Plasma in Extreme Conditions - QED and Particle-In-Cell for the Next Generation of Laser-Matter Interactions

Marija Vranic

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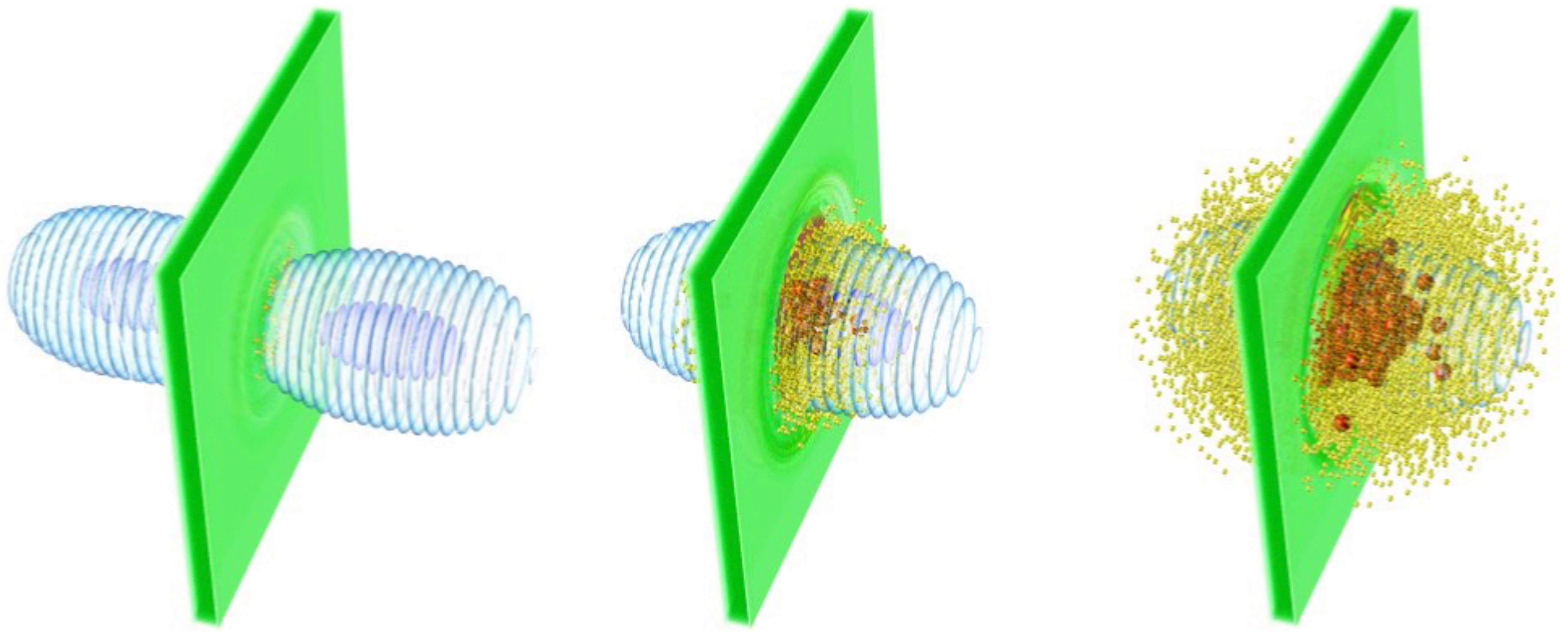

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Acknowledgements

TÉCNICO LISBOA

Work in collaboration with:

IST: T. Grismayer, B. Martinez, R. Babjak, O. Amaro, B. Barbosa, R. Torres, F. Del Gaudio, R. A. Fonseca, L. O. Silva (IST)

UCLA: F. Li, K. Miller, J. Pierce, V. Decyk, W. B. Mori

Simulation results obtained at Jugene/Juqueen, SuperMUC, Jaguar, Fermi/Marconi, Salomon, MareNostrum.

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What happens in a plasma in the presence of extreme fields?

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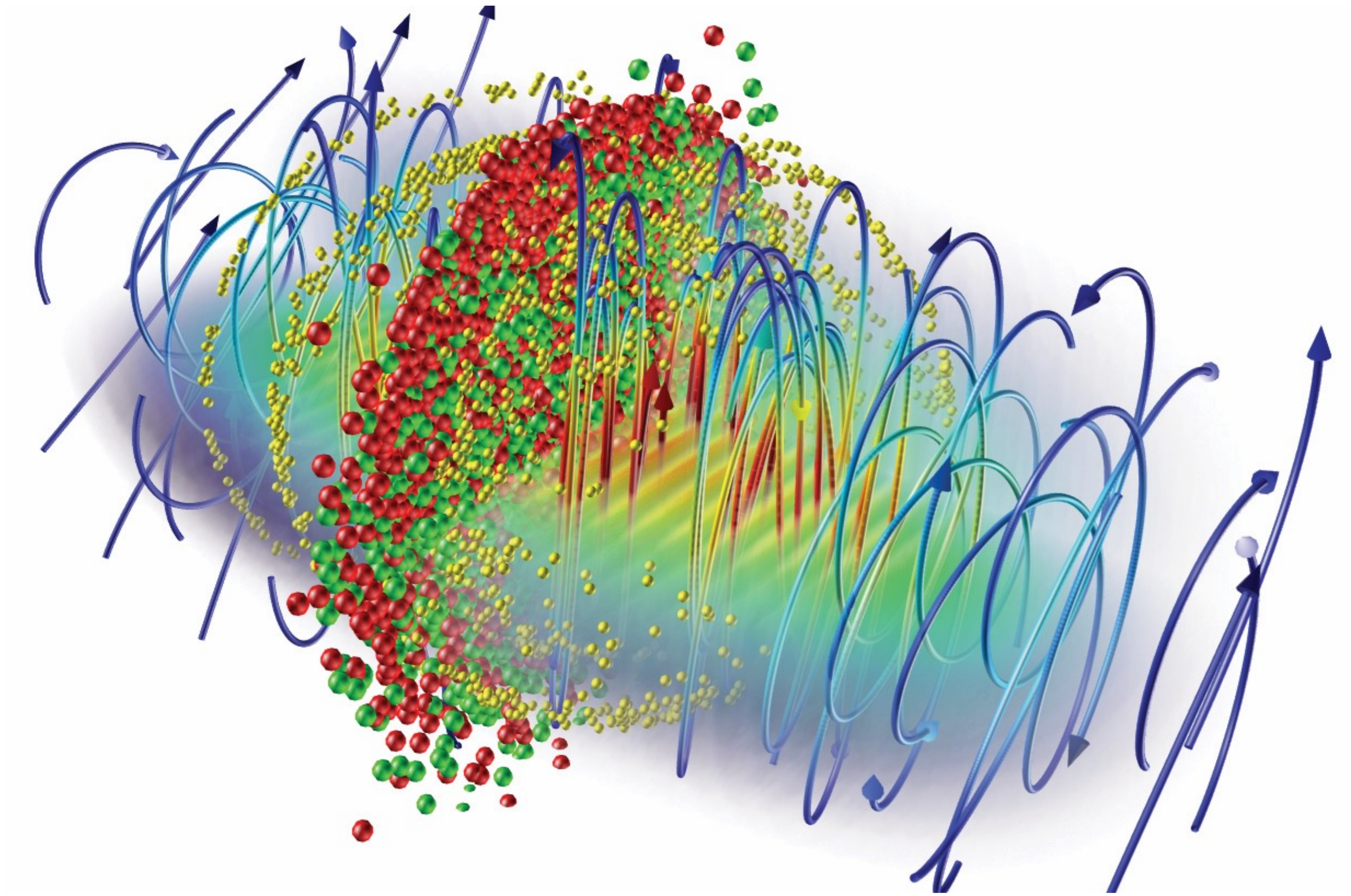


- relativistic particles
- radiation reaction
- hard photon emission
- e+e- pair production
- QED cascades
- EM field depletion by self-created plasma

These plasma are highly nonlinear!

Where can these plasmas exist?

When intense lasers interact with matter

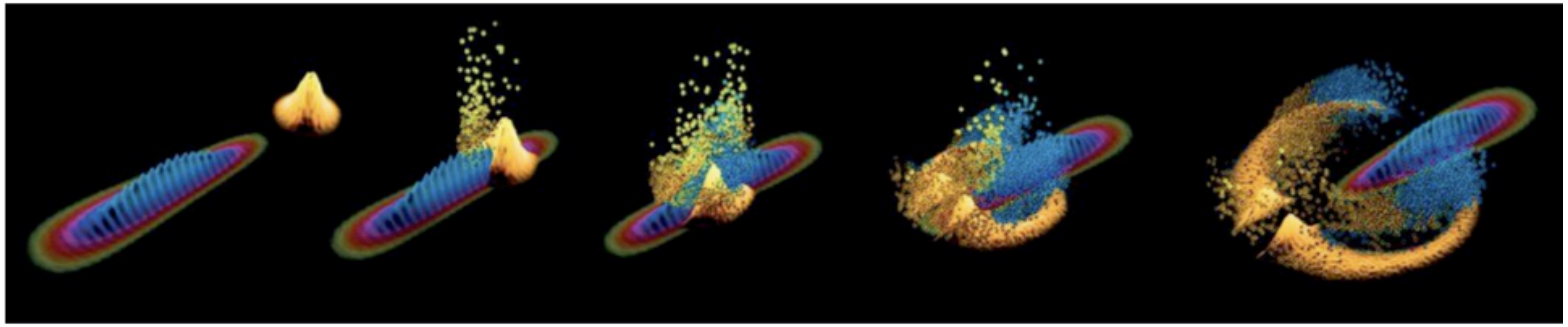


Image: Marija Vranic, European Physical Society Conference official poster 2018

In magnetospheres of neutron stars

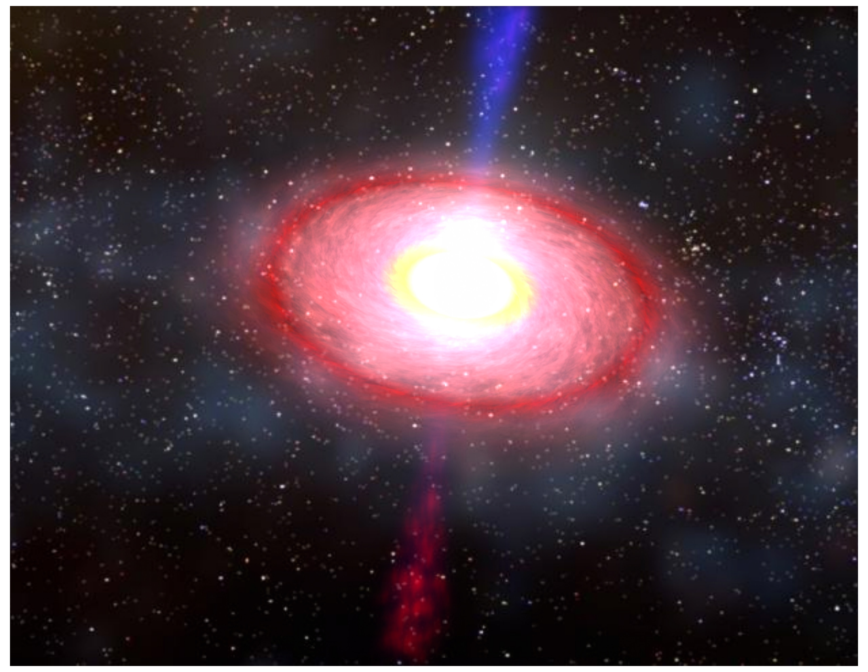


Image: Dana Berry / NASA

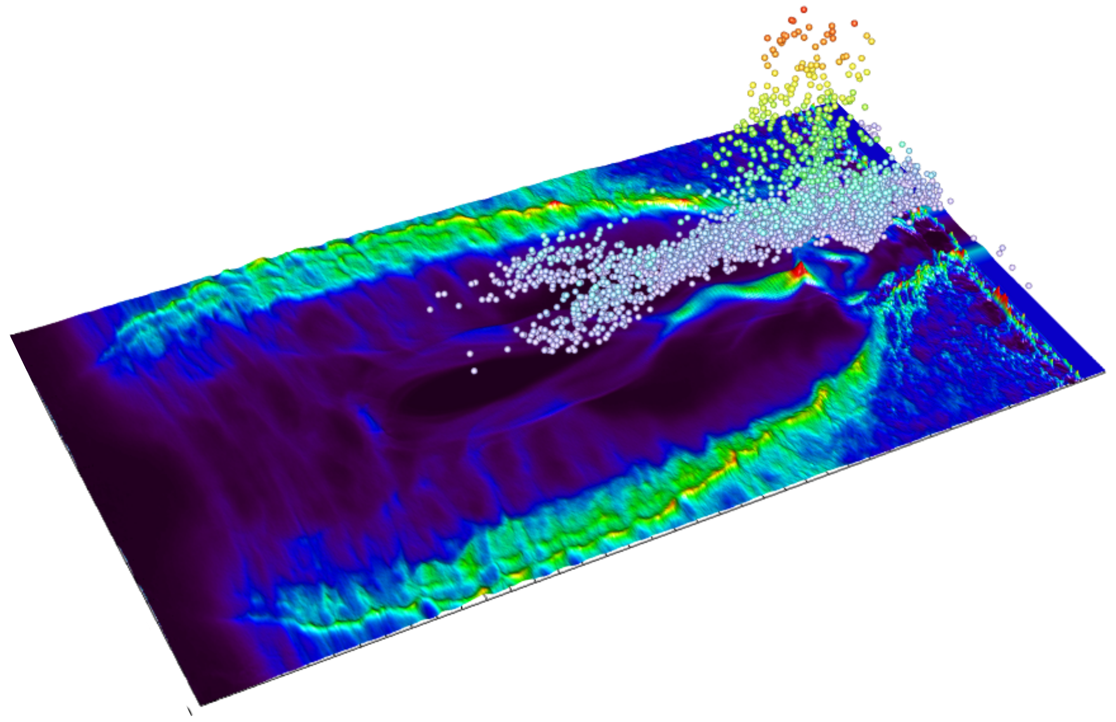
Around black holes

Image: Event Horizon Telescope collaboration, M87 / NASA

Why should we care?

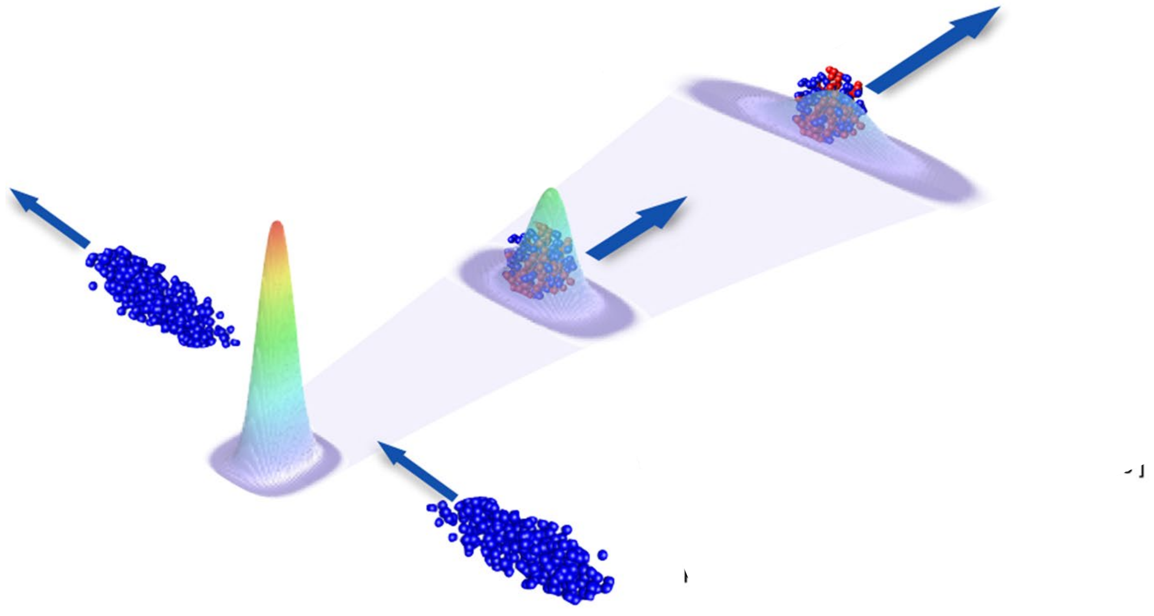
There are both fundamental and practical open questions

- What is the maximum allowed field before the breakdown of the vacuum?



M.Vranic et al, PPCF (2018)

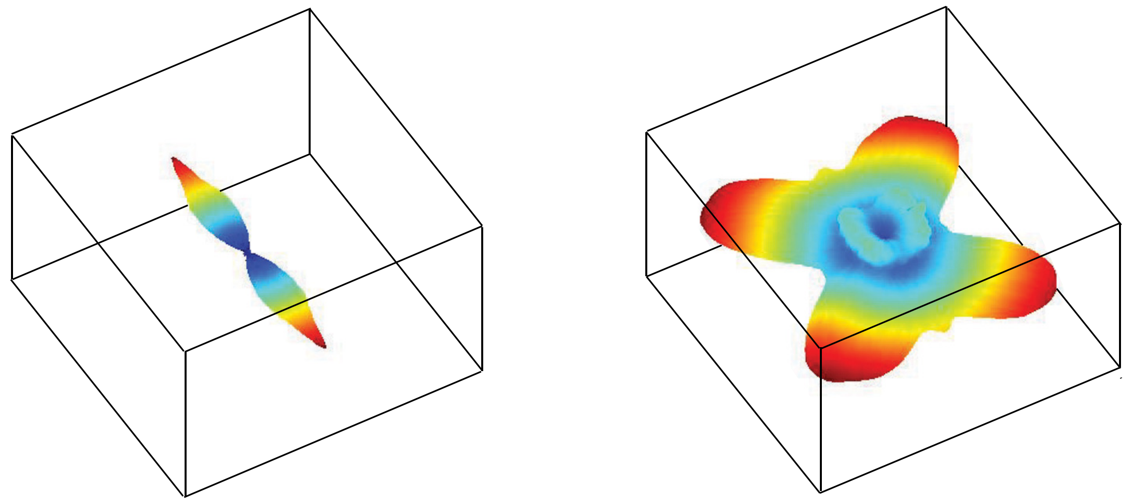
- Can we make particle acceleration in plasmas better with extreme laser intensities? Are there paradigm shifts?



M.Vranic et al, SciRep (2018)

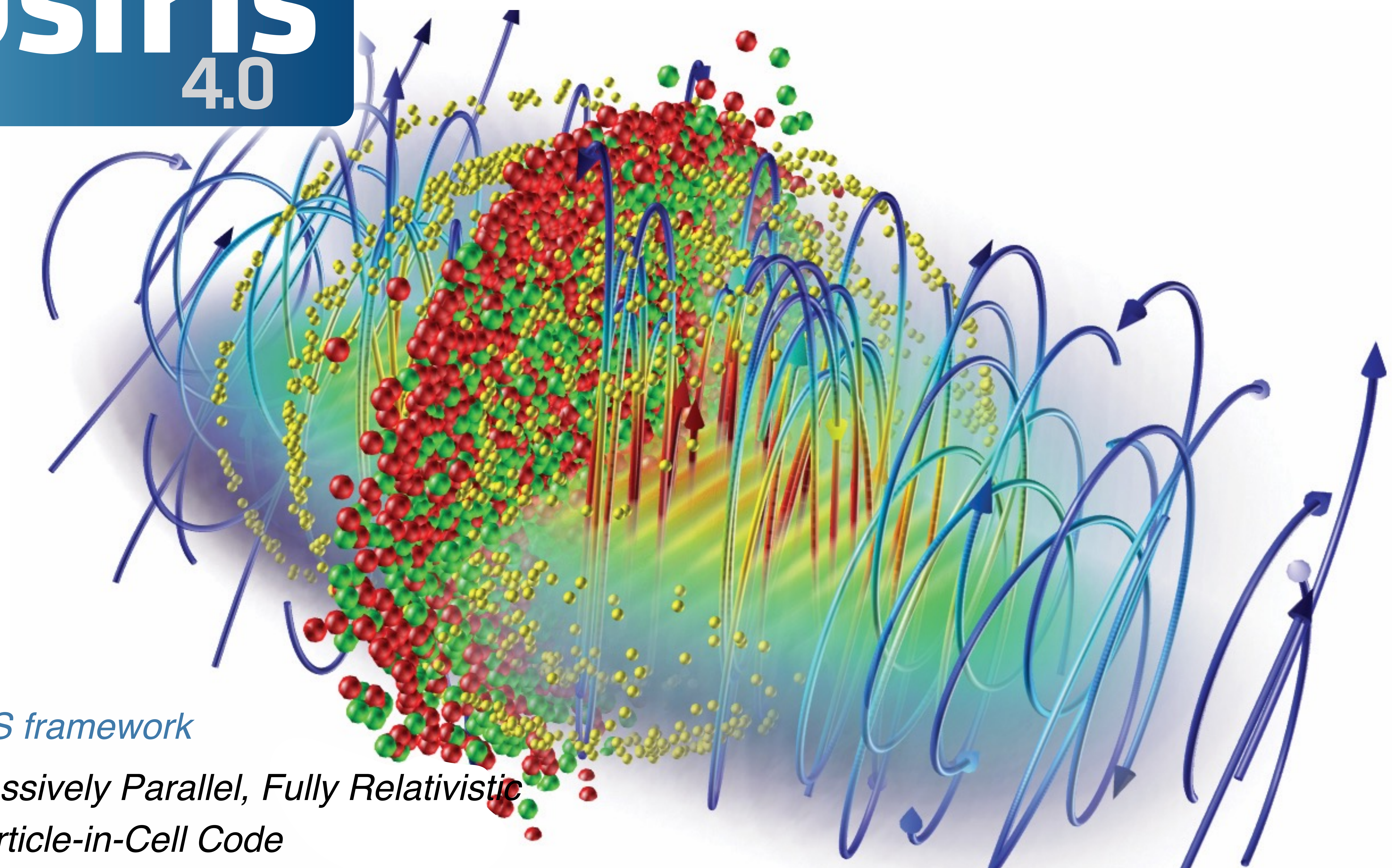
- Can we transform cascades to positron sources? Maybe they could serve as injectors for electron-positron colliders?

- Can we construct tunable radiation sources, with high conversion efficiency ranging all the way to gamma-rays?



T. Grismayer et al, POP (2016)

Osiris 4.0



Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

http://epp.tecnico.ulisboa.pt/

OSIRIS framework

- *Massively Parallel, Fully Relativistic Particle-in-Cell Code*
- *Parallel scalability to 2 M cores*
- *Explicit SSE / AVX / QPX / Xeon Phi / CUDA support*
- ***GPU and dynamic load balancing***
- ***Extended physics/simulation models***

visXD

UCLA

TÉCNICO LISBOA

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

OSIRIS
open-source pic simulations

Download | Documentation | Community | Contribute

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UCLA

Project

The OSIRIS open-source project aims to provide a PIC code capable of tapping into Exascale resources with all the tools required for plasma physics science and applications from laser-plasma accelerators to novel radiation sources.

Code features

Quickstart

OSIRIS can be run on many architectures, ranging from the most advanced HPC systems in the world to simple workstations and laptops with modest resrouces. It can easily be compiled from source or run from a Docker container.

Start using OSIRIS

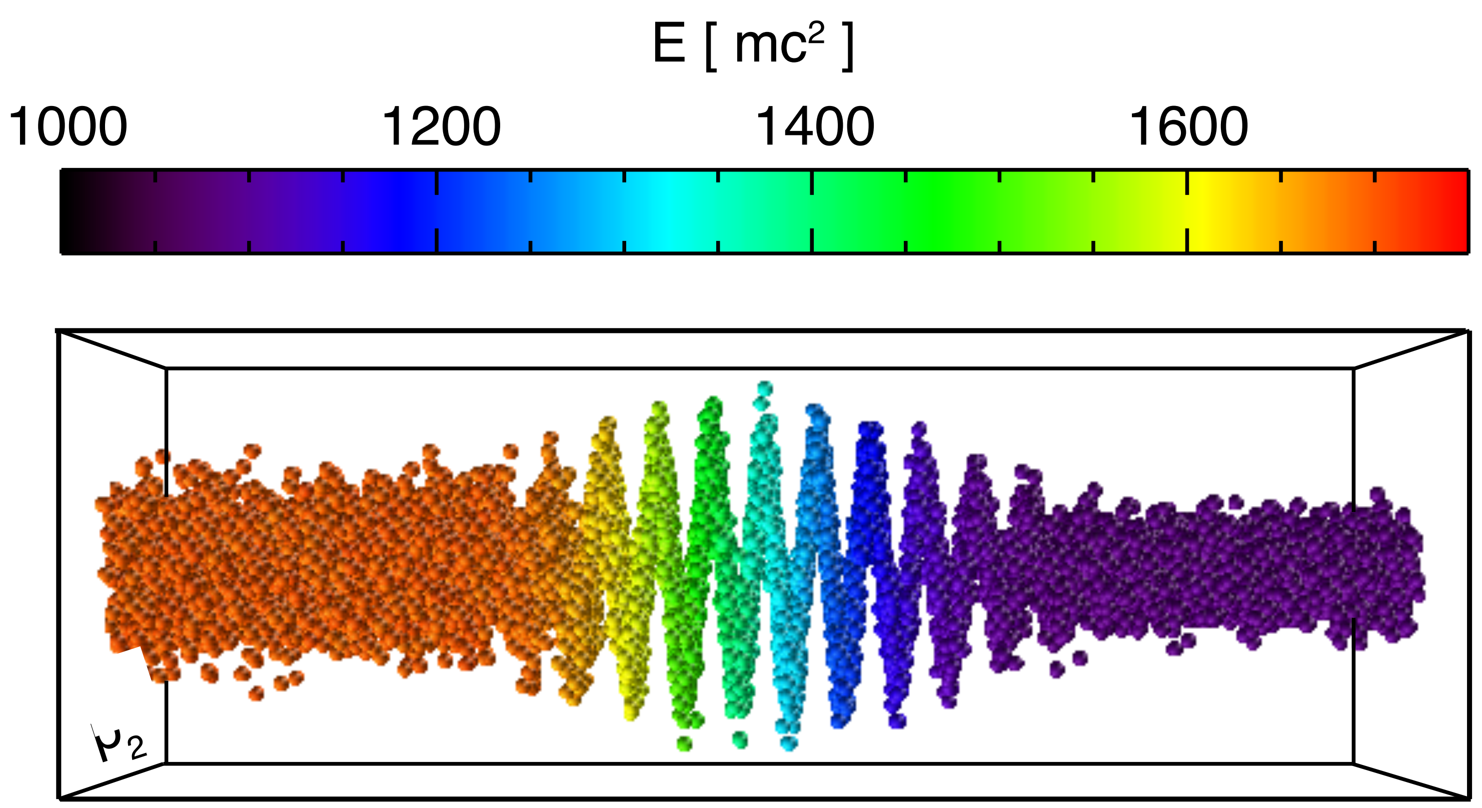
Consortium

OSIRIS has been continuously developed for over two decades by the members of the OSIRIS consortium and is used extensively throughout the plasma physics community. New collaborations are always welcome!

Meet the team

Contents

Radiation reaction in classical electrodynamics



Continuous energy loss to radiation!

Self-consistent solution given by coupling Maxwell's eq. and Lorentz force

- ultra-relativistic limit of Landau & Lifshitz

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L - \frac{2}{3}\frac{e^4\gamma}{m^3c^5}\mathbf{p}(\mathbf{E}_\perp + \frac{\mathbf{p}}{\gamma mc} \times \mathbf{B})^2$$

Radiation dominated regime

$$\alpha\gamma^2 \frac{E}{E_S} \sim 1 \qquad E_S = \frac{m^2c^3}{e\hbar}$$

for laser-solid $I > 10^{22} W/cm^2$

A. Di Piazza et al., Rev. Mod. Phys., 84, 3 (2012)

Threshold for QED processes is attainable with lasers

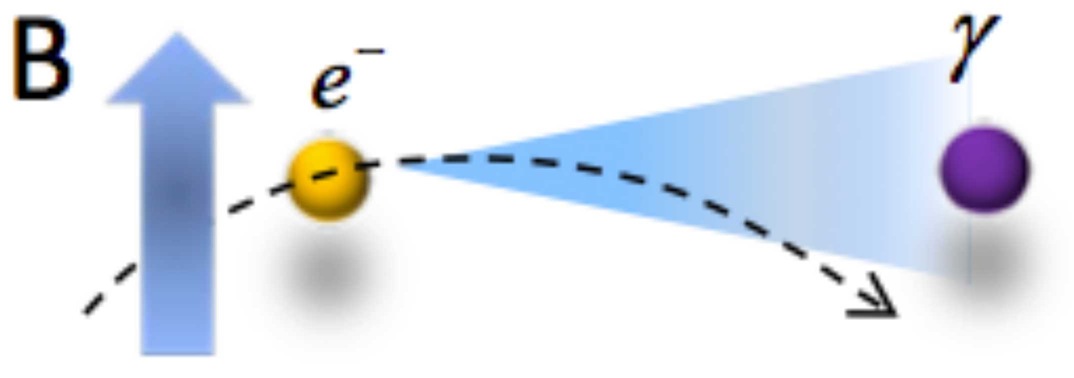
Schwinger critical field

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

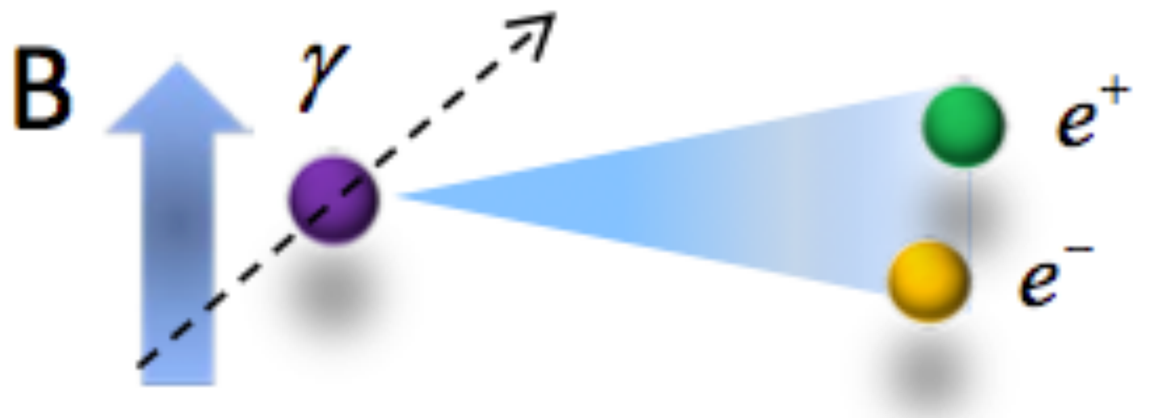
- Field strong enough to spontaneously create e+e- pairs from vaccuum
- Field srong enough to transfer one mc^2 of energy to leptons over one Compton wavelength
- A laser with $E_0 = E_S$ would have $I \sim 10^{29}$ W/cm^2
- Relativistic particles can feel E_S in their rest frame even at $I \sim 10^{22}$ W/cm^2

First QED processes

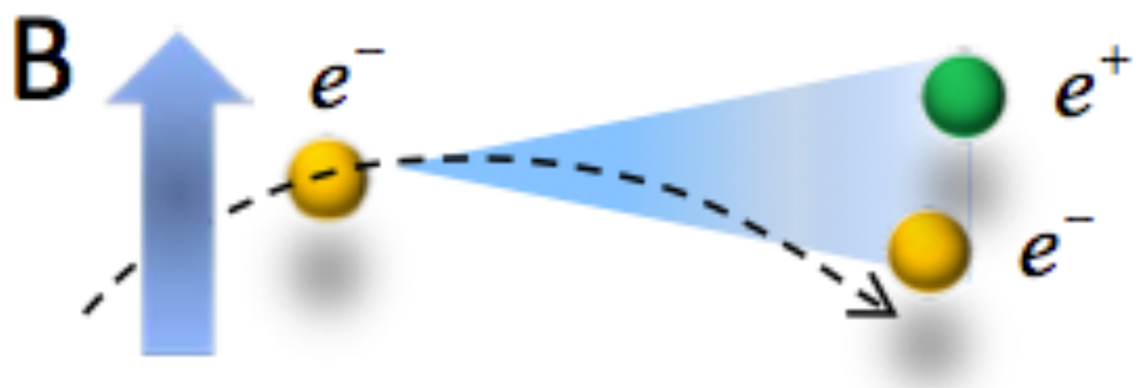
Non-linear Compton emission



Non-linear Breit-Wheeler pair creation



EM trident pair creation

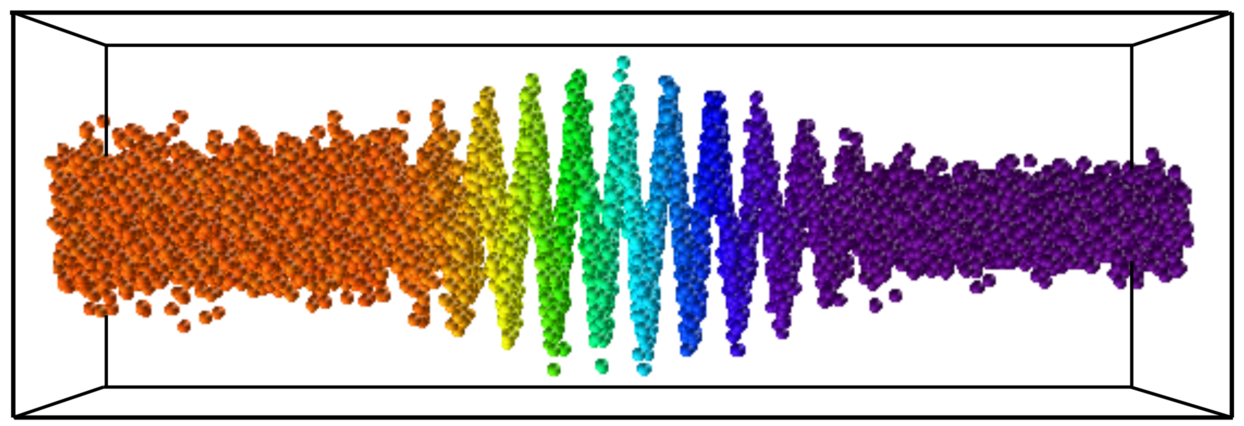


Credit: M. Lobet, B. Martinez

What new features are needed for plasma modeling?

Adding classical radiation reaction

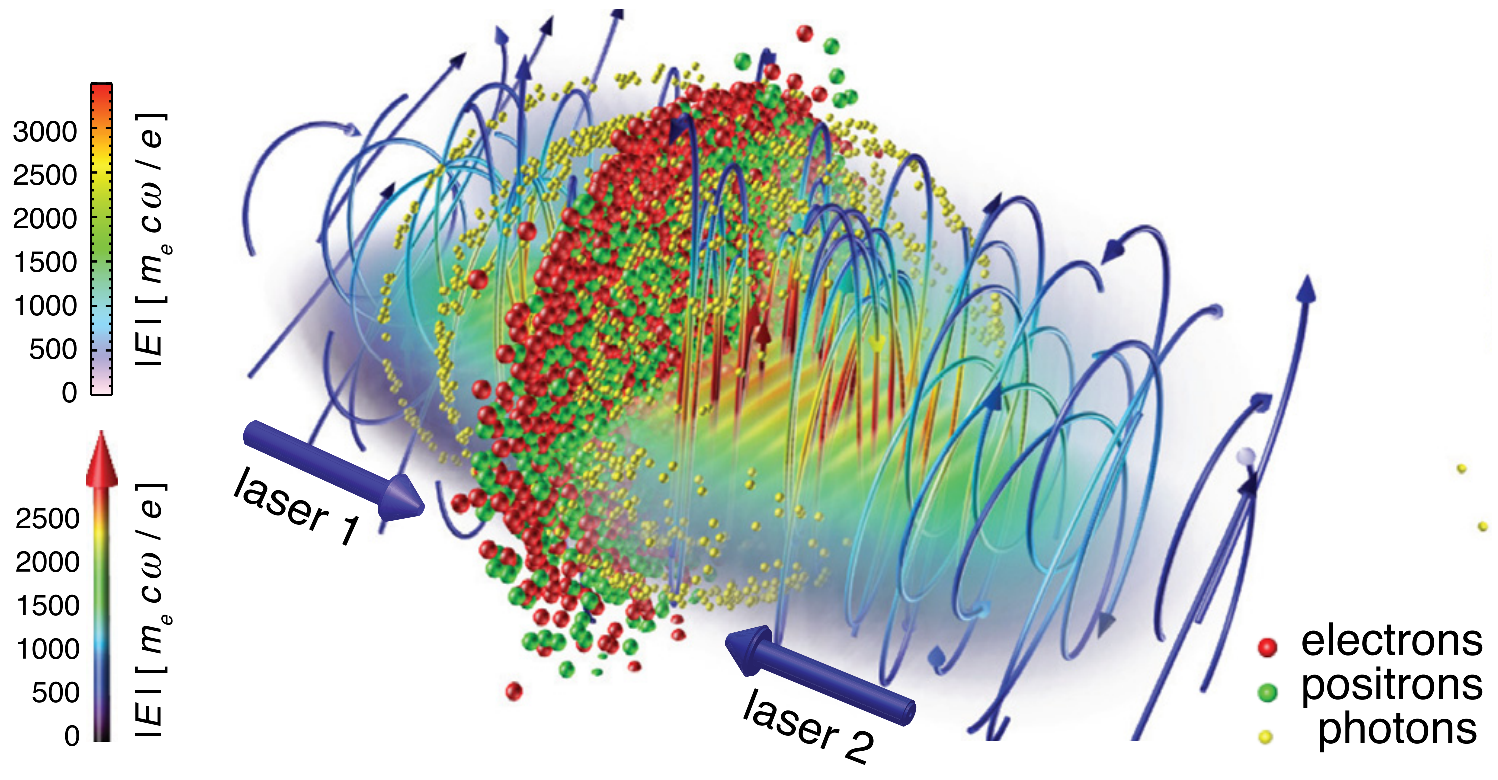
- Modelling electron beam slowdown in scattering configurations
- Modelling other configurations where only a fraction of electrons may be subject to RR but where this can alter qualitative behaviour



M.Vranic et al., PRL (2014); M.Vranic et al., CPC (2016); M.Vranic et al, PPCF (2018)

Adding quantum processes

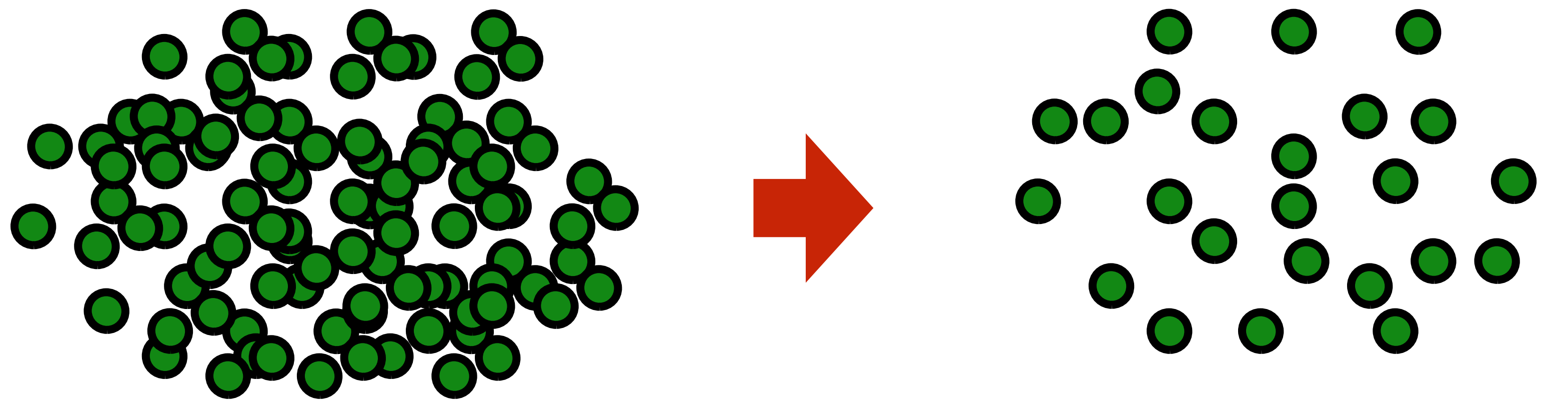
- Modelling the onset of QED, RR from quantum perspective
- Modelling e+e- pair production
- QED cascades, nonlinear regimes where many particles are created and collective plasma dynamics can alter the background fields



M.Vranic et al, NJP (2016); T. Grismayer et al, POP (2016); T. Grismayer et al, PRE (2017); J. L. Martins et al, PPCF (2016); M.Vranic et al, PPCF (2017); M.Vranic et al, SciRep (2018);

Adding performance improvements (particle merging, advanced dynamic load balancing schemes, Quasi-3D geometry)

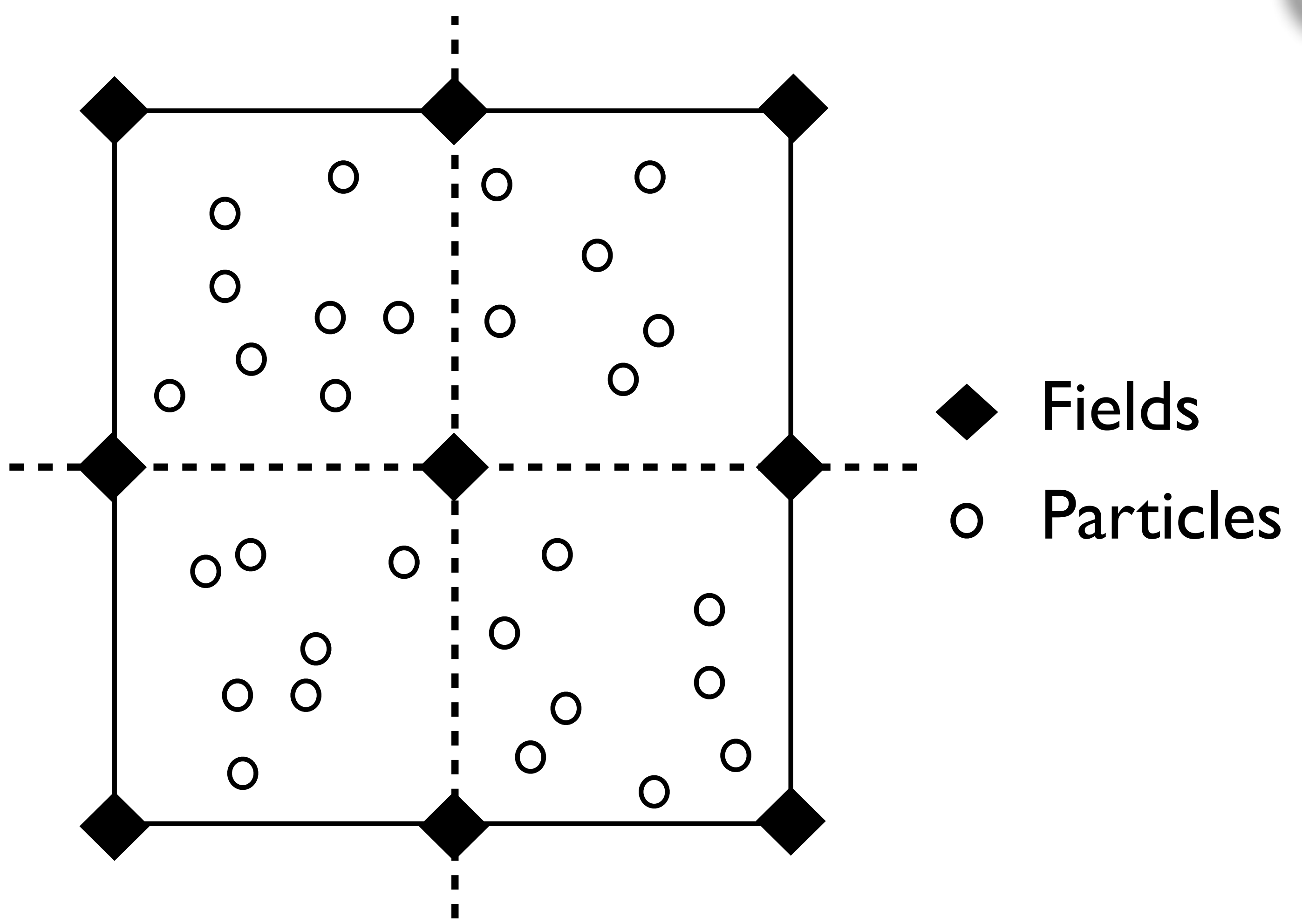
- Essential for all the projects with strong QED effects

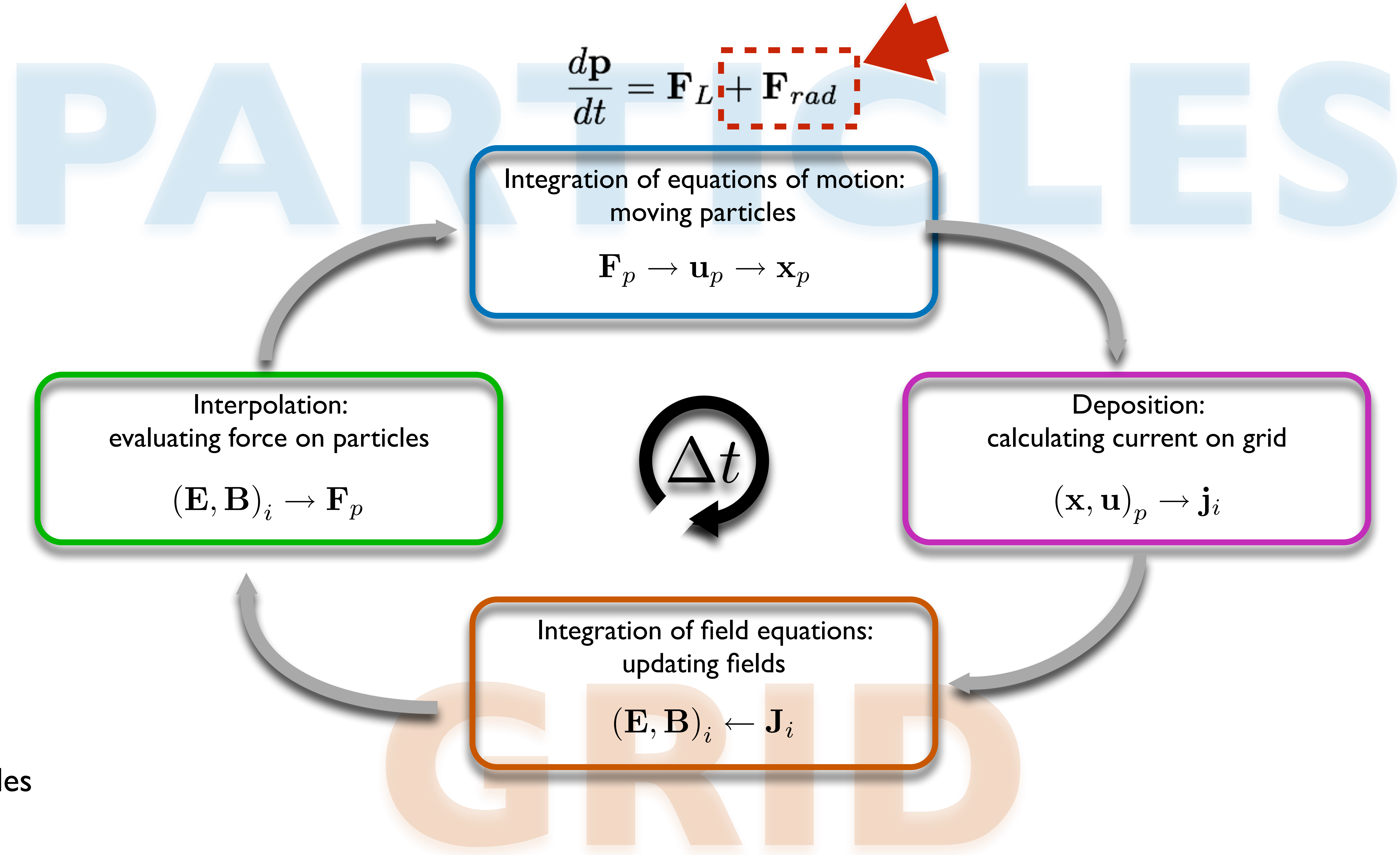


M.Vranic et al, CPC (2015), A. Davidson et al, JCP (2015), F. Li et al, JCP (2021)

Classical radiation reaction

One can replace the Lorentz force in the particle pusher with the Landau & Lifshitz equation of motion (or similar*)





RaDiO's algorithm*

PIC Codes and Líenard-Wiechert Fields

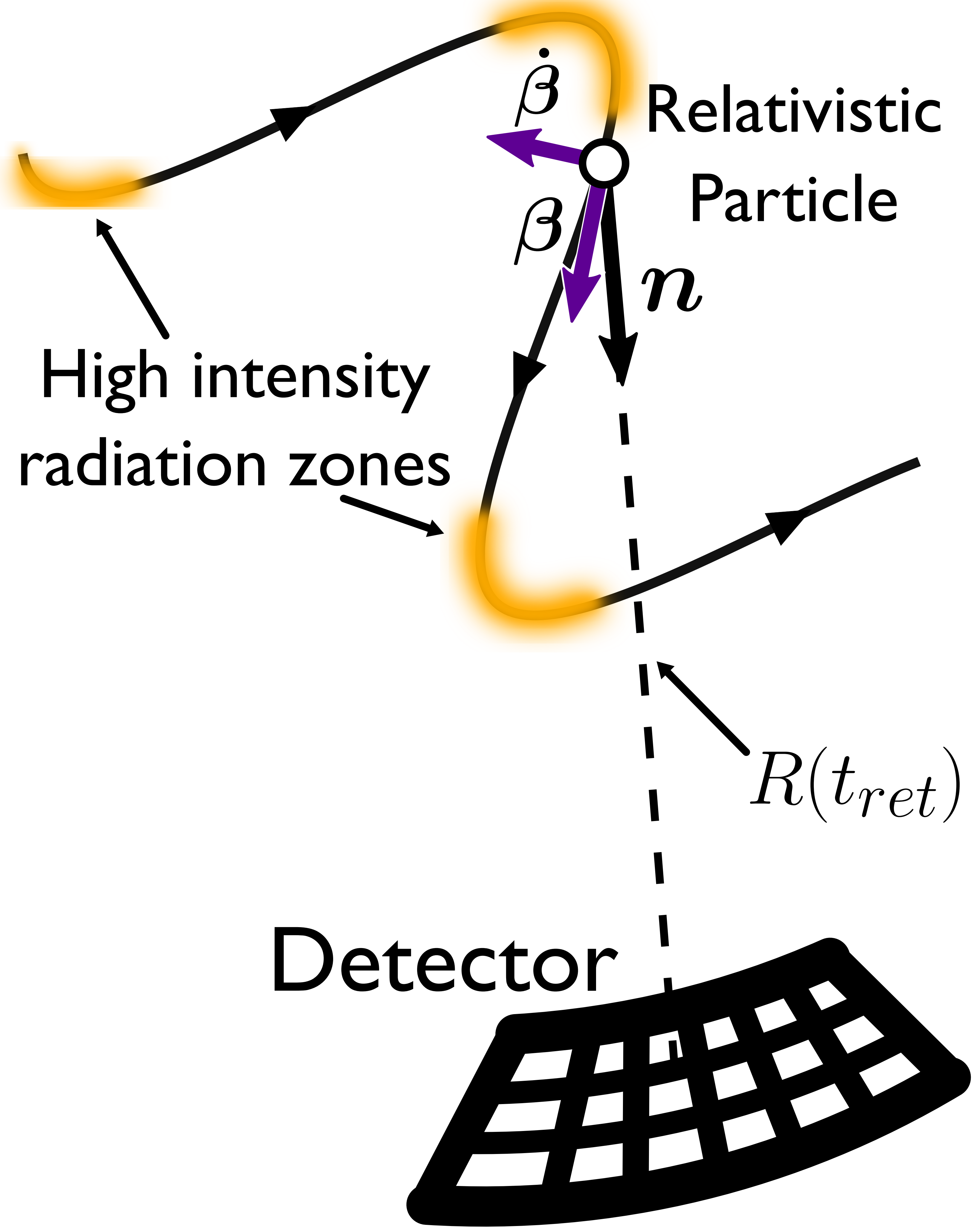
Particles exist in a **grid** which intermediates **EM interactions.**

The PIC grid resolves the particle's motion, **but** relativistic particles ($\gamma > 100$) **emit short wavelengths**

Resolving such wavelengths in the PIC grid would require $\sim \gamma^2$ **more cells**

The Liénard-Wiechert Potentials **allow us** to capture radiation **without increasing** the PIC resolution

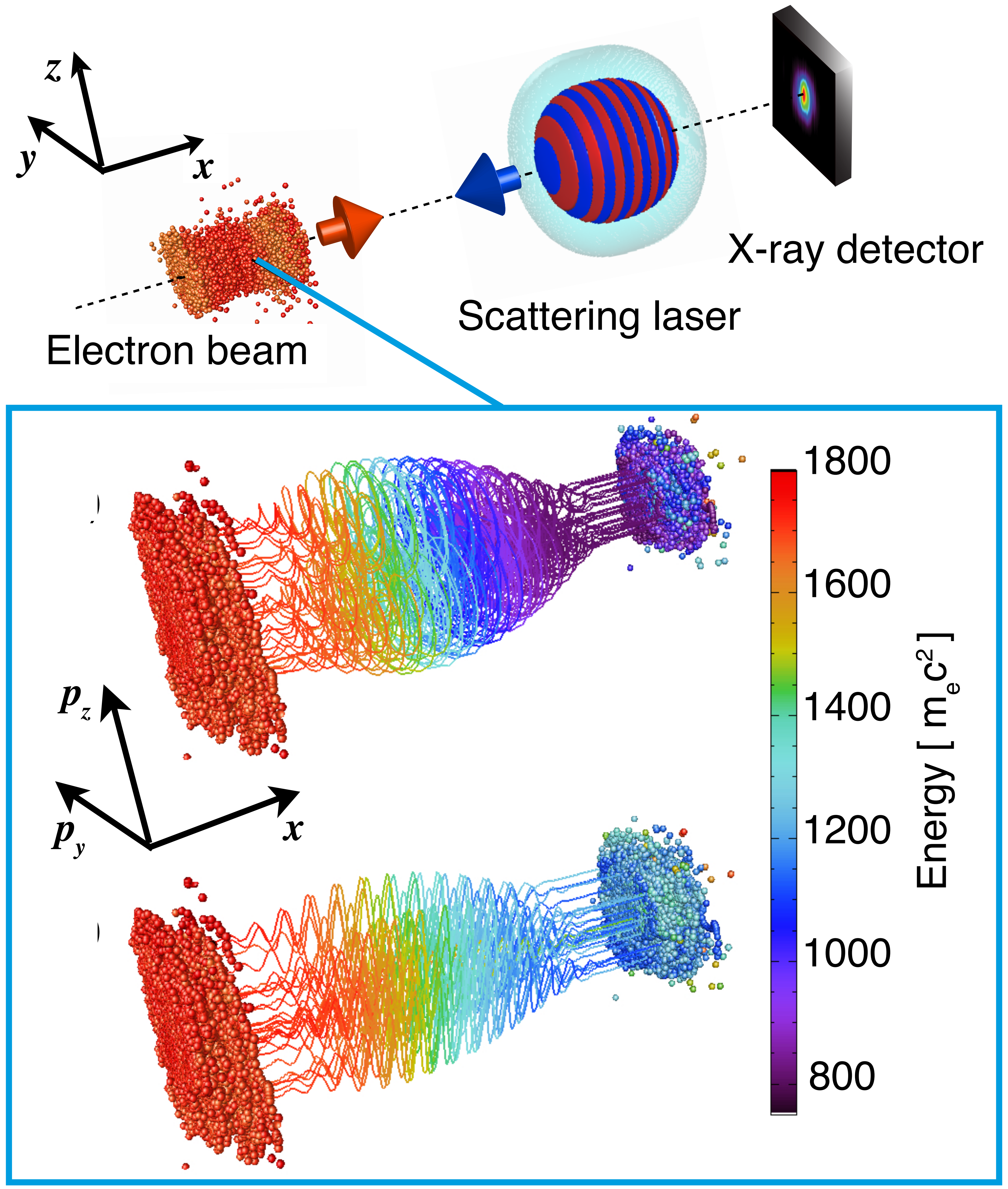
$$\mathbf{E}(\mathbf{x}, t_{det}) = \frac{q_e}{c}\left[\frac{\mathbf{n} \times [(\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}})]}{(1 - \boldsymbol{\beta} \cdot \mathbf{n})^3 R}\right]_{\text{ret}}$$

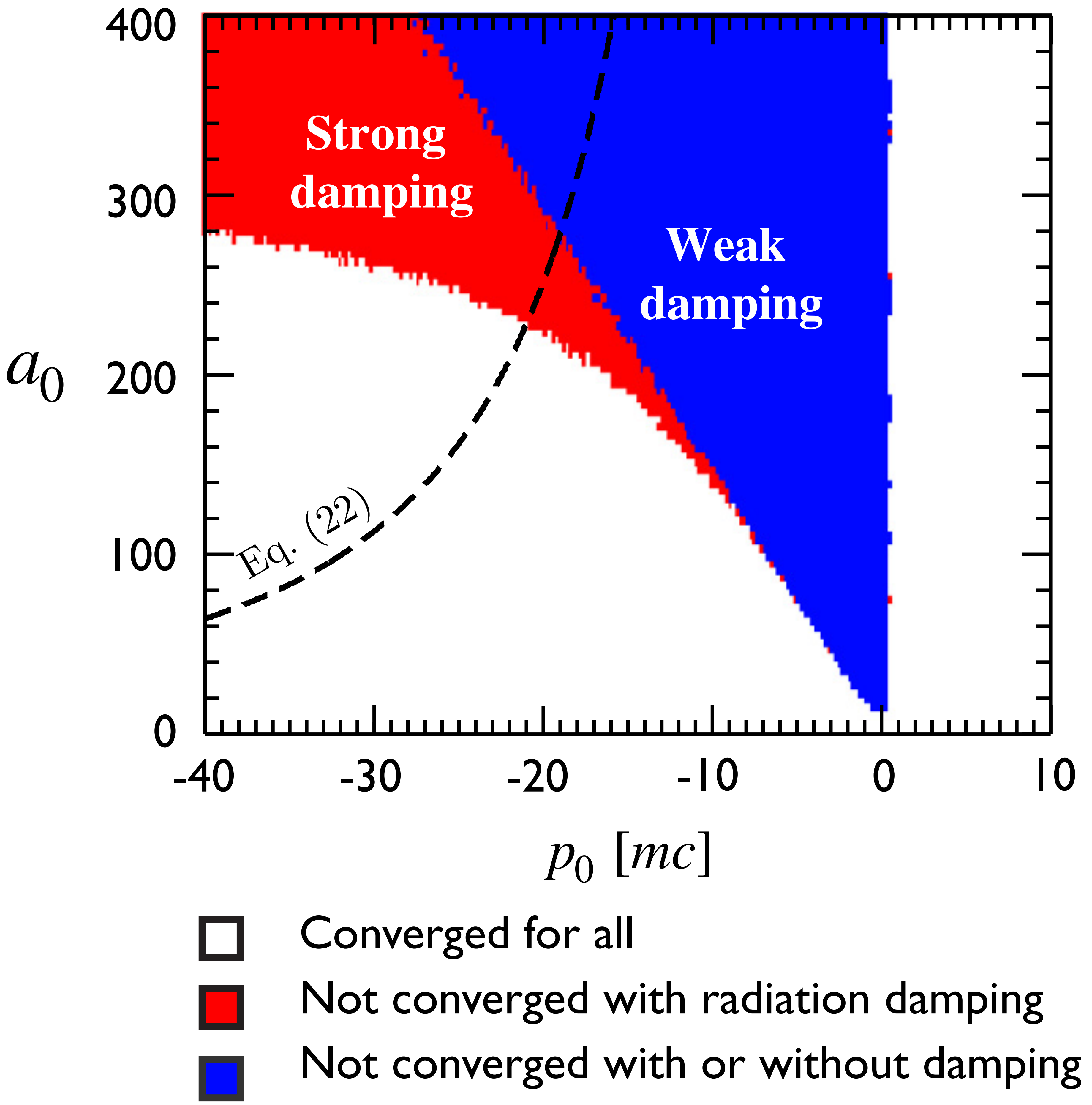


*M. Pardal, *et al*, Comput. Phys. Comm. 285, (2022)

Interacting with a laser, electrons oscillate and lose energy

Convergence criteria for simulating these trajectories depend on whether the radiation damping is strong or not



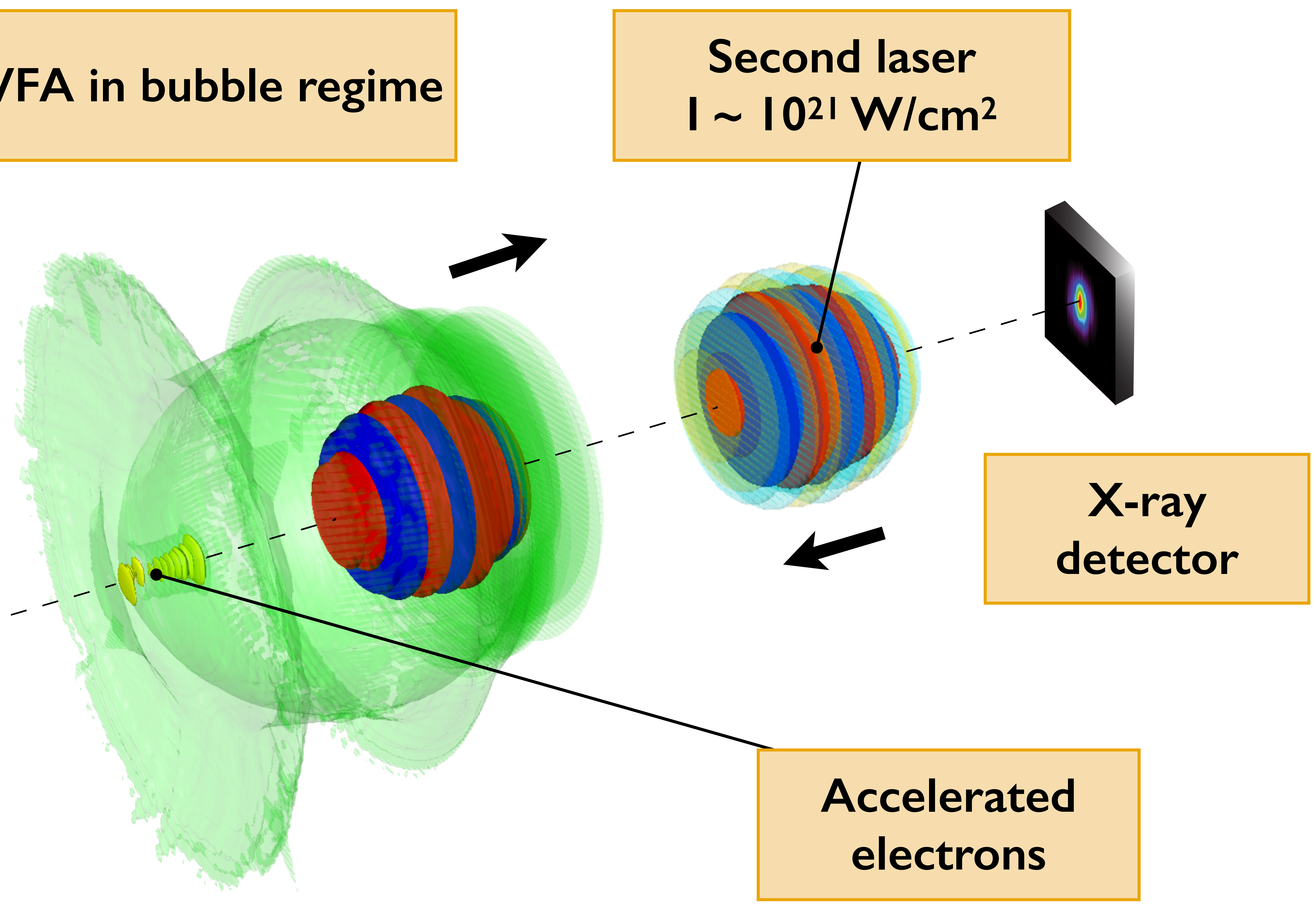


M.Vranic et al., Comput. Phys. Comm. 204, 141-157 (2016)

All-optical acceleration and “optical wiggler"

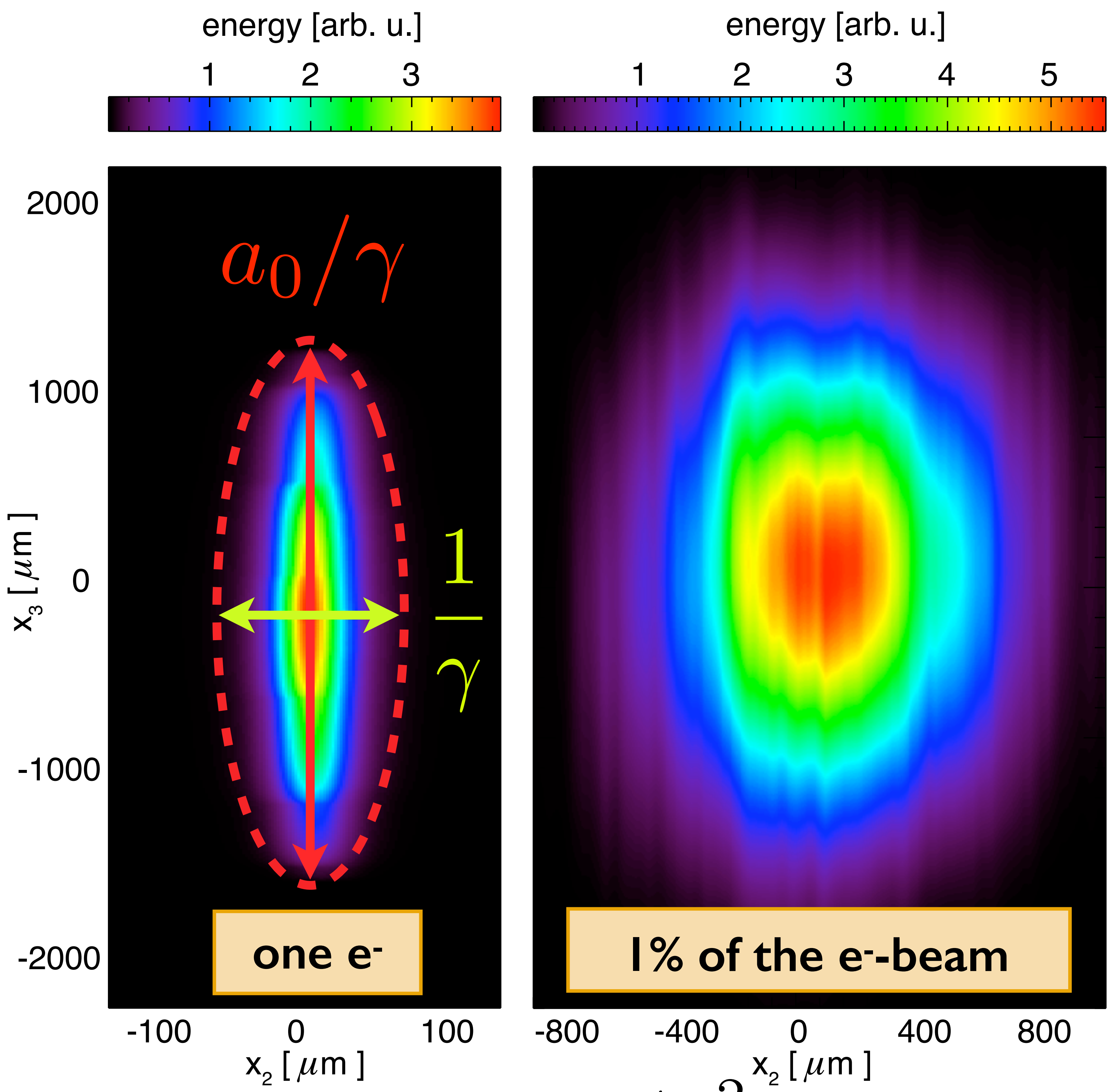
~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm^2

Setup



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

Output radiation on the virtual detector

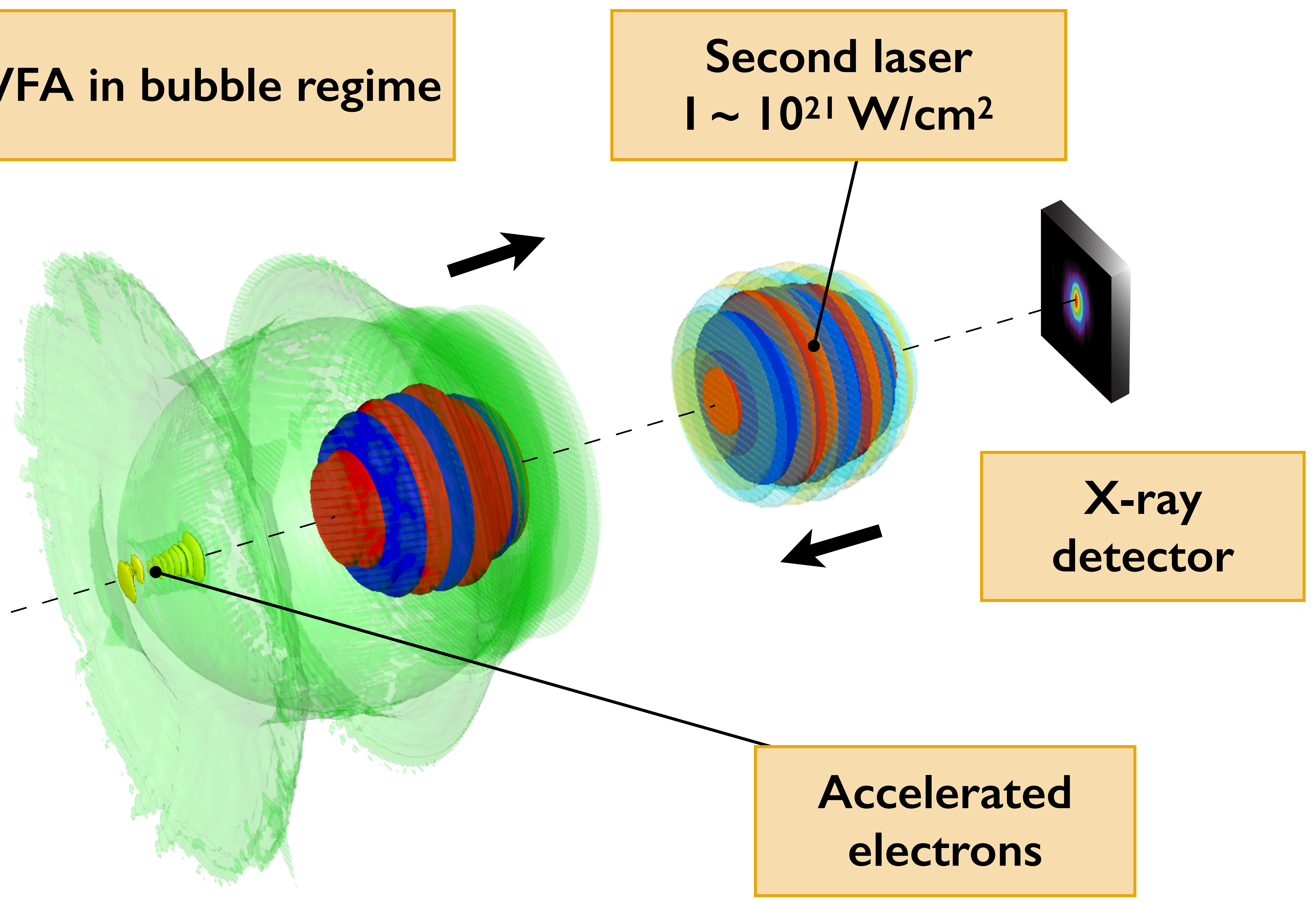


$$\frac{\omega_R}{\omega_L} = \frac{4\gamma^2}{a_0^2/2+1}$$

All-optical acceleration and "optical wiggler"

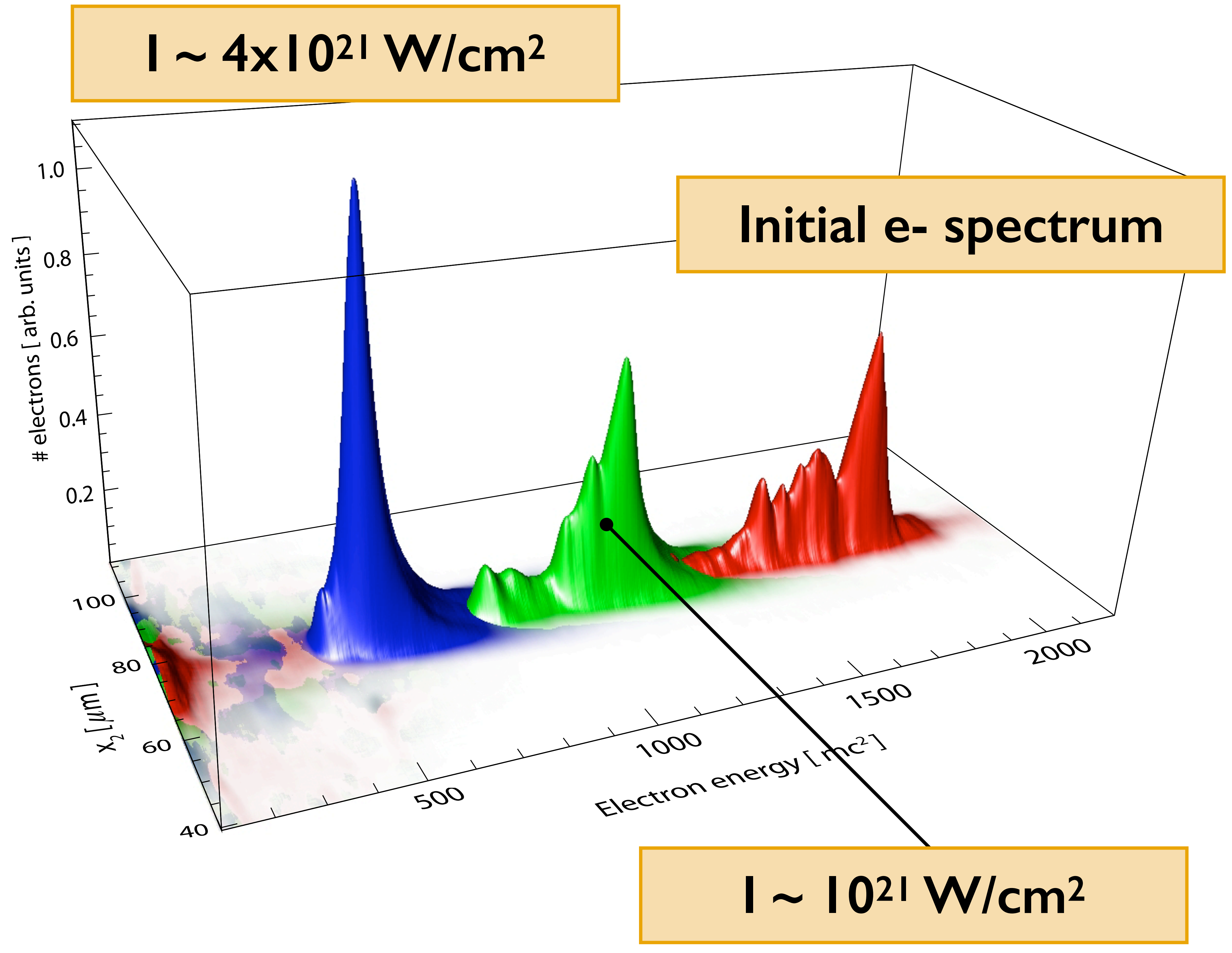
~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm^2

Setup



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

The electrons lose energy in the emission



How much energy can be converted to photons in a laser - electron beam scattering?

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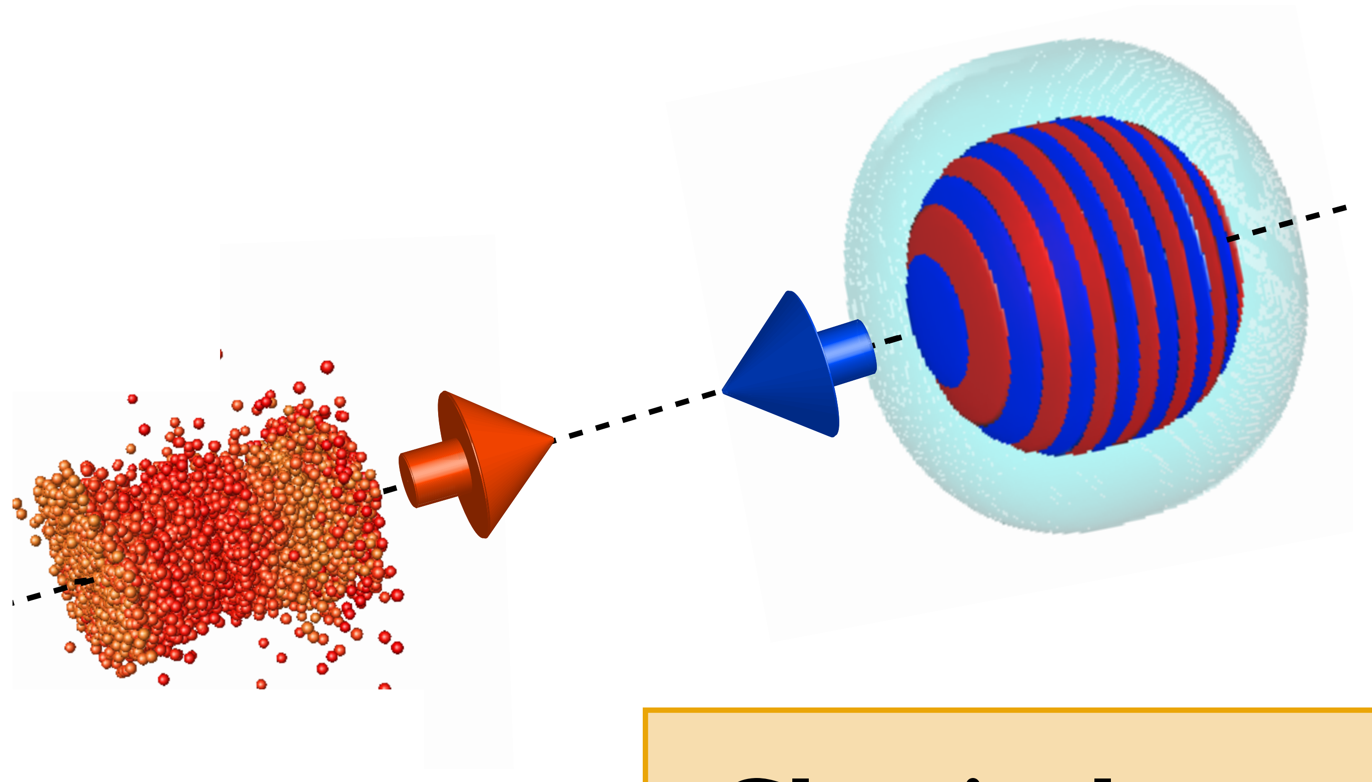
For highly relativistic beams, most of the energy comes from the electrons (rather than the scattering laser)



Classical: $\chi \ll 1$

QED: $\chi \simeq 1$

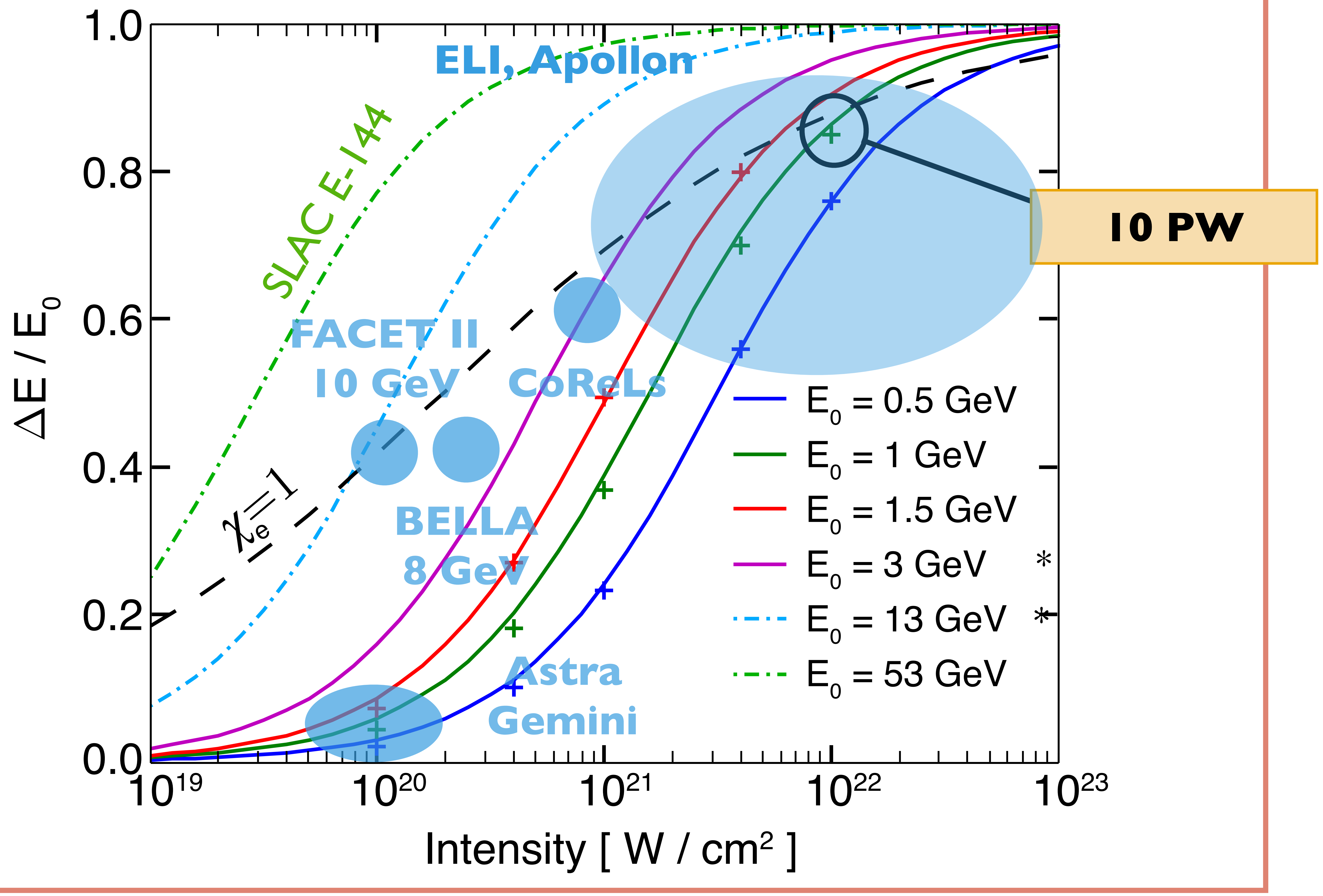
$$\chi \sim \gamma \frac{E}{E_S}$$

$a_0 \sim 10 \qquad I \sim 10^{20} \mathrm{W/cm^2}$

$$\chi \sim \xi_e \,[\mathrm{GeV}] \times \frac{a_0}{100}$$

M.Vranic et al., PRL 113, 134801 (2014)
M.Vranic et al., CPC 204, 141-157 (2016)

Relative energy loss as a function of electron initial energy and the laser intensity (30 fs lasers)



Contents

QED PIC loop in OSIRIS

Osiris

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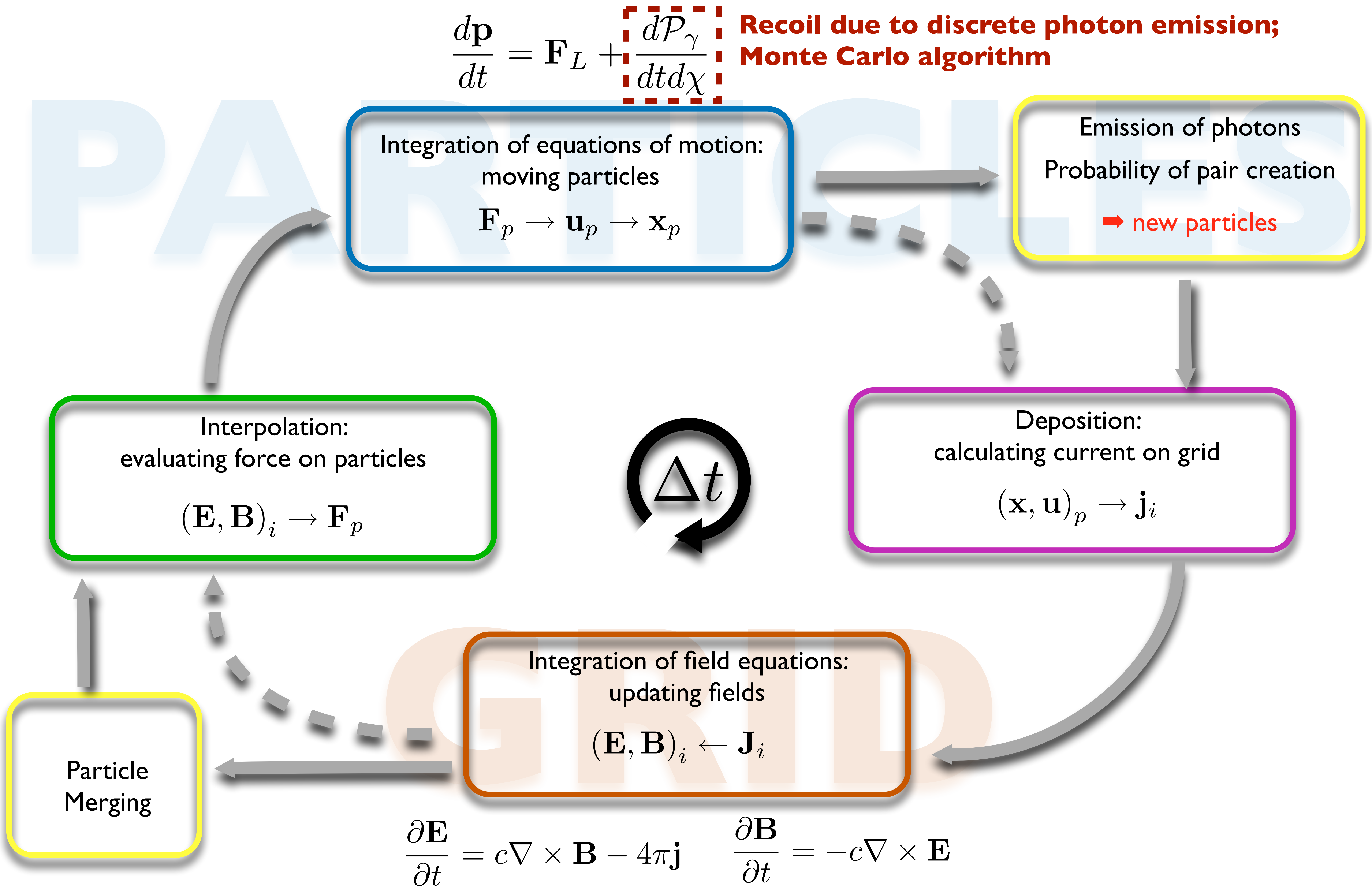
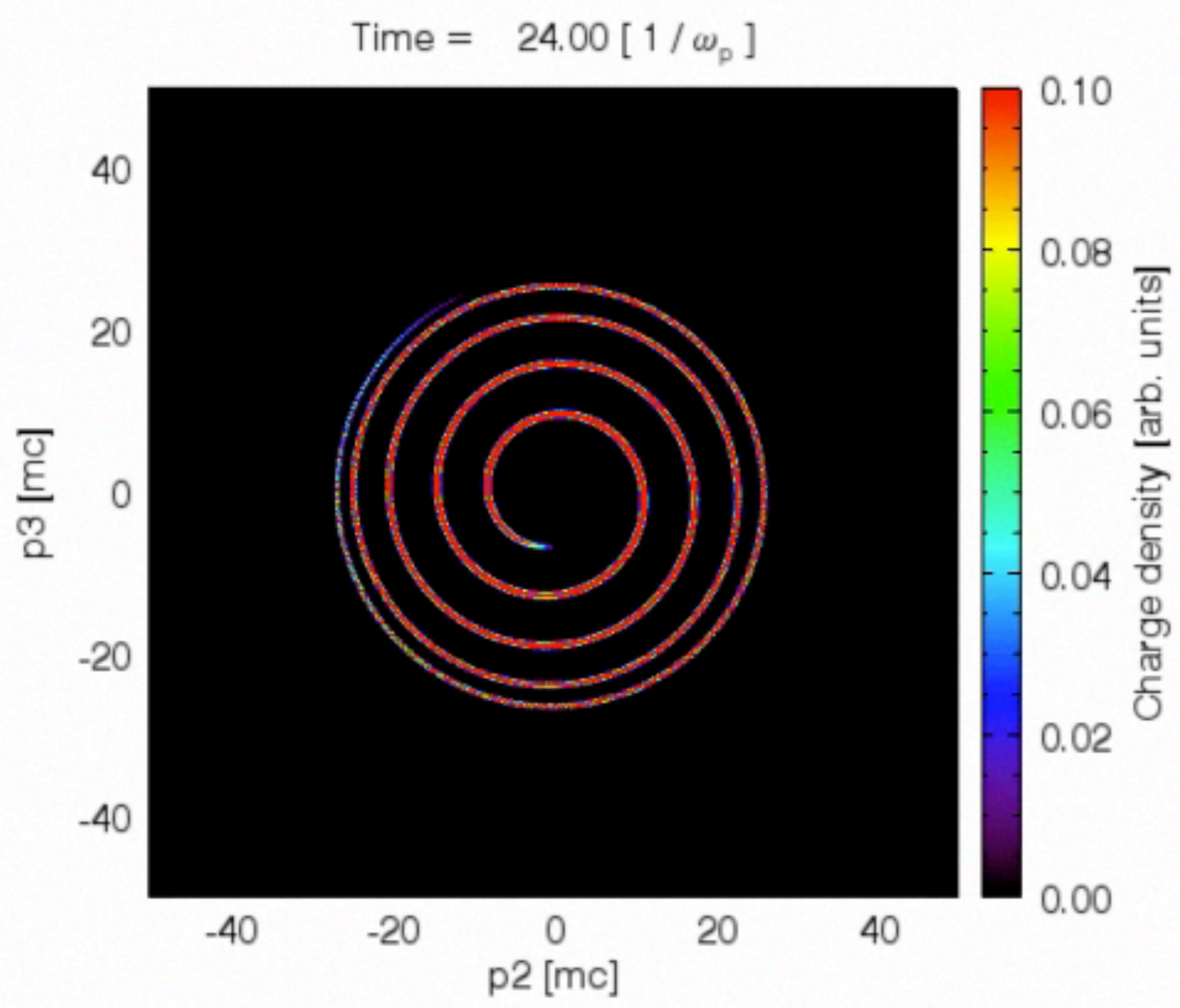


E.N Nerush et al. PRL (2011), C. P. Ridgers et al. , PRL. (2012), N.V. Elkina et al. PRSTAB (2011), A. Gonoskov et al., PRE (2015), T. Grismayer et al., POP (2016), T. Grismayer et al., PRE (2017)

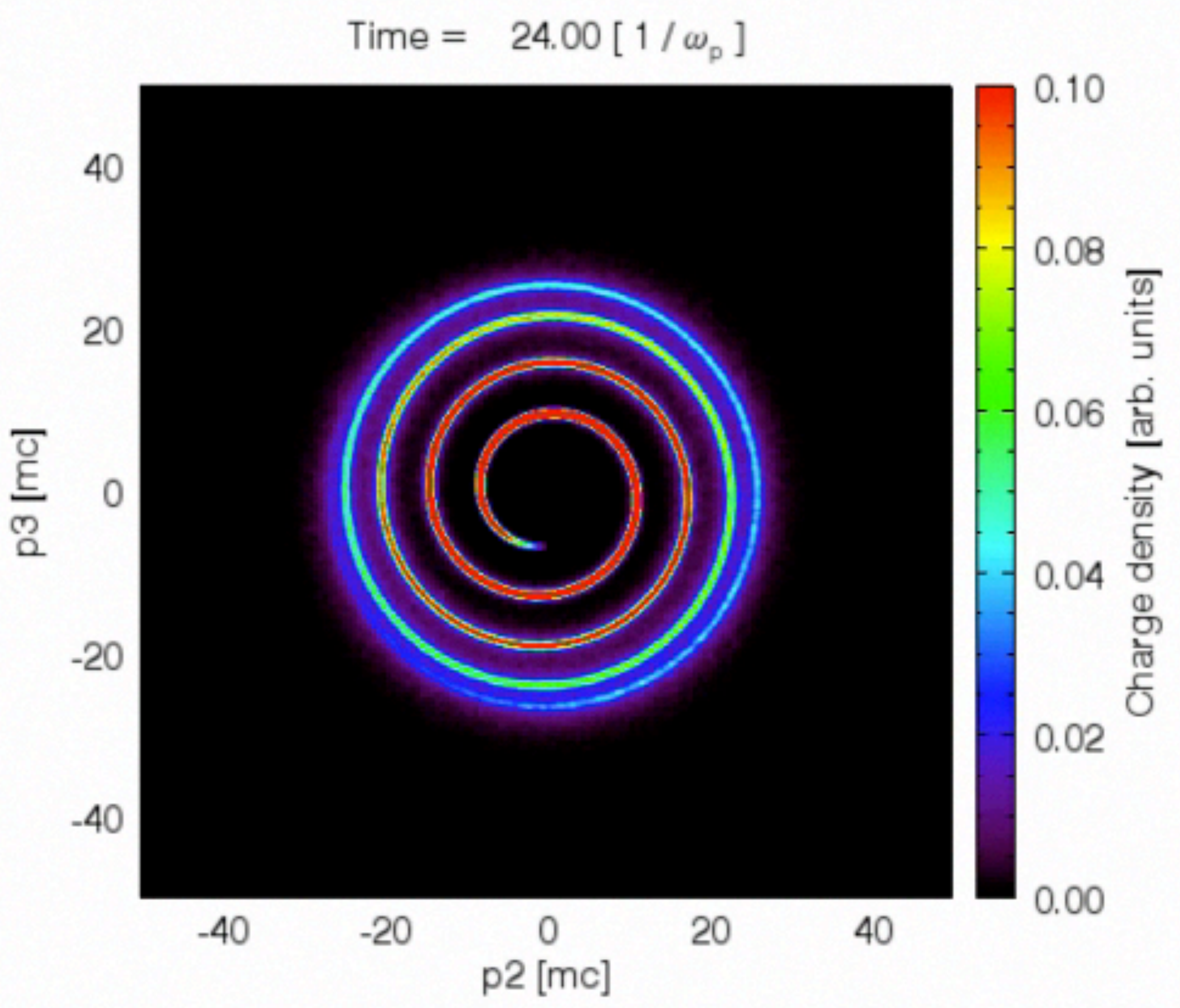
Average angle between the electron momentum and the laseer axis is equal in classical and QED radiation reaction

QED stochasticity introduces fluctuations in the distribution function that persist after the interaction

Classical RR

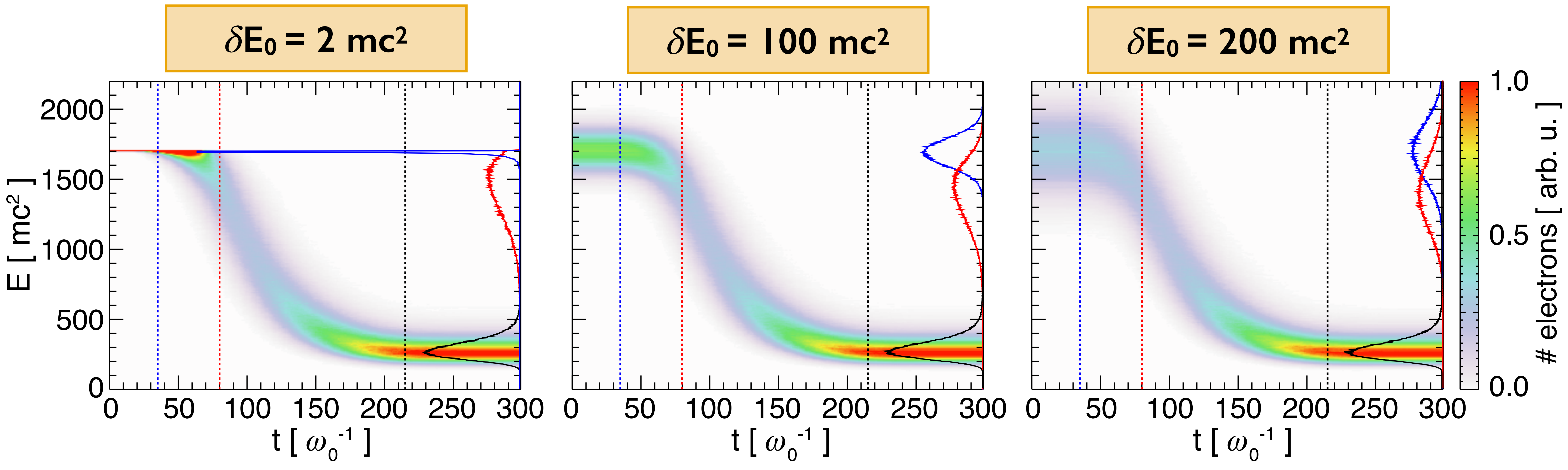


Quantum RR



Expected value for final energy spread emerges from stochastic diffusion

Energy vs. time for interaction with a 150 fs laser at a_0 = 27



δE_F = 67 mc²

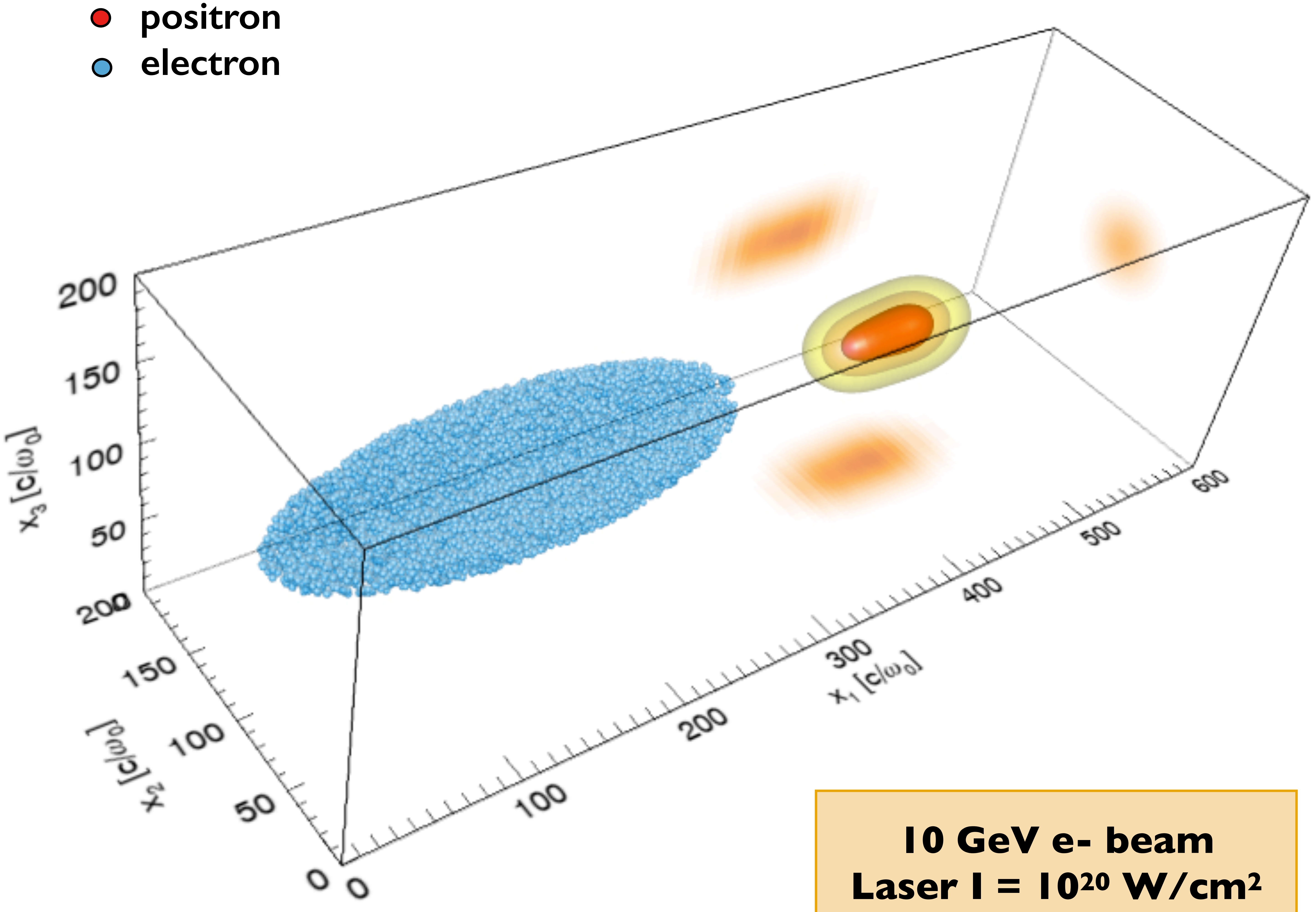
Final energy spread can be predicted analytically*

$$\sigma_F^2 \lesssim 1.455 \times 10^{-4} \sqrt{I_{22}} \frac{\gamma_0^3}{(1 + 6.12 \times 10^{-5} \gamma_0 \; I_{22} \; \tau_0[\text{fs}])^3}$$

$$I_{22} = I \, [10^{22} \text{ W/cm}^2]$$

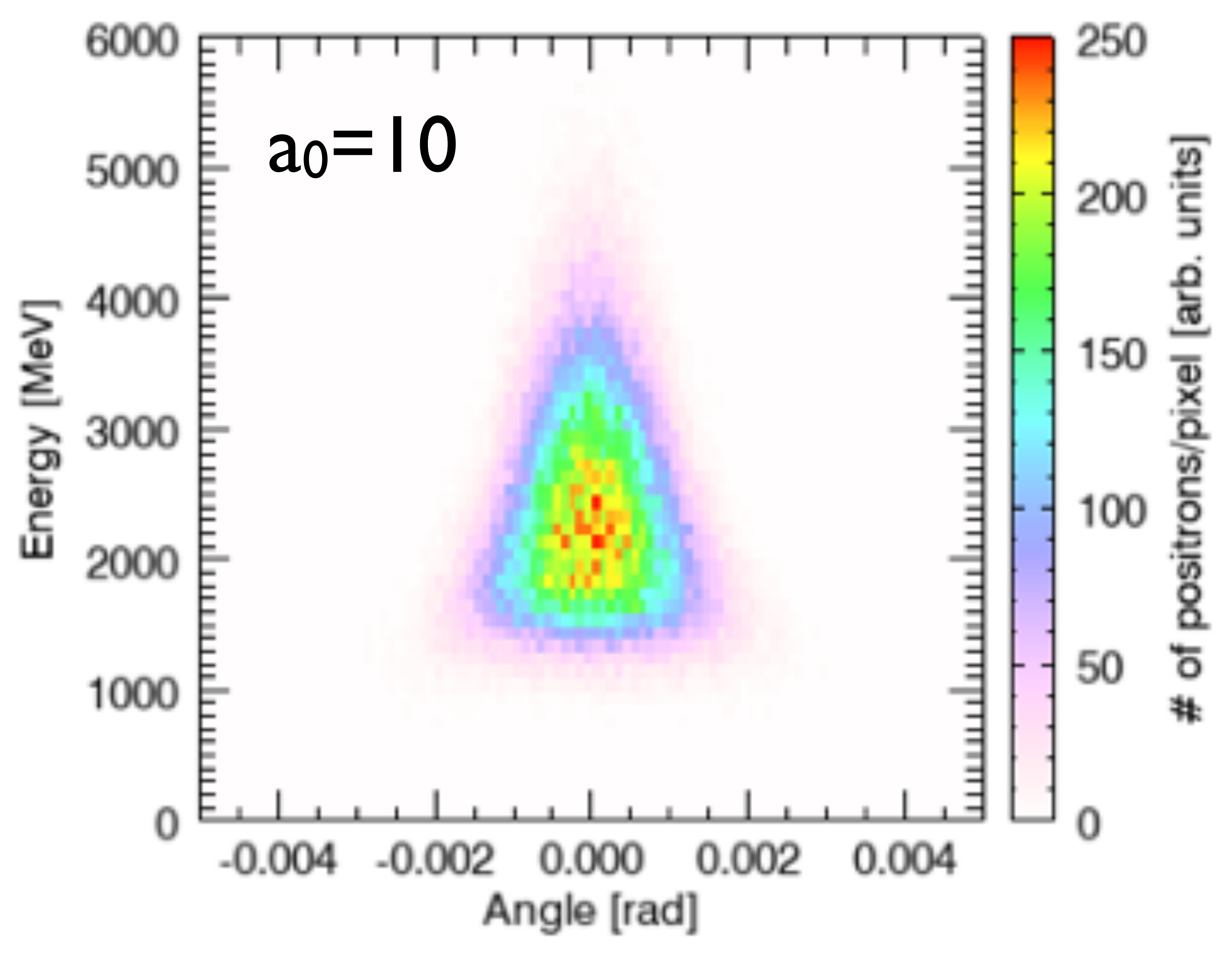
* M.Vranic et al., NJP 18, 073035 (2016)

Modeling the SFQED experiment at FACET-II



10 GeV e- beam
Laser I = 10^{20} W/cm²

Positrons: energy vs angle

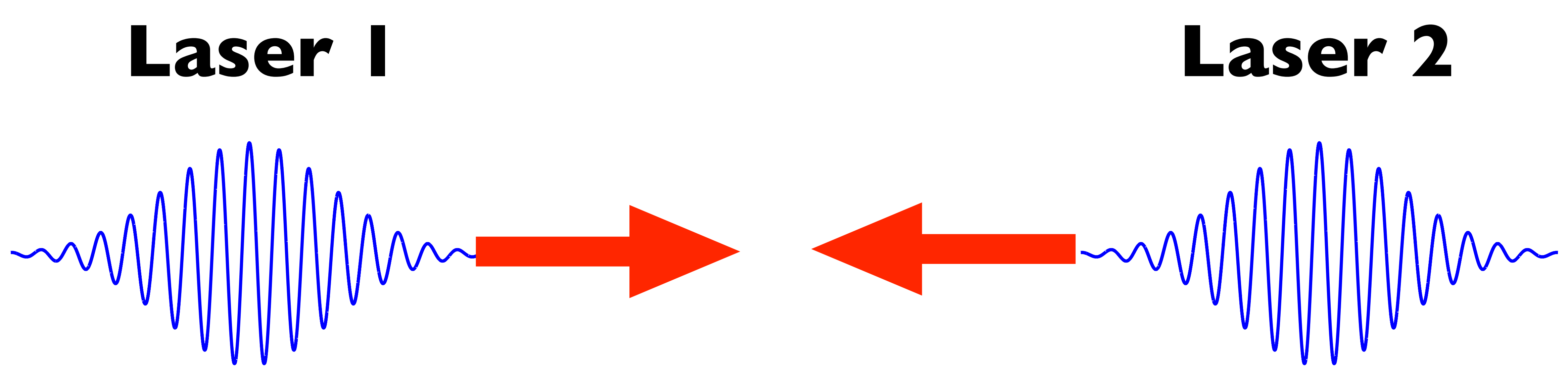


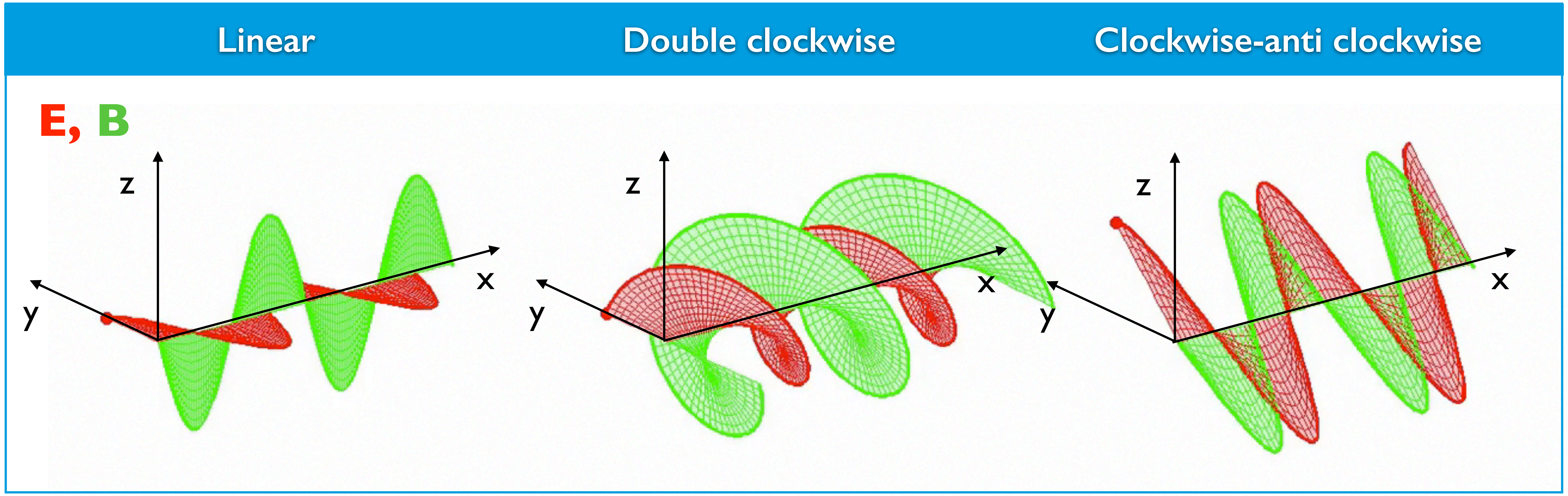
1 nC electron beam gives ~ 0.2 pC of positrons

Contents

Standing wave configurations for QED cascades

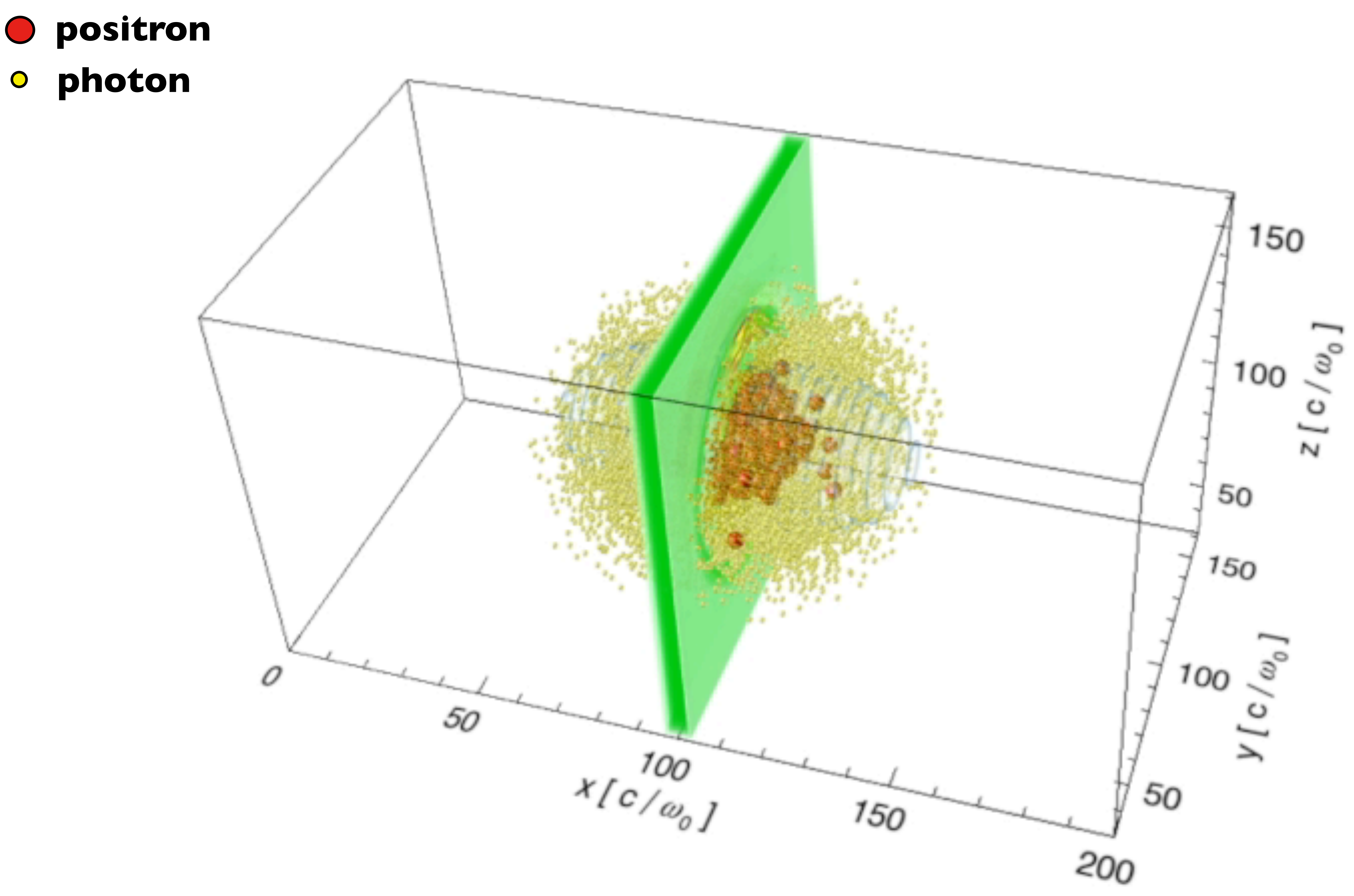
Pairs can get re-accelearted and initiate a new cycle of gamma-ray emission and pair production





A.R Bell and J. G Kirk PRL, 101, 200403 (2008); M.A Fedotov et al. PRL 105, 080402 (2010)
E.N Nerush et al., 106 035201, PRL (2011); T. Grismayer et al., POP 23, 056706 (2016)

Positrons from a hydrogen ice target



Target parameters

initial n =10 nc
1 μm thickness

Laser parameters

$I \sim 10^{24}$ W/cm^2
30 fs, 1 μm wavelength

M.Vranic et al., POP **26**, 053103 (2019)

Macroparticle merging algorithm

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M. Vranic et al, CPC 2015

Calculate the number of merging cells and their size

Calculate the number of particles within each merging cell

Find the p_{min} and p_{max} of the particles in every merging cell

↓

Bin the momentum space

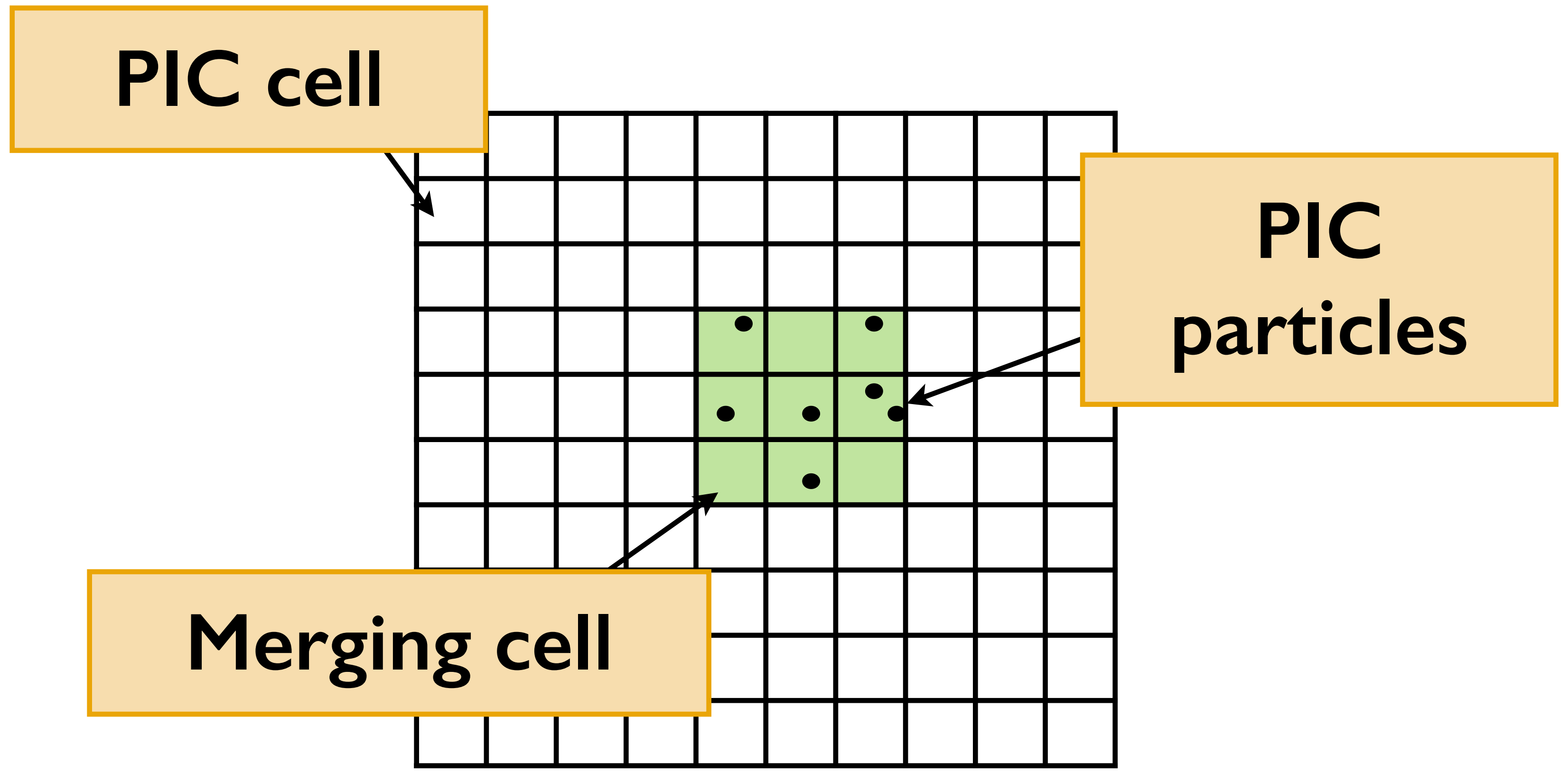
Distribute the particles of every merging cell in its momentum bins

↓

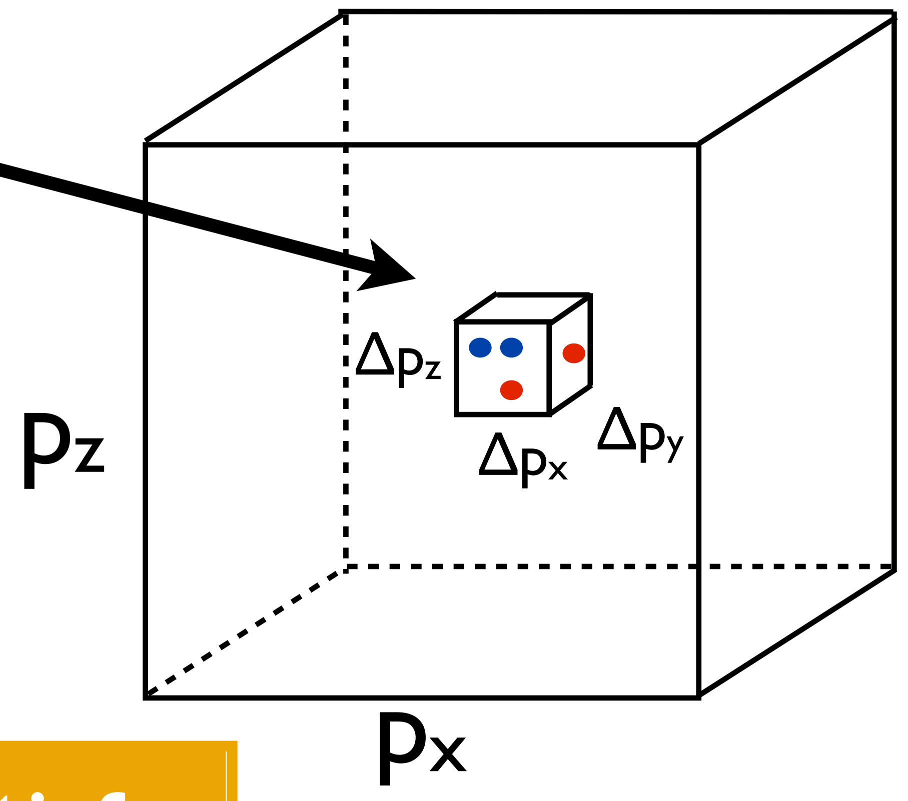
Calculate the total weight, momentum, energy in every momentum bin

Merge the particles in every momentum bin into 2 new particles

Remove all the former particles



Particles close
- in real space
- in momentum space

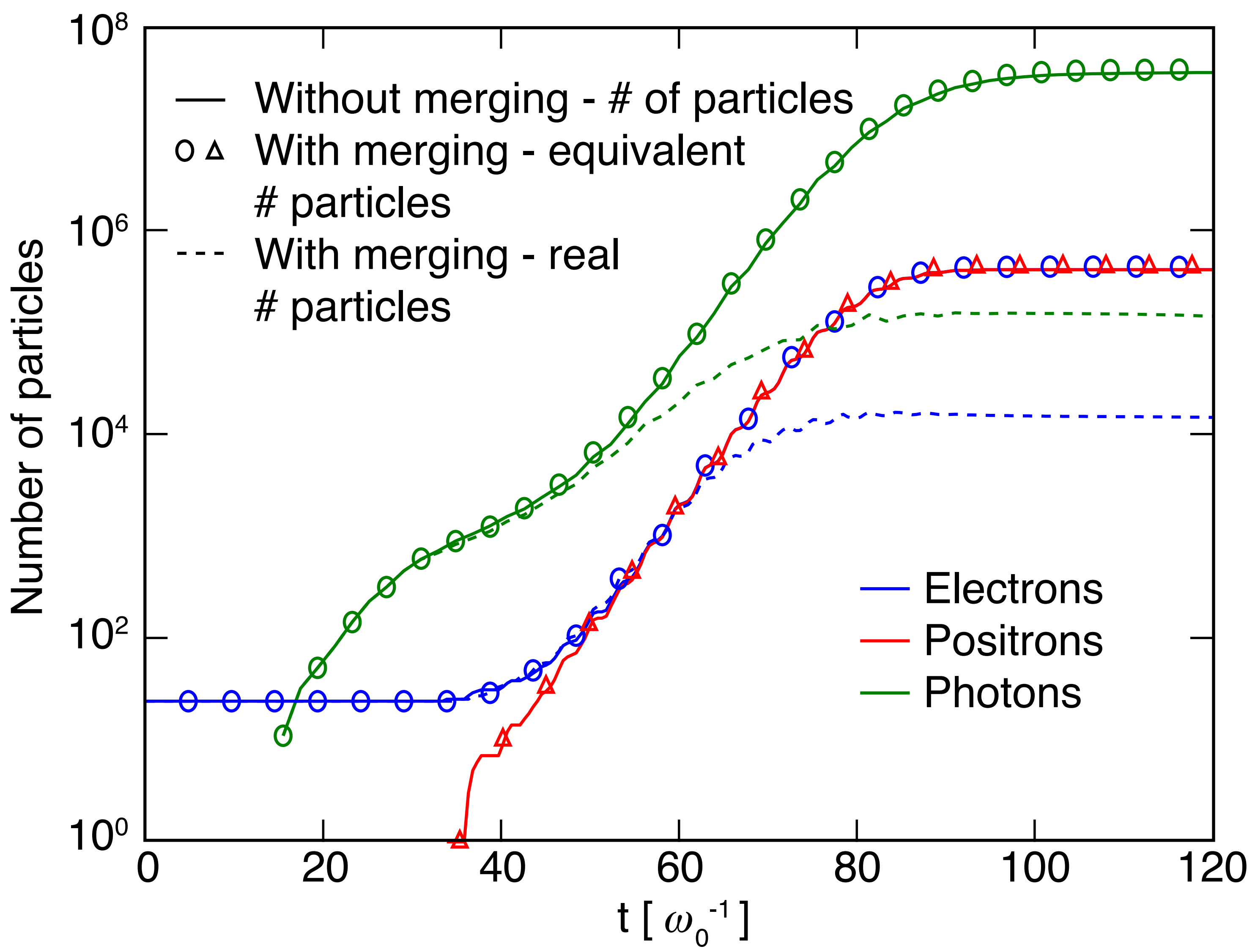


Equations to satisfy

$$w_t = w_a + w_b \ ,$$
$$\vec{p}_t = w_a \vec{p}_a + w_b \vec{p}_b$$
$$\epsilon_t = w_a \epsilon_a + w_b \epsilon_b$$

Example: cascade simulation

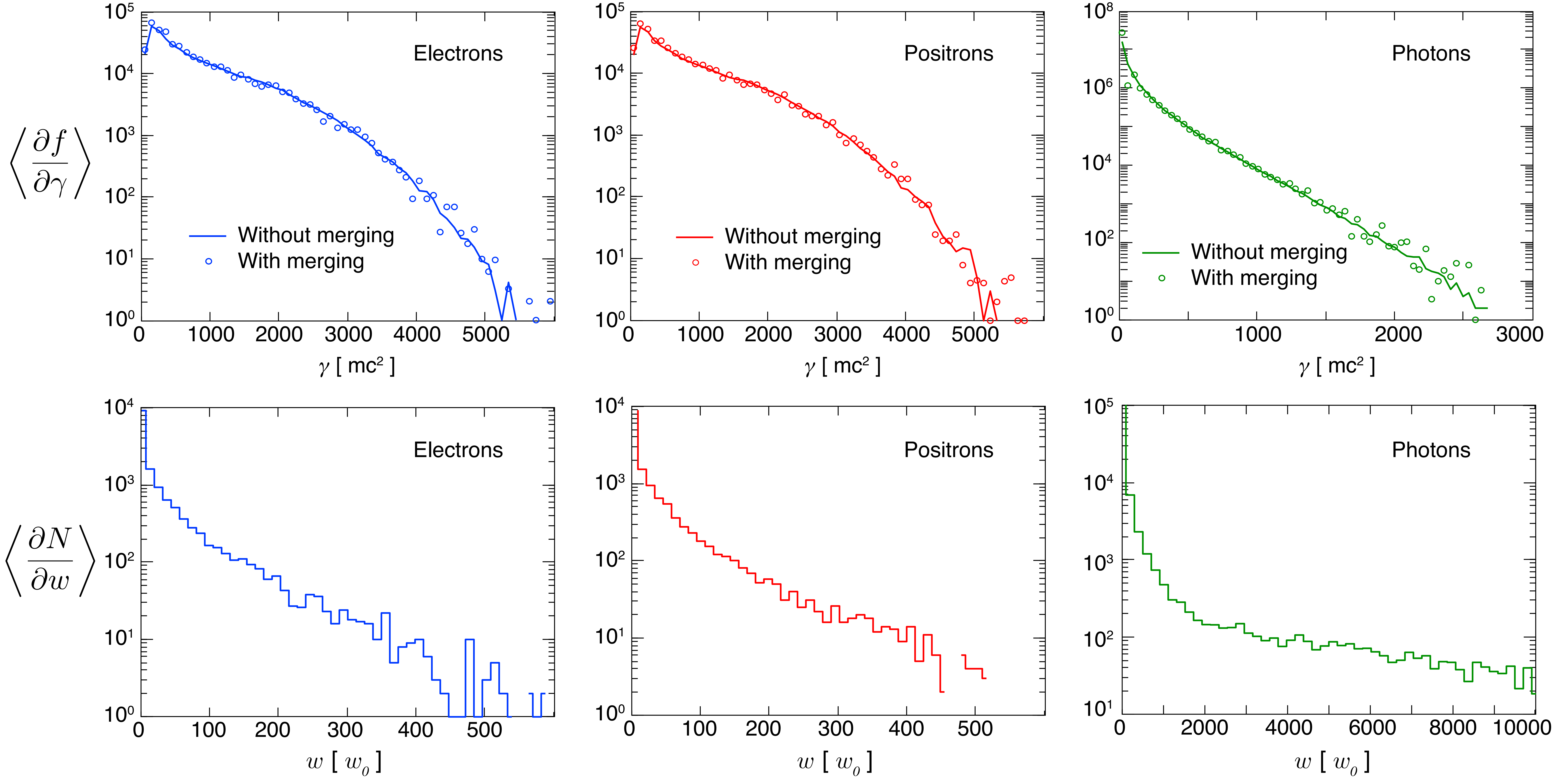
- ➡ two colliding lasers
- ➡ a_0 = 1000, λ = 1 um
- ➡ τ = 32 fs, W_0 = 3.2 um



Same results, 30x faster sim, 100x fewer particles in the end

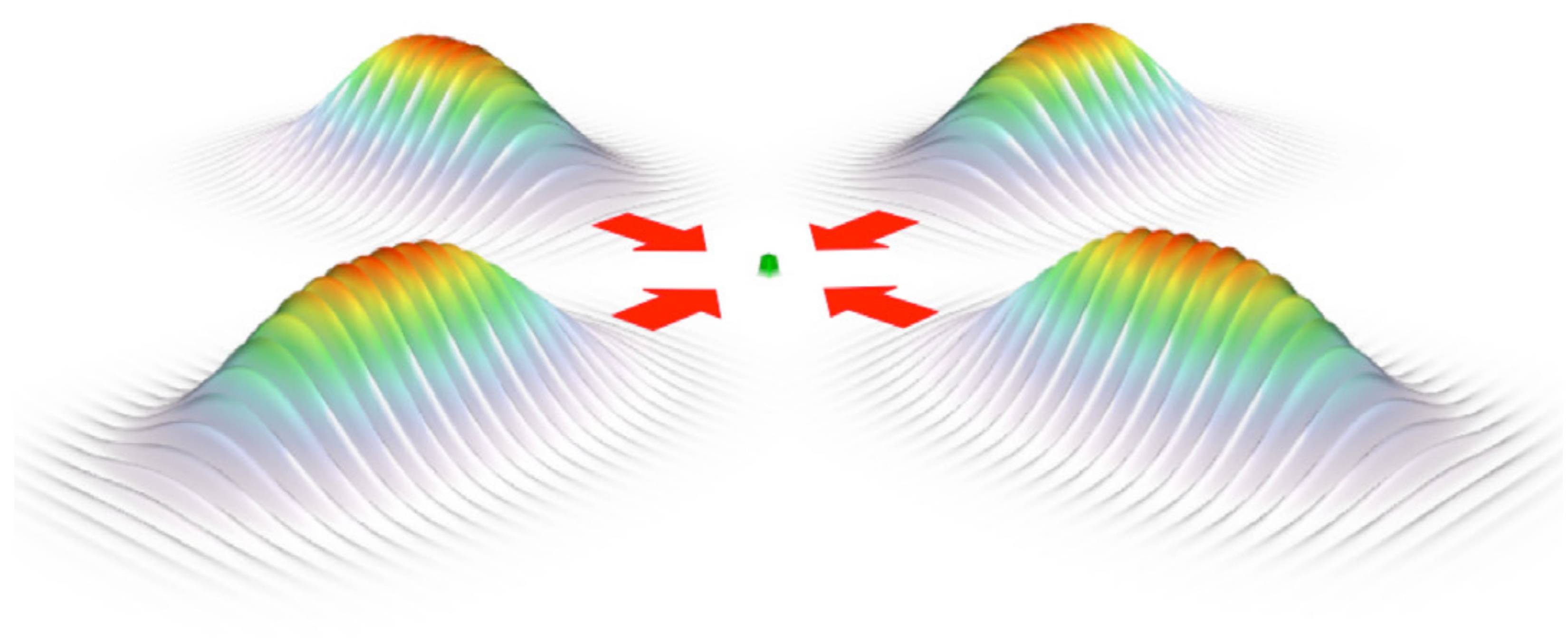
The physics must not be affected by the coalescence of particles

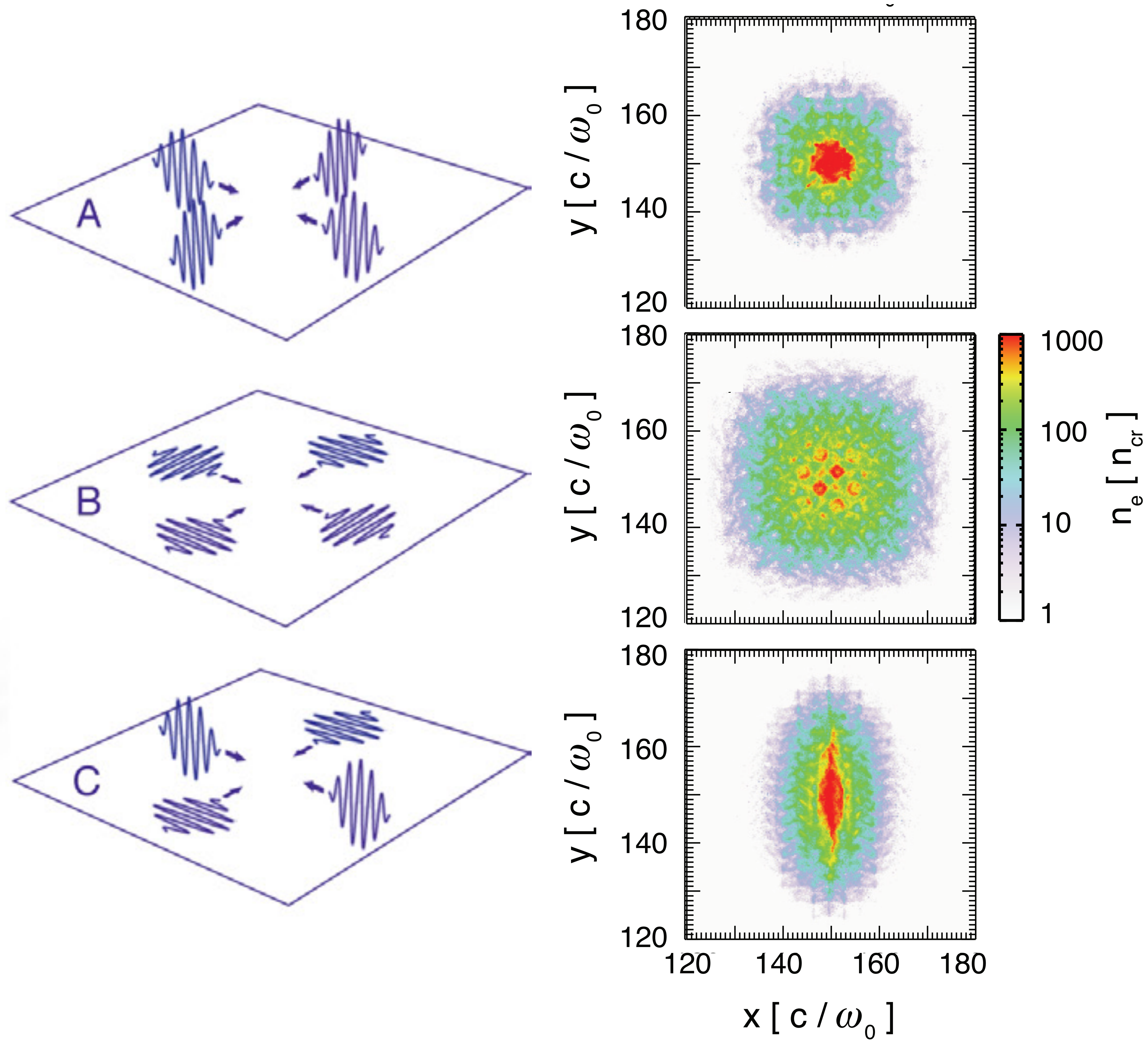
Moments of the distribution functions are recovered even with several orders of magnitude differences in particle weights



QED cascades with multiple laser pulses

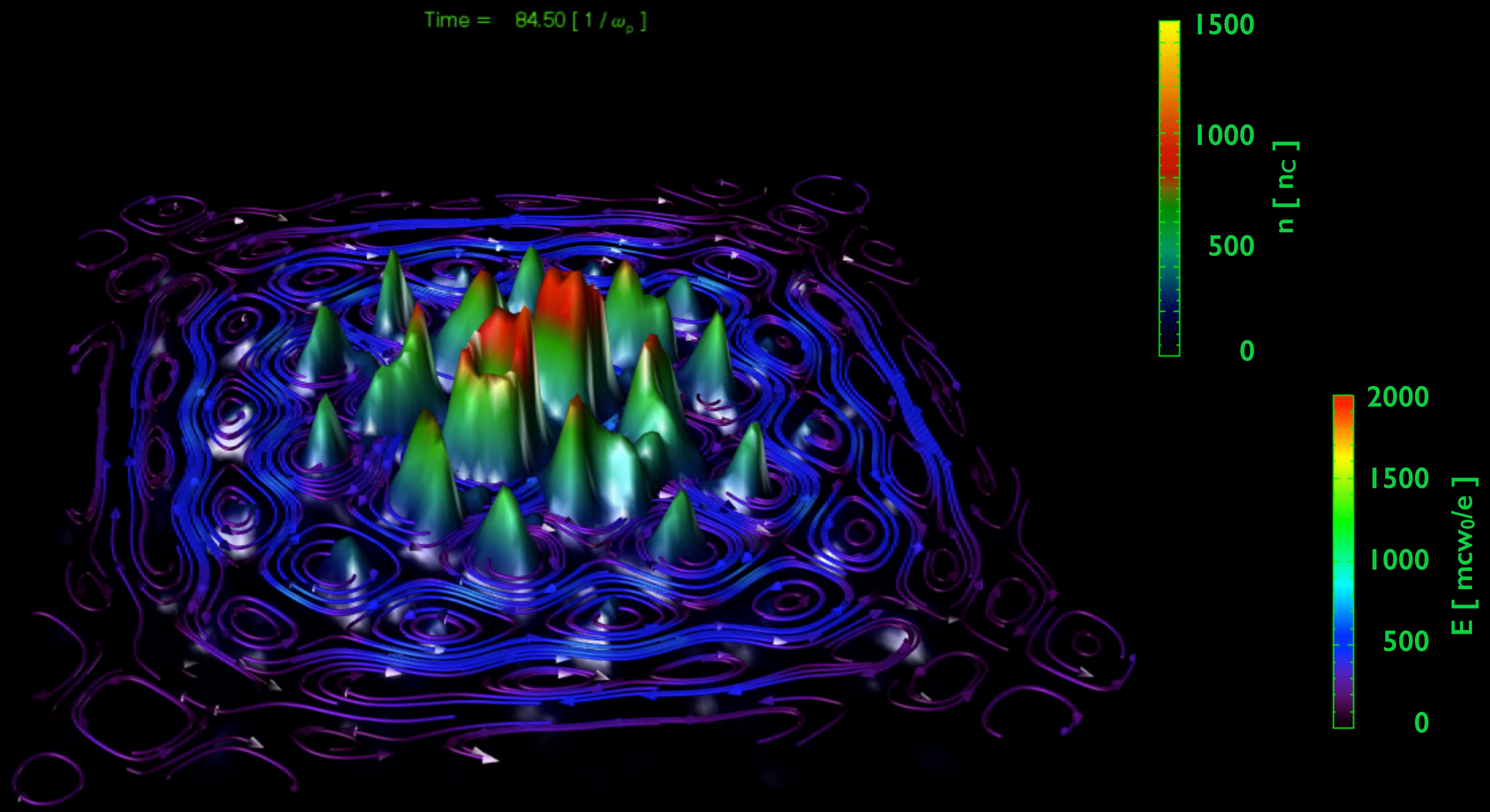
Different polarisation combinations yield different microstructures





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

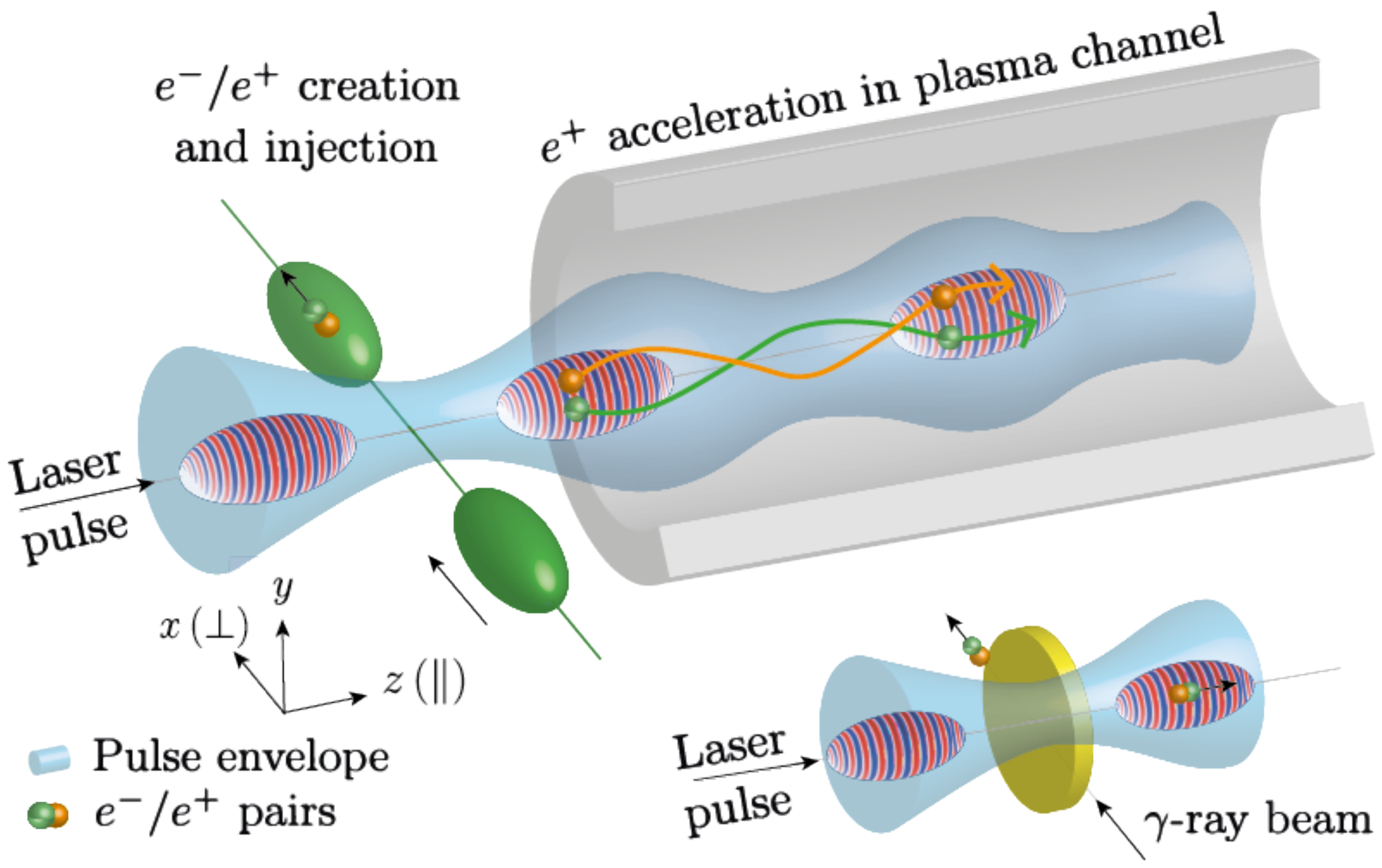
Enough plasma is produced to disrupt the 2D standing wave



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

Modelling geometry: quasi-3D

Some problems cannot be simulated in full-scale in 3D geometry, even in the biggest supercomputers



B. Martinez et al, Phys. Rev. AB 26, 011301 (2023)

Quasi-3D: Fourier decomposition in azimuthal modes

Fields are decomposed $\mathbf{F} = \mathscr{R}\left\{\sum_{m\geq 0} \mathbf{F}(r,z)e^{im\phi}\right\}$

The grid is in cylindrical coordinates (z, r, ϕ)

Axisymmetric self-generated channel fields, mode $m = 0$

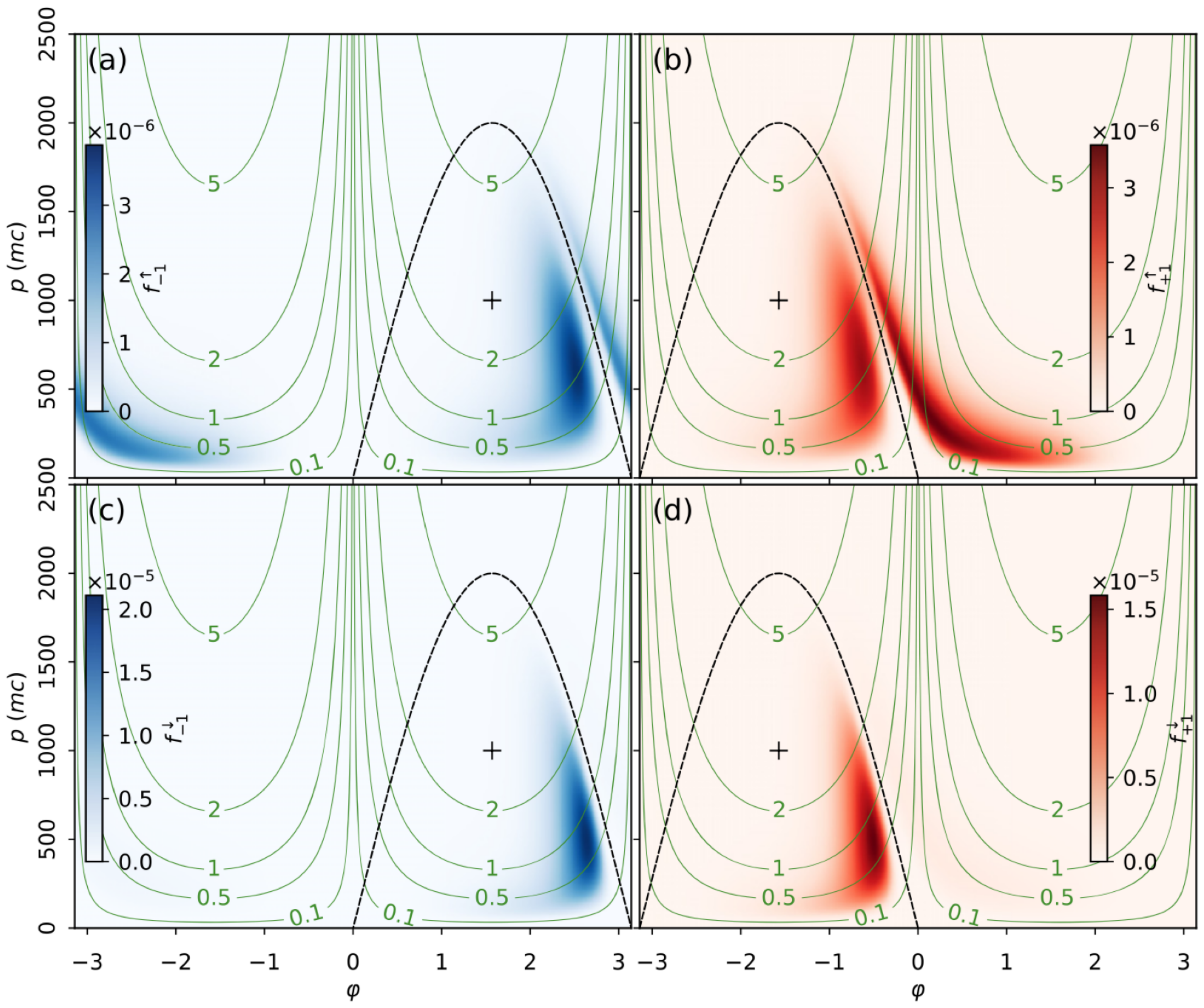
Non-axisymmetric linearly polarised laser field, mode $m = 1$

A. Lifschitz et al., JCP **228**(5), 1803-1814 (2009)
A. Davidson et al., JCP **281**, 1063-1077 (2015)

Quasi-3D is more than 2D cylindrical
It has the correct 3D laser field evolution!

Spin polarisation module

Includes spin precession and spin-flip correction to QED emission and pair creation rates



D. Seipt, et al., New J. Phys. 23 053025 (2022)

Applied to intense laser-plasma interactions and identified macroscopic signatures for experiments.

Q. Qian et al, to be sumbitted

OSIRIS-GR: Extreme plasmas

Framework

- Massively Parallel, Fully General-Relativistic Particle-in-cell code
- Adapted to curvilinear coordinates
- Global magnetospheric simulations with multiple pair production regions
- Charge conservation at every timestep

~1M CPUh simulations running @ LUMI supercomputer

R. Torres *et al.*, in prep. (2023)

Thank you!

The next generation of laser pulses requires the next generation of plasma modeling.

Numerical simulations at the extreme regime require different physics models and higher resolution (especially a smaller timestep).

QED cascades can create abundant plasma (exponentially growing number of particles). Performance enhancements, creative geometries and coalescence schemes are critical.

CPU, GPU, Exascale…