Energy loss versus intensity



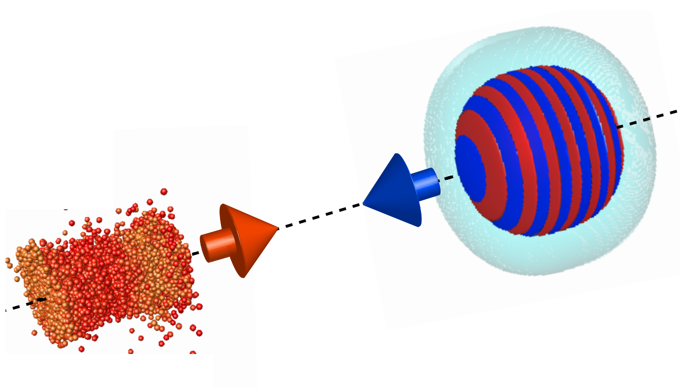
M. Vranic et al., PRL 113, 1348001(2014)

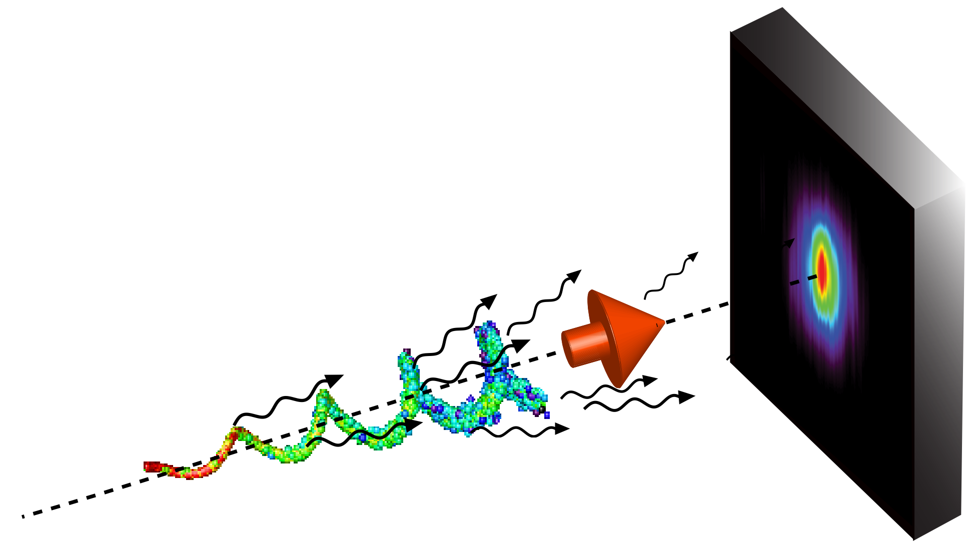
Anomalous radiative trapping



A. Gonoskov et al., PRL 113, 014801(2014)

QED radiation reaction





QED parameters

$$E_s = \frac{m^2 c^3}{e\hbar} \qquad \chi = \frac{\sqrt{(p_\mu F^{\mu\nu})^2}}{E_s\, mc}$$

$$\chi_\gamma = \frac{\sqrt{(k_\mu F^{\mu\nu})^2}}{E_s\, mc}$$

Classical: $\chi \ll 1$

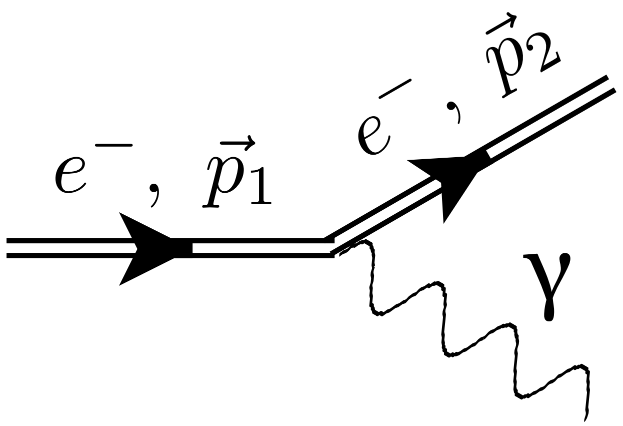
QED: $\chi \simeq 1$

Quantum recoil

Photon emission has a probabilistic character.

Radiation reaction is discrete.

Energy spread and divergence are expected to grow*.



* T. G. Blackburn et al, PRL (2014) D. G. Green et al, PRL (2014), N. Neitz et al, PRL 111, 054802 (2013)

Implementation of QED effects

Radiation Reaction

Different types of Radiation reaction models

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \begin{cases} \mathbf{F}_{rad} & \text{Continuous damping rate*} \\ \dfrac{d^2P}{dt\,d\chi_\gamma} & \text{QED probabilistic approach**} \end{cases}$$

Implementation in PIC codes

- Continuous damping rate: particle pusher with $\mathbf{F}_{rad}$ $\quad \gamma < 10$

- QED probabilistic approach: particle pusher + Monte Carlo module
  - every Δt : probability of photon emission
  - Select a photon in QED synchrotron spectrum
  - Update particle momentum due to quantum recoil

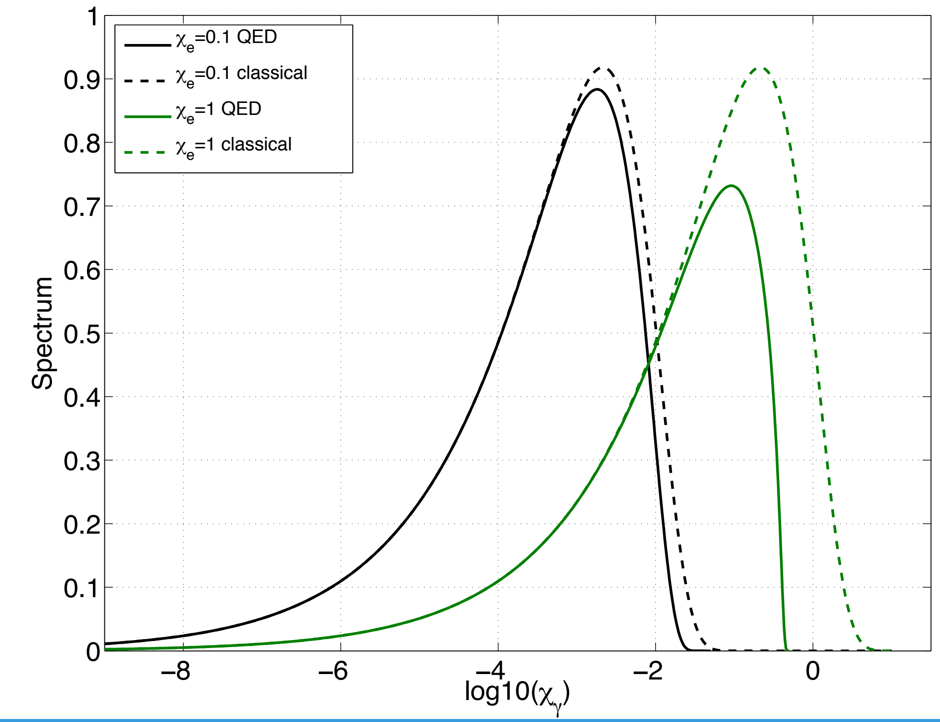
- The QED approach can be generalized to any external EM fields under the conditions: $t_{carac}(\vec{E},\vec{B}) \gg t_{coh} \implies a_0 \gg 1$
  - quasi-static fields
  - weak fields $\quad \chi_e^2 \gg \mathrm{Max}(f,g) \quad (f,g) \ll 1$

$f = F_{\mu\nu}^2/E_{crit}^2 \qquad g = F^*_{\mu\nu}F_{\mu\nu}/E_{crit}^2 \qquad E_{crit} = m^2c^3/e\hbar \qquad \chi_{e,\gamma} = \dfrac{|F_{\mu\nu}p^\nu_{e,\gamma}|}{E_{crit}mc}$

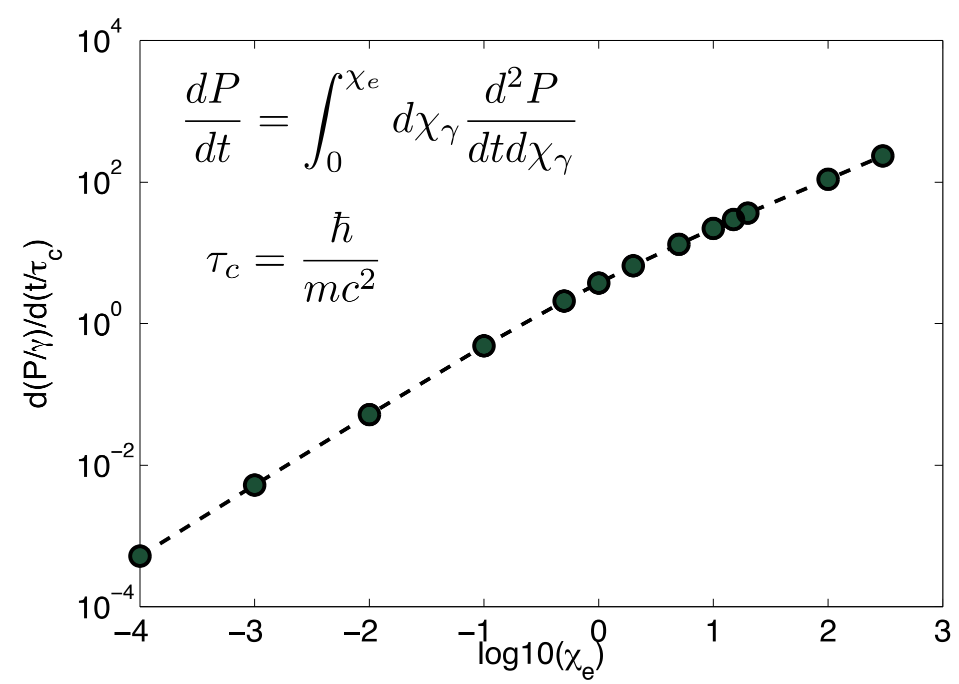
* Landau & Lifshitz (Theory of Fields)

** A.I. Nikishov & V.I. Ritus (1967), N.P. Kelpikov (1954), V.N. Baier & V.M. Katkov (1967)

Synchrotron Spectrum

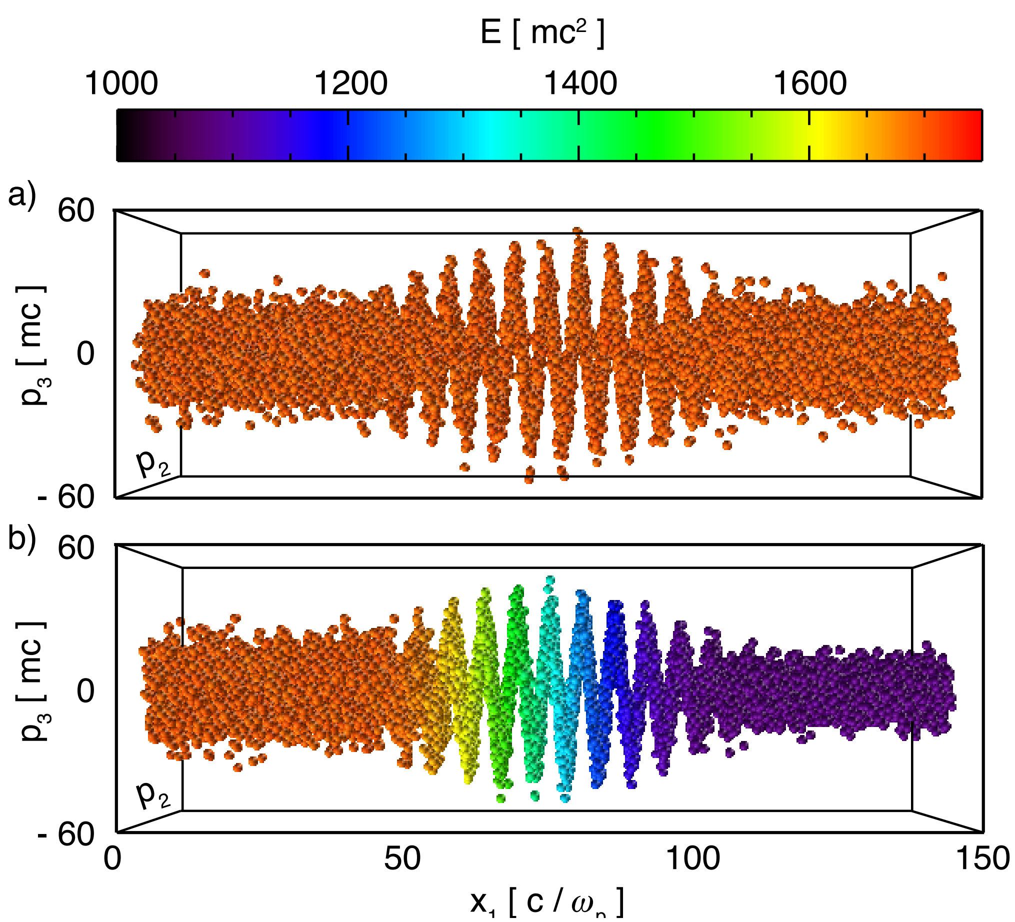


Emission rate



Quantum effects are strongest for the case of counter-propagation

But, the interaction at 90 degrees has only a factor of two lower electron chi



$$\chi = \frac{\sqrt{(p_\mu F^{\mu\nu})^2}}{E_s\, mc}$$

$$\chi_e = \frac{1}{E_s}\sqrt{\left(\gamma\vec{E} + \frac{\vec{p}}{mc}\times\vec{B}\right)^2 - \left(\frac{\vec{p}}{mc}\cdot\vec{E}\right)^2}$$

$$a_0 = 0.8\sqrt{I[10^{18}\ \mathrm{W/cm^2}]}\lambda[\mu\mathrm{m}]$$

Counter-propagation

$$\chi \approx 2\ \gamma_0 a_0 \times 2\times 10^{-6}$$

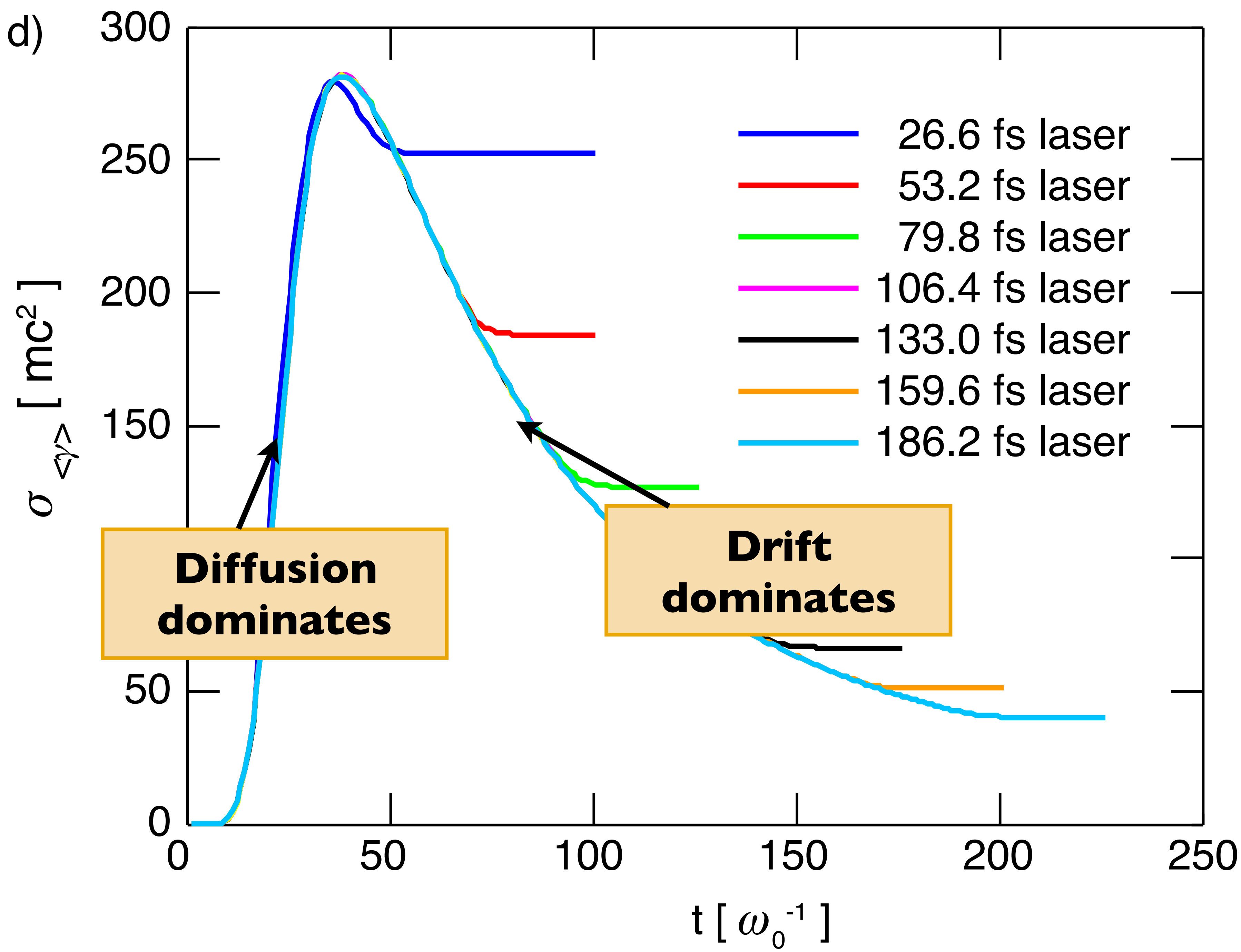
Co-propagation

$$\chi \approx \frac{a_0}{2\gamma_0} \times 2\times 10^{-6}$$

Interaction at 90 deg.

$$\chi \approx \gamma_0 a_0 \times 2\times 10^{-6}$$

Energy spread increases due to stochasticity



M. Vranic et al, NJP 18, 073035 (2016)

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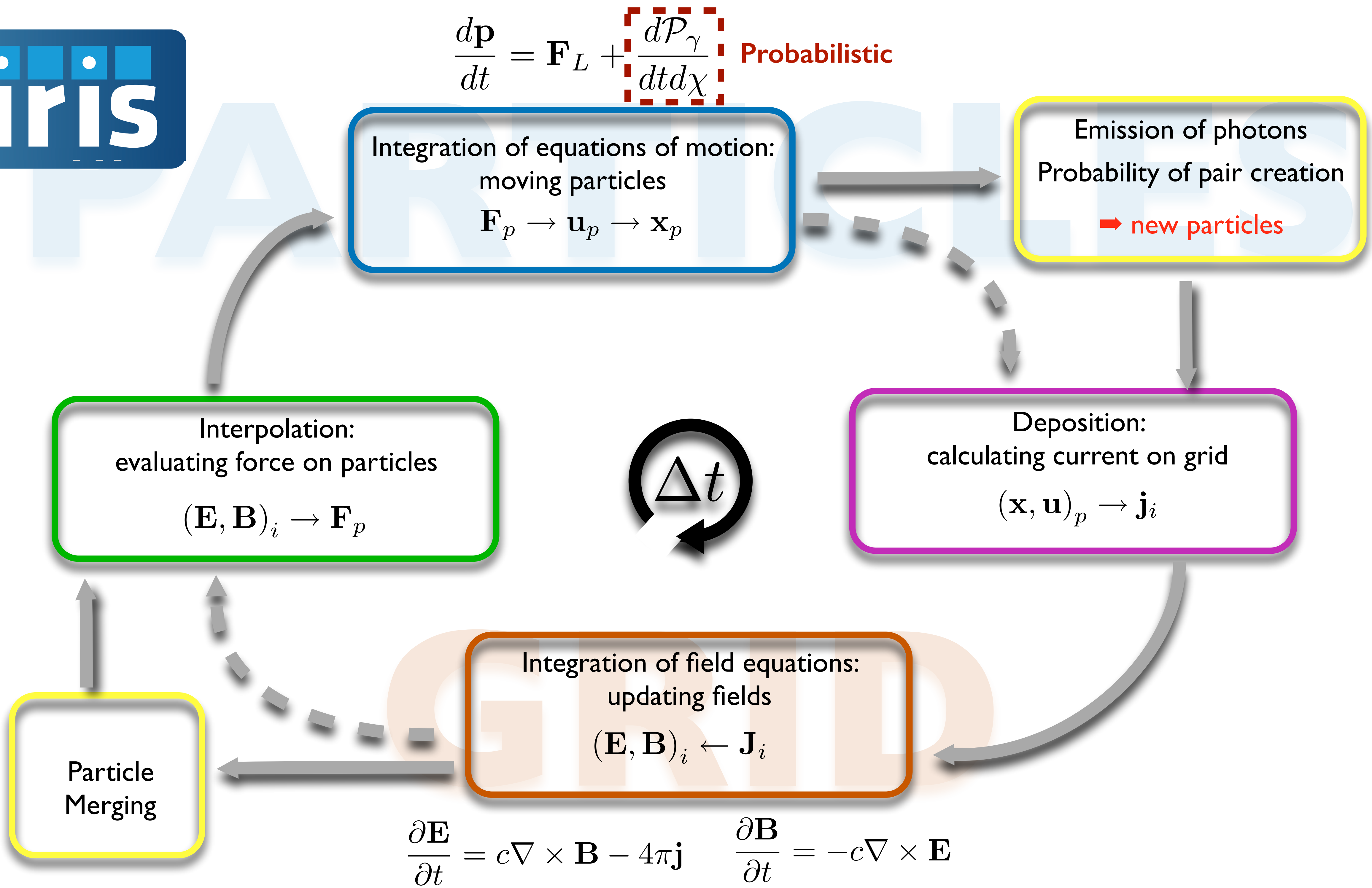
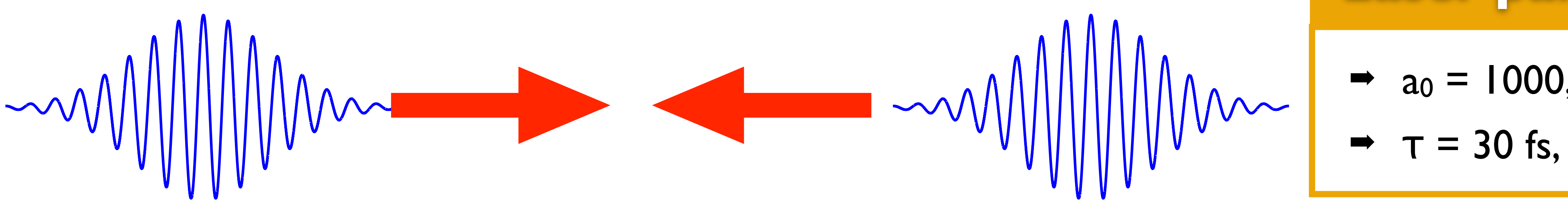
QED-PIC loop in OSIRIS



E.N Nerush et al. PRL (2011), C. P. Ridgers et al. , PRL. (2012)
N.V. Elkina et al. PRSTAB (2011), A. Gonoskov et al., PRE (2015)
T. Grismayer et al., POP (2016), F. Niel et al., PRE (2018)

Standing wave configurations for QED cascades

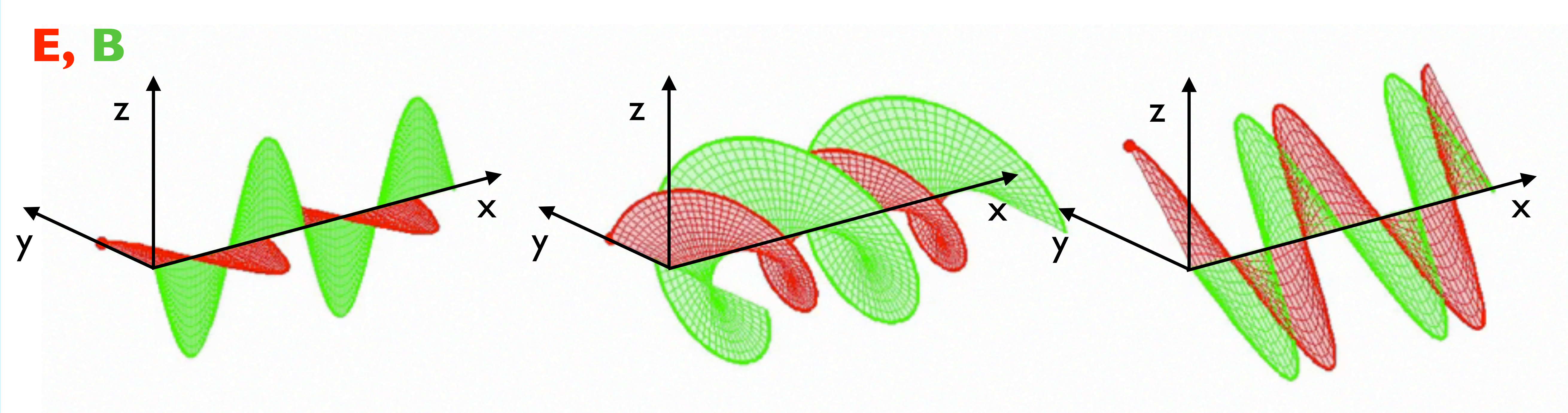
Laser 1 **Laser 2**



Laser parameters

- ➡ a_0 = 1000, λ = 1 um,
- ➡ τ = 30 fs, W_0 = 3.2 um

Linear	Double clockwise	Clockwise-anti clockwise



3D OSIRIS QED - colliding laser cascades at $\chi \gg 1$

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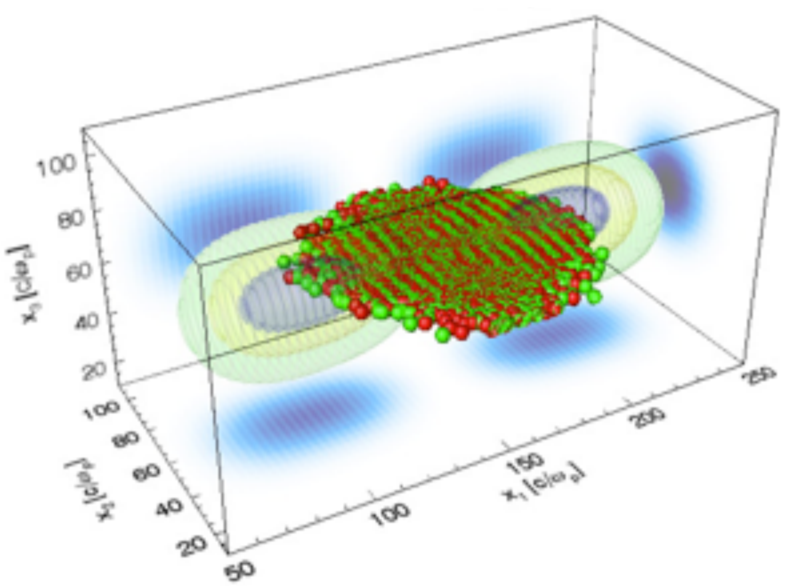
Linear

Laser parameters

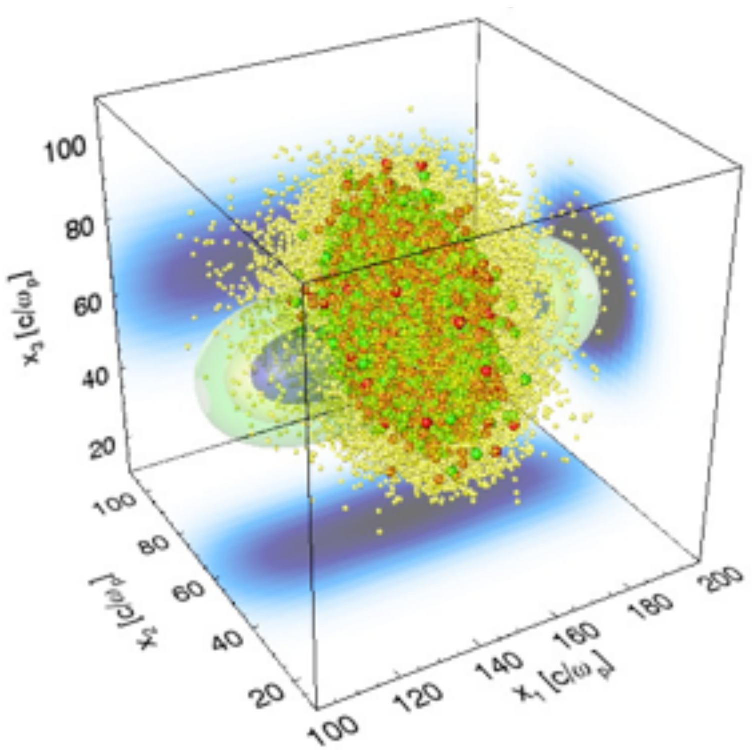
- ➡ a_0 = 1000, λ = 1 um,
- ➡ τ = 30 fs, W_0 = 3.2 um



Particles remain in the x-y plane

Double clockwise

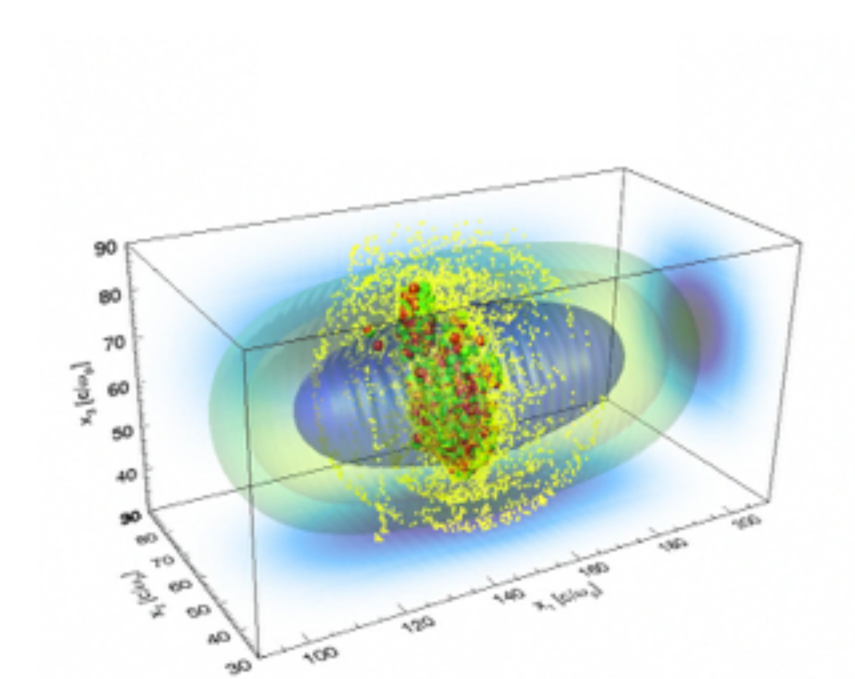
- electron
- positron
- photon



Particles explore the whole space

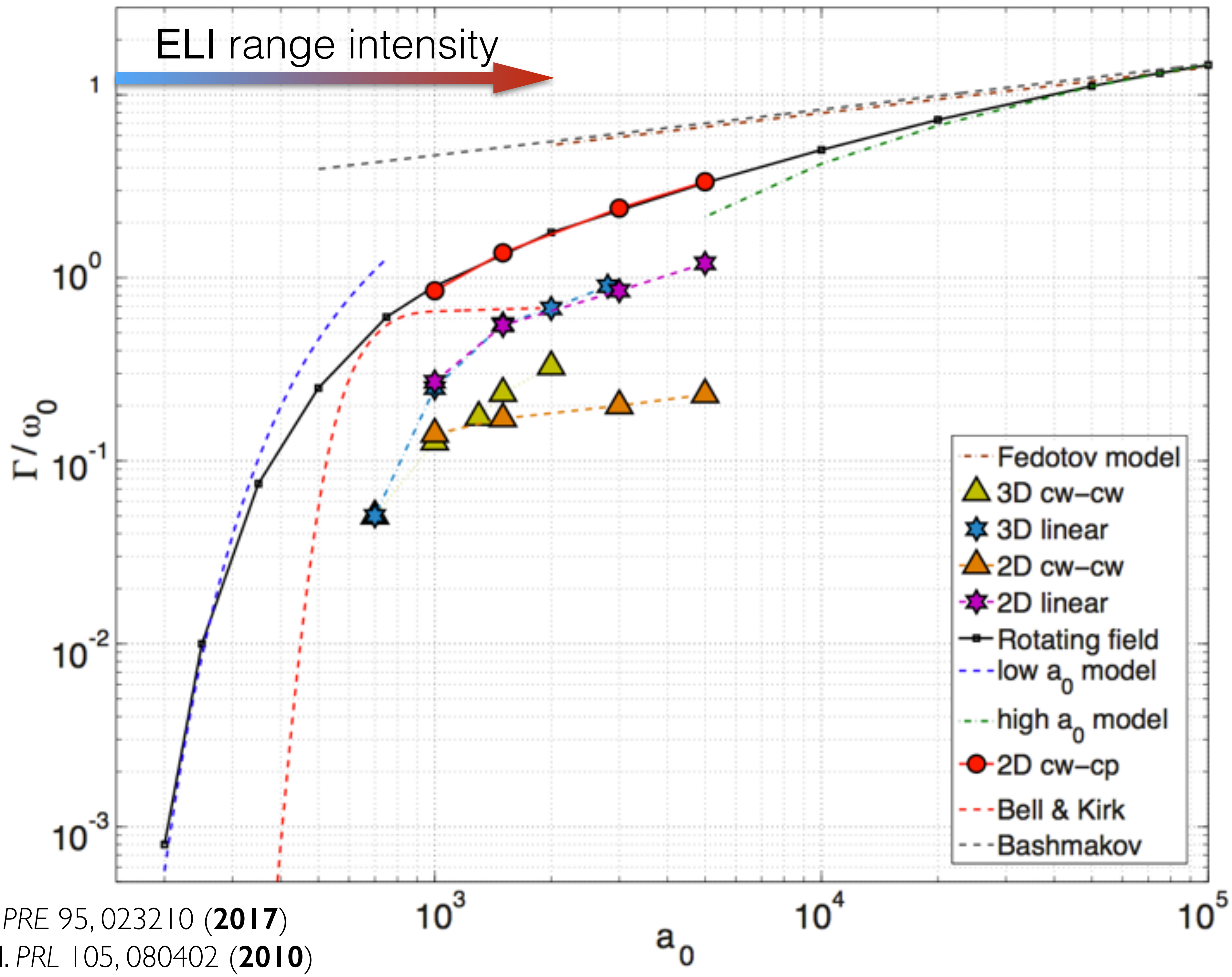
Clockwise-anti clockwise

- electron
- positron
- photon



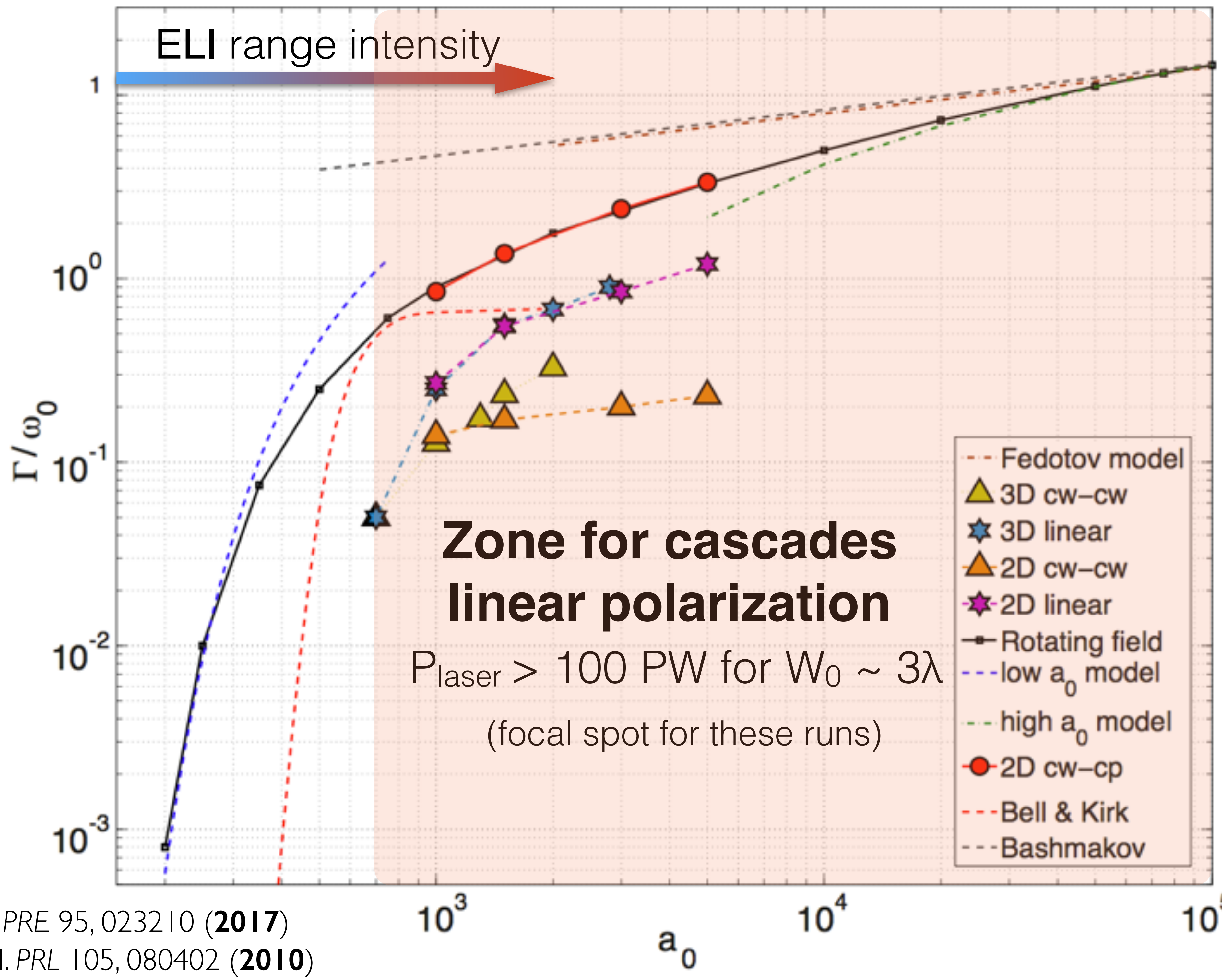
Particles rotate in the y-z plane

Cascade's growth rate in 2 lasers setup



T. Grismayer et al. *PRE* 95, 023210 (**2017**)
M. A Fedotov et al. *PRL* 105, 080402 (**2010**)
A.R Bell and J. G Kirk *PRL*, 101, 200403 (**2008**)
V. F. Bashmakov et al. *PoP* 21, 013105 (**2014**)

Cascade's growth rate in 2 lasers setup



T. Grismayer et al. *PRE* 95, 023210 (**2017**)
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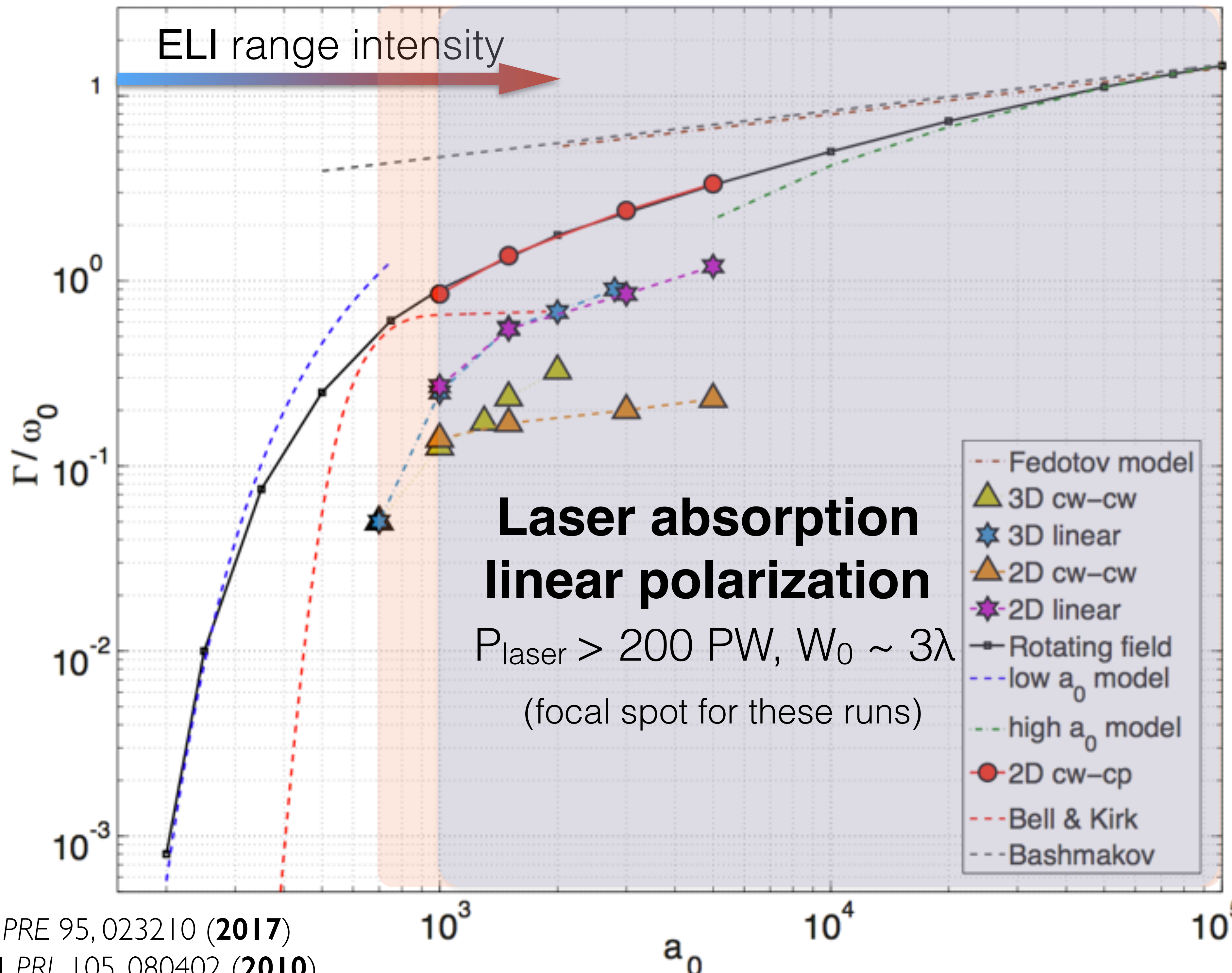

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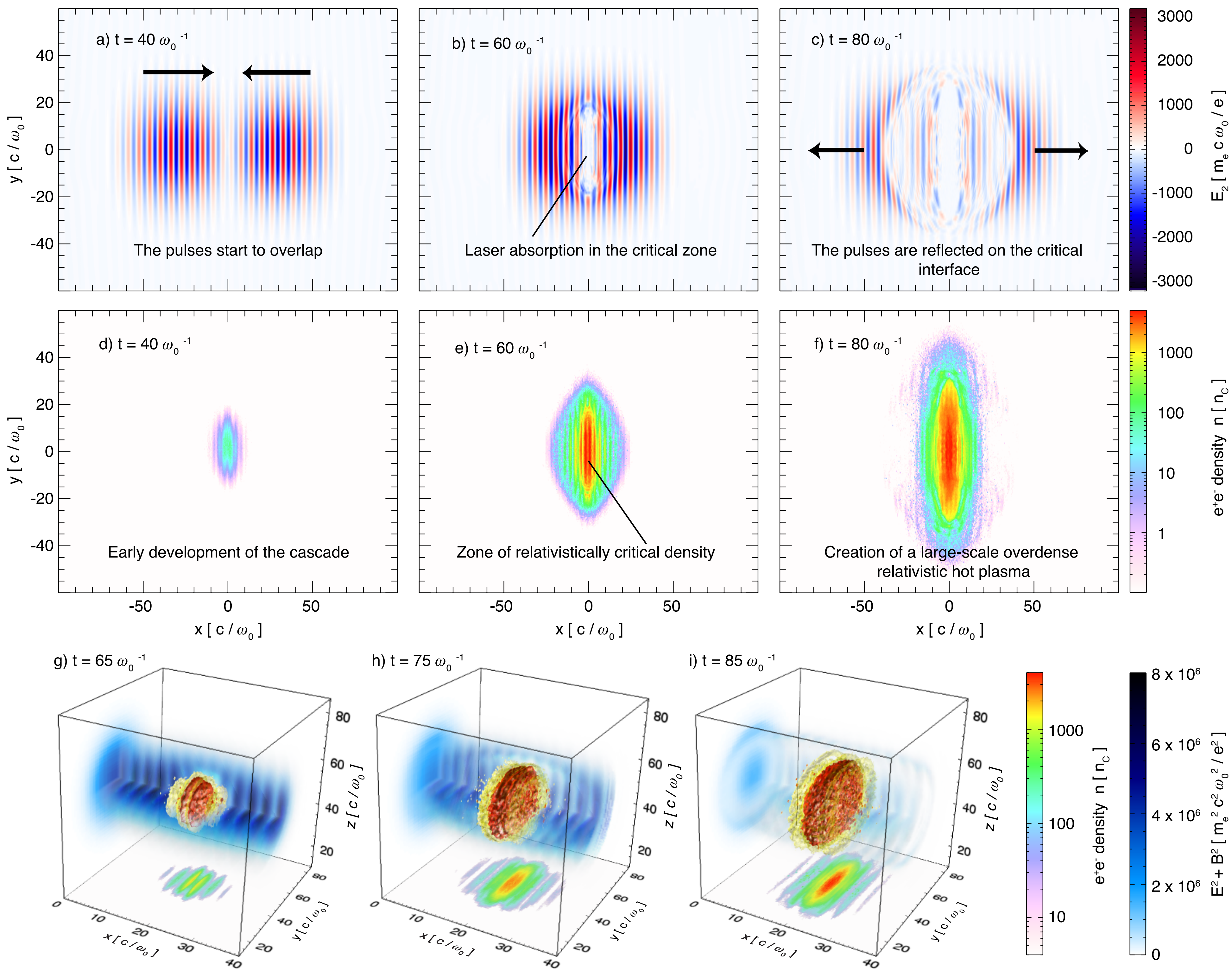
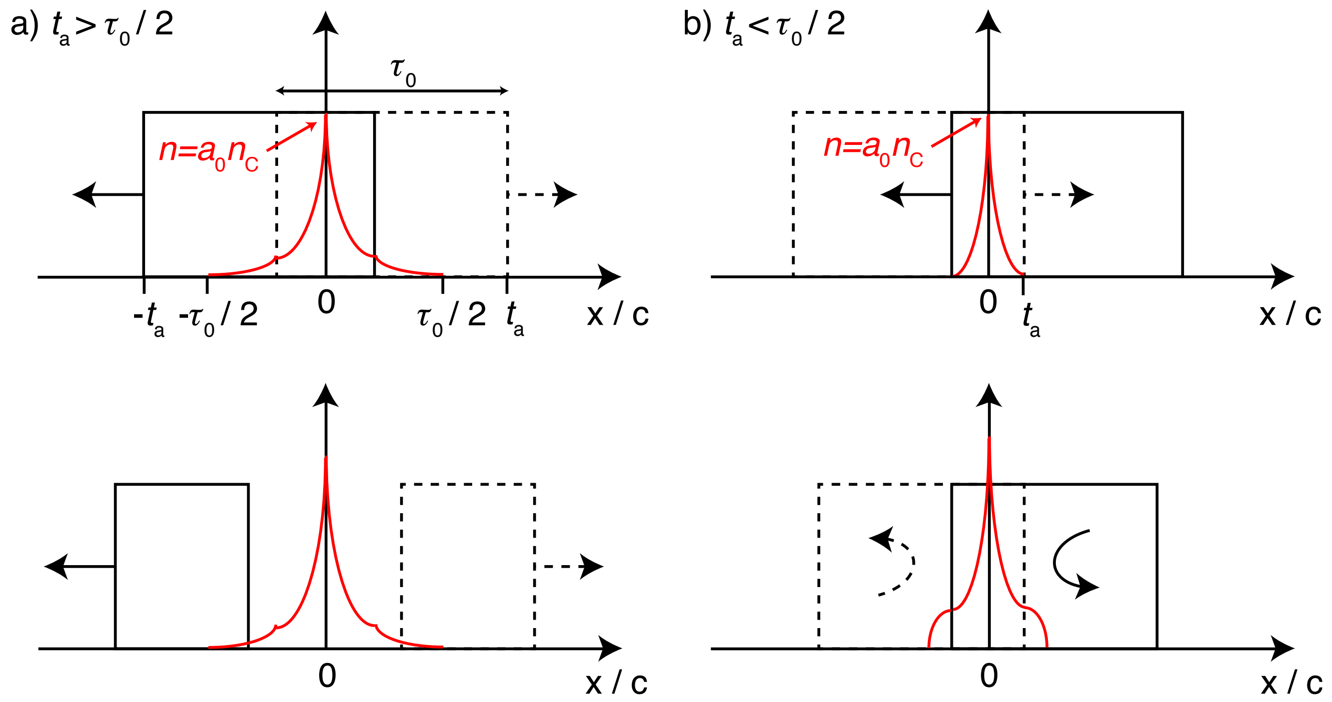
Laser absorption in QED cascades



T. Grismayer et al. *PoP* 23, 056706, (**2016**)
E.N Nerush et al., *PRL* 106, 035001 (**2011**)

A simple model for laser absorption

When does the laser absorption become important ?



a) the absorption time is bigger than half of the pulse duration → fraction of the pulse can escape

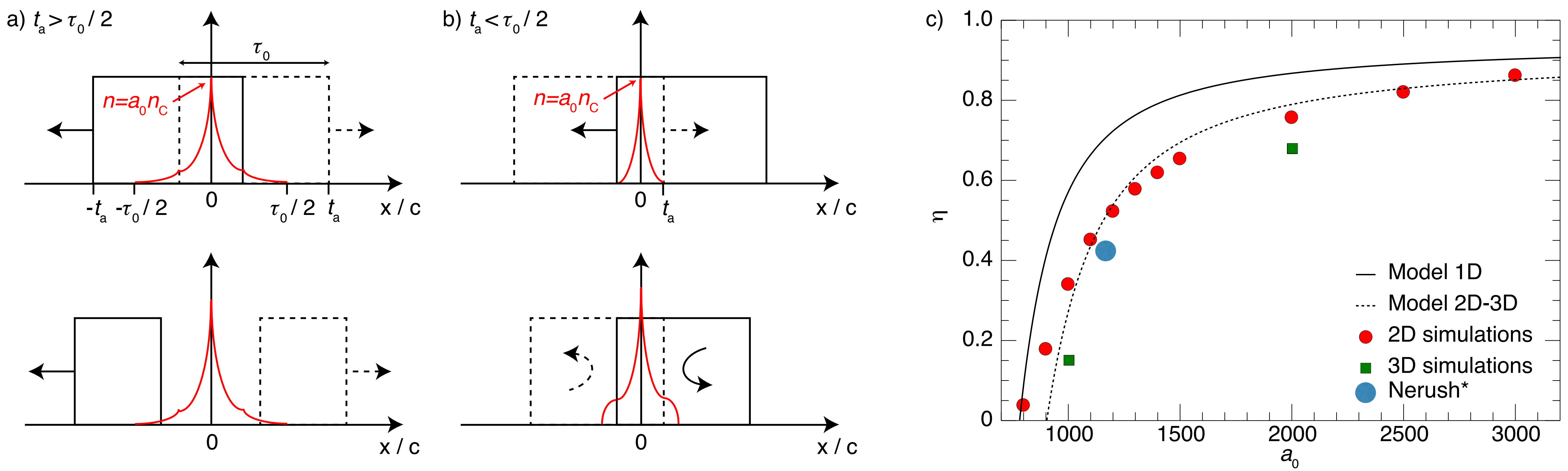
b) the absorption time is smaller than half of the pulse duration → the reflected wave can reform a standing wave

$$\eta = \frac{\mathcal{E}_a}{\mathcal{E}_p} = 1 - \frac{t_a}{\tau}$$

T. Grismayer et al. *PoP* 23, 056706, (**2016**)
E.N Nerush et al., *PRL* 106, 035001 (**2011**)

A simple model for laser absorption

When does the laser absorption become important ?



a) the absorption time is bigger than half of the pulse duration → fraction of the pulse can escape

b) the absorption time is smaller than half of the pulse duration → the reflected wave can reform a standing wave

$$\eta = \frac{\mathcal{E}_a}{\mathcal{E}_p} = 1 - \frac{t_a}{\tau}$$

- Model 1D

$$t_a = \frac{ln(a_0 n_c / n_0)}{\Gamma}$$

- Model 2D-3D

$$t_a = \frac{ln(a_0 n_c \sigma_0^2 \tau_0 c / n_0 \lambda_0^3)}{\Gamma}$$

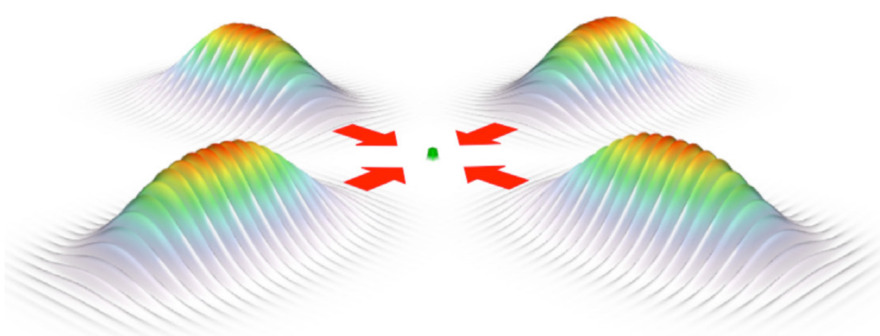
T. Grismayer et al. *PoP* 23, 056706, (**2016**)

*E.N Nerush et al., *PRL* 106, 035001 (**2011**)

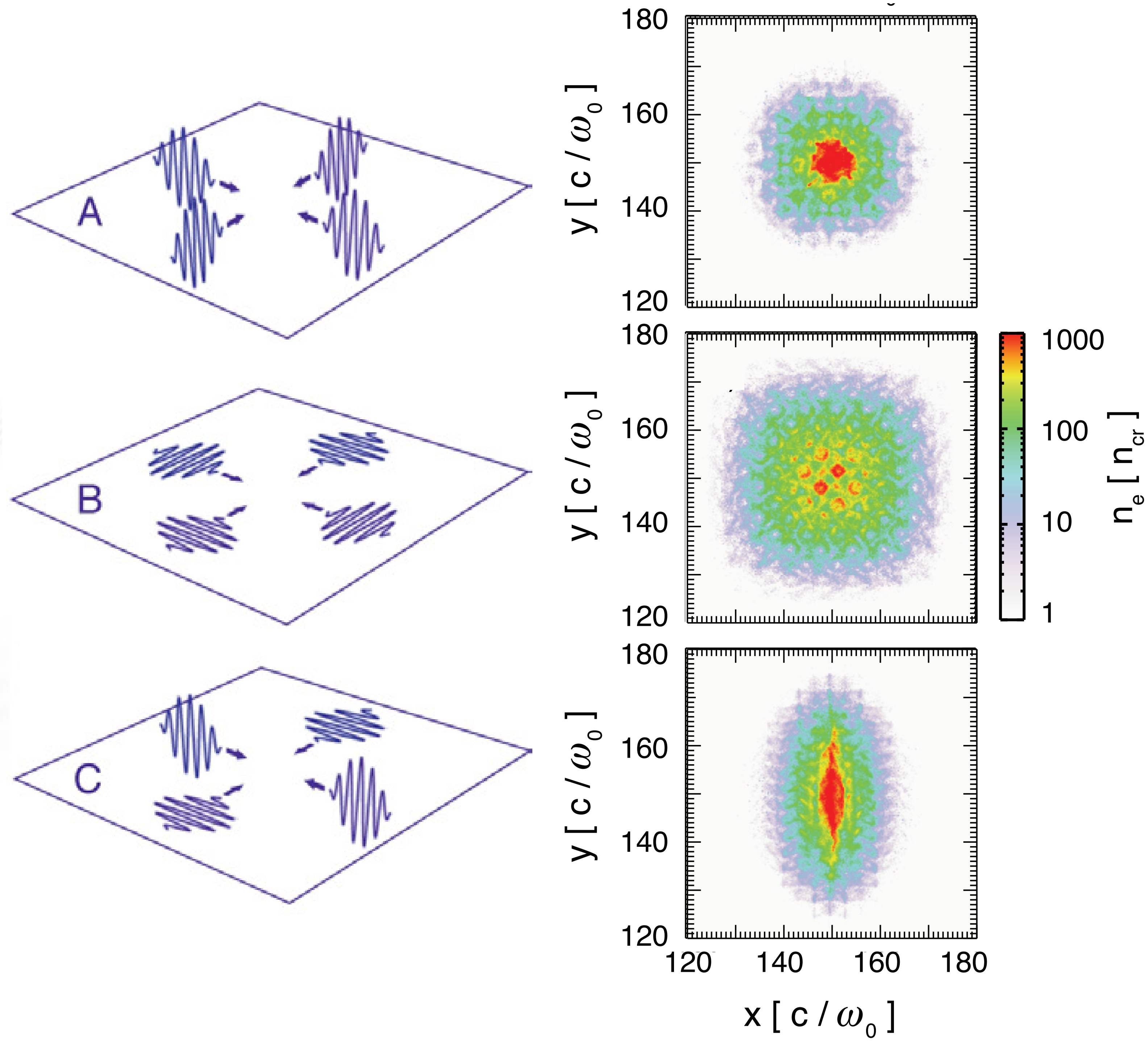
4-laser cascades - effect of polarisation

TÉCNICO LISBOA

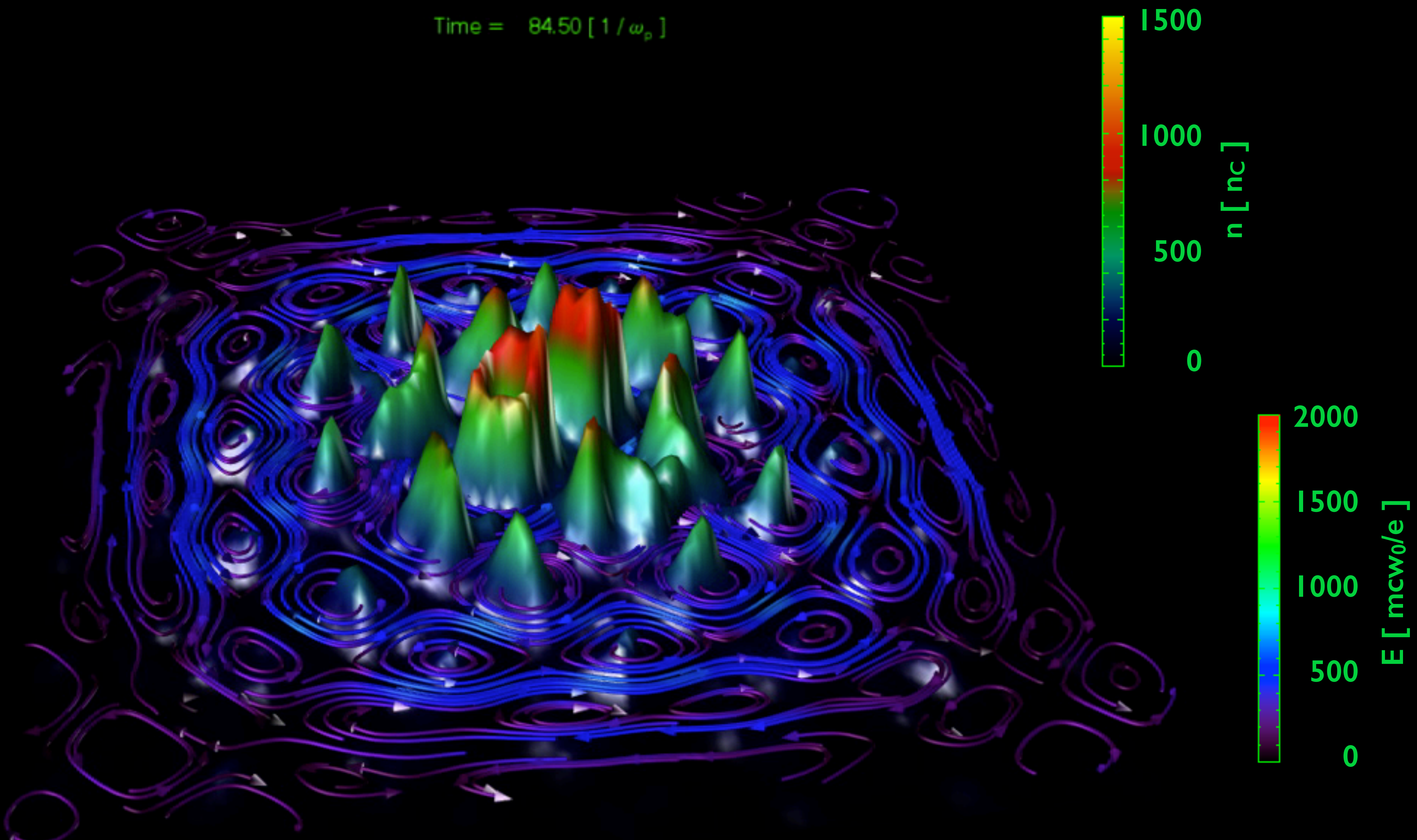
Growth rates, absorption and output radiation



M. Vranic et al.,
PPCF 59, 014040 (2017)

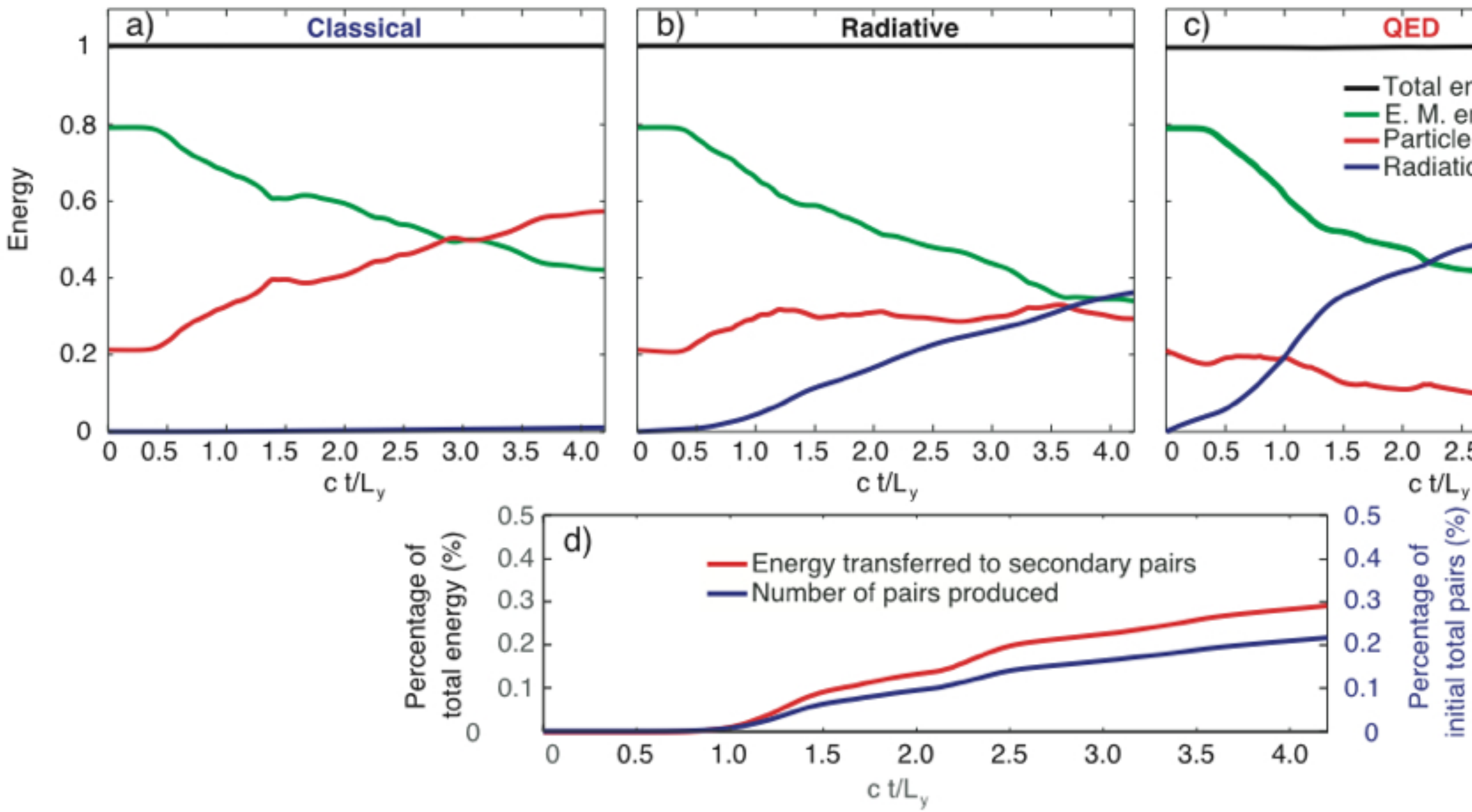


“In plane” - vortex electric field structure



Contents

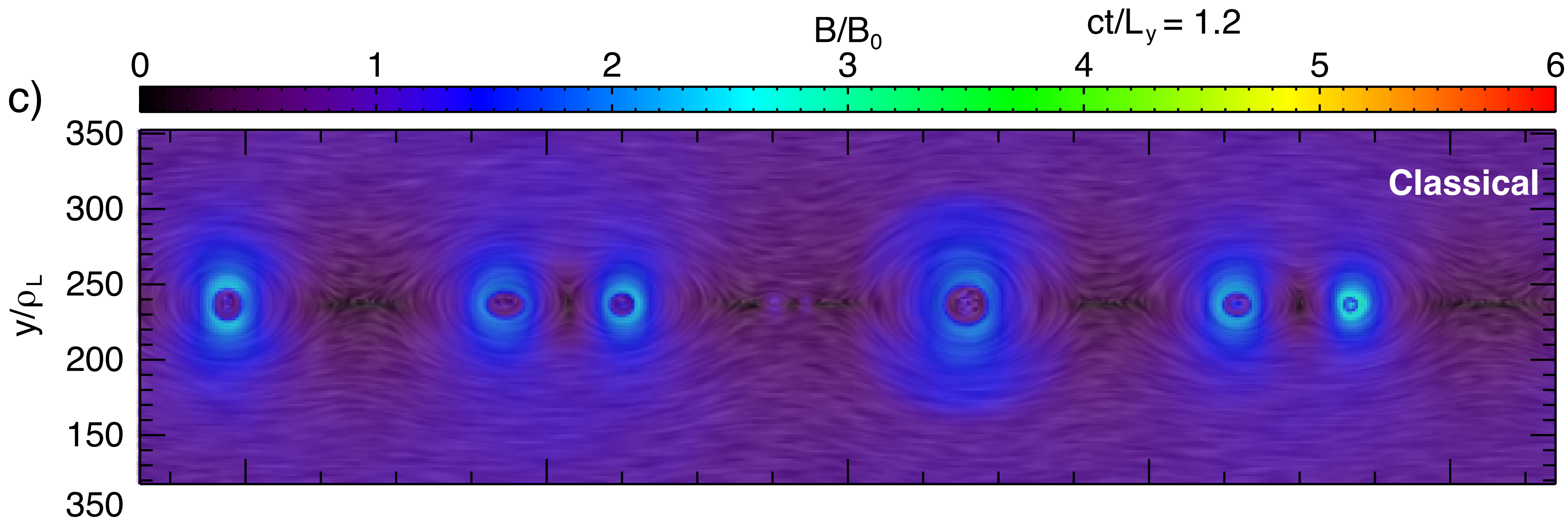
Magnetic reconnection : energy conversion

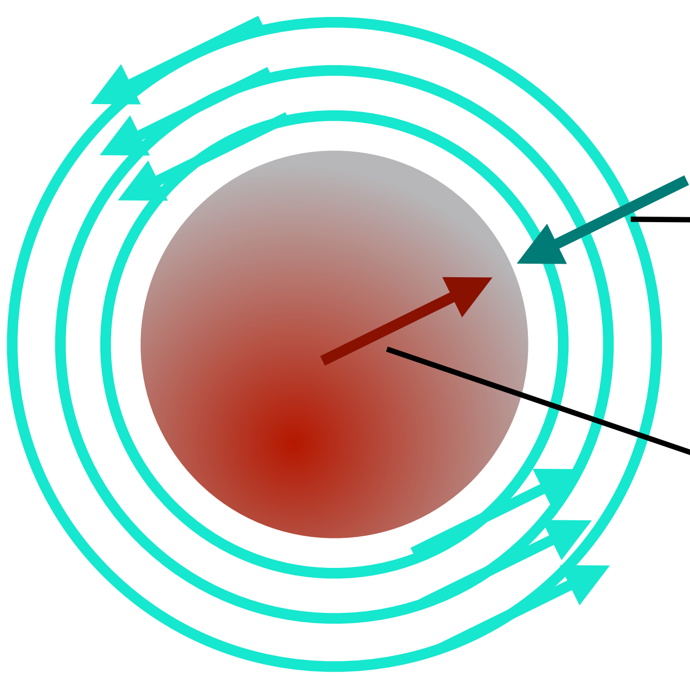


K. Schoeffler et al. *APJ* 870, (**2019**)

Classical magnetic Islands reach pressure balance

Classical relativistic reconnection





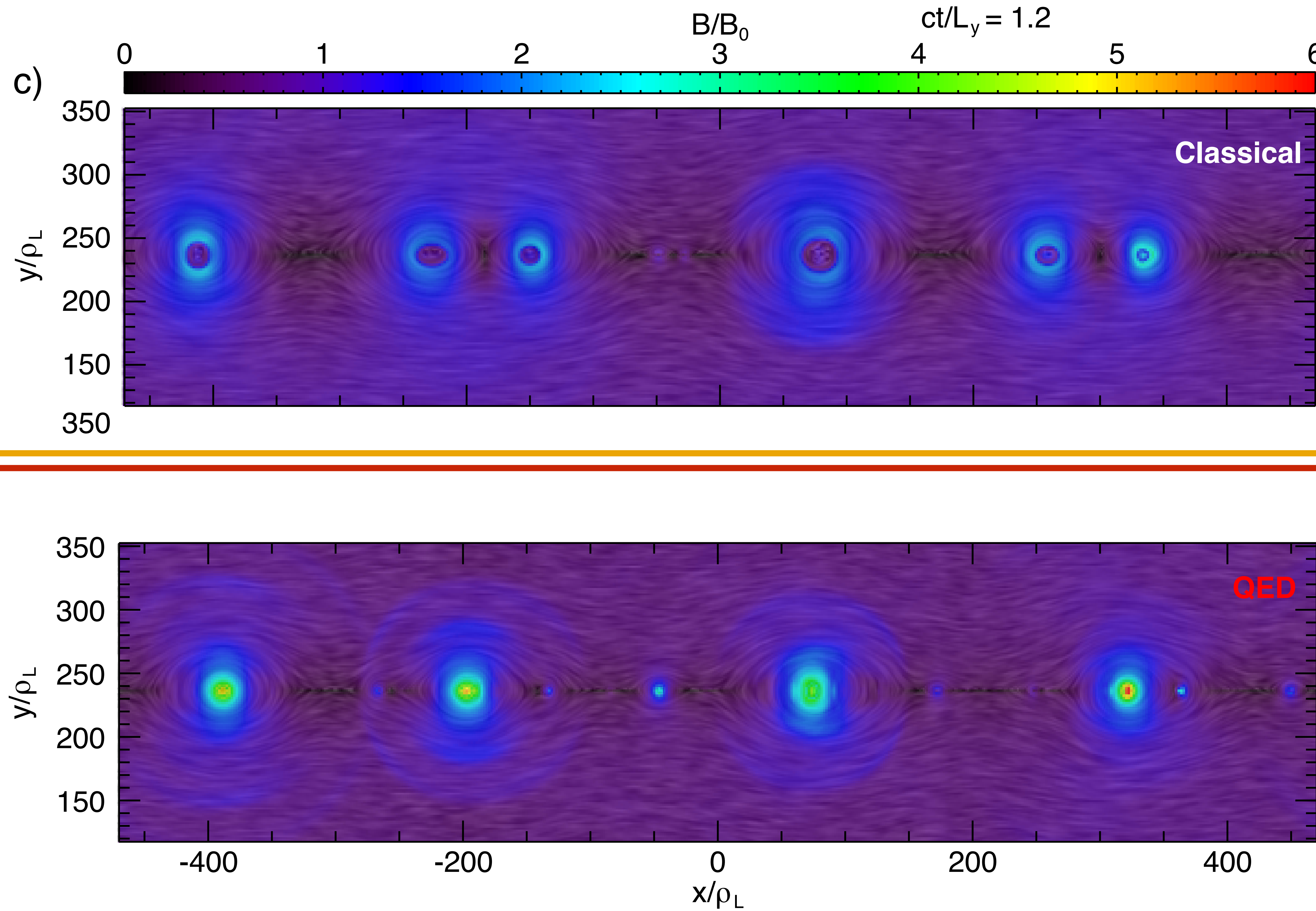
Pinch equilibrium (Bennett)

Magnetic tension $\frac{B \cdot \nabla B}{4\pi}$

Plasma pressure $\nabla\left(P + \frac{B^2}{8\pi}\right)$

Radiation induced compression of magnetic field

Classical relativistic reconnection

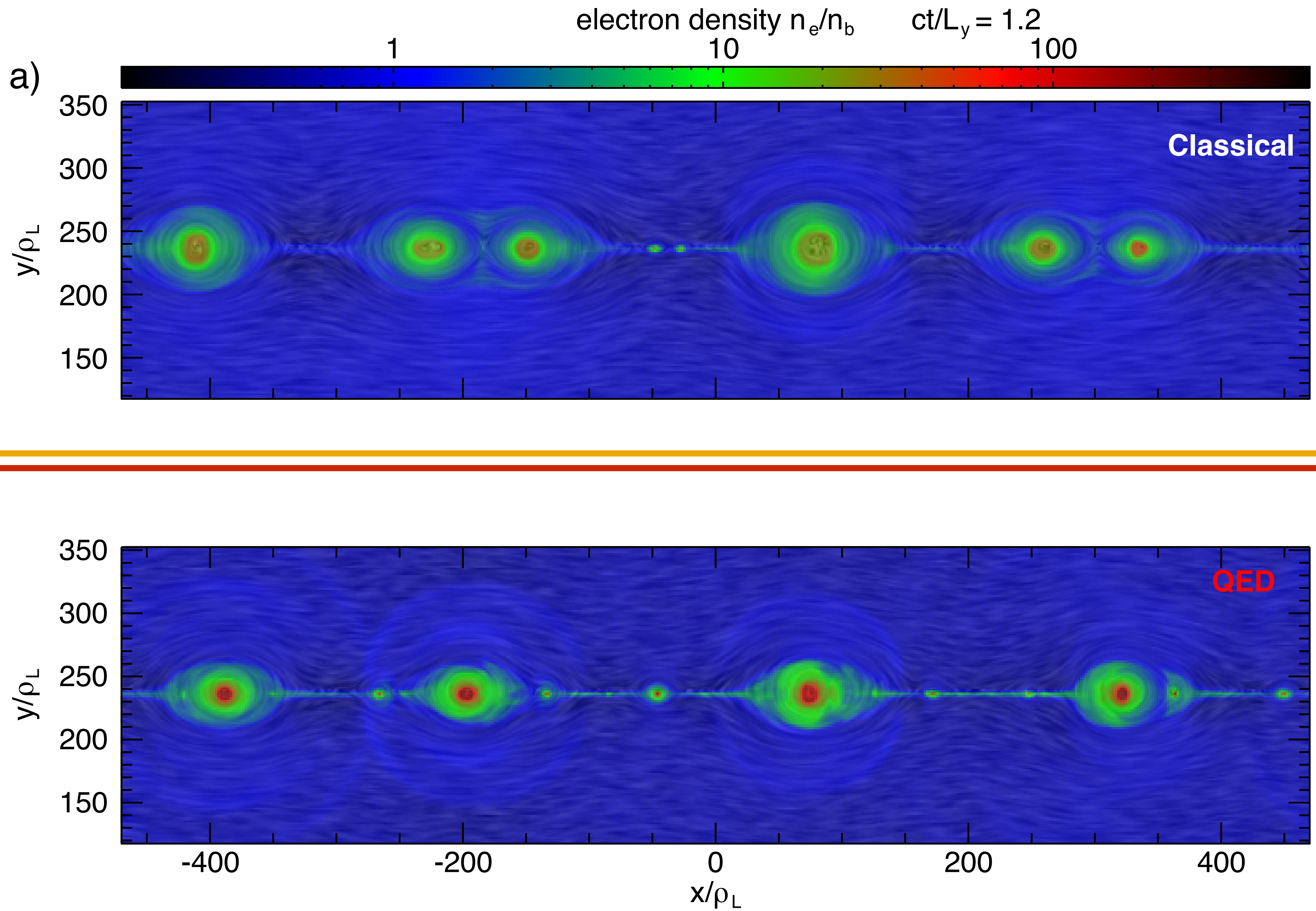


Radiative reconnection

Radiation induced compression of density

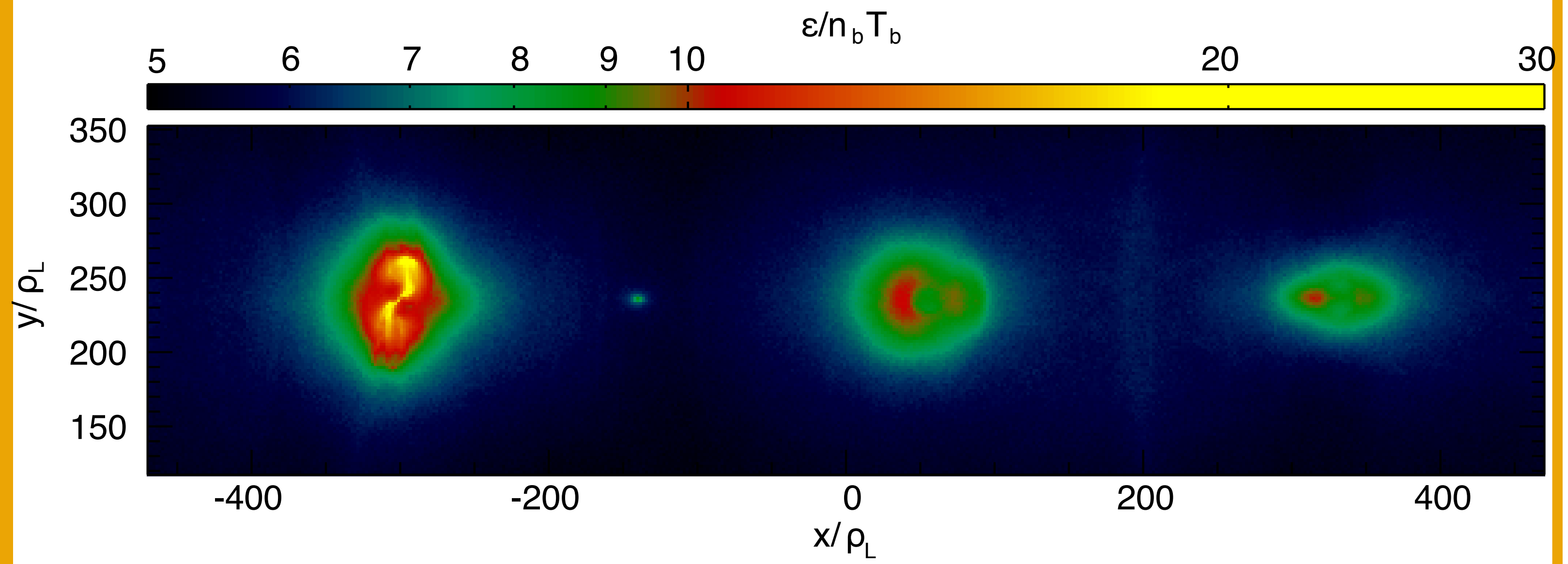
Classical relativistic reconnection

Radiative QED reconnection



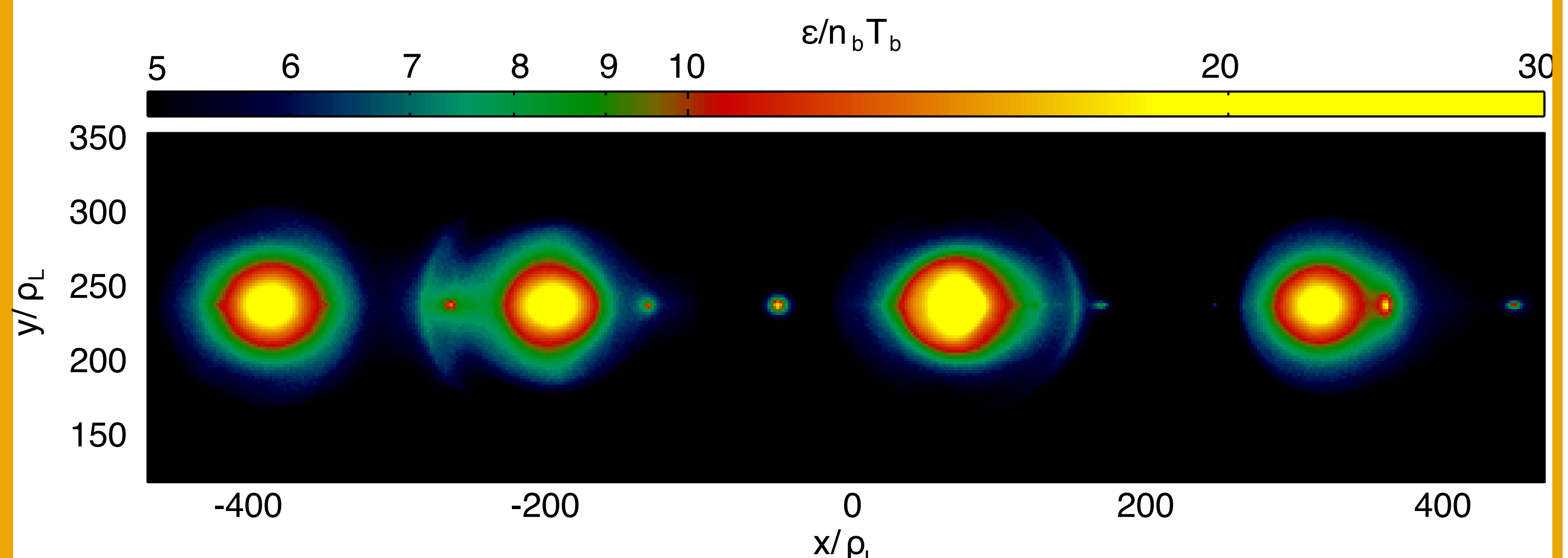
Gamma rays/ Pairs produced inside islands

Late t = 2.2 Ly/c



Gamma rays

Early t = 1.2 Ly/c



Pair creation rate density