Particle-in-Cell Numerical Extensions to Model Plasmas in the Presence of Extreme Fields

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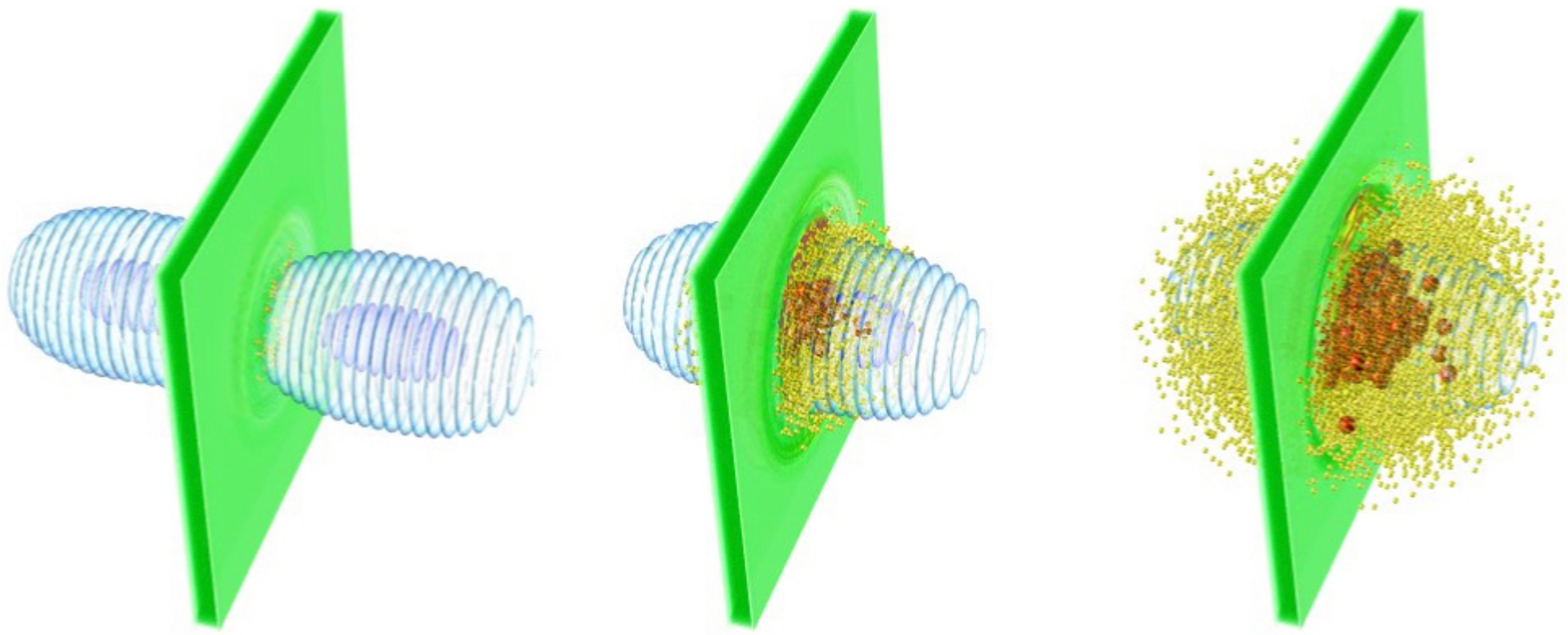

Acknowledgements

Work in collaboration with:

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

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

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Laserlab Europe

PRACE

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HiPER

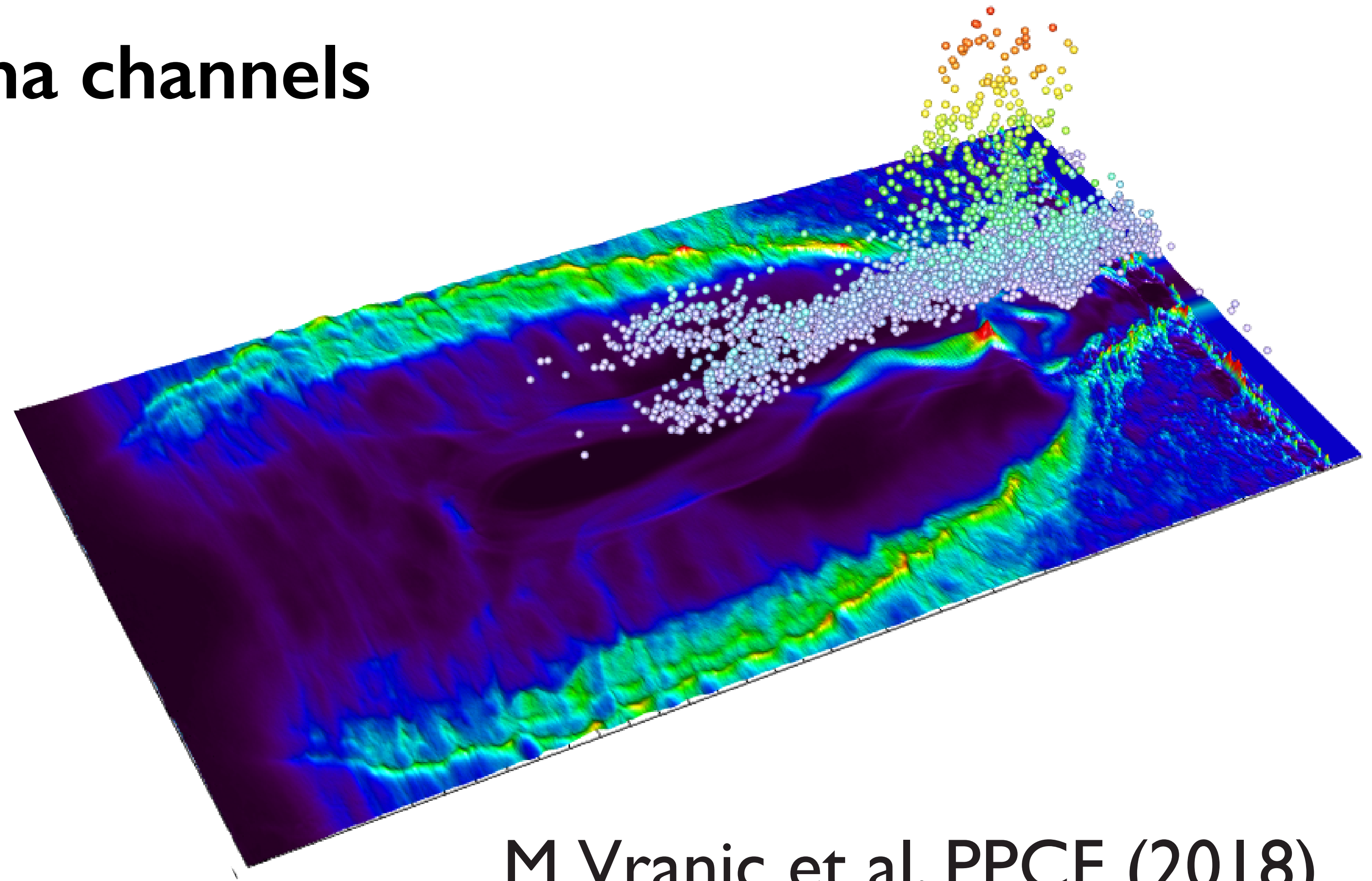
What can we do with the next generation of lasers?

TÉCNICO LISBOA

New opportunities for particle acceleration

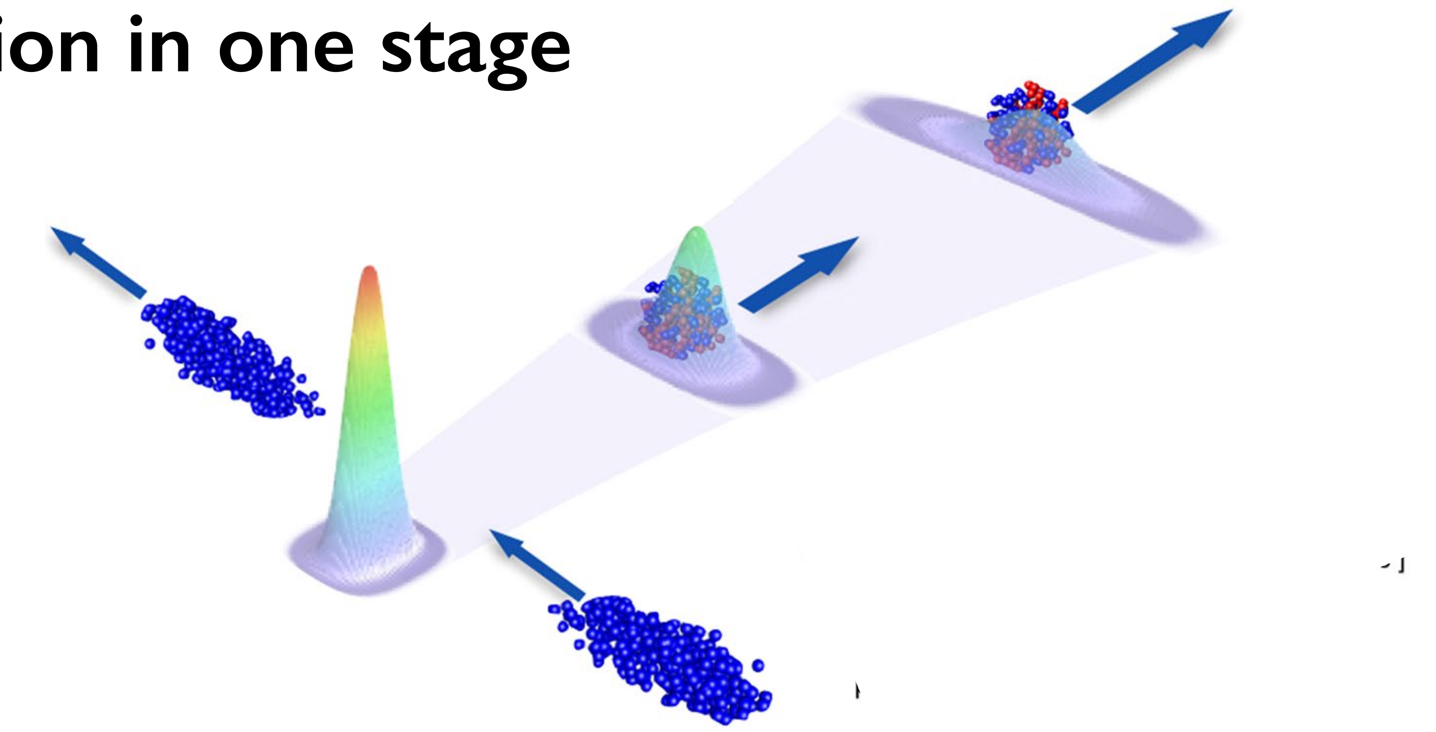
- **Electron acceleration in plasma channels**

B. Quiao eta al, POP (2017)
A. Arefiev et al, POP (2016)
V. Khudik et al, POP (2016)
L. L. Ji et al, PRL (2014)
APS Robinson et al, PRL (2013)
Naseri et al, PRL (2012)
SPD Mangles et al, PRL (2005)
A. Pukhov et al, POP (1999)
M. Jirka et al, in prep.



M. Vranic et al, PPCF (2018)

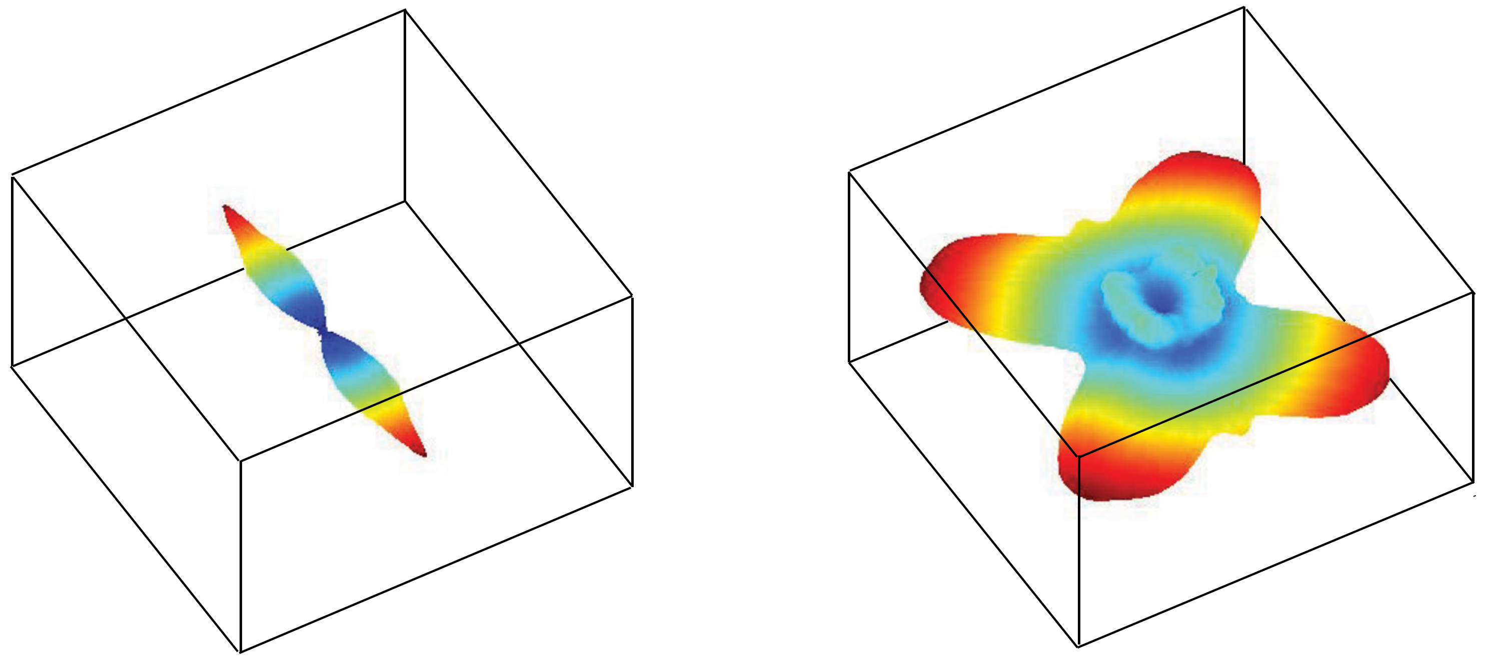
- **Electron-positron production & acceleration in one stage**



M. Vranic et al, SciRep (2018)

Design of tunable high-energy photon sources

N. Lemos, PPCF (2018); F. Albert, POP (2018)
W. Yan, Nat. Phot (2017); Gonoskov, PRX (2017)
A. Arefiev et al, PRL (2016); J. L. Martins et al, PPCF (2016)
K. Ta Phuoc, NatPhot (2012); Z. Gong, PRE (2017)
E. Esarey PRA (1992); S. Kneip, PRL (2009)



T. Grismayer et al, POP (2016)

What can we do with the next generation of lasers?

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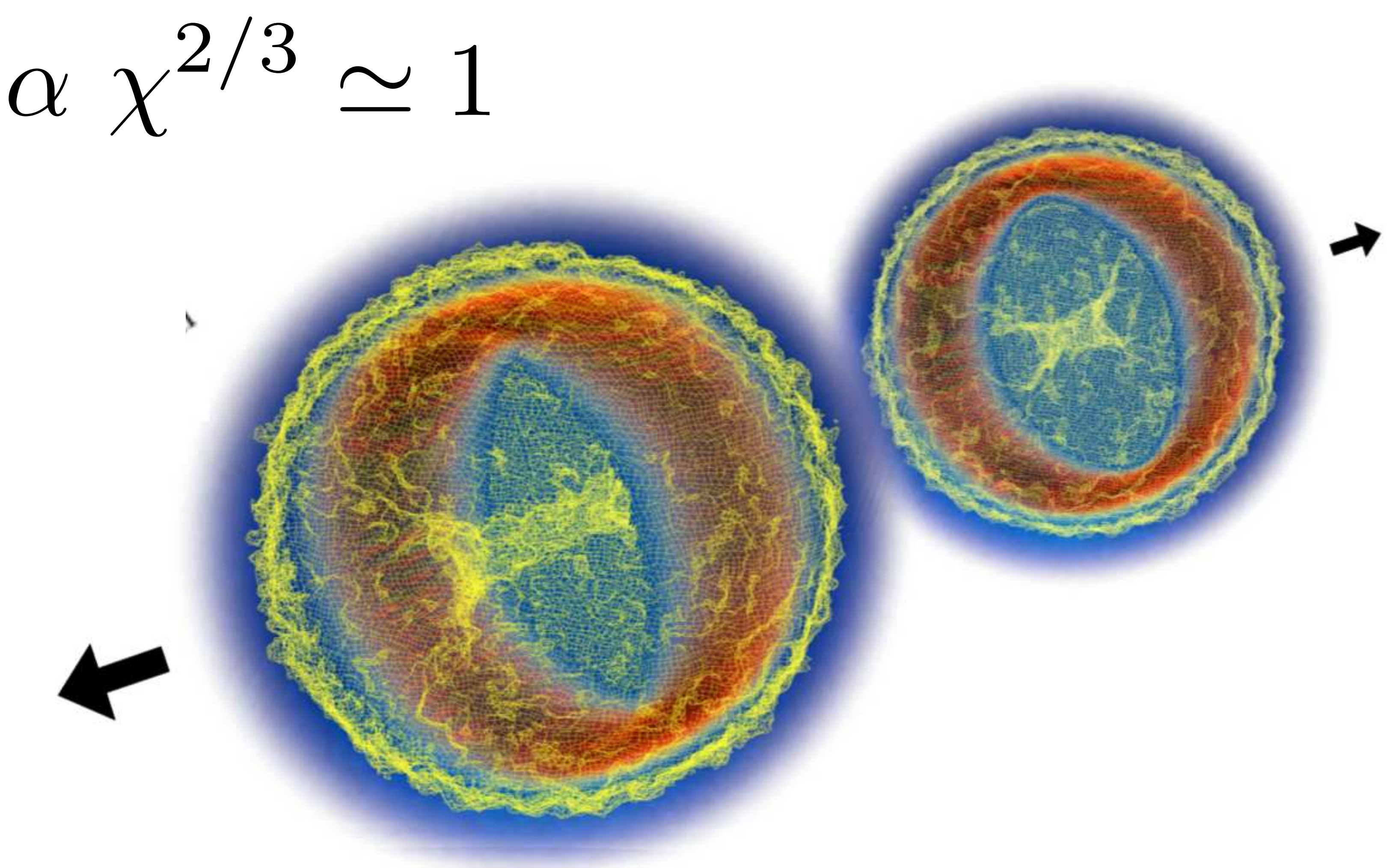
Study of the classical and quantum radiation reaction

M. Tamburini, NIMR (2011); Neitz & DiPiazza, PRL (2013); Ilderton and Torgrimsson, PLB (2013); Zhidkov, PRSTAB (2014);
M. Vranic, PRL (2014); T. Blackburn, PRL (2014); S. Yoffee, NJP (2015); M. Vranic, CPC (2016); M. Vranic, NJP (2016);
C. Ridgers, JPP (2017): F. Neil, PRE (2017) and PPCF(2018); J. Cole PRX (2018); K. Poder PRX(2018);

Probing the onset of non-pertubative QED

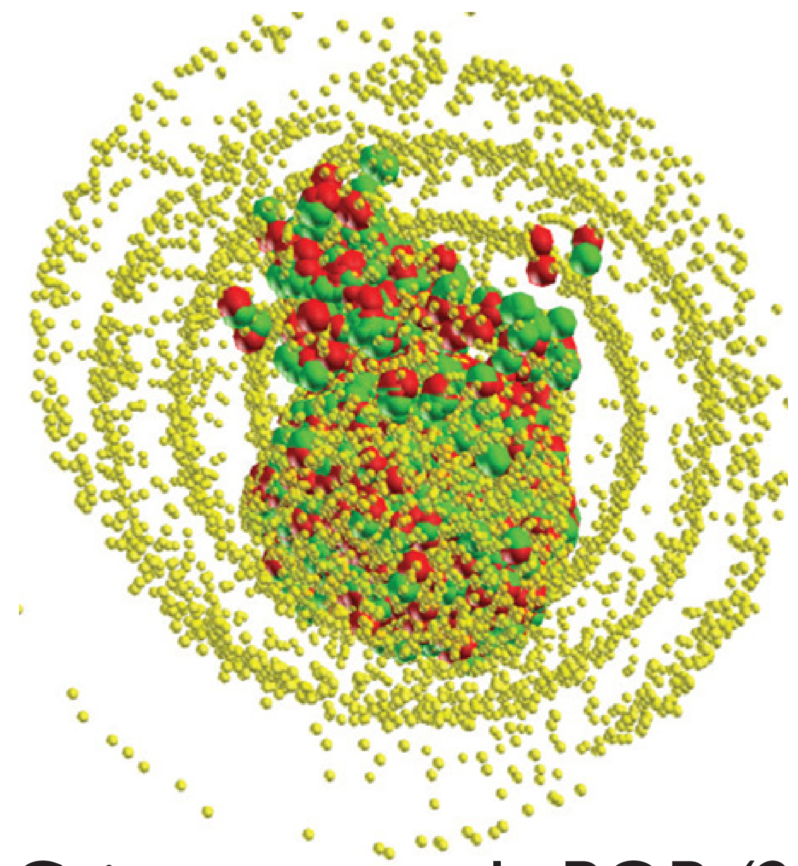
$$\alpha\ \chi^{2/3} \simeq 1$$



V. Yakimenko et al, PRL, 122, 190404 (2019)
F. Del Gaudio et al, PRAB 22, 023402(2019)
C. Baumann et al., ArXiv:1811.03990

Evolution of self-generated e+e- plasmas

T. Bell and J. Kirk, PRL (2010)
A. Fedotov, PRL (2010)
S. Bulanov, PRL (2010)
E. Nerush, PRL (2011)
N. Elkina, PRSTAB (2011)
C. Ridgers, PRL (2012)
V. F. Bashmakov, POP (2015)
A. Gonoskov, PRE (2015)
M. Jirka, PRE (2016)
T. Grismayer, POP (2016)
X. Ribeyre et al, PRE(2016)
M. Tamburini, Sci Rep (2017)
M. Vranic, PPCF (2017)
X. Zhu, NComm (2017)
T. Grismayer, PRE (2017)
M. Lobet et al, PRAB (2017)
I. Kostyukov et al, PAST (2018)



T. Grismayer et al, POP (2016)

Different regimes of laser interaction with a plasma

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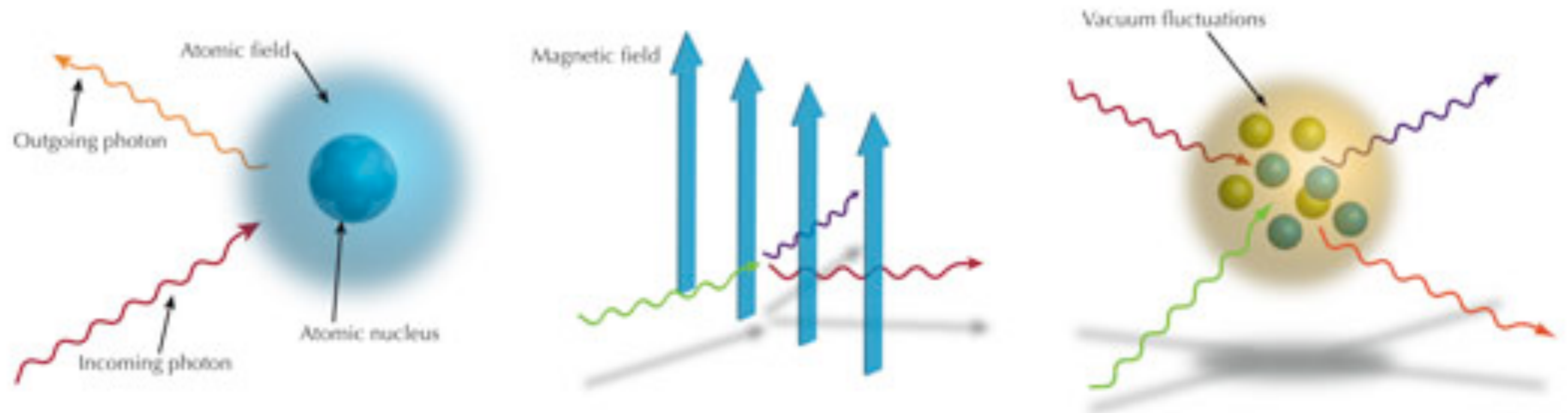


ELI

QED Photons interaction

Near-future facilities

- Pulse duration : 20-150 fs
- 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
  $a_0 << 1$ $\quad I \sim 10^{18}$ 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
- quantum
  $a_0 \sim 1000$ $\quad I \sim 10^{24}$ W/cm^2

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

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

Quantum effects are controlled by parameter χ

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

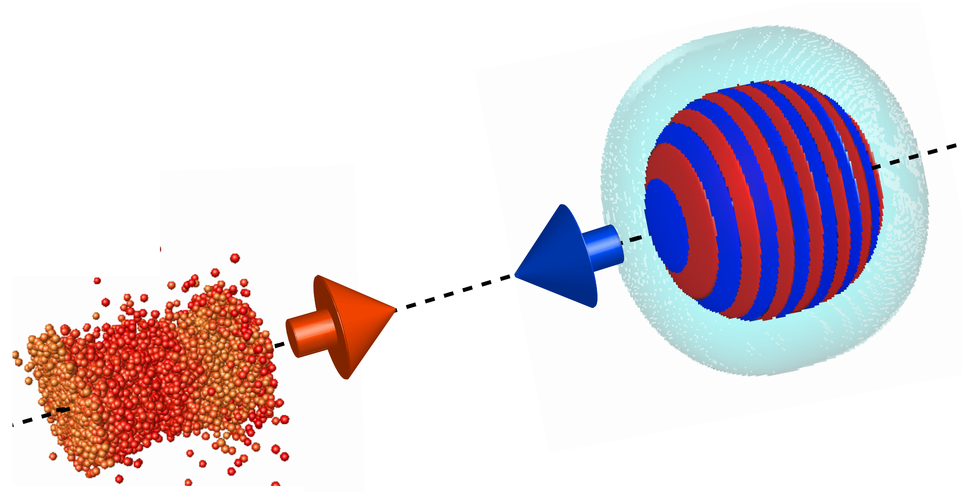
Unity is achieved when particle feels E=Es in its own rest frame

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

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

Classical: $\chi \ll 1$

QED: $\chi \simeq 1$



Counter-propagation

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

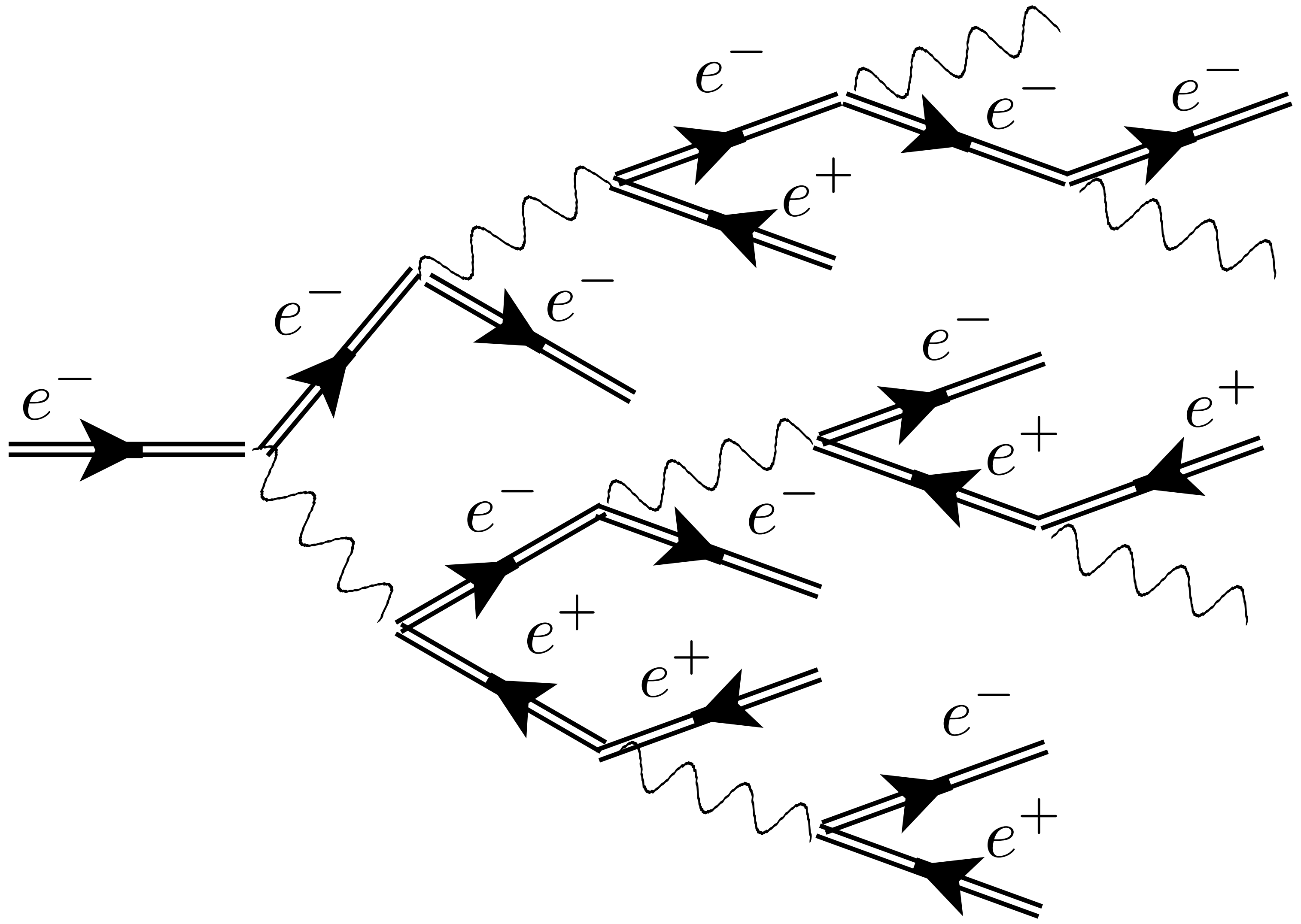
Co-propagation

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

Interaction at 90 deg.

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

QED cascade

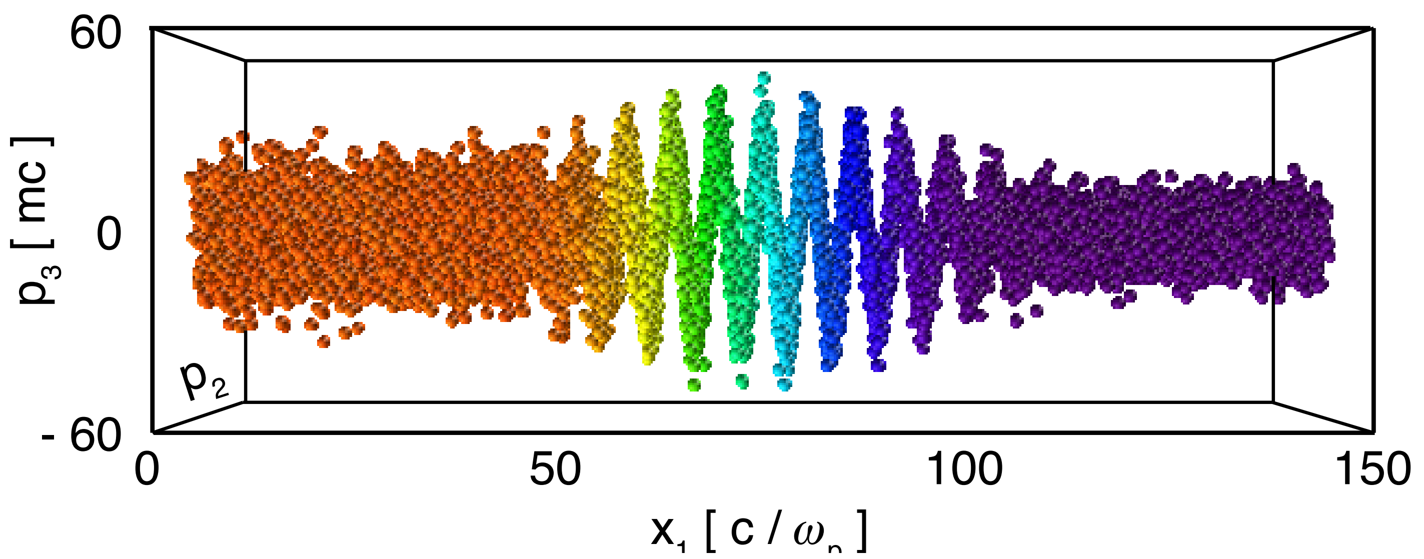


What kind of developments are necessary?

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)



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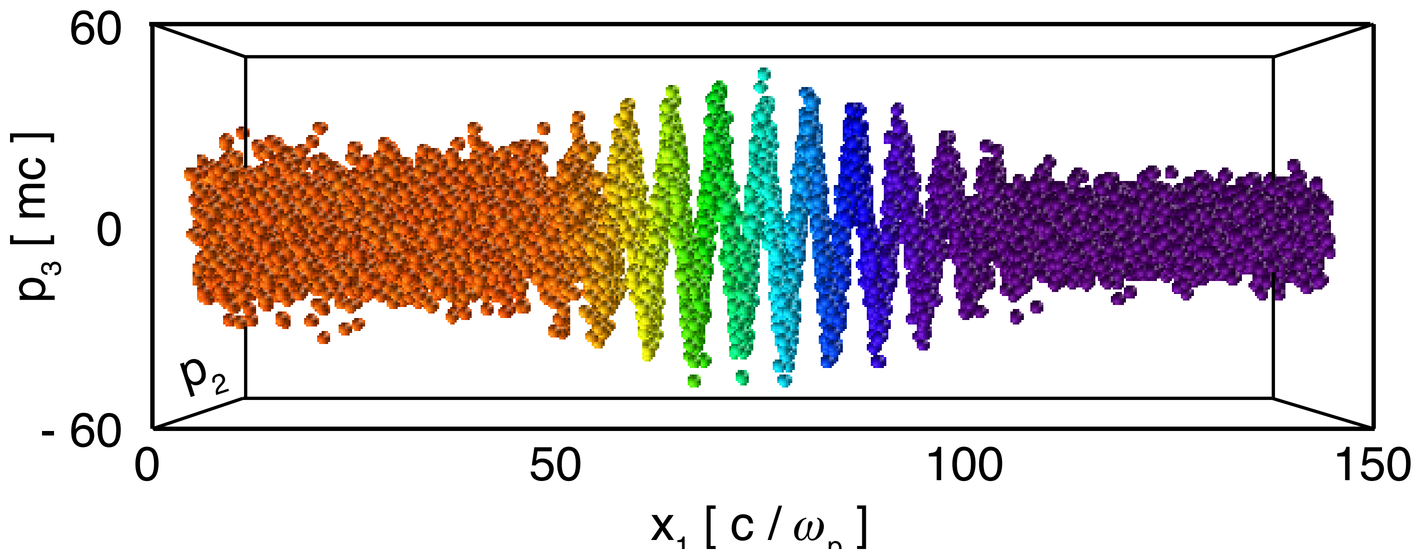
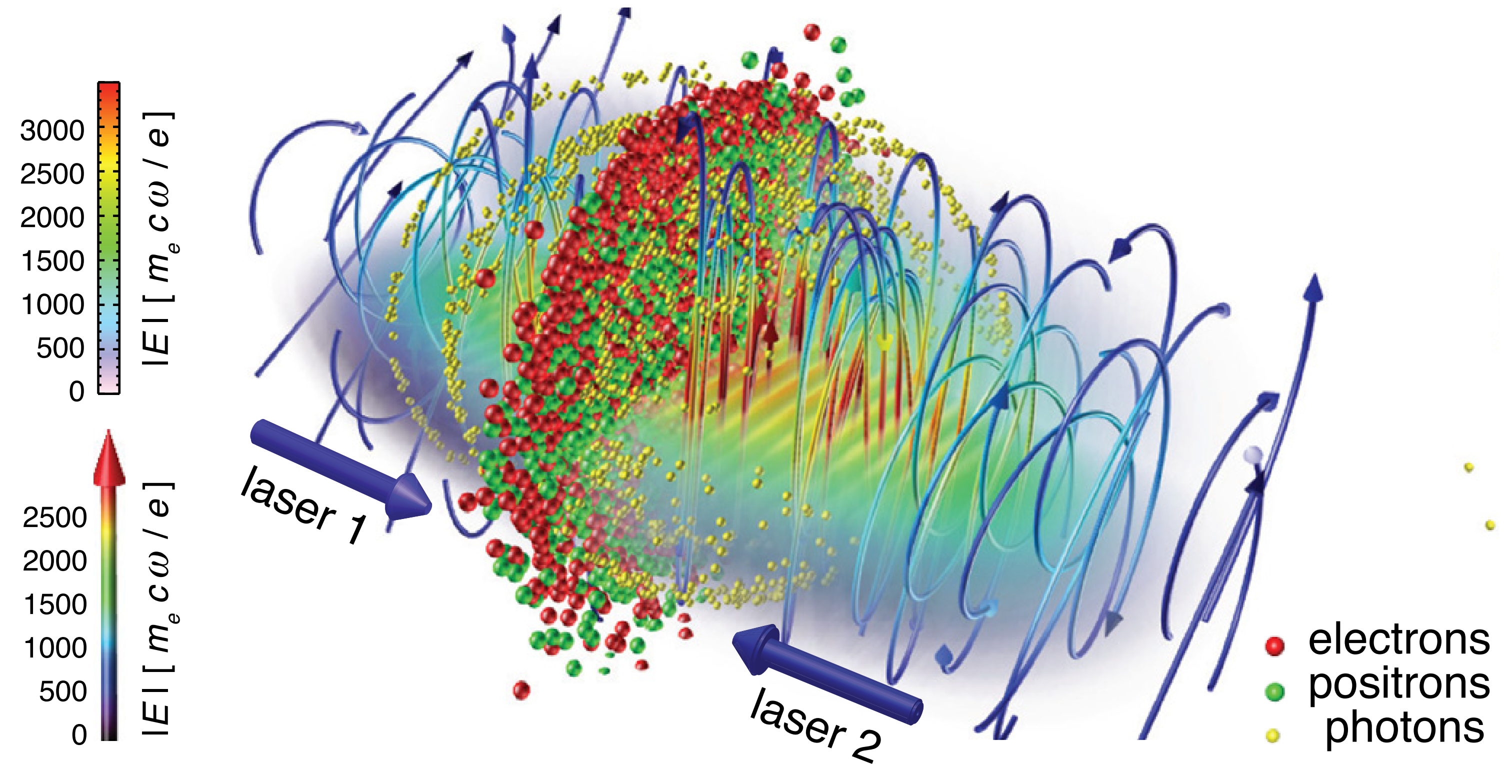


Adding quantum processes

- 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);



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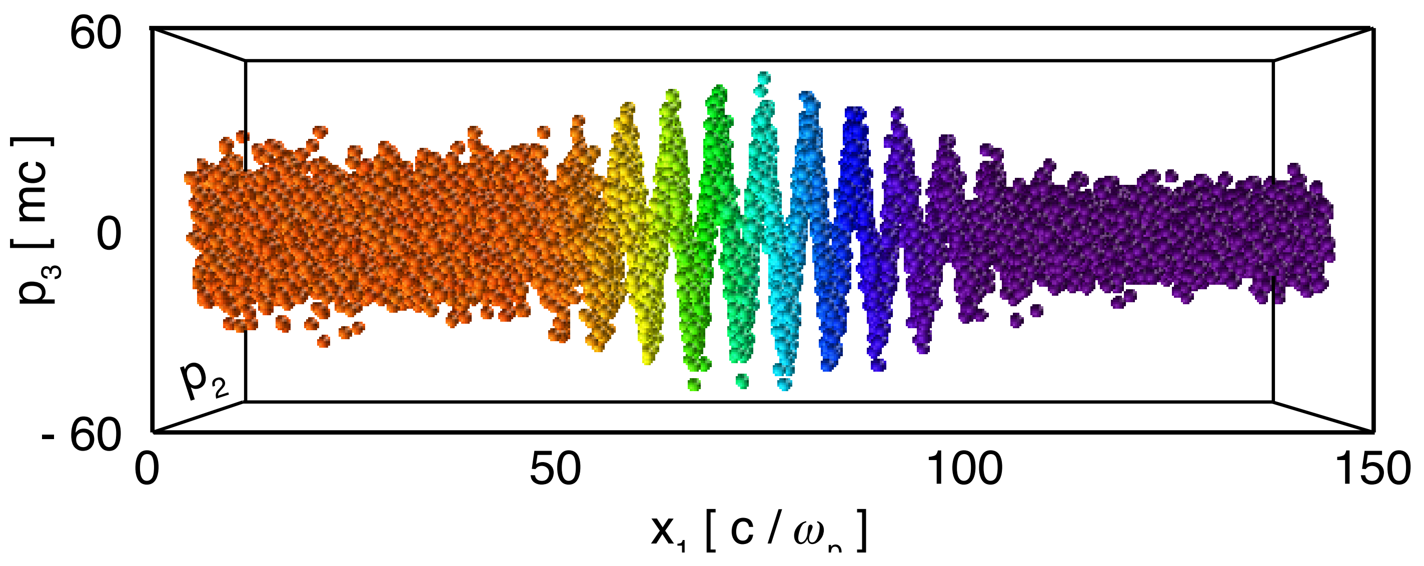

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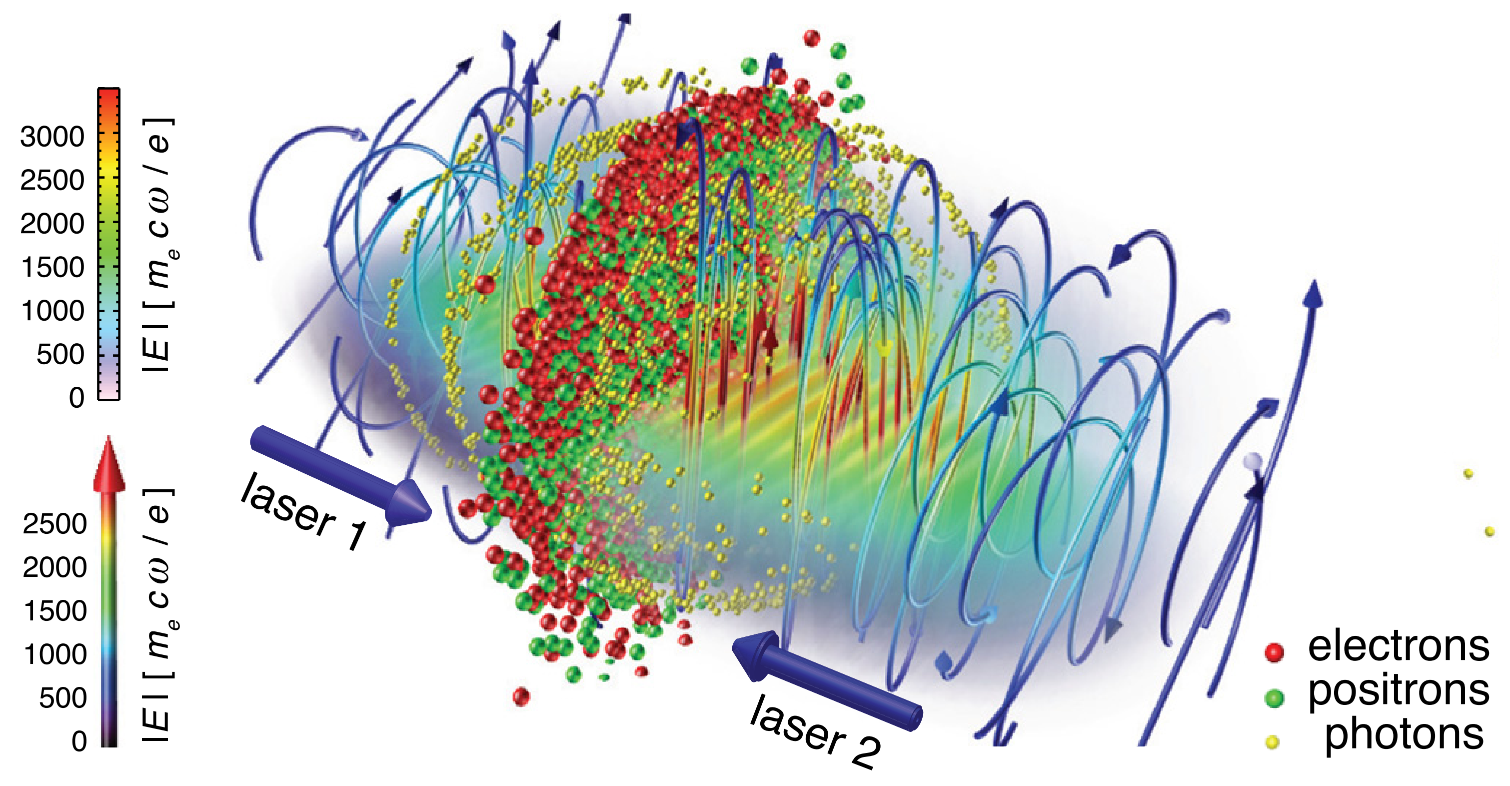
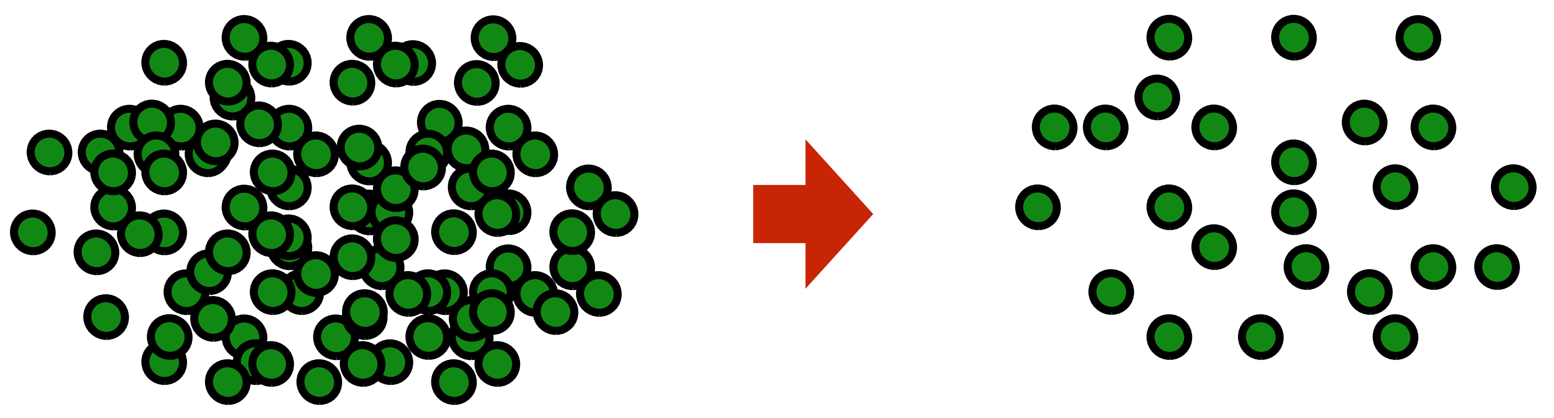


Adding performance improvements (particle merging, advanced load balancing schemes)

- Essential for all the projects with strong QED effects

M.Vranic et al., CPC (2015)



OSIRIS 4.0 is prepared to model interaction at extreme intensities

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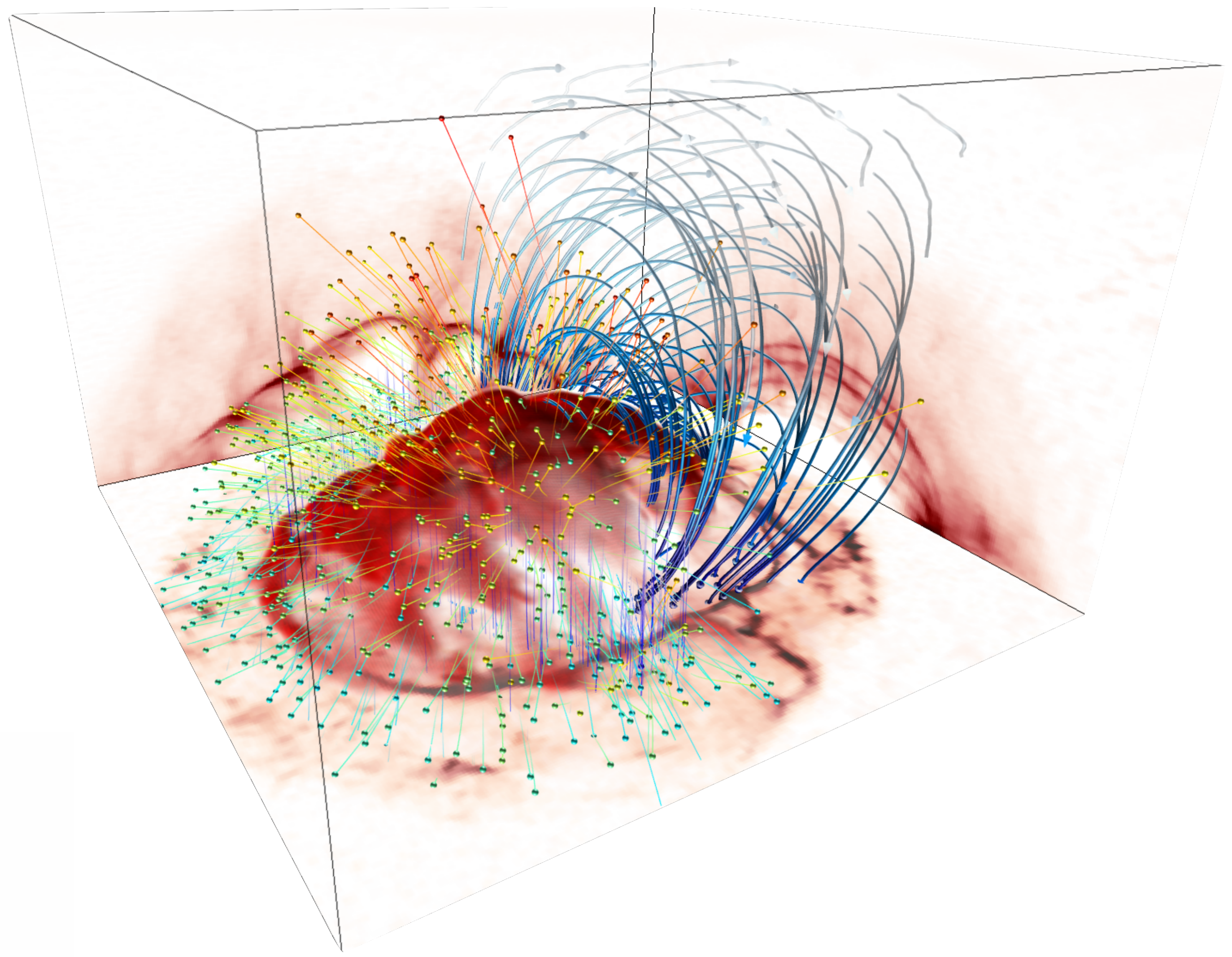
Osiris

osiris framework

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



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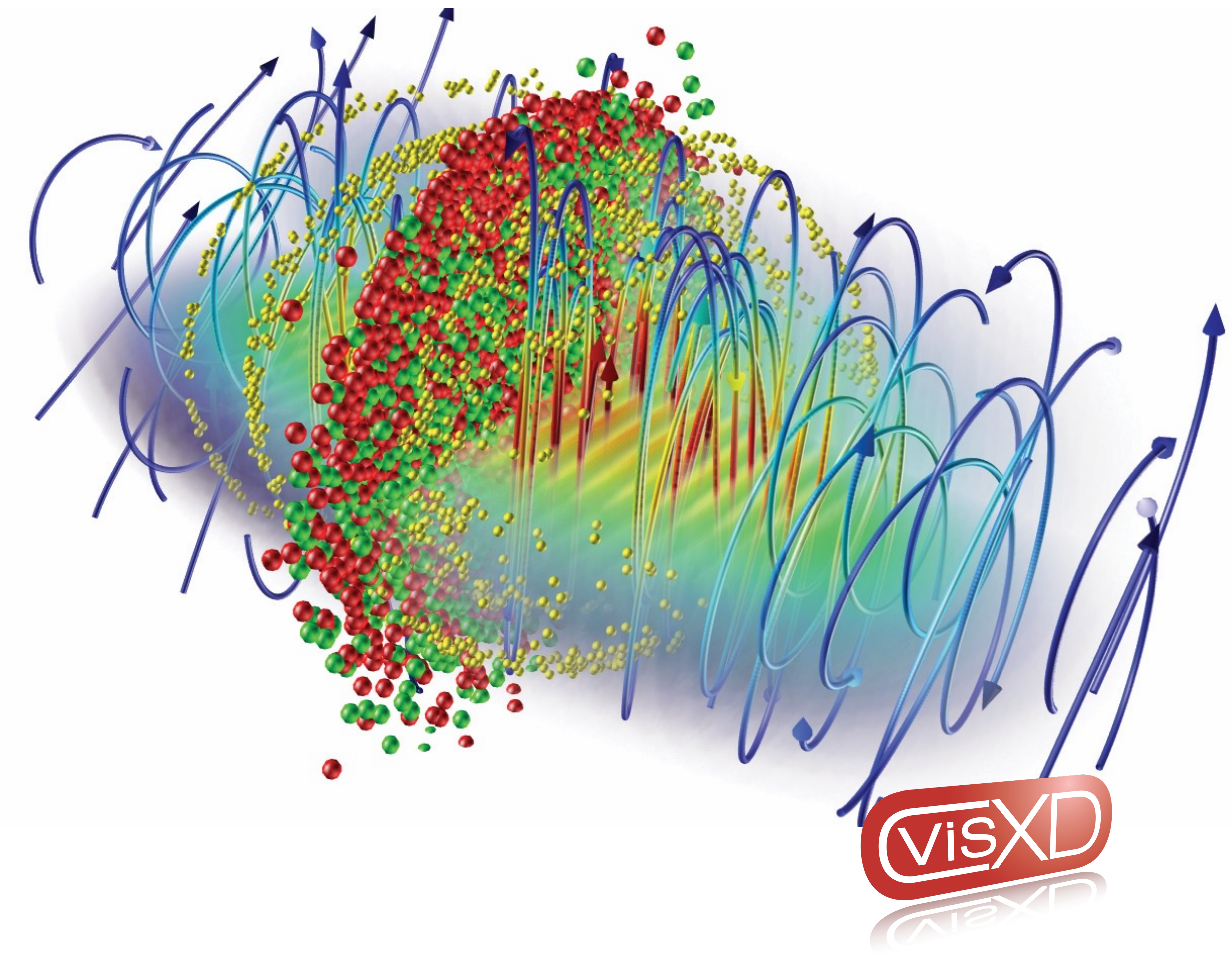

code features

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

QED PIC loop in OSIRIS

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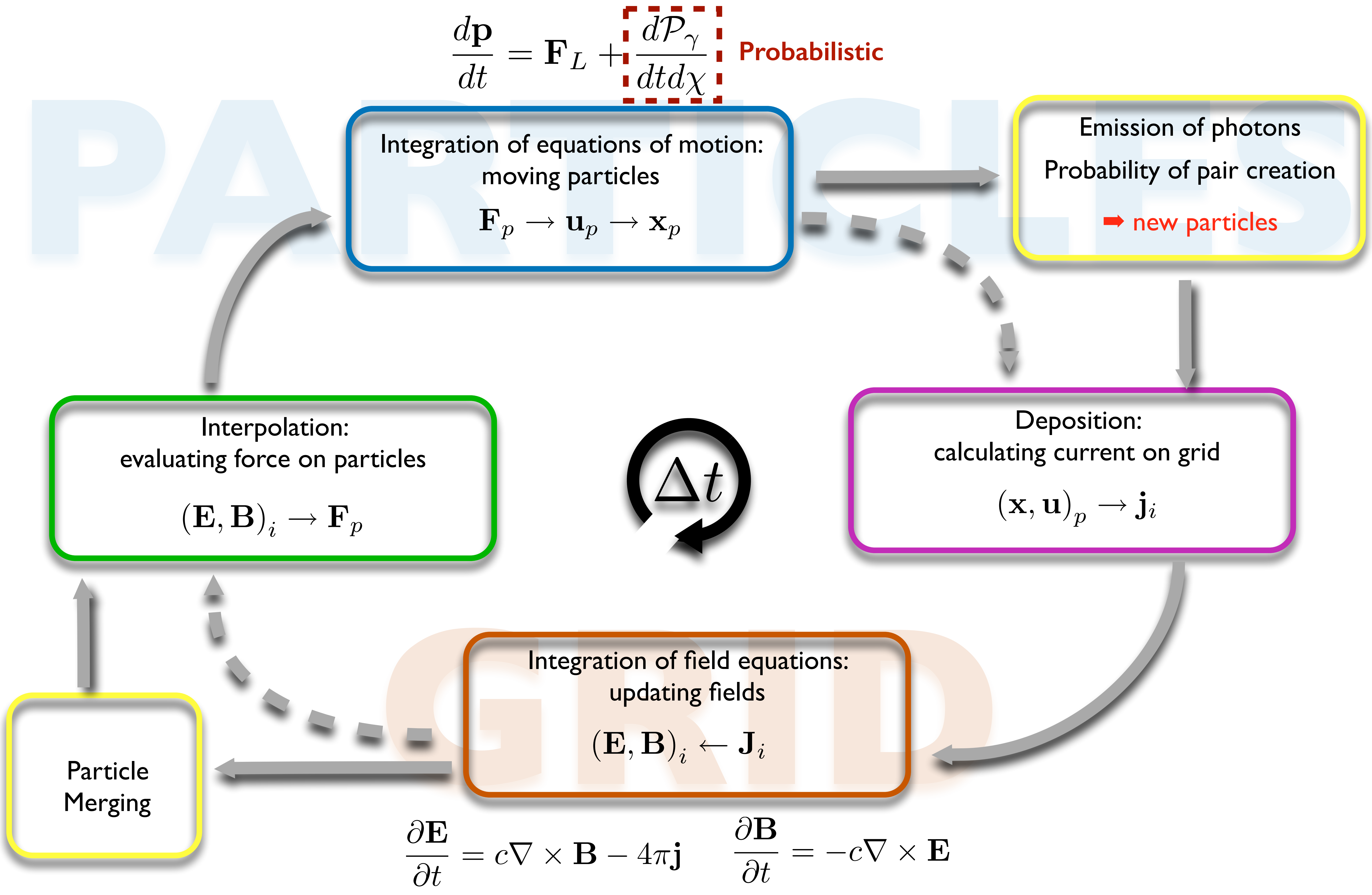
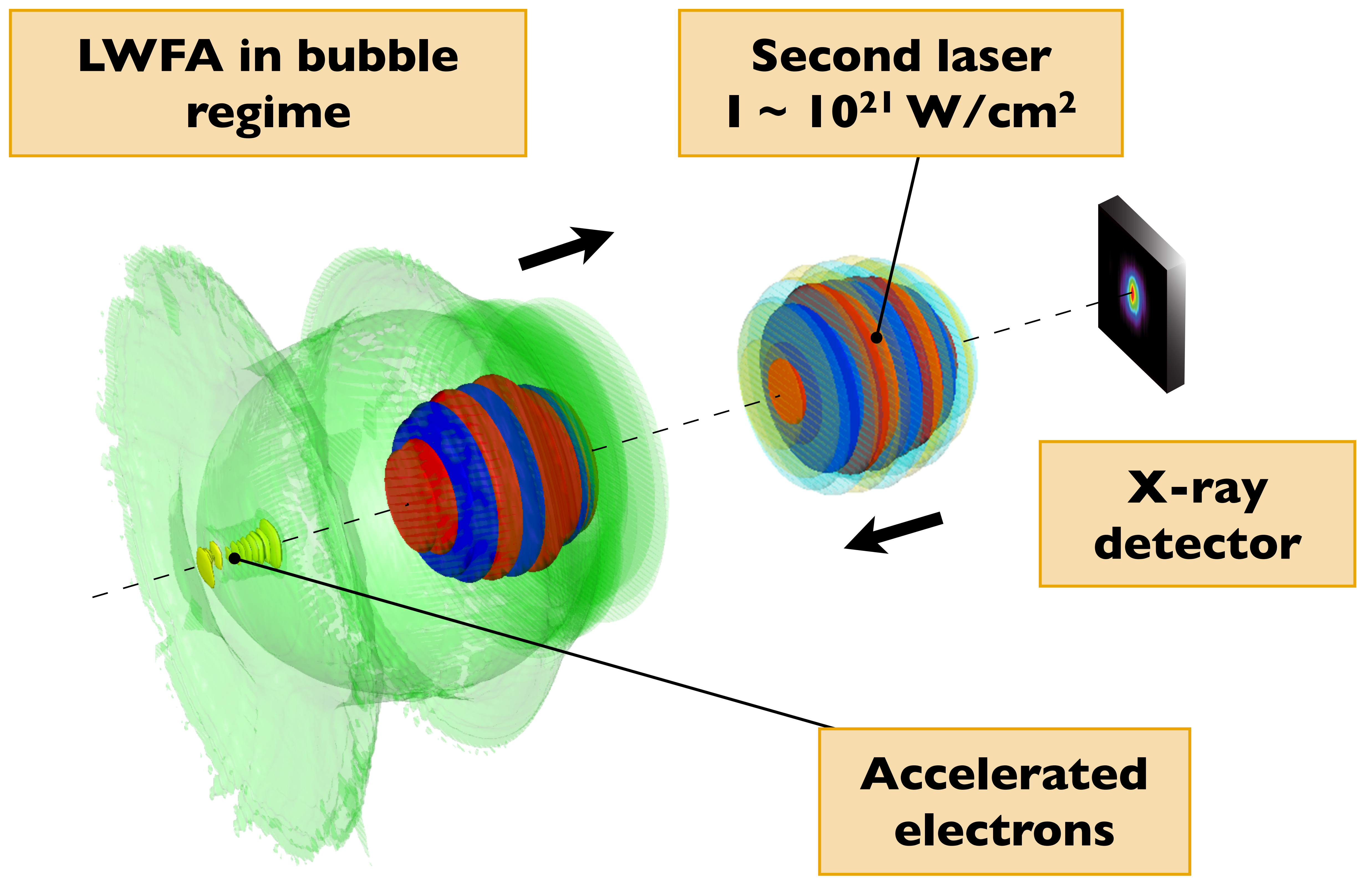


E.N Nerush et al. PRL (2011), C. P. Ridgers et al. , PRL. (2012), N.V. Elkina et al. PRSTAB (2011), A. Gonoskov et al., PRE (2015), T. Grismayer et al., POP (2016), T. Grismayer et al., PRE (2017)

All-optical acceleration and "optical wiggler"

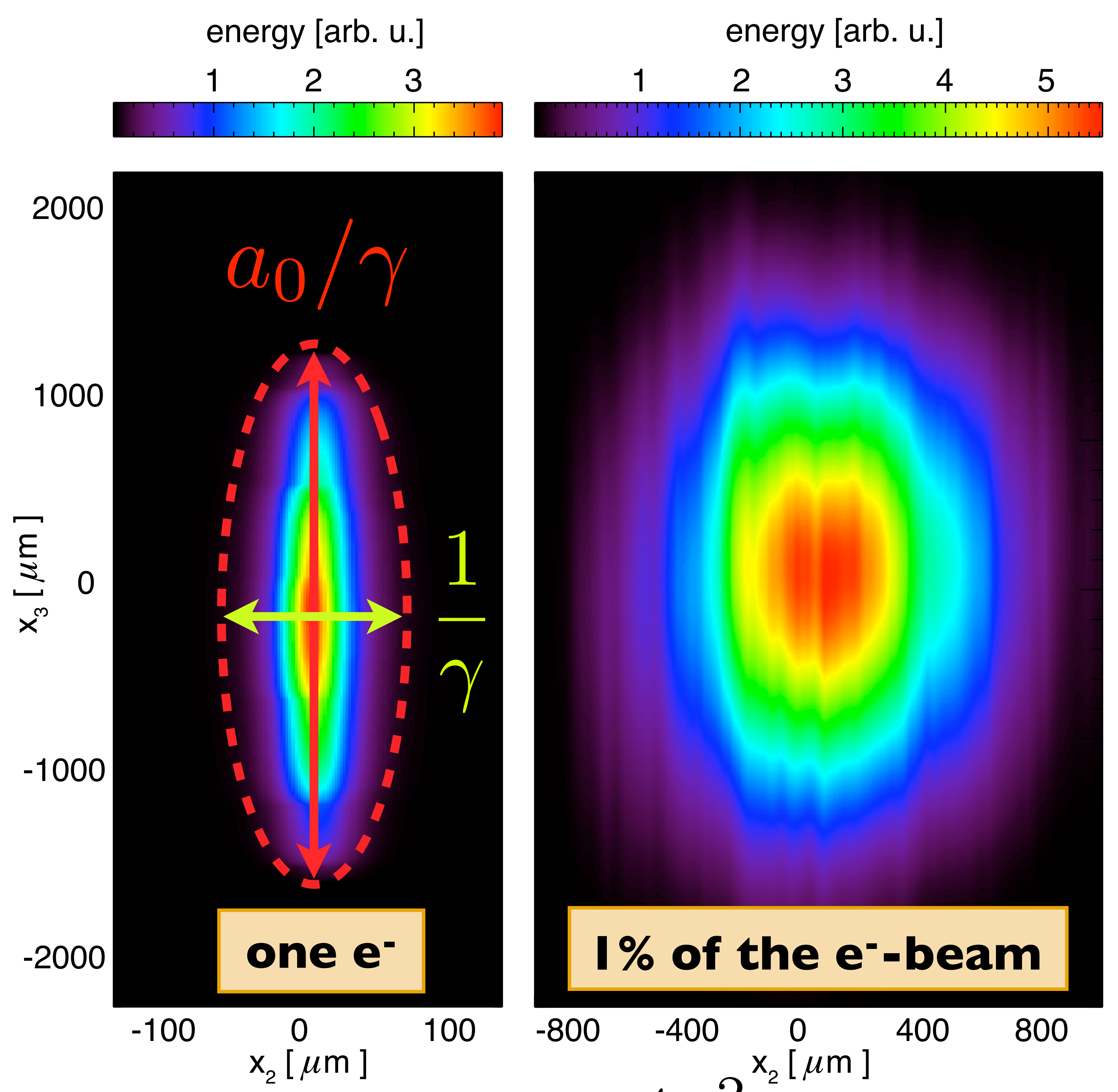
~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm^2

Setup



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

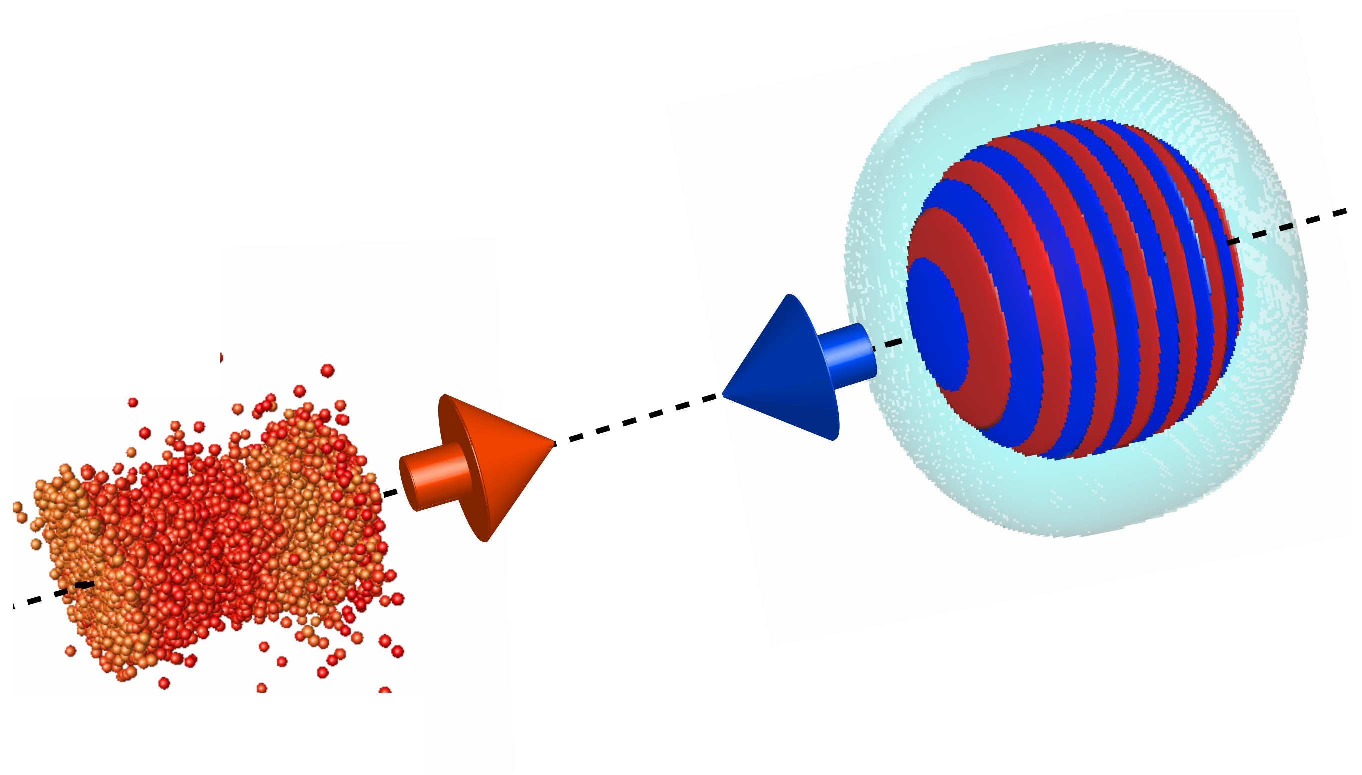
Output radiation on the virtual detector



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

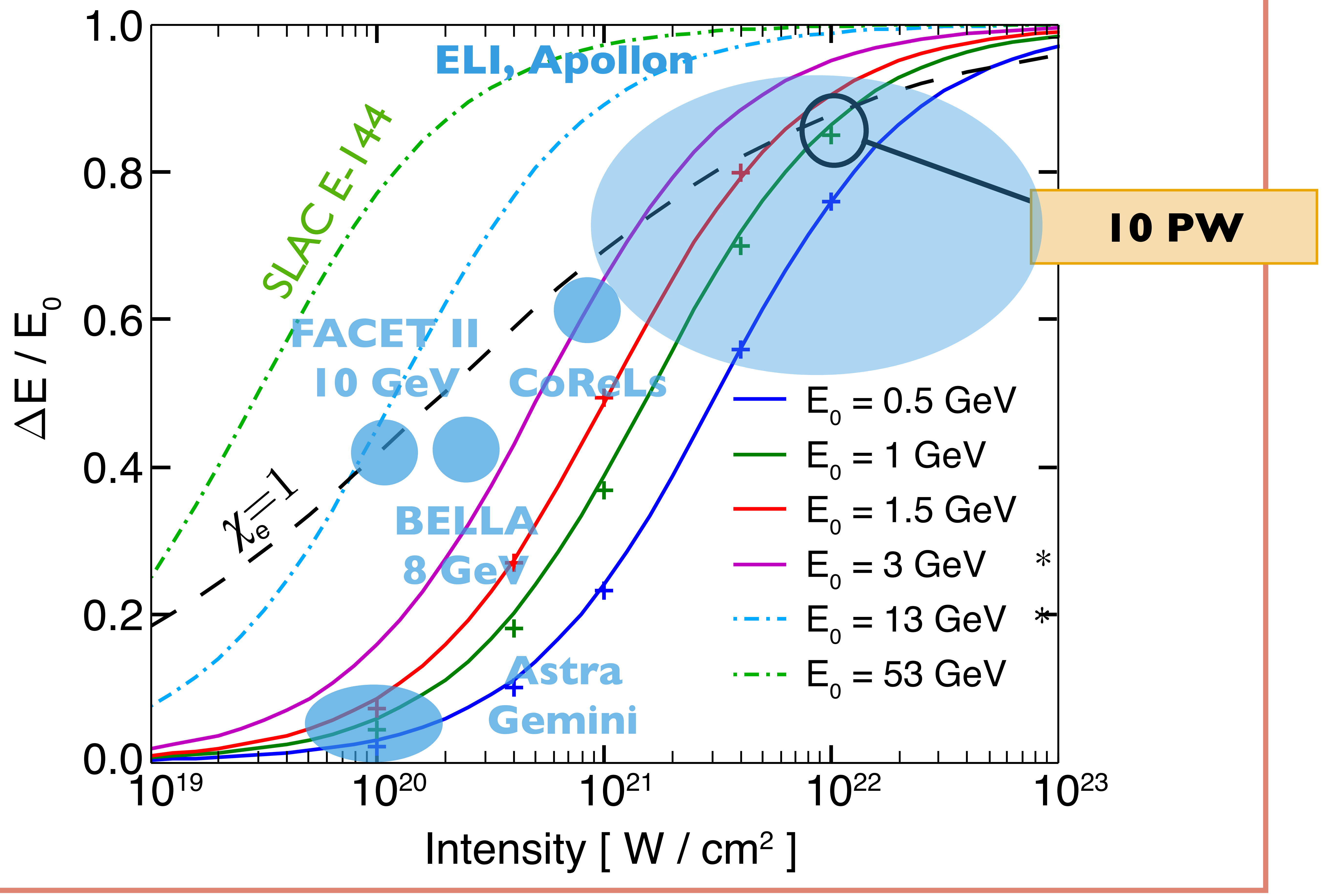
How much energy can be converted to photons in a laser - electron beam scattering?

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

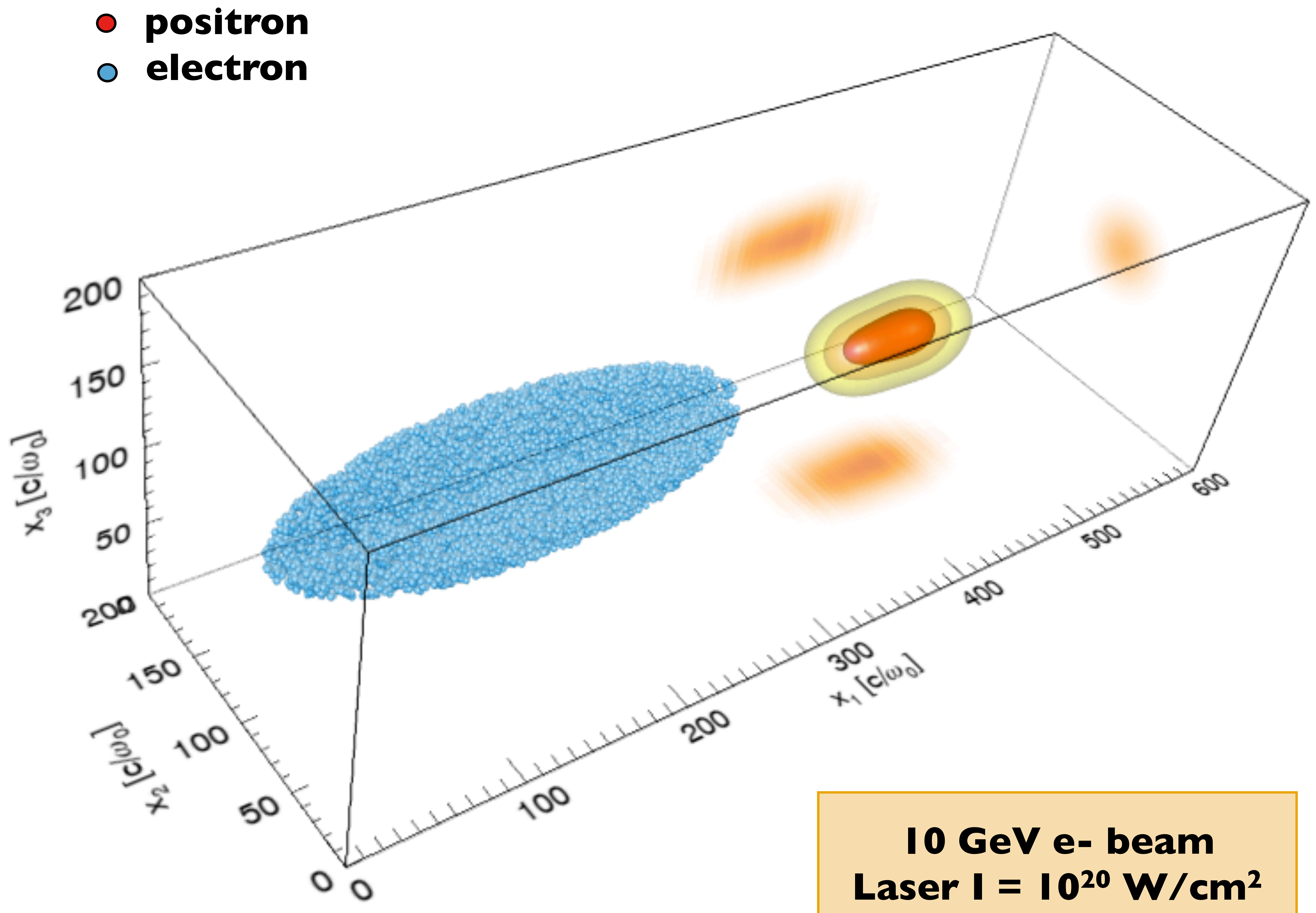


$$\chi \sim \xi_e \,[\mathrm{GeV}] \times \frac{a_0}{100}$$

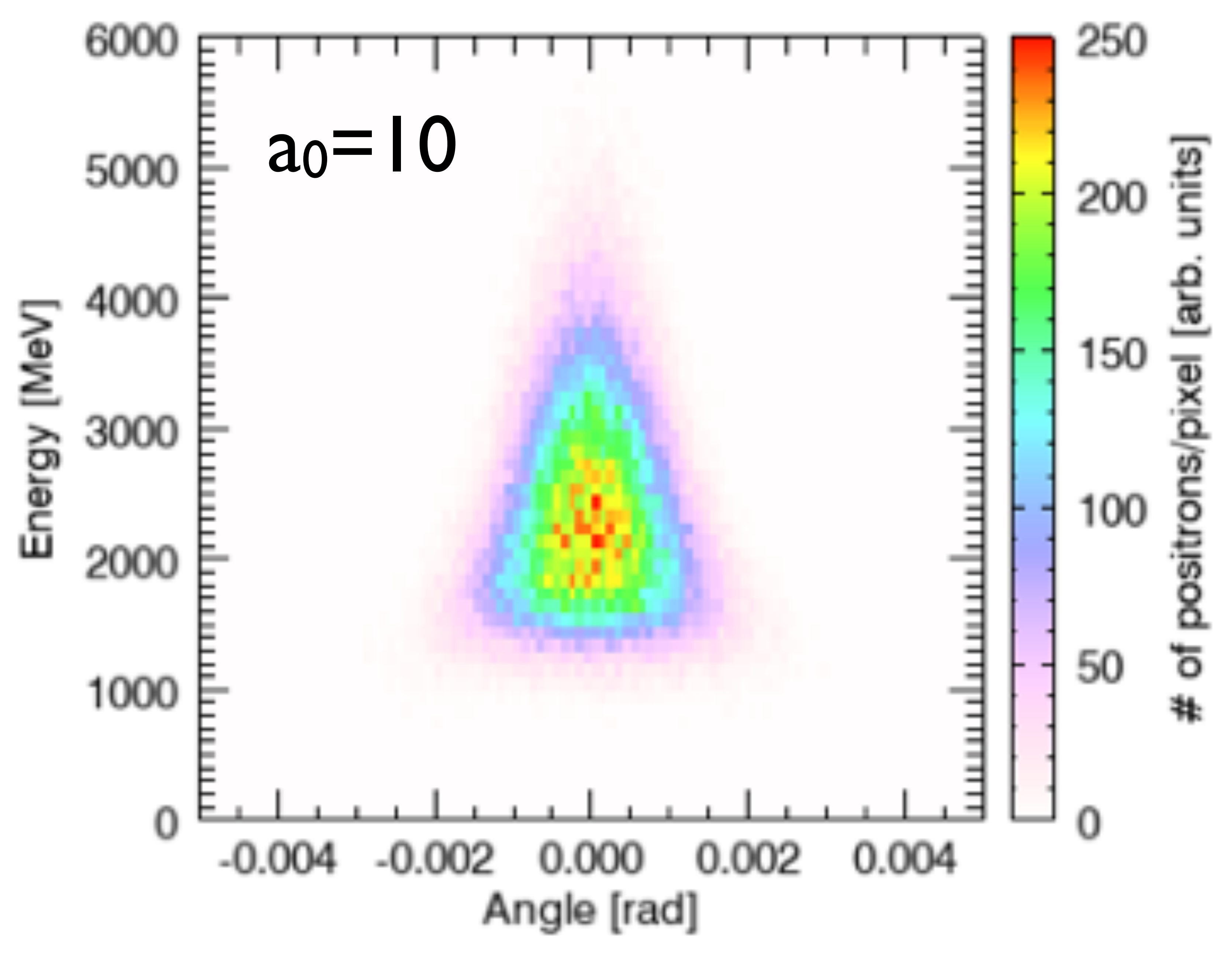
Relative energy loss as a function of electron initial energy and the laser intensity (30 fs lasers)



A fraction of radiated photons decays into electron-positron pairs



Positrons: energy vs angle

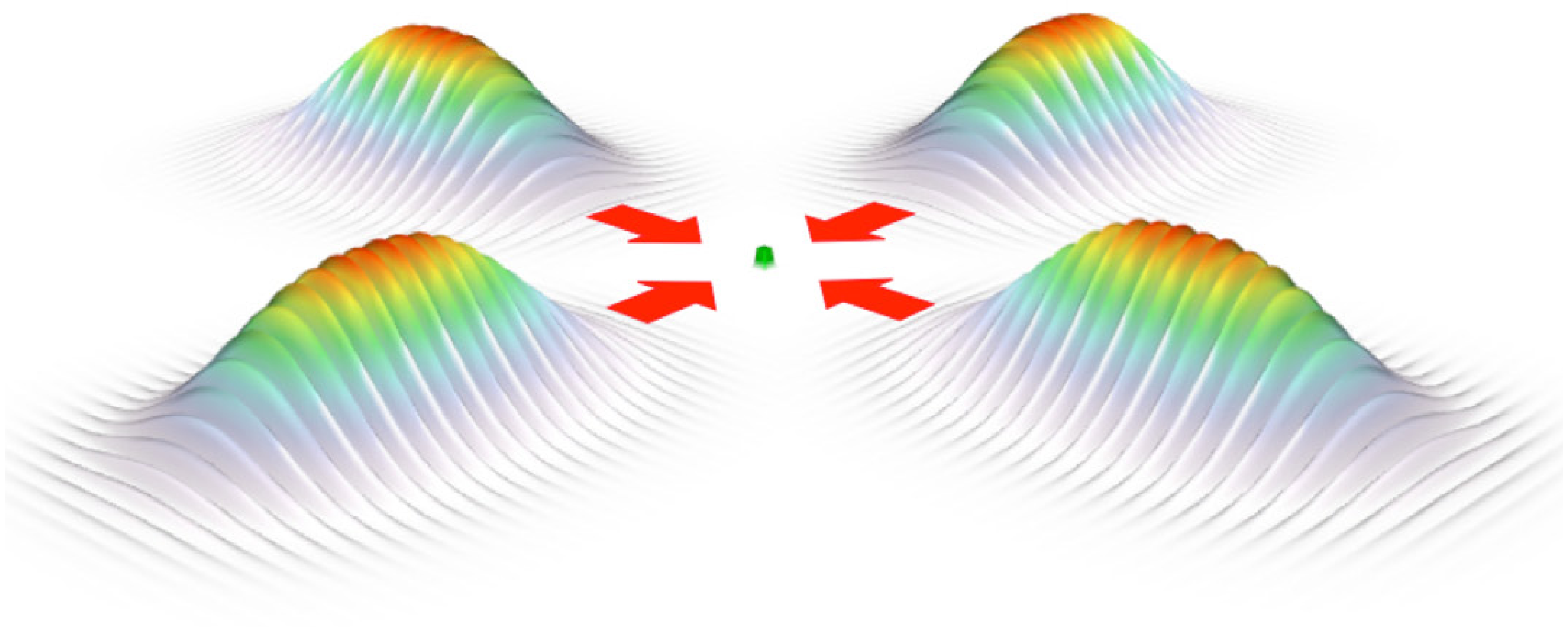


10 GeV e- beam
Laser I = 10^{20} W/cm^2

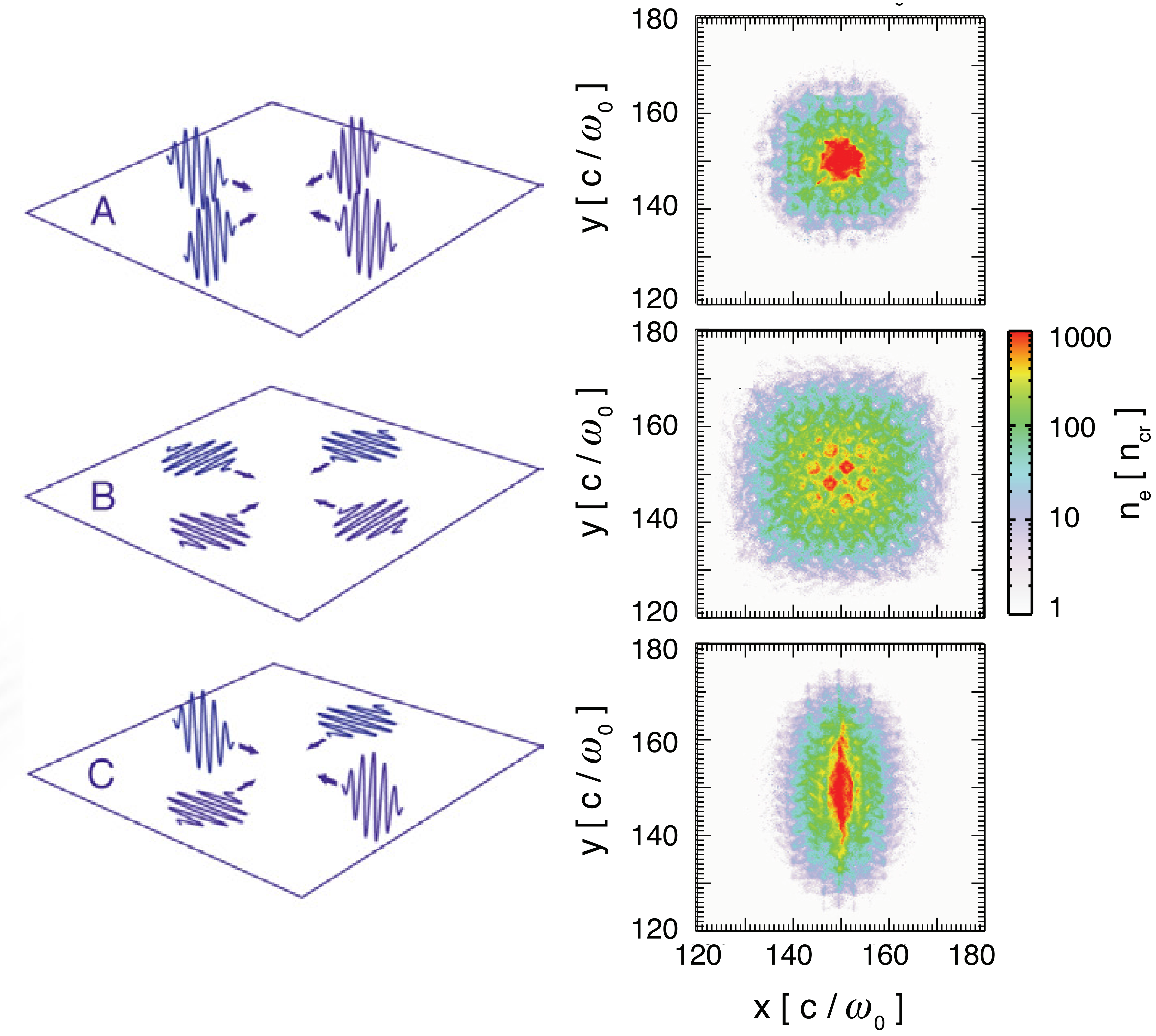
1 nC electron beam gives ~ 0.2 pC of positrons

QED cascades with multiple laser pulses

Different polarisation combinations yield different microstructures



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



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

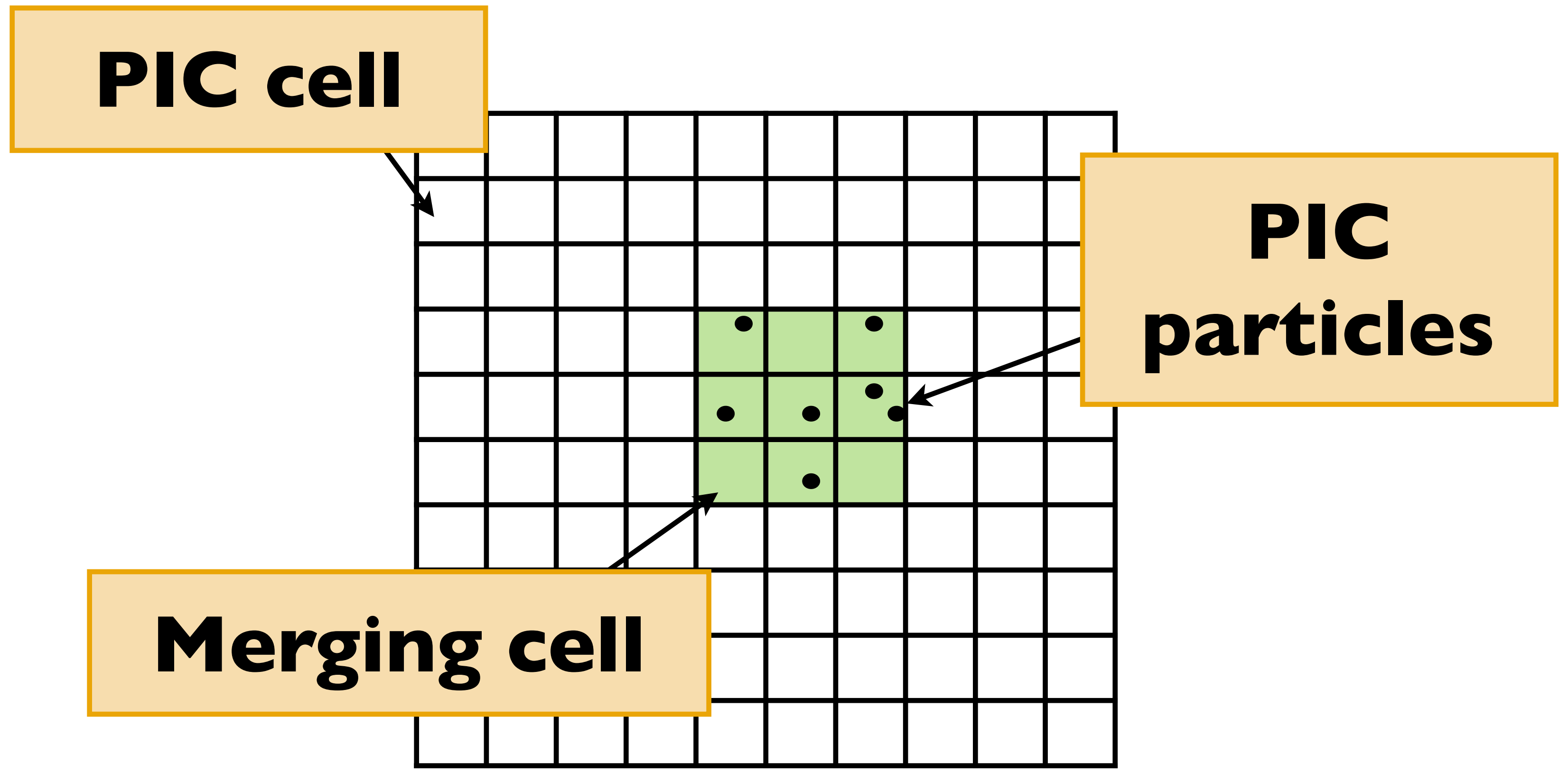
Distribute the particles of every merging cell in its momentum bins

↓

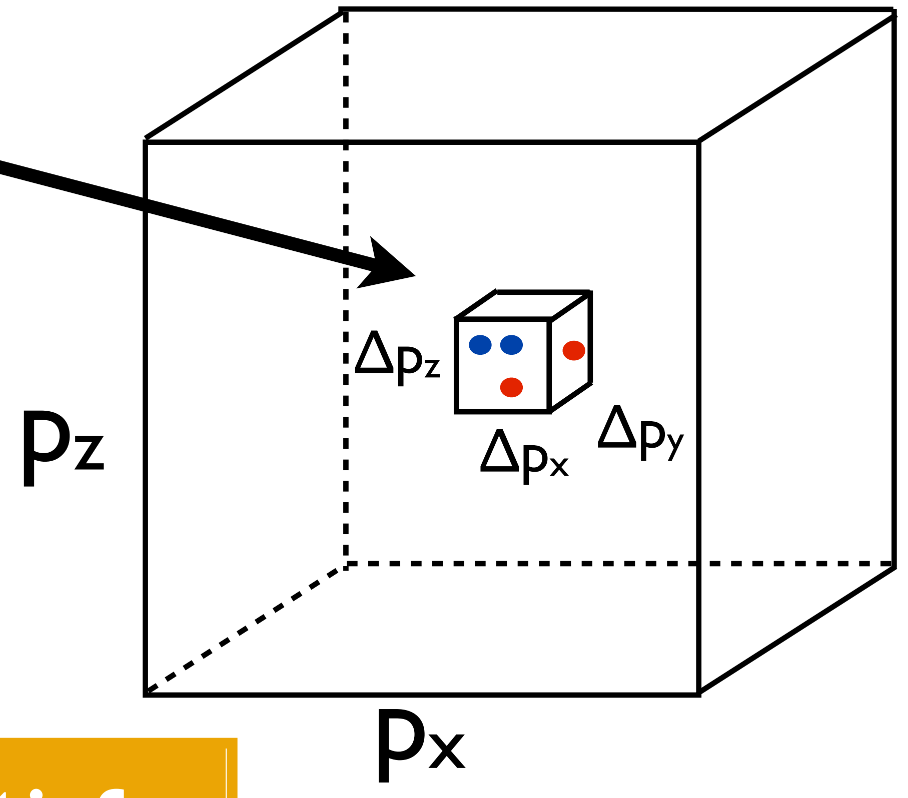
Calculate the total weight, momentum, energy in every momentum bin

Merge the particles in every momentum bin into 2 new particles

Remove all the former particles



Particles close
- in real space
- in momentum space



Equations to satisfy

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

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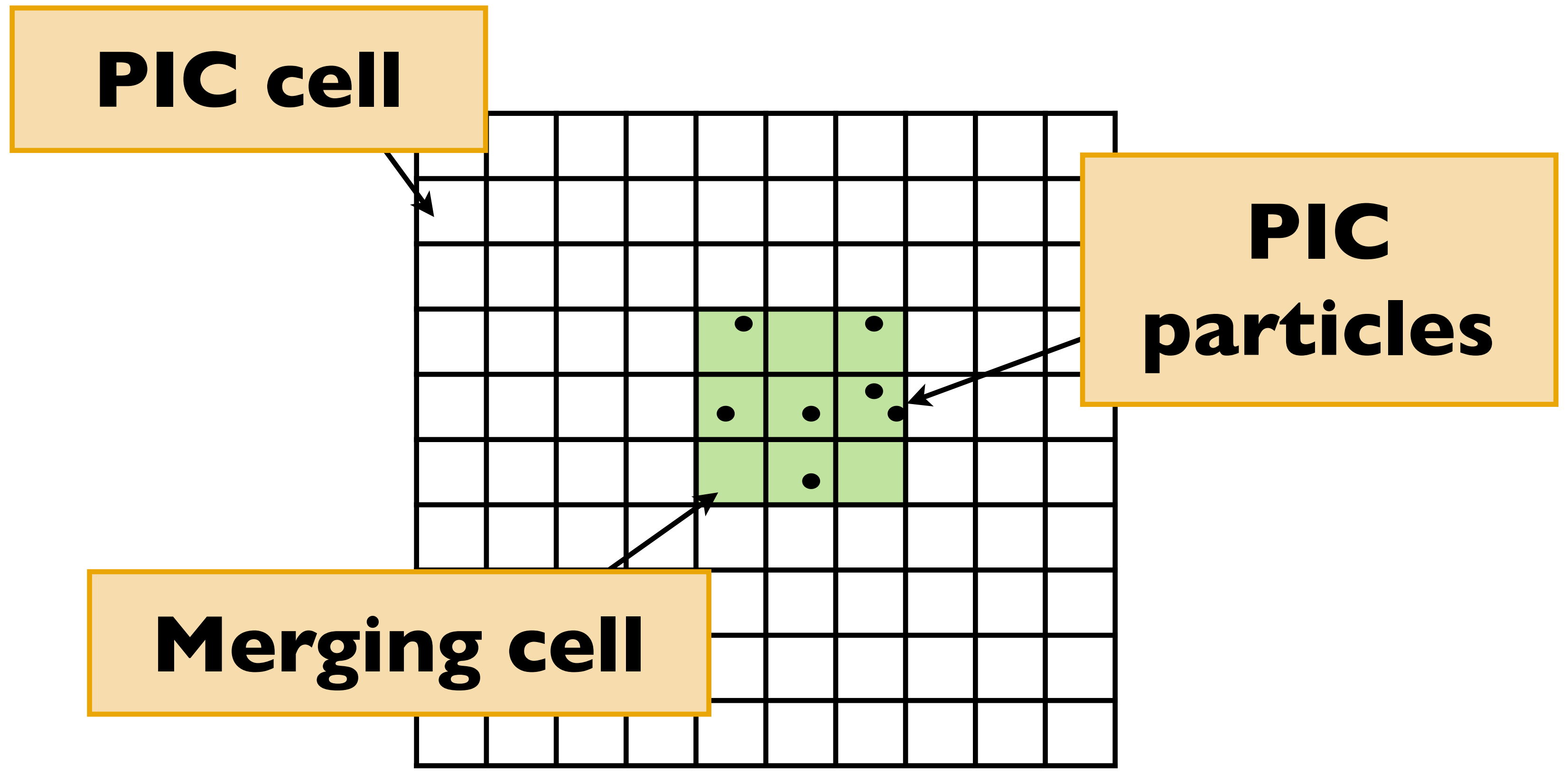

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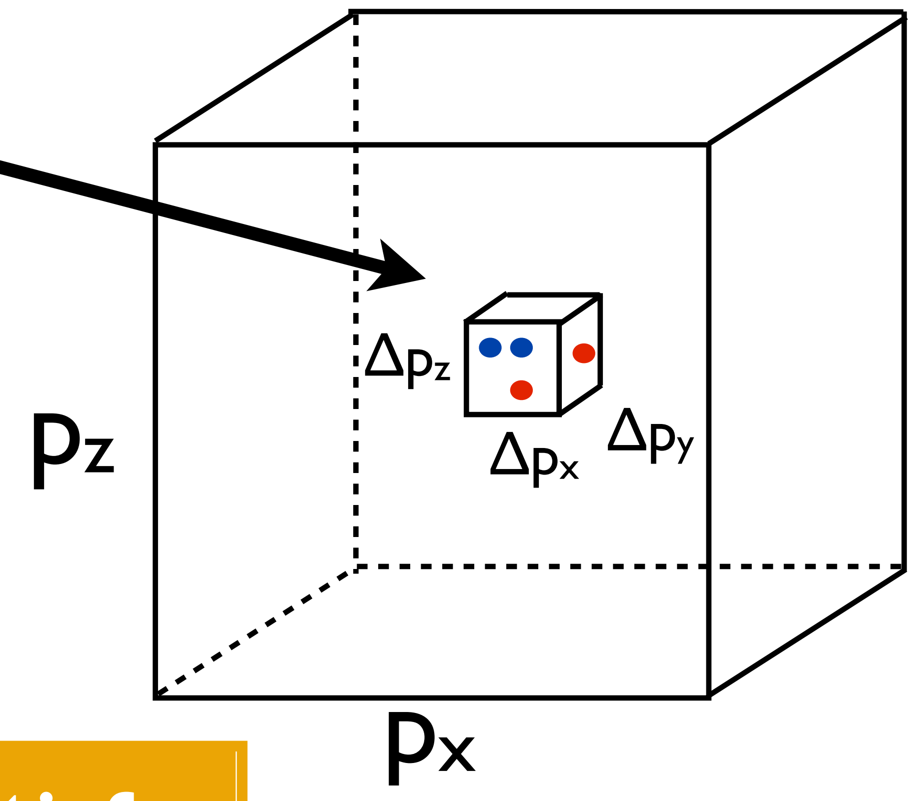

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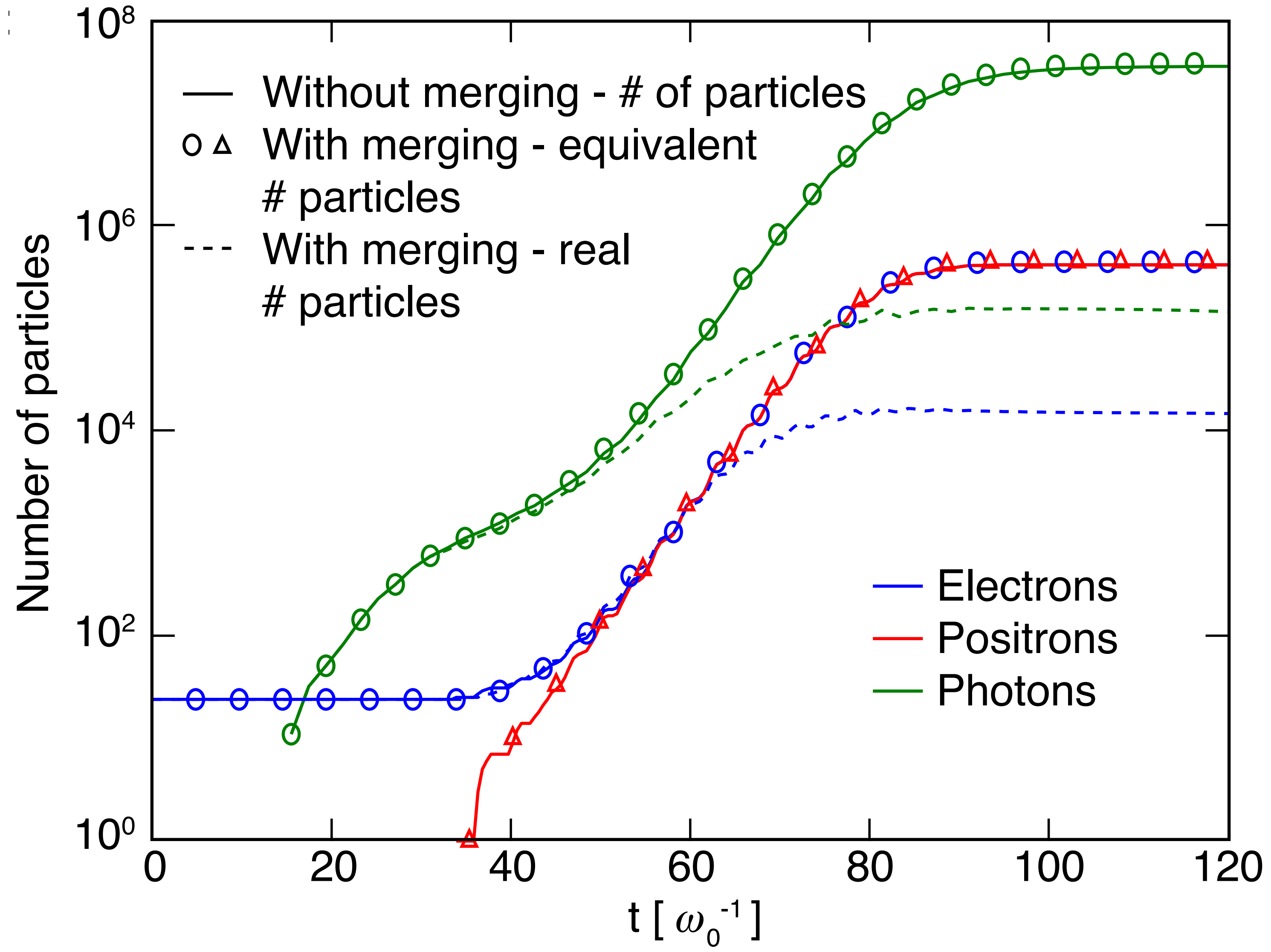
Example: cascade simulation

- 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

Linear Compton scattering in QED-OSIRIS

Fabrizio Del Gaudio & Thomas Grismayer

Algorithm

- **Particle sorting**

  Particles are sorted per collision cell

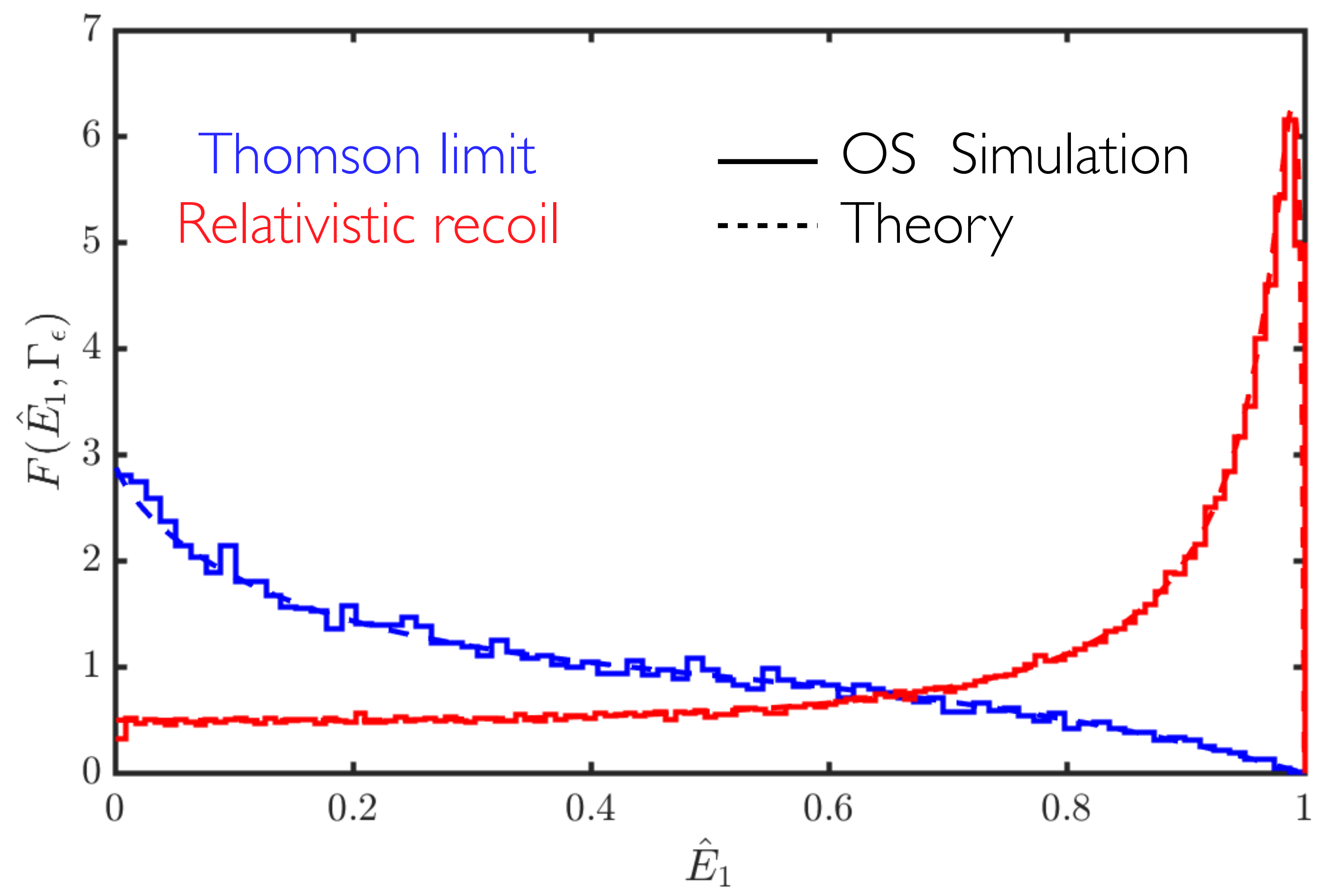
- **Collision list**

  The number of macro scatterings is chosen by the No-Time-Counter method where the full Klein-Nishina cross section is used

- **Momenta update**

  Momenta are updated according to the Compton frequency shift and the momentum conservation

Single scattering spectra*

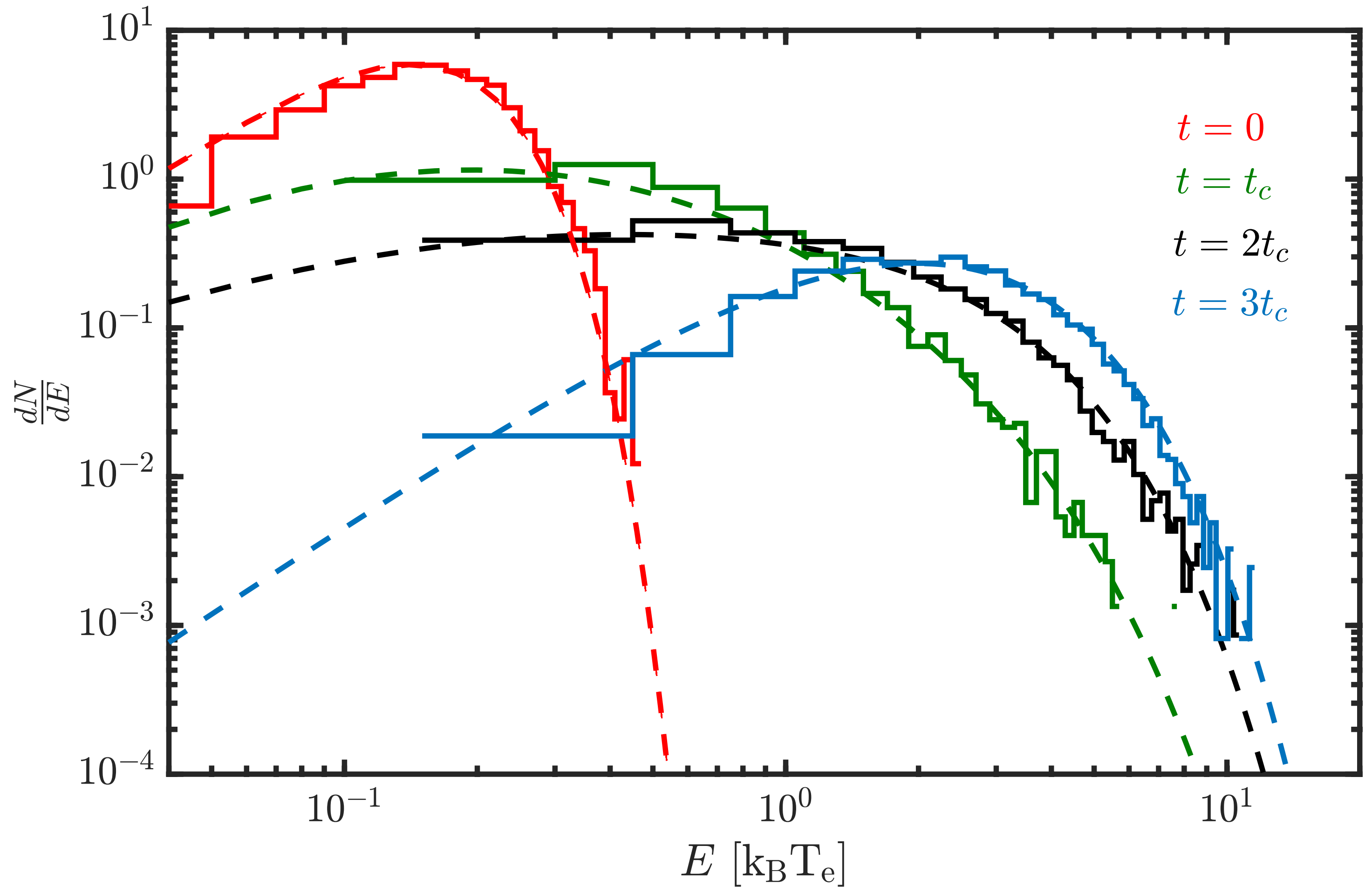


Photon thermalisation (linear Kompaneets**)

Electrons thermal bath at $k_B T_e$= 5 keV

— OS Simulation

---- Linear Kompaneets

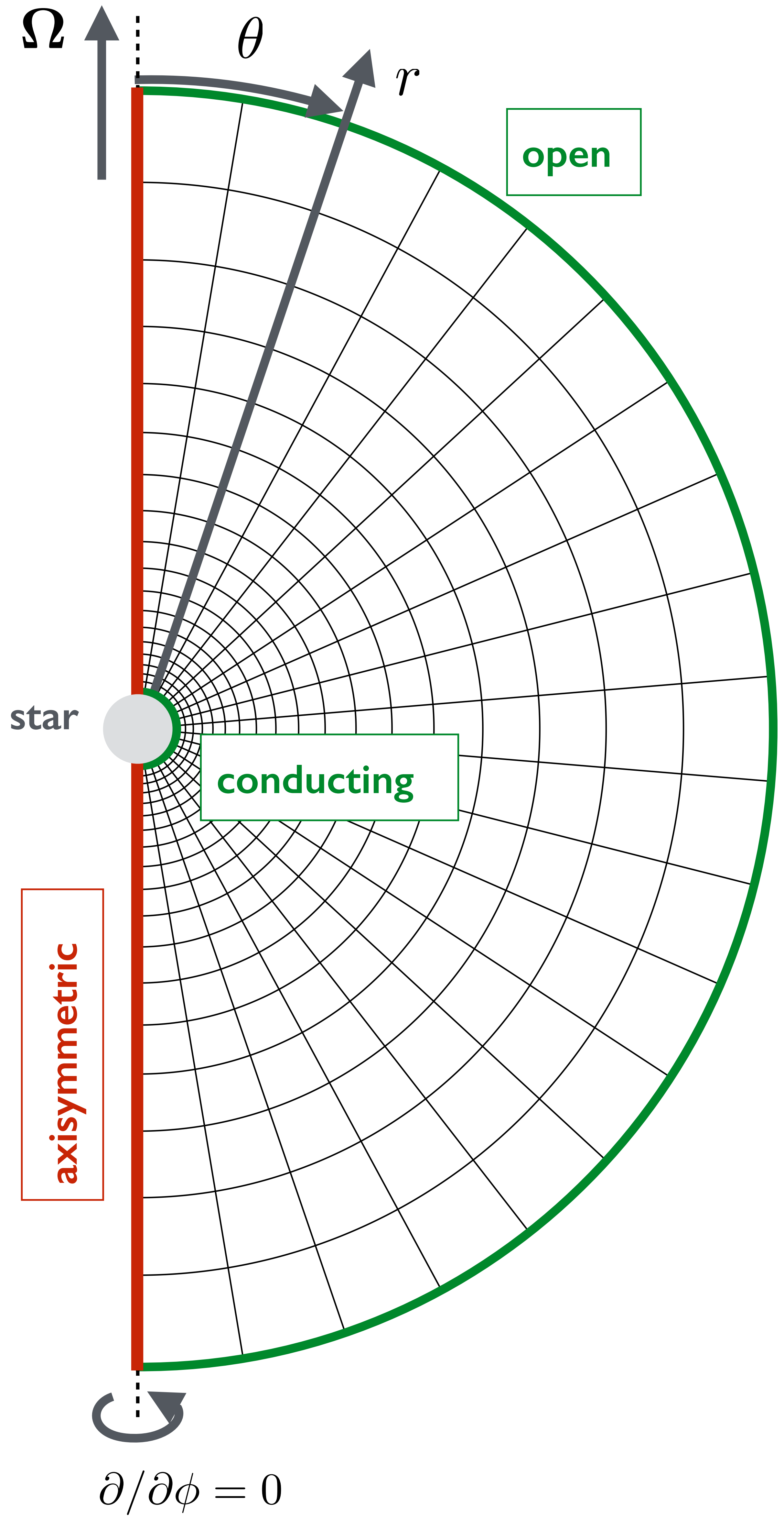


* G. R. Blumenthal, R. J. Gould at Rev. Mod. Phys 42, 2 (1970)
** A. S. Kompaneets at J.E.T.P. 4, 5 (1957)

Spherical coordinates for multi-scale modelling of pulsar magnetospheres

TÉCNICO LISBOA

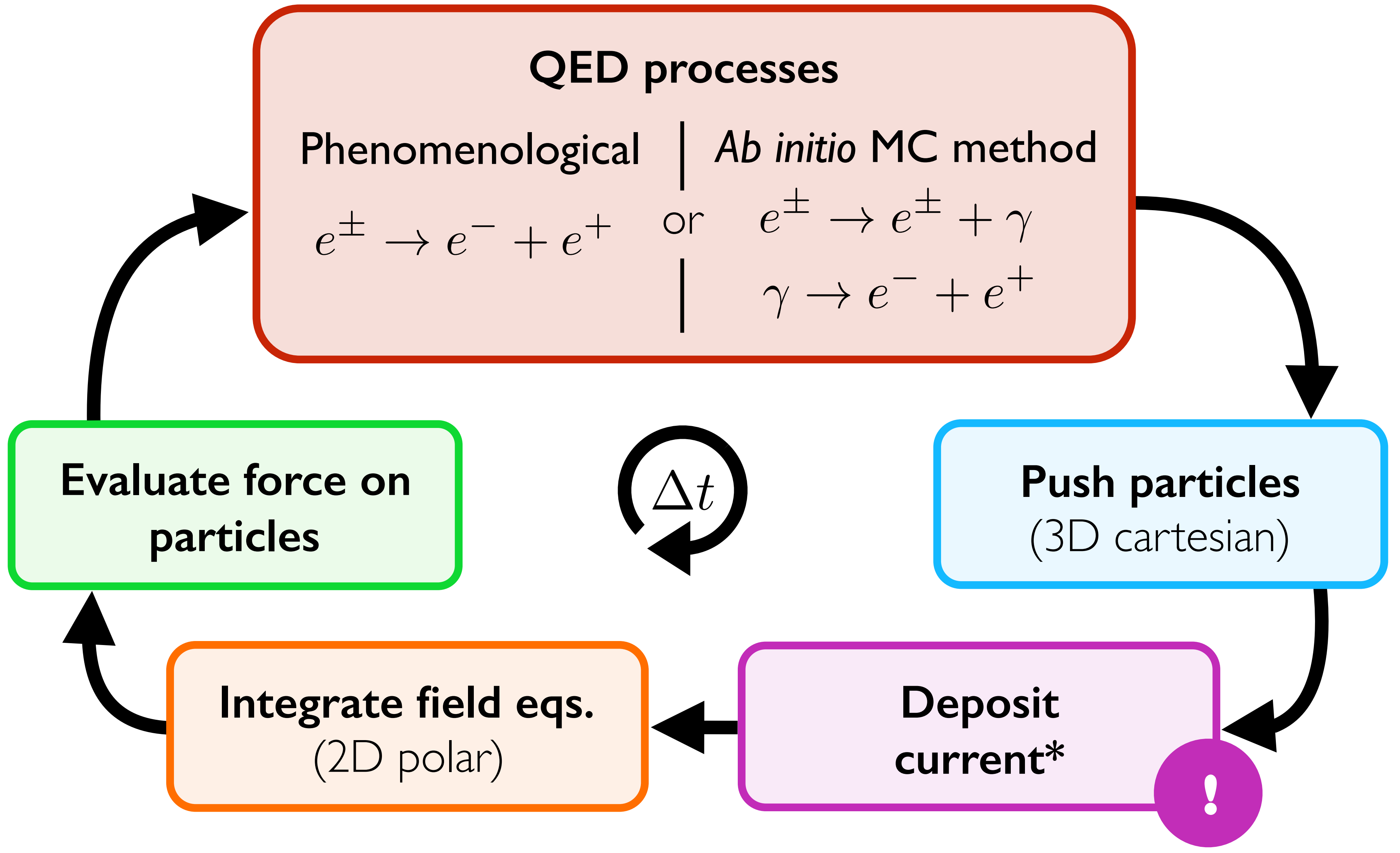
Fabio Cruz



PIC in spherical coordinates

Higher densities close to the star suggest use of **logarithmically spaced radial grid**

Cell shape, differential operators are more complex and **change across the grid**



* F. Cruz *et al.*, in prep. (**2019**)

Conclusions

- It is essential to include additional physics to PIC codes for modelling the next generation of laser experiments.

- Classical vs. quantum radiation reaction can be studied in future experiments. Especially interesting is crossing the quantum threshold from radiation-dominated regime.

- QED cascades can create abundant plasma and lead to a very efficient energy transfer from the laser into gamma-rays.

- Performance developments are also necessary to tackle the new computational challenges associated with exponential growth of the number of particles, intrinsic load imbalance etc.