Laser-matter interactions at the extreme

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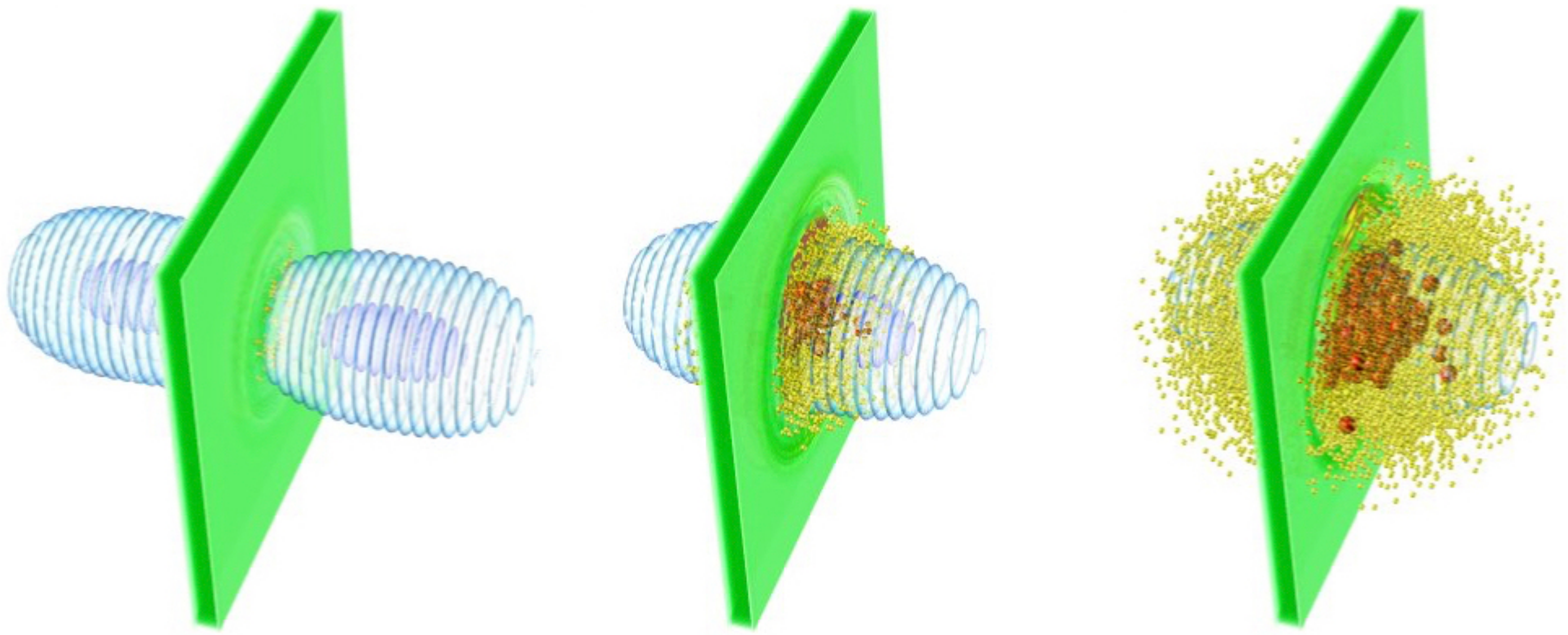

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Work in collaboration with:

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

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

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Contents

- **Short intro to simulations of laser - matter interactions at the extreme**

- **Radiation reaction and radiation emission for ATF**

Contents

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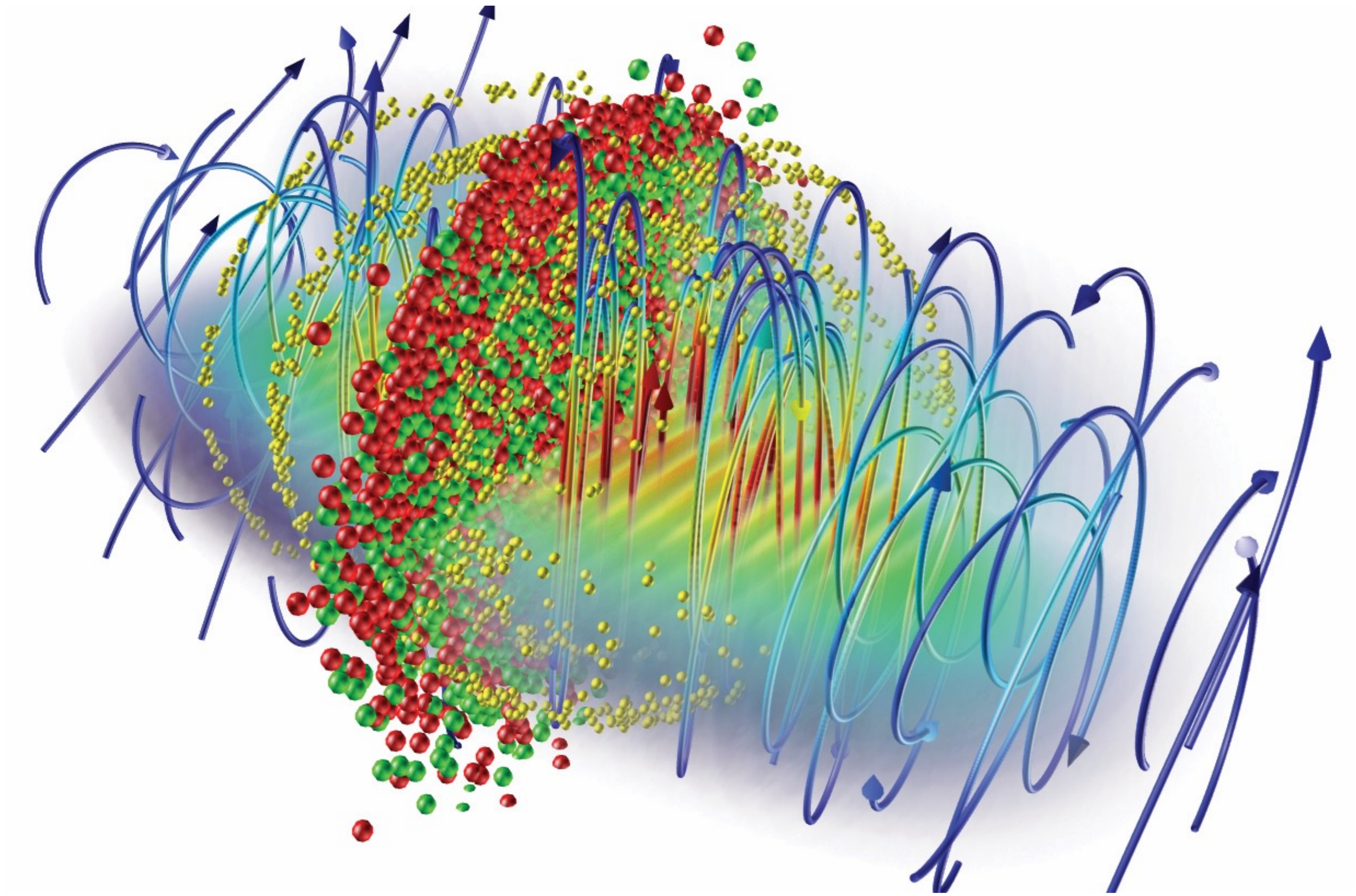
Short intro to simulations of laser - matter interactions at the extreme

Radiation reaction and radiation emission for ATF

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



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

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 and 10 PW (1kJ)

NP: 10 PW and γ-ray beam

CoReLS

1 laser of 4 PW (100 J)

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

Which intensity?

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

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

- non relativistic

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

- weakly nonlinear, relativistic

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

- relativistic, nonlinear

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

- quantum

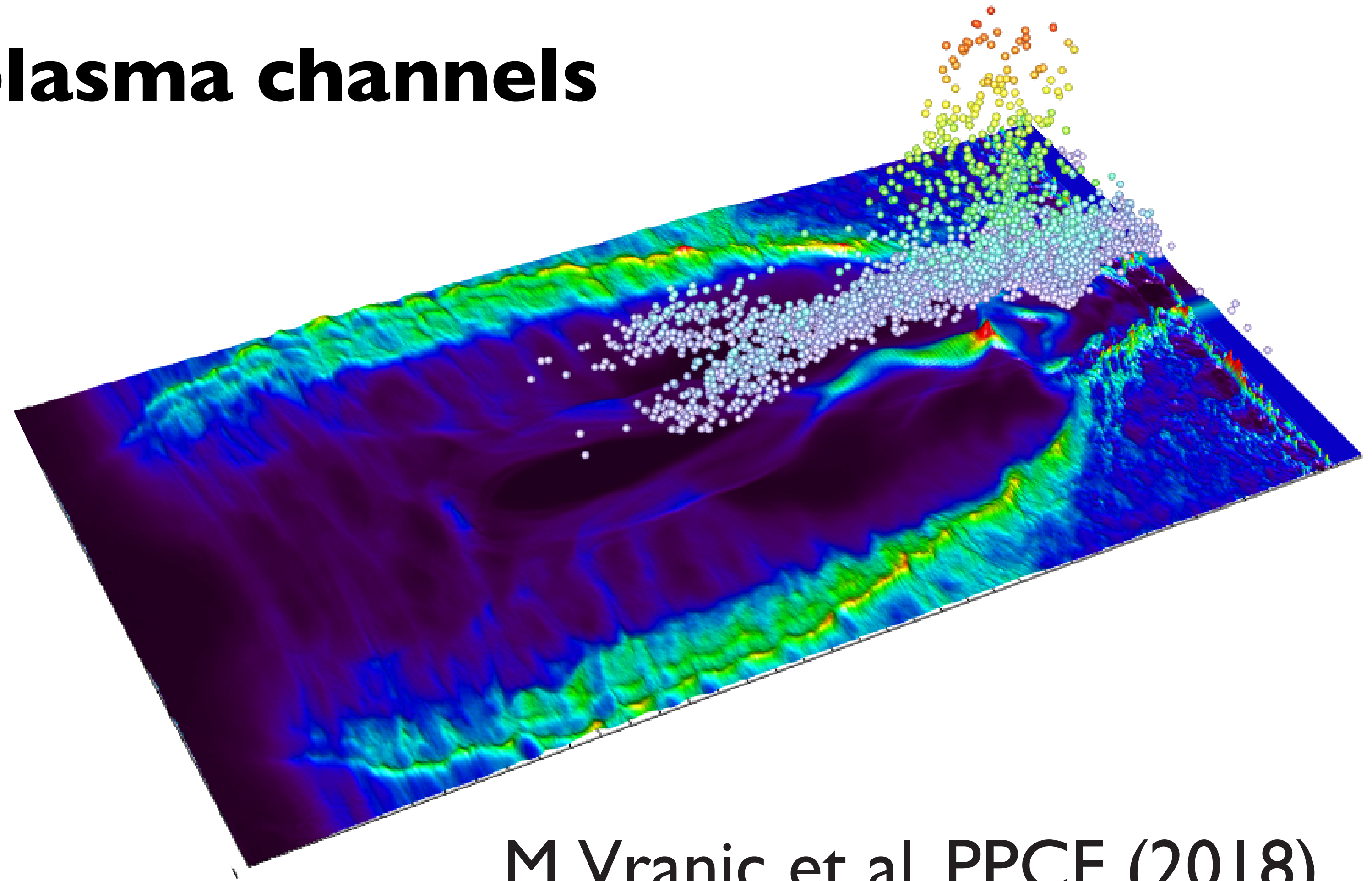
  $a_0 \sim 1000$ $\quad$ $I \sim 10^{24}\mathrm{W/cm^2}$

What can we do with the next generation of lasers?

New opportunities for particle acceleration

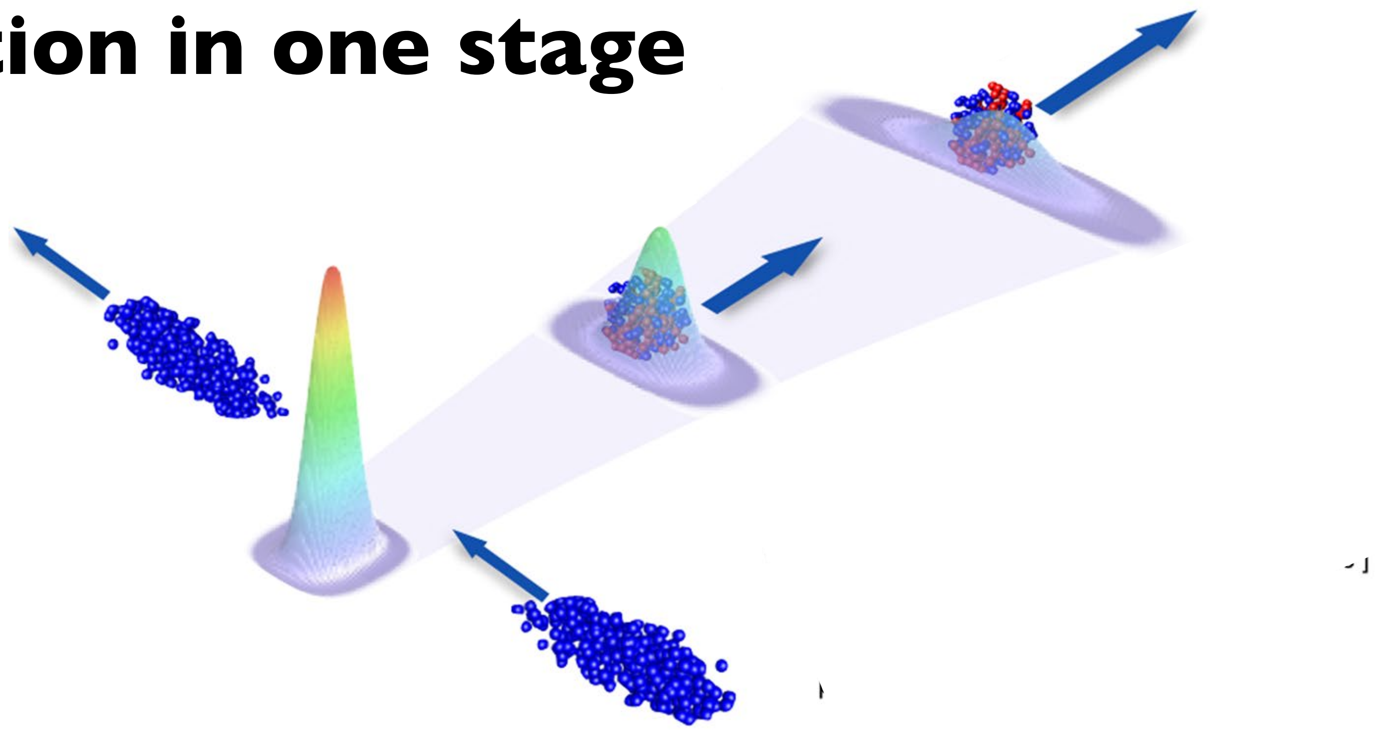
- **Electron acceleration in plasma channels**

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)

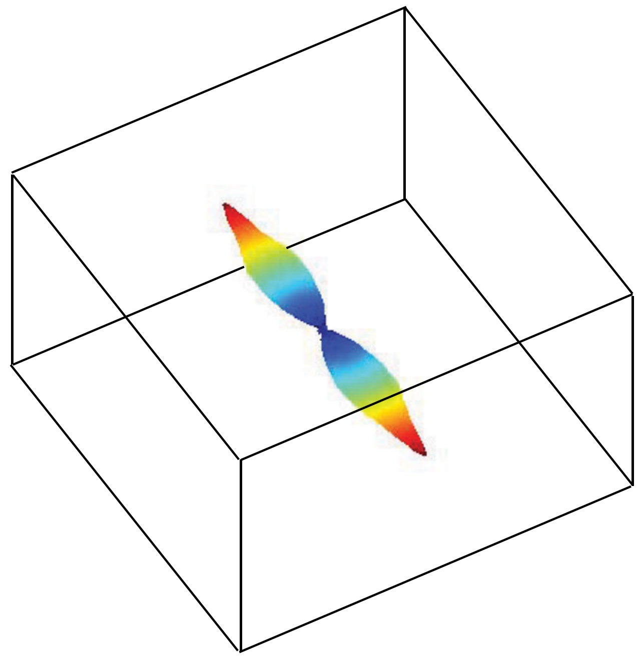
- **Electron-positron production & acceleration in one stage**

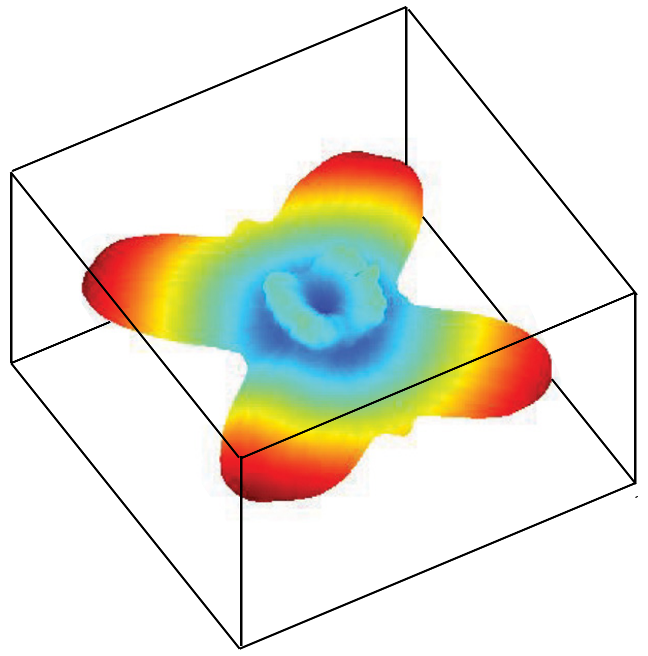


M.Vranic et al, SciRep (2018)

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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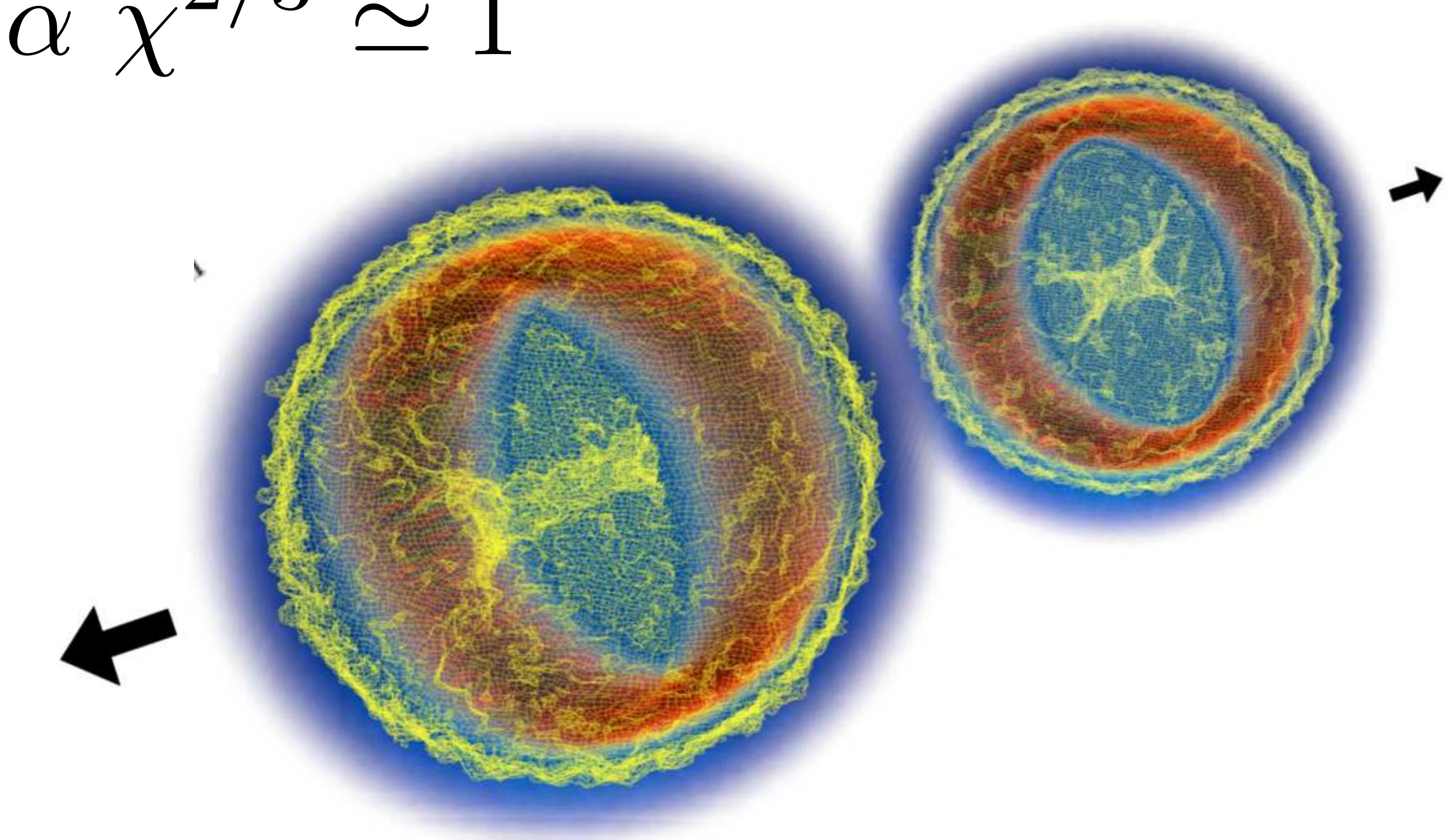
Study of the classical and quantum radiation reaction

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

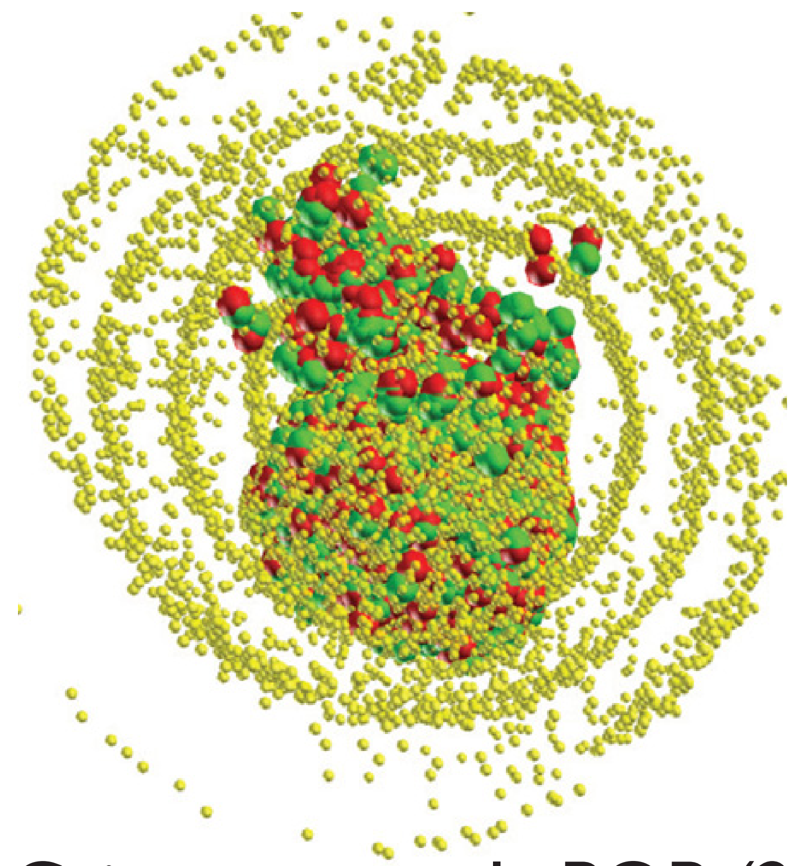
$$\alpha\ \chi^{2/3} \simeq 1$$



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)



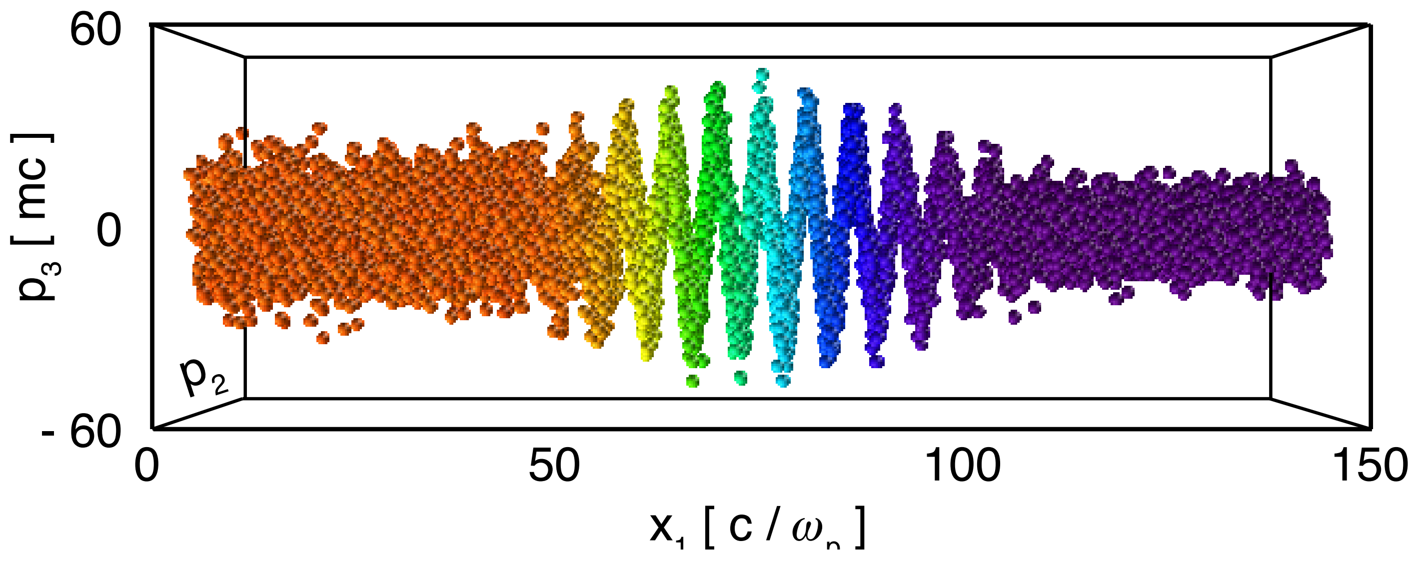
T. Grismayer et al, POP (2016)

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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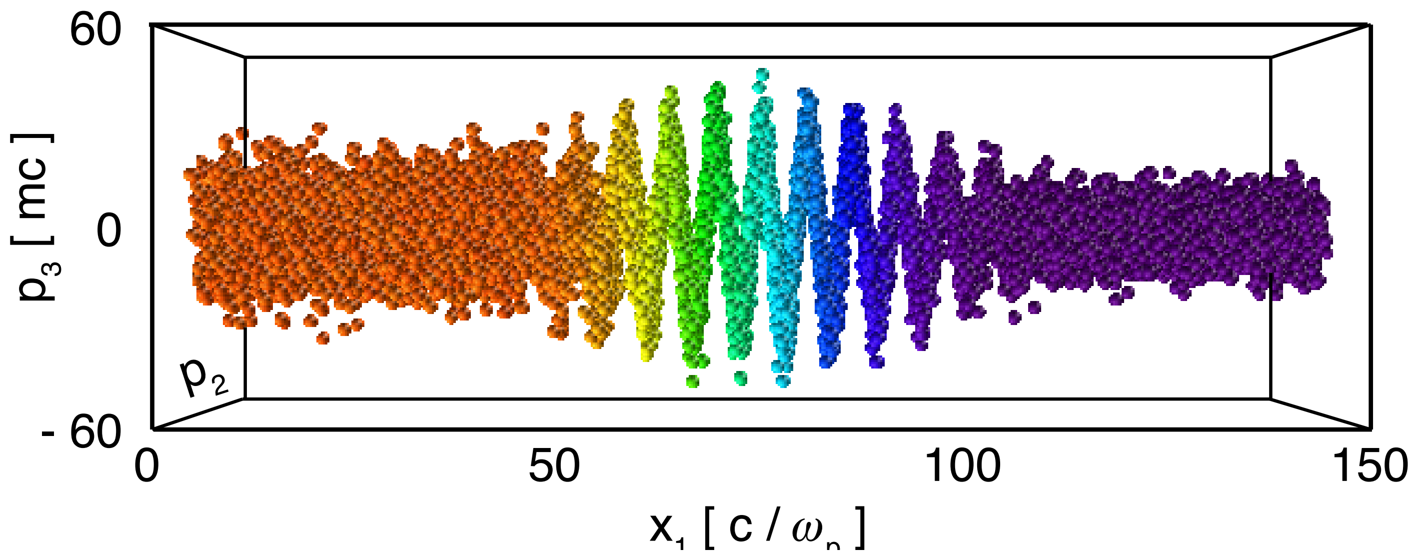
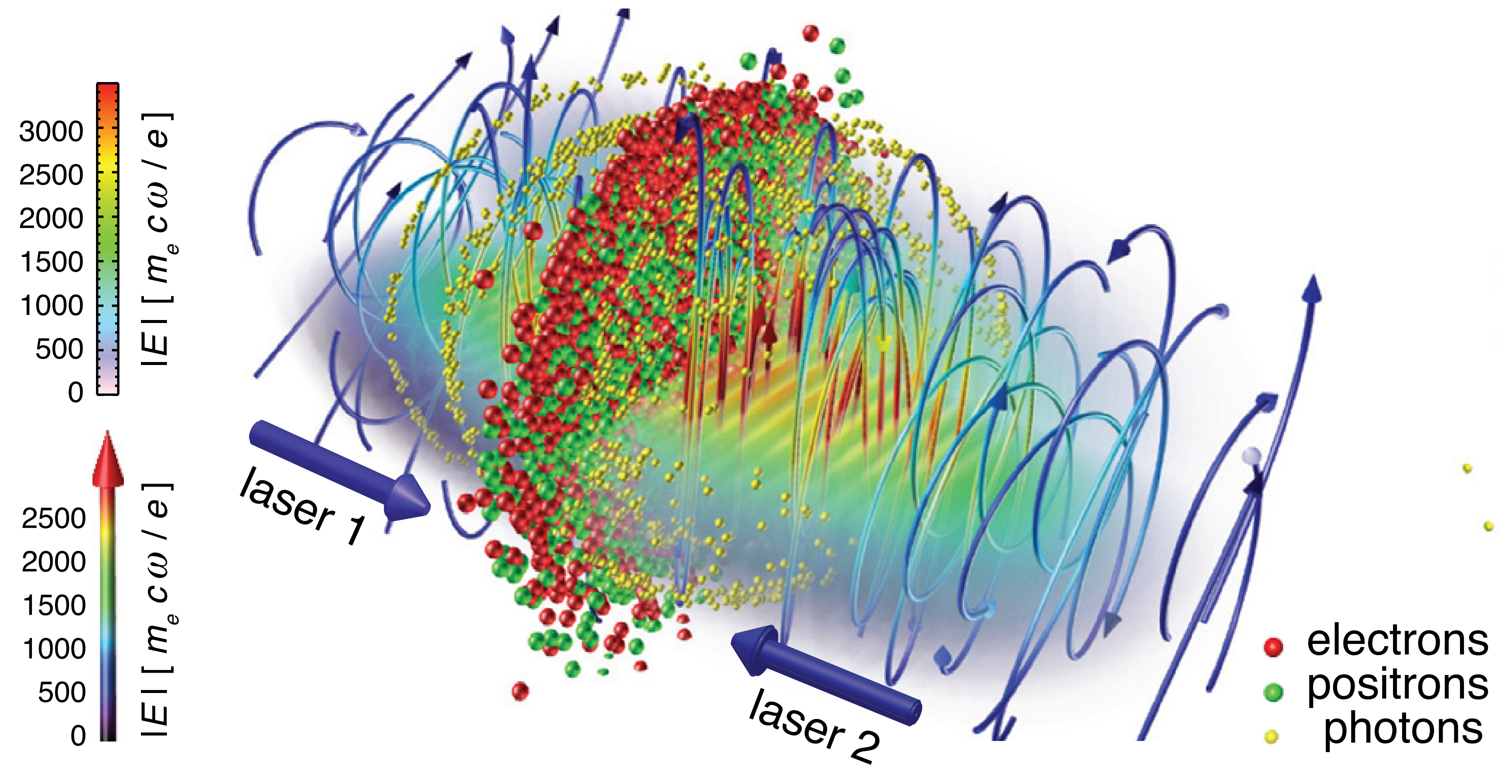


Adding quantum processes

- 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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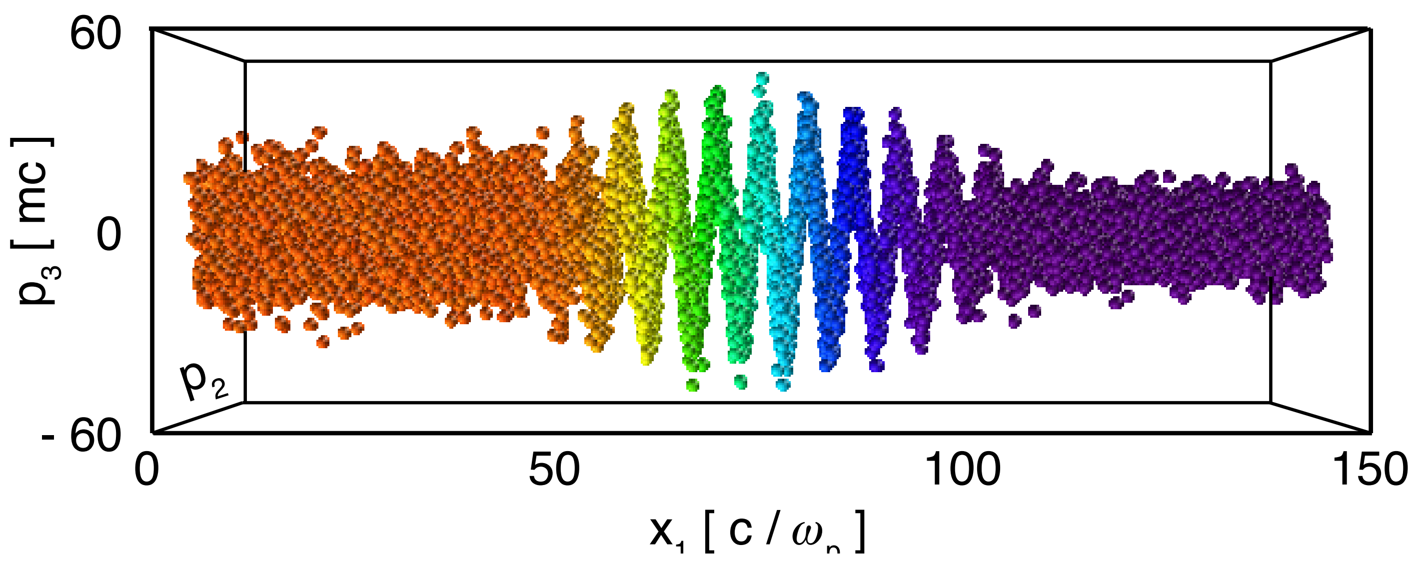

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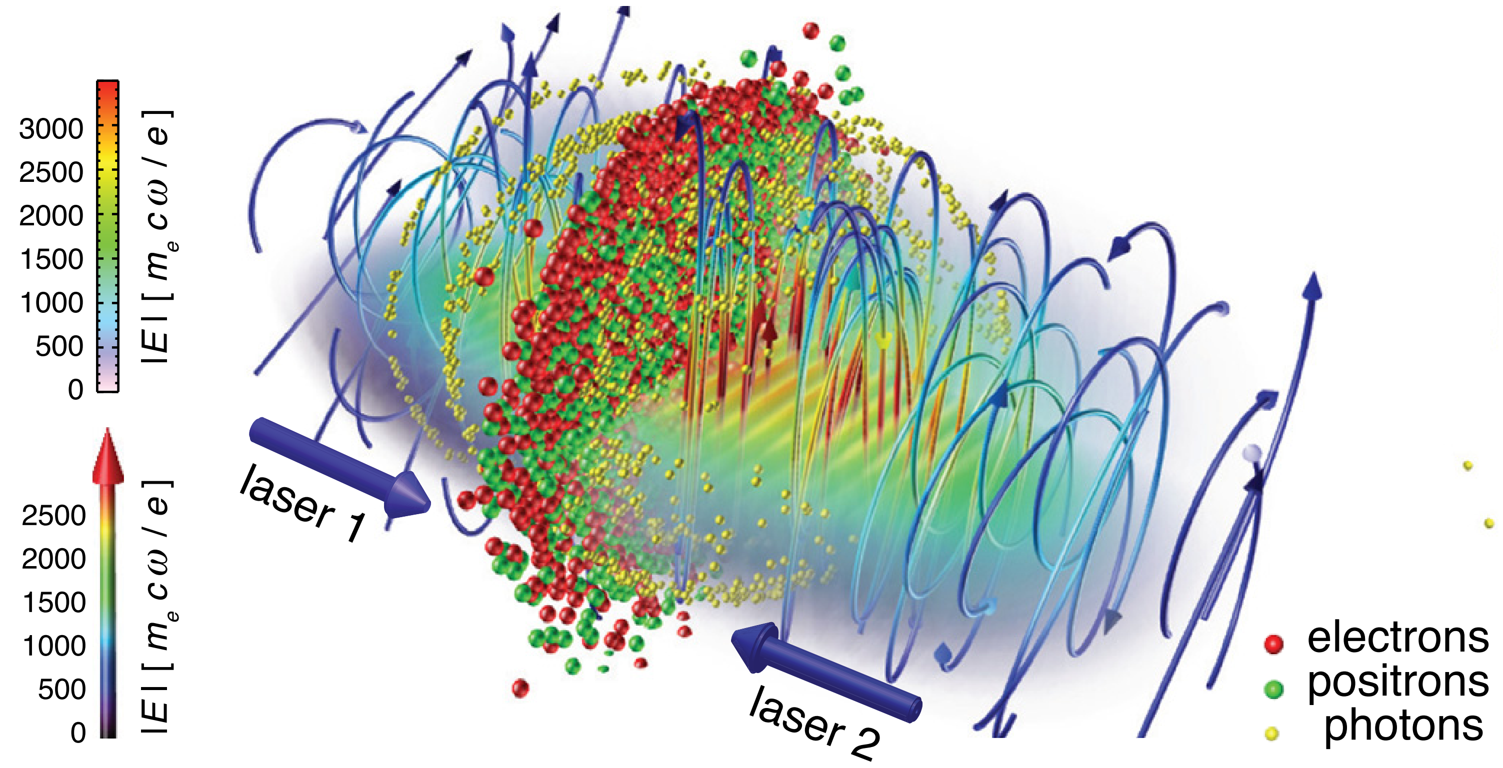
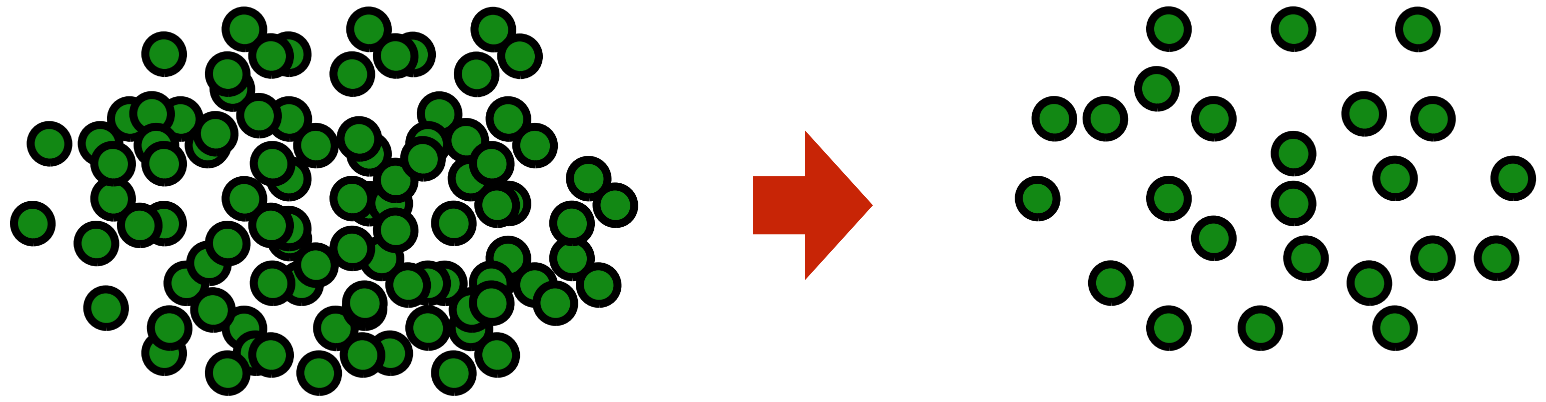


Adding performance improvements (particle merging, advanced load balancing schemes)

- Essential for all the projects with strong QED effects

M.Vranic et al., CPC (2015)



QED PIC loop in OSIRIS

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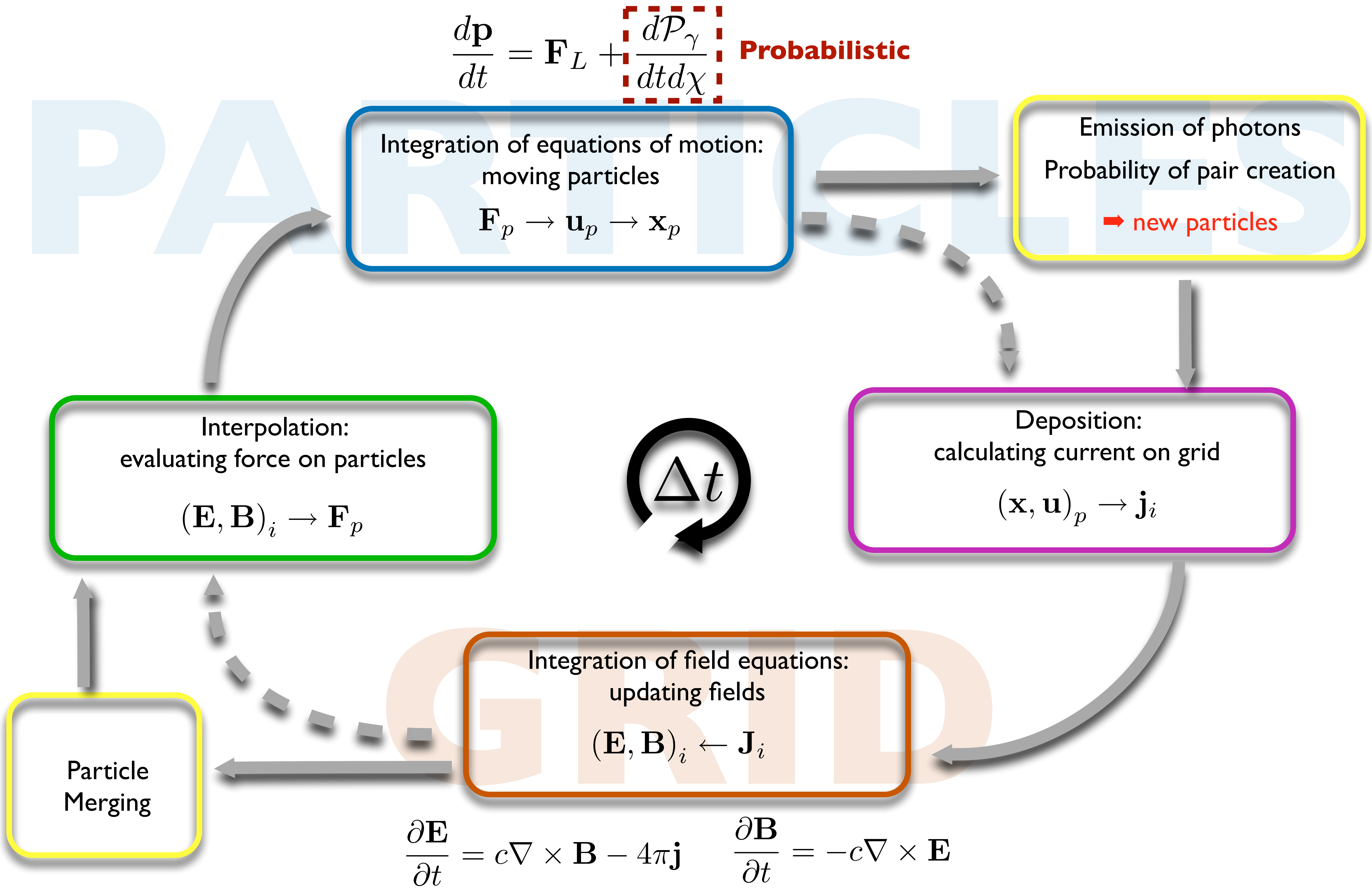
http://plasmasim.physics.ucla.edu/



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)

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TÉCNICO LISBOA

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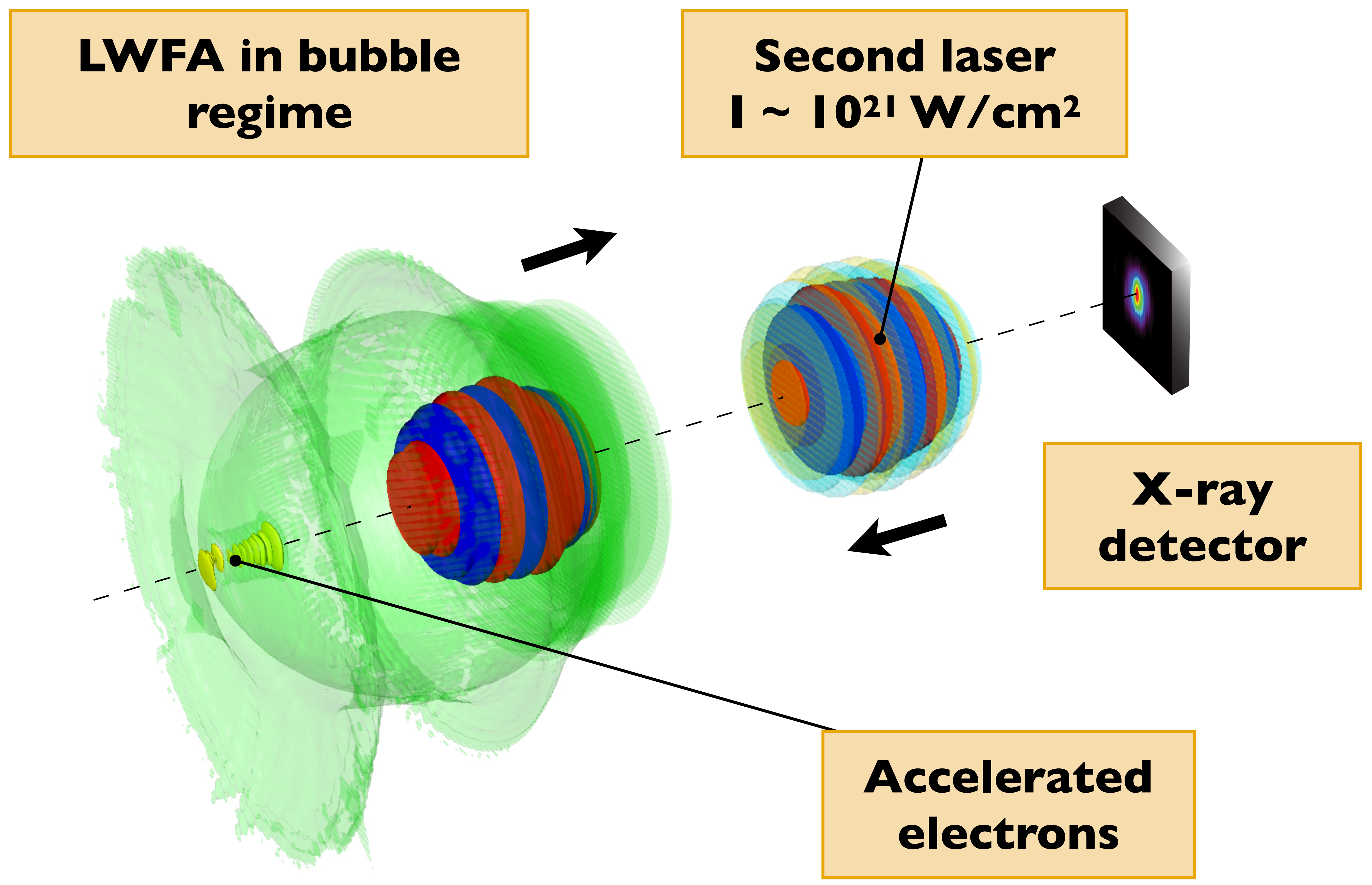
Radiation reaction and radiation emission for ATF

All-optical acceleration and "optical wiggler"

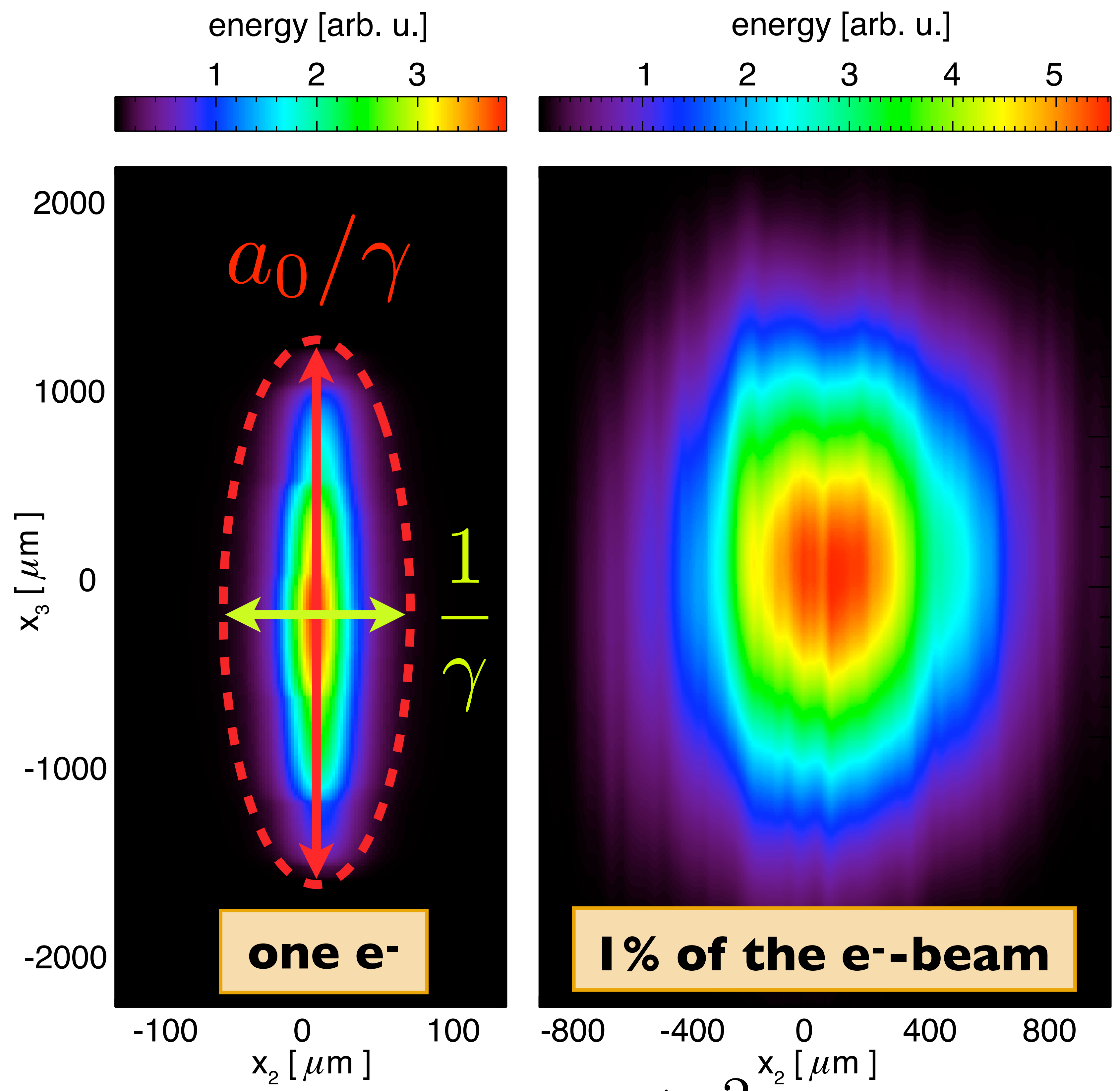
~ 40% energy loss for a 1 GeV beam at 10^{21} W/cm² (for a laser with 1 μm wavelength, and 30 fs duration)

Setup



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

Output radiation on the virtual detector



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

All-optical acceleration and "optical wiggler"

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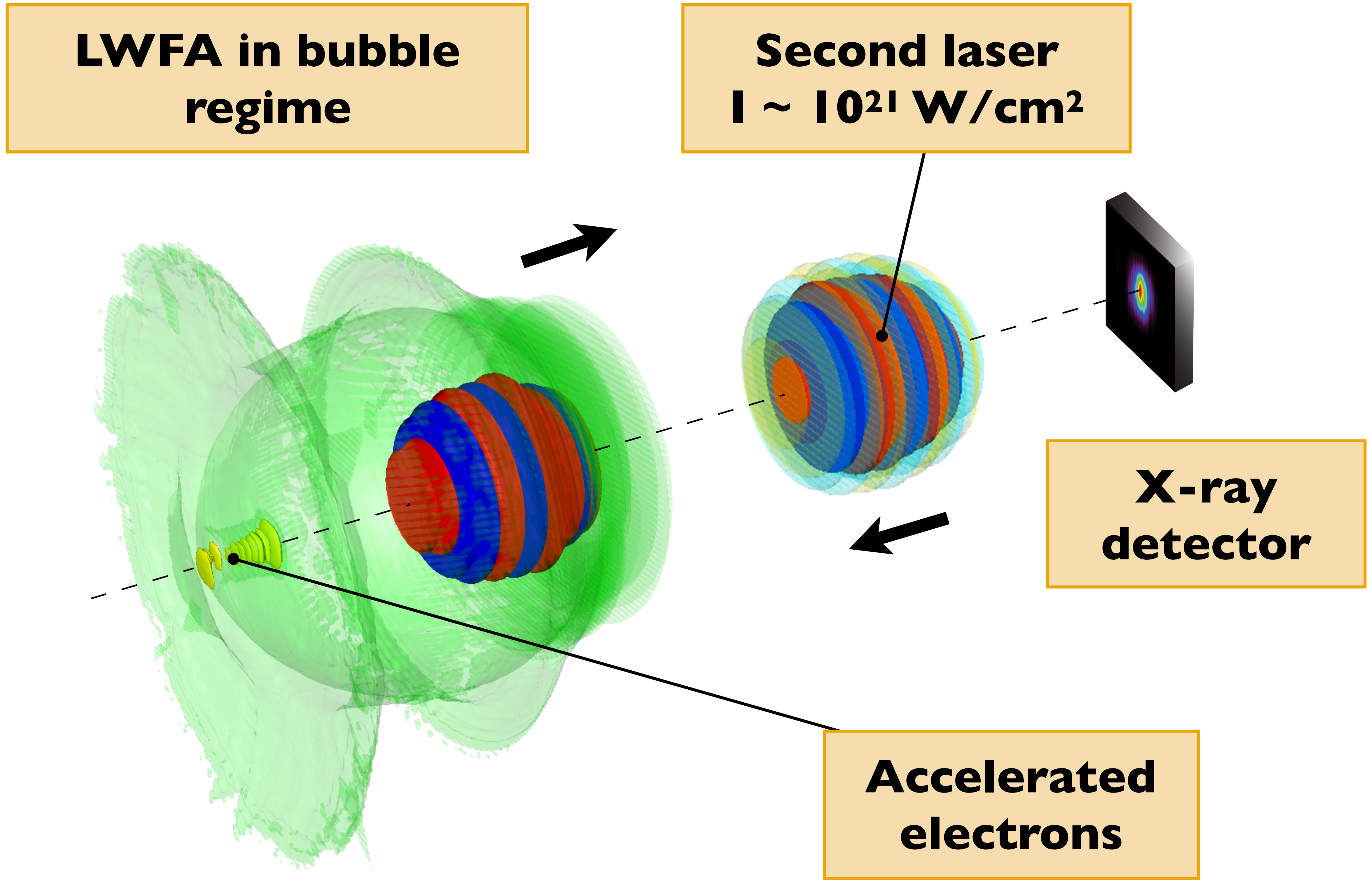
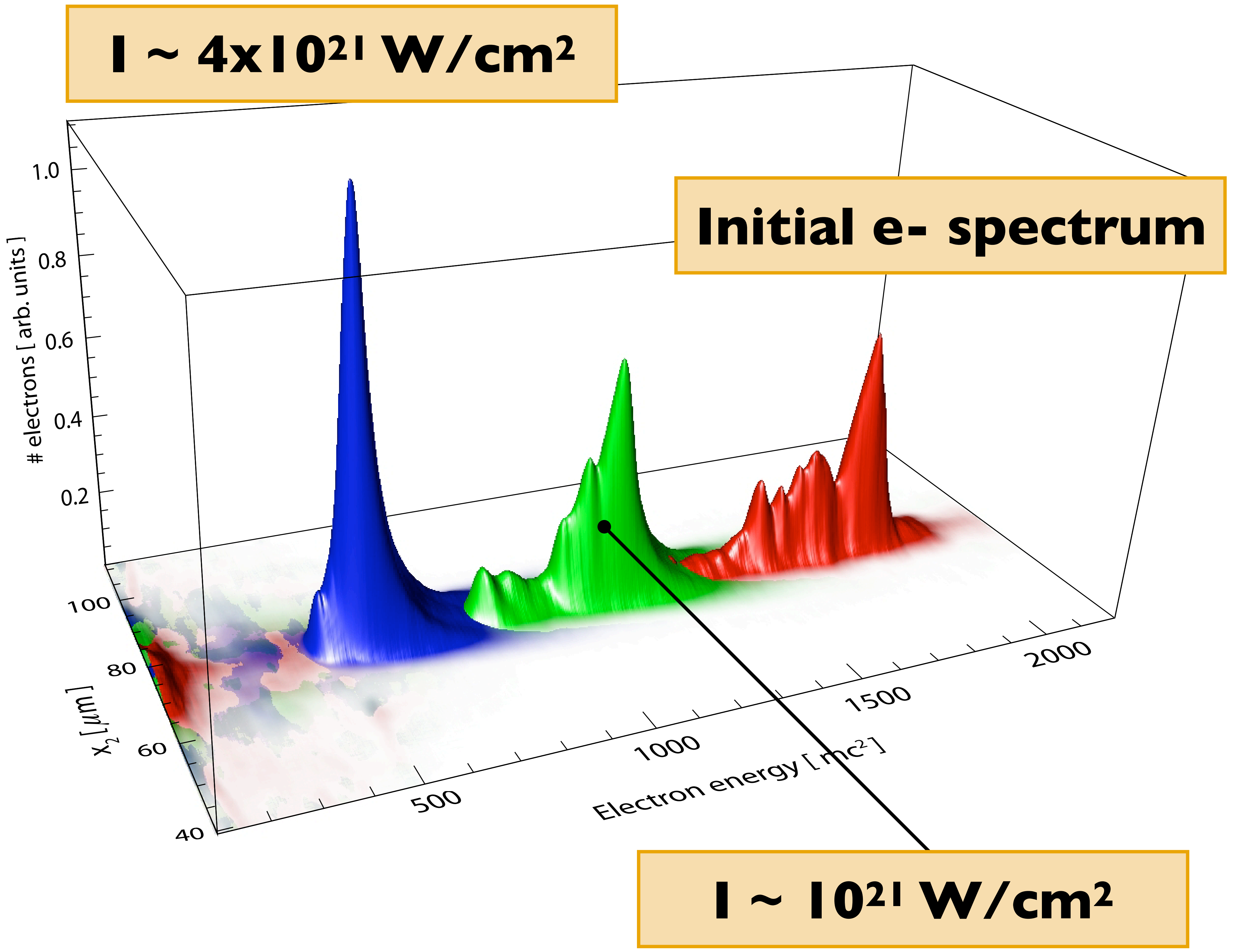
Setup

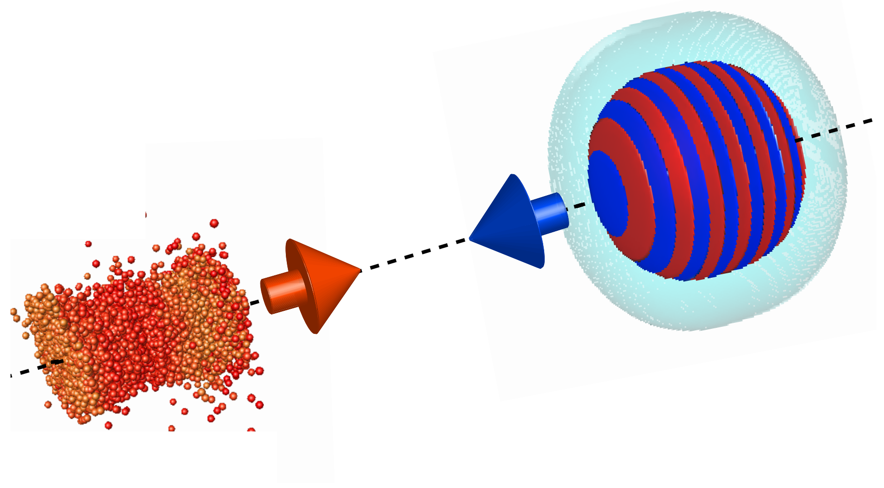


M.Vranic et al., PRL 113, 134801 (2014)
M.Vranic et al., CPC 204, 141-157 (2016)

The electrons lose energy in the emission



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



Classical: $\chi \ll 1$

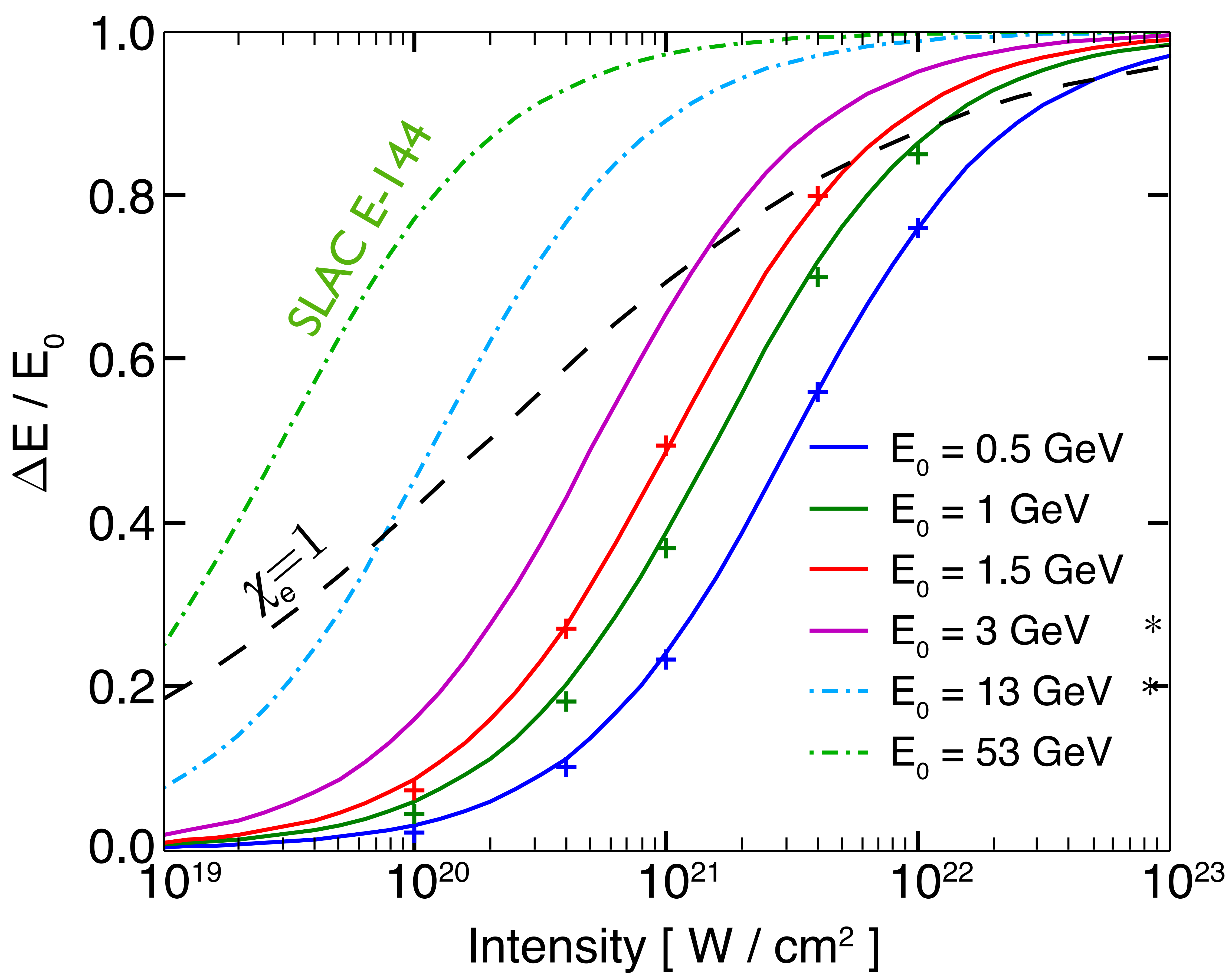
QED: $\chi \simeq 1$

1 µm laser

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

10 µm laser

$$\chi \sim \xi_e \,[\mathrm{GeV}] \times \frac{a_0}{1000}$$



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

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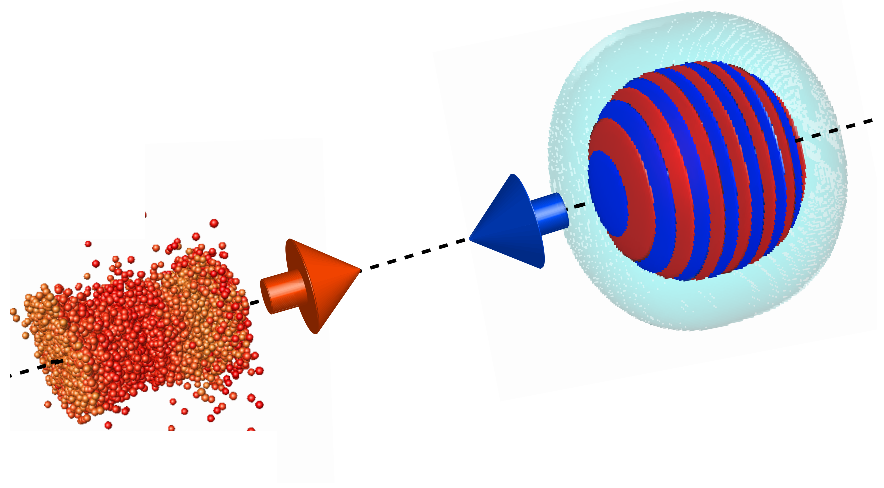

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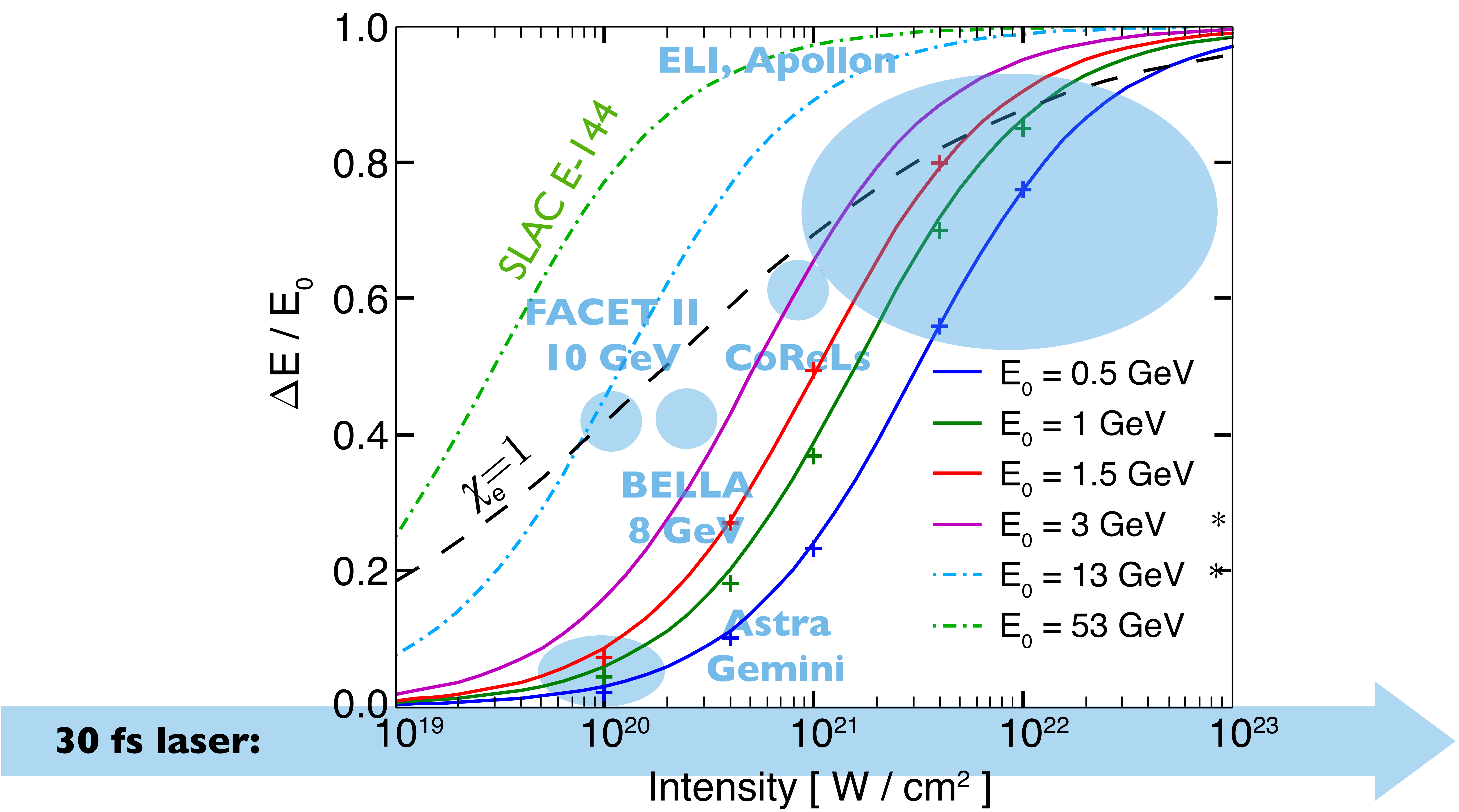

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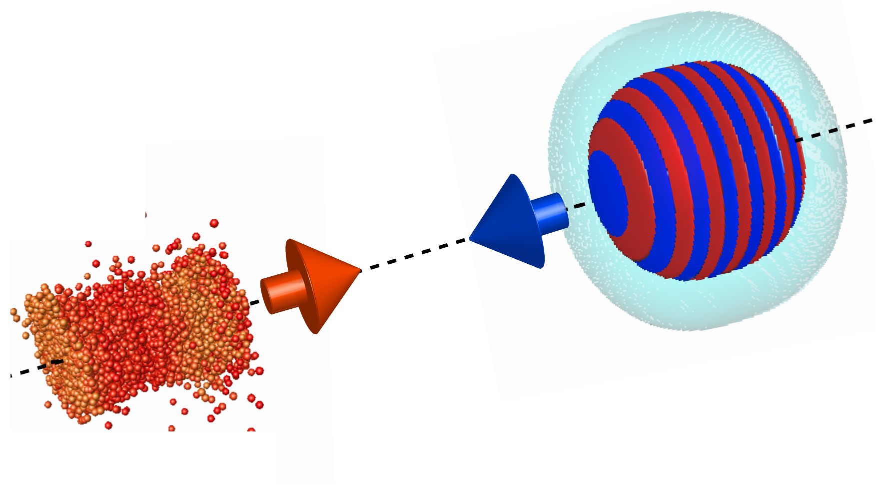

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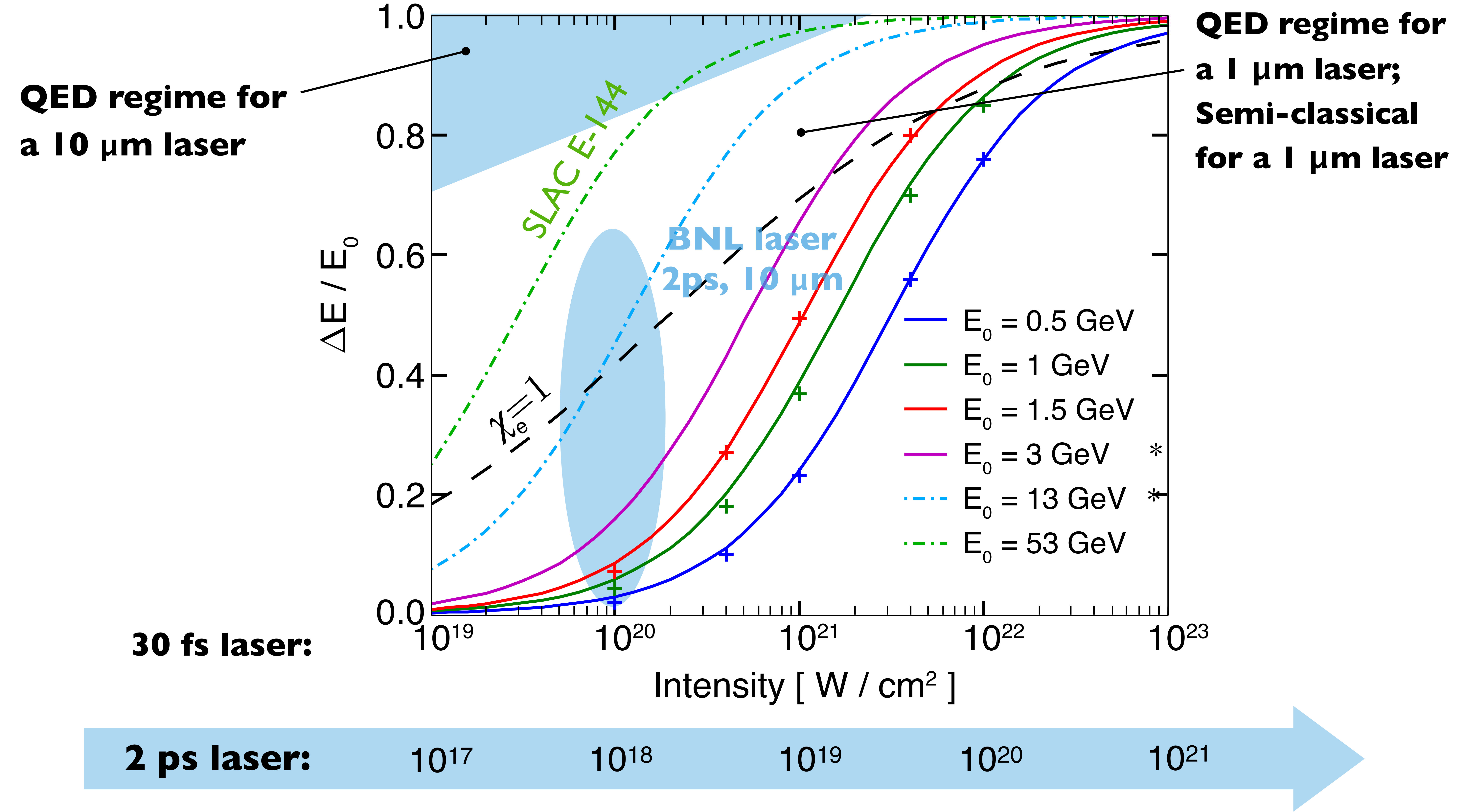
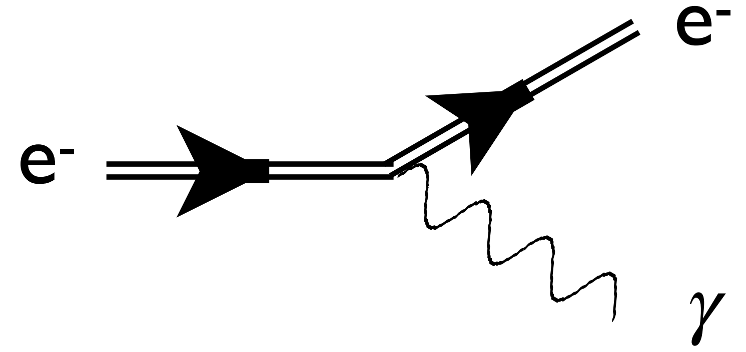


M.Vranic et al., PRL 113, 134801 (2014)

QED radiation and radiation reaction

- Determine the evolution of single electron state in background field + radiation field
- How do we connect the physical picture of classical and QED RR?



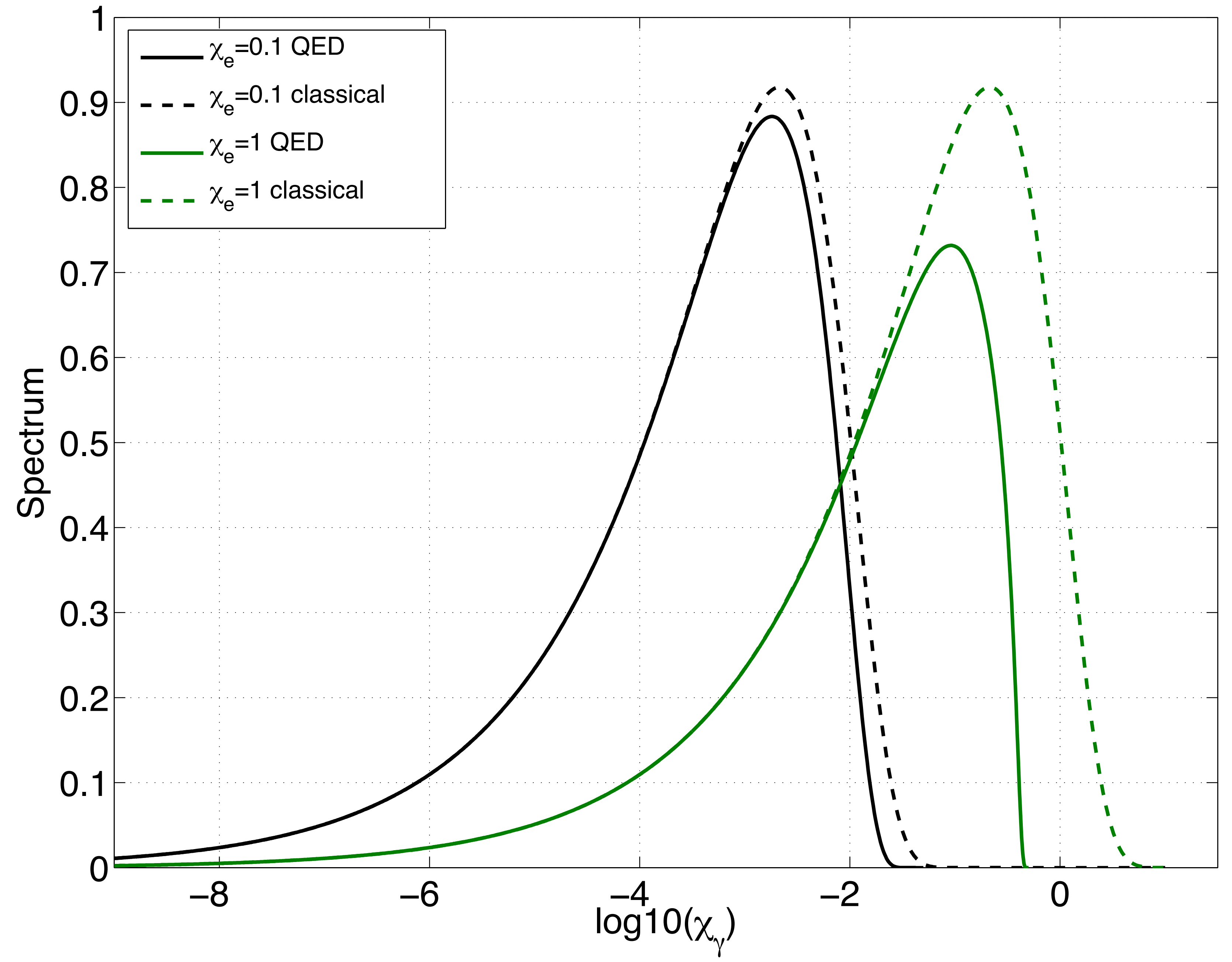
Probability and Spectrum

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

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

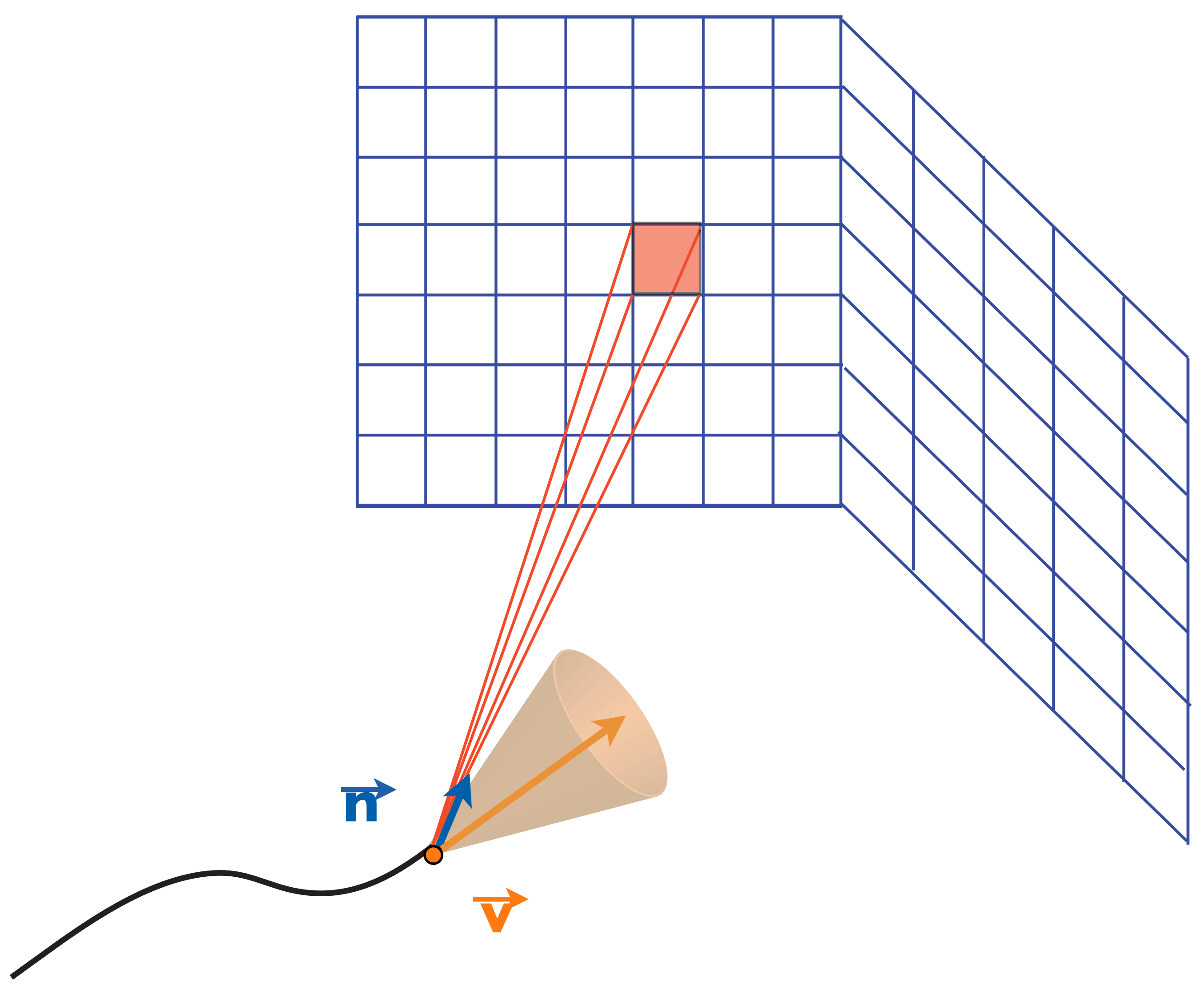
$$\frac{d\mathcal{P}}{dtd\chi_\gamma} = f(\gamma, \chi_e, \chi_\gamma)$$

in strong field, particle emits 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)

Emitted radiation with quantum corrections

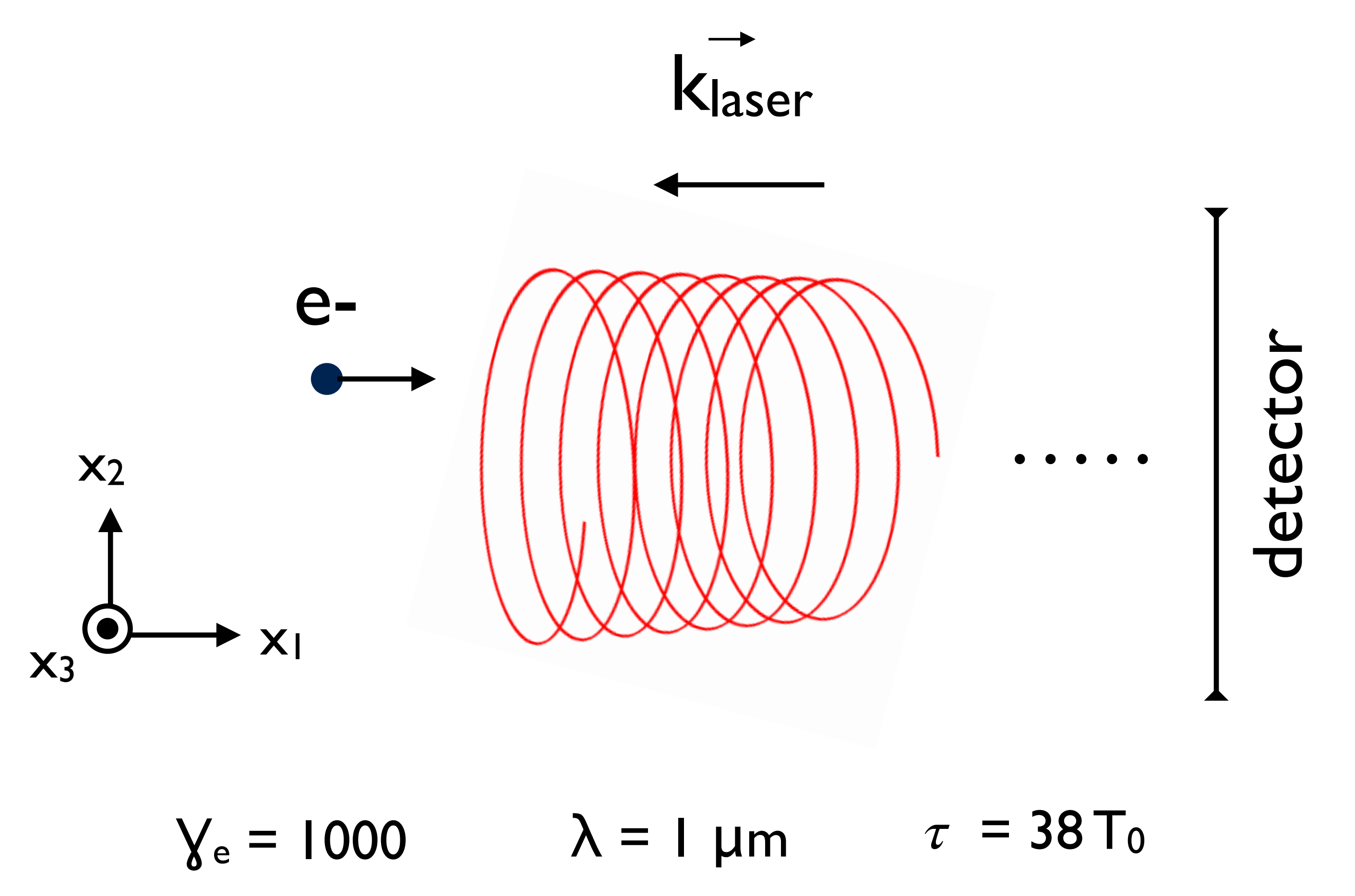


10 µm laser

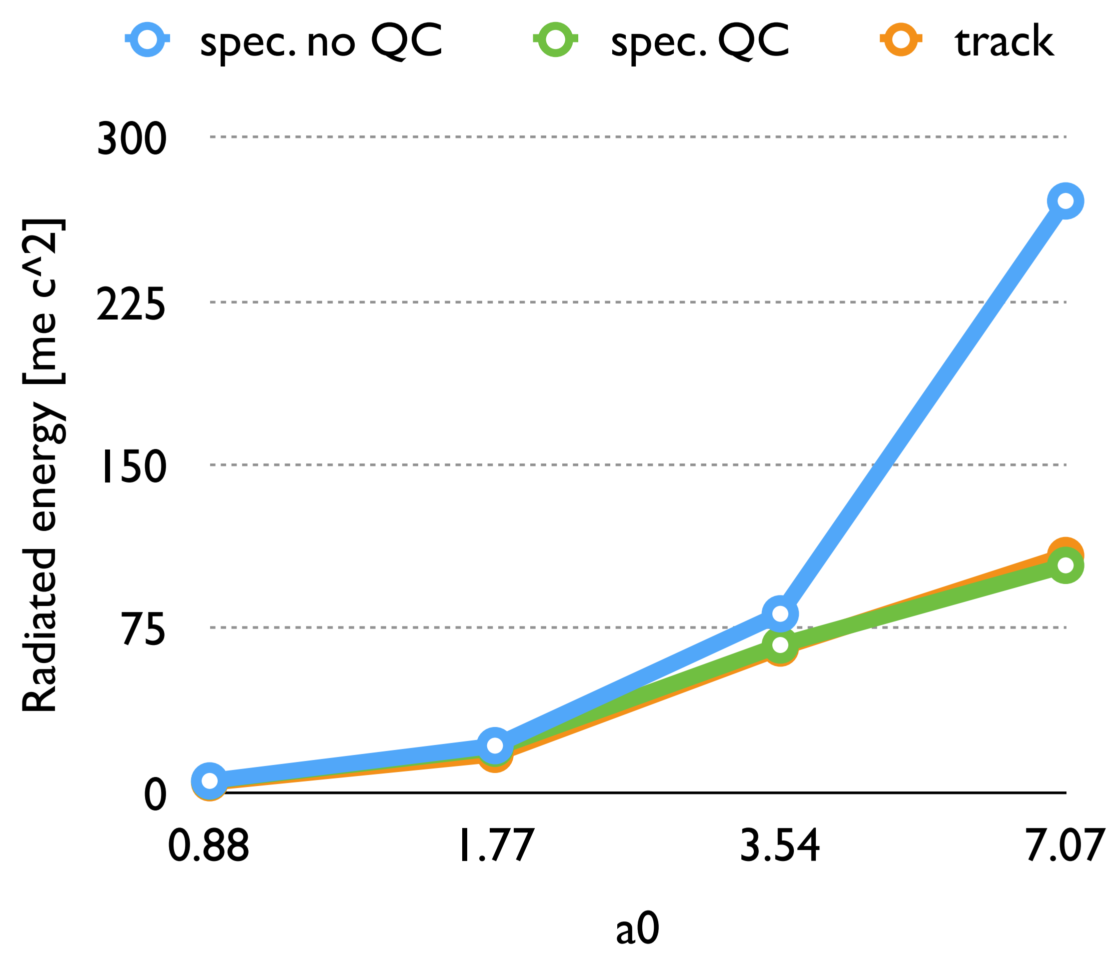
QC in e- emission spectrum important for energy ~ 5 GeV

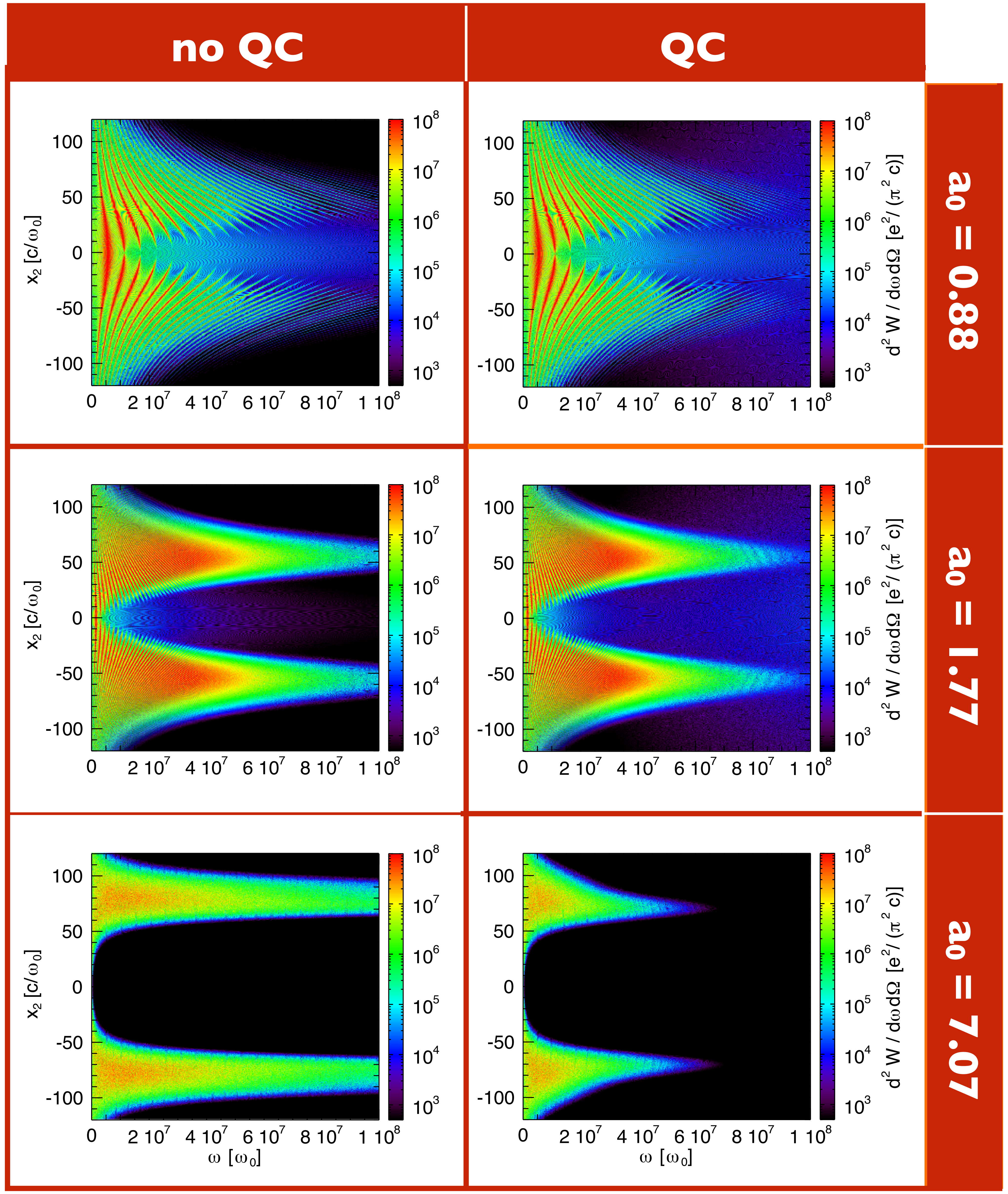
J. L. Martins et al, PPCF (2016)

Circular polarisation plane wave



Total radiated energy





Weakly quantum interaction between 5 GeV electrons and CO_2 laser

$$\gamma_F \simeq \frac{\gamma_0}{1 + k\gamma_0}$$

$$k = 3.2 \times 10^{-5}\, I_{22}\, \tau_0[\mathrm{fs}]\, (1 - \cos\theta)^2$$

$$I_{22} = I_0[10^{22}\ \mathrm{W/cm^2}]$$

$$\sigma_F[mc^2] \lesssim \left(\frac{1.5 \times 10^{-4} I_{22}^{1/2}\, \gamma_0^3}{(1 + 6.1 \times 10^{-5} \gamma_0\, I_{22}\, \tau_0[\mathrm{fs}])^3} \right)^{1/2}$$

$$\theta_F \simeq \sqrt{\frac{2}{\pi}} \frac{a_0}{\gamma_F^2}\, \sigma_F$$

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

For a 5 GeV beam + 2ps laser at a_0=10

Expected energy loss: **20%**

Expected stochastic spreading of the electron distribution function: **10%**

Additional divergence due to stochasticity: **0.1 mrad**

Conclusions

Scattering of relativistic electrons with a CO_2 laser will be in the nonlinear Thompson regime at $1<a_0<10$.

Analytical theory covers QED and fully classical regime. There is an on-going discussion regarding what happens in the transition regime.

Scattering experiments using a CO_2 laser may be able to provide valuable insight regarding the nonlinear, weakly quantum (or semi-classical) interaction.