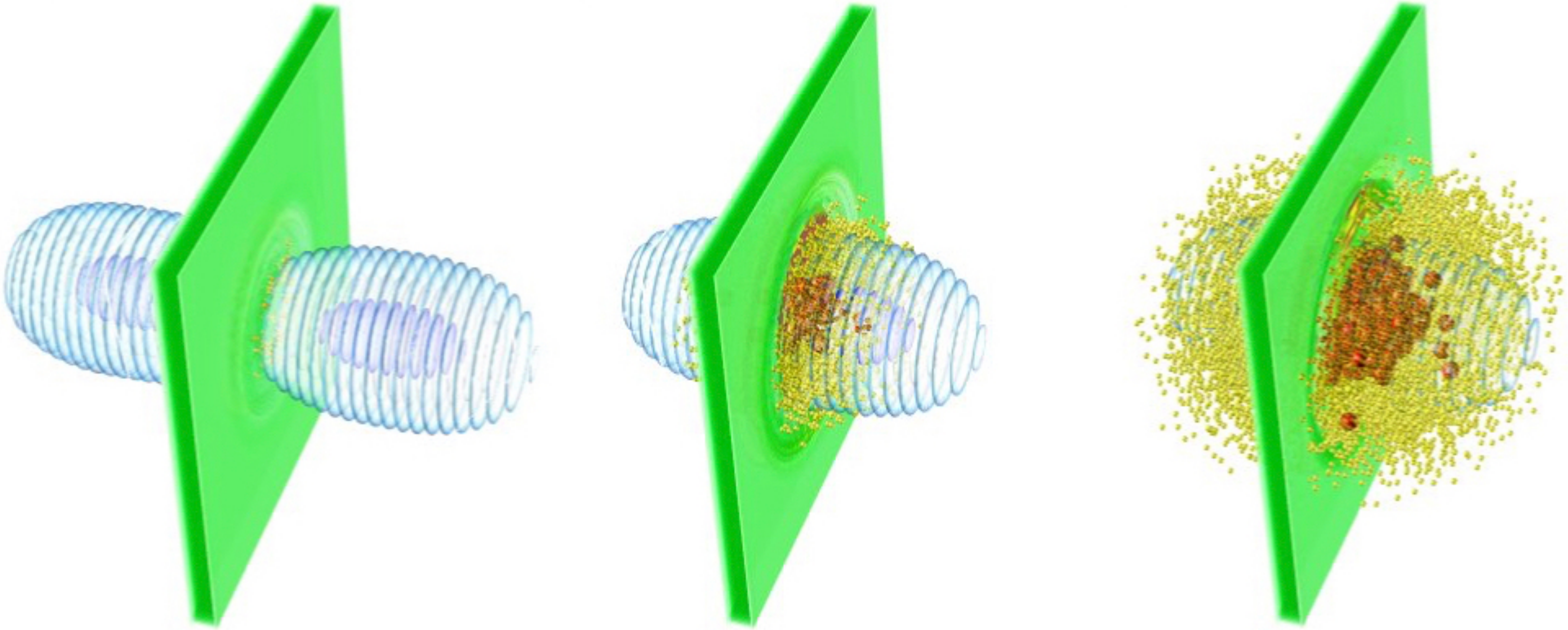
Extreme plasmas on a supercomputer

Marija Vranic

GoLP / Instituto de Plasmas e Fusão
Nuclear Instituto Superior Técnico,
Lisbon, Portugal

epp.tecnico.ulisboa.pt || **golp**.tecnico.ulisboa.pt



Funded by the European Union

Acknowledgements

TÉCNICO LISBOA


Ada King, Countess of Lovelace

PRACE

Acknowledgements

Work in collaboration with:

IST: T. Grismayer, J. L. Martins, F. Del Gaudio, R. A. Fonseca, L. O. Silva (IST)

ELI: M. Jirka, O. Klimo, G. Korn, S. Weber

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

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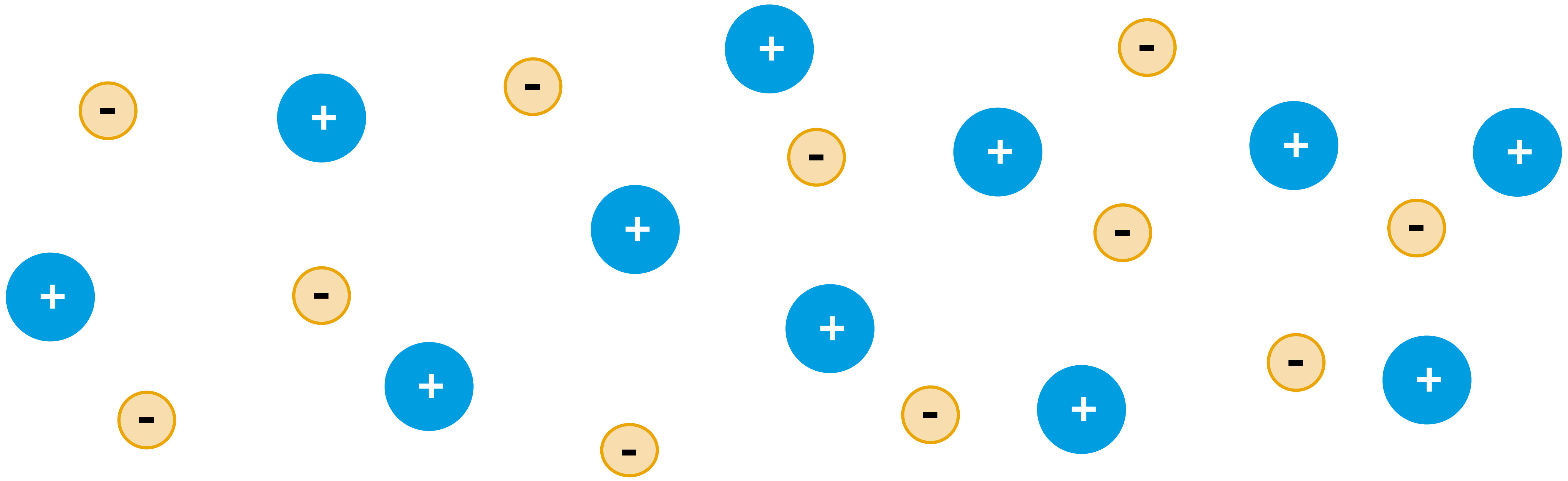
What is a plasma?



- Plasma is a quasi-neutral ionised gas formed by an approximately equal number of electrons and ions

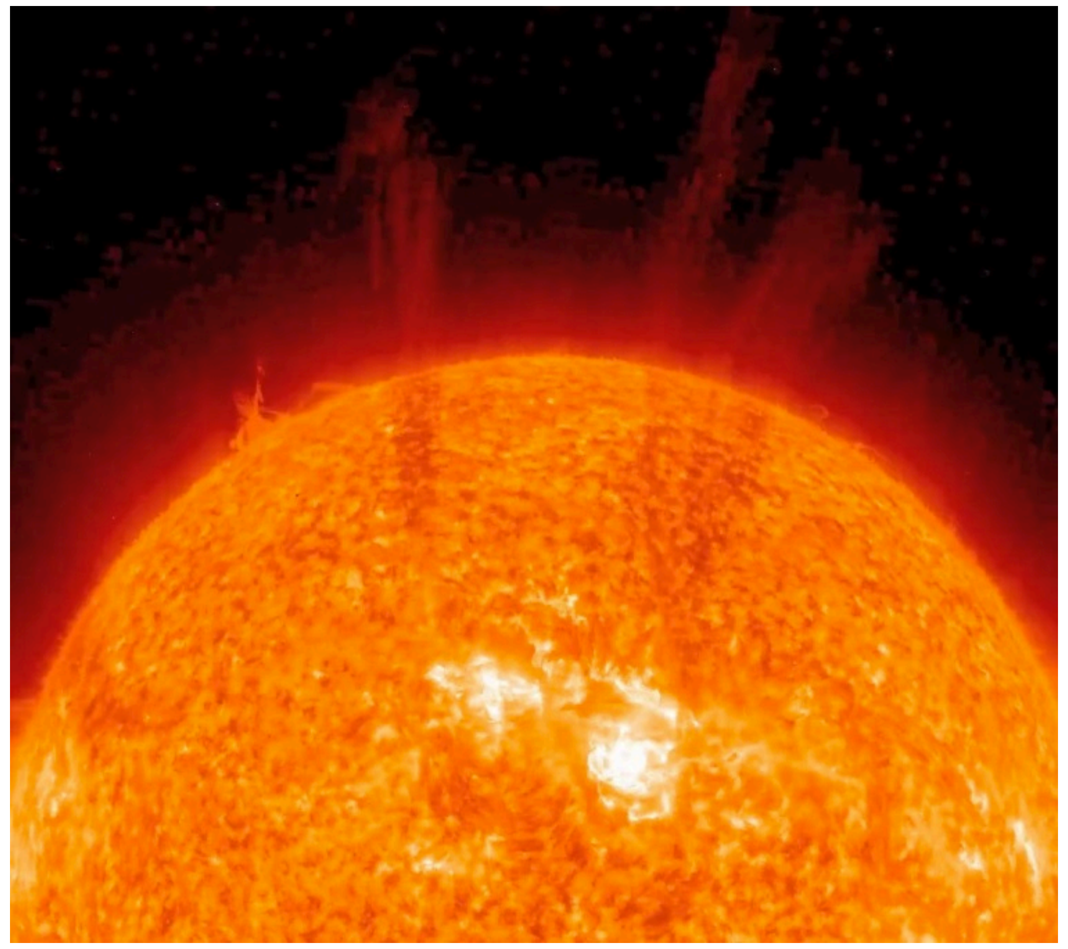
- Over 99% of the visible Universe is in the plasma state

- Most (or all) molecular bonds are broken

- In a way, plasma is an "already destroyed" material

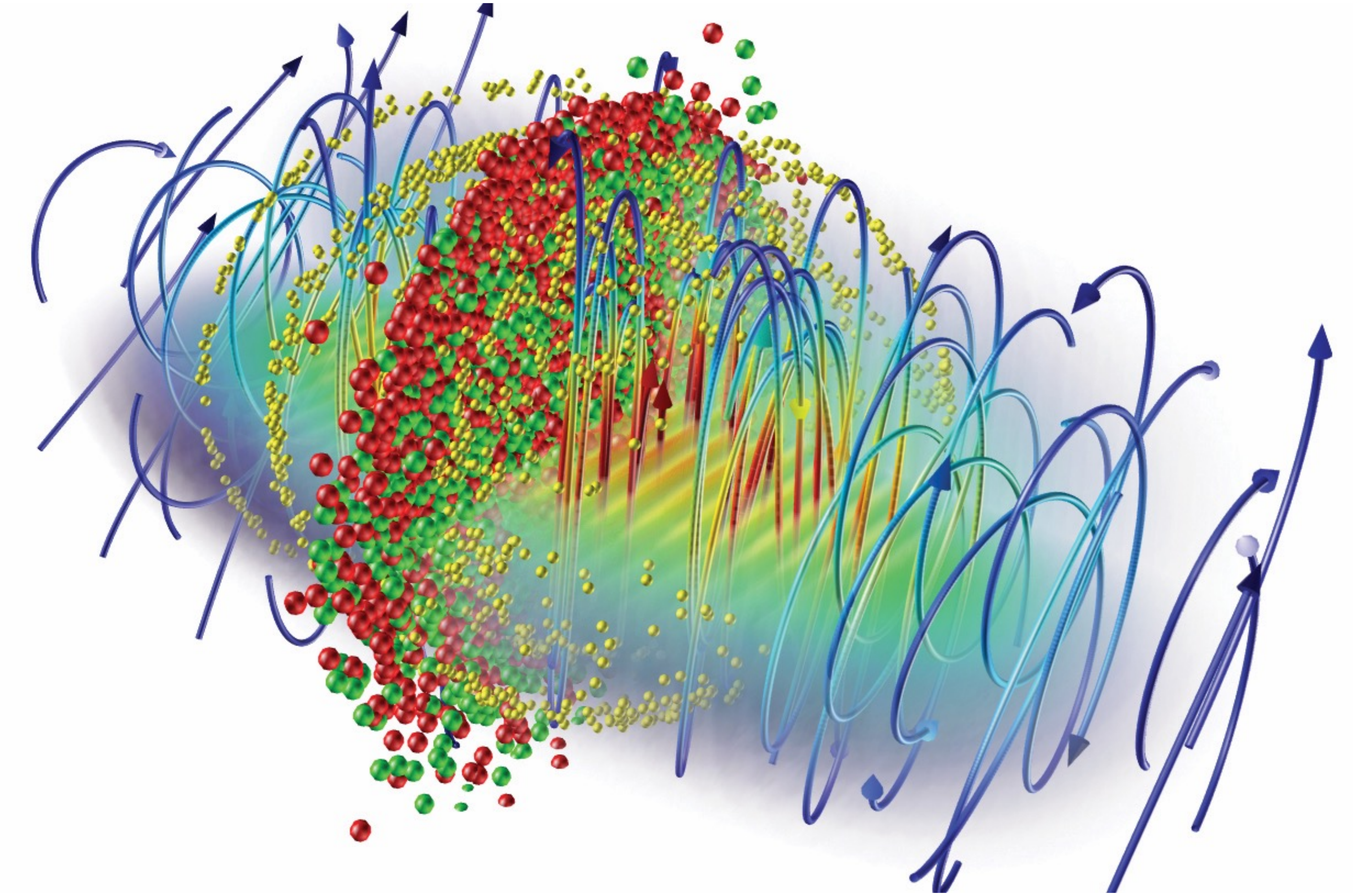
- This allows very strong fields to exist in plasmas - the fields that would destroy any other material

4th state of matter



Credit: NASA

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



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

Where can these plasmas exist?

When intense lasers interact with matter

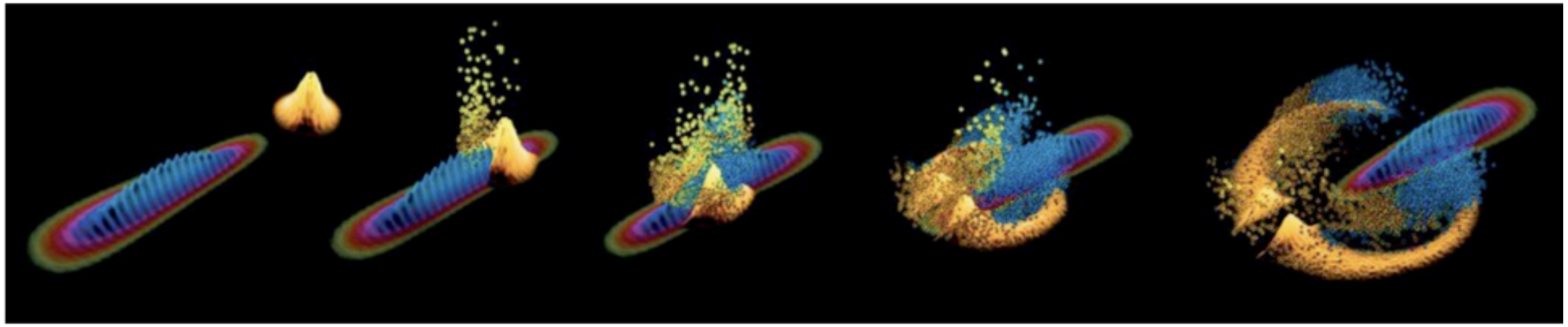


Image: Marija Vranic, European Physical Society Conference official poster 2018

In magnetospheres of neutron stars

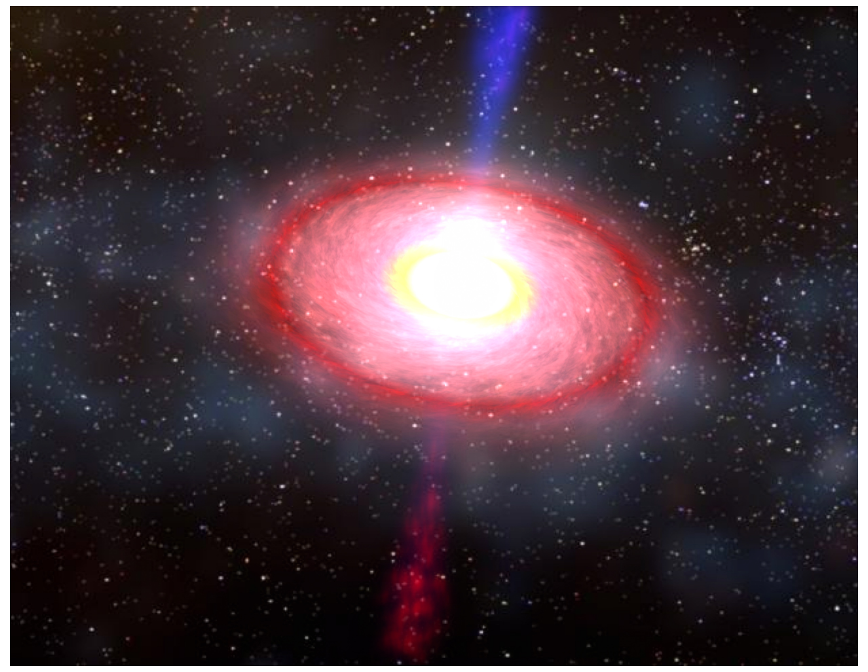


Image: Dana Berry / NASA

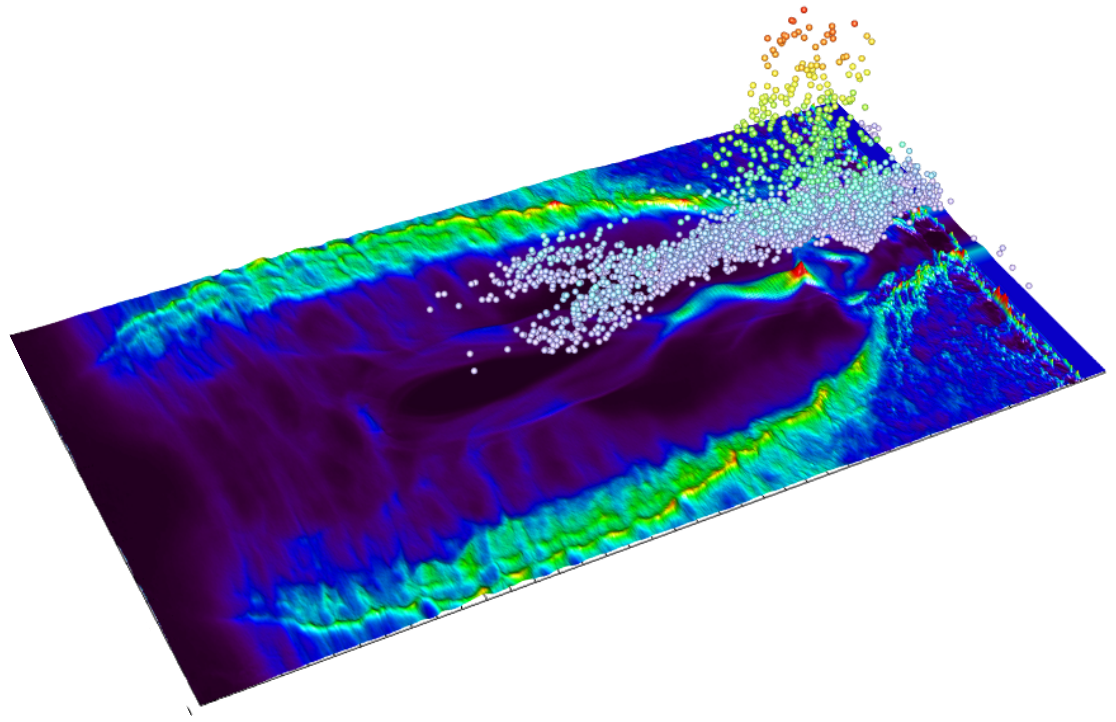
Around black holes

Image: Event Horizon Telescope collaboration, M87 / NASA

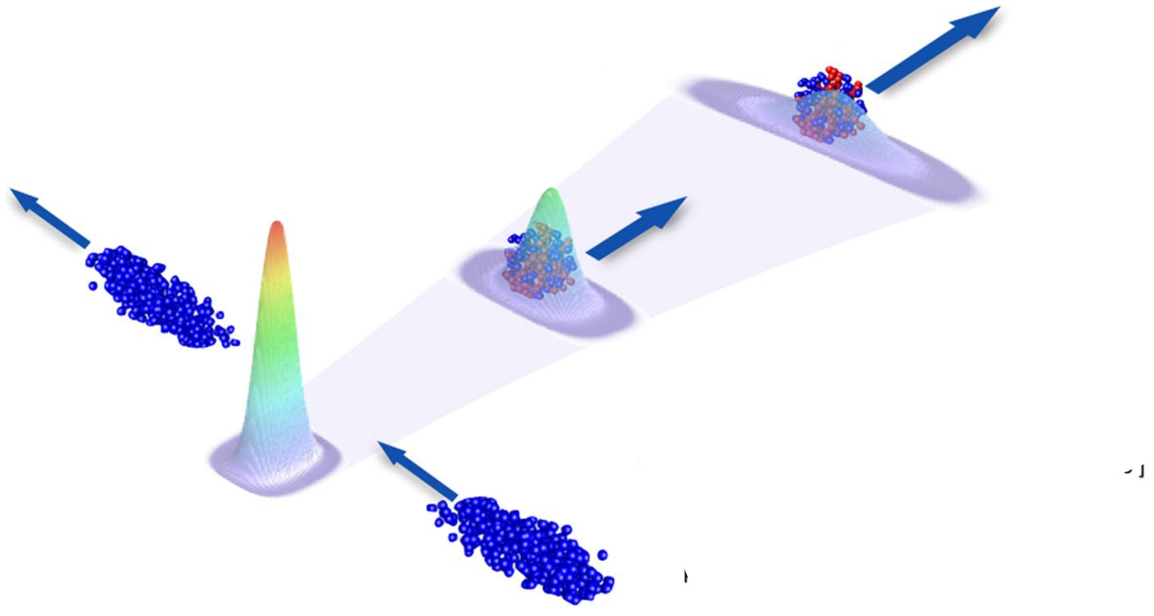
Why should we care?

There are both fundamental and practical open questions

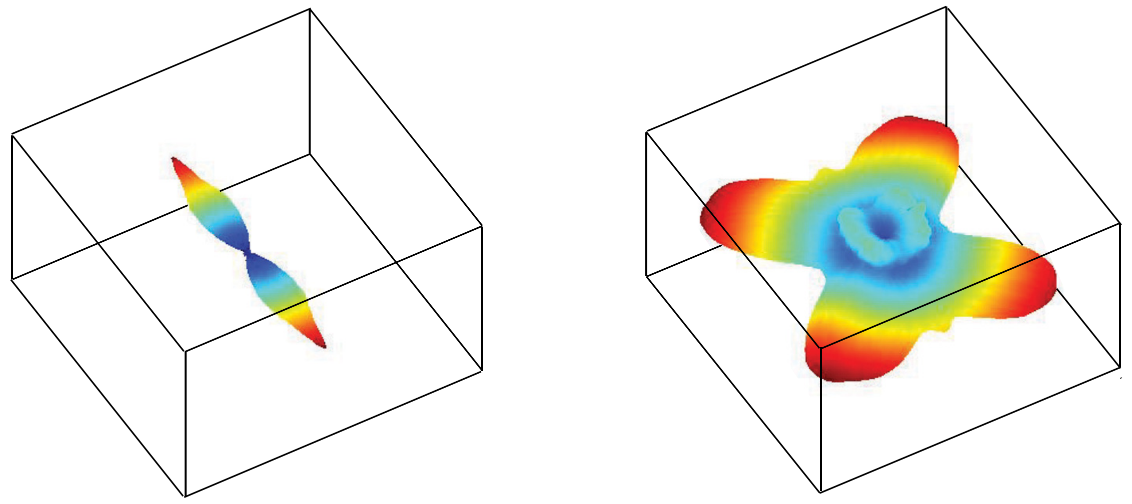
- What is the maximum allowed field before the breakdown of the vacuum?
- Can we make particle acceleration in plasmas better with extreme laser intensities? Are there paradigm shifts?
- Can we transform cascades to positron sources? Maybe they could serve as injectors for electron-positron colliders?
- Can we construct tunable radiation sources, with high conversion efficiency ranging all the way to gamma-rays?



M.Vranic et al, PPCF (2018)



M.Vranic et al, SciRep (2018)



T. Grismayer et al, POP (2016)

Contents

- Basic concepts & classical radiation reaction
- Quantum radiation reaction
- Pair creation, QED cascades & optical traps

Facilities and orders of magnitude…

Ultra intense Laser Facilities

Apollon 2 lasers

10 PW (150 J)
1 PW (15 J)

ELI

beamlines : 3 lasers
2 ×1 PW & 10 PW (1kJ)
NP: 10 PW & γ-ray beam

CoReLS

1 laser of 4 PW (100 J)

ZEUS

3 PW (80 J) & 0.5 PW (15 J)

Pulse duration : 20-150 fs
Wavelength ~ 1 µm
Intensity ~10^{21} - 10^{24} W/cm^2
Extreme acceleration regime

Which intensity?

classical nonlinear parameter $a_0 = \dfrac{eE_0}{m\omega c}$

$$a_0 \sim \sqrt{I_{[10^{18}\ \mathrm{W/cm^2}]}\lambda^2_{[\mu\mathrm{m}]}}$$

- non relativistic

  $a_0 \ll 1 \qquad I \ll 10^{18}\mathrm{W/cm^2}$

- weakly nonlinear, relativistic

  $a_0 \sim 1 \qquad I \sim 10^{18}\mathrm{W/cm^2}$

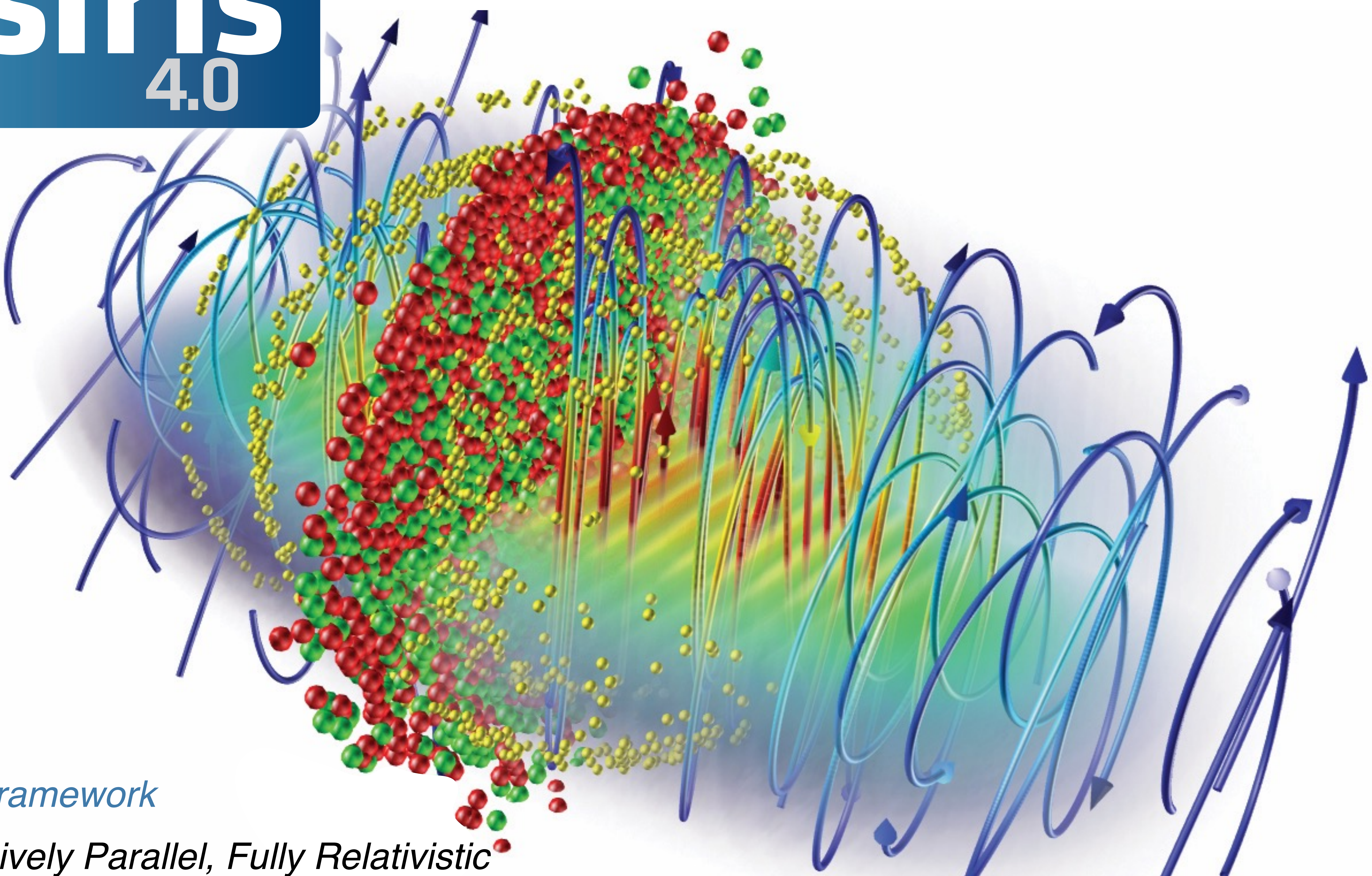
- relativistic, nonlinear

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

- quantum

  $a_0 \sim 1000 \qquad I \sim 10^{24}\mathrm{W/cm^2}$

Osiris 4.0



OSIRIS framework

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

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/

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

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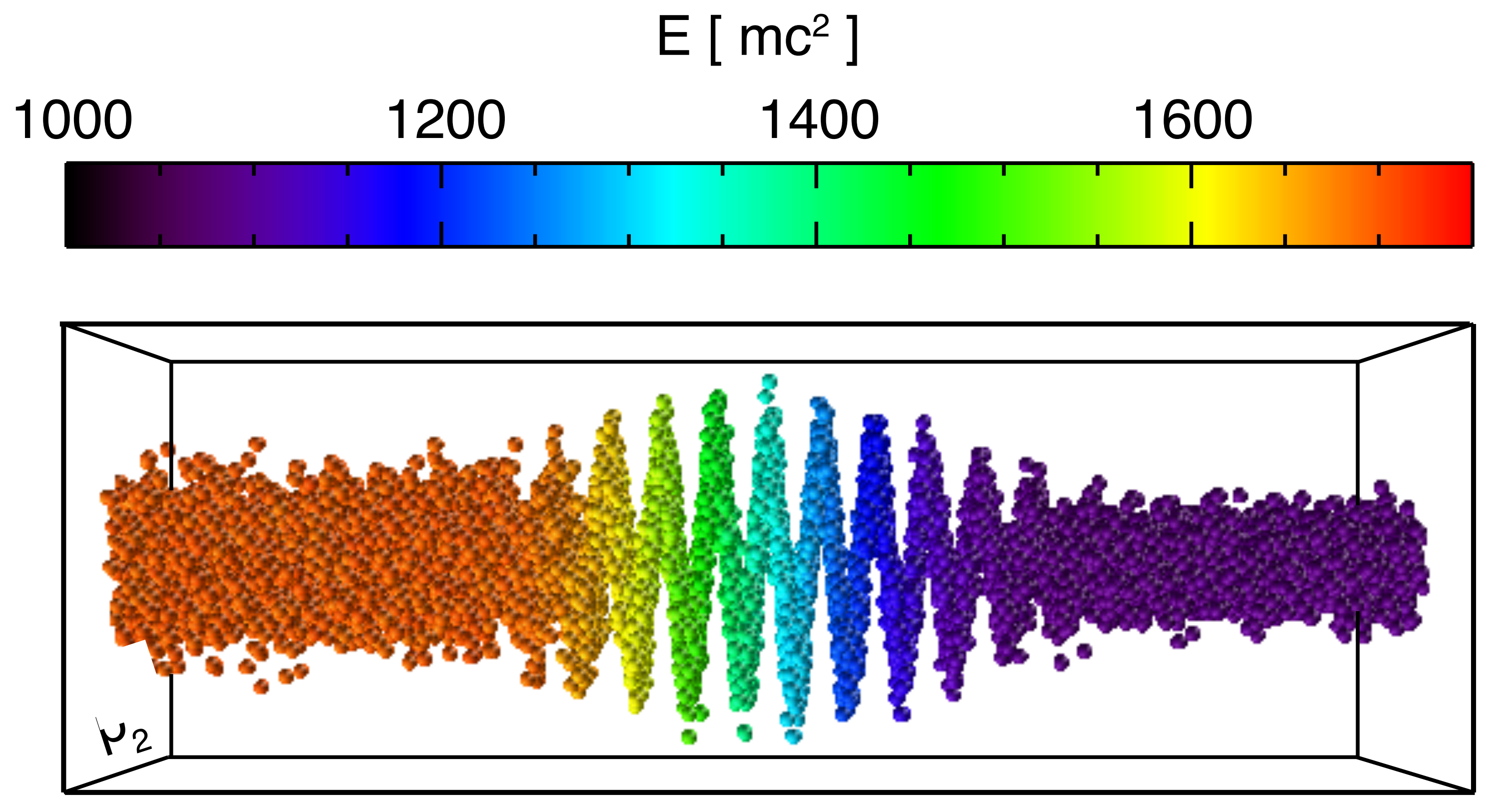
Radiation reaction in classical electrodynamics

Highest value is obtained for relativistic particles counter-propagating with a laser

Non-relativistic radiation reaction

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



Relativistic motion and high field

- frequency emitted $\omega' \sim \gamma^2\omega$
- classical nonlinear parameter $\boxed{a_0 = \frac{eE_0}{m\omega c}}$
- transverse momentum $p_\perp = a_0 mc$

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

- ultra-relativistic limit of Landau & Lifshitz

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

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

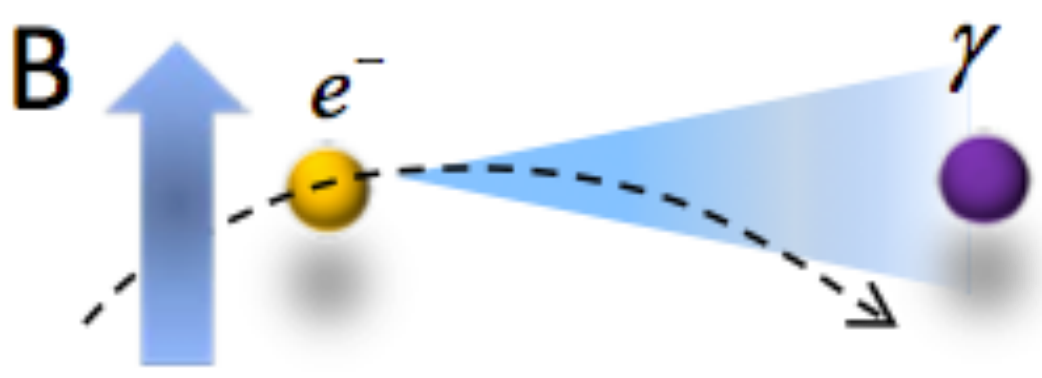
Schwinger critical field

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

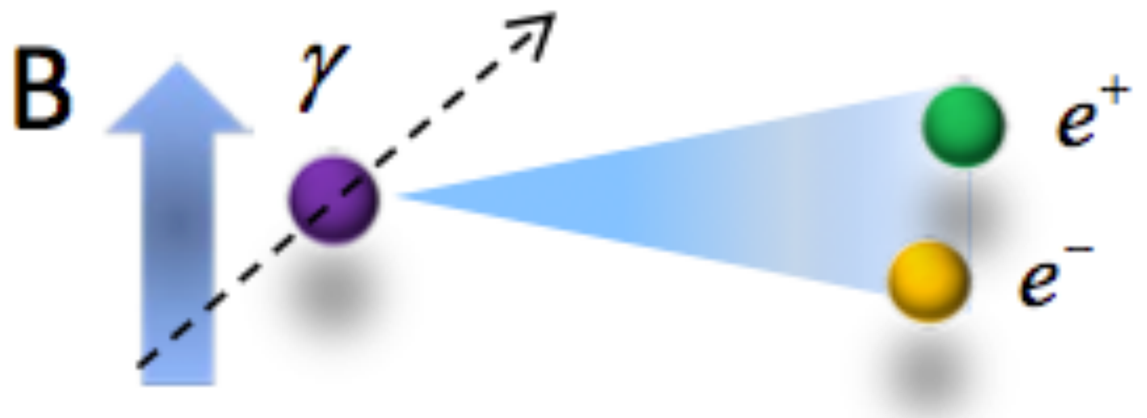
- Field strong enough to spontaneously create e+e- pairs from vaccuum
- Field srong enough to transfer one mc^2 of energy to leptons over one Compton wavelength
- A laser with $E_0 = E_S$ would have $I \sim 10^{29}$ W/cm^2
- Relativistic particles can feel E_S in their rest frame even at $I \sim 10^{22}$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

First QED processes

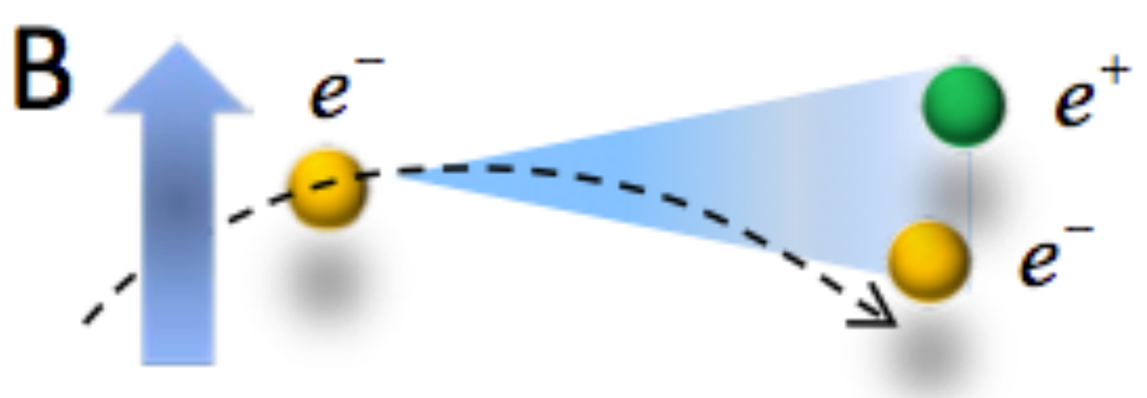
Non-linear Compton emission



Non-linear Breit-Wheeler pair creation



EM trident pair creation

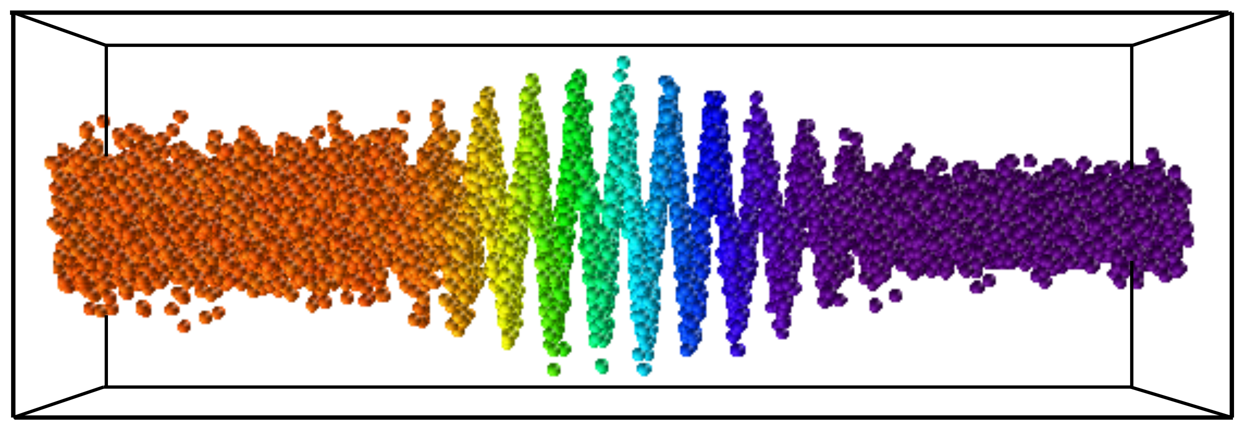


Credit: M. Lobet, B. Martinez

What new features are needed for plasma modeling?

Adding classical radiation reaction

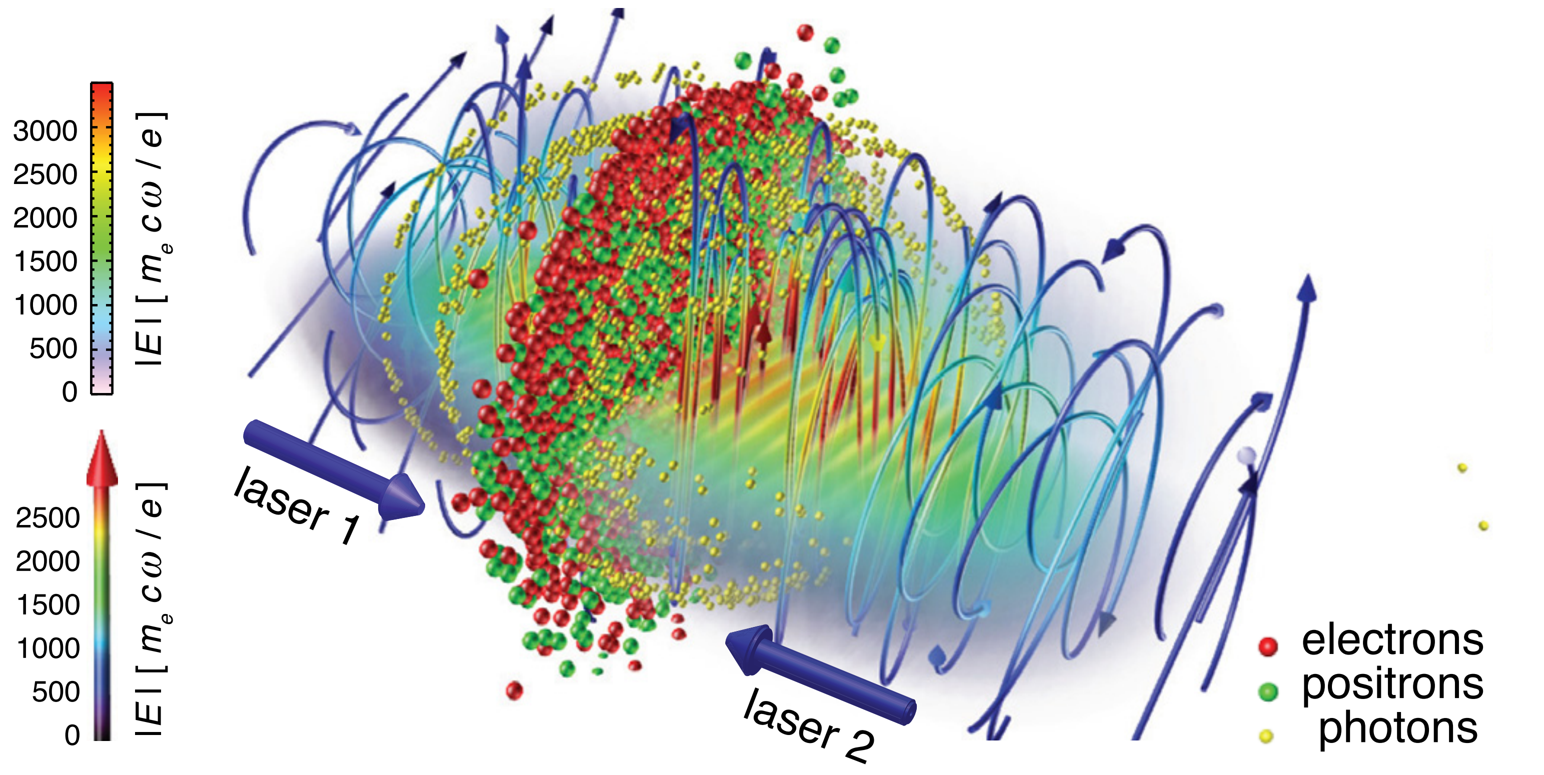
- Modelling electron beam slowdown in scattering configurations
- Modelling other configurations where only a fraction of electrons may be subject to RR but where this can alter qualitative behaviour



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

Adding quantum processes

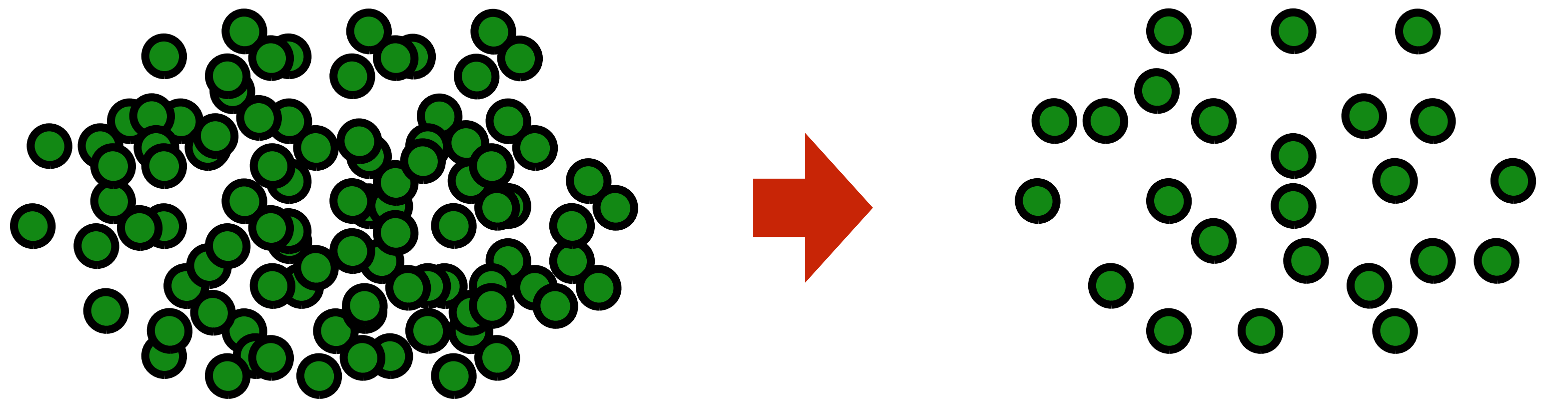
- Modelling the onset of QED, RR from quantum perspective
- Modelling e+e- pair production
- QED cascades, nonlinear regimes where many particles are created and collective plasma dynamics can alter the background fields



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 load balancing schemes)

- Essential for all the projects with strong QED effects



M.Vranic et al., CPC (2015)

Classical radiation reaction

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

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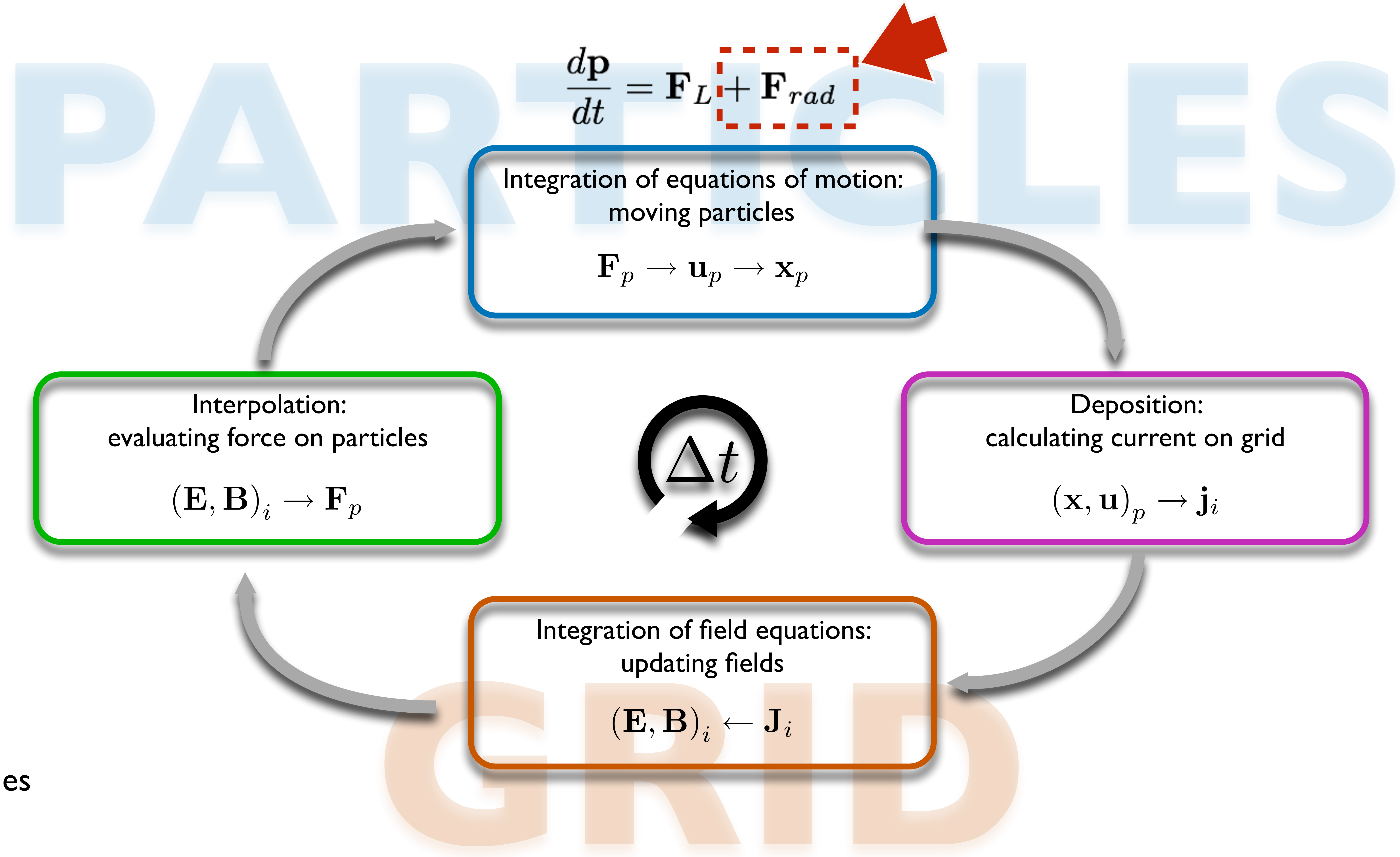
UCLA



PARTICLES

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

Integration of equations of motion:
moving particles

$$\mathbf{F}_p \rightarrow \mathbf{u}_p \rightarrow \mathbf{x}_p$$

Interpolation:
evaluating force on particles

$$(\mathbf{E},\mathbf{B})_i \rightarrow \mathbf{F}_p$$

$$\Delta t$$

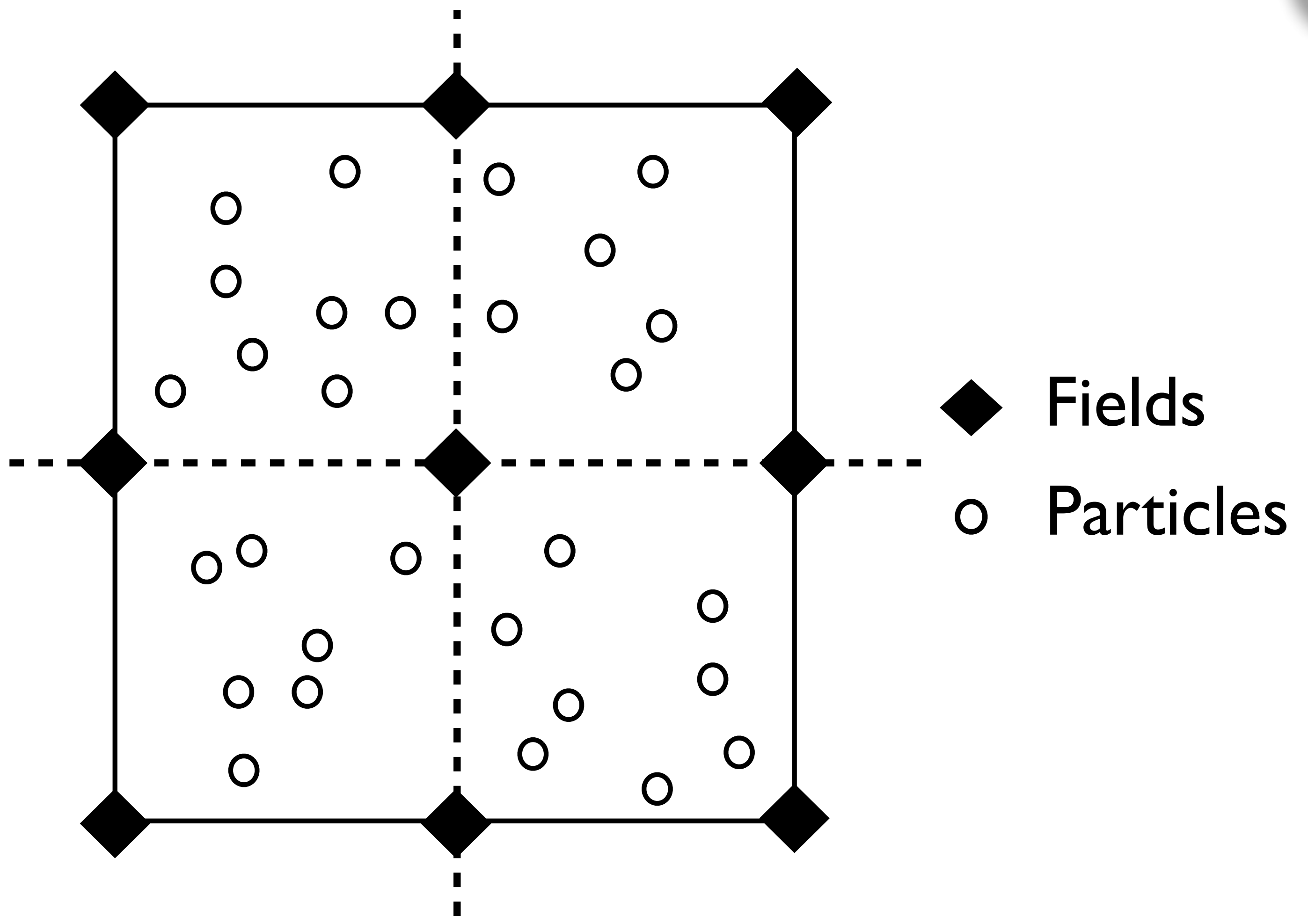
Deposition:
calculating current on grid

$$(\mathbf{x},\mathbf{u})_p \rightarrow \mathbf{j}_i$$

Integration of field equations:
updating fields

$$(\mathbf{E},\mathbf{B})_i \leftarrow \mathbf{J}_i$$

GRID



Classical radiation reaction models

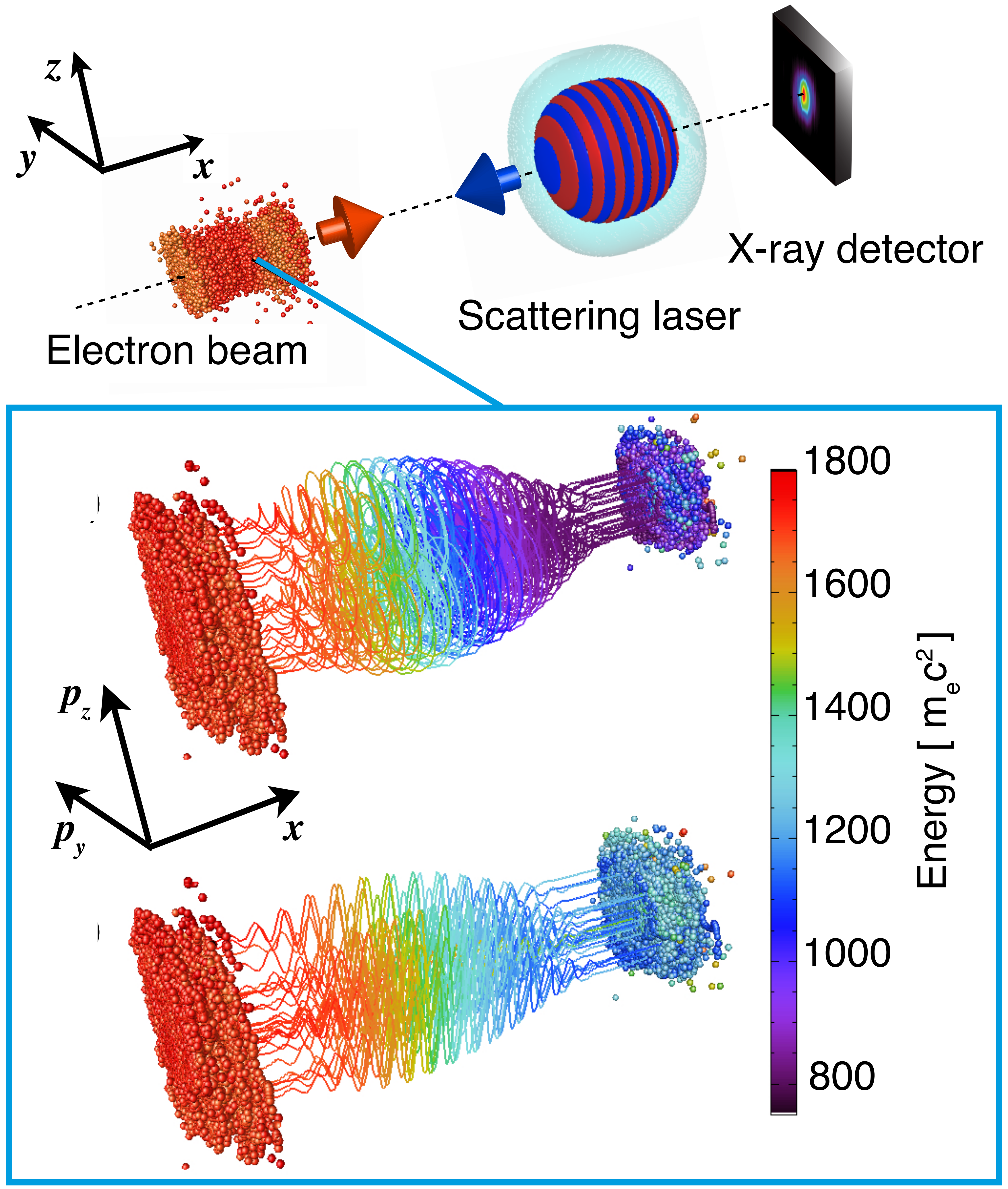
$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L \boxed{+\, \mathbf{F}_{rad}}$$

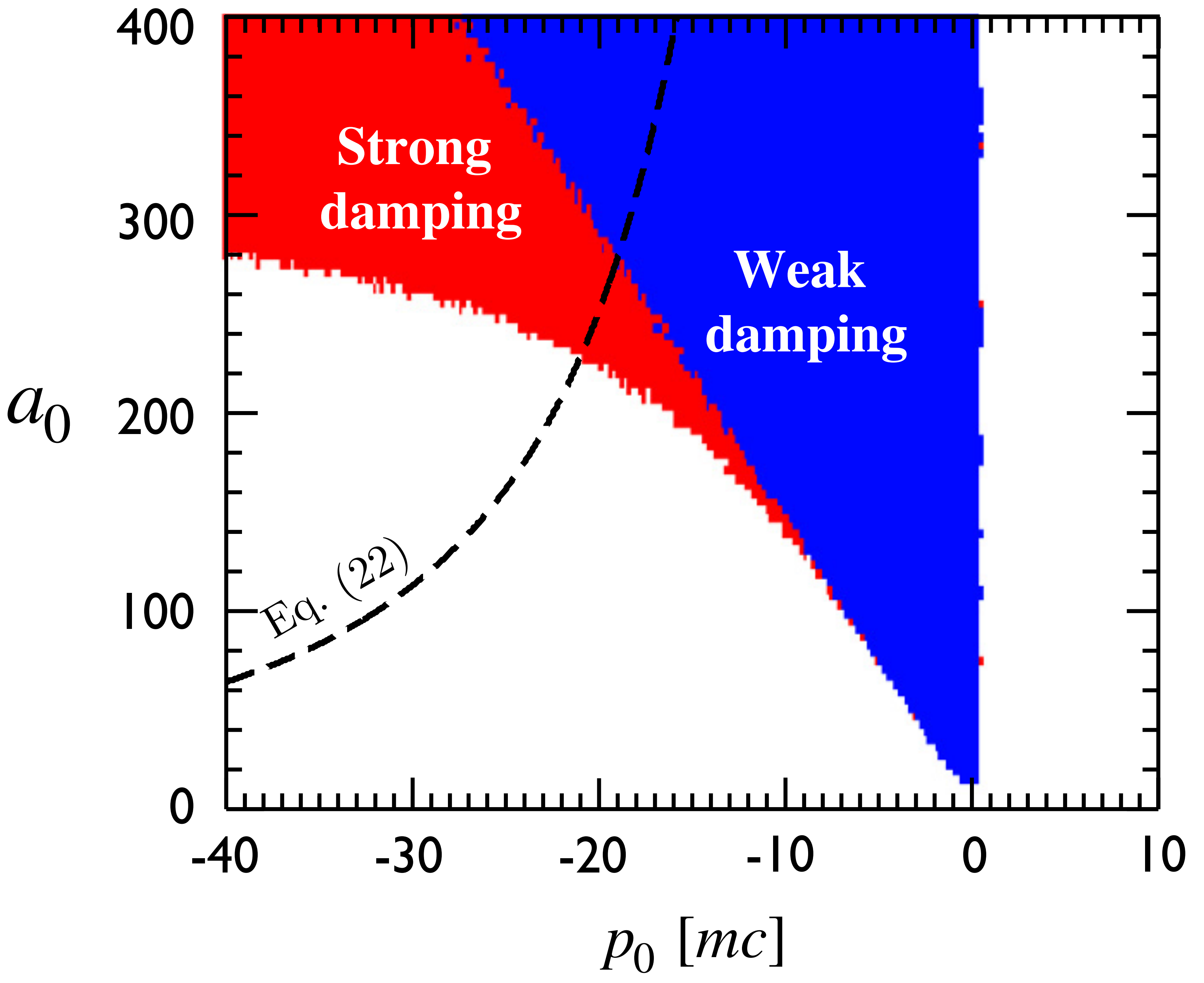
1	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} - \frac{2}{3}\frac{e^4\gamma}{m^3c^5}\mathbf{p}\left(\mathbf{E}_\perp + \frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2$	[Bell 2008]
2	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} + \frac{2e^3}{3mc^3}\left\{\gamma\left(\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{\gamma m}\cdot\nabla\right)\mathbf{E} + \frac{\mathbf{p}}{\gamma mc}\times\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}}{\gamma m}\cdot\nabla\right)\mathbf{B}\right) + \frac{e}{mc}\left(\mathbf{E}\times\mathbf{B} + \frac{1}{\gamma mc}\mathbf{B}\times(\mathbf{B}\times\mathbf{p}) + \frac{1}{\gamma mc}\mathbf{E}(\mathbf{p}\cdot\mathbf{E})\right) - \frac{e\gamma}{m^2c^2}\mathbf{p}\left(\left(\mathbf{E} + \frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2 - \frac{1}{\gamma^2m^2c^2}(\mathbf{E}\cdot\mathbf{p})^2\right)\right\}$	[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	$\frac{d\mathbf{p}}{dt} = \mathbf{F_L} + \frac{2e^3}{3mc^3}\left\{\frac{e}{mc}\left(\mathbf{E}\times\mathbf{B} + \frac{1}{\gamma mc}\mathbf{B}\times(\mathbf{B}\times\mathbf{p}) + \frac{1}{\gamma mc}\mathbf{E}(\mathbf{p}\cdot\mathbf{E})\right) - \frac{e\gamma}{m^2c^2}\mathbf{p}\left(\left(\mathbf{E} + \frac{\mathbf{p}}{\gamma mc}\times\mathbf{B}\right)^2 - \frac{1}{\gamma^2m^2c^2}(\mathbf{E}\cdot\mathbf{p})^2\right)\right\}$	

M.Vranic et al., CPC 204, 141-157 (2016)

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





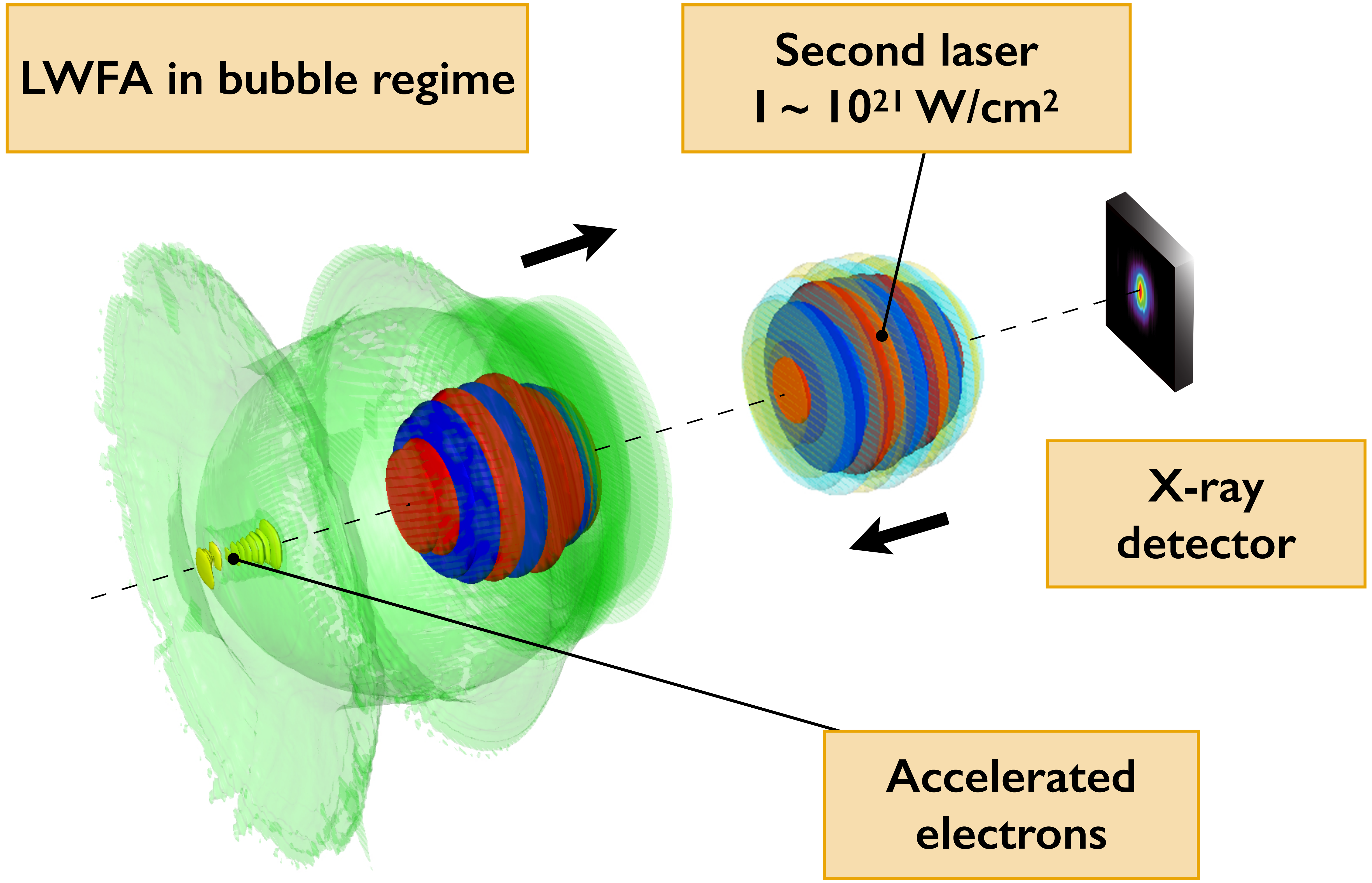
☐ Converged for all
🟥 Not converged with radiation damping
🟦 Not converged with or without damping

M.Vranic et al., CPC 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



LWFA in bubble regime

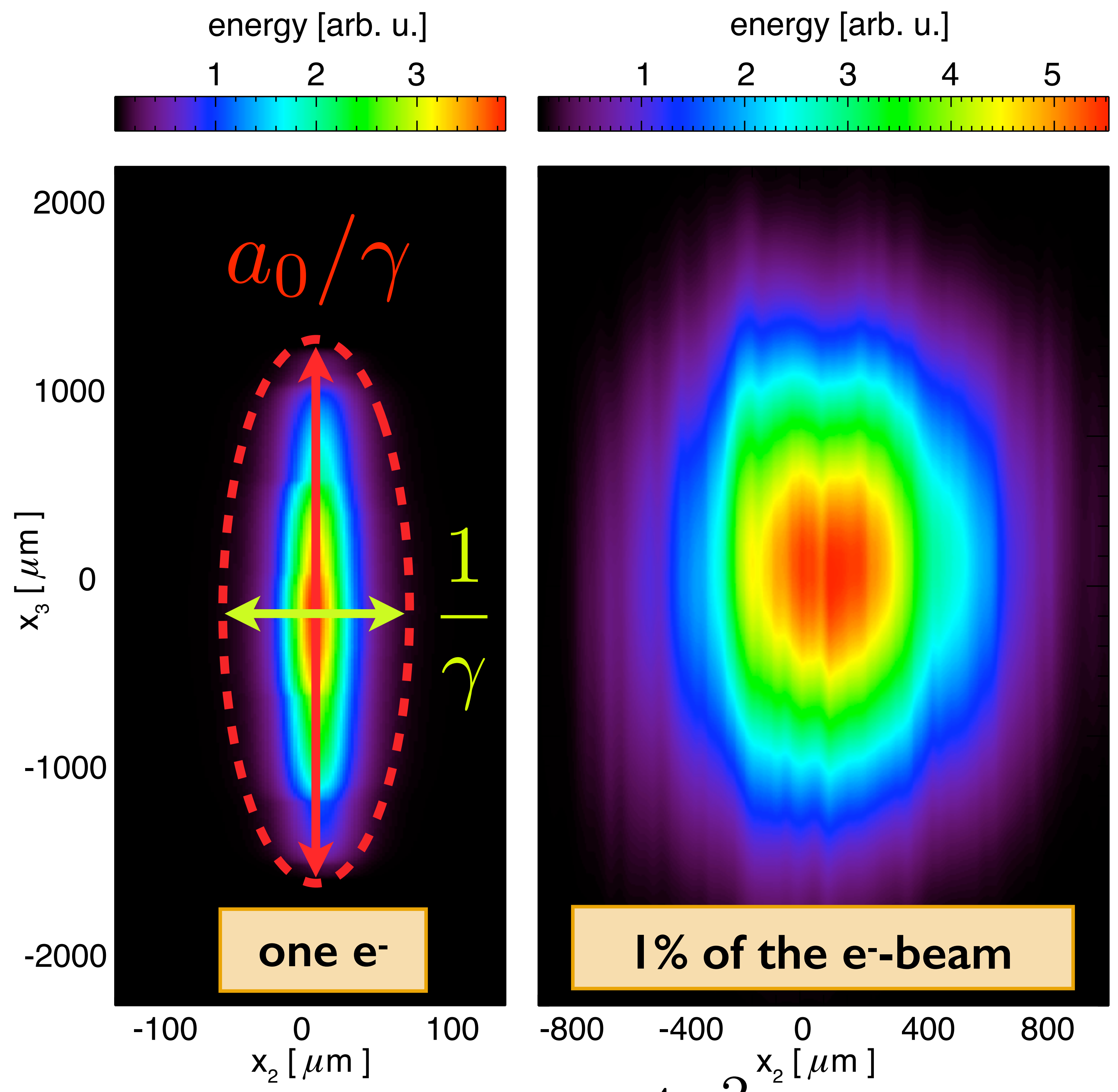
Second laser
I ~ 10^{21} W/cm^2

X-ray detector

Accelerated electrons

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

Output radiation on the virtual detector

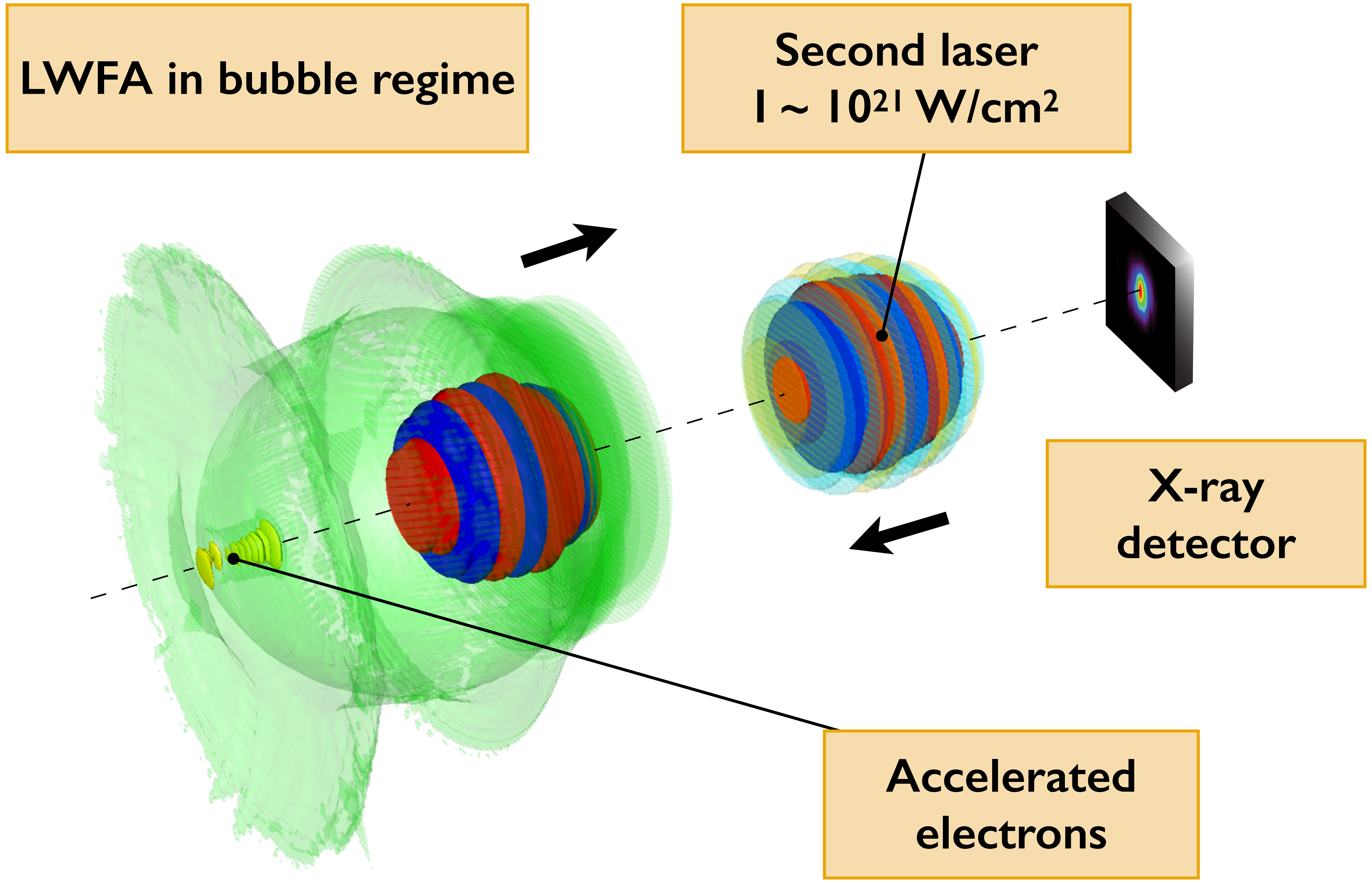


$$\frac{\omega_R}{\omega_L} = \frac{4\gamma^2}{a_0^2/2+1}$$

All-optical acceleration and “optical wiggler"

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

Setup


LWFA in bubble regime

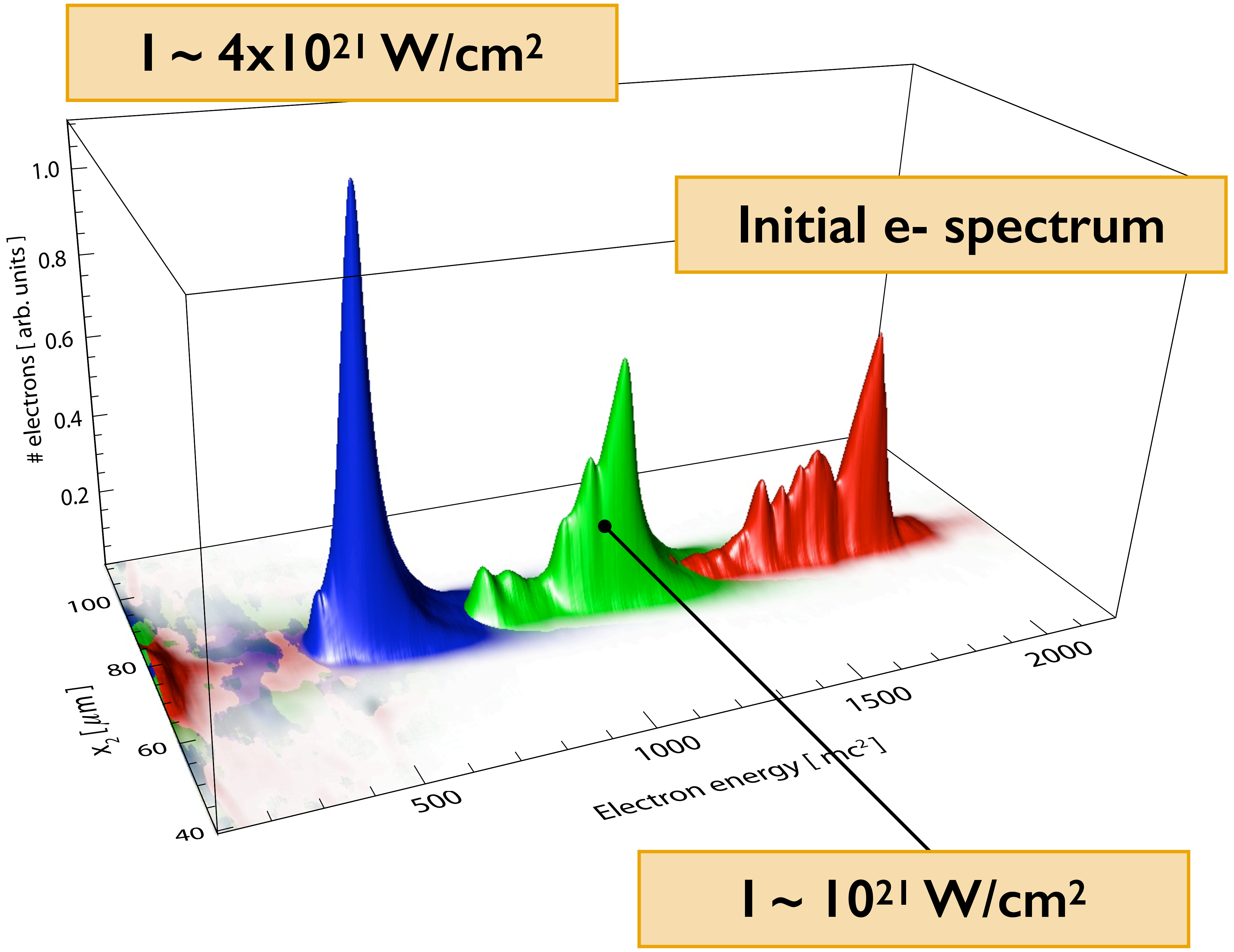
Second laser
I ~ 10^{21} W/cm^2

X-ray detector

Accelerated electrons

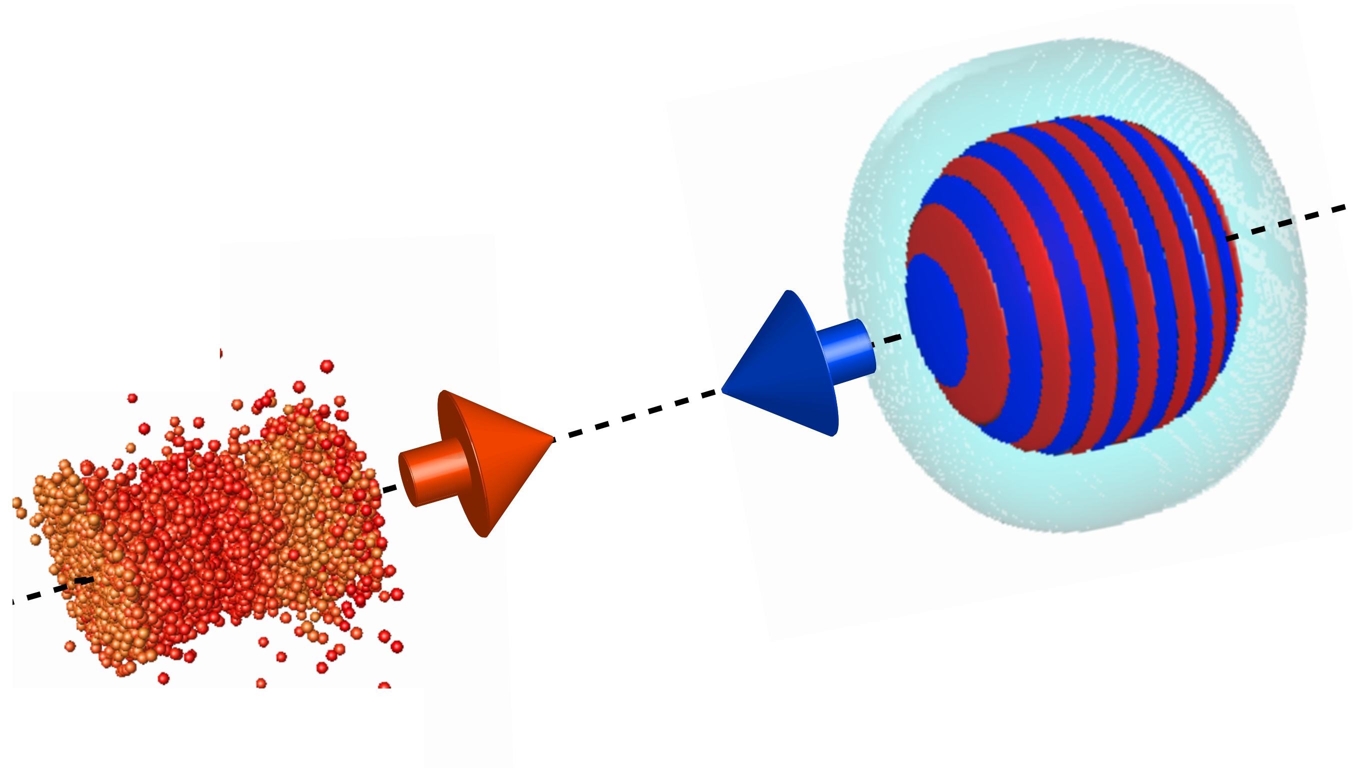
M.Vranic et al., PRL 113, 134801 (2014)

The electrons lose energy in the emission



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

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



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

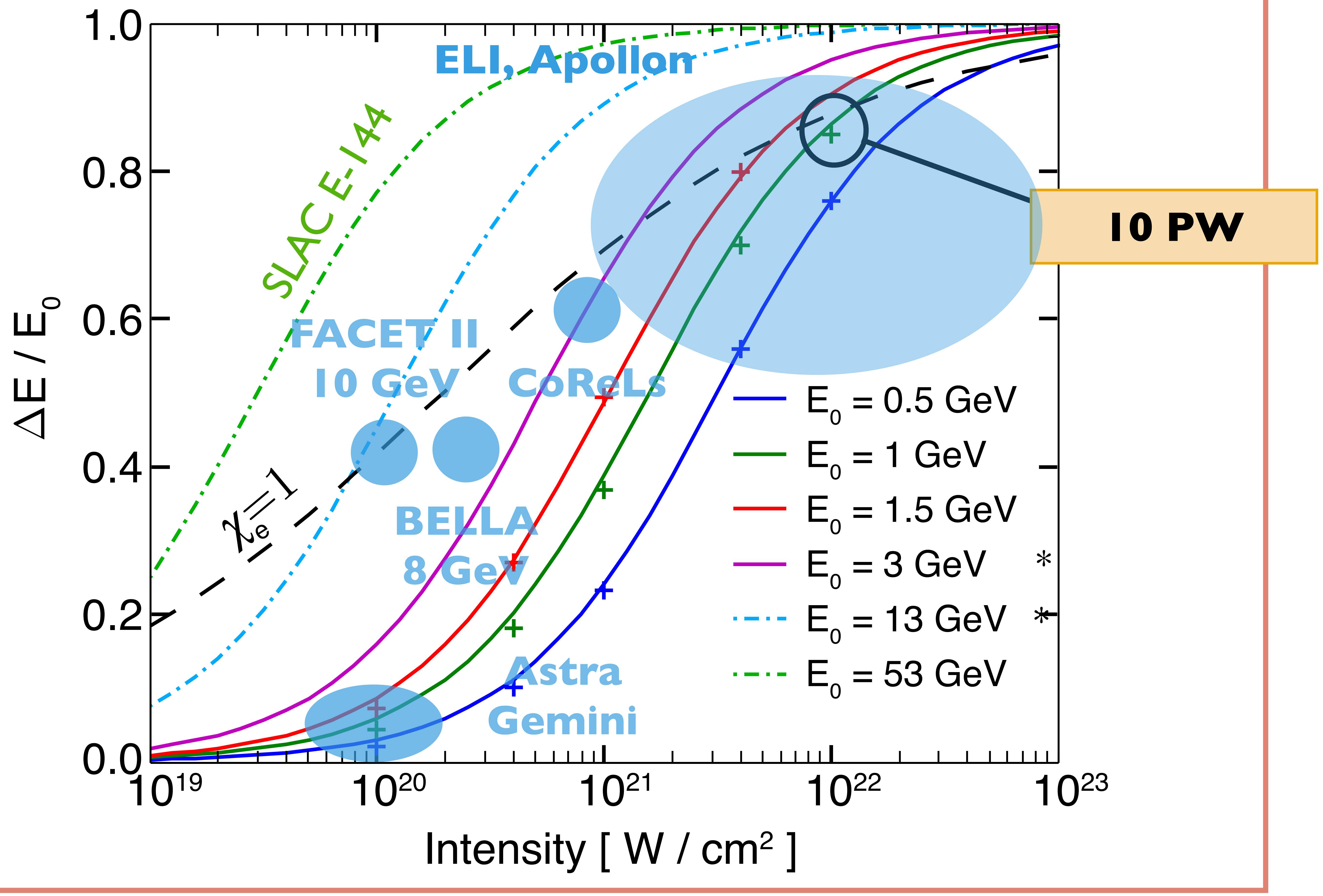
Classical: $\chi \ll 1$

QED: $\chi \simeq 1$

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

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)



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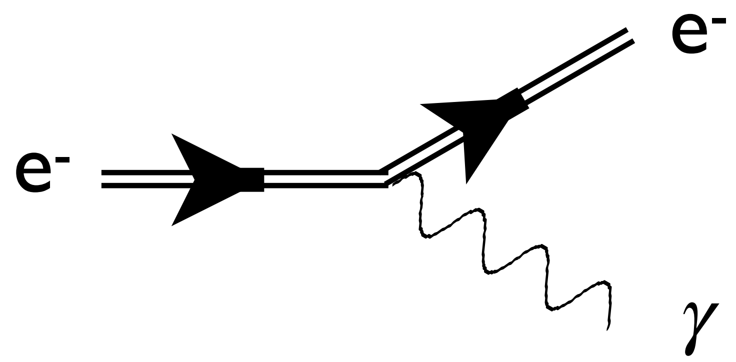
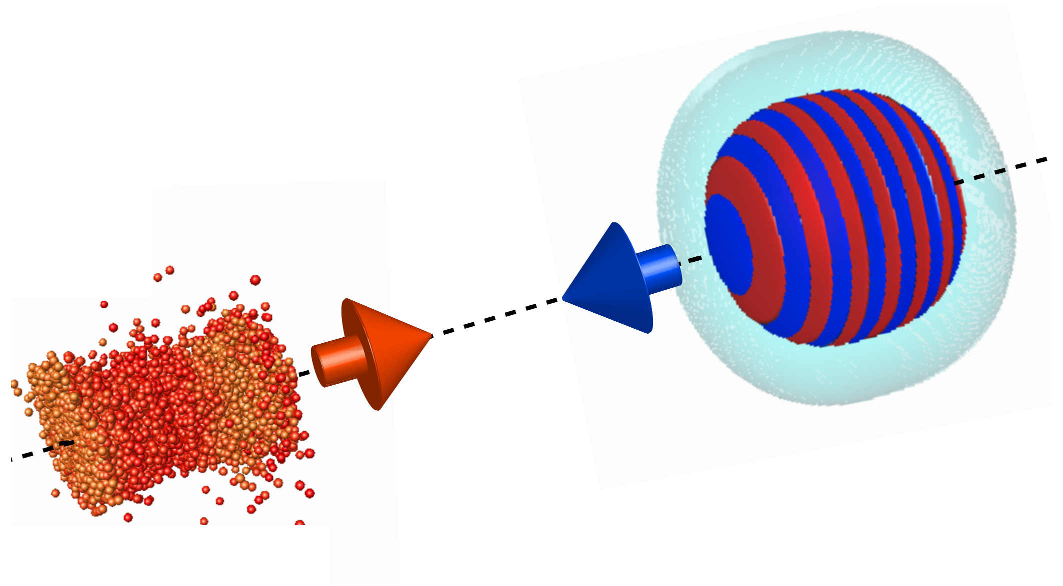
How do we connect the physical picture of classical vs. QED RR?





Probability and Spectrum

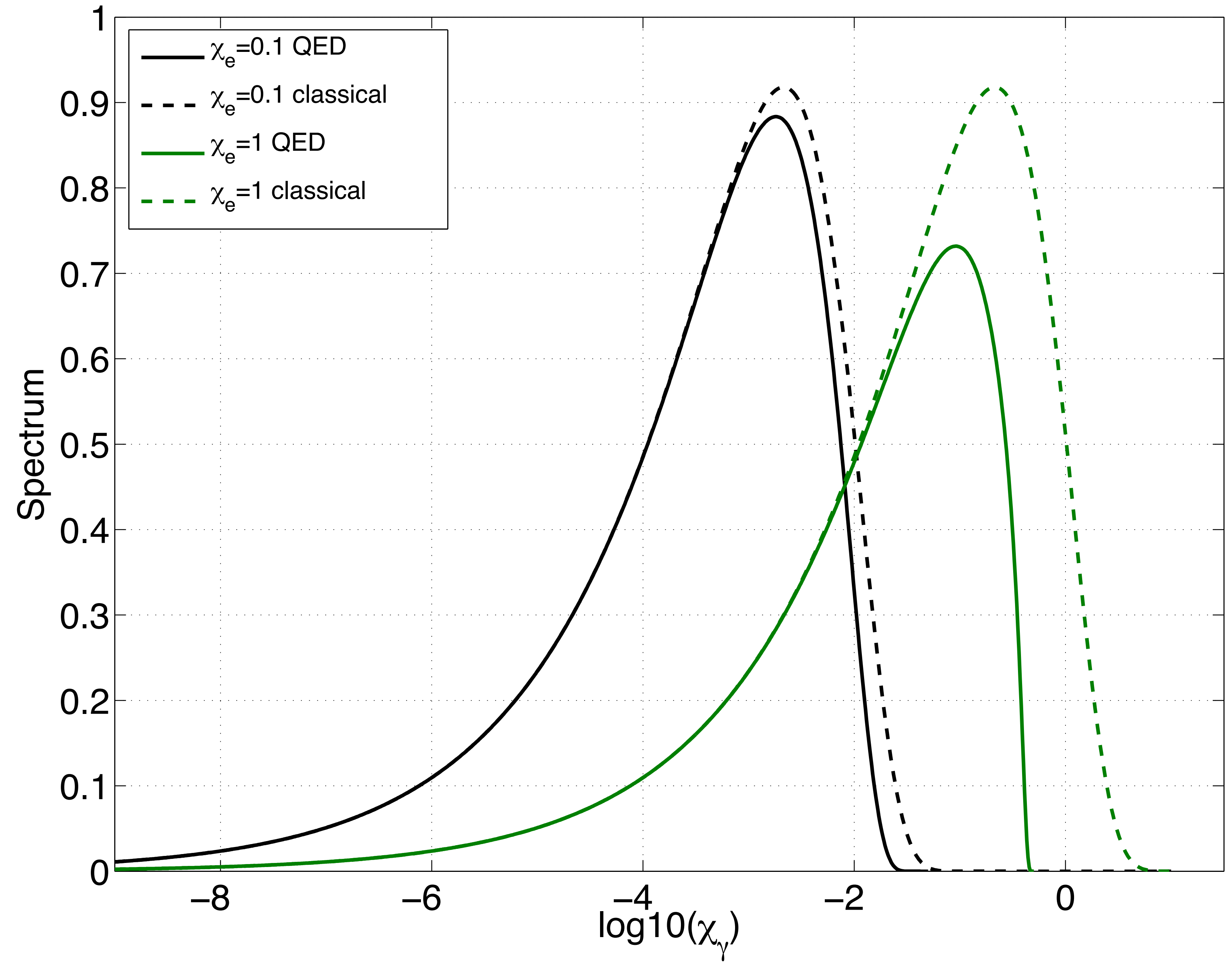
Ratio of critical frequency to particle energy: χ

$$\chi = \frac{1}{E_S}\sqrt{\left(\gamma\mathbf{E} + \frac{\mathbf{p}}{mc}\times\mathbf{B}\right)^2 - \left(\frac{\mathbf{p}}{mc}\cdot\mathbf{E}\right)^2} \simeq \frac{\gamma F_\perp}{eE_S}$$

QED: probability of emitting a photon per unit of time per χ

$$\frac{d\mathcal{P}}{dtd\chi_\gamma} = f(\gamma, \chi_e, \chi_\gamma)$$

in strong field, particle emit QED synchrotron like spectrum



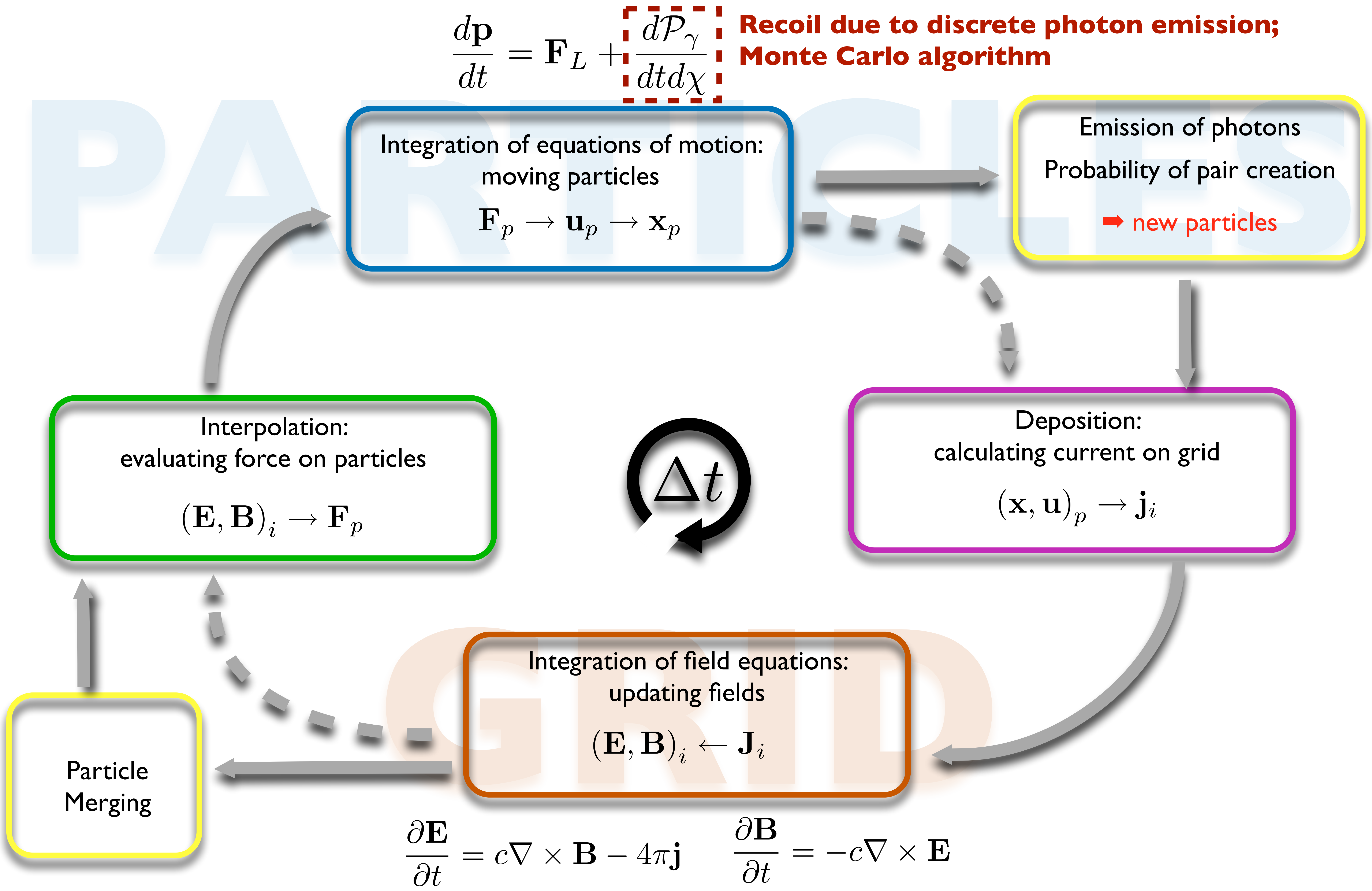
A. Di Piazza et al., Rev. Mod. Phys., 84, (2012)
F. Mackenroth & A. Di Piazza, 84, 032106 PRA (2011)

A. Ilderton & G. Torgrimsson, Phys Lett B 725. 481 (2013)
V. Ritus, J. Sov. Laser Res. 6, 497 (1985)

QED PIC loop in OSIRIS

Ricardo Fonseca
ricardo.fonseca@tecnico.ulisboa.pt
Frank Tsung
tsung@physics.ucla.edu

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/



$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \boxed{\frac{d\mathcal{P}_\gamma}{dtd\chi}}$$

Recoil due to discrete photon emission; Monte Carlo algorithm

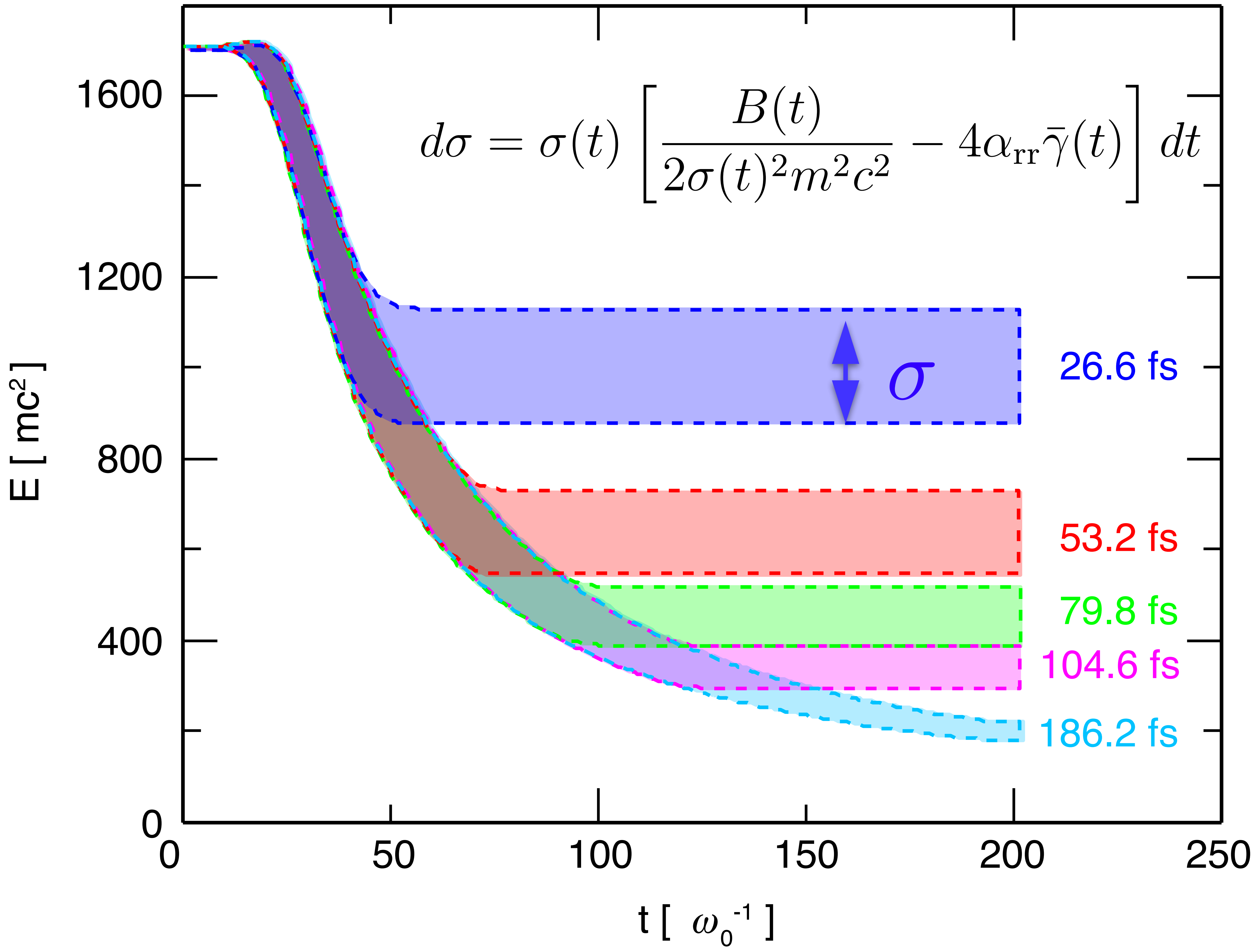
$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi\mathbf{j} \qquad \frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

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)

Quantum radiation reaction

Evolution of the electron distribution function can be described through Fokker-Planck equation

Electron beam energy evolution with standard deviation as a margin



$$d\sigma = \sigma(t)\left[\frac{B(t)}{2\sigma(t)^2m^2c^2} - 4\alpha_{\mathrm{rr}}\bar{\gamma}(t)\right]dt$$

Transport equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_\alpha}\left[A_\alpha f + \frac{1}{2}\frac{\partial}{\partial p_\beta}(B_{\alpha\beta}f)\right]$$

Average classical "drift"

$$A \approx \frac{2}{3}\frac{\alpha m^2c^3}{\hbar}\chi_e^2$$

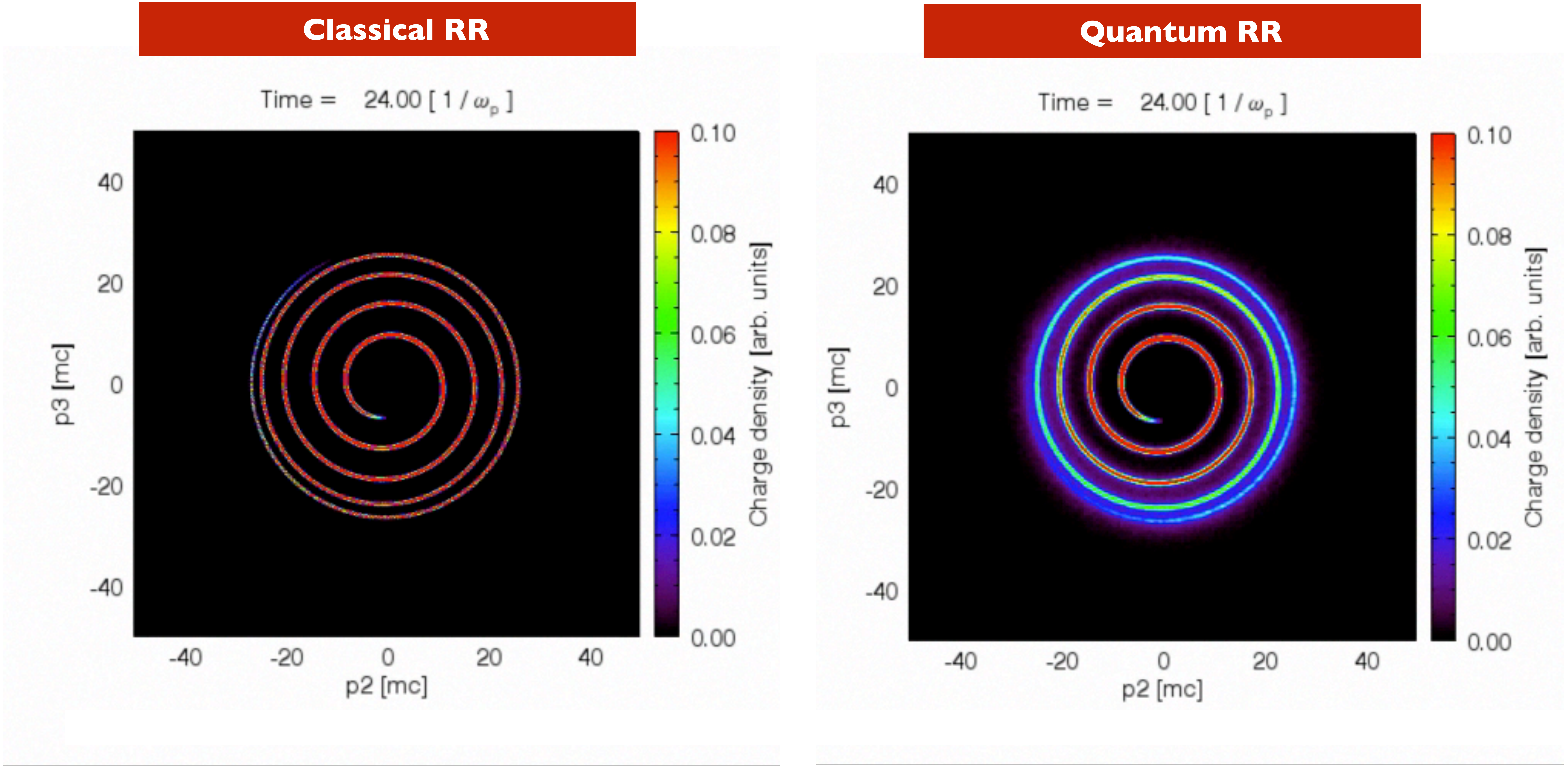
Stochastic QED "diffusion"

$$B \approx \frac{55}{24\sqrt{3}}\frac{\alpha m^3c^4}{\hbar}\gamma\,\chi_e^3$$

V. N. Baier & V. M. Katkov, PRA (1967), N. Neitz & A. Di Piazza, PRL (2013), D. G. Green et al, PRL (2014), S. Yoffe et al, NJP (2015), M. Vranic et al, NJP (2016), C. Ridgers et al, JPP (2017), F. Niel et al, PRE (2018)

Average angle between the elecctron 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



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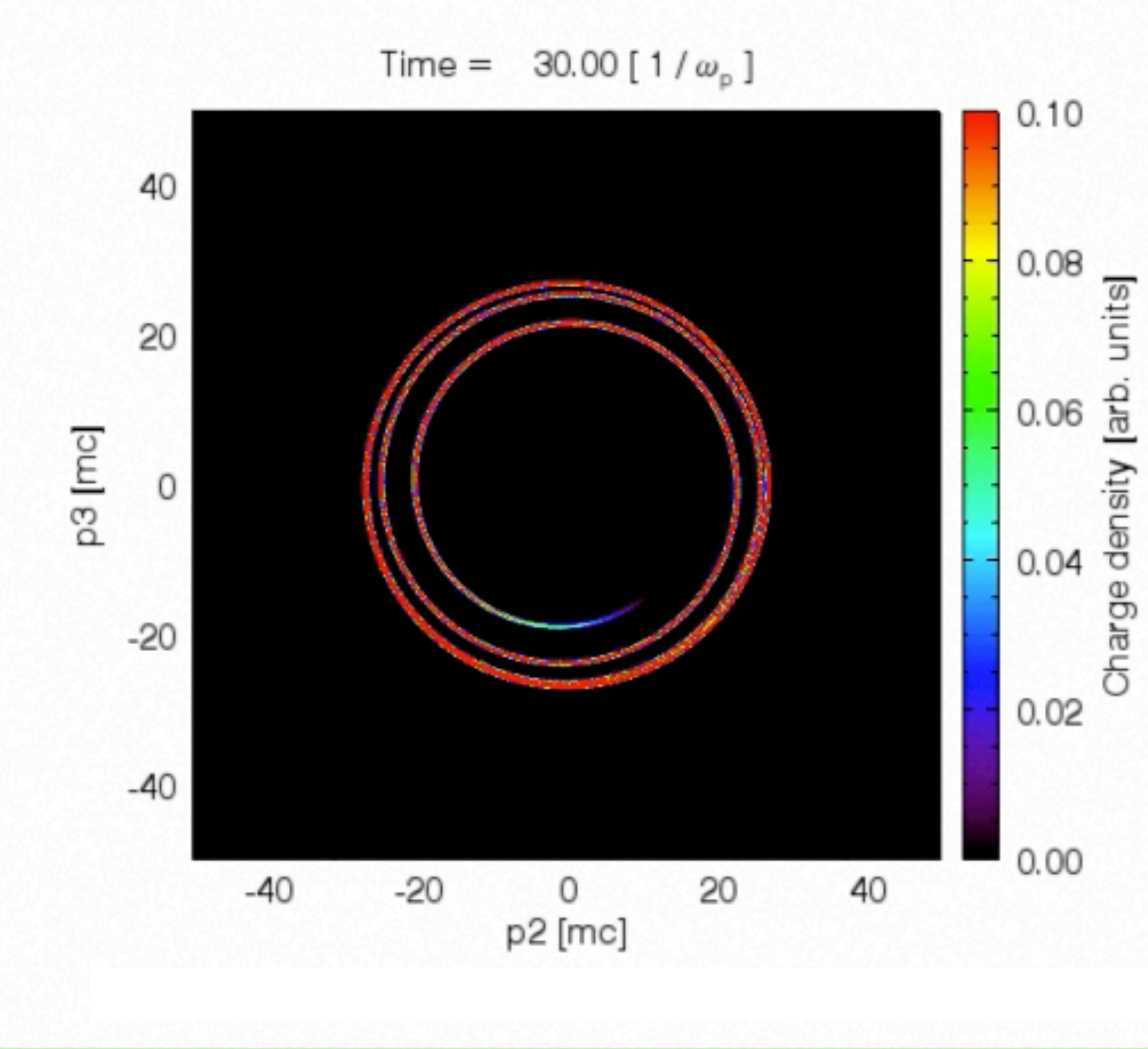
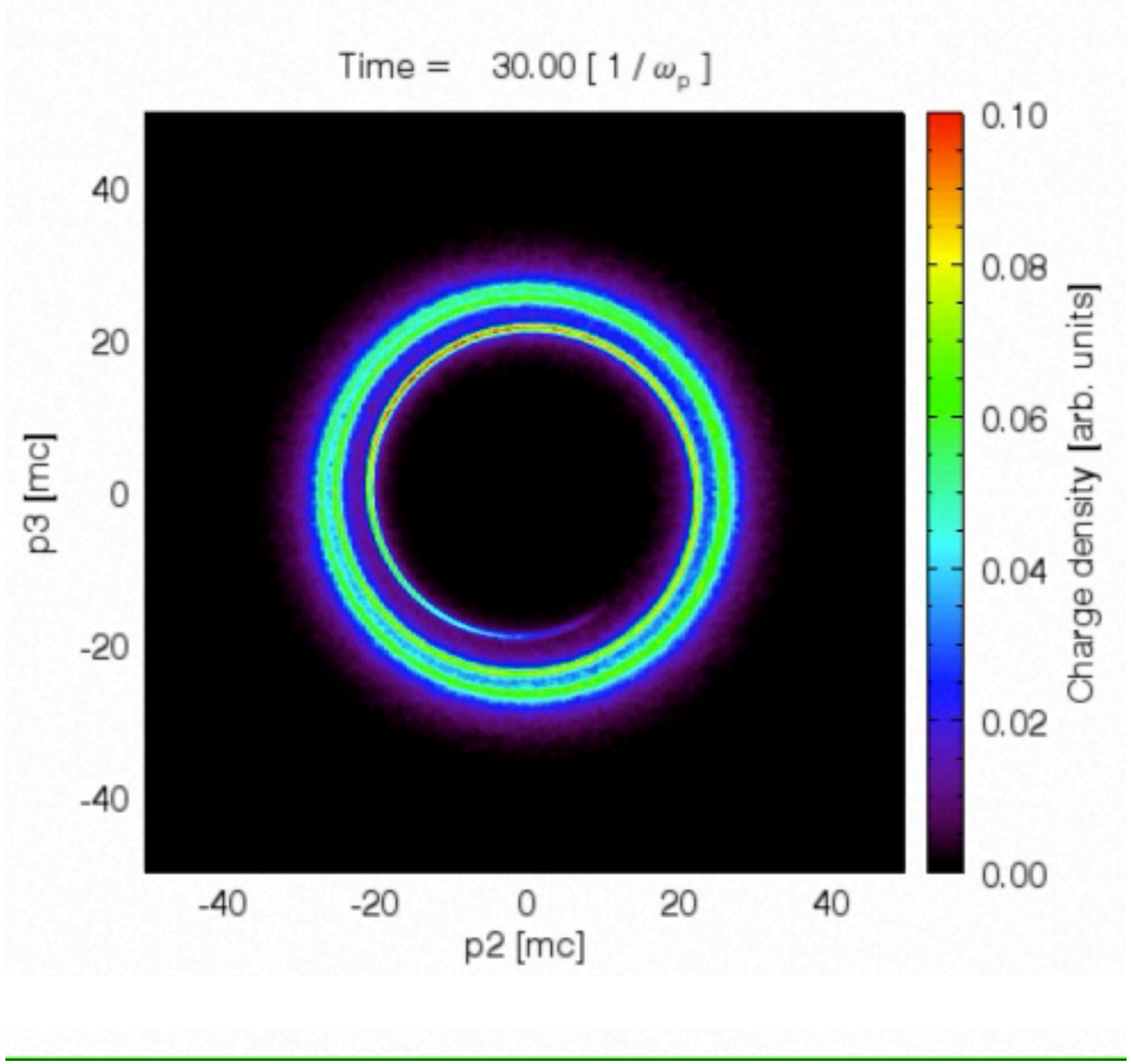
Classical RR



Quantum RR



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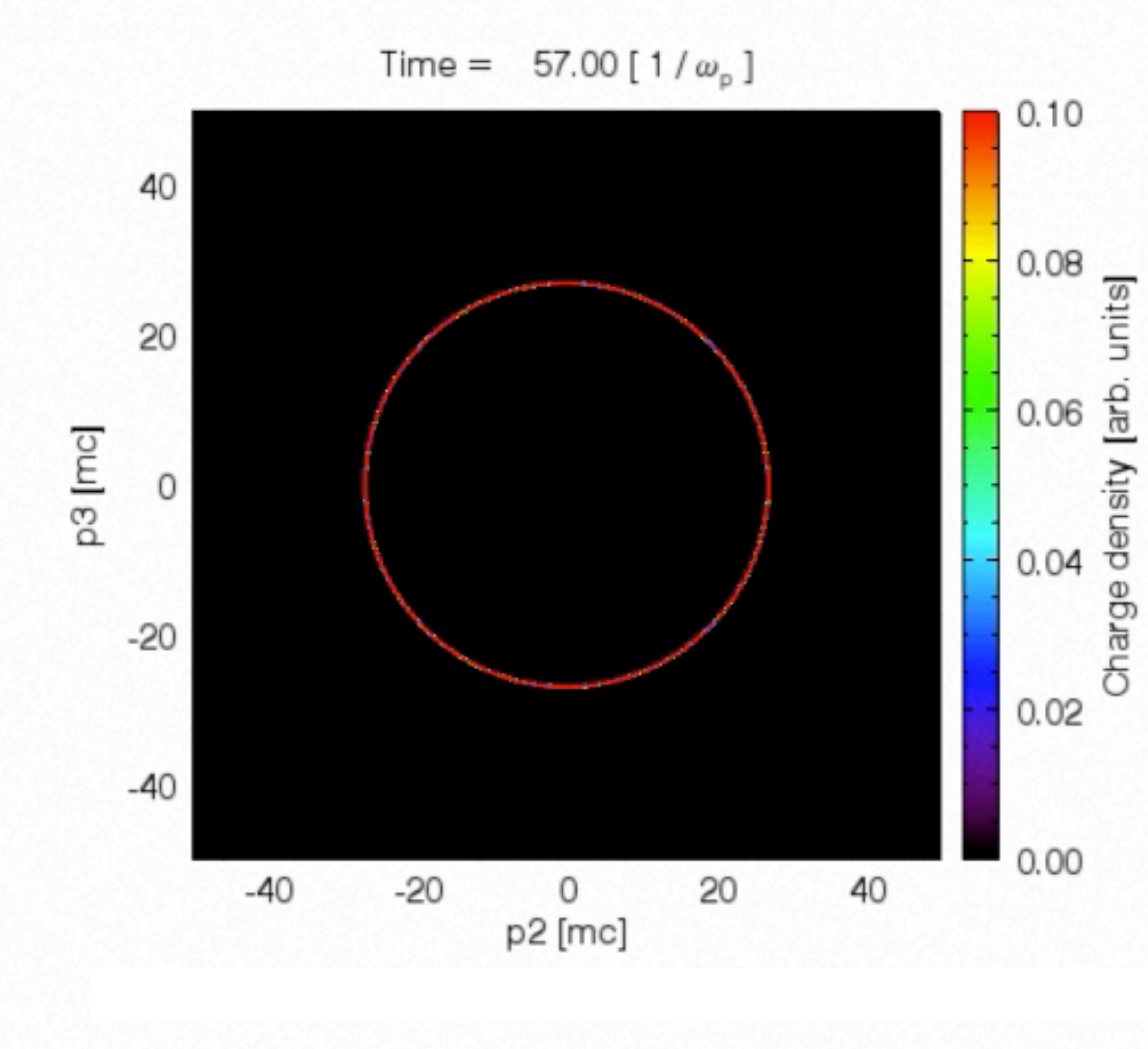
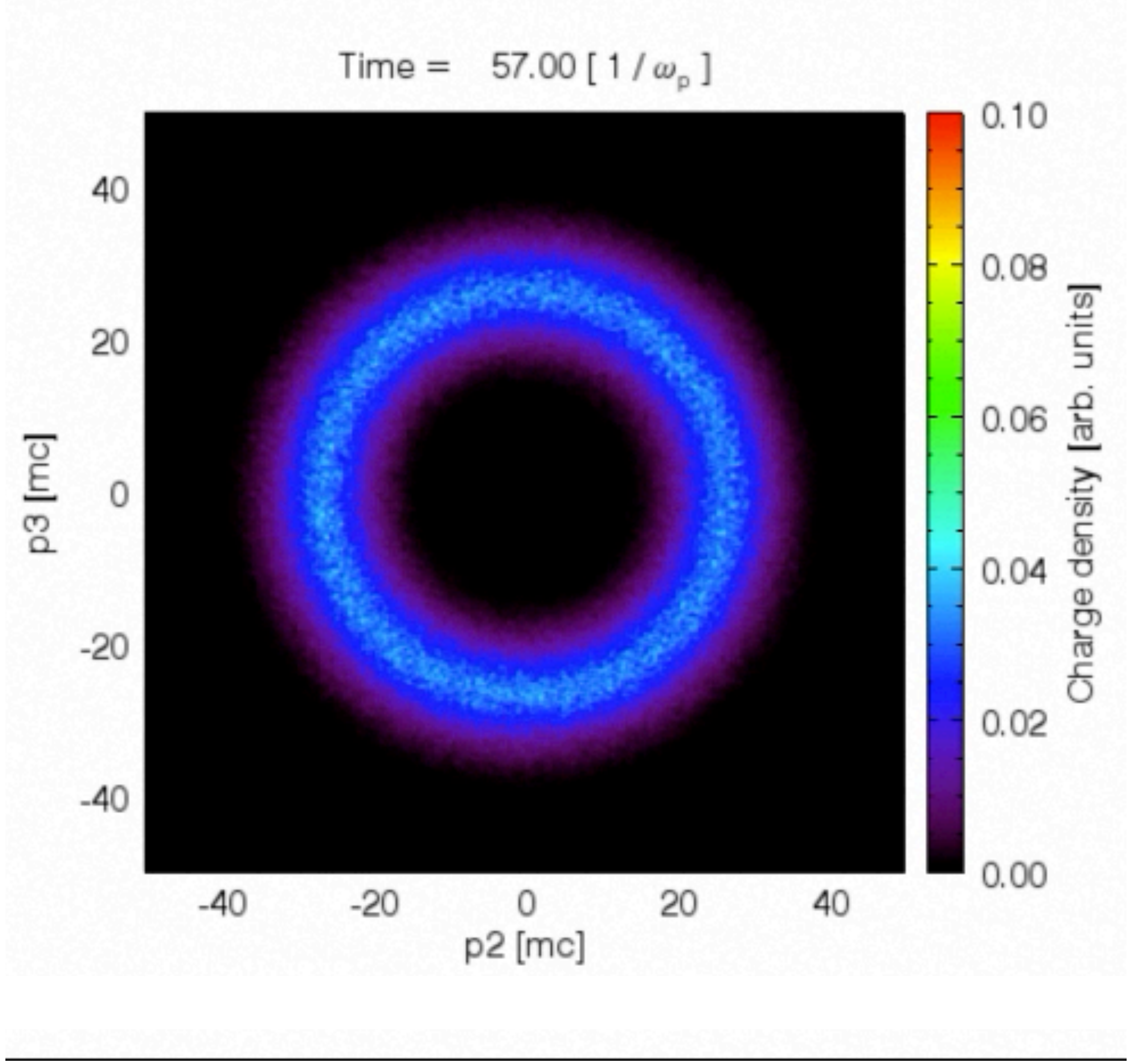


Quantum RR



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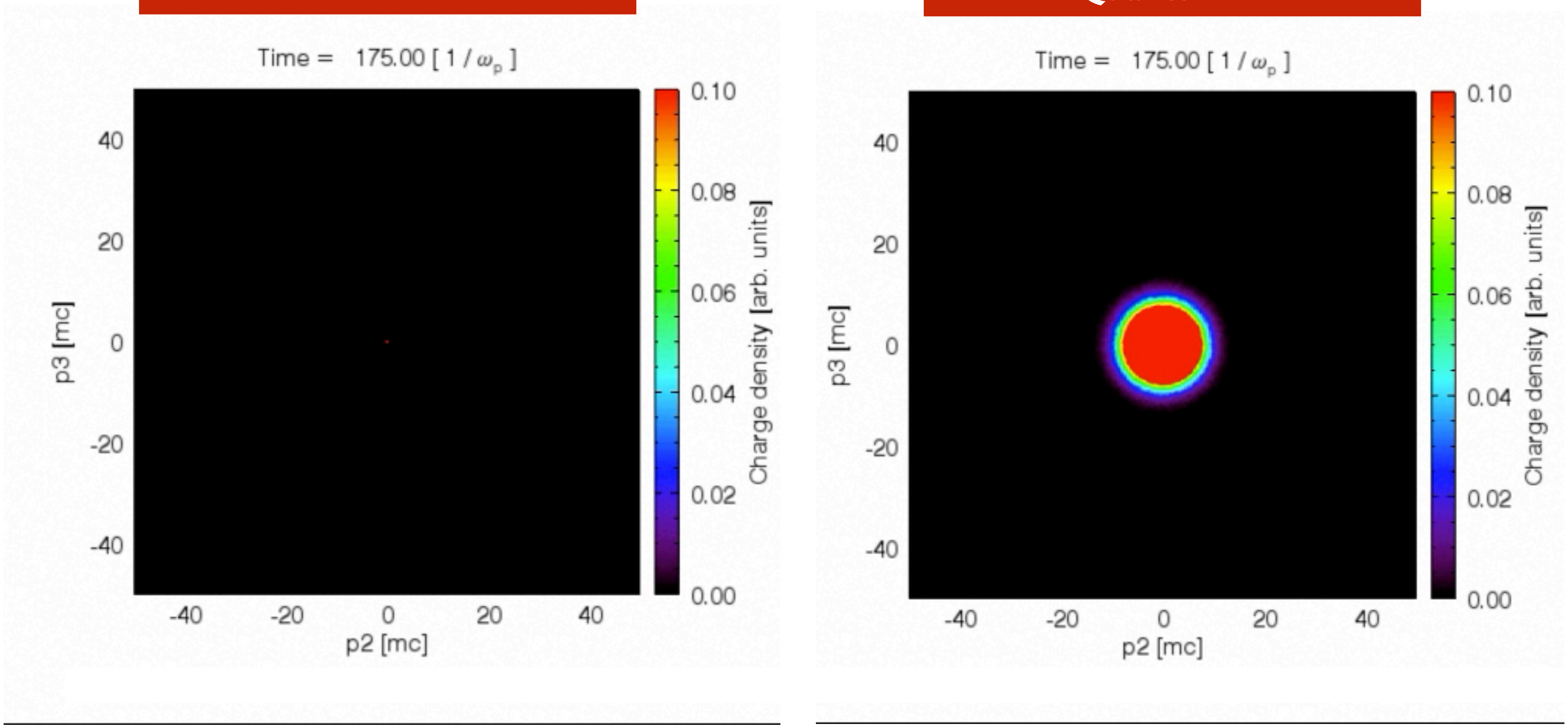
Classical RR

Quantum RR

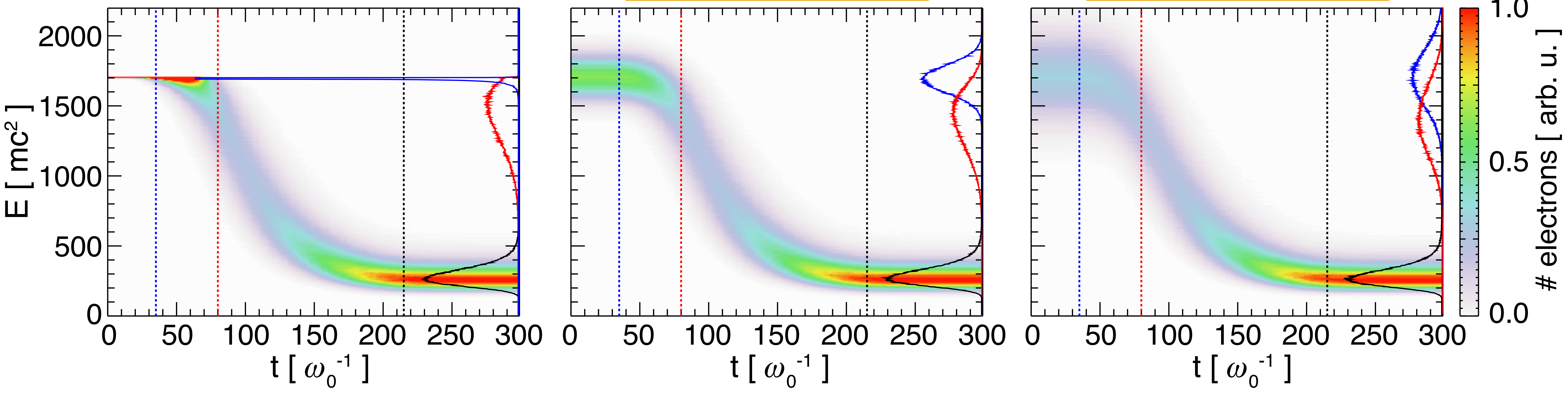


Expected value for final energy spread emerges from stochastic diffusion

TÉCNICO LISBOA

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

$\delta E_0 = 2\ mc^2$ | $\delta E_0 = 100\ mc^2$ | $\delta E_0 = 200\ mc^2$



$\delta E_F = 67\ mc^2$

Final energy spread can be predicted analytically*

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

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

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

Contents

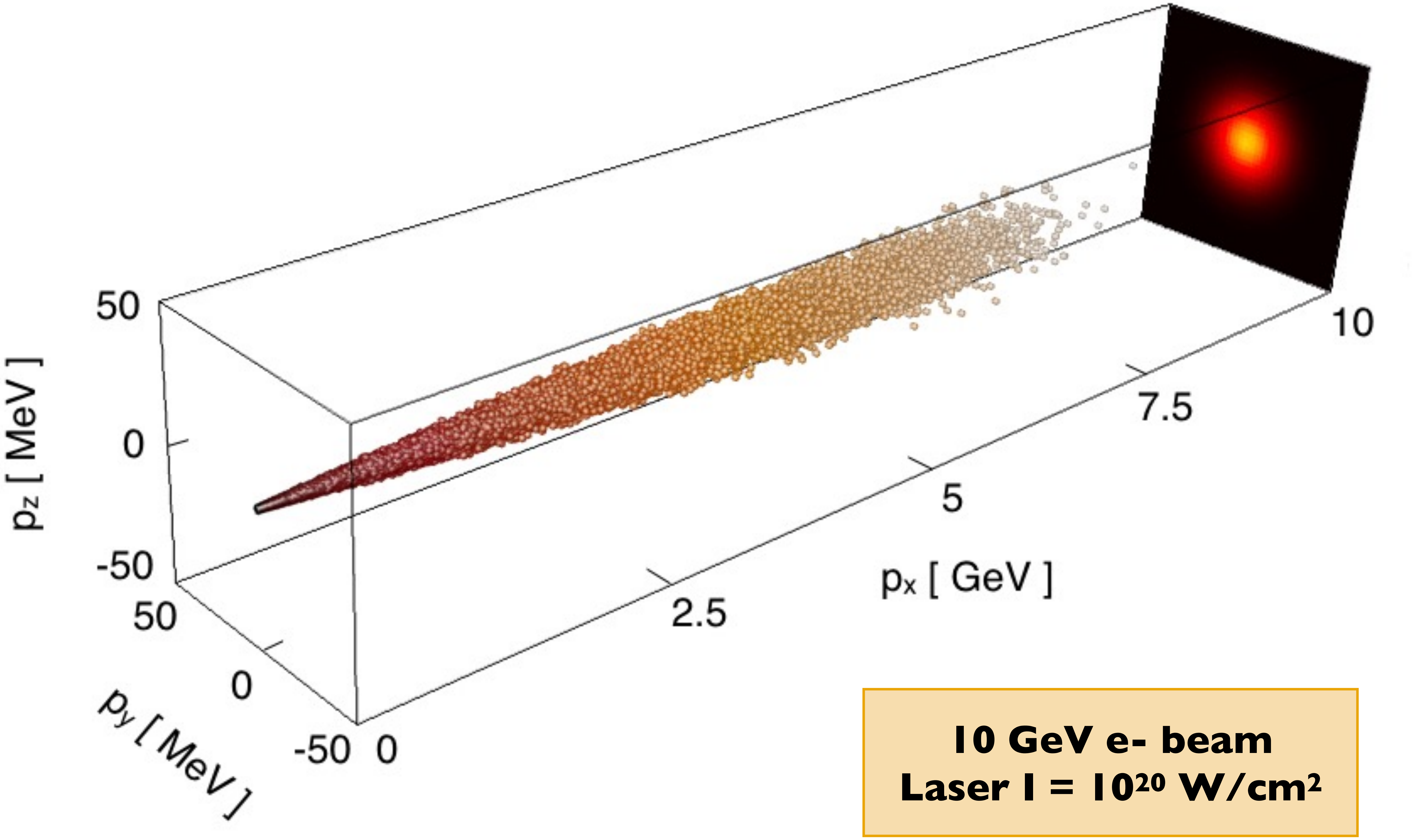
- **Basic concepts & classical radiation reaction**
- **Quantum radiation reaction**
- **Pair creation, QED cascades & optical traps**

Parameters similar to SFQED experiment planned at FACET-II

A large amount of beam energy can be converted to high-frequency photons (hard X-rays and Gamma-rays)

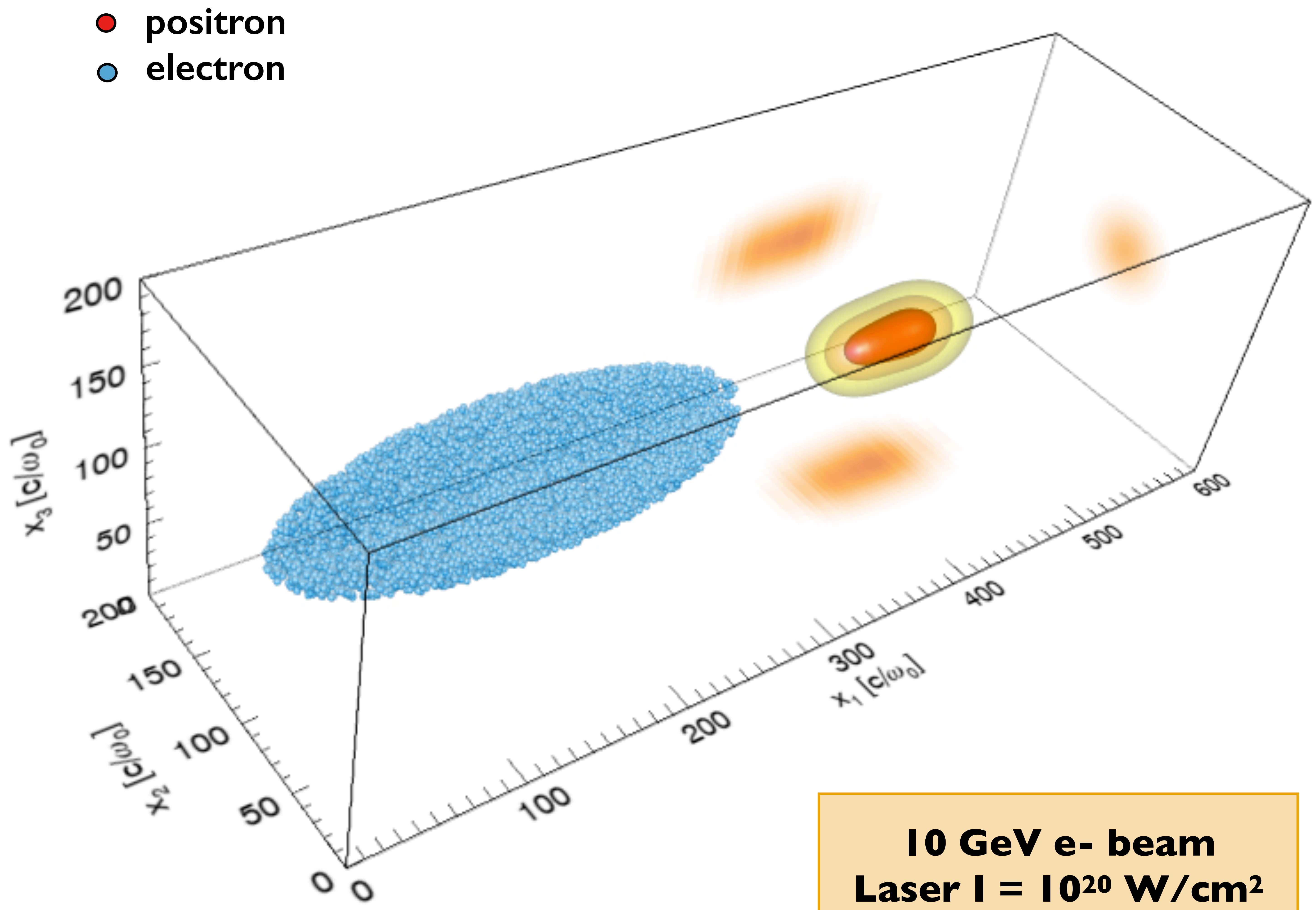
Photon source properties

- divergence < 1 mrad
- tunable energy range (cutoff > 1 GeV)
- possible to attain very high energies (~10 GeV)
- Energy conversion ~ 40%

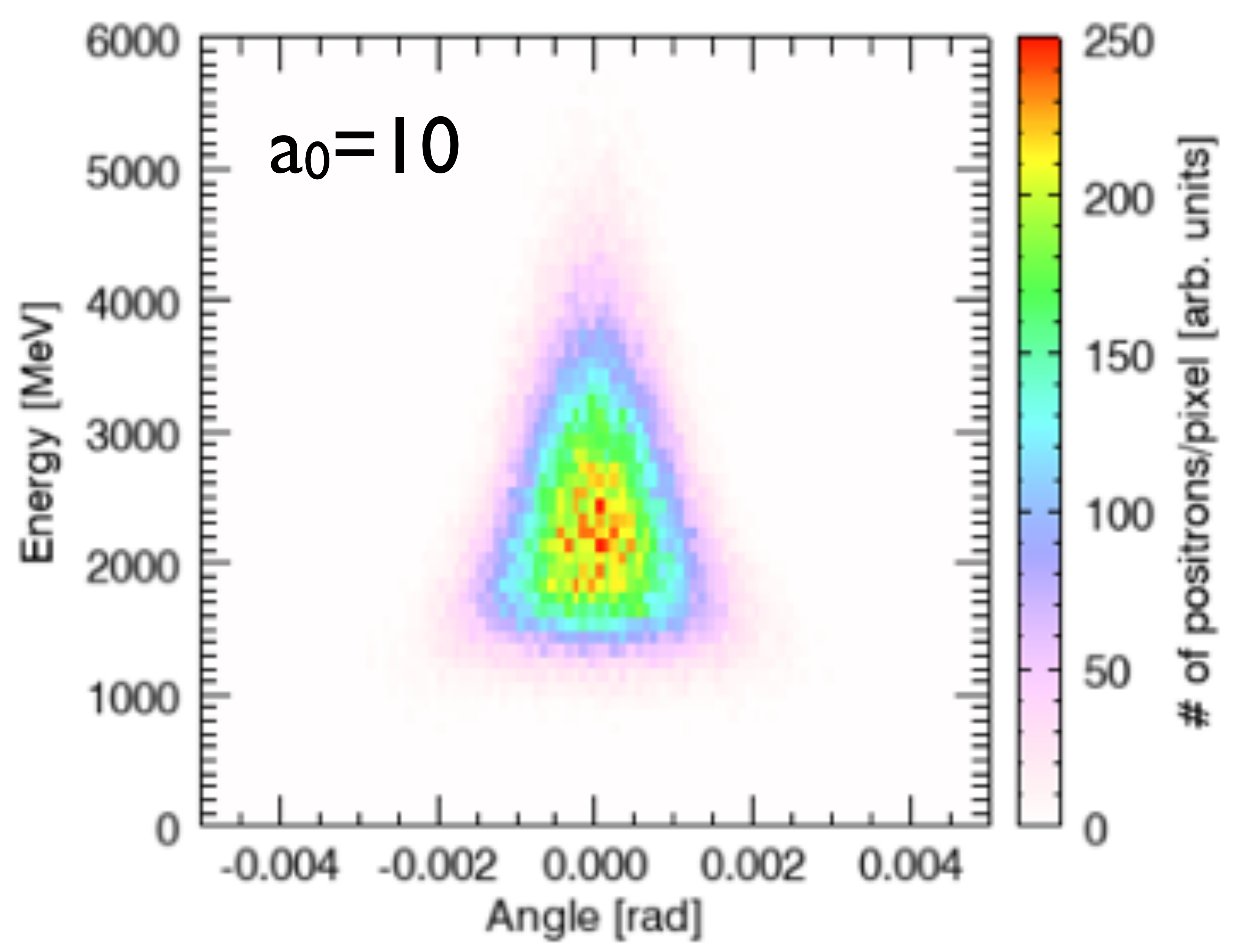


10 GeV e- beam
Laser I = 10^{20} W/cm^2

A fraction of radiated photons decays into electron-positron pairs



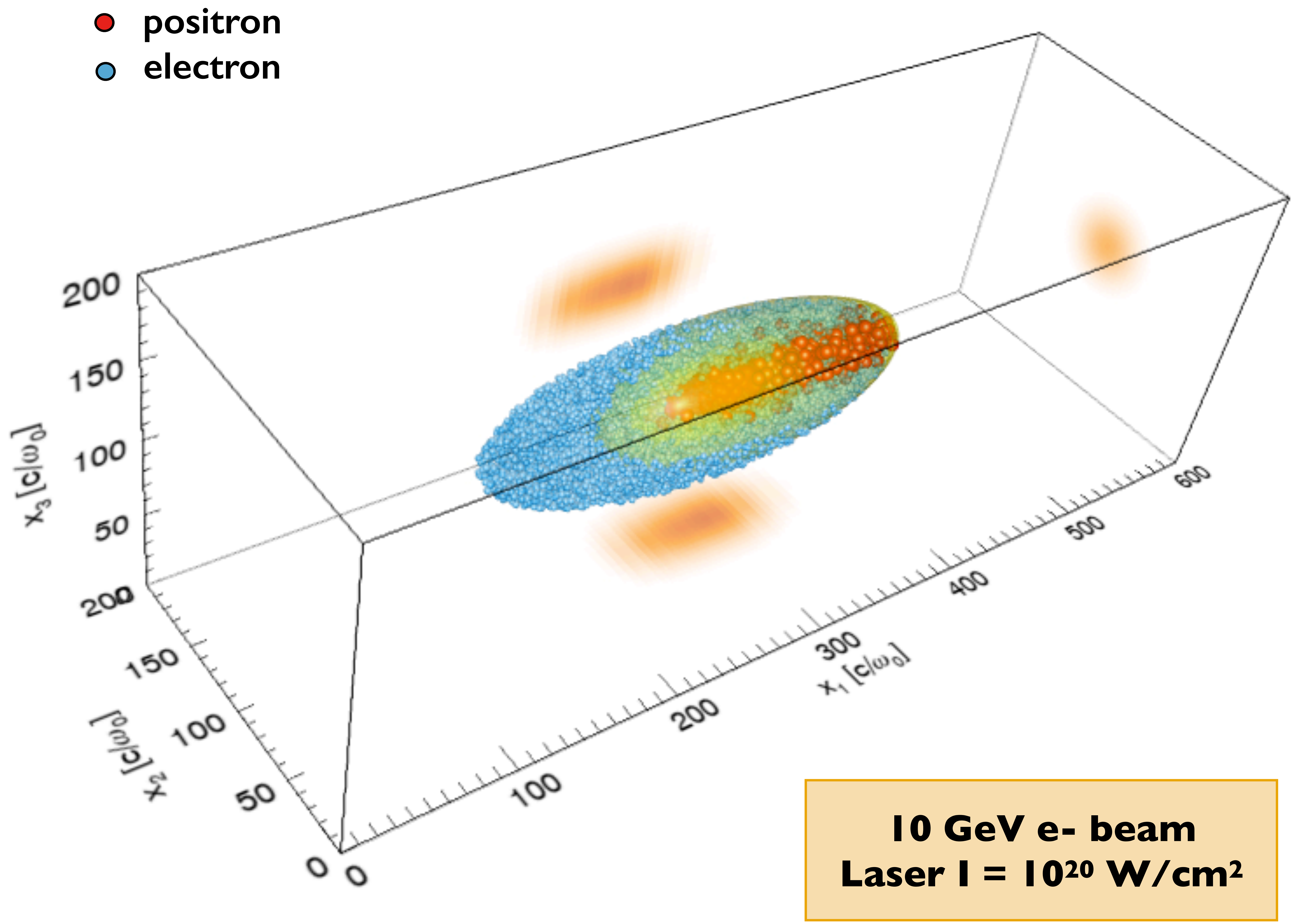
Positrons: energy vs angle



10 GeV e- beam
Laser I = 10^{20} W/cm^2

1 nC electron beam gives
~ 0.2 pC of positrons

A fraction of radiated photons decays into electron-positron pairs



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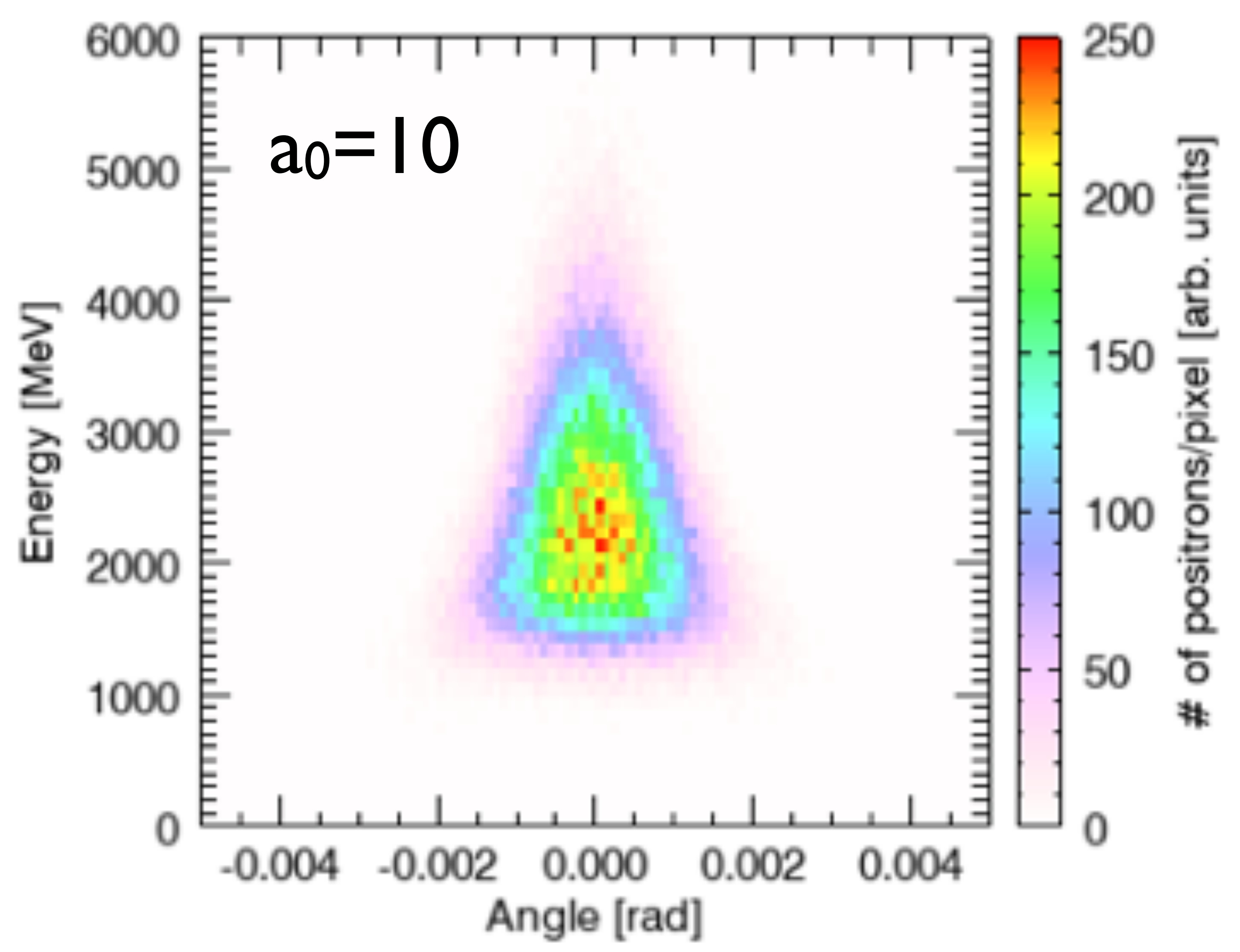

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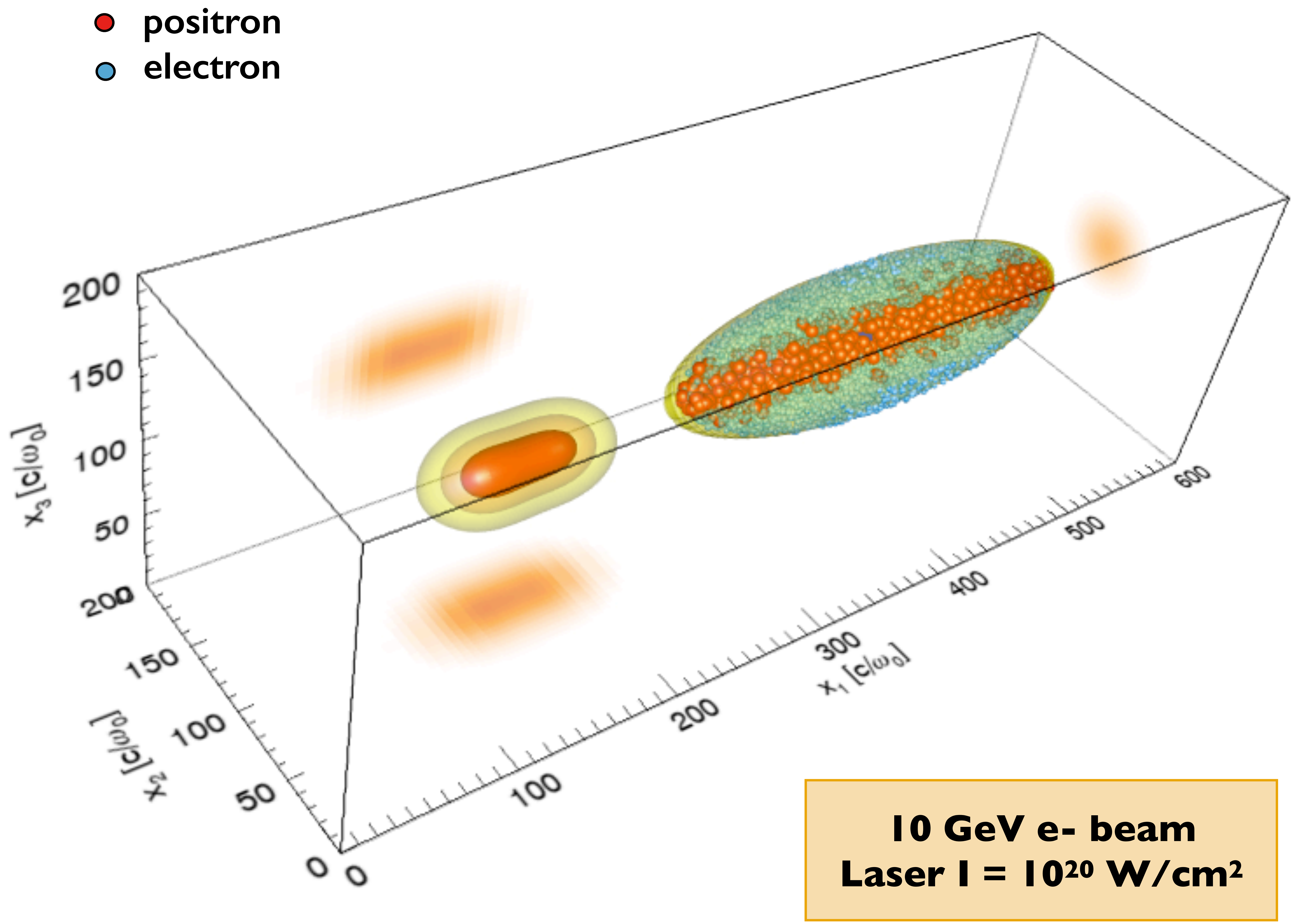
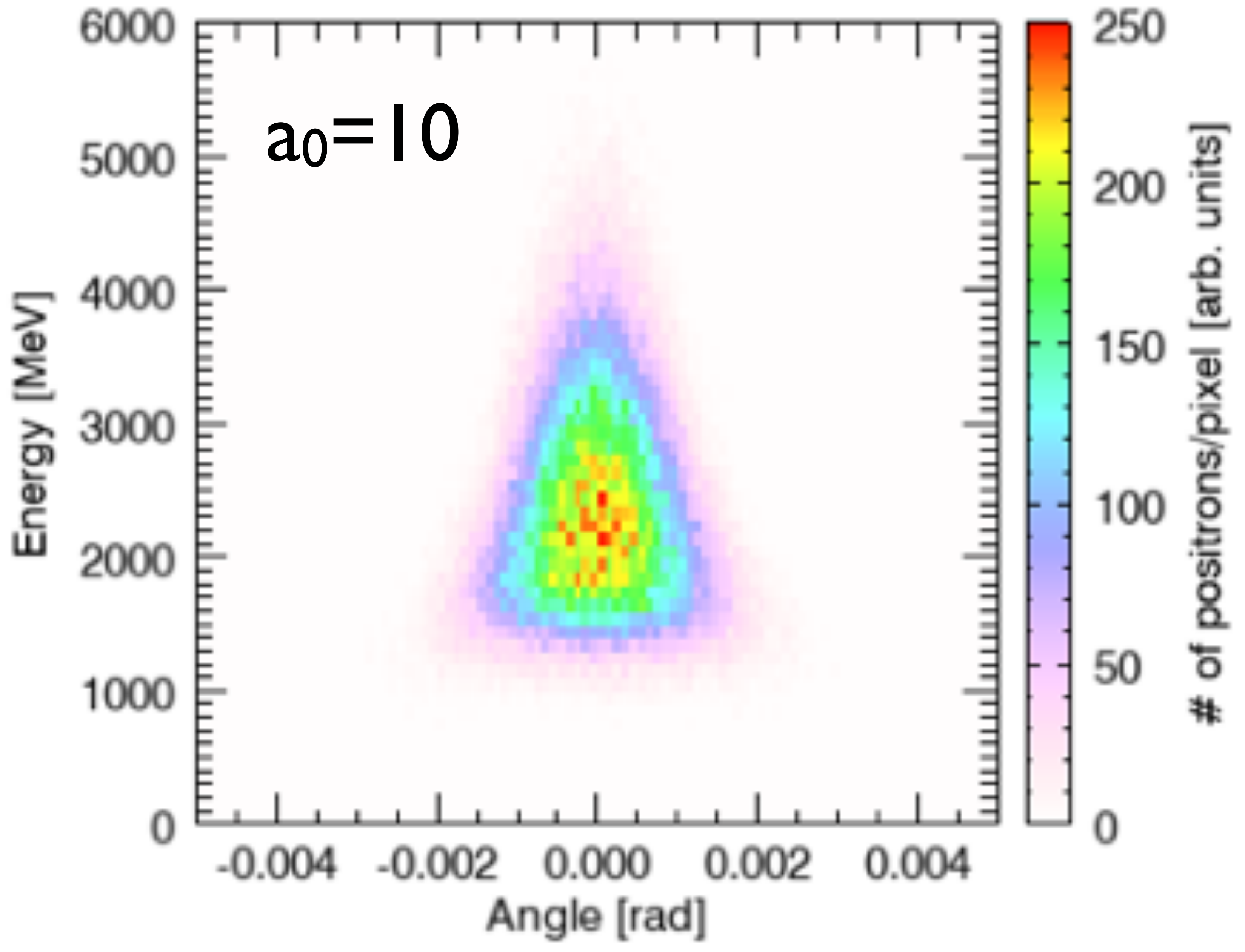


Positrons: energy vs angle



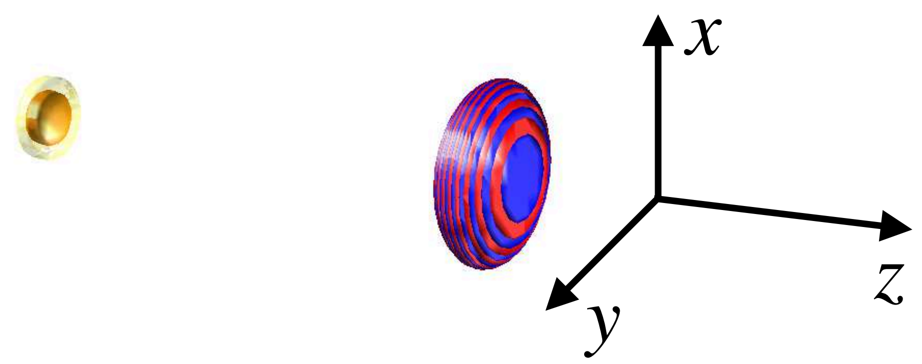
10 GeV e- beam
Laser I = 10^{20} W/cm^2

1 nC electron beam gives
~ 0.2 pC of positrons

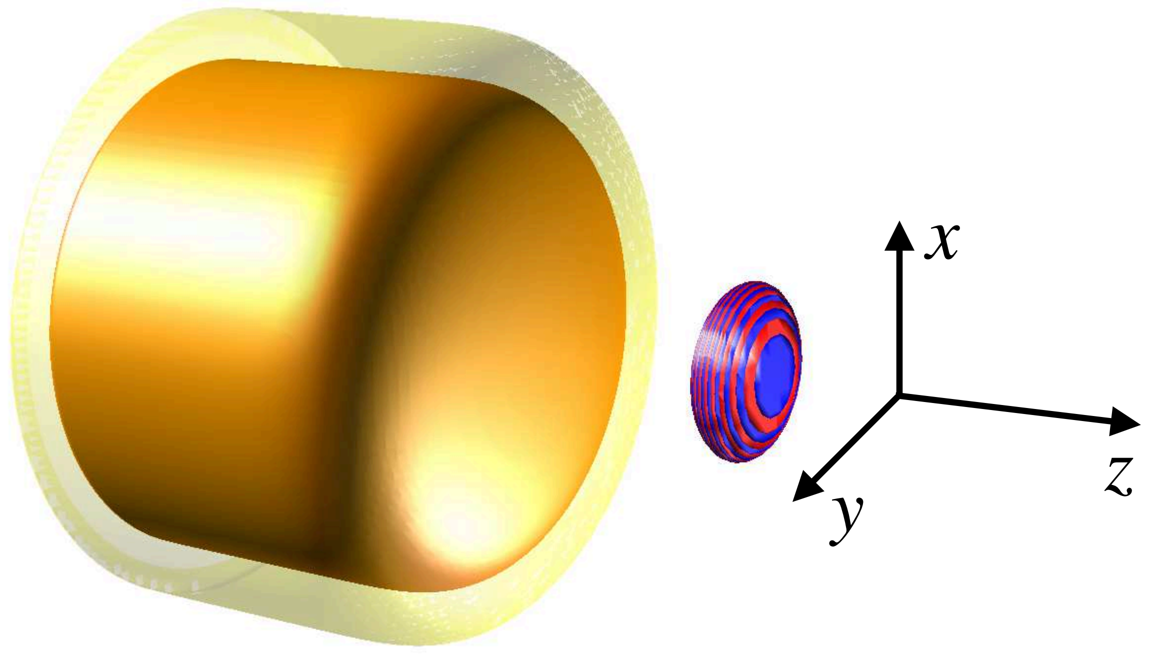
Different beam shapes and sizes lead to different number of pairs

Effective laser intensity of interaction is reduced for non-ideal beams

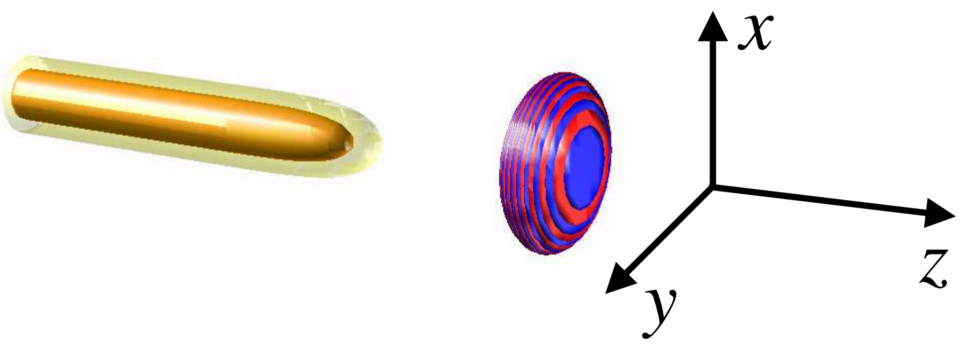
Single electron



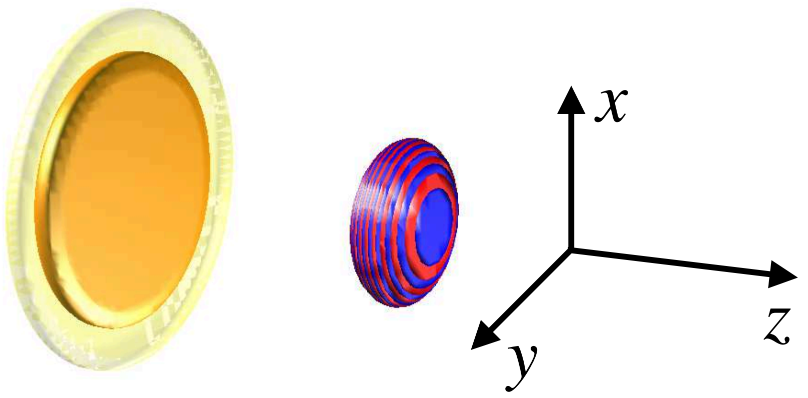
Wide electron beam



Thin electron beam



Short electron beam (any size)



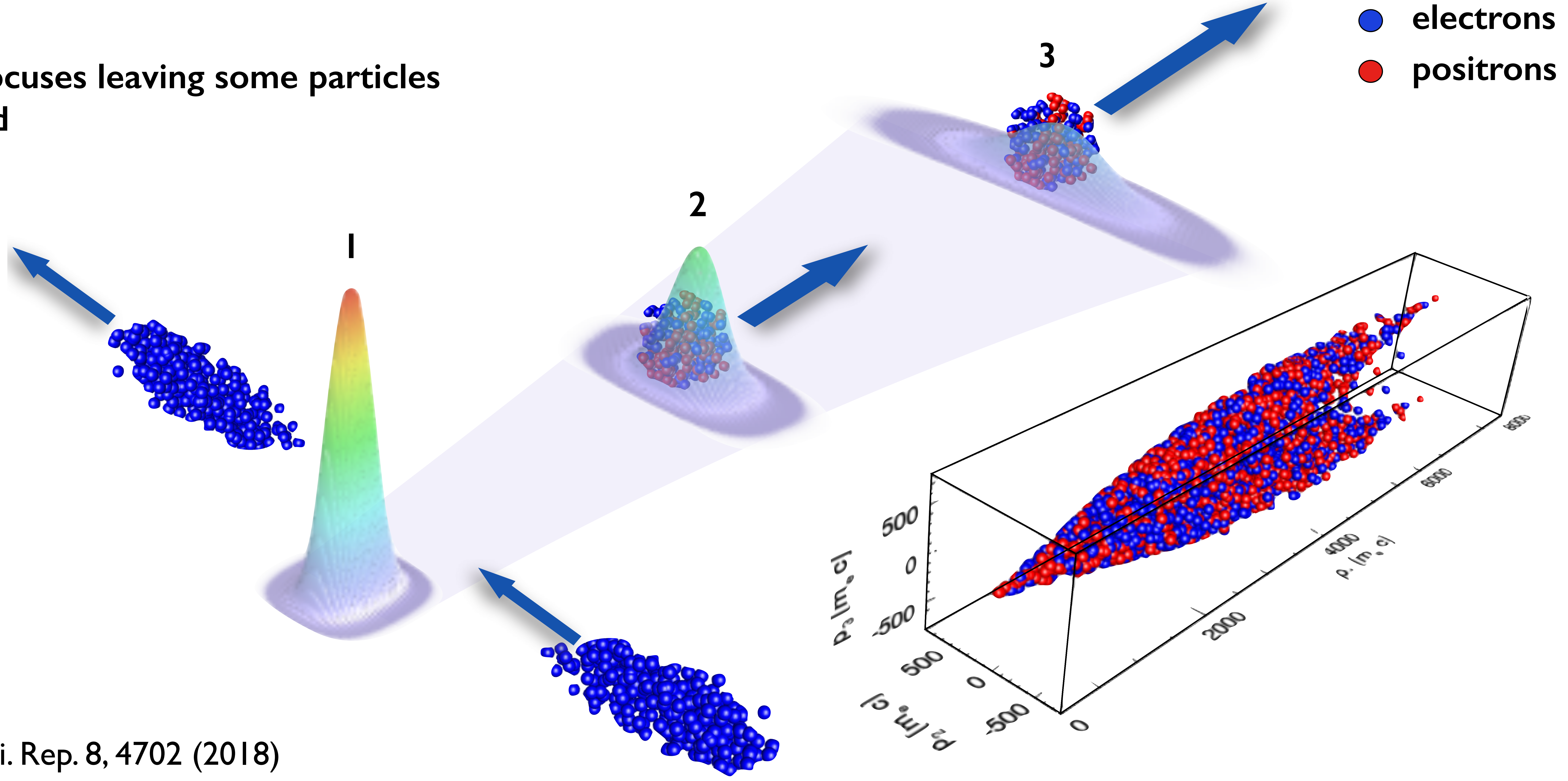
Analytical model can predict the number of pairs for non-ideal spatio temporal syncronization and realistic beams*

* O. Amaro and M. Vranic, NJP 23, 115001 (2021)

Creating an e+e- beam from laser - e- scattering at 90°

1. LWFA electrons collide with the laser; pairs are produced in the highest field region
2. E+e- beam is accelerated by the laser in vacuum
3. Laser defocuses leaving some particles accelerated

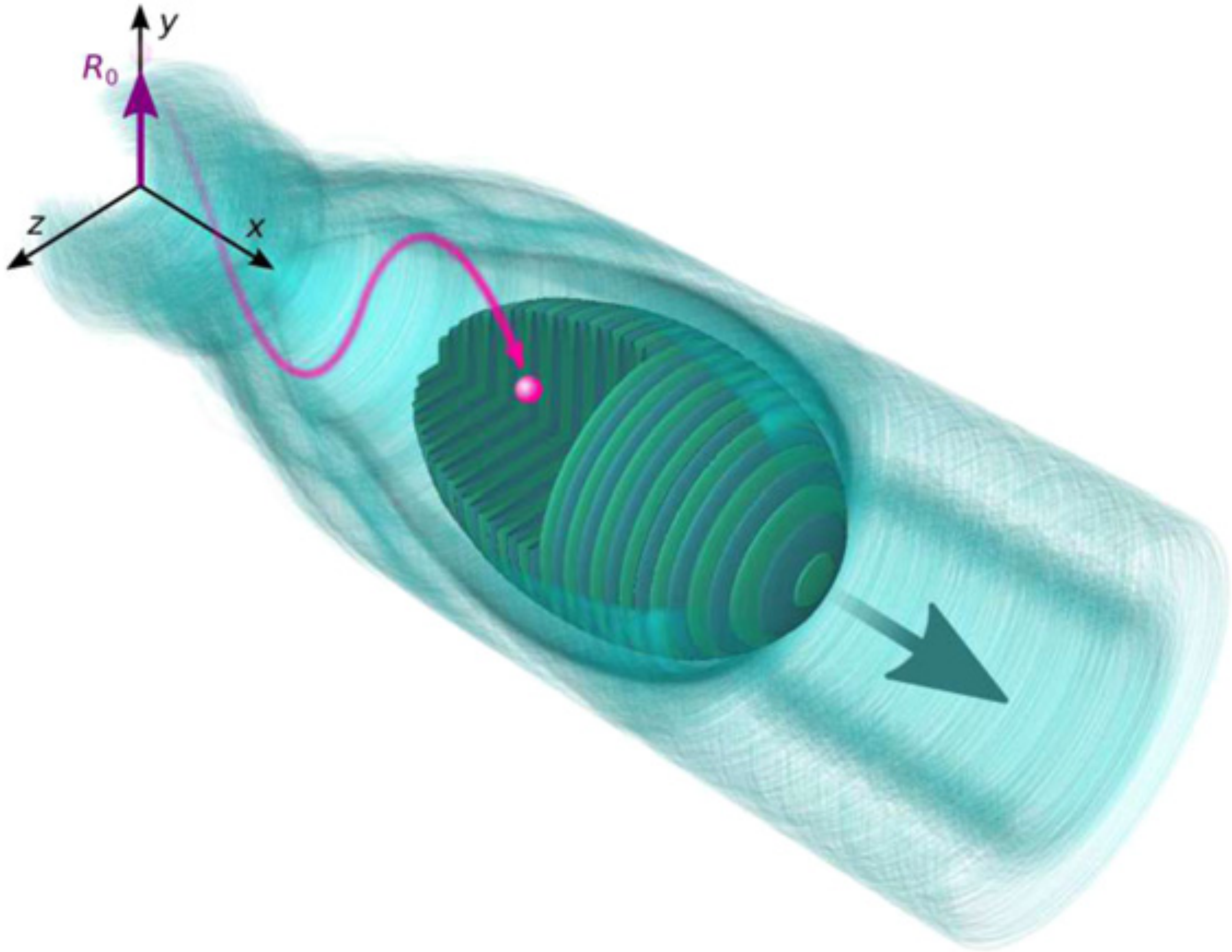
Pair creation and acceleration are decoupled!



M.Vranic et. al., Sci. Rep. 8, 4702 (2018)

Electrons and positrons can be further accelerated in a plasma channel

A resonance between plasma background fields and the intense laser fields accelerates leptons



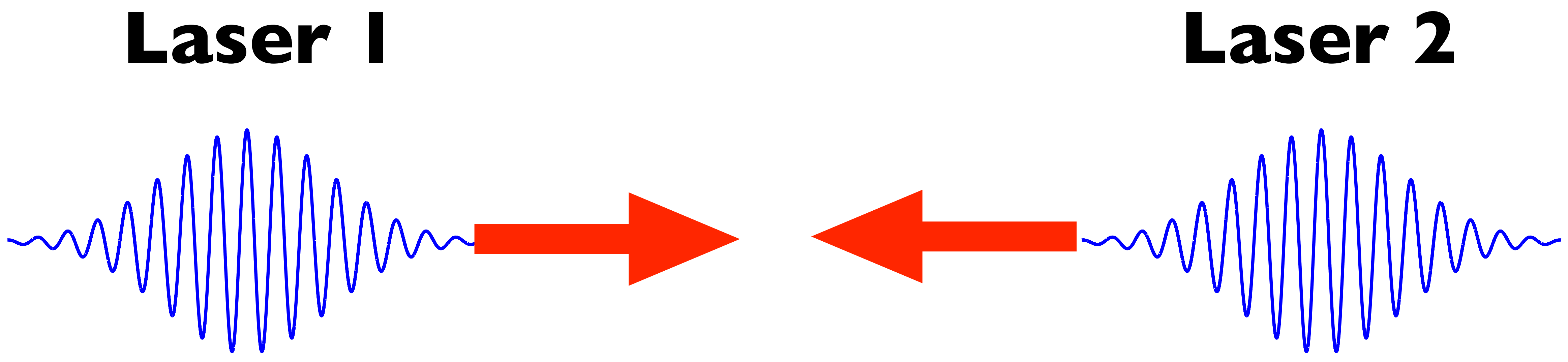
The mechanism is called direct laser acceleration (DLA).

Advantage: this scheme can accelerate electrons and positrons in the same direction!

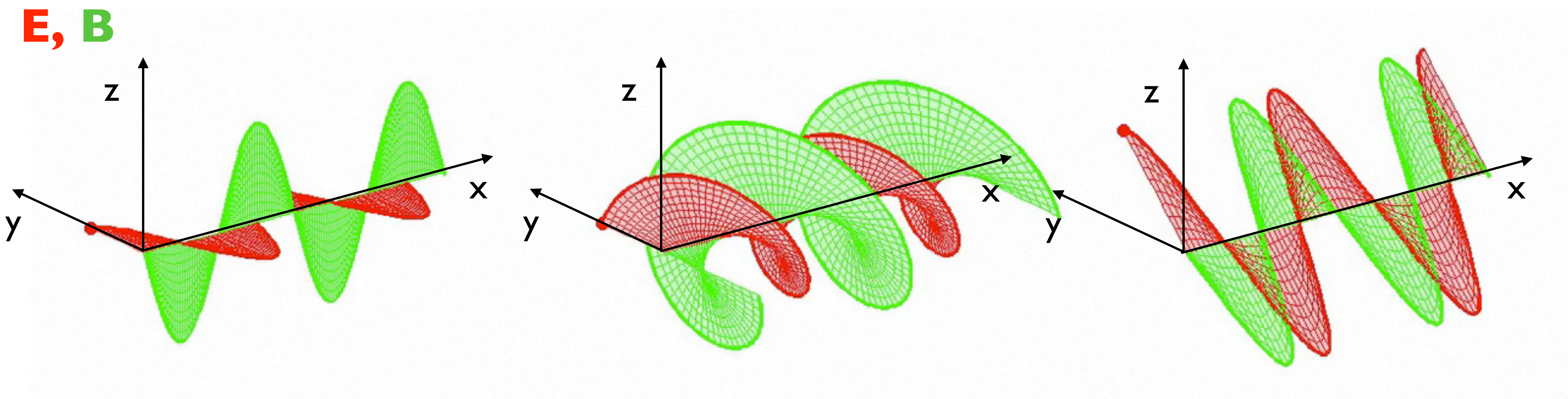
M. Jirka et. al., NJP, 22 083058 (2020)
B. Martinez et al., to be submitted (2022)

Standing wave configurations for QED cascades

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



Linear	Double clockwise	Clockwise-anti clockwise



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)

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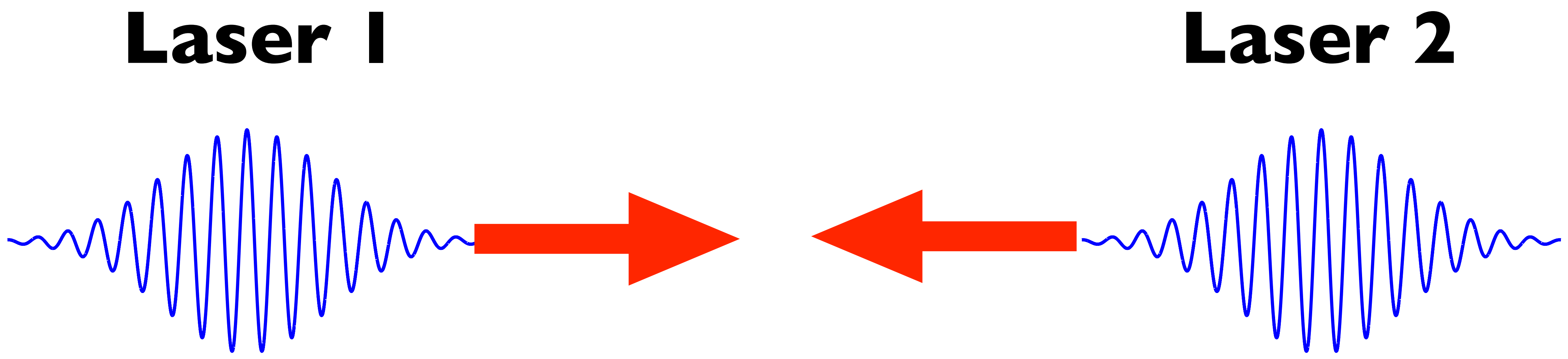

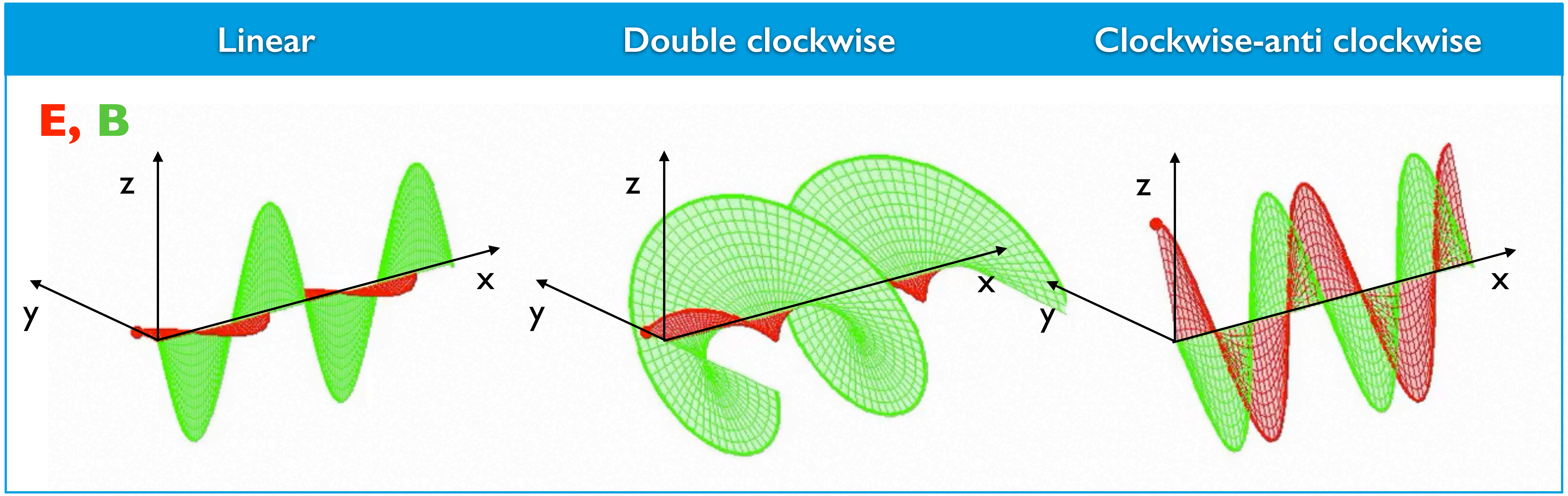

A.R Bell and J. G Kirk PRL, 101, 200403 (2008); M.A Fedotov et al. PRL 105, 080402 (2010)
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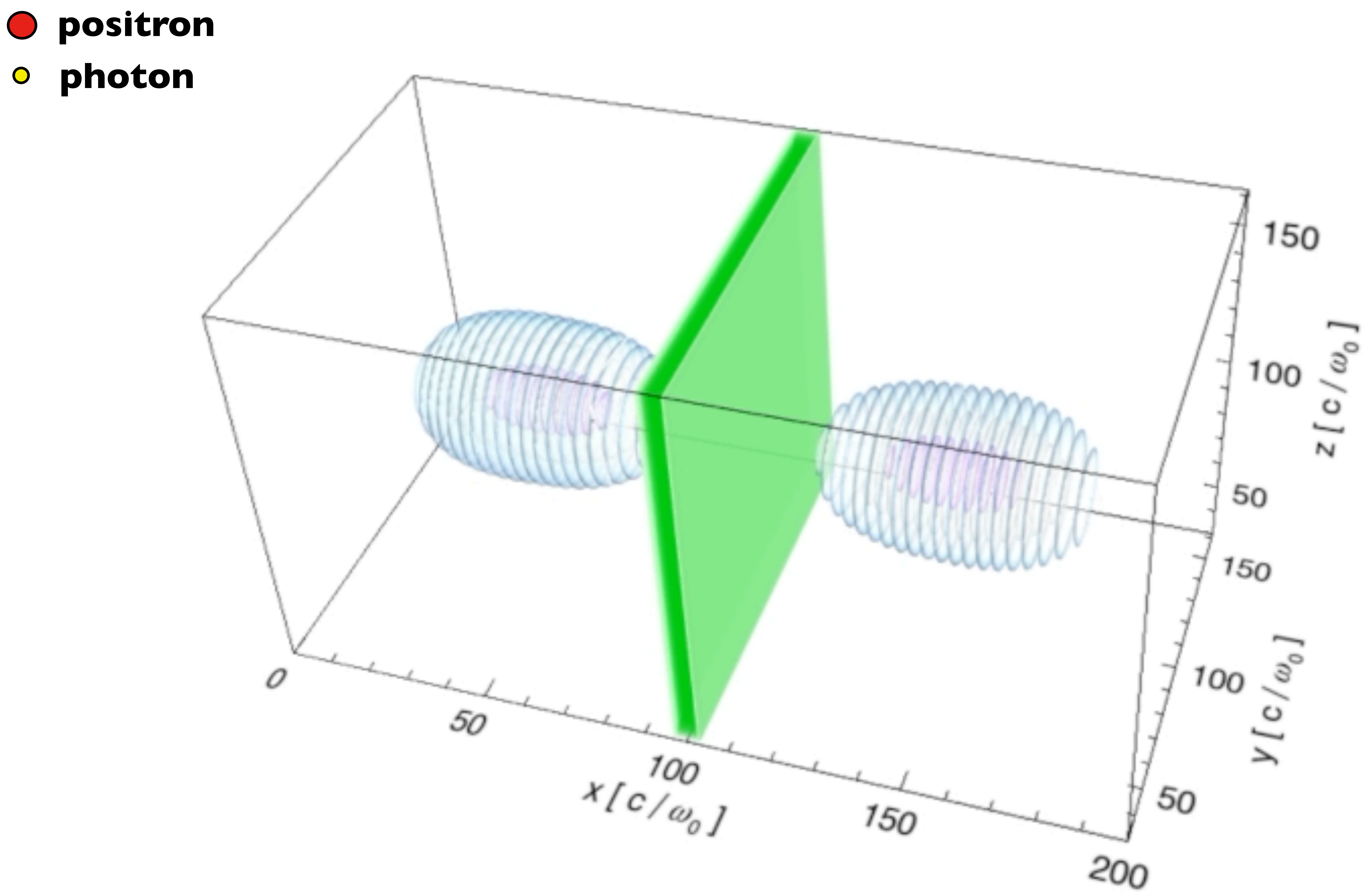
Positrons from a hydrogen ice target



Target parameters

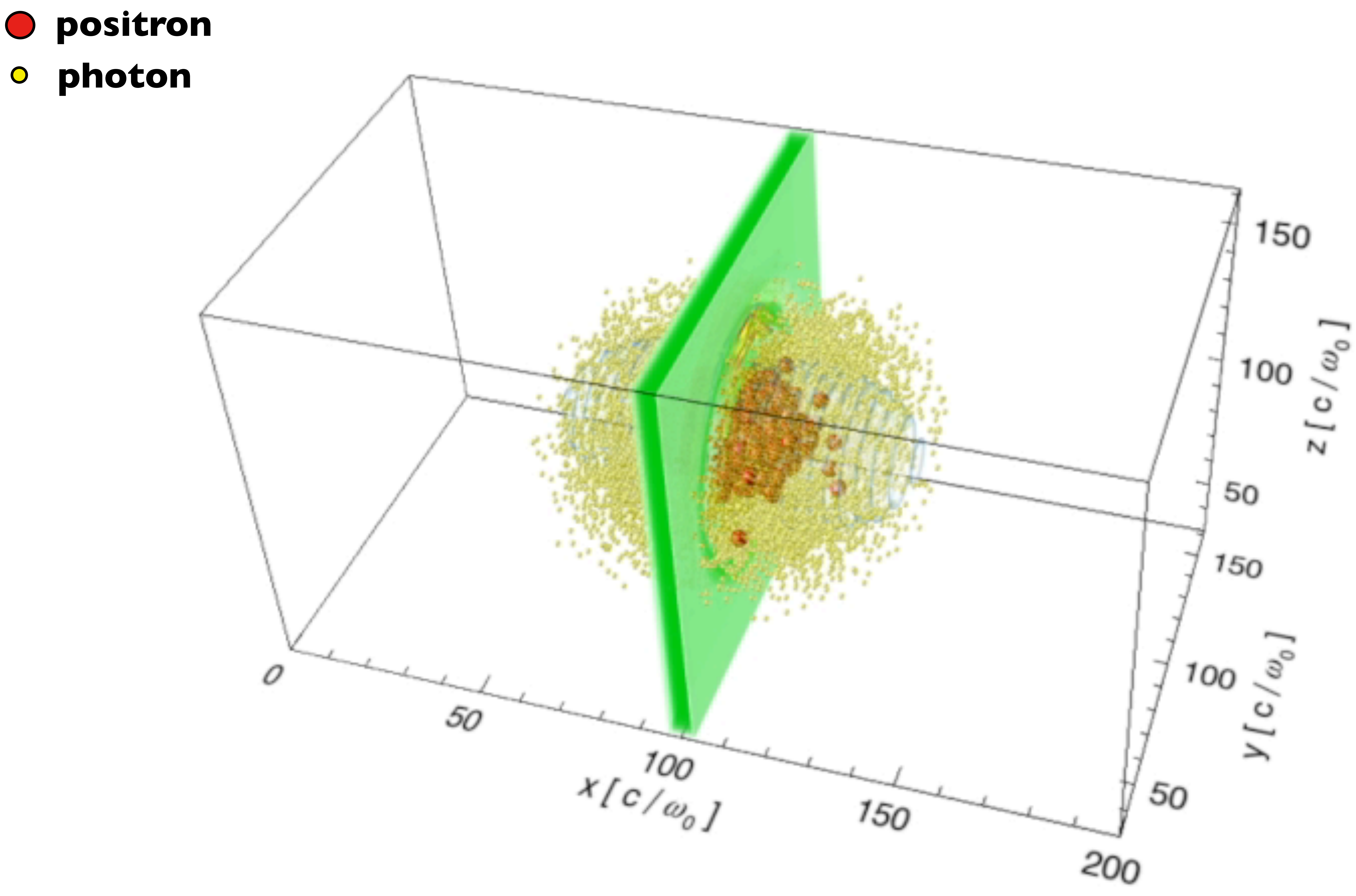
initial n =10 nc
1 μm thickness

Laser parameters

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

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

Positrons from a hydrogen ice target



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

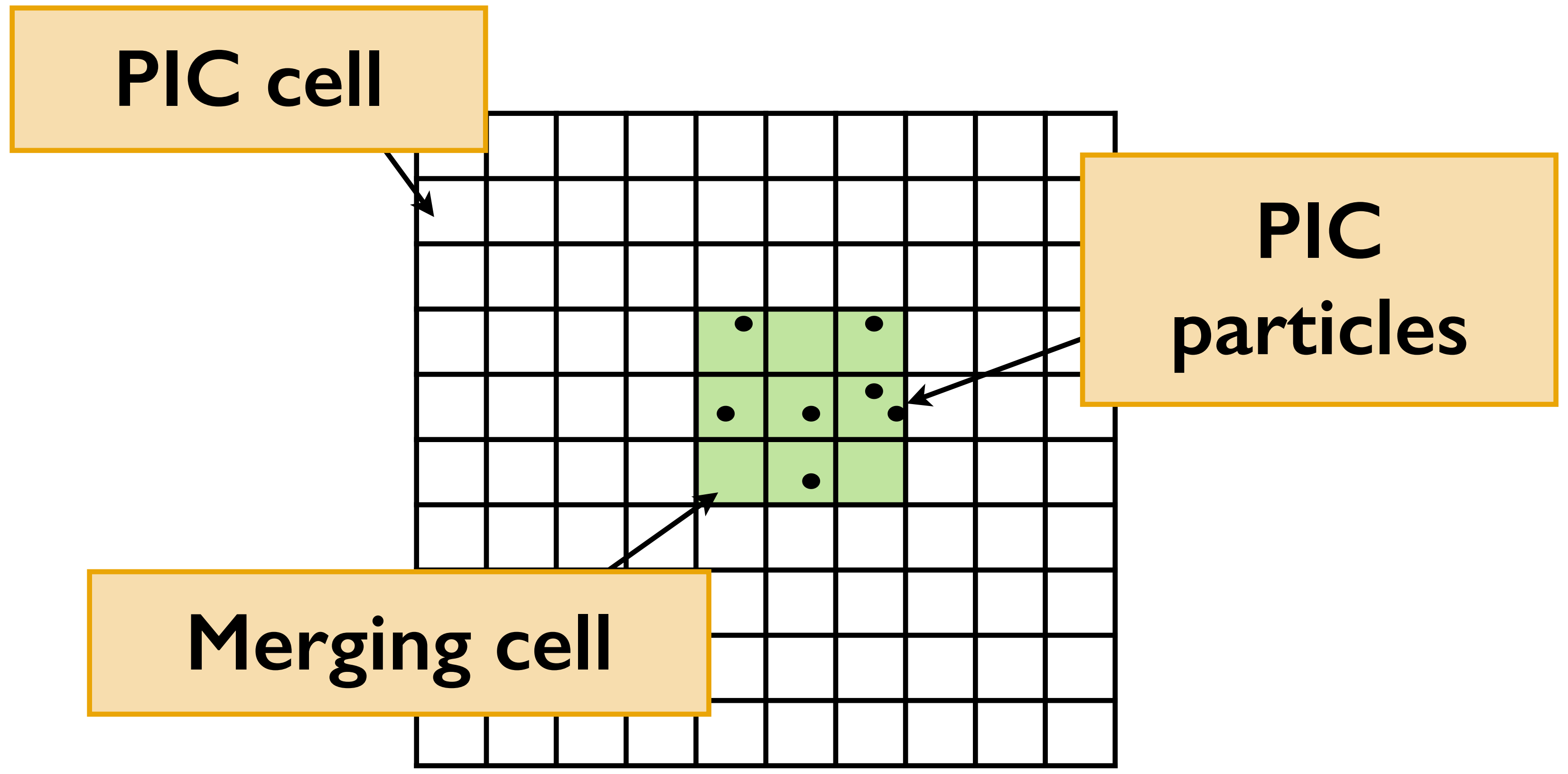
Macroparticle merging algorithm

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



PIC cell

PIC particles

Merging cell

Macroparticle merging algorithm

M. Vranic et al, CPC 2015

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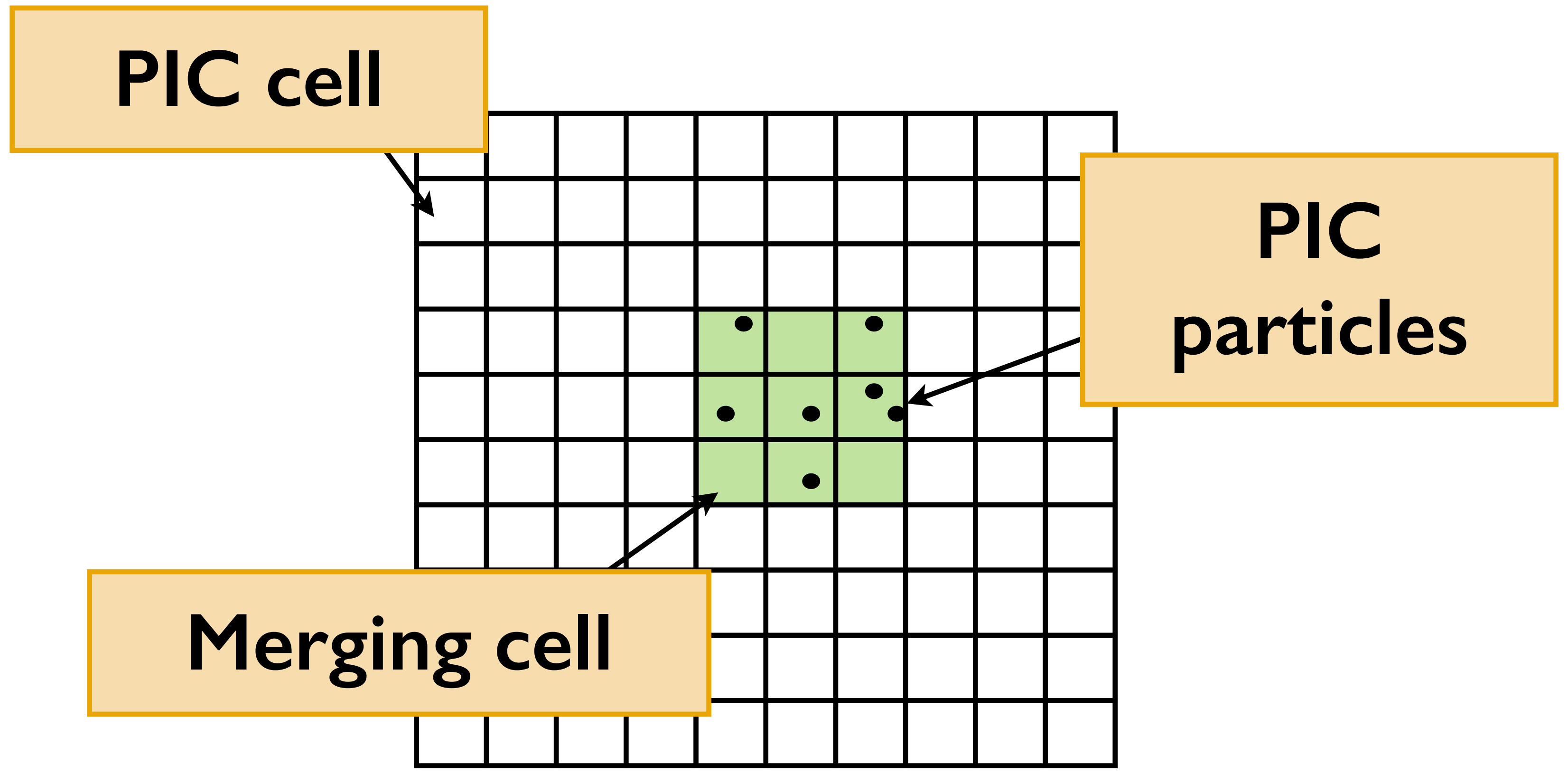
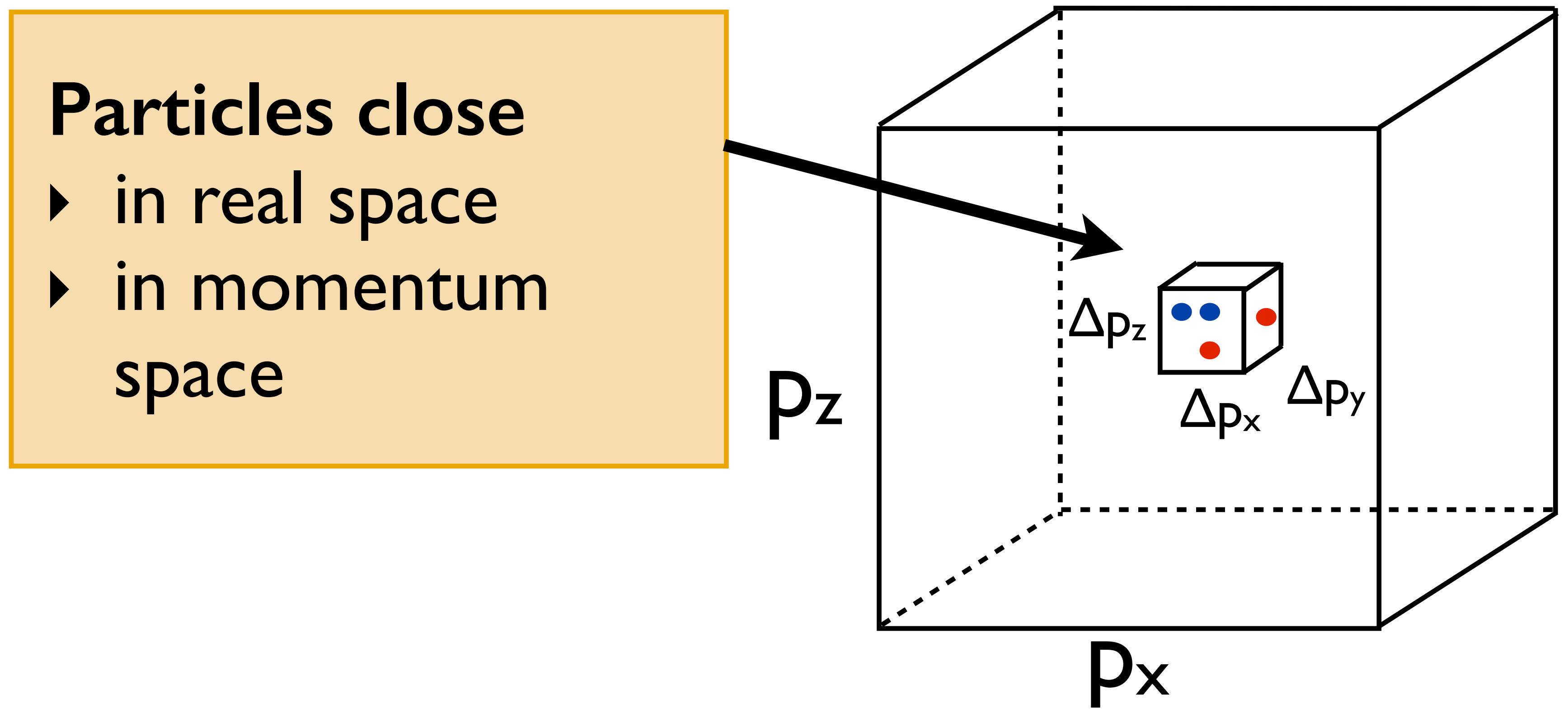
Bin the momentum space

Distribute the particles of every merging cell in its momentum bins

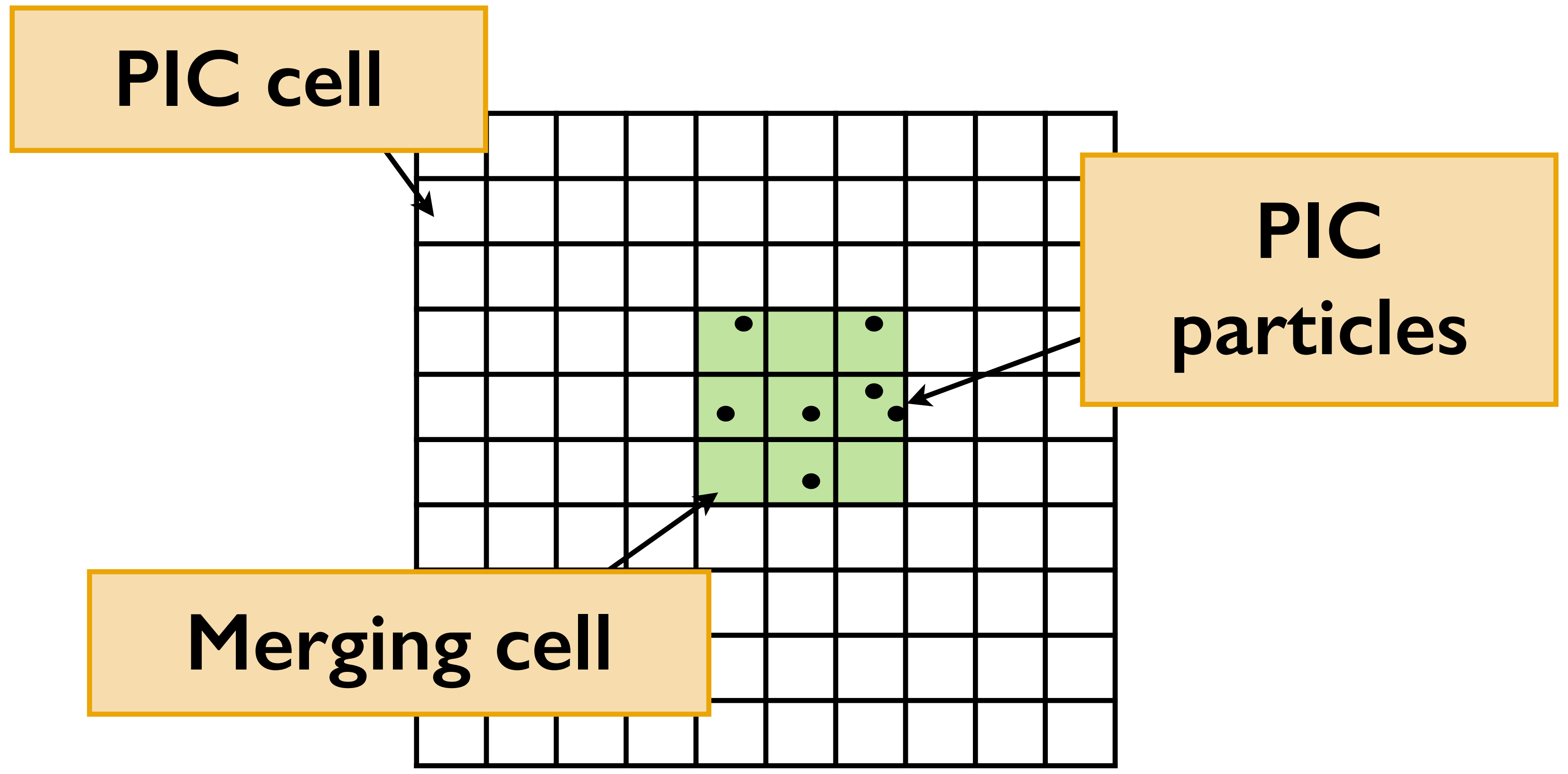



Particles close
- in real space
- in momentum space

Macroparticle merging algorithm

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



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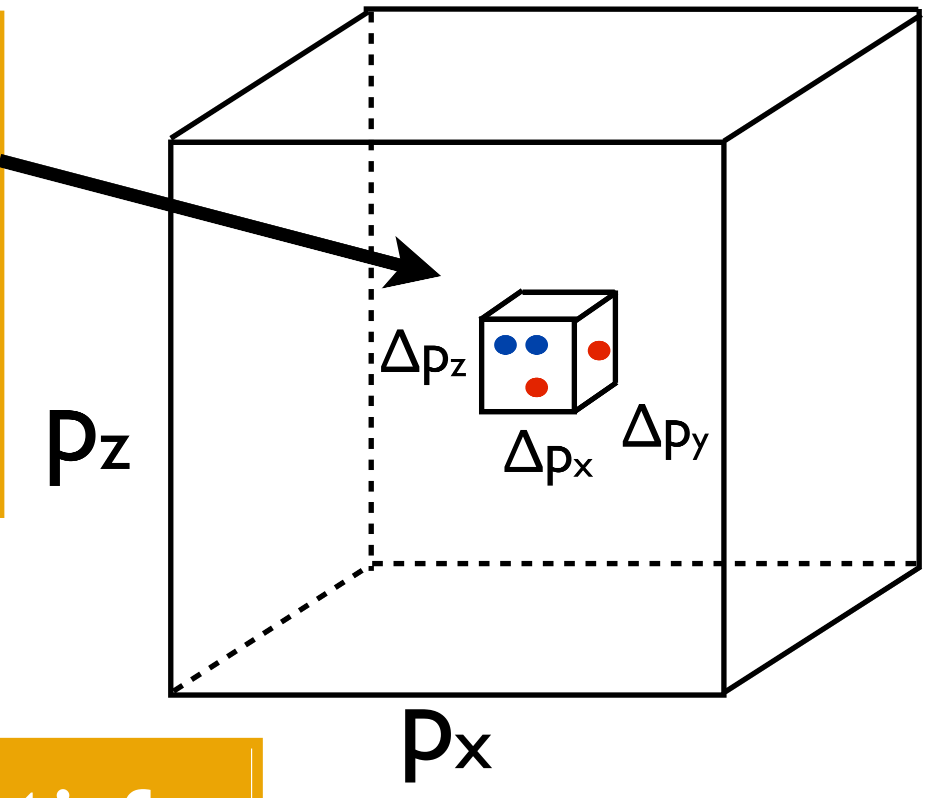

Equations to satisfy

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

Macroparticle merging algorithm

M. Vranic et al, CPC 2015

- Calculate the number of merging cells and their size
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- Find the p_{min} and p_{max} of the particles in every merging cell

↓

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↓

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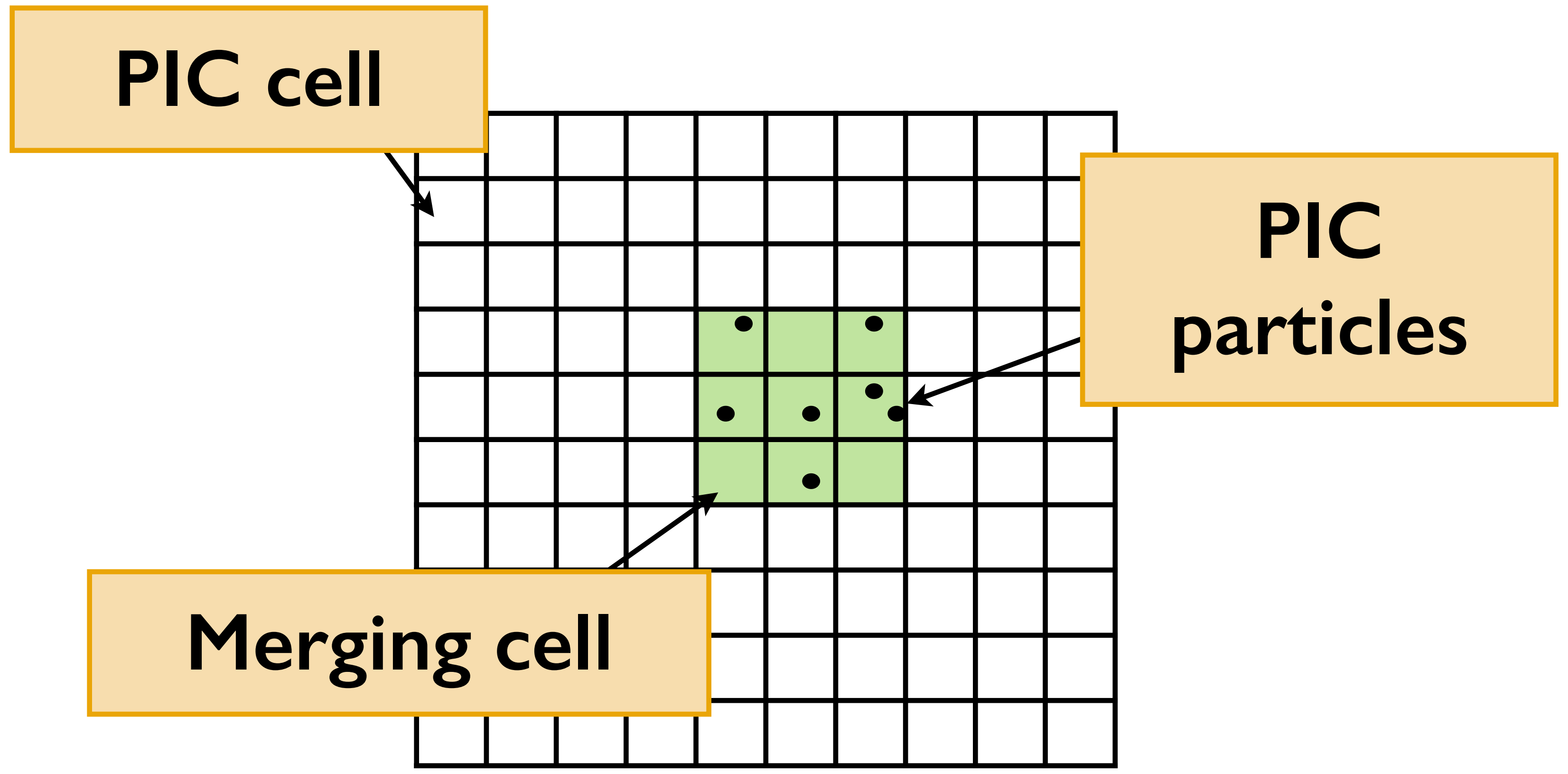
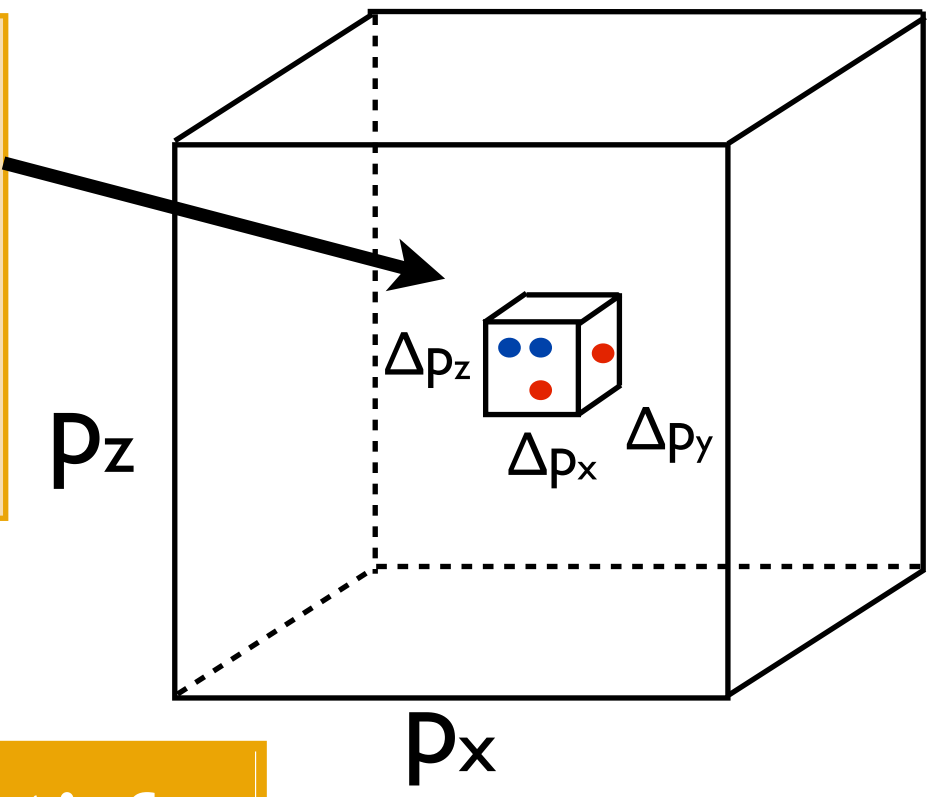


Particles close

- in real space
- in momentum space



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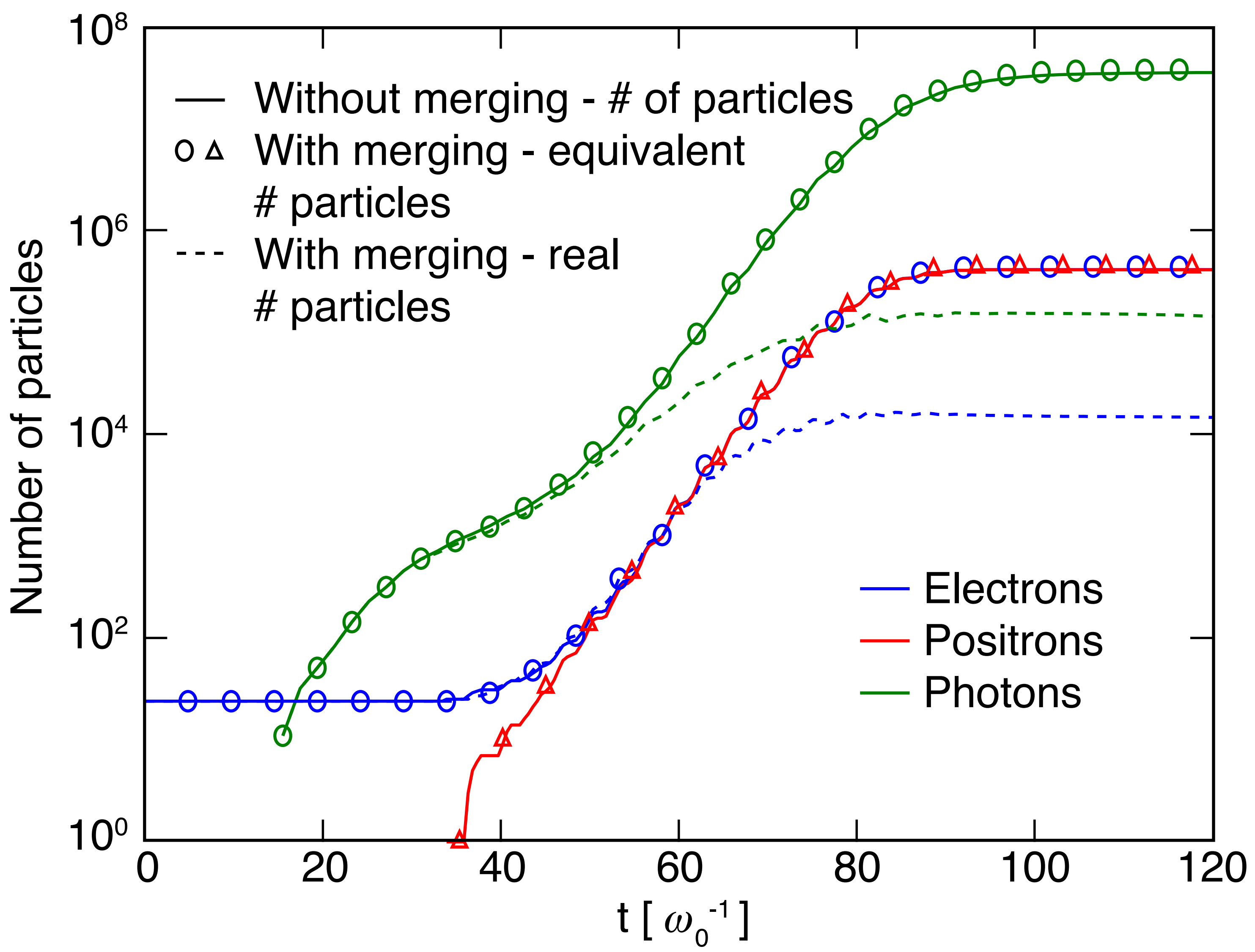
$$\epsilon_t = w_a \epsilon_a + w_b \epsilon_b$$

Example: cascade simulation

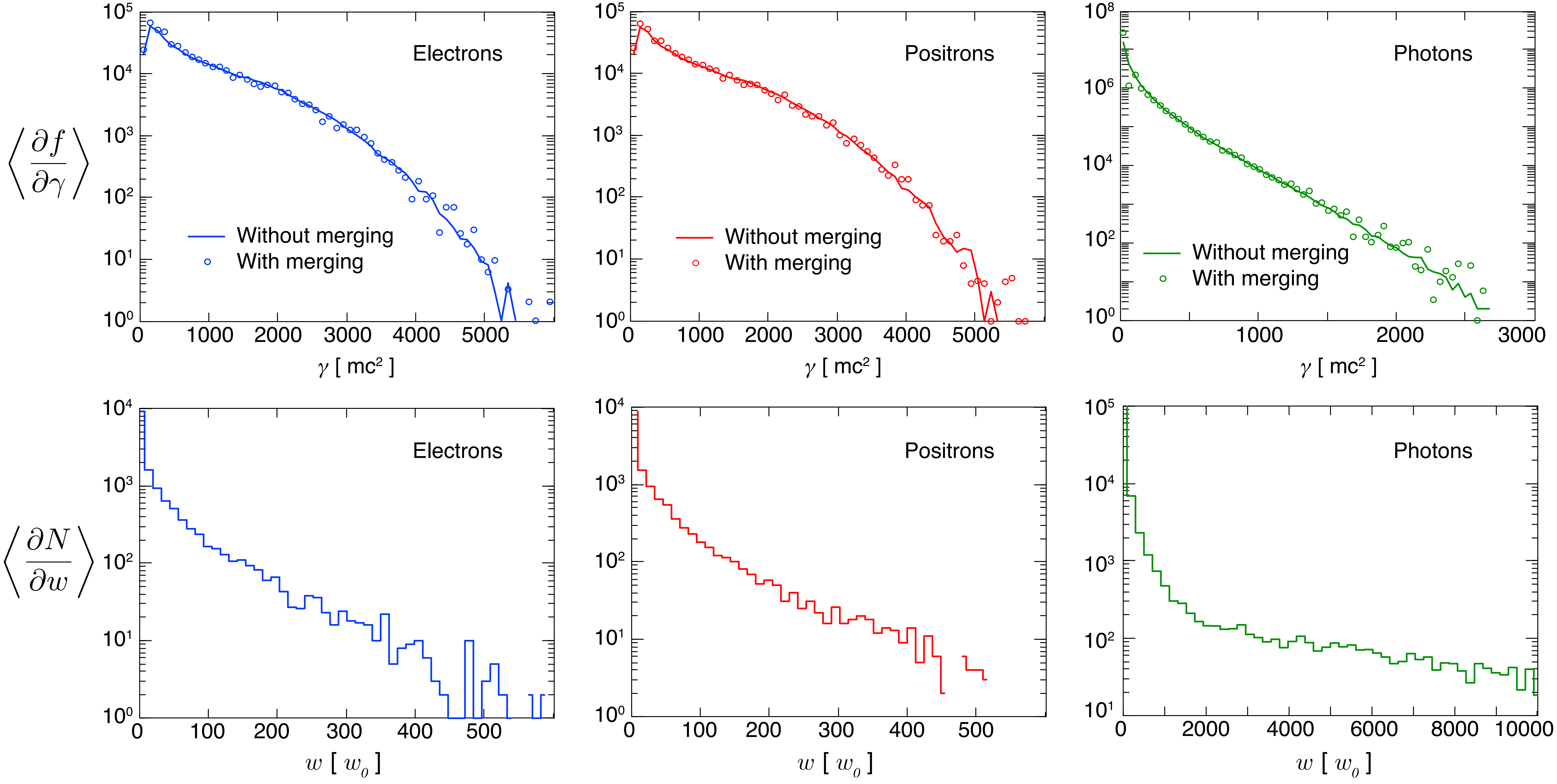
- ➡ two colliding lasers
- ➡ $a_0 = 1000, \lambda = 1$ um
- ➡ $\tau = 32$ fs, $W_0 = 3.2$ um



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

The physics must not be affected by the coalescence of particles

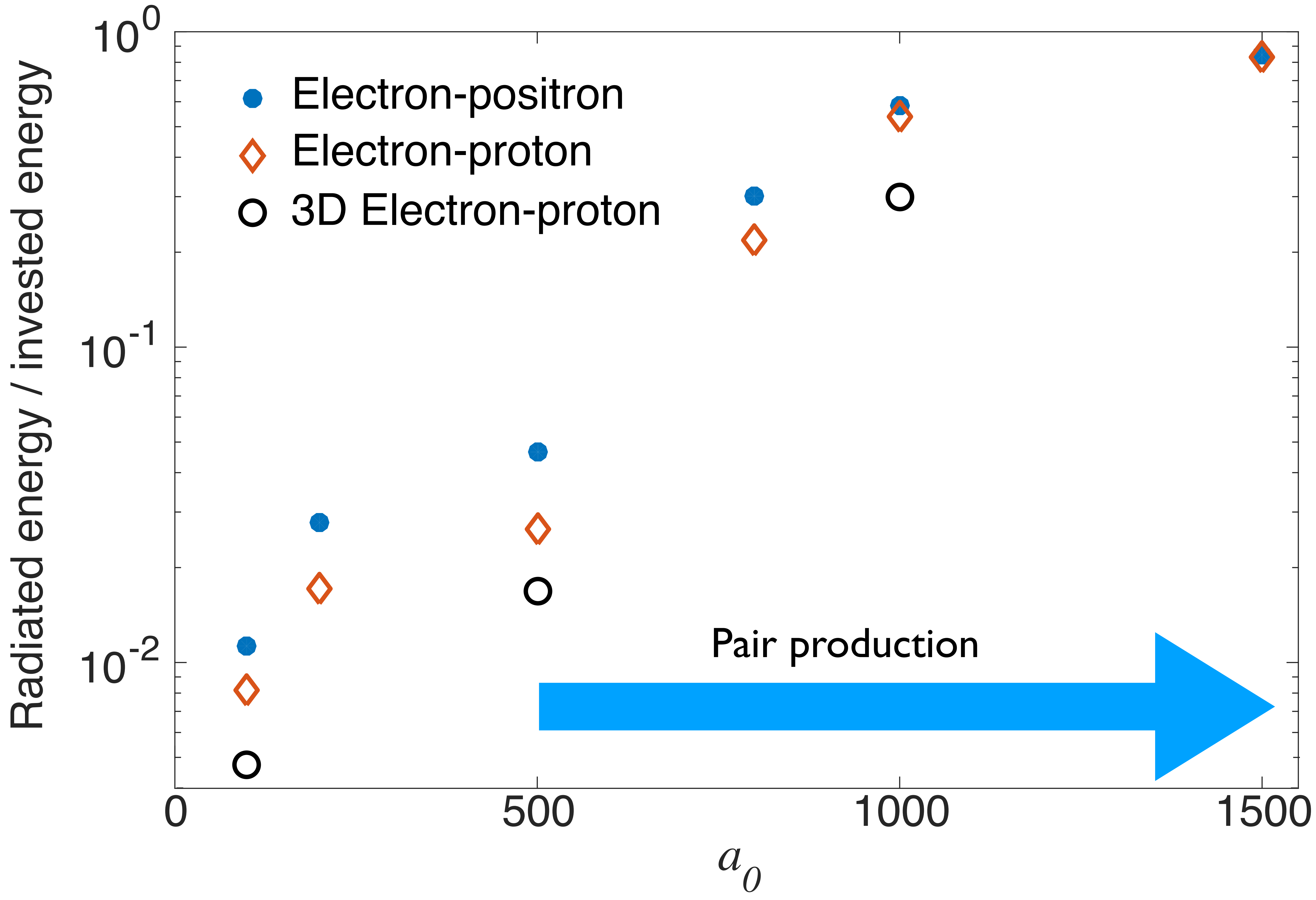
Moments of the distribution functions are recovered even with several orders of magnitude differences in particle weights



With currently available targets, we could transfer more than 50% of energy to gamma-rays

We get ~ a pair per interacting particle at a_0=500

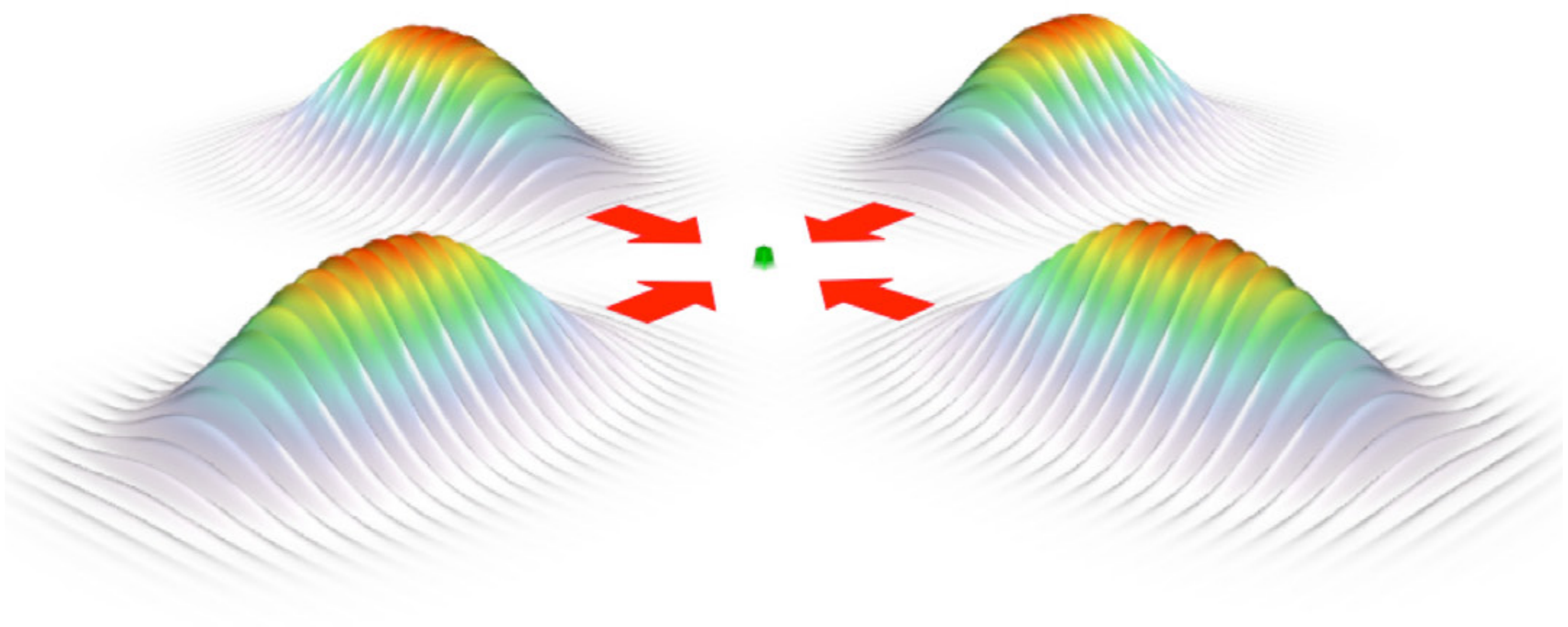
Conversion to gamma-rays in a 10 nc, 1 um thick target



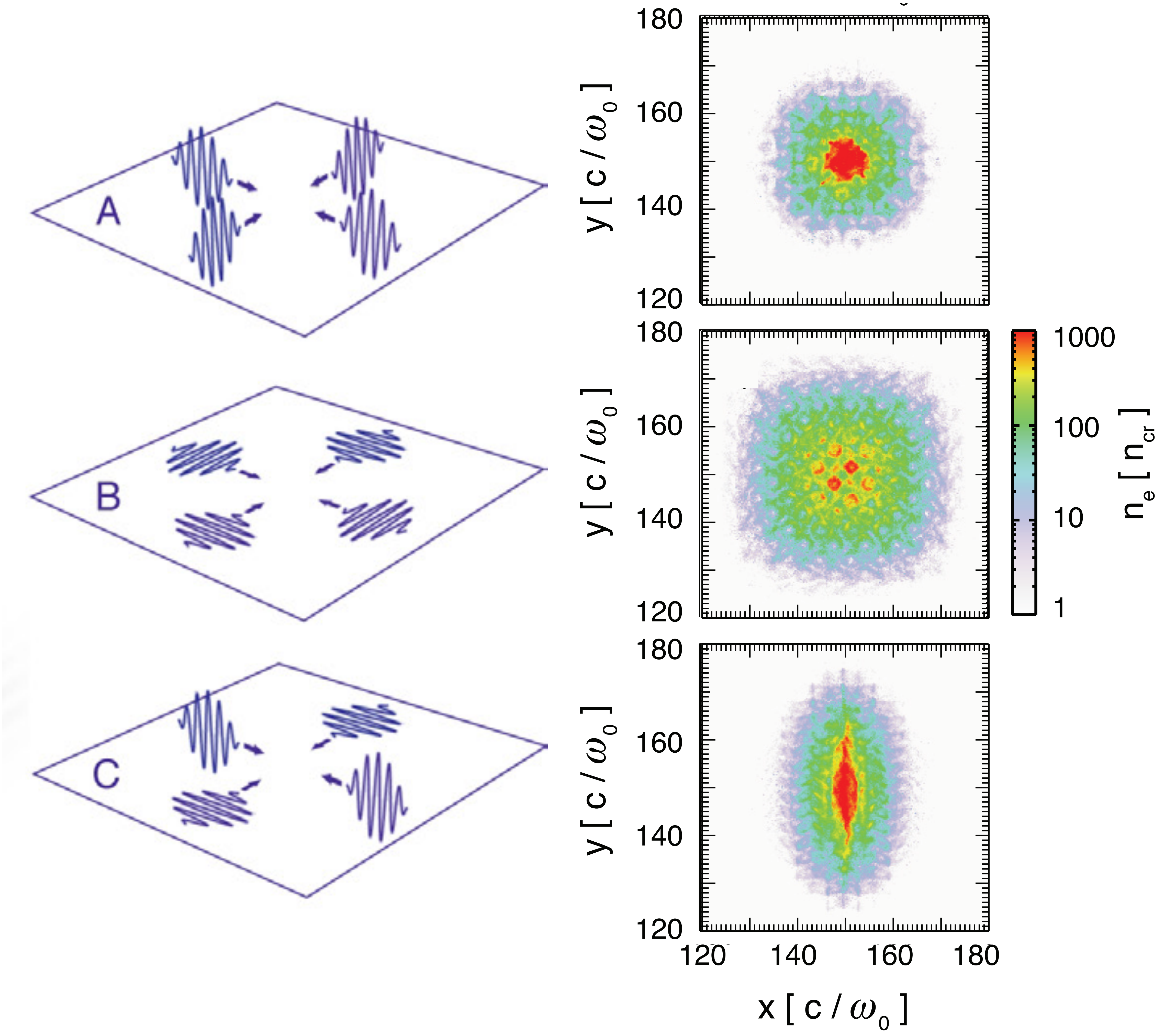
* M.Vranic et al., POP **26**, 053103 (2019)

QED cascades with multiple laser pulses

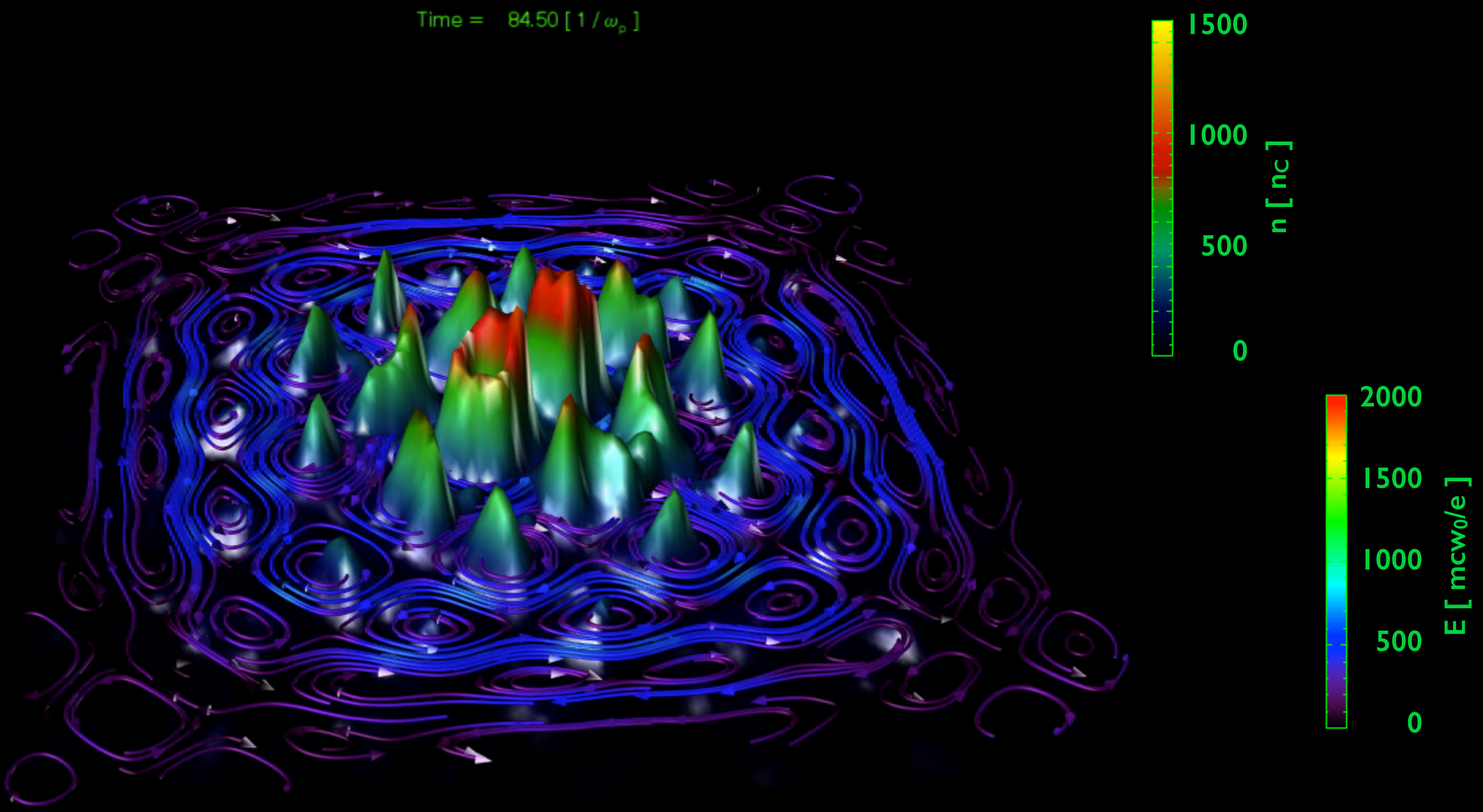
Different polarisation combinations yield different microstructures



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



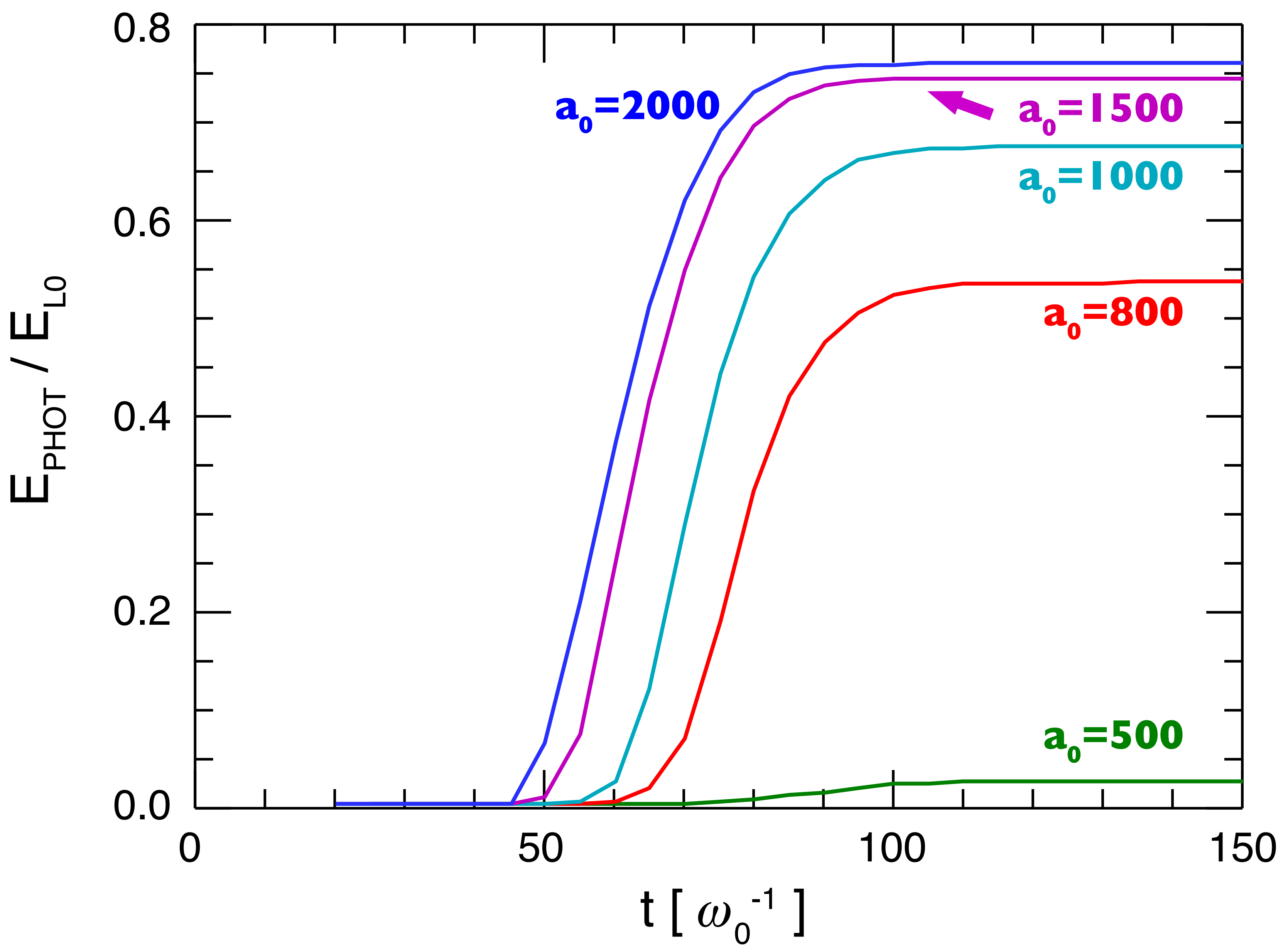
Enough plasma is produced to disrupt the 2D standing wave



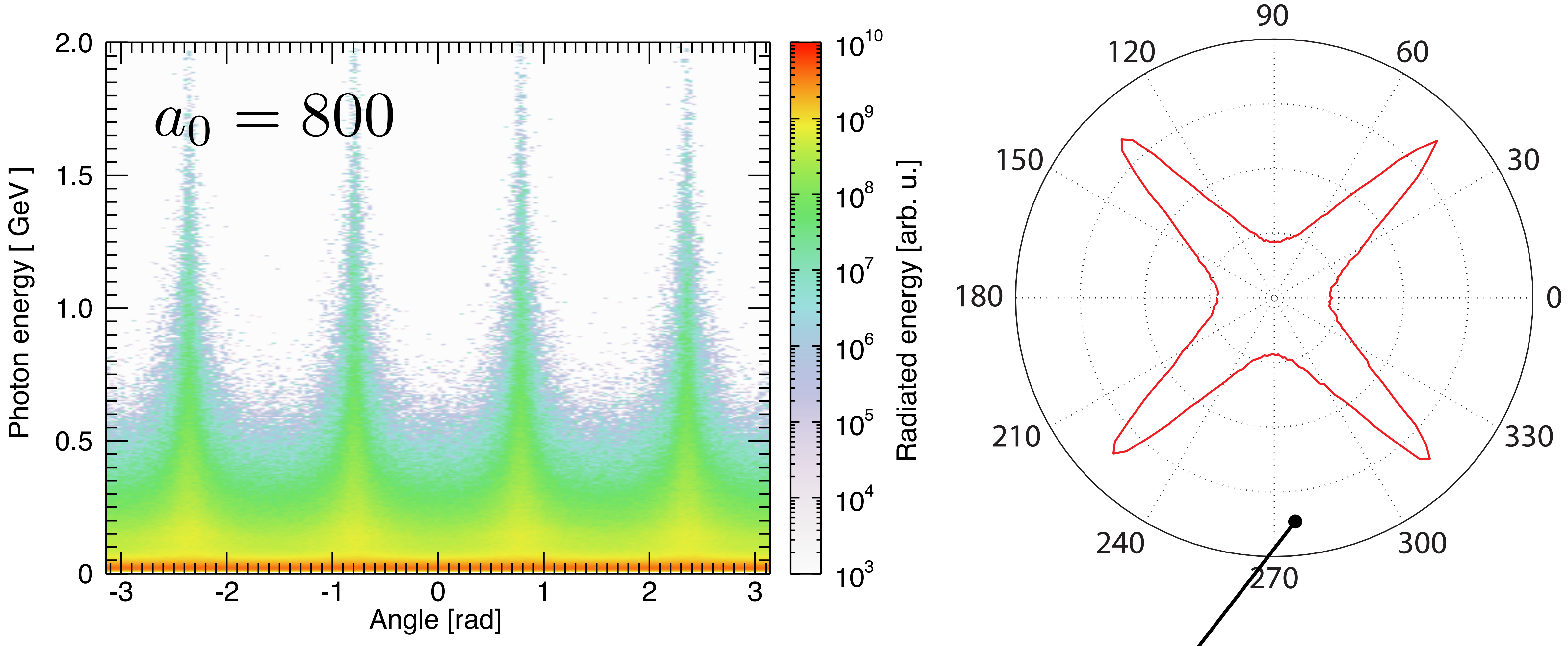
M.Vranic et al., PPCF 59, 014040 (2017)

Laser energy efficiently converted to hard photons

Fraction of total laser energy converted to photons



Angularly resolved freq. spectrum



Photons above 100 MeV (25 %)

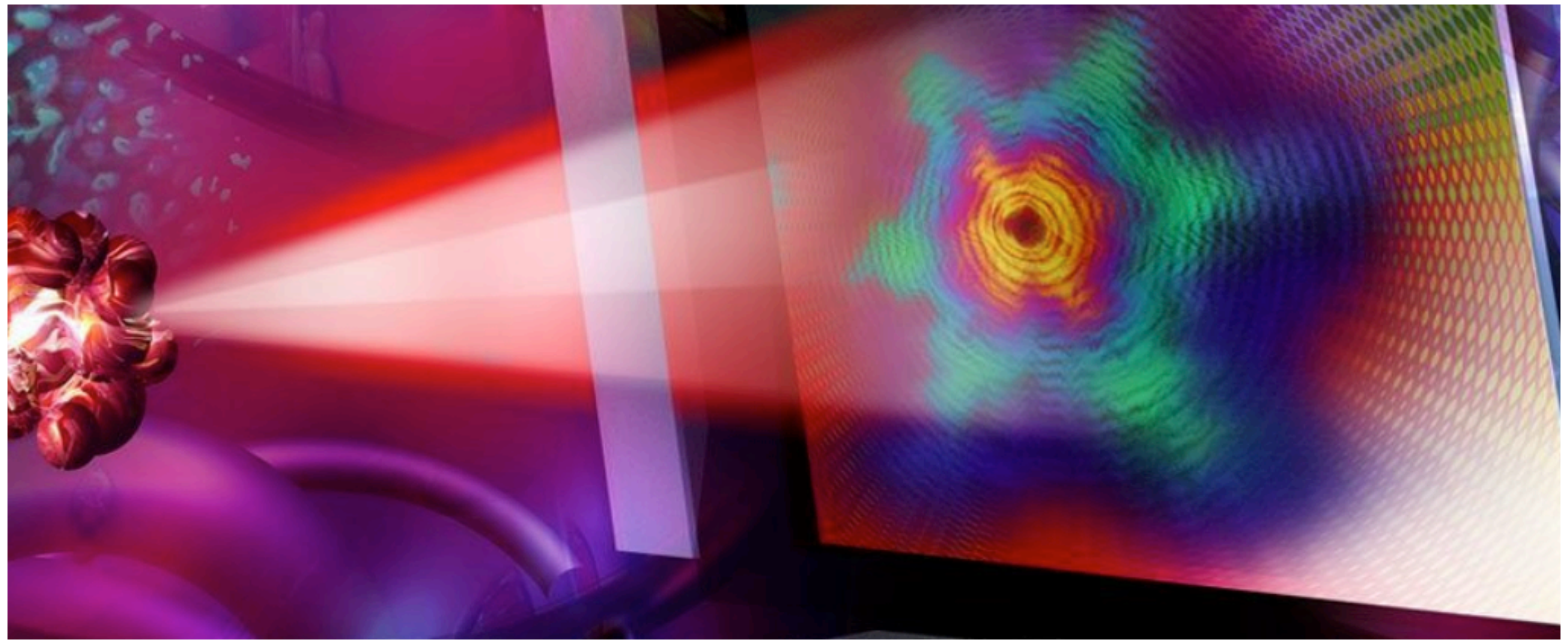
M. Vranic et al., PPCF 59, 014040 (2017)

Conclusions

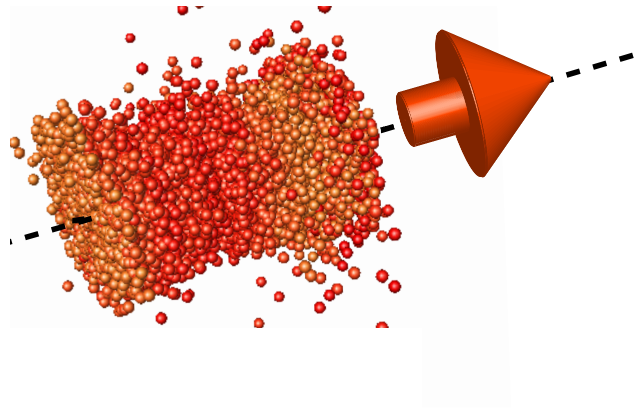
- Classical vs. quantum radiation reaction can be studied in future experiments. Especially interesting is crossing the quantum threshold in the radiation-dominated regime.
- Numerical simulations at the extreme regime require different models and higher resolution (especially a smaller timestep).
- Experiment at FACET II will be able to create some pairs and show ~ 40 % energy loss on the electrons.
- Electron-positron pairs can be created and accelerated in a single stage by scattering an electron beam with a laser at 90 degrees, and accelerating in vacuum or in a plasma.
- QED cascades can create abundant plasma and lead to an efficient energy transfer from the laser into gamma-rays.

A look into the future

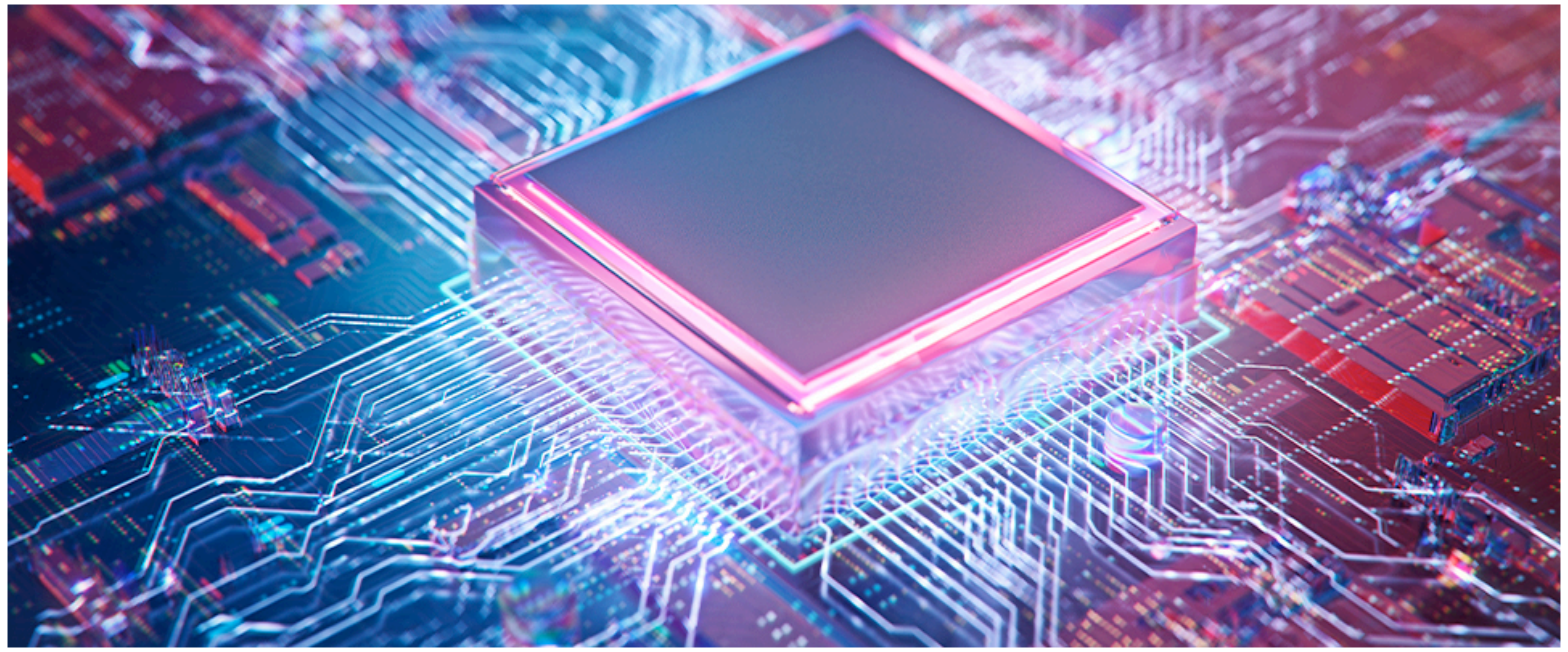
Exotic physics at the extreme



Particle and radiation sources



Quantum computing for plasmas



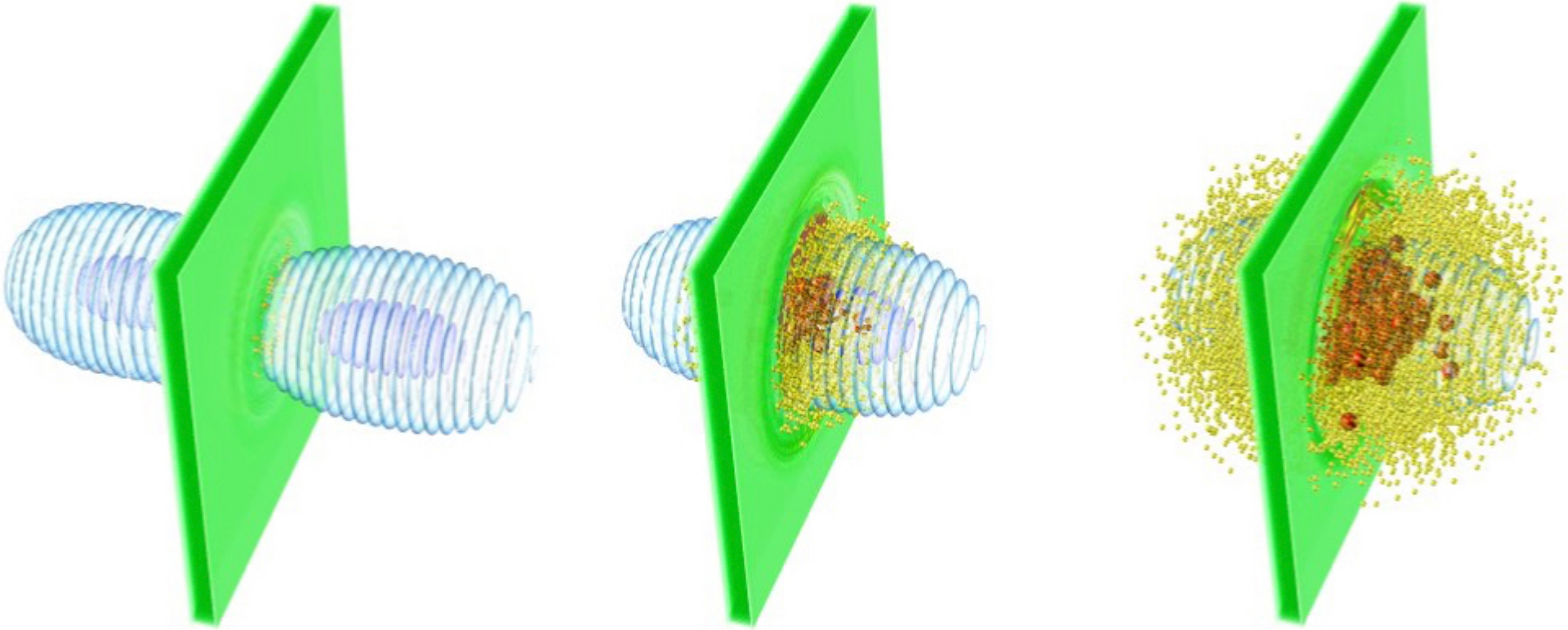
High - performance computing

Extra slides

Marija Vranic

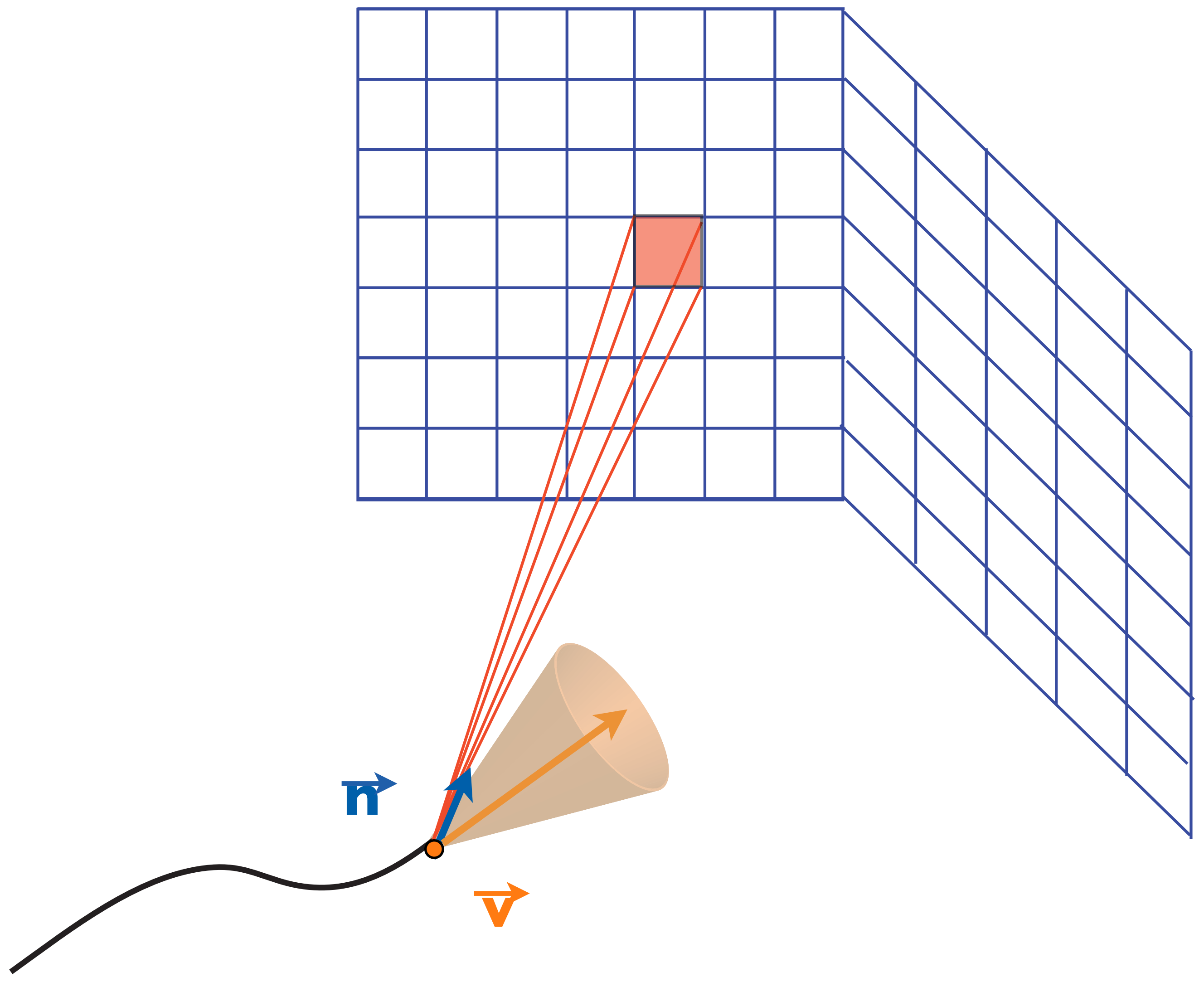
GoLP / Instituto de Plasmas e Fusão Nuclear Instituto Superior Técnico,
Lisbon, Portugal

epp.tecnico.ulisboa.pt || **golp**.tecnico.ulisboa.pt



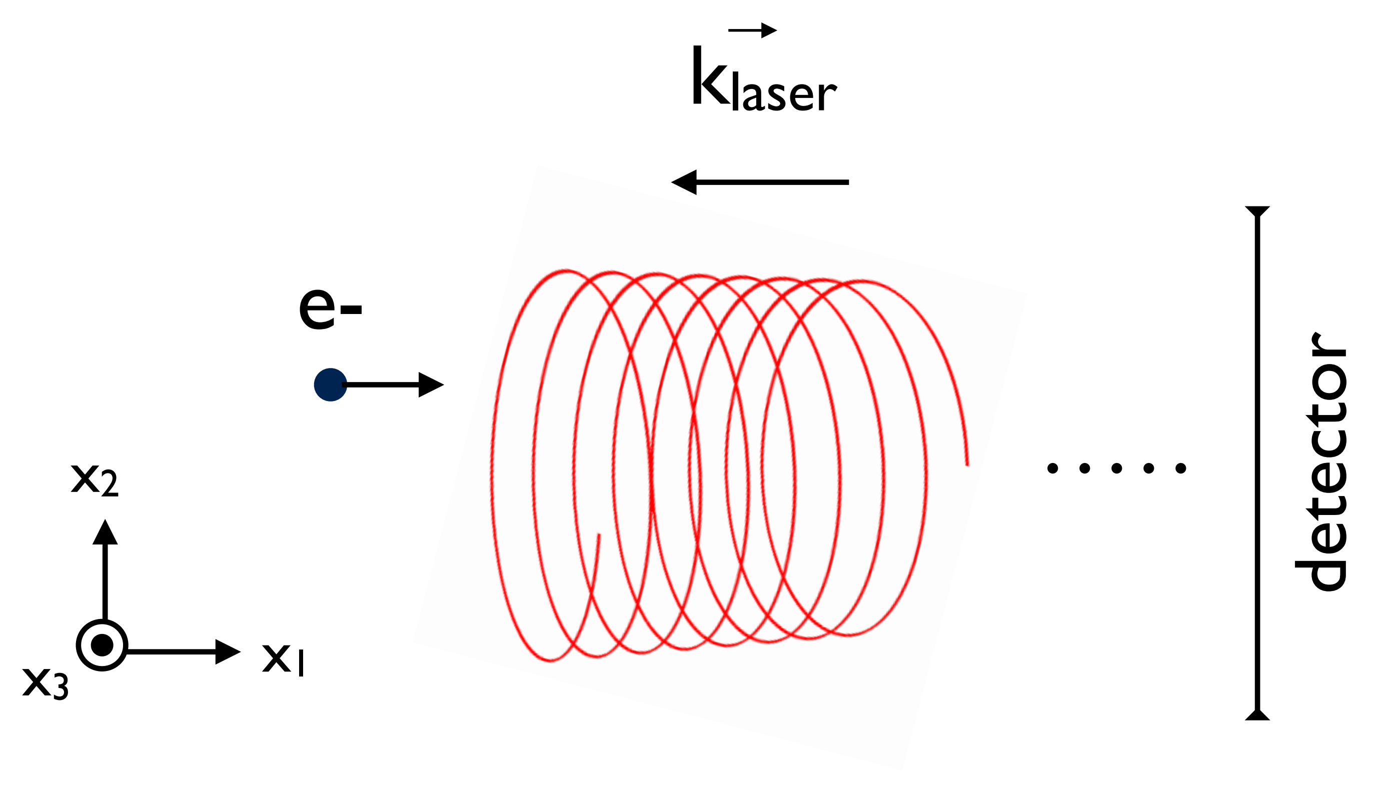
Funded by the European Union

Emitted radiation with quantum corrections



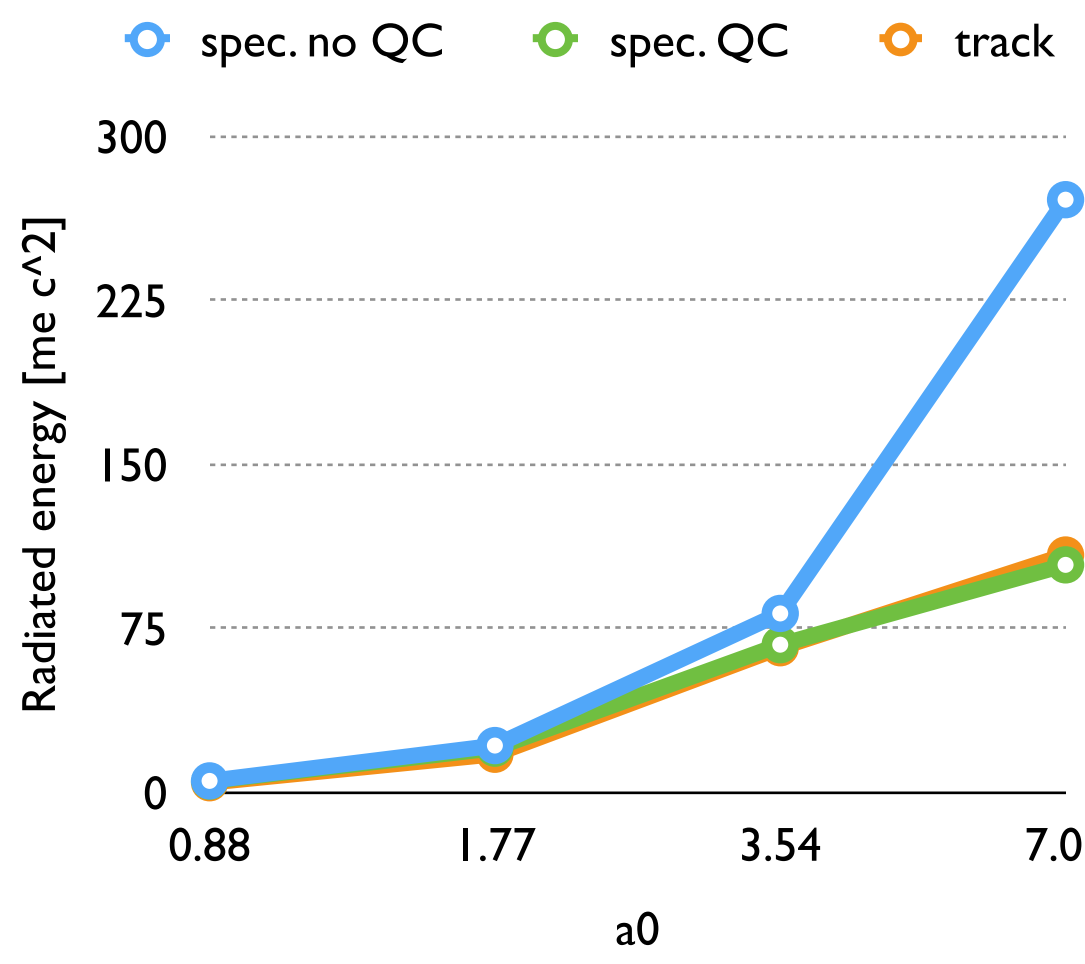
J. L. Martins et al, PPCF (2016)

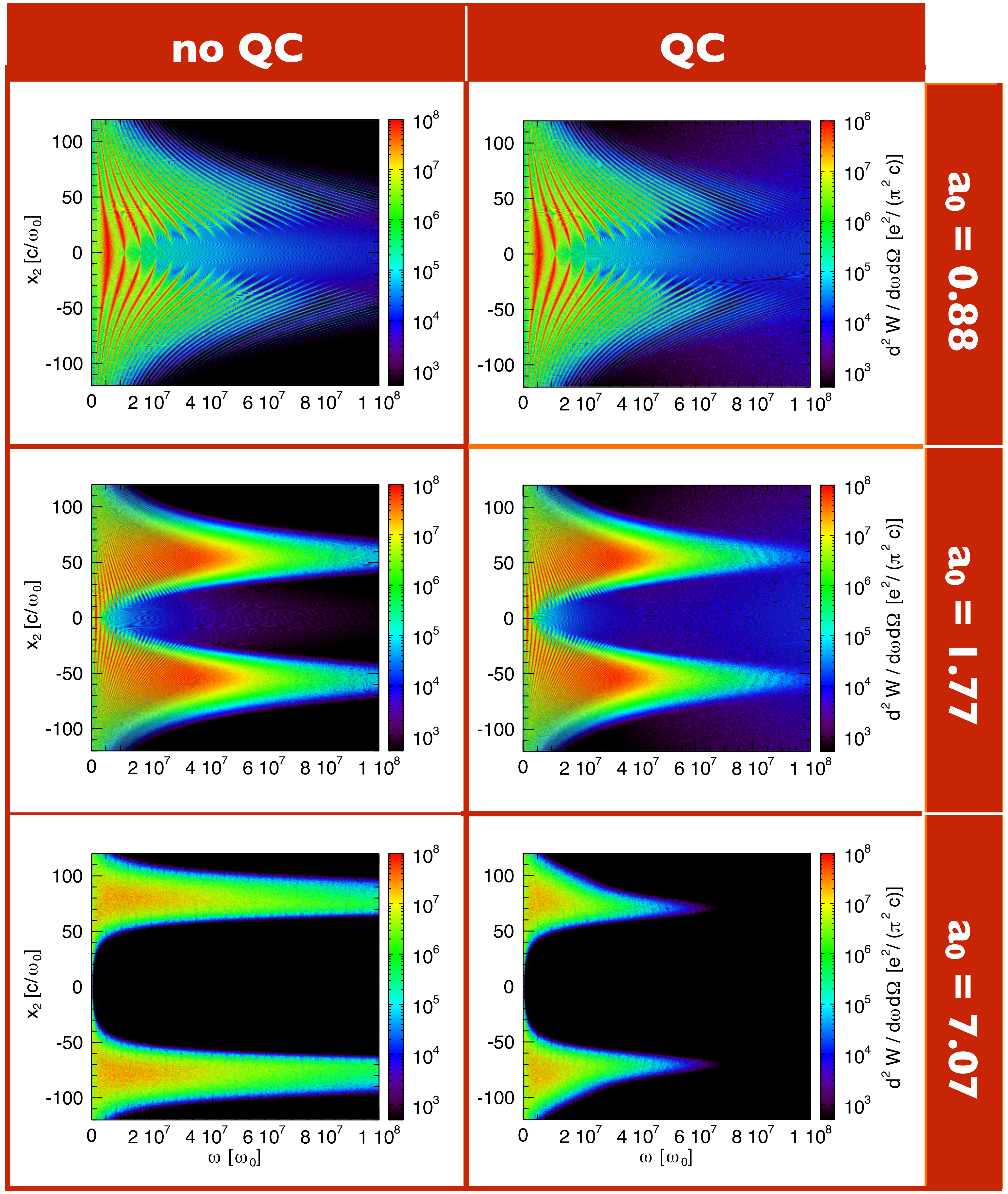
Circular polarisation plane wave



γ_e = 1000 λ = 1 μm τ = 38 T_0

Total radiated energy



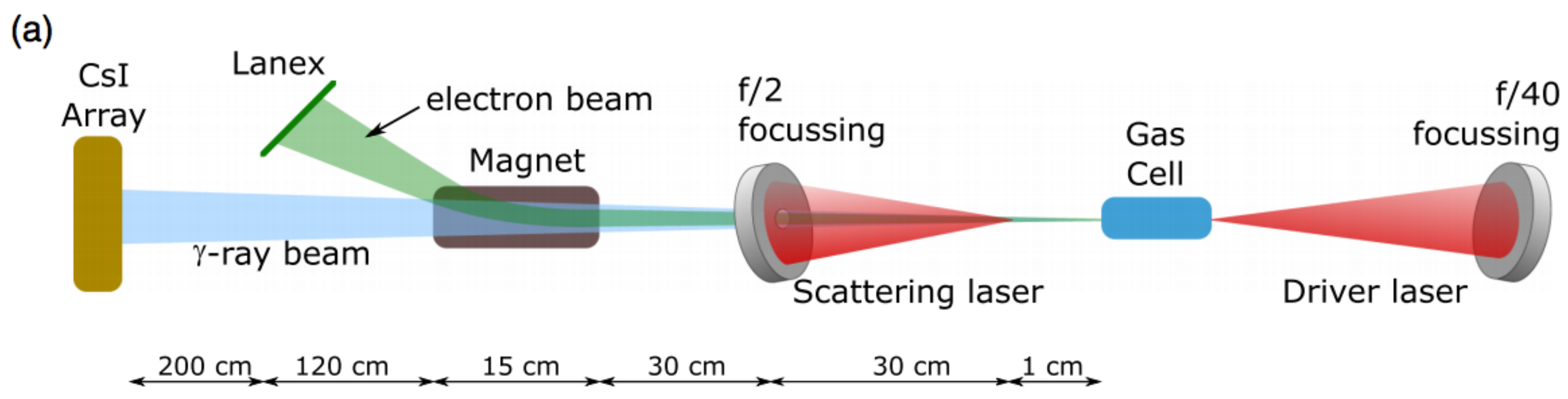


Recent experiments show slowdown

Experimental setup*

Wakefield electron beam ~ **GeV**

Intense scattering laser **I > 10^{20} W/cm^2**

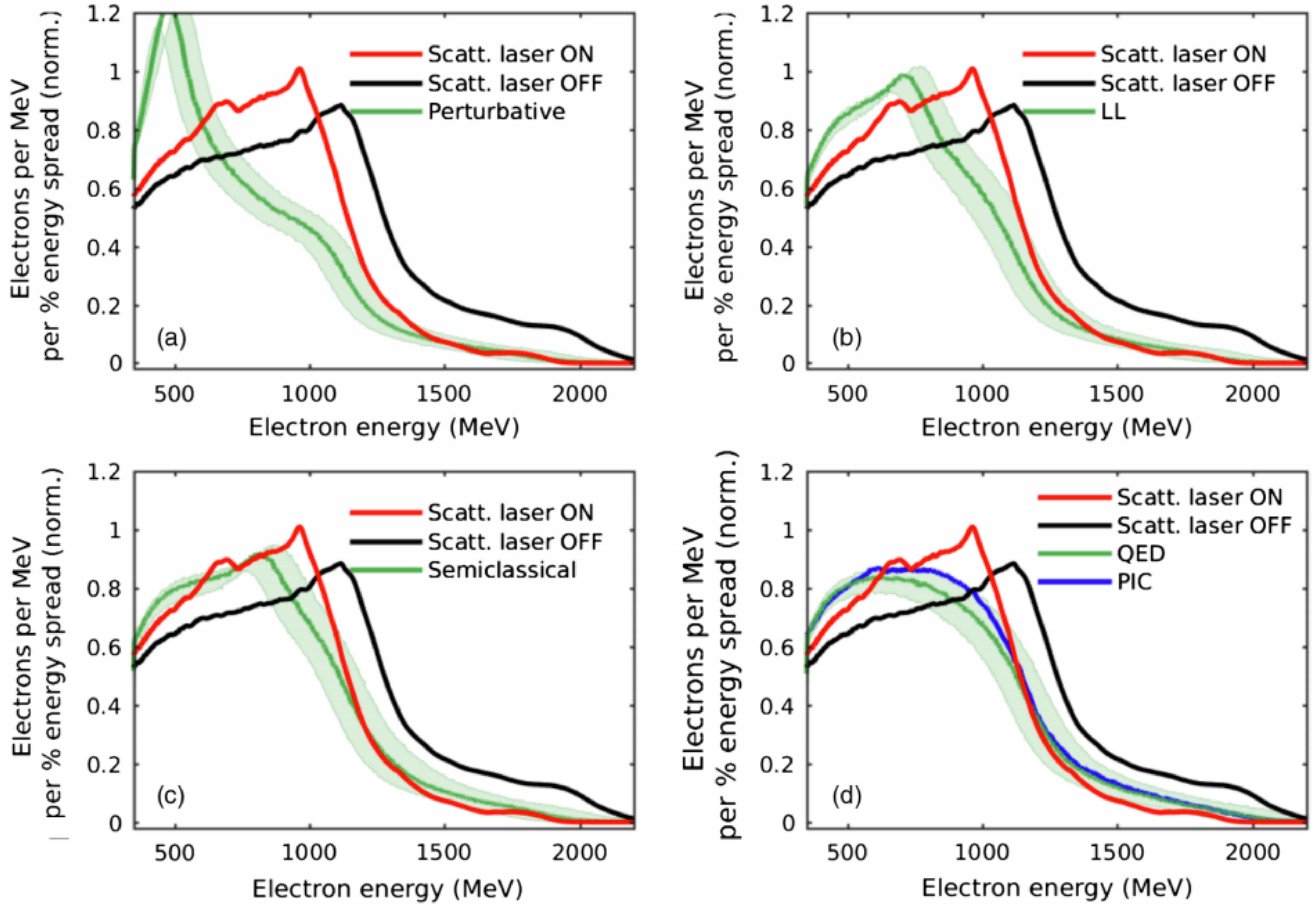


Experimental Results*

Evidence of **energy loss 30%**

How quantum? **χ ~ 0.2**

Agreement is found for the **semiclassical correction of the Landau-Lifshitz equation**



*K. Poder et al., PRX 8, 031004 (2018) J. M. Cole et al., PRX 8, 011020 (2018)