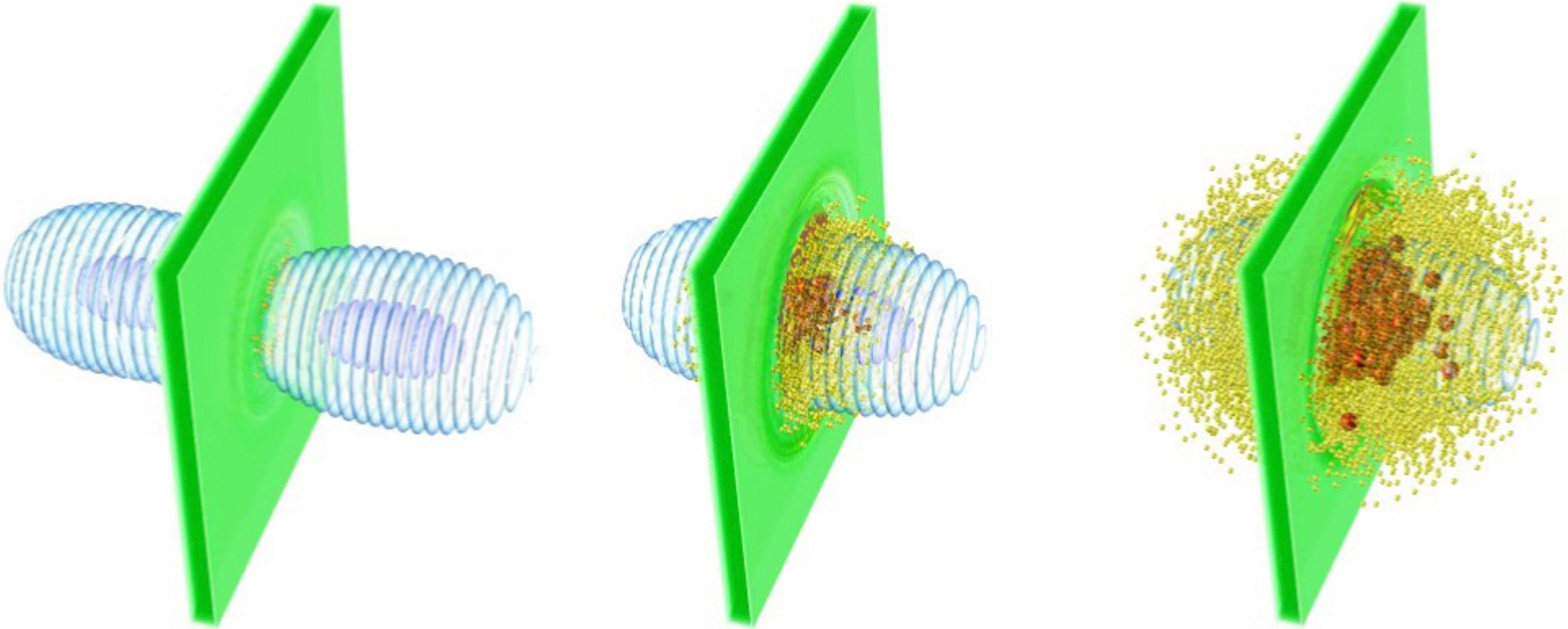
# Laser-Electron Collisions and Laser-Plasma Interaction in QED Regime

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

Work in collaboration with:

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

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

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

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

PRACE

Supported by the
Seventh Framework
Programme of the
European Union

eli

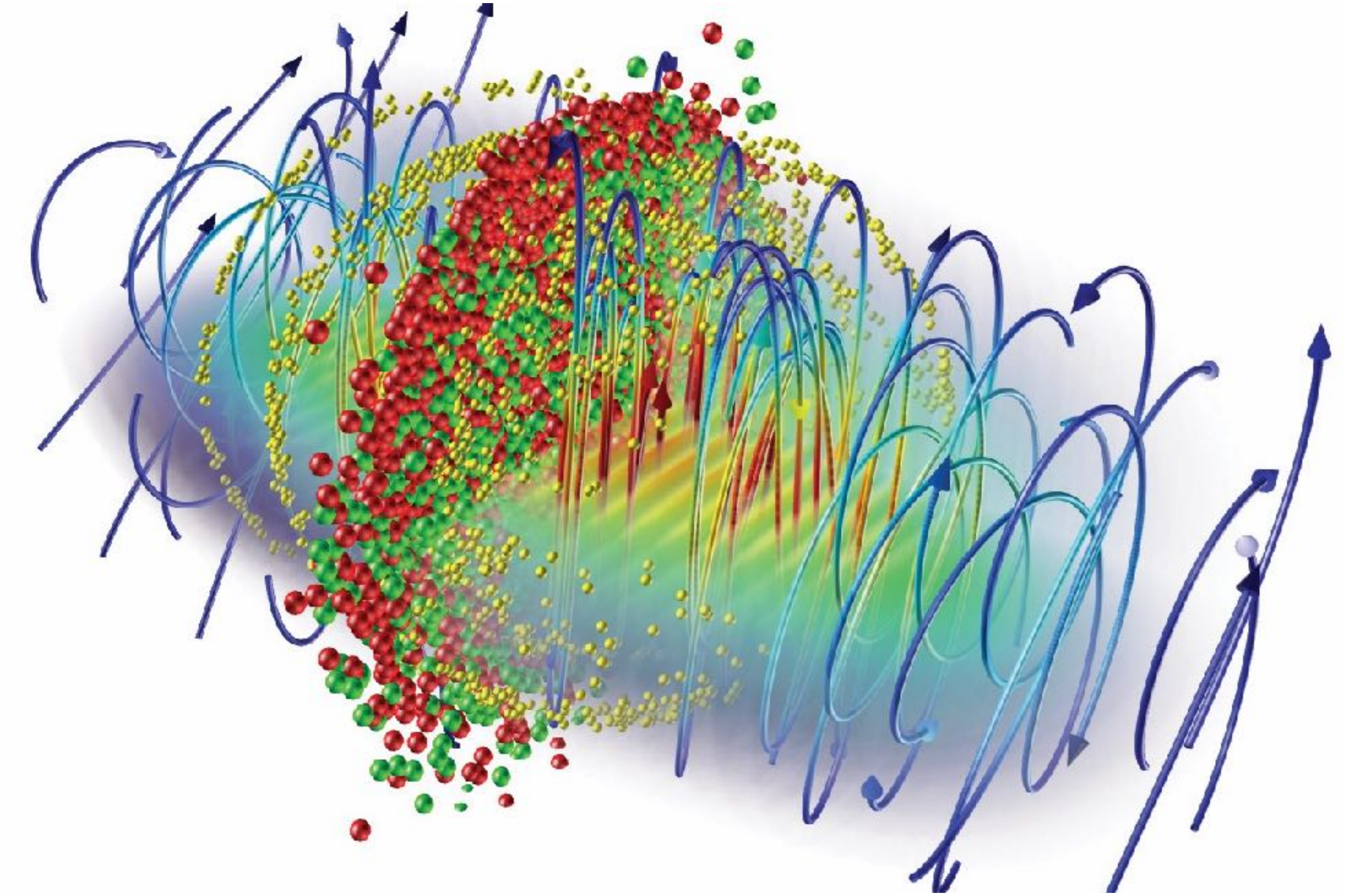
IT4I

RES
RED ESPAÑOLA DE SUPERCOMPUTACIÓN

RNCA
REDE NACIONAL DE COMPUTAÇÃO AVANÇADA

FCCN
UNIDADE DA FCT
Tecnologia para o Conhecimento

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



- relativistic particles
- radiation reaction
- anomalous radiative trapping
- 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

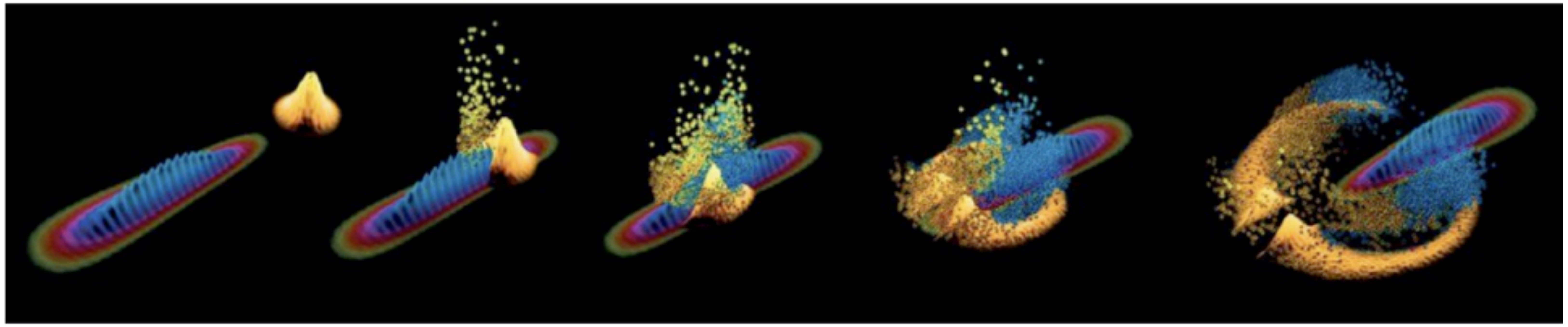


Image: Marija Vranic, European Physical Society Conference official poster 2018

In magnetospheres of neutron stars

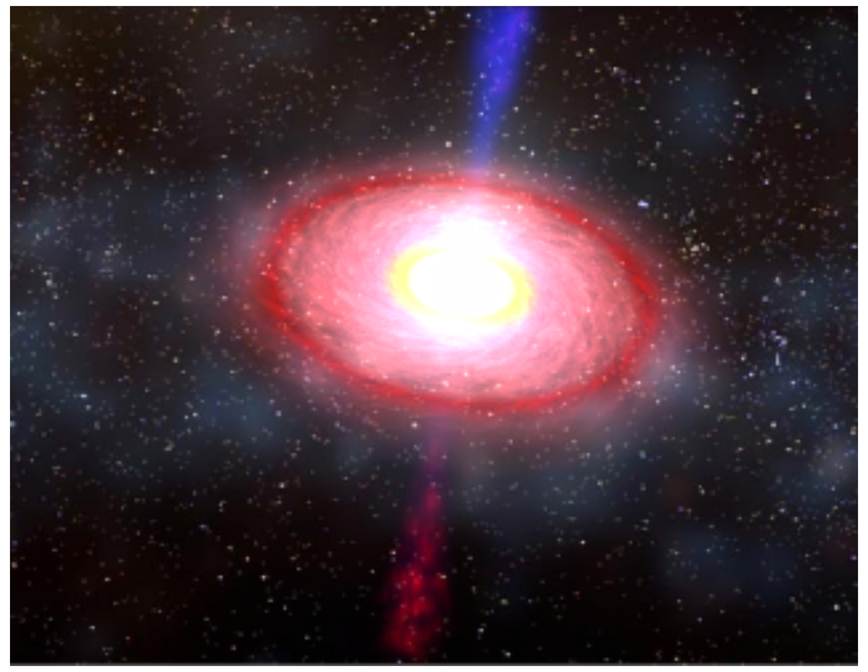


Image: Dana Berry / NASA

Around black holes

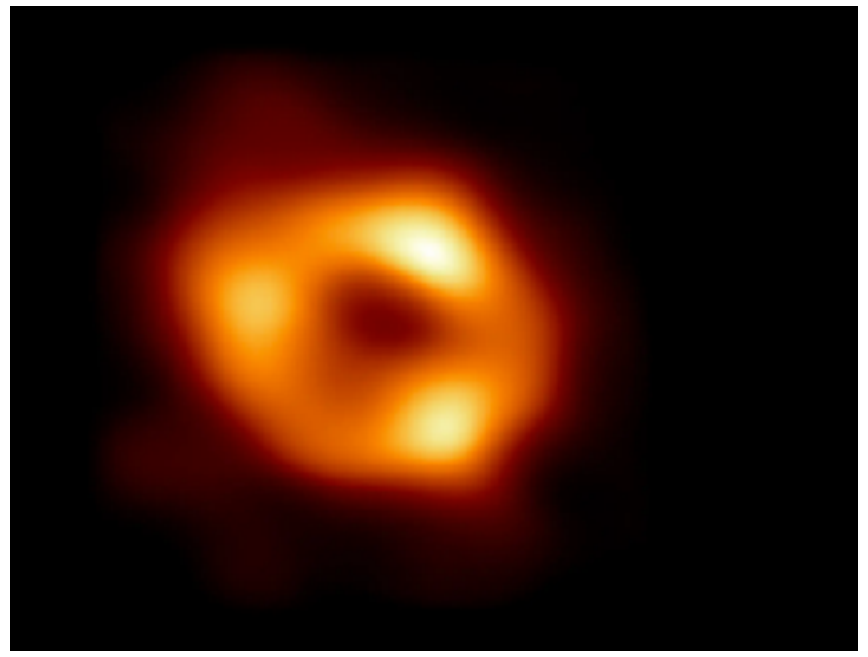
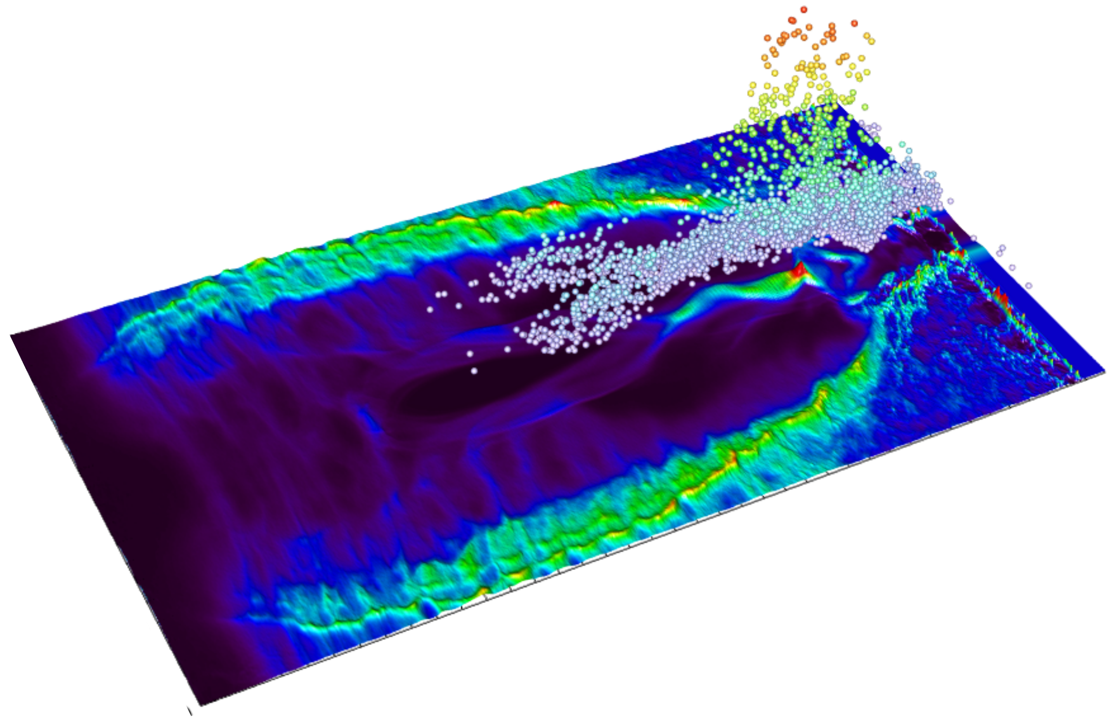


Image: Event Horizon Telescope collaboration, Sgt A*

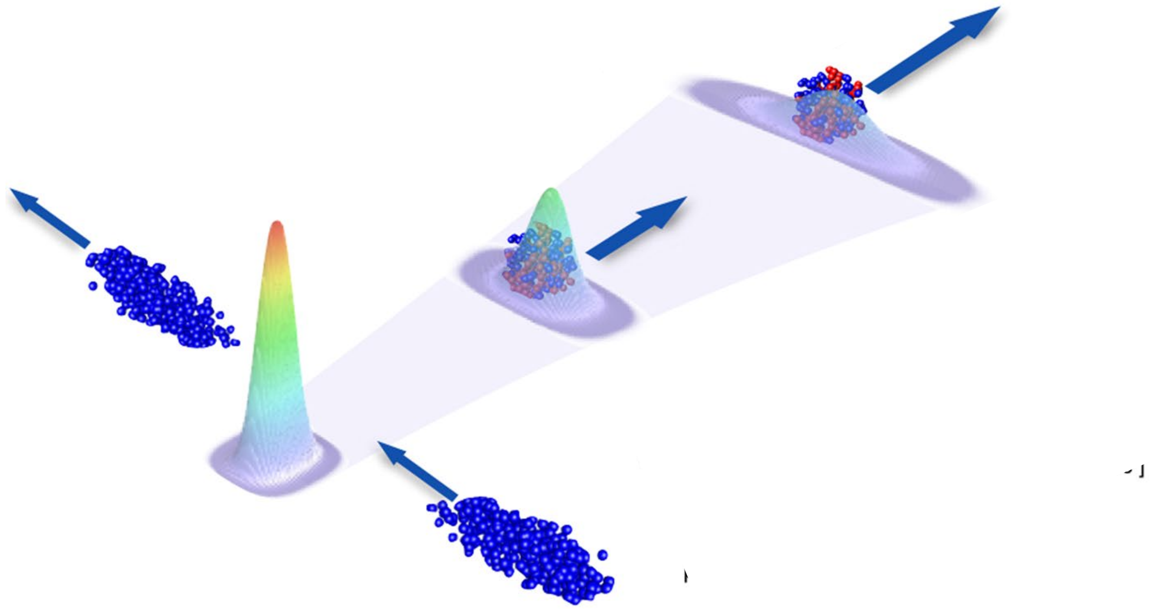
# Why should we care?

**There are both fundamental and practical open questions**

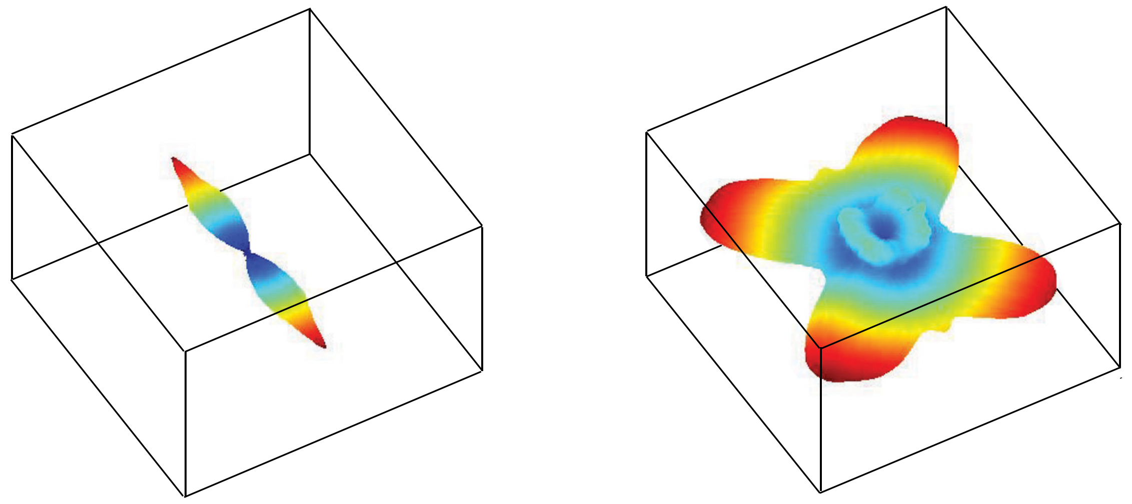
- What is the maximum allowed field before the breakdown of the vacuum?
- Can we make particle acceleration in plasmas better with extreme laser intensities? Are there paradigm shifts?
- Can we transform cascades to positron sources? Maybe they could serve as injectors for electron-positron colliders?
- 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

- Classical radiation reaction
- Quantum radiation reaction
- Pair creation and acceleration

# 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 & $\gamma$-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 $a_0 = \frac{eE_0}{m\omega c}$

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

- 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

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

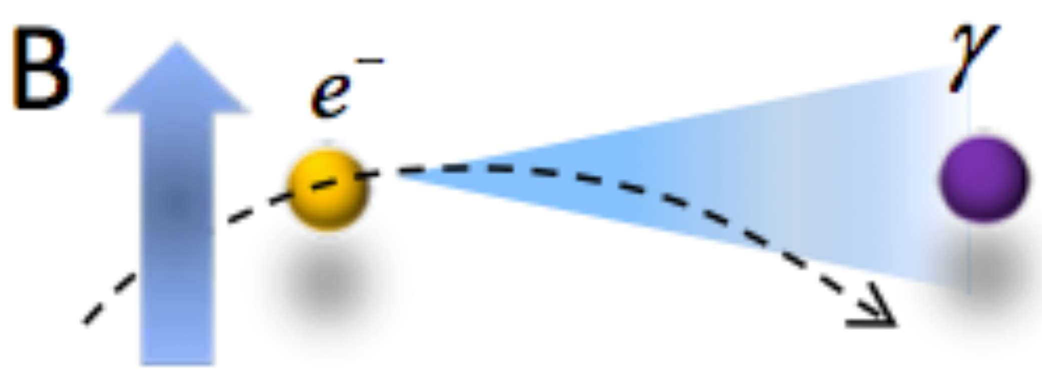
# Threshold for QED processes is attainable with lasers

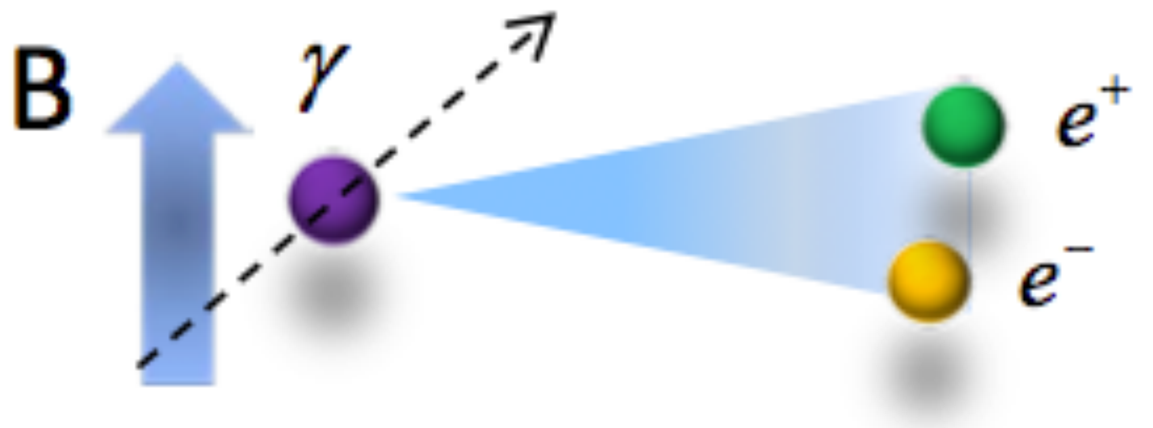
**Schwinger critical field**

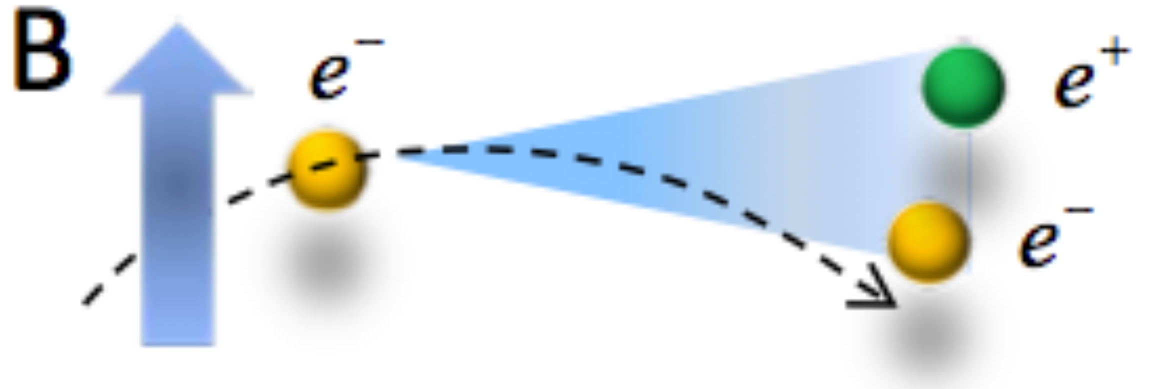
$$E_S = \frac{m^2c^3}{e\hbar}$$

- 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

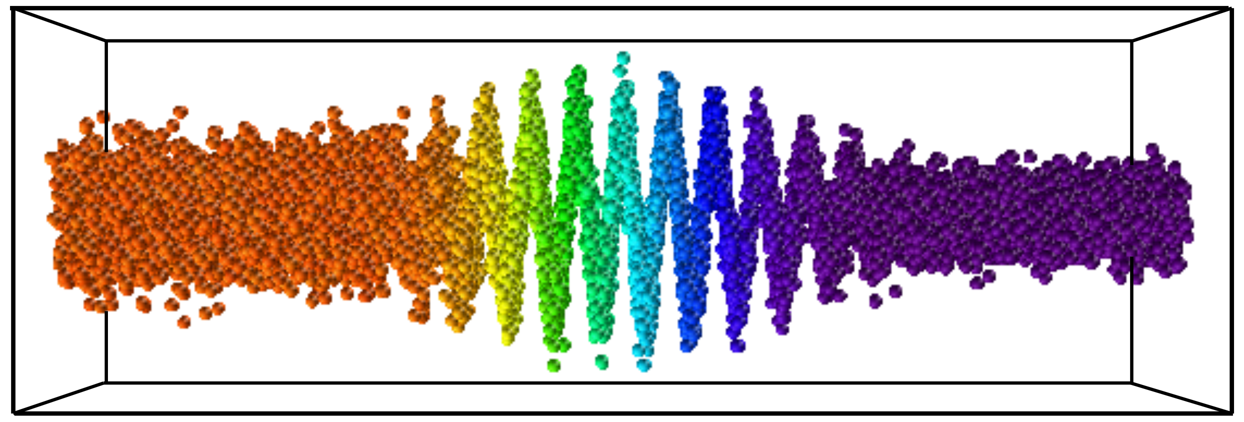
Credit: M. Lobet, B. Martinez

# What new features are needed for plasma modeling at extremes?

## 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

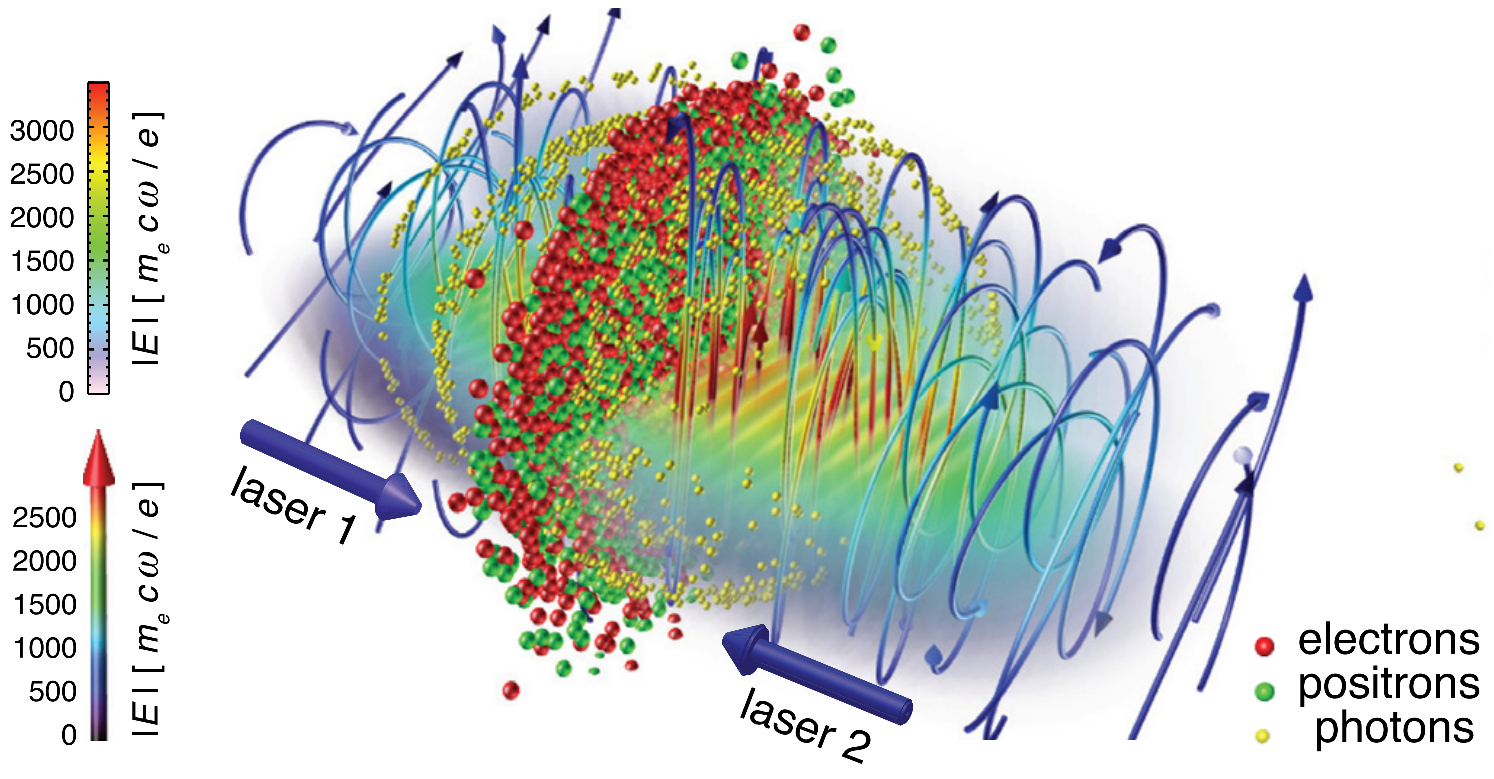
M.Vranic et al., PRL (2014); M.Vranic et al., CPC (2016); M.Vranic et al, PPCF (2018)



## 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

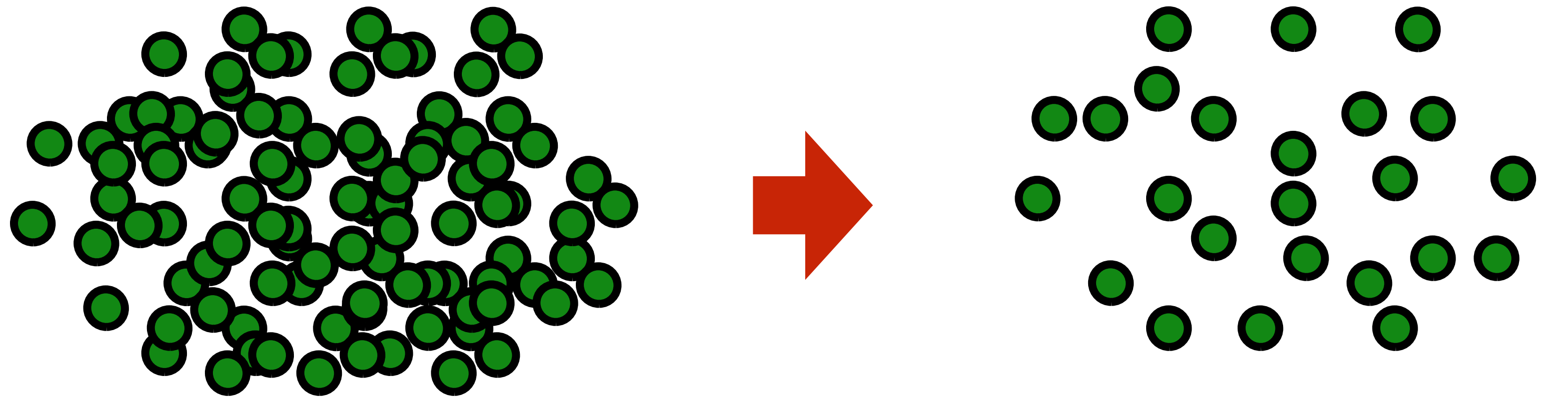
M.Vranic et al, NJP (2016); T. Grismayer et al, POP (2016); T. Grismayer et al, PRE (2017); J. L. Martins et al, PPCF (2016); M.Vranic et al, PPCF (2017); M.Vranic et al, SciRep (2018);



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

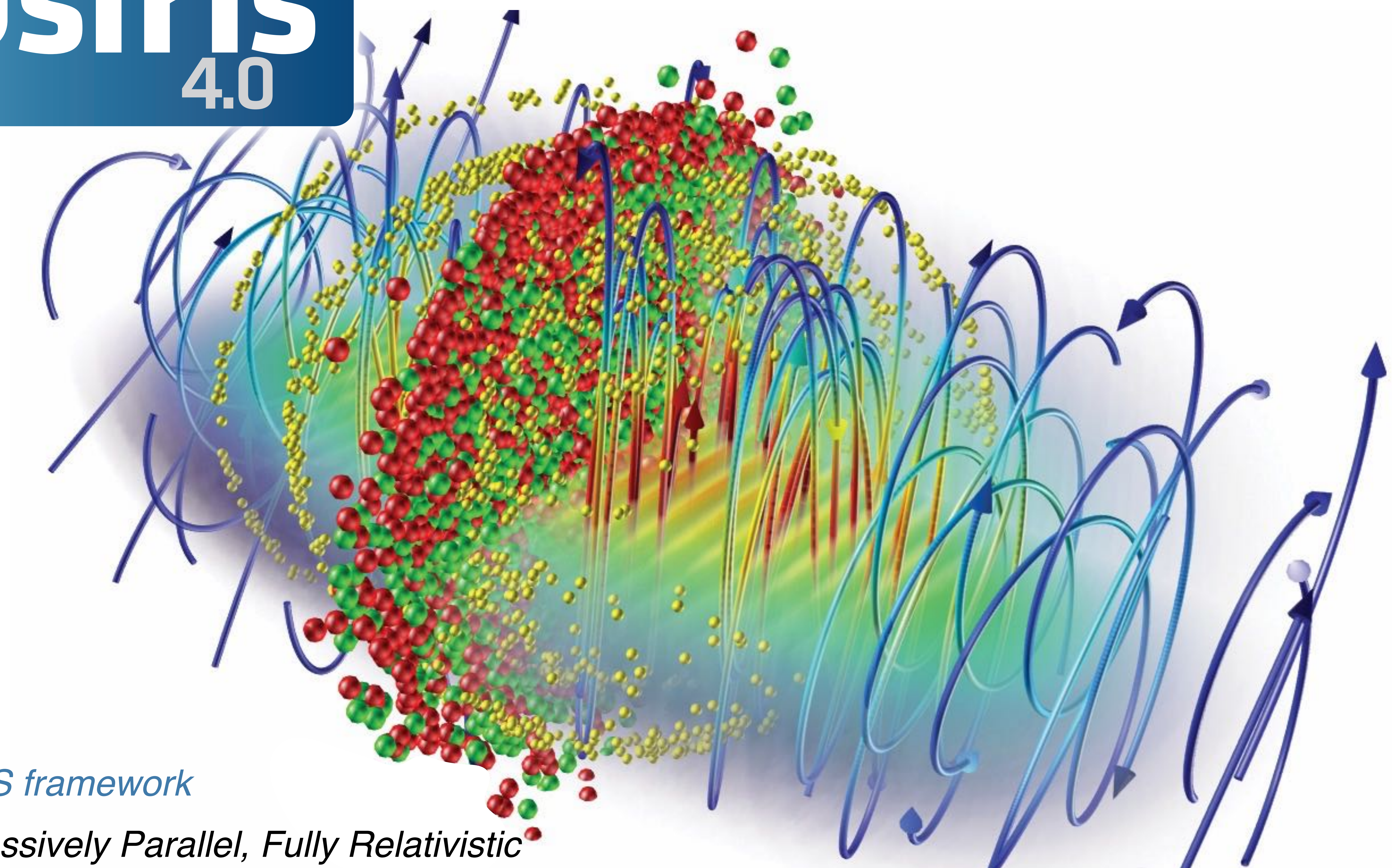
- Essential for all the projects with strong QED effects

M.Vranic et al., CPC (2015)



# Contents

- Classical radiation reaction
- Quantum radiation reaction
- Pair creation



## 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
- Extended physics/simulation models

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

# Classical radiation reaction + particle-in-cell algorithm

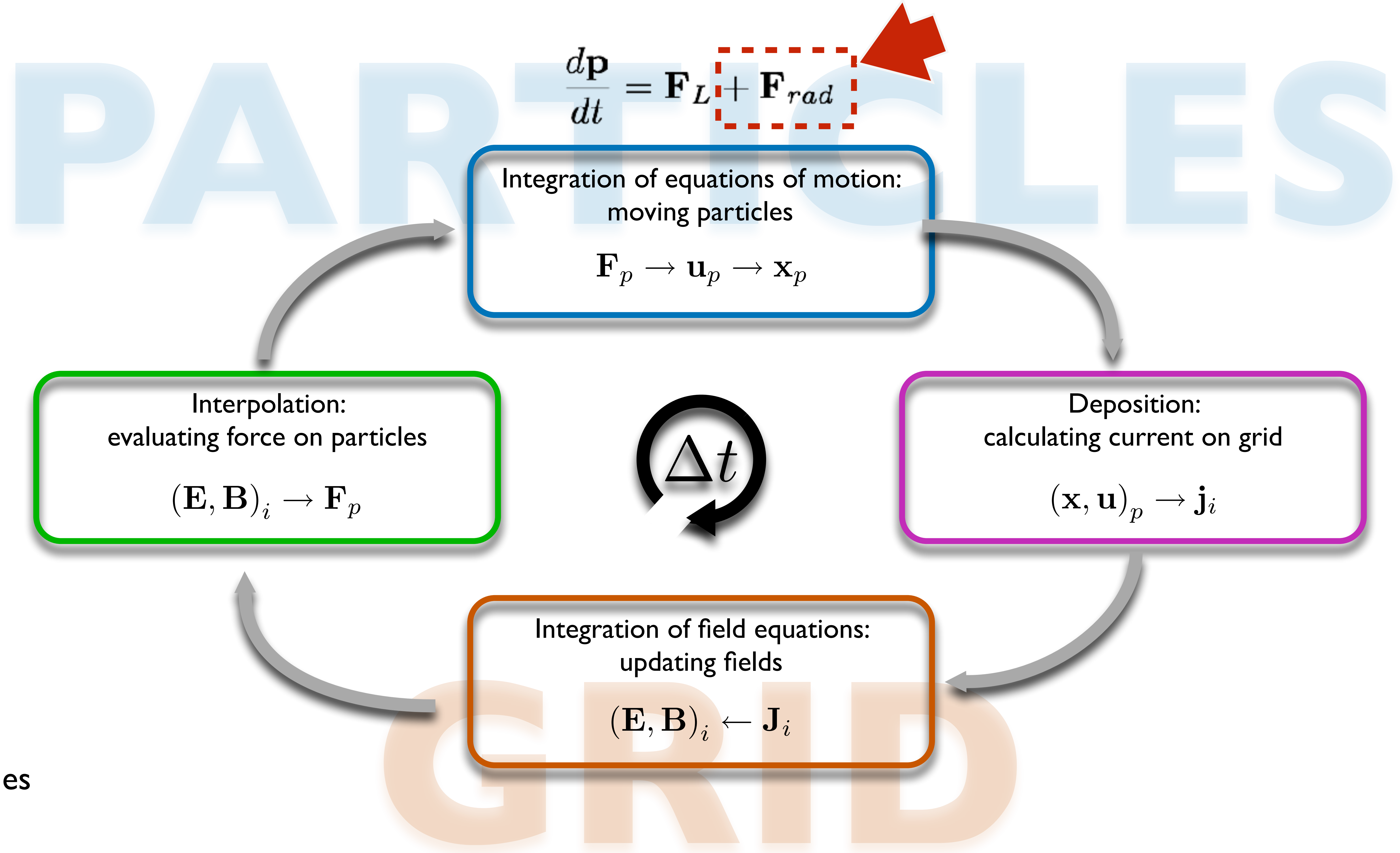
TÉCNICO LISBOA

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

Osiris 4.0

TÉCNICO LISBOA

UCLA



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

Integration of equations of motion:
moving particles

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

Deposition:
calculating current on grid

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

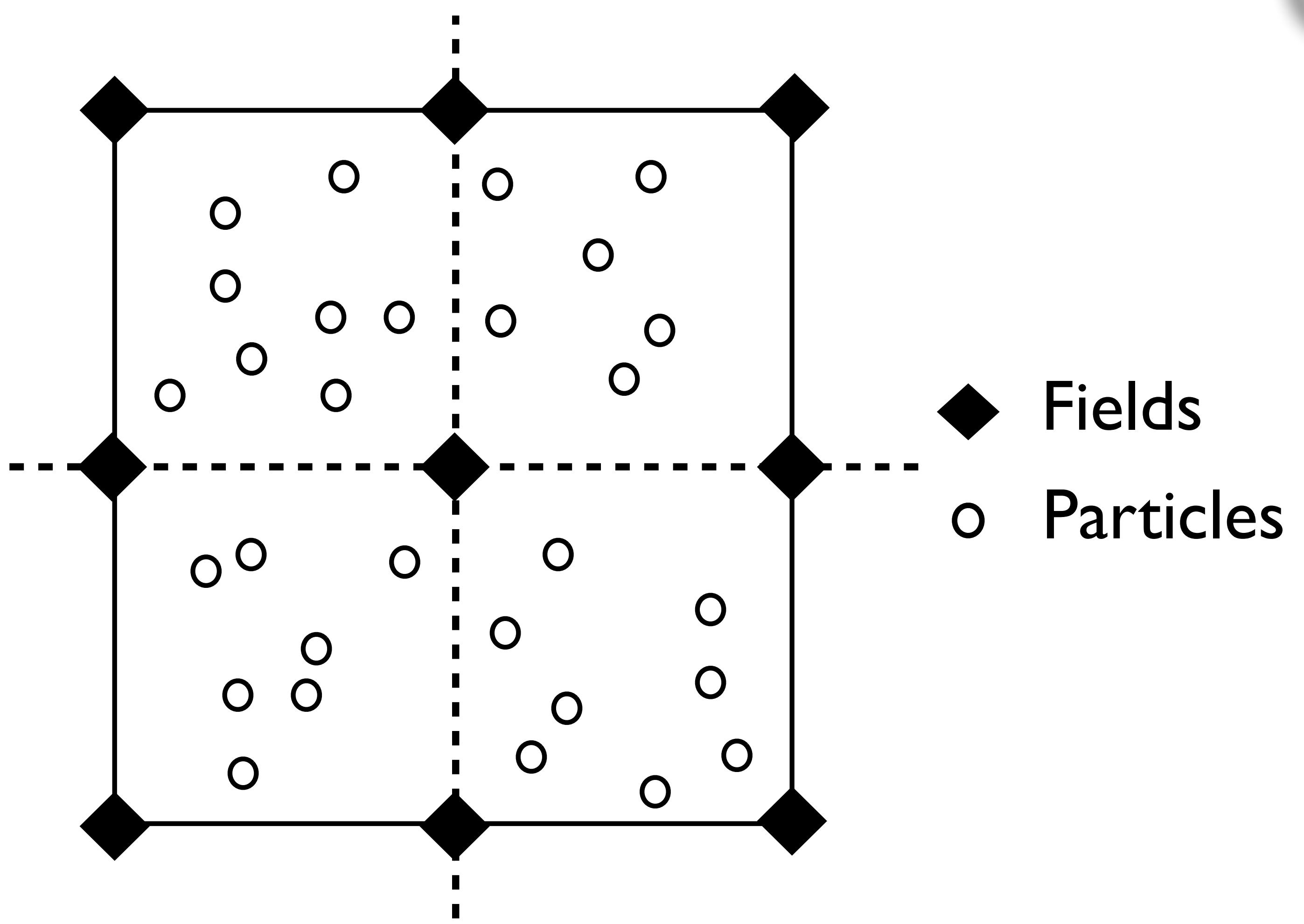
$$\Delta t$$

Integration of field equations:
updating fields

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

Interpolation:
evaluating force on particles

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

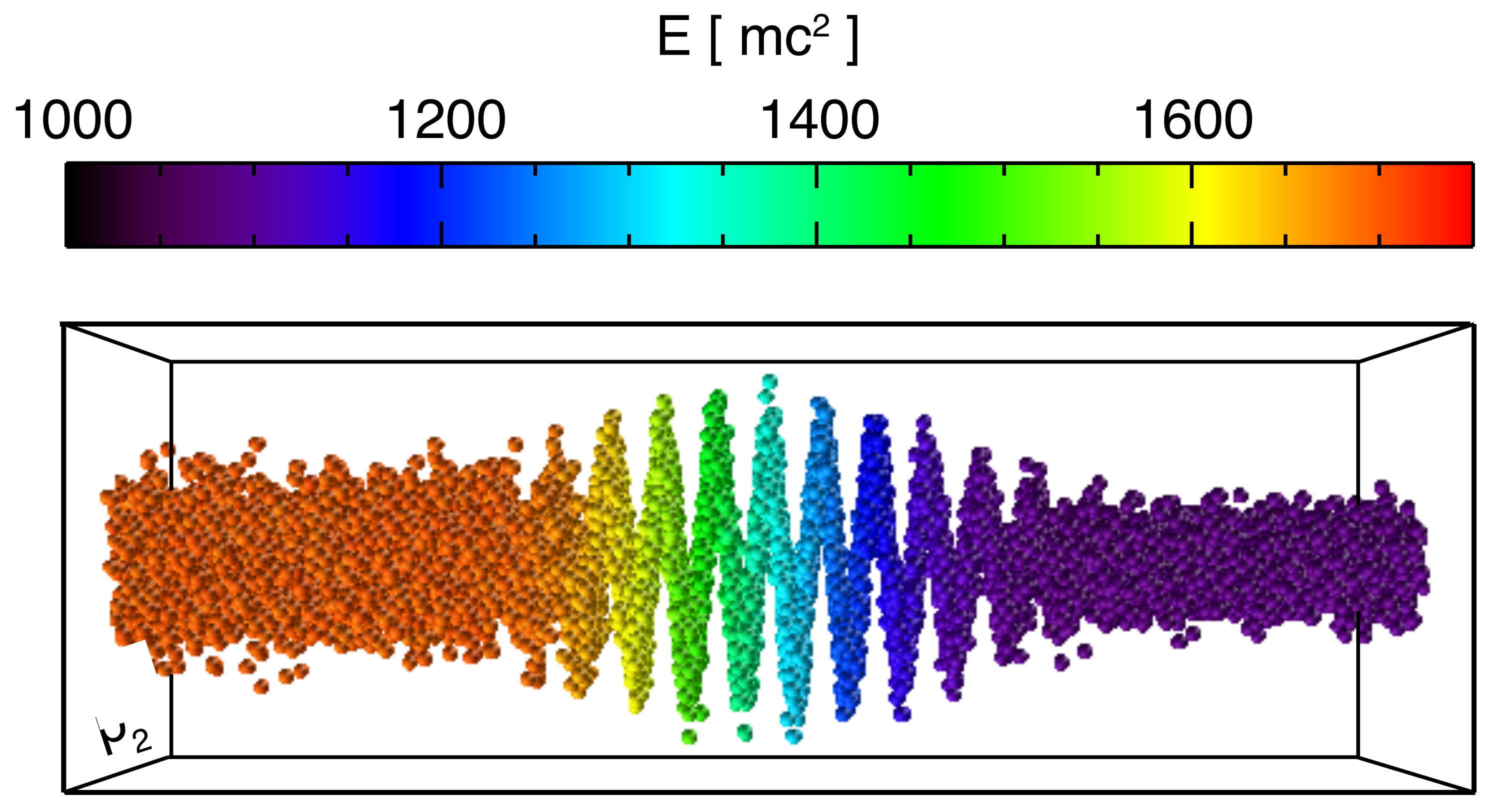


# Radiation reaction in classical electrodynamics

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

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

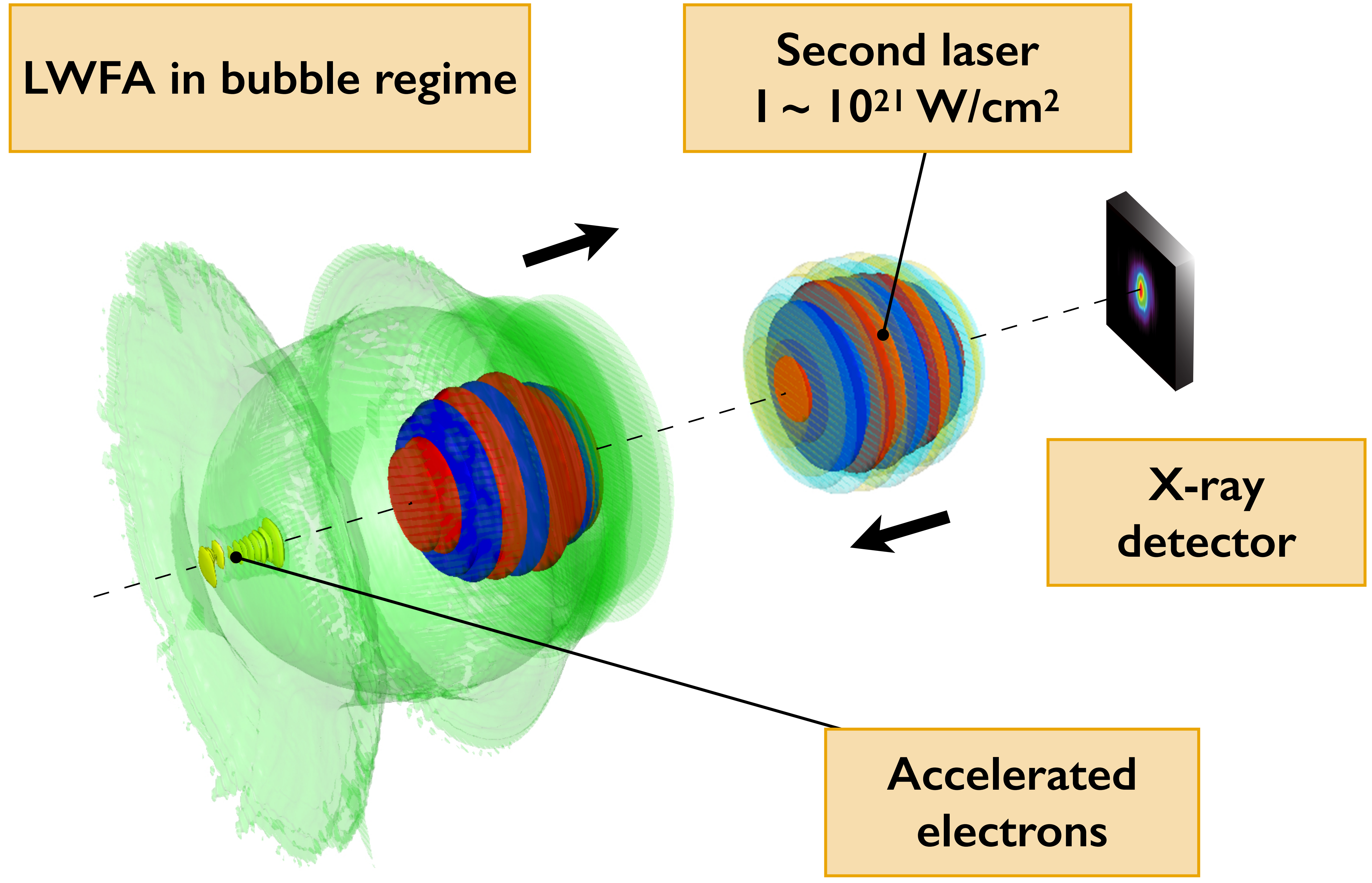
for laser-solid $I > 10^{22} W/cm^2$

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

# 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

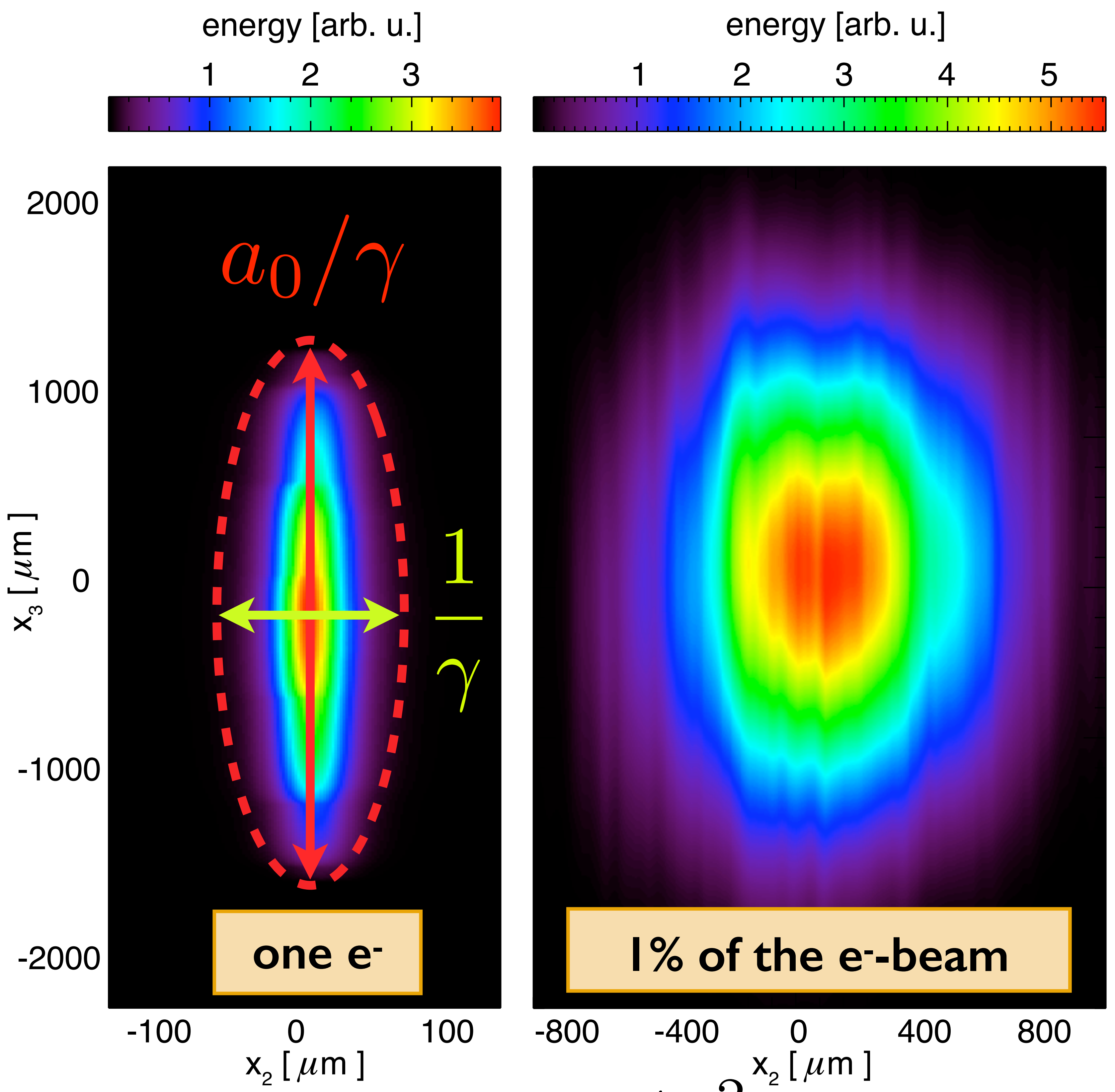
Second laser
I ~ $10^{21}$ W/cm$^2$

X-ray detector

Accelerated electrons

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

## Output radiation on the virtual detector

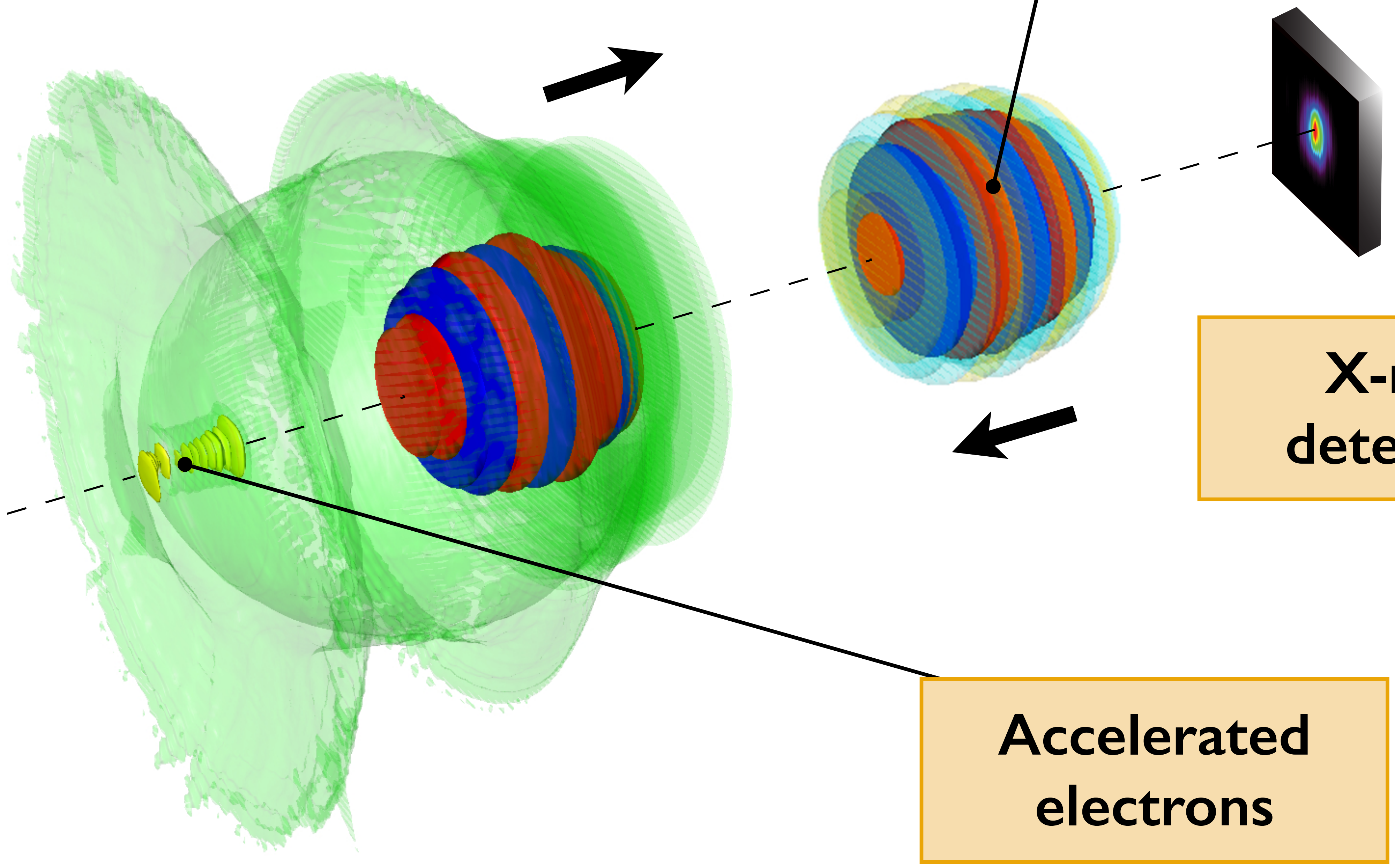


$$\frac{\omega_R}{\omega_L} = \frac{4\gamma^2}{a_0^2/2+1}$$

# 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

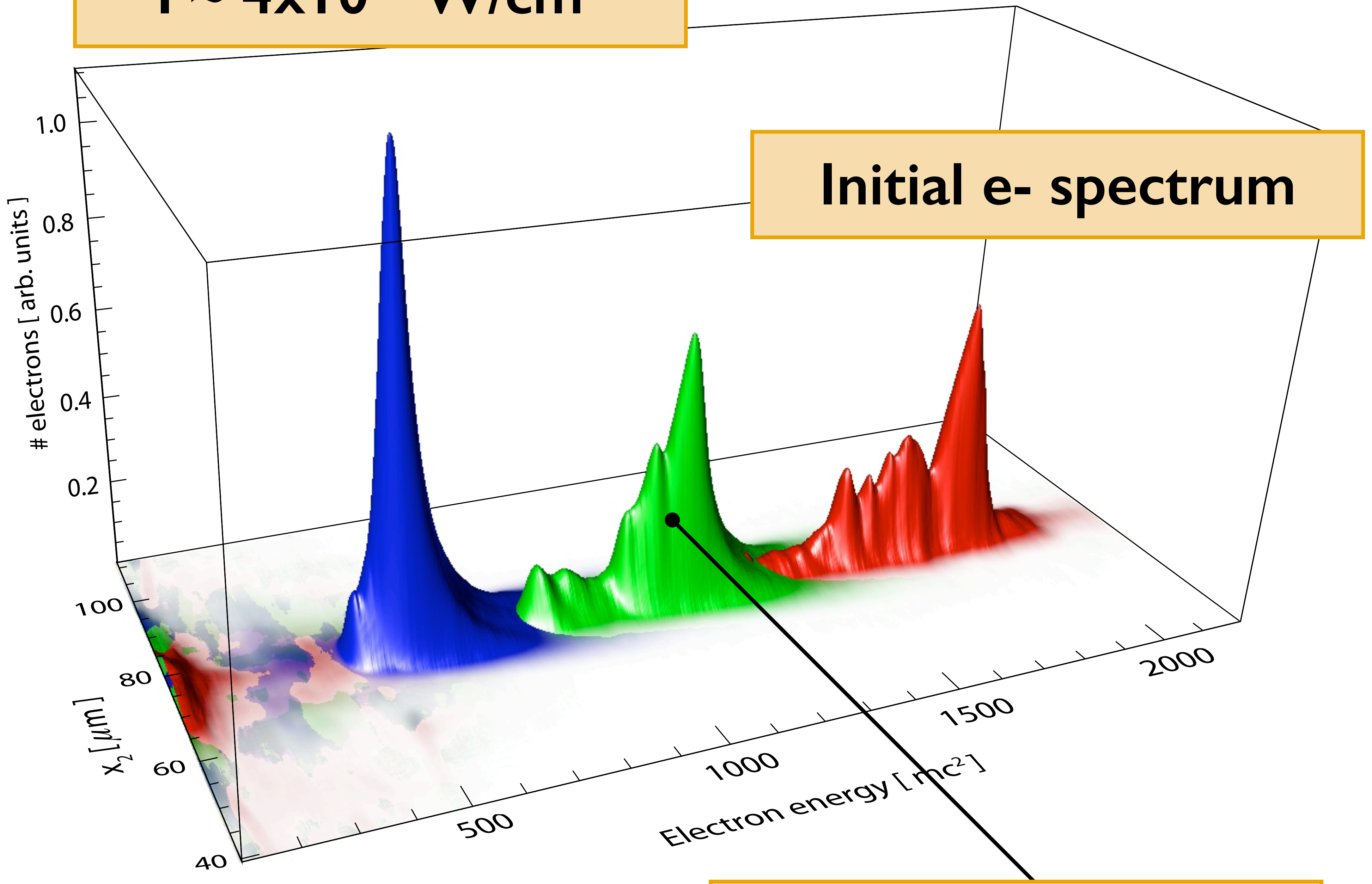
Second laser
I ~ $10^{21}$ W/cm$^2$

X-ray
detector

Accelerated
electrons

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

## The electrons lose energy in the emission



I ~ 4x$10^{21}$ W/cm$^2$

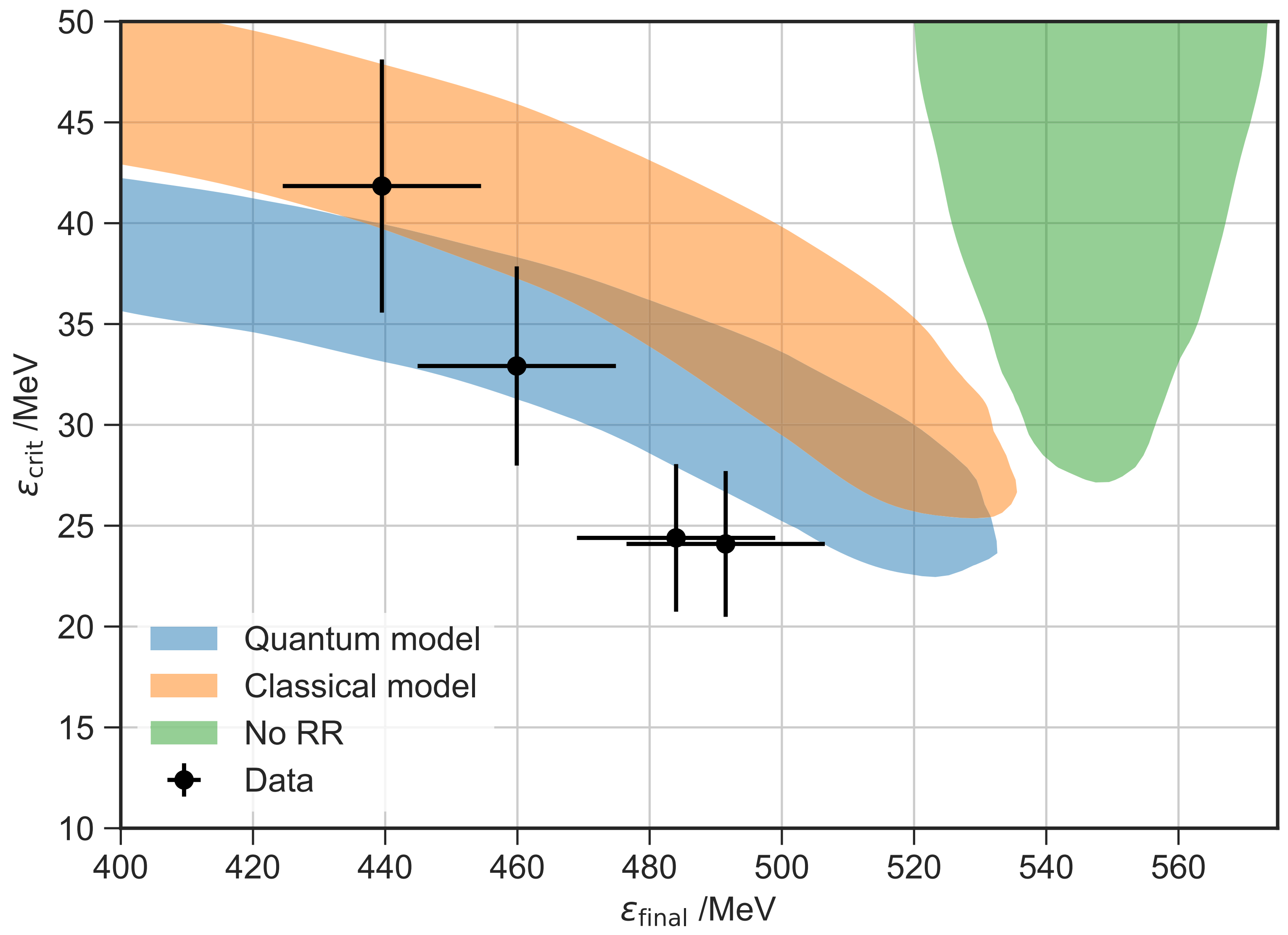
Initial e- spectrum

I ~ $10^{21}$ W/cm$^2$

# Recent experiments show slowdown

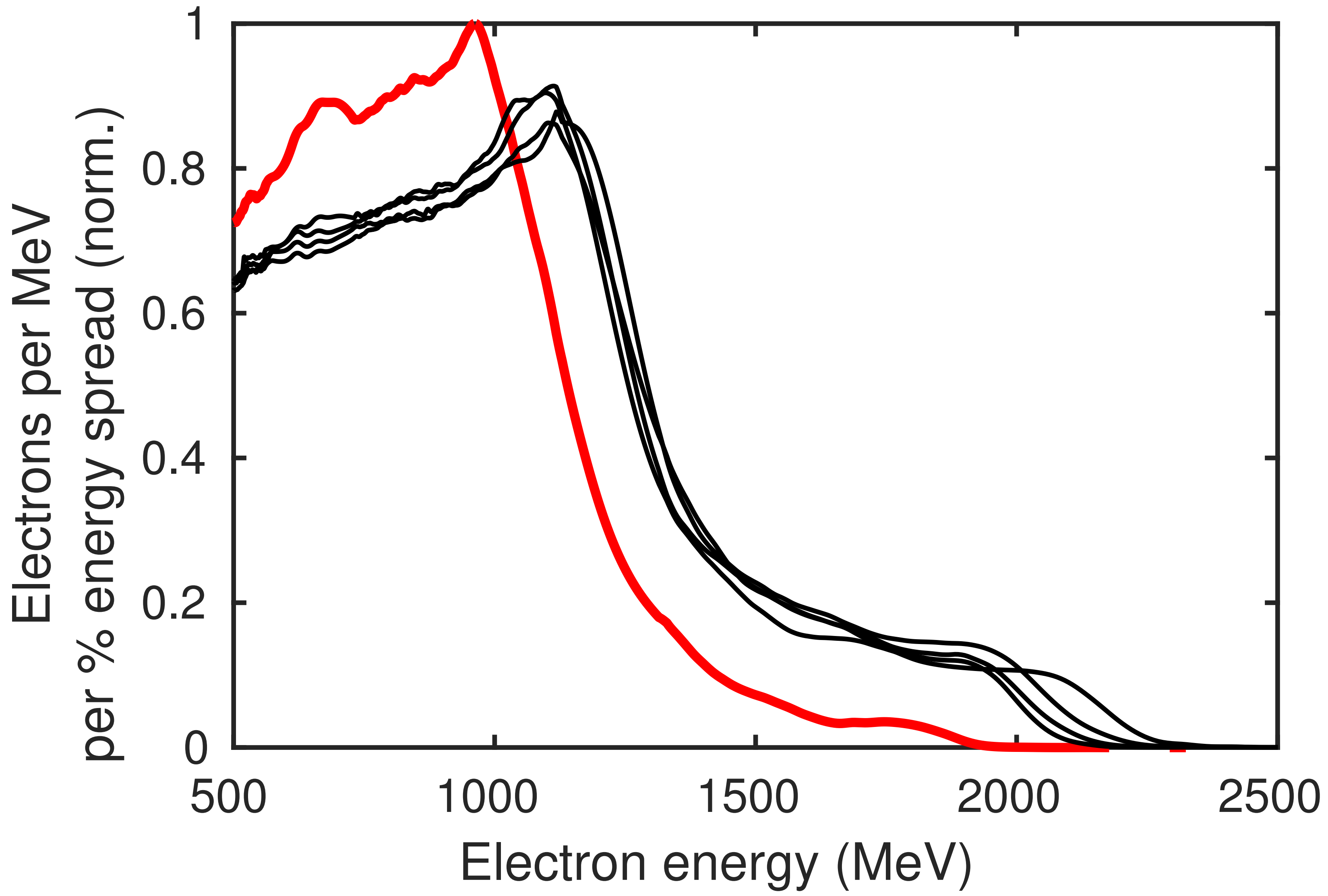
**Broad or unstable initial electron spectrum makes it difficult to get reliable quantitative measurements, of the slowdown or the energy spread.**

## Photon emission



J. Cole et al., PRX 8, 011020 (2018)

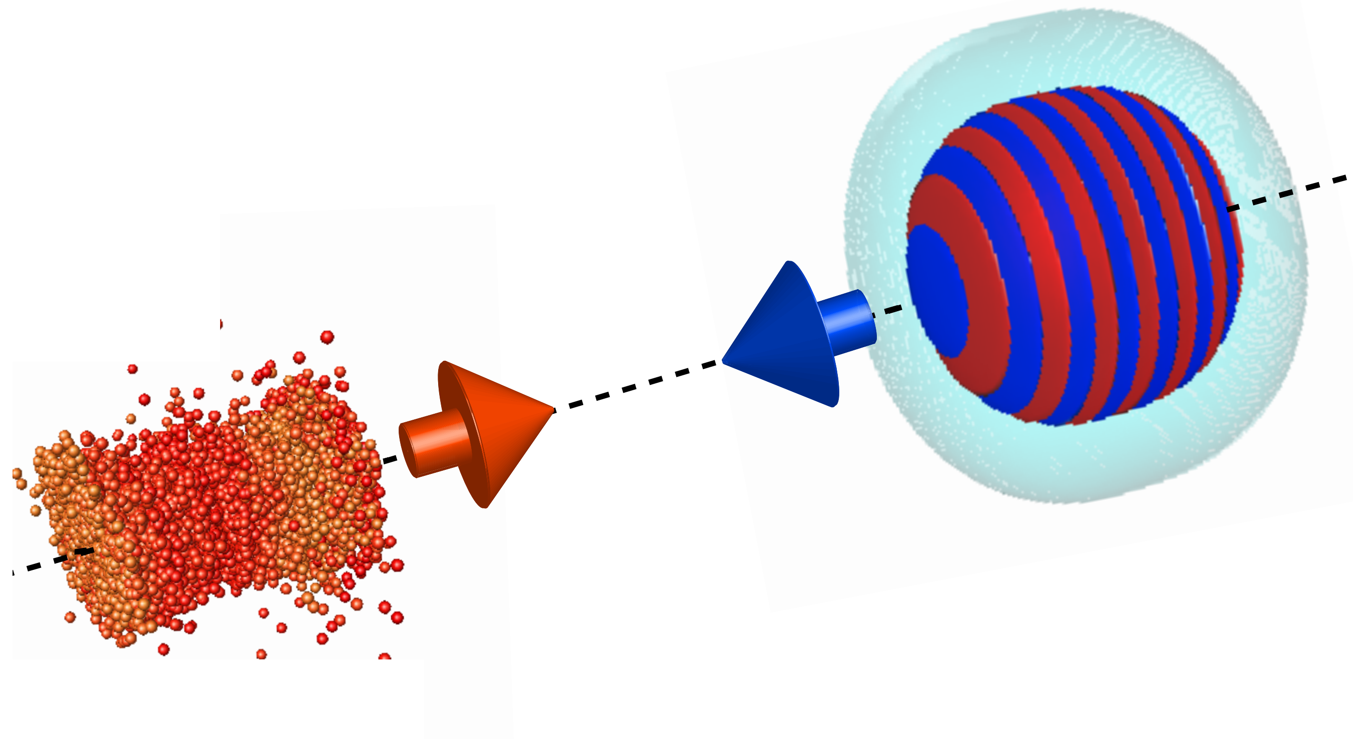
## Electron spectrum



K. Poder et al., PRX (2018)

# 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)**



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

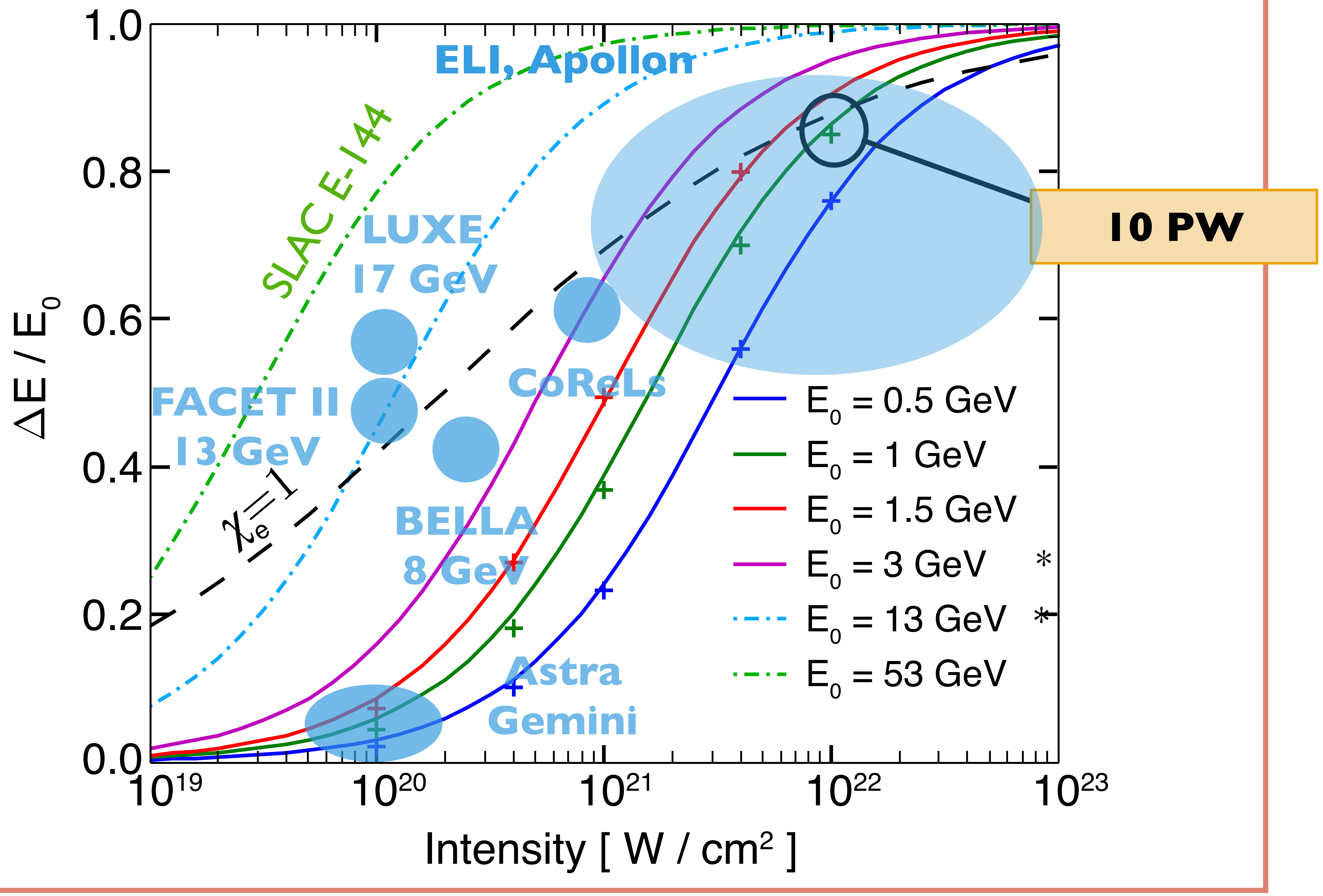
**Classical:** $\chi \ll 1$

**QED:** $\chi \simeq 1$

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

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

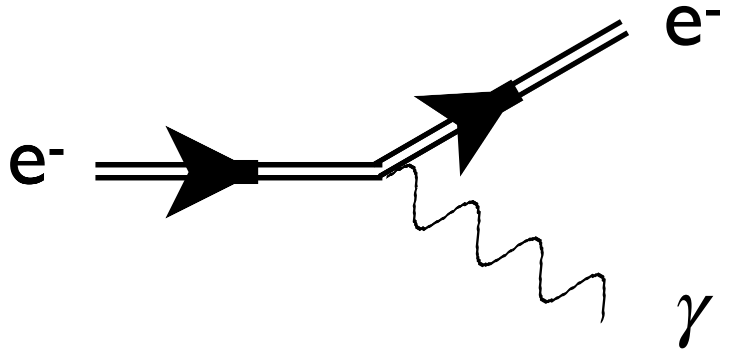
**Relative energy loss as a function of electron initial energy and the laser intensity (30 fs lasers)**

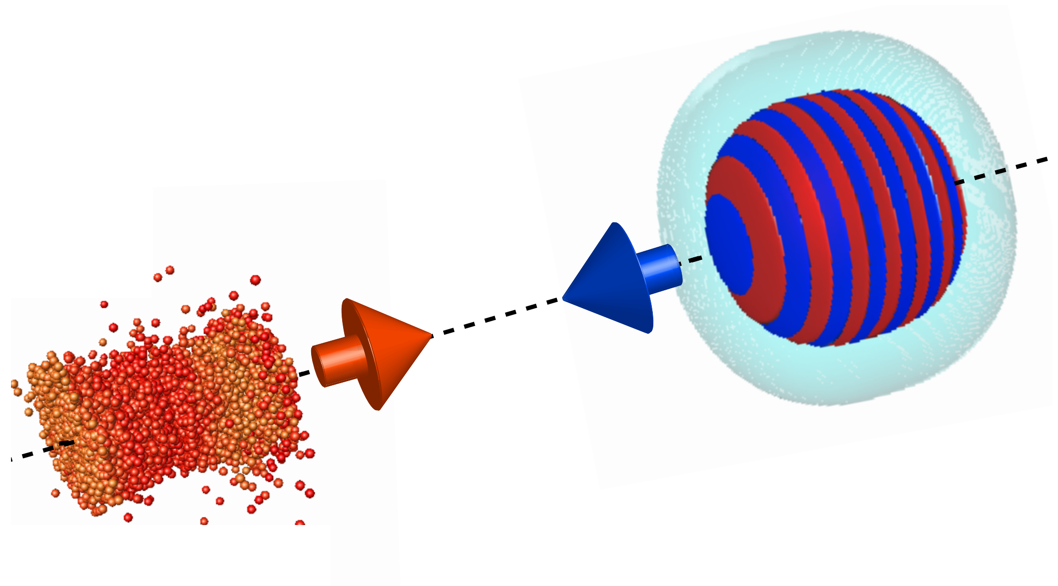


# Contents

- Classical radiation reaction
- Quantum radiation reaction
- Pair creation and acceleration

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





## Probability and Spectrum

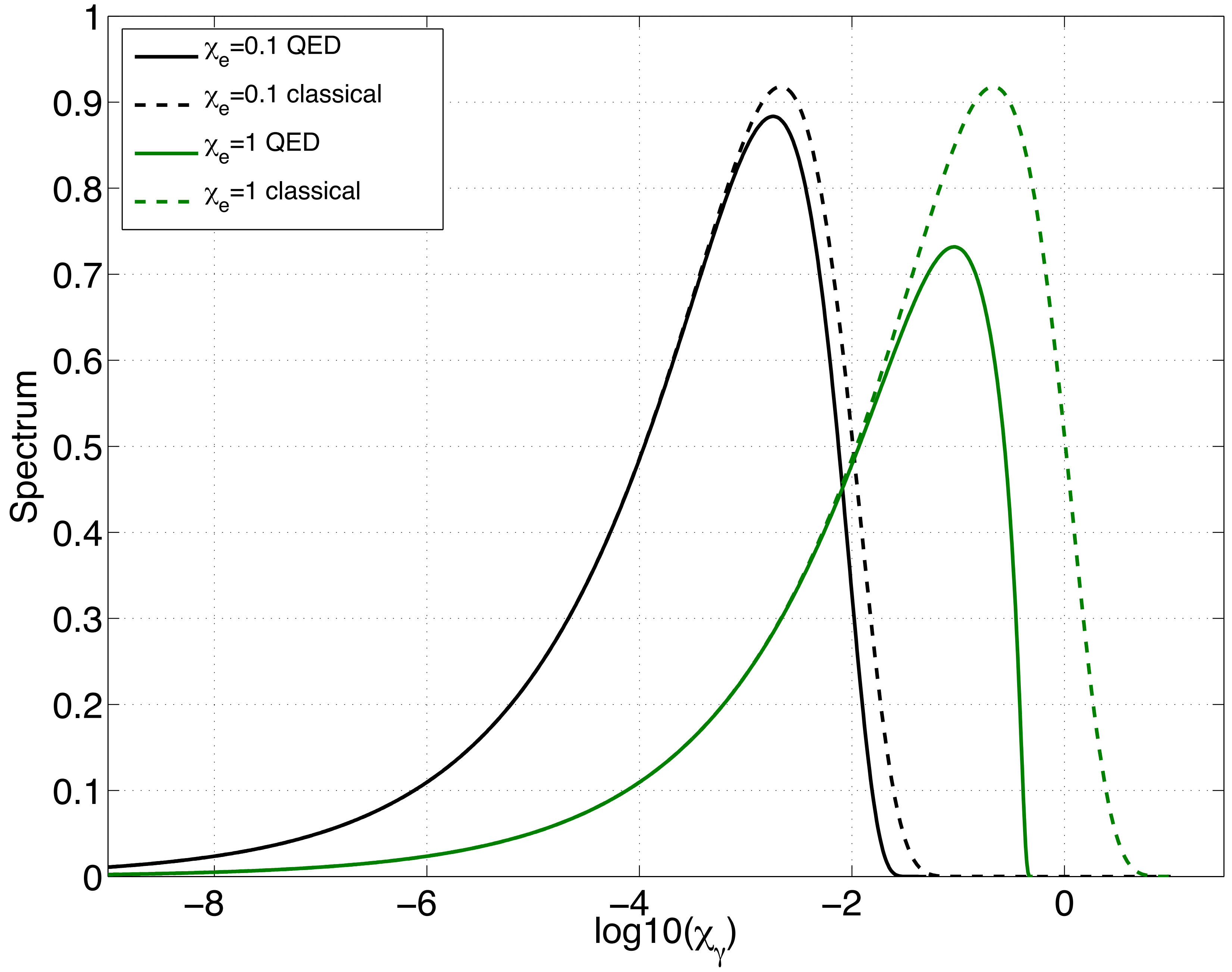
Ratio of critical frequency to particle energy: $\chi$

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

QED: probability of emitting a photon per unit of time per $\chi$

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

in strong field, particle emit QED synchrotron like spectrum



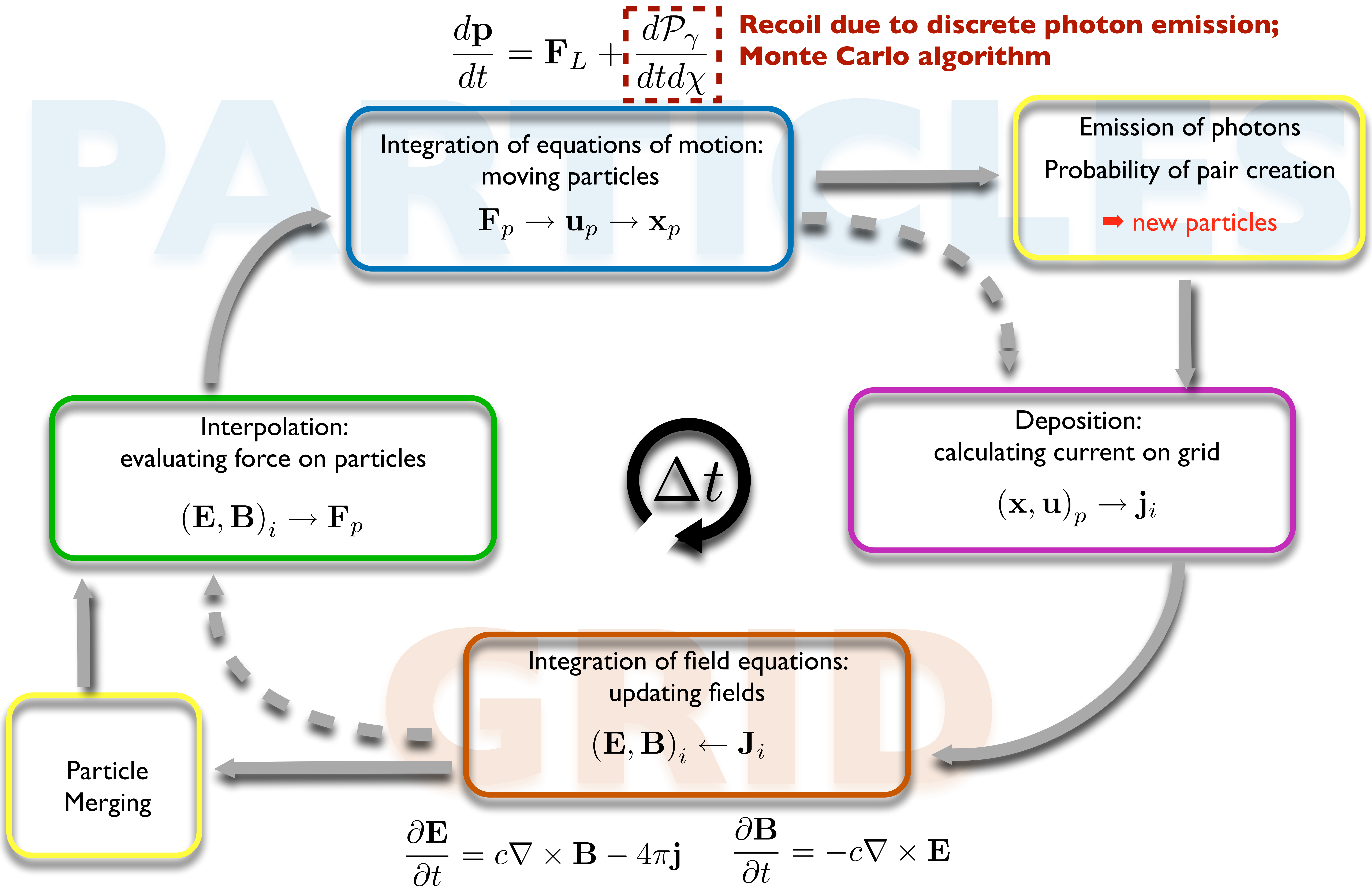
A. Di Piazza et al., Rev. Mod. Phys., 84, (2012)
F. Mackenroth & A. Di Piazza, 84, 032106 PRA (2011)

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/



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

**Recoil due to discrete photon emission; Monte Carlo algorithm**

Integration of equations of motion: moving particles

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

Emission of photons
Probability of pair creation
➡ new particles

Deposition: calculating current on grid

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

Integration of field equations: updating fields

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

Interpolation: evaluating force on particles

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

Particle Merging

$\Delta t$

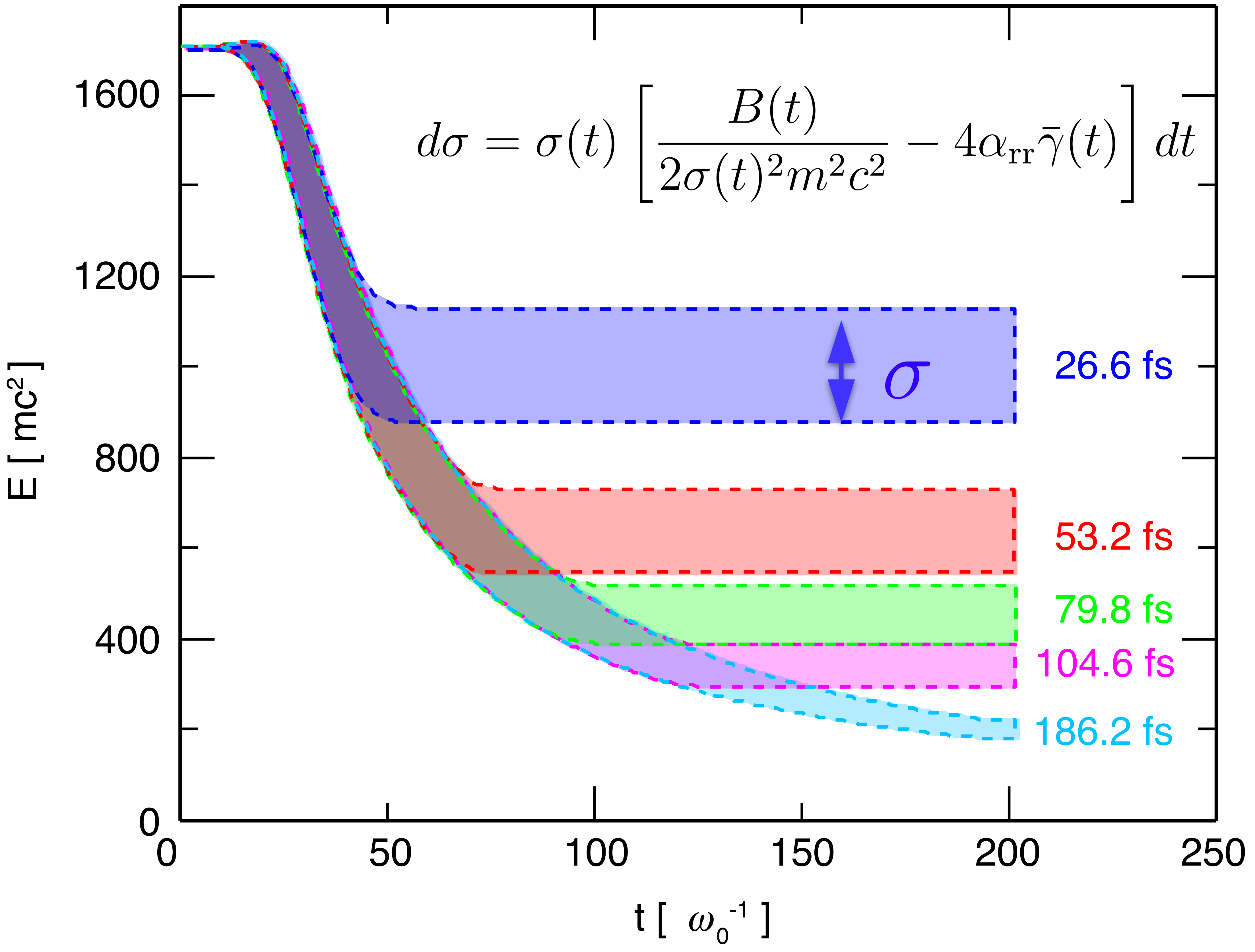
$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi\mathbf{j} \qquad \frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

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



## 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"

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

## Stochastic QED "diffusion"

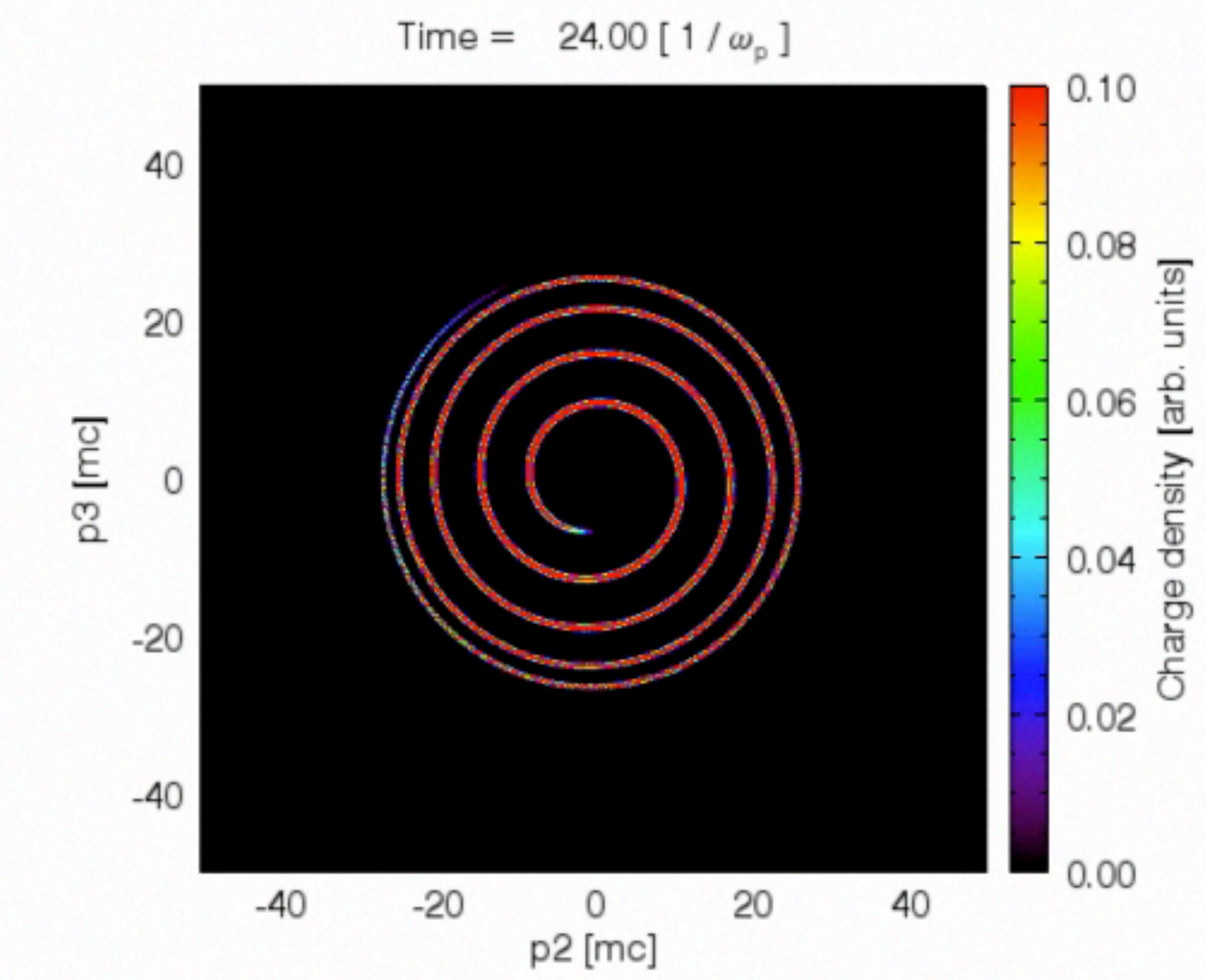
$$B \approx \frac{55}{24\sqrt{3}}\frac{\alpha m^3 c^4}{\hbar}\gamma\,\chi_e^3$$

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)

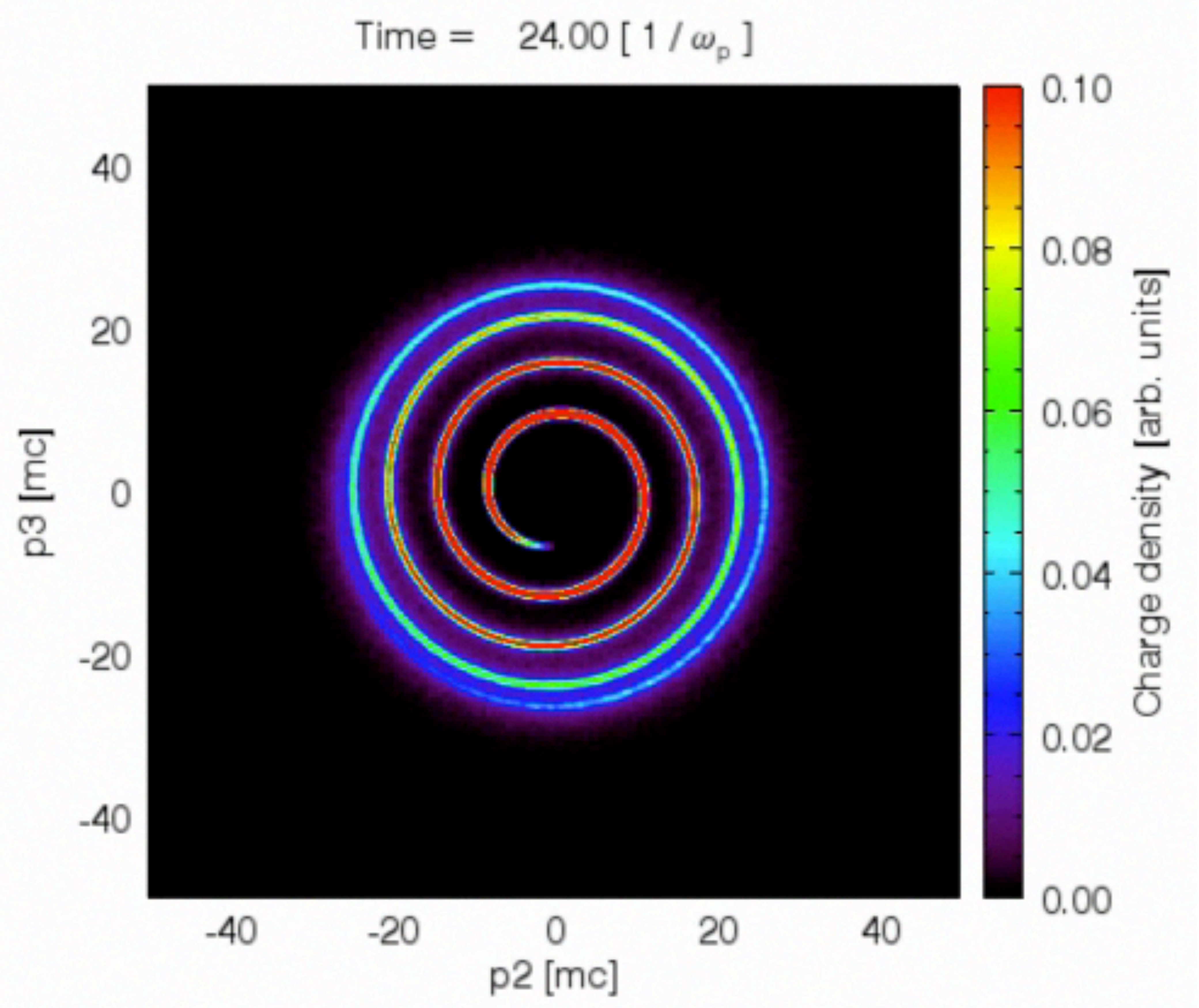
# Average angle between the elecctron momentum and the laseer axis is equal in classical and QED radiation reaction

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

**Classical RR**

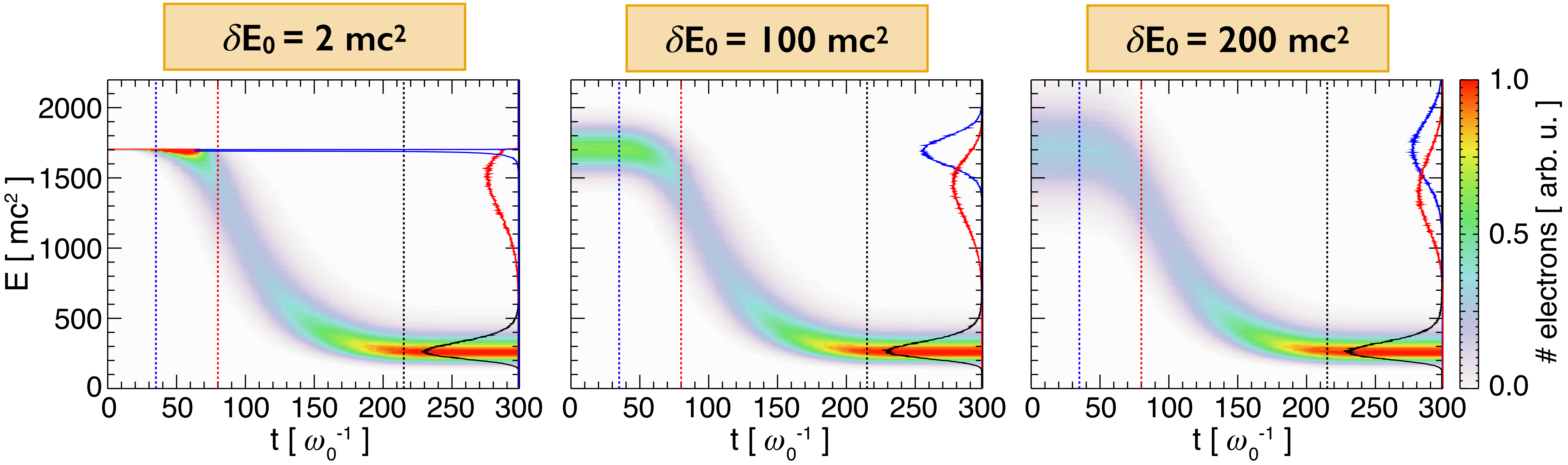


**Quantum RR**



# Expected value for final energy spread emerges from stochastic diffusion (and we can also predict the residual beam divergence)

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



**$\delta E_F$ = 67 mc²**

## Final energy spread can be predicted analytically*

| | |
|---|---|
| $\sigma_F^2 \lesssim 1.455 \times 10^{-4} \sqrt{I_{22}} \dfrac{\gamma_0^3}{(1 + 6.12 \times 10^{-5} \gamma_0\ I_{22}\ \tau_0[\mathrm{fs}])^3}$ | $I_{22} = I\,[10^{22}\ \mathrm{W/cm^2}]$ |

* M.Vranic et al., NJP (2016), M.Vranic et al., POP (2019)

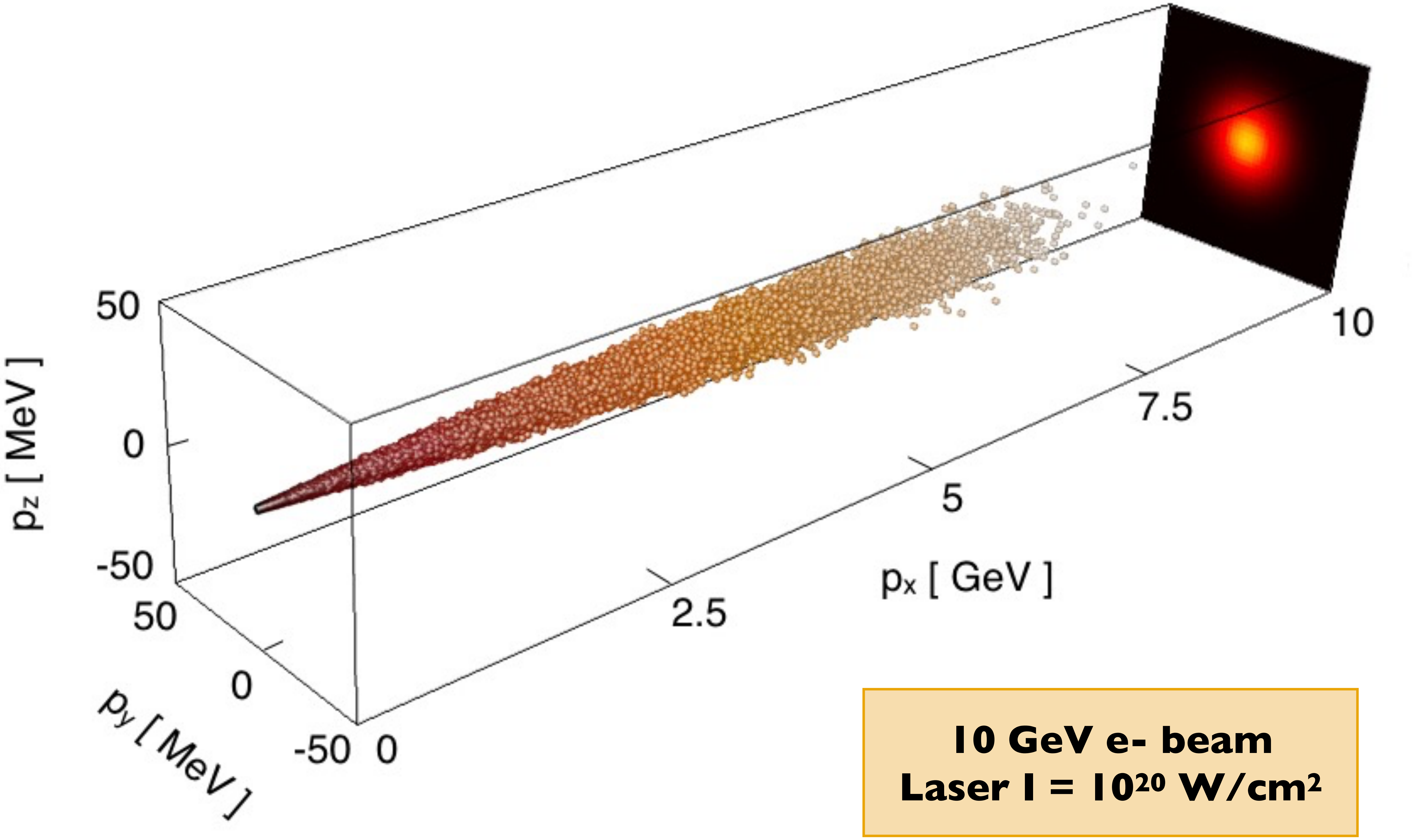
# Contents

# 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)**

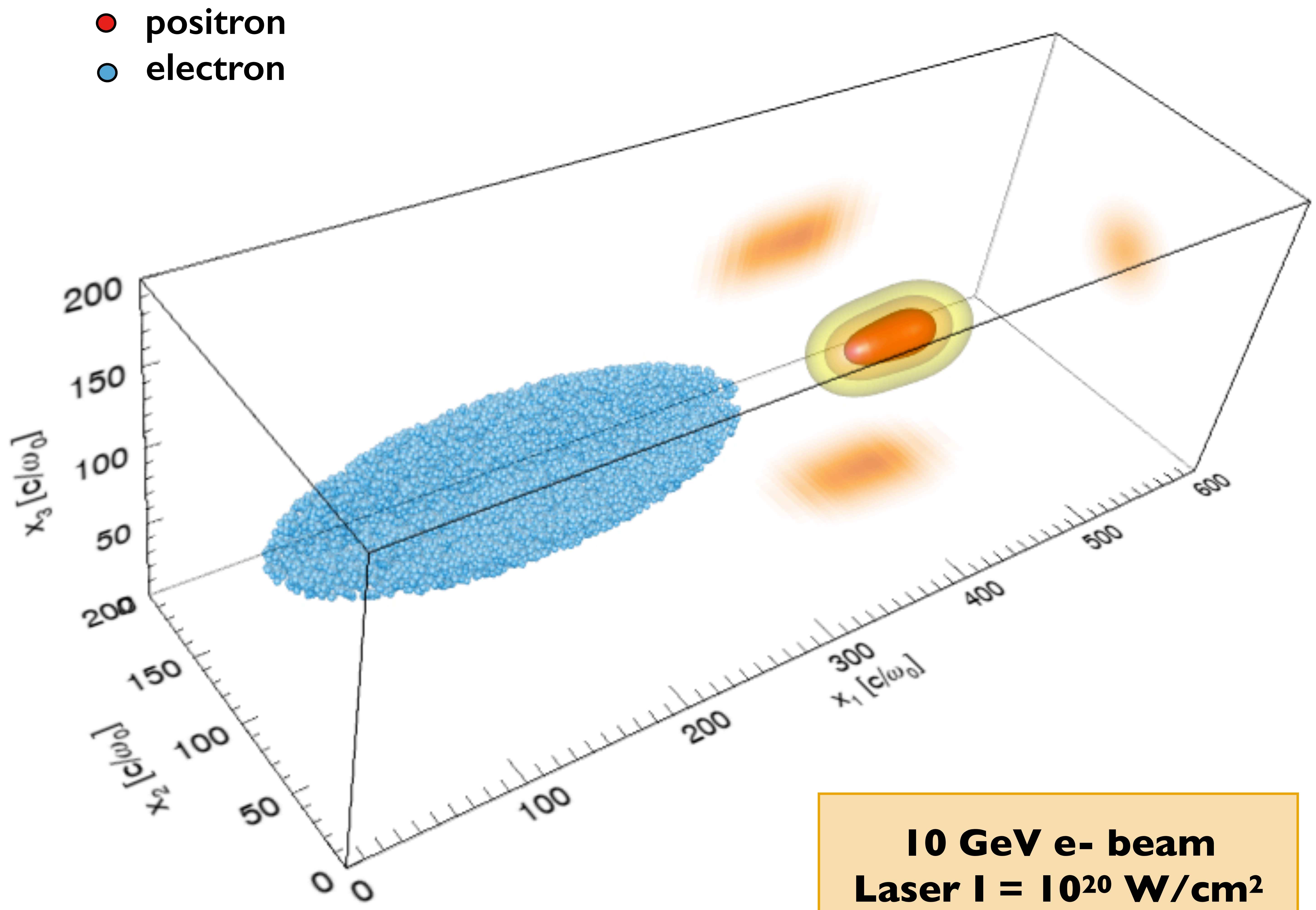
**Photon source properties**

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

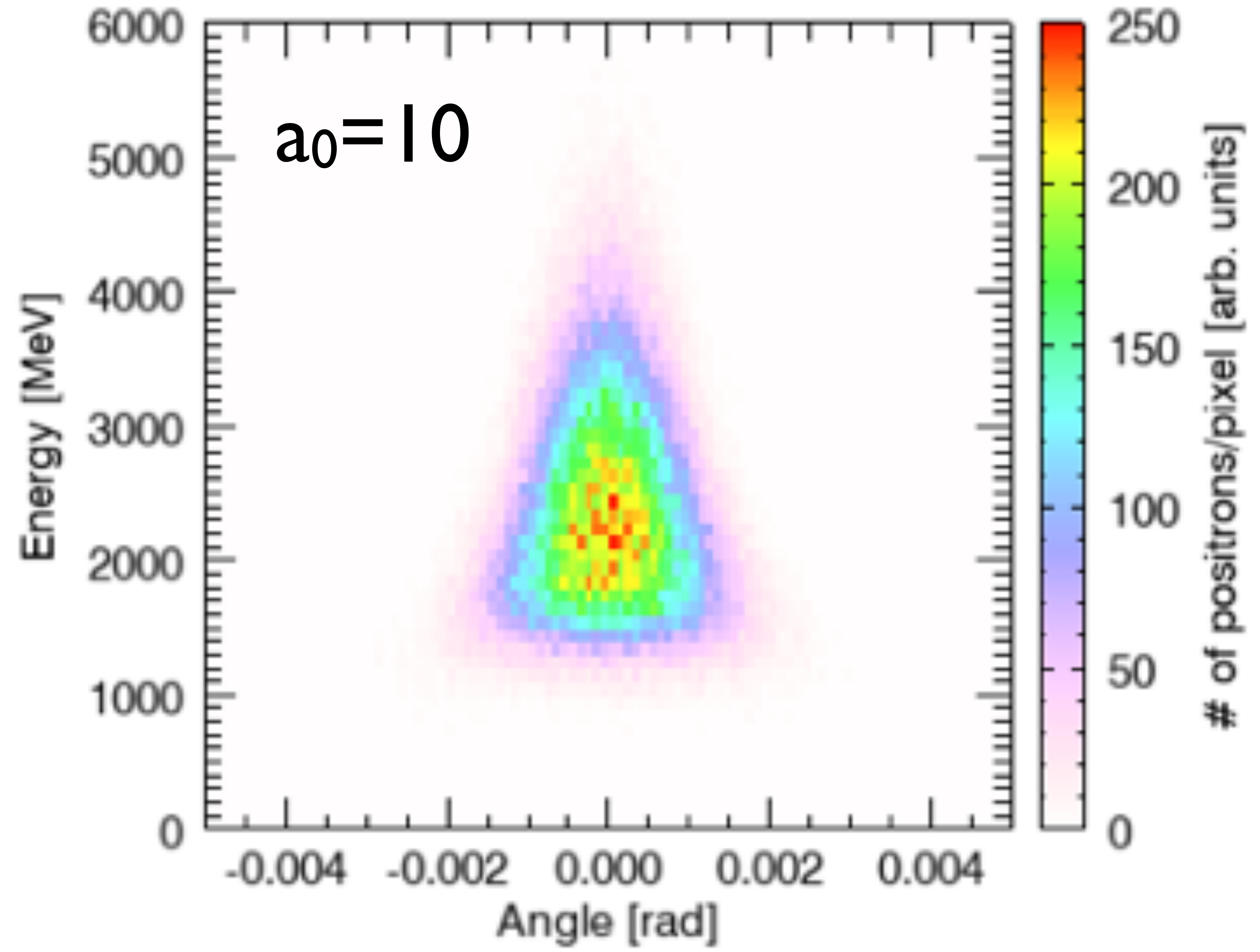


**10 GeV e- beam**
**Laser I = $10^{20}$ W/cm$^2$**

# A fraction of radiated photons decays into electron-positron pairs



**Positrons: energy vs angle**



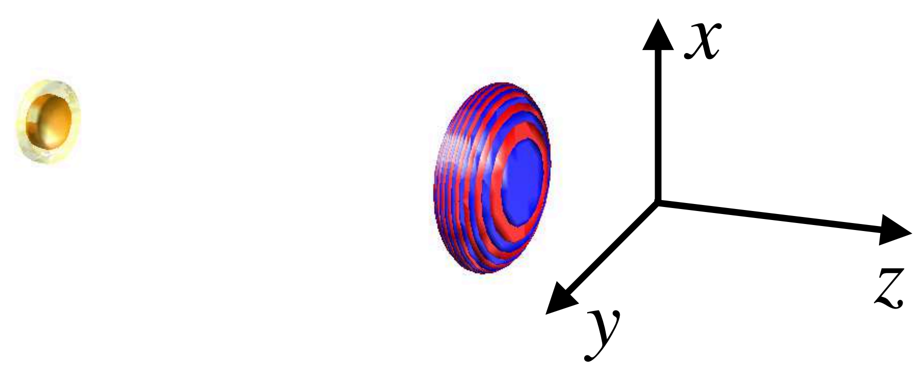
**10 GeV e- beam**
**Laser I = $10^{20}$ W/cm²**

**1 nC electron beam gives**
**~ 0.2 pC of positrons**

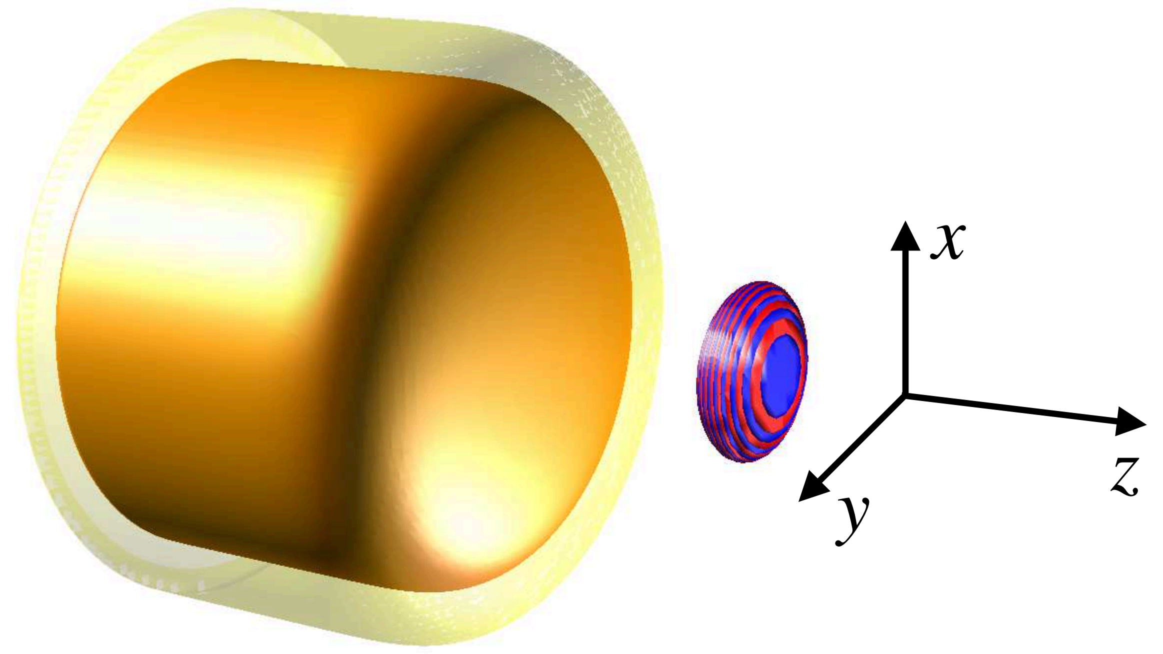
# Effective laser intensity of interaction is reduced for non-ideal beams

**Different beam sizes and shapes lead to different positron count**

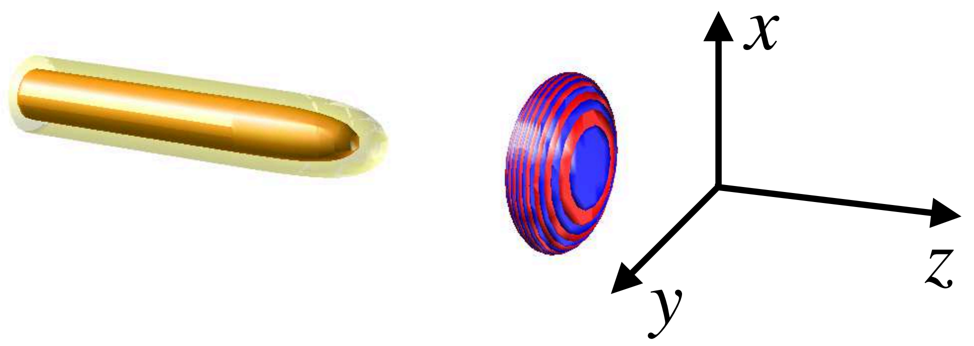
**Single electron**



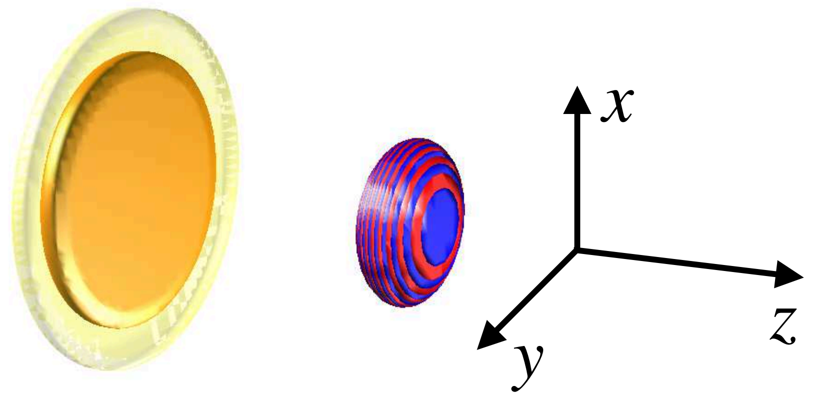
**Wide electron beam**



**Thin electron beam**



**Short electron beam (any size)**



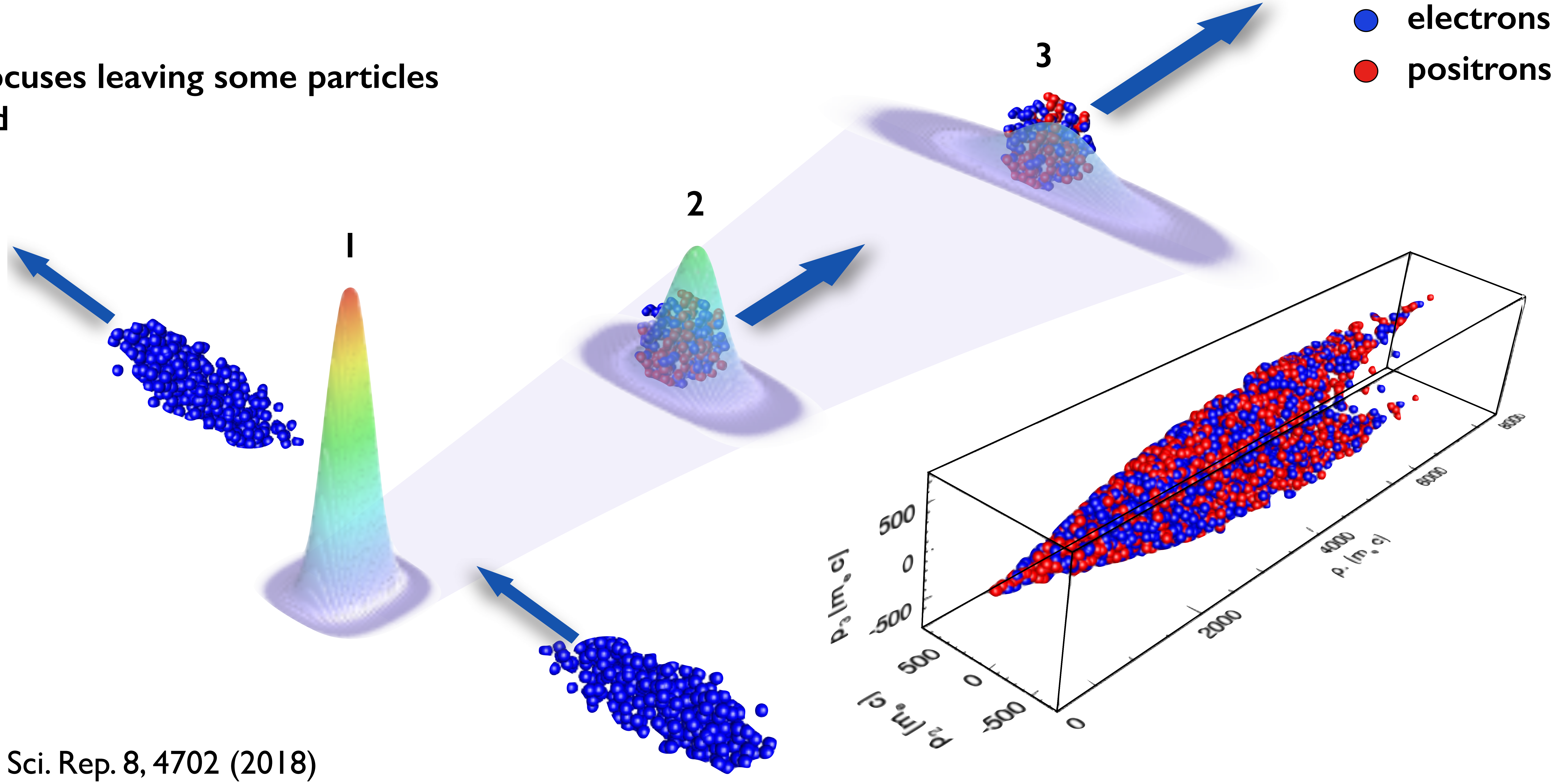
Analytical model can predict the number of pairs for non-ideal spatio temporal syncronization and realistic beam sizes*

We can also predict asymptotic properties of the electron beam and output radiation

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

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

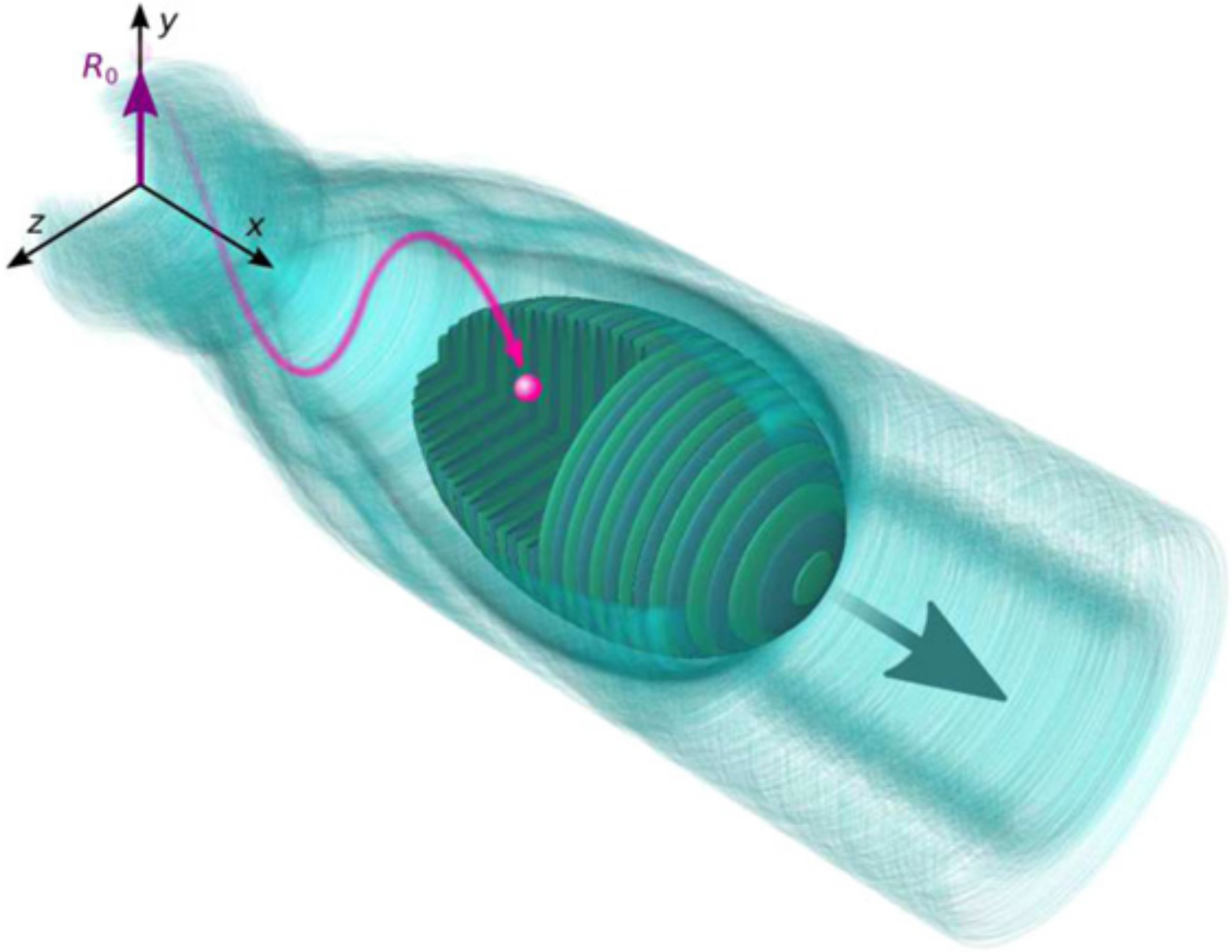
1. **LWFA electrons collide with the laser; pairs are produced in the highest field region**
2. **E+e- beam is accelerated by the laser in vacuum**
3. **Laser defocuses leaving some particles accelerated**

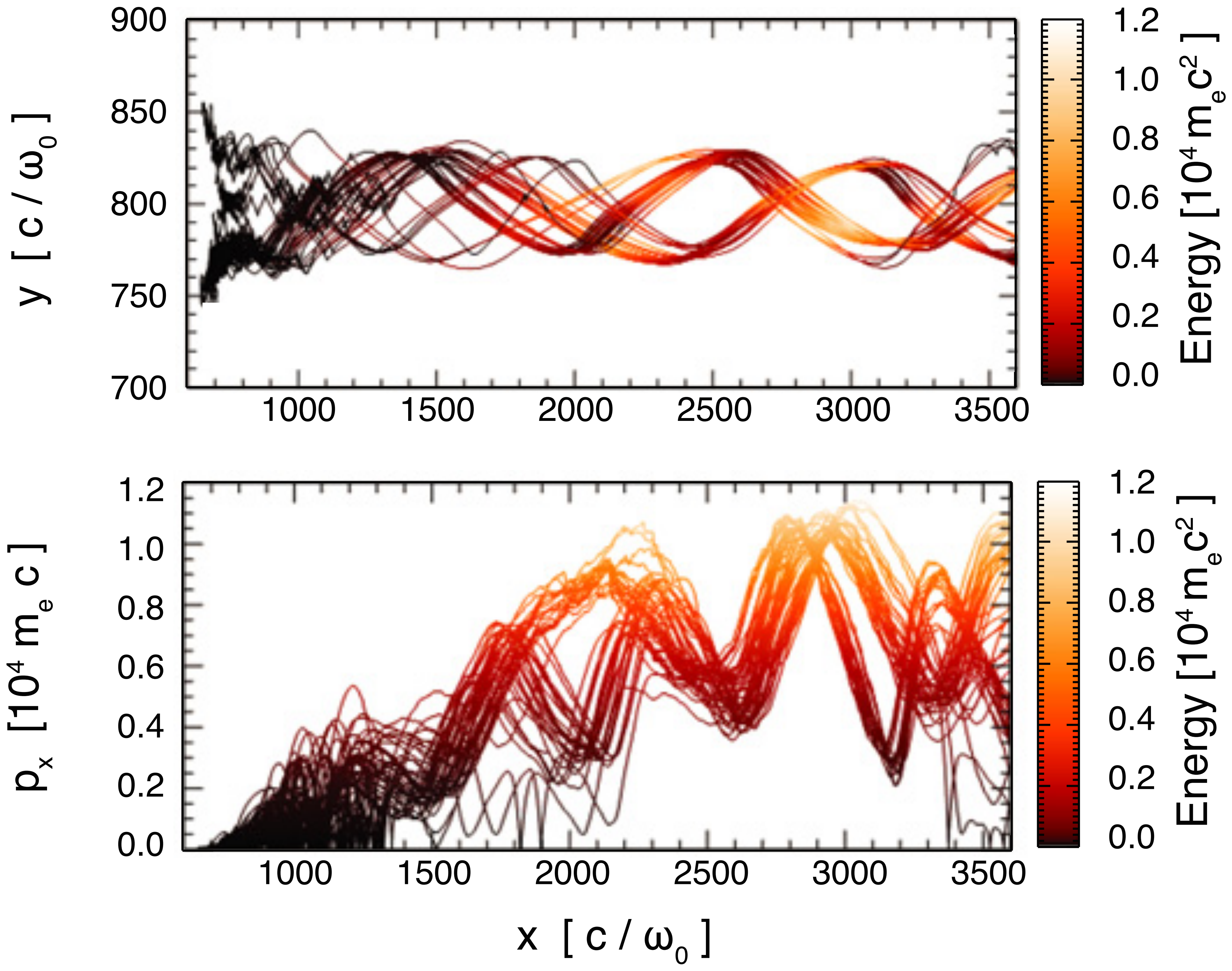


M. Vranic et. al., Sci. Rep. 8, 4702 (2018)

# Why not use a plasma channel to further accelerate the pairs?

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



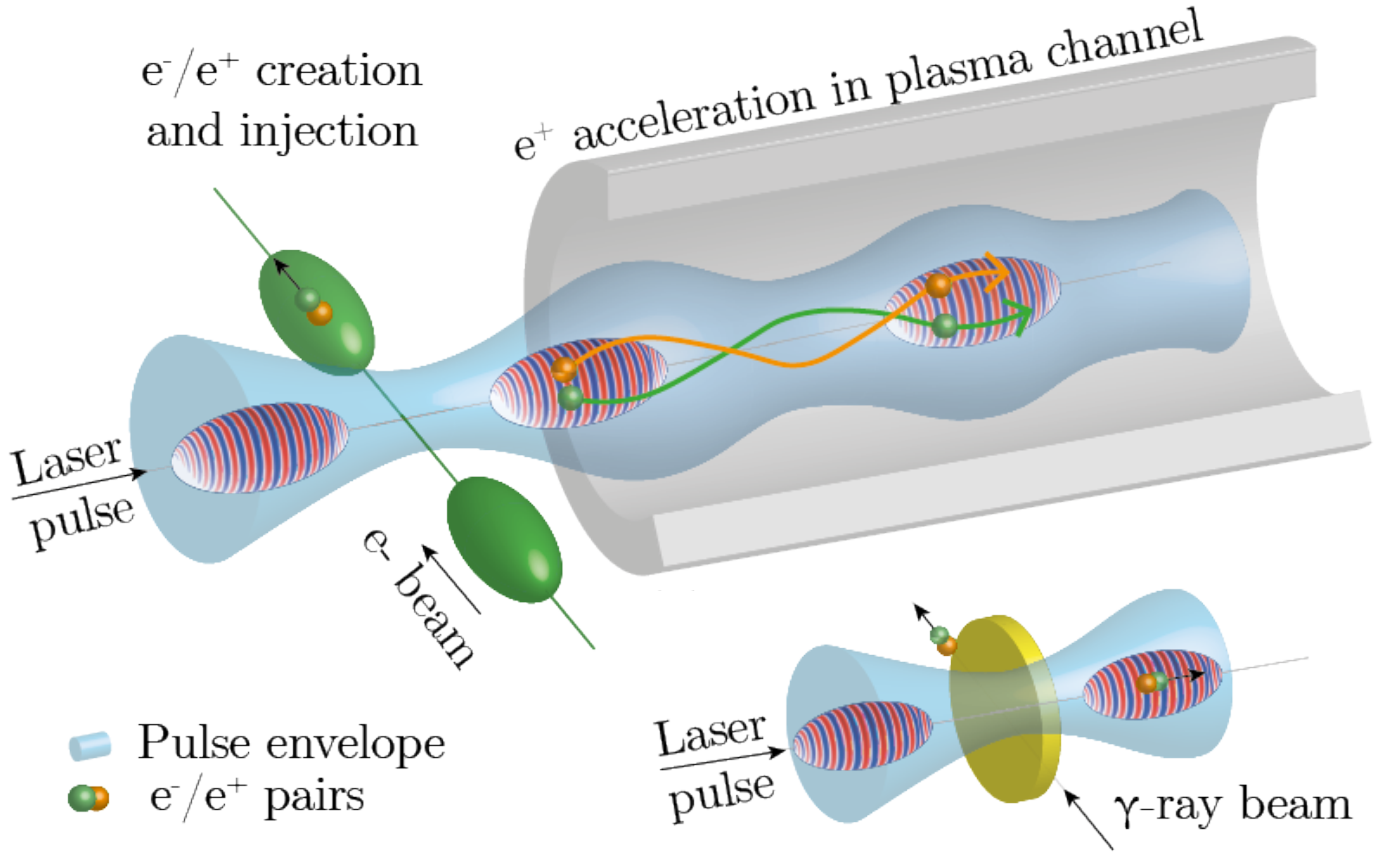


**Direct laser acceleration (DLA) can accelerate electrons to ~10 GeVs. Positrons could be accelerated as well!**

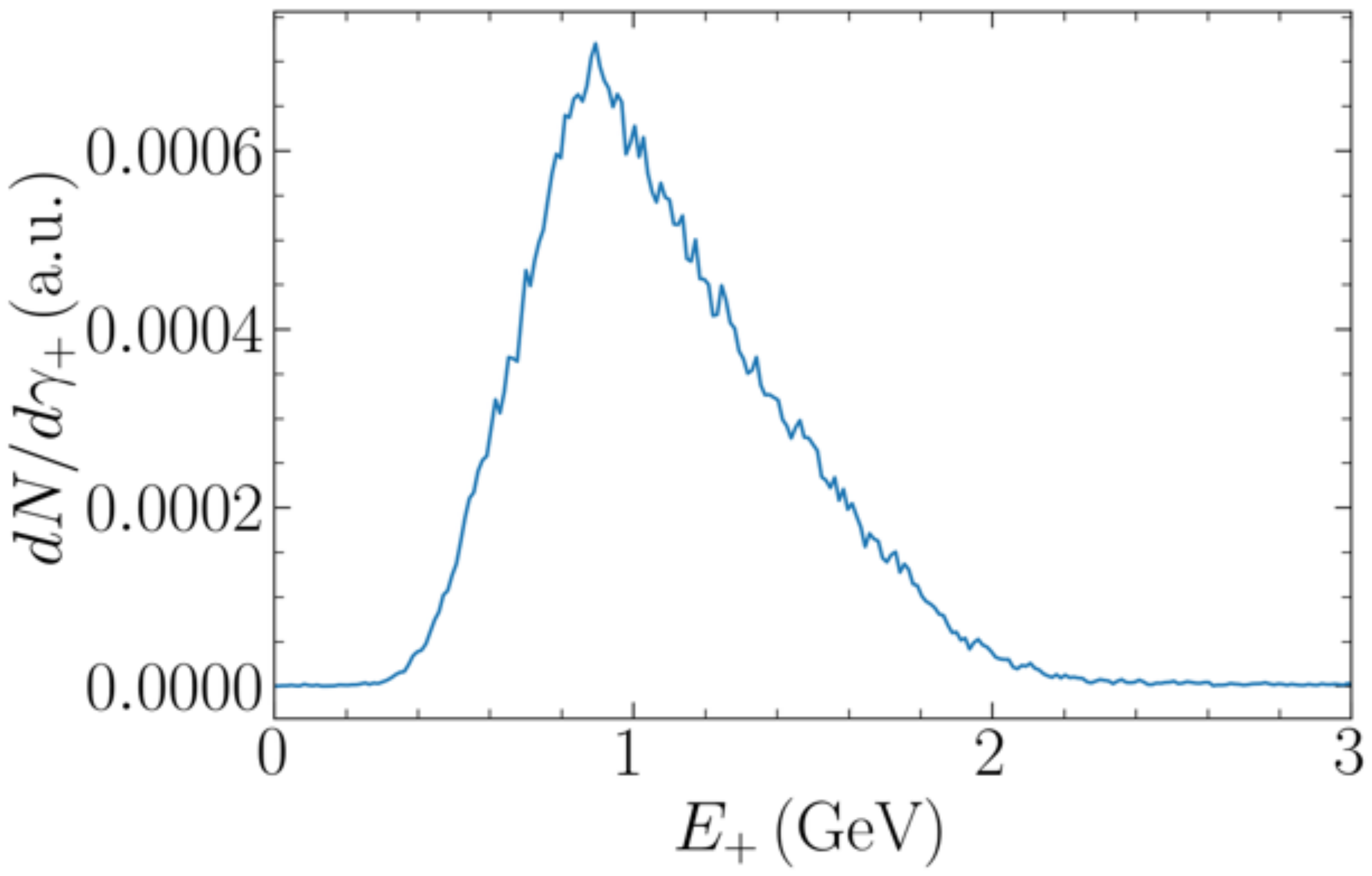
M. Jirka et. al., NJP, 22 083058 (2020)

# Positrons can indeed be accelerated within the plasma channel

**The results depend on the efficiency of e+ injection and the electron beam loading (to create focusing fields)***



### Positron spectra



2 GeV e-, charge $\sim 10\,\mathrm{pC}$

**This can be modelled in Quasi-3D geometry****

Energy peak around 1 GeV

Charge of $\sim 0.1\,\mathrm{pC}$

*B. Martinez et al, to be submitted (2022)
**A. Liftshitz et al, JCP (2009)

# Conclusions

TÉCNICO LISBOA

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

- E-320 experiment at FACET II will be able to create pairs and show ~ 40 % energy loss on the electrons.

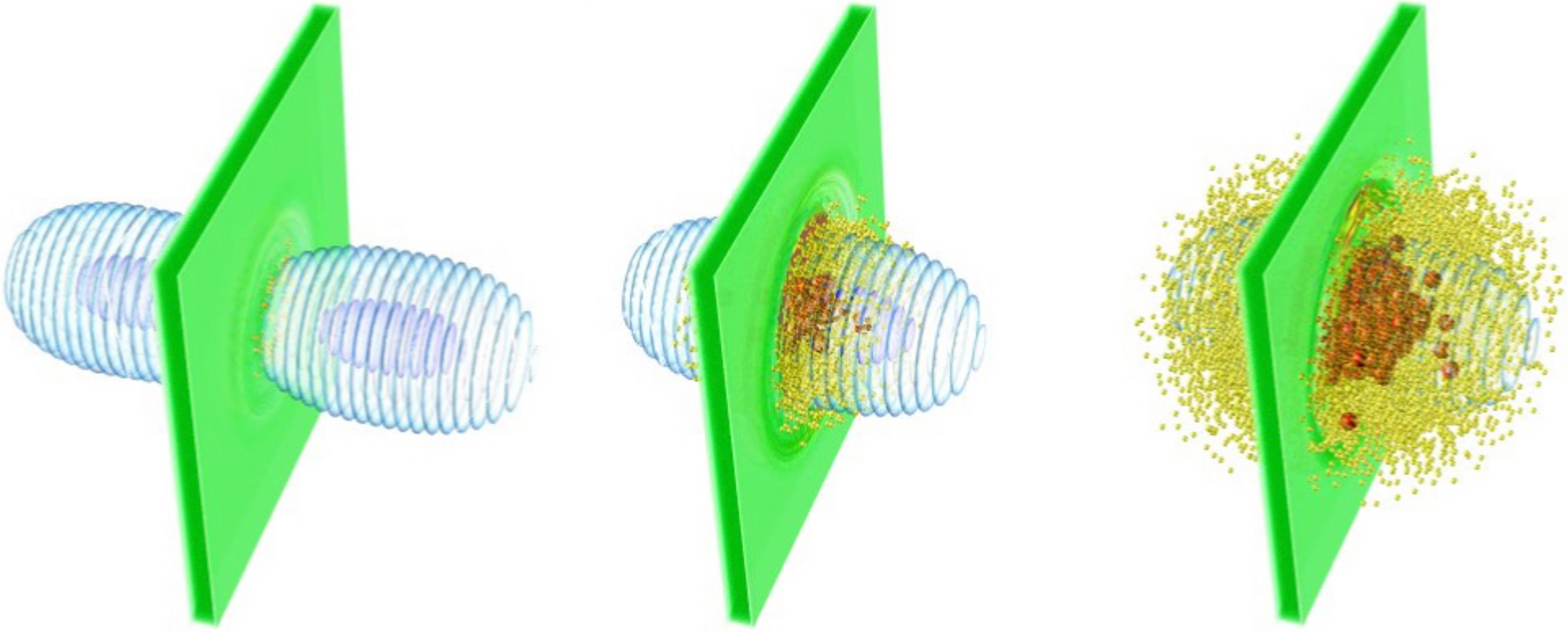
- Electron-positron pairs can be created and accelerated in a single stage by scattering an electron beam with a laser at 90 degrees, and accelerating in vacuum or in a plasma.

- Direct laser acceleration in a plasma channel is a good candidate to accelerate positrons, or electron-positron beams (not monoenergetic, but possible to obtain high charge and energy).

# Extra slides

## Marija Vranic

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

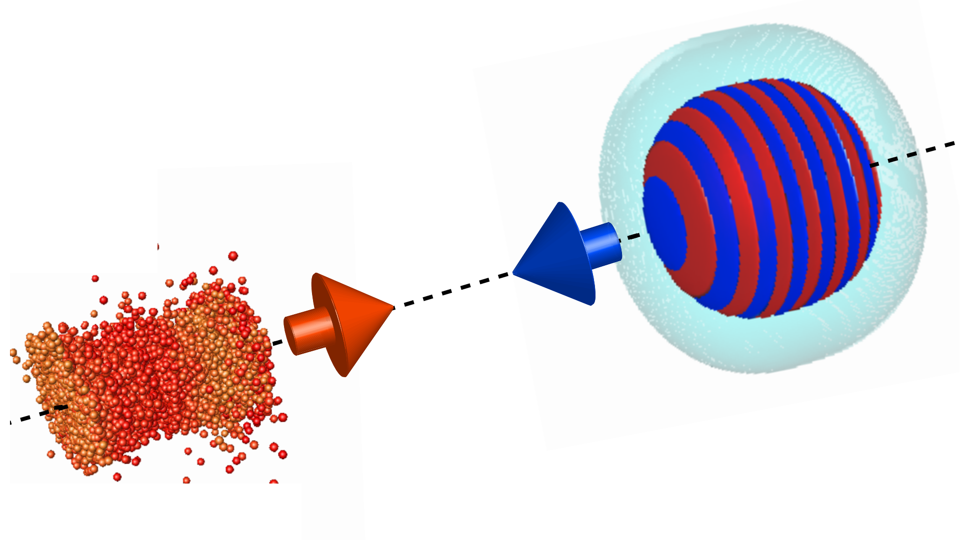


**epp**.tecnico.ulisboa.pt || **golp**.tecnico.ulisboa.pt

Funded by the European Union

# What is required to convert 1 Joule of energy to gamma-rays?

## The scattering configuration



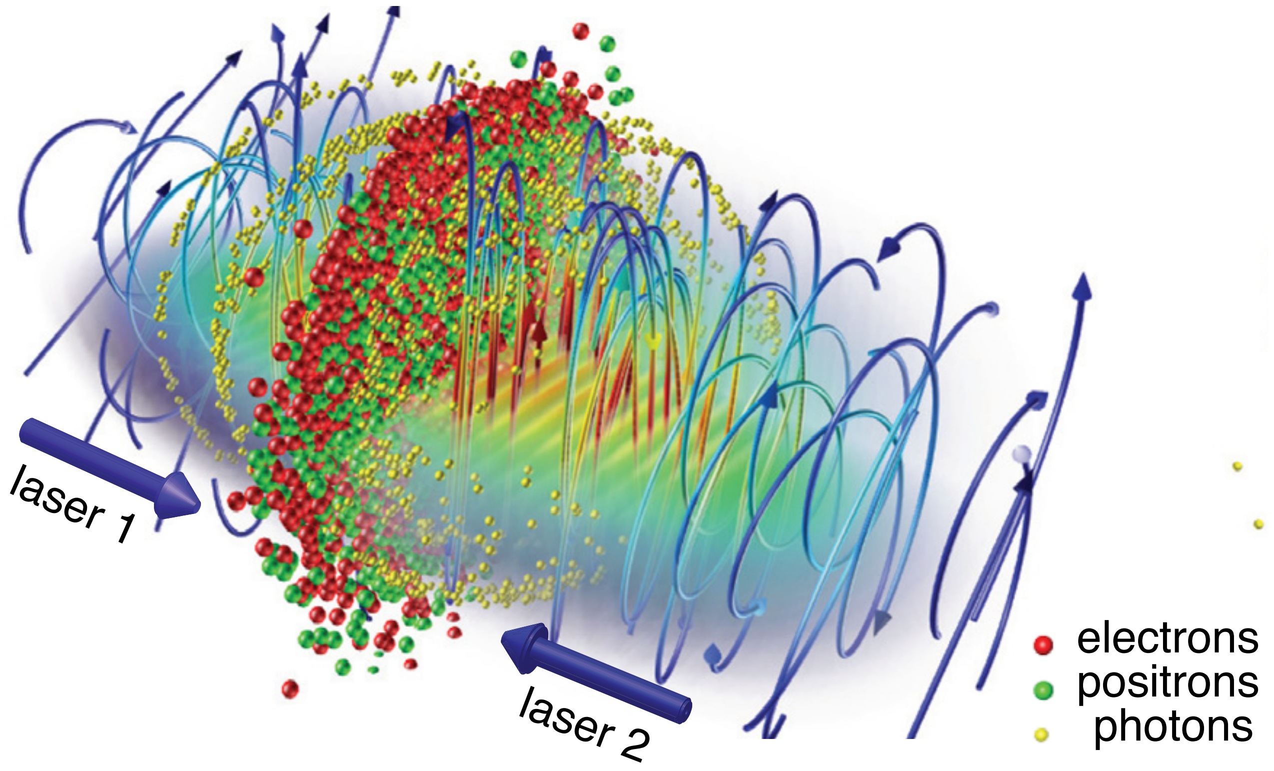
### High energy, low charge

- 100 pC electron bunch
- 10 GeV energy
- Laser I ~$10^{20}$ W/cm$^2$

### High charge, low energy

- 1 nC electron bunch
- 1 GeV energy
- Laser I ~$10^{21}$ W/cm$^2$

## QED cascade



### Controled emission

- Laser I ~$10^{23}$ W/cm$^2$
- Low density plasma seed
- Self-created plasma $n < a_0 n_c$

### Emission in dense plasma

- Laser I ~$2\text{x}10^{22}$ W/cm$^2$
- Dense plasma seed
- Density achieved $n > a_0 n_{cr}$

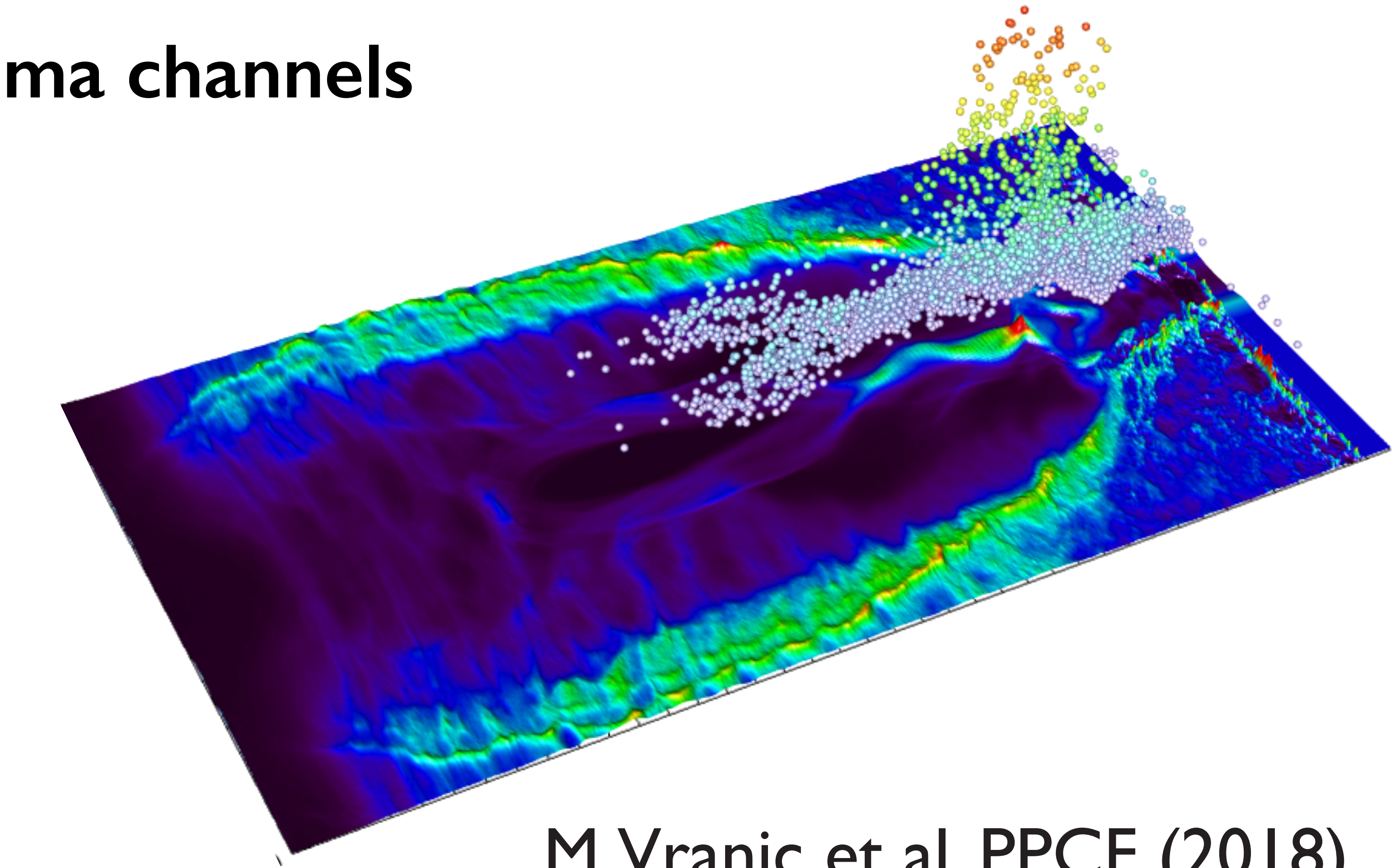
# Challenges and opportunities

**Novel configurations, or using extreme intensity as a game changer to the existing ones**

## New opportunities for particle acceleration

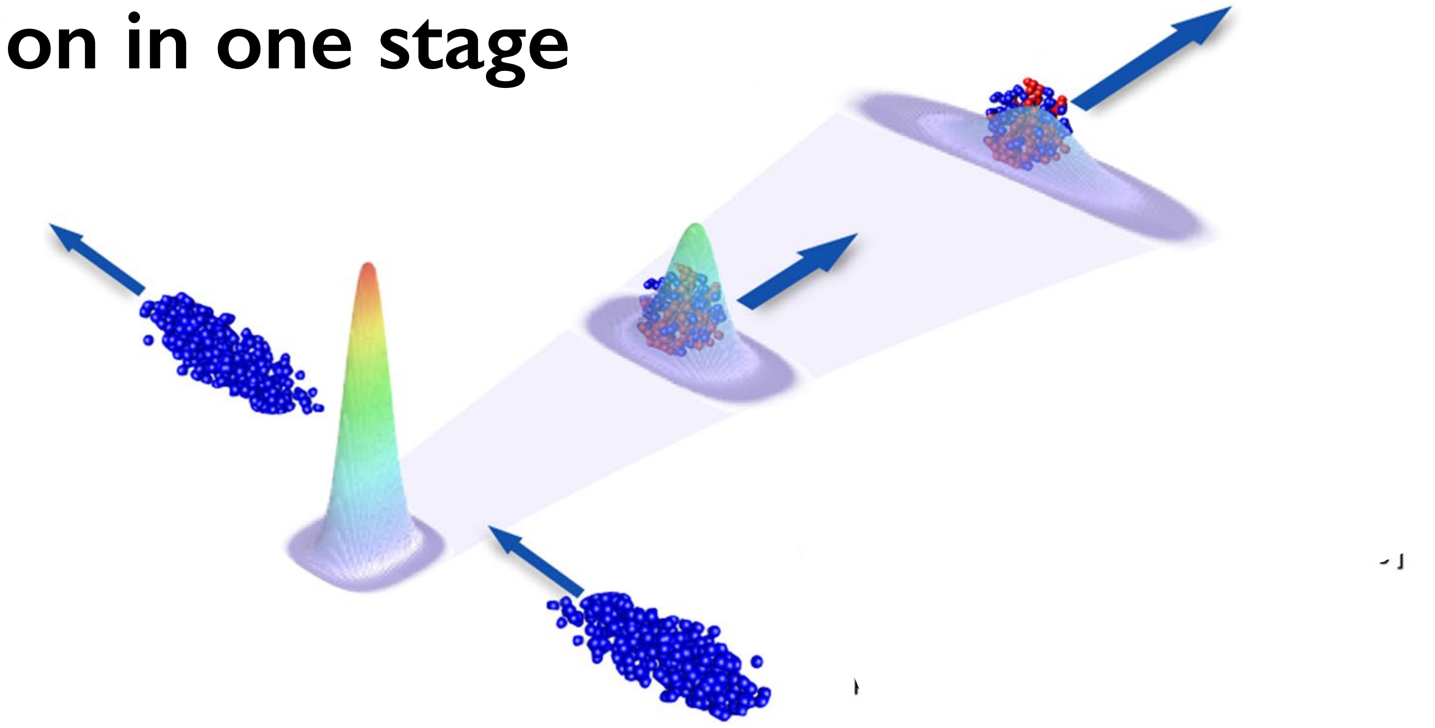
- **Electron acceleration in plasma channels**

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)

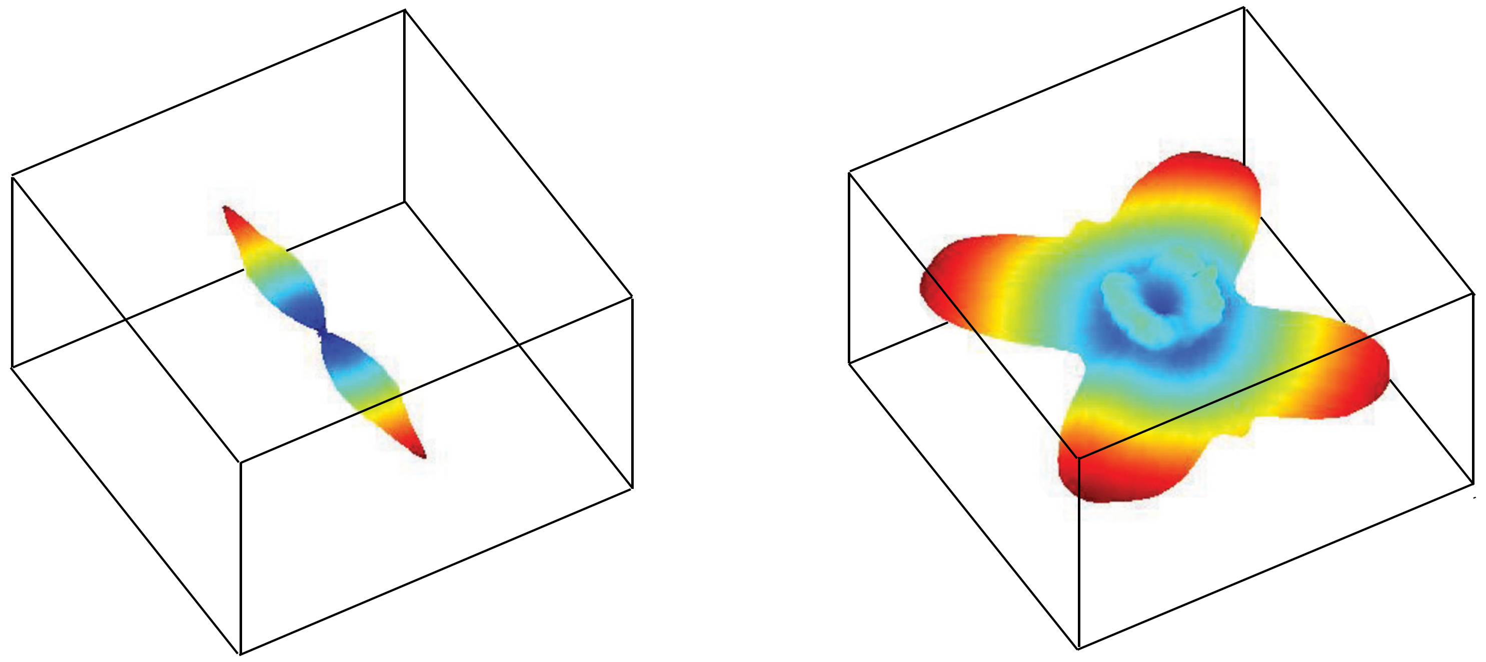
- **Electron-positron production & acceleration in one stage**



M. Vranic et al, SciRep (2018)

## Design of photon sources tunable up to GeV energies

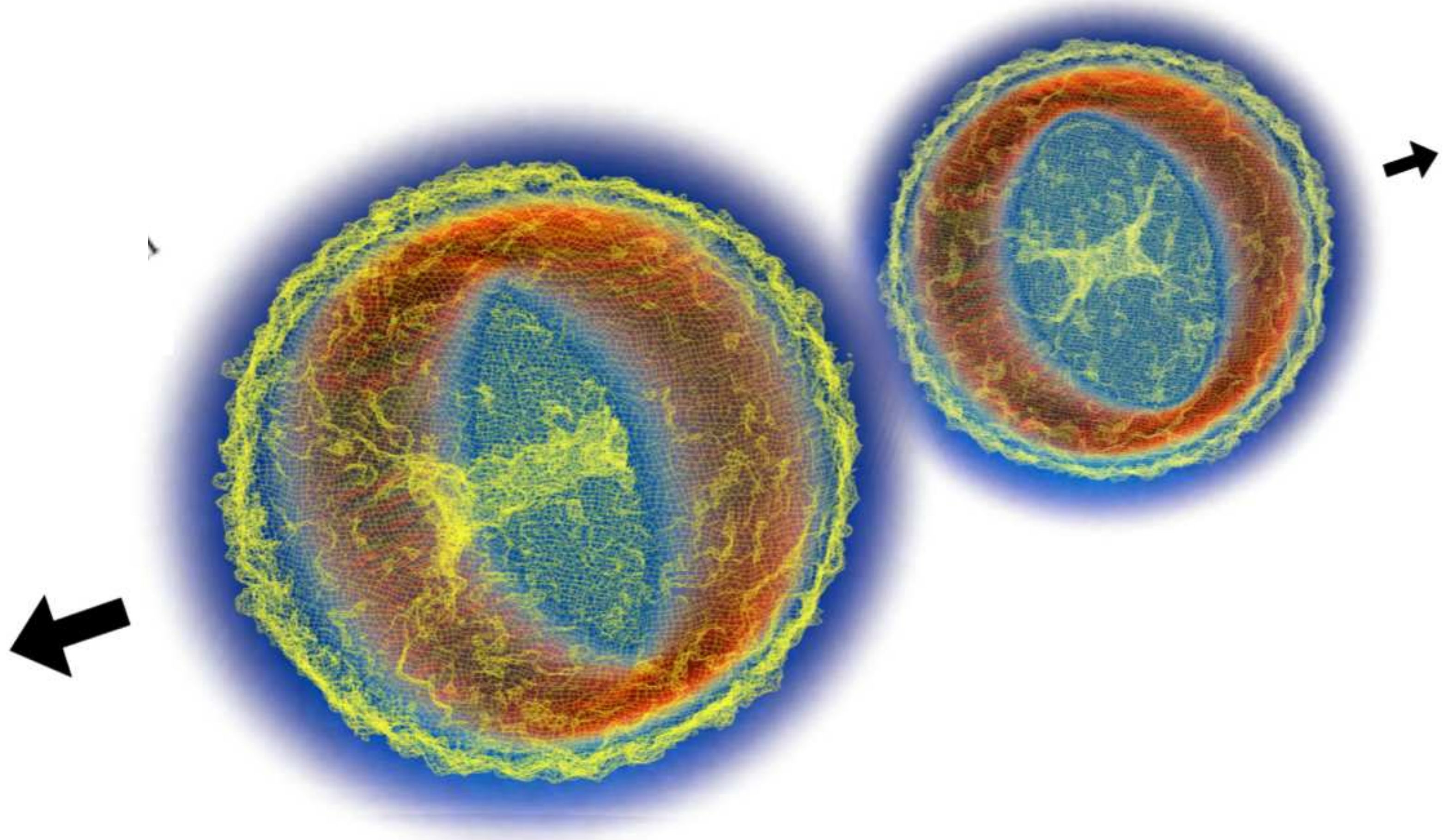
N. Lemos, PPCF (2018); F. Albert, POP (2018)
W. Yan, Nat. Phot (2017); Gonoskov, PRX (2017)
A. Arefiev et al, PRL (2016); J. L. Martins et al, PPCF (2016)
K. Ta Phuoc, NatPhot (2012); Z. Gong, PRE (2017)
E. Esarey PRA (1992); S. Kneip, PRL (2009)



T. Grismayer et al, POP (2016)

# Challenges and opportunities

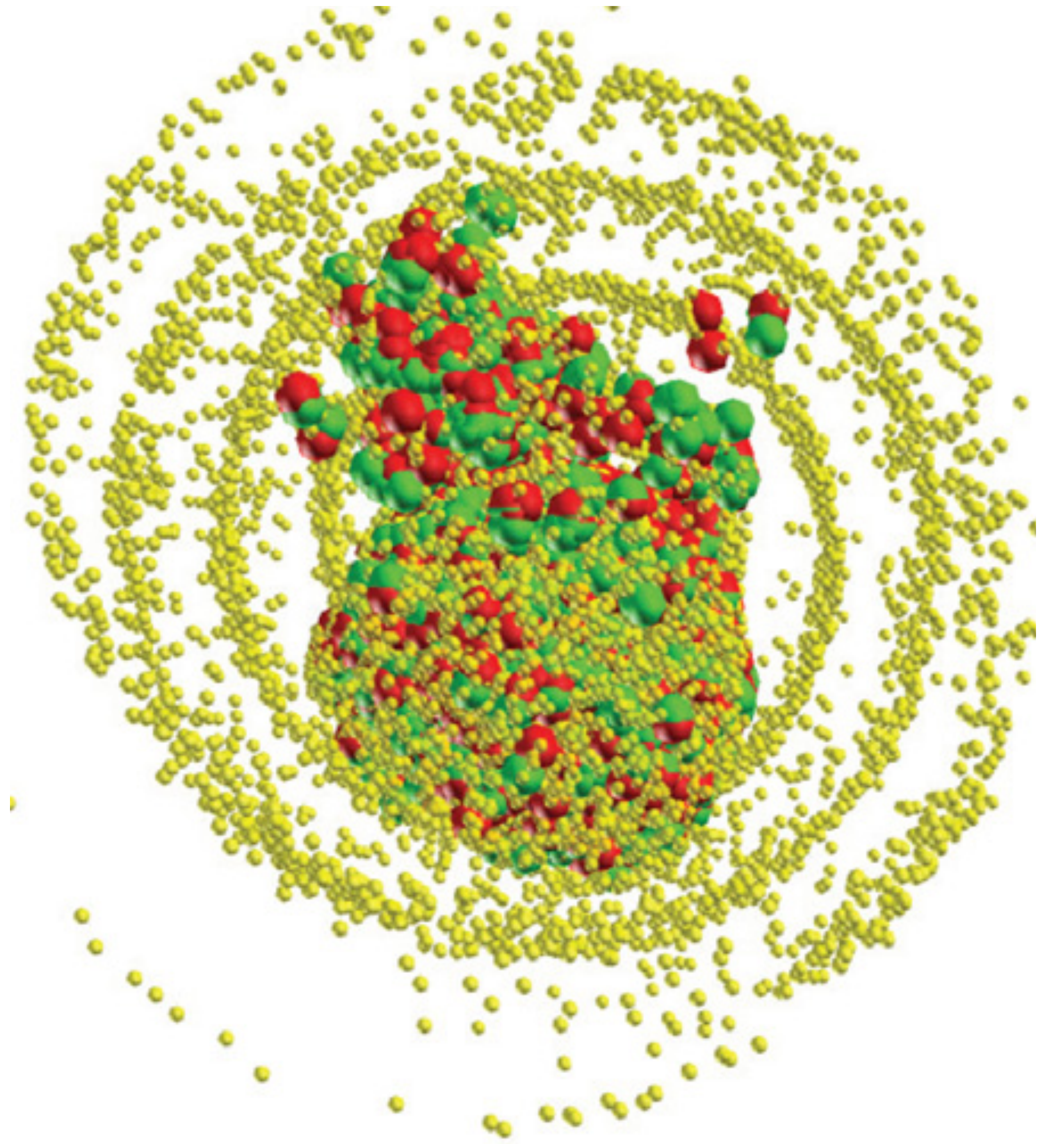
## Probing the onset of non-pertubative QED



V. Yakimenko et al, submitted (2018)
F. Del Gaudio et al, sumbitted (2018)

## Evolution of self-generated e+e- plasmas

T. Bell and J. Kirk, PRL (2010)
A. teFedotov, 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)
M. Tamburini, Sci Rep (2017)
M. Vranic, PPCF (2017)
X. Zhu, NComm (2017)
T. Grismayer, PRE (2017)



T. Grismayer et al, POP (2016)

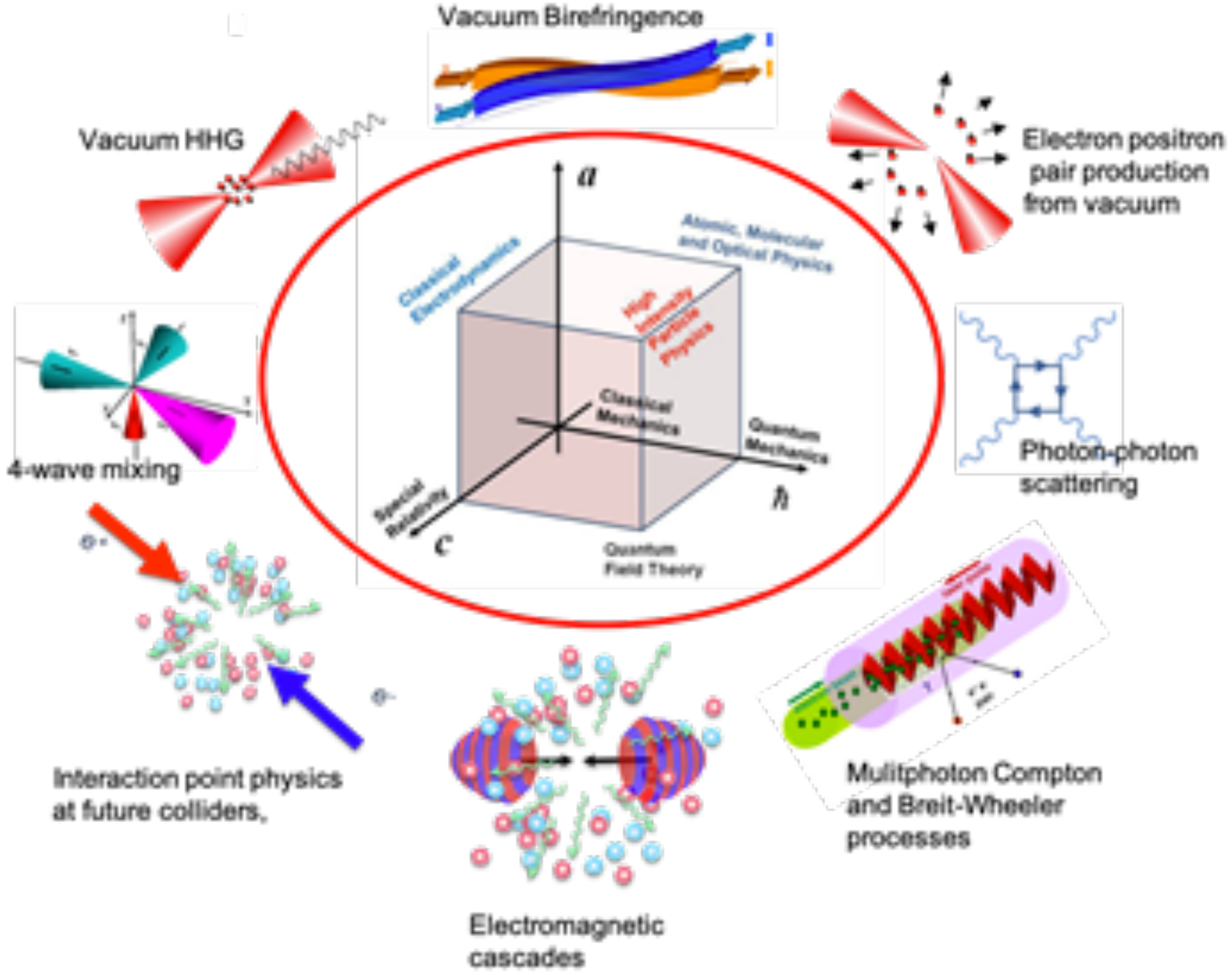
## Study the classical and quantum radiation reaction

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);

# Special issues on high field laser-matter interaction physics

**New Journal of Physics 2021**

Focus on Strong Field Quantum Electrodynamics with high power lasers and particle beams



**Plasma Physics and Controlled Fusion 2017-now**

Special issue on high field laser plasma interactions associated with EPS Plasma Physics Satellite Meeting on High-Field phenomena