Direct laser acceleration of positrons with intense lasers

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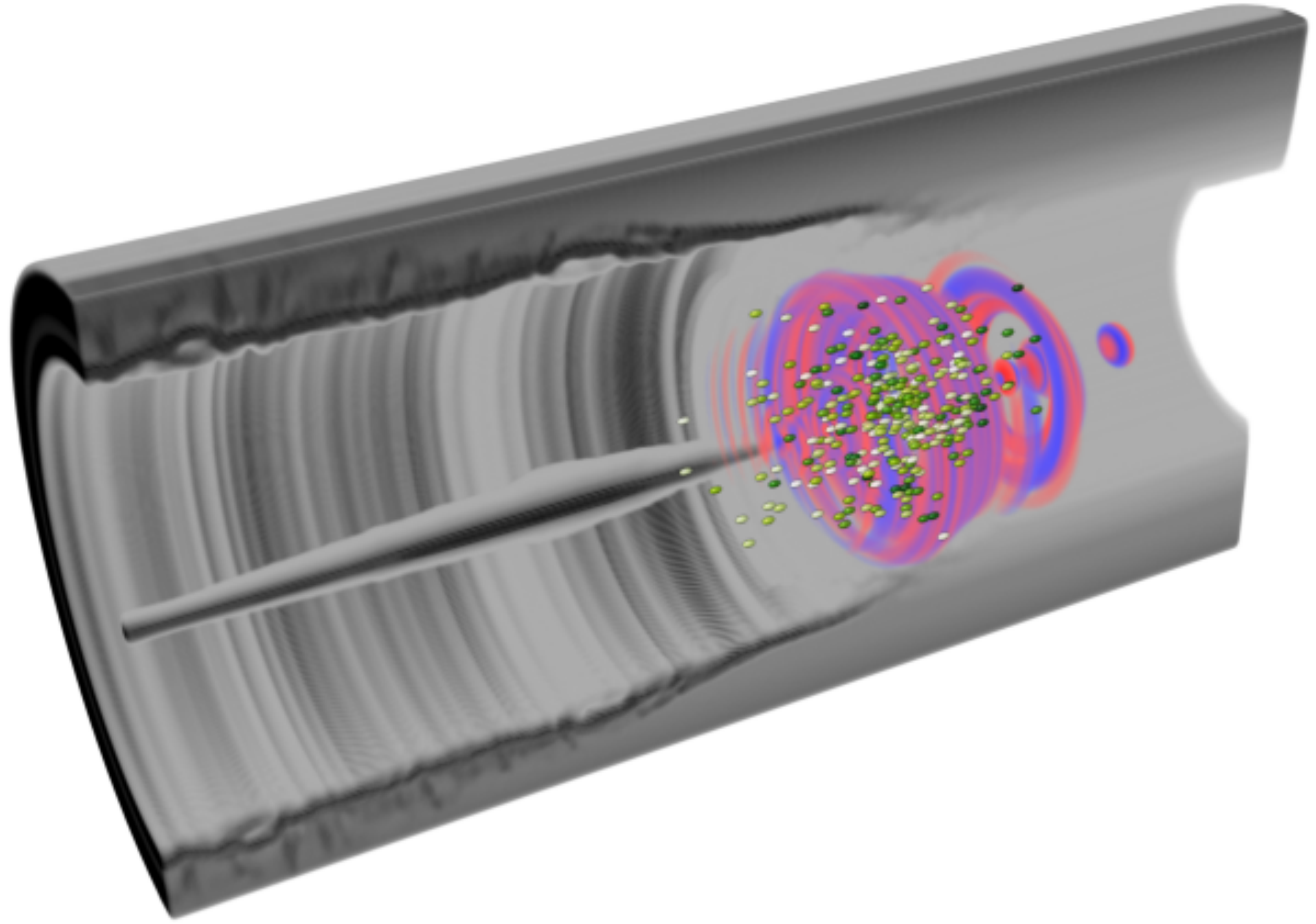

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Acknowledgments

Simulation results obtained at the MareNostrum supercomputer, based in the Barcelona Supercomputing Centre (Spain)

Portuguese Science Foundation (FCT) Grant No. CEECIND/01906/2018 and PTDC/FIS-PLA/3800/2021.

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Positron acceleration: an experimental and numerical challenge

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Post-acceleration of positrons in plasma wakefield[1-7]

e^+ beam from linear accelerator (2 km at SLAC) →

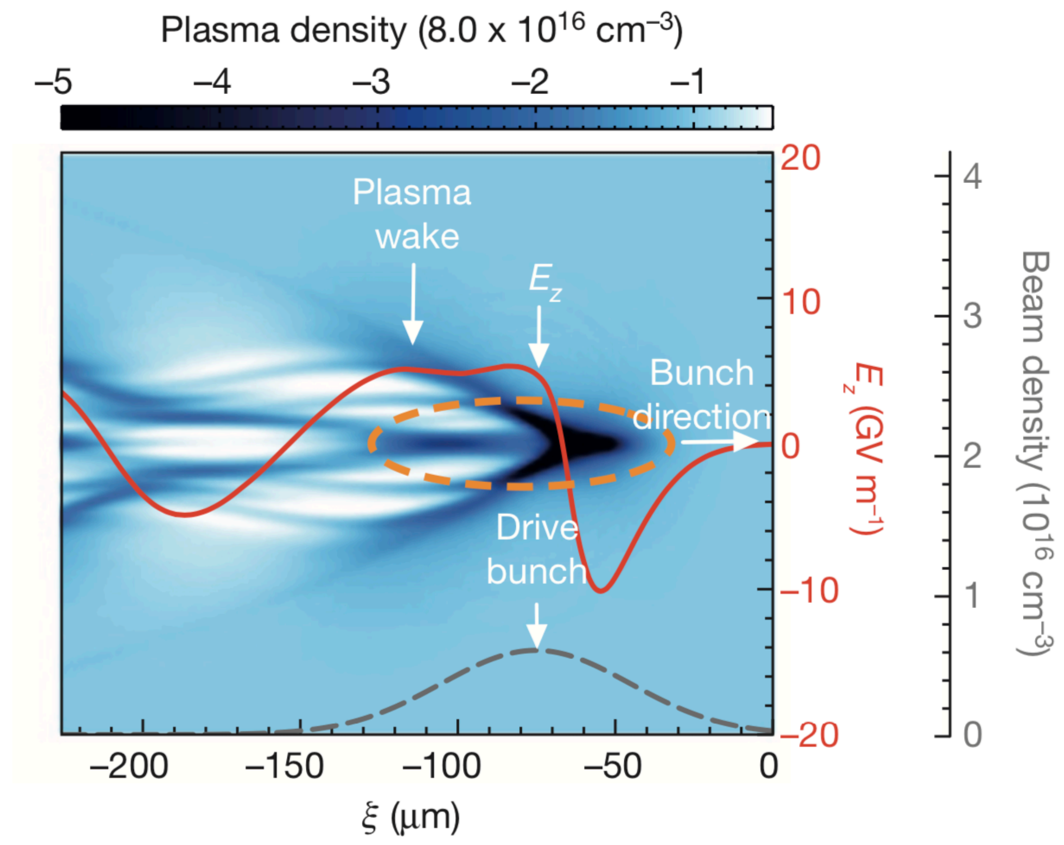


Image credit to S. Corde et al., Nat. **524**, 442-445 (2015)

High charge and quality beam, experimental availability
But, no in-situ creation of positrons

Positron creation with multi-PW lasers[8-10]

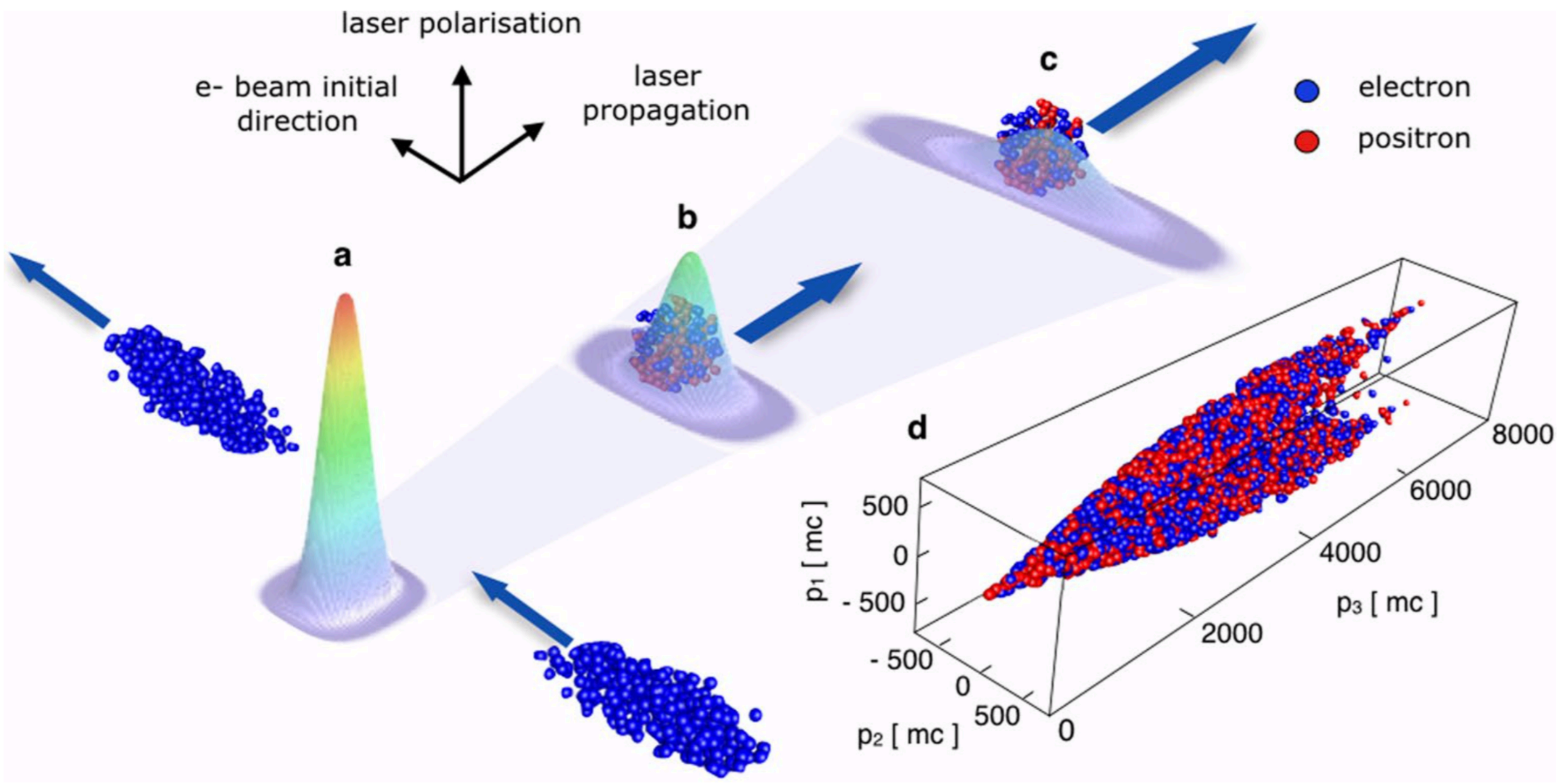


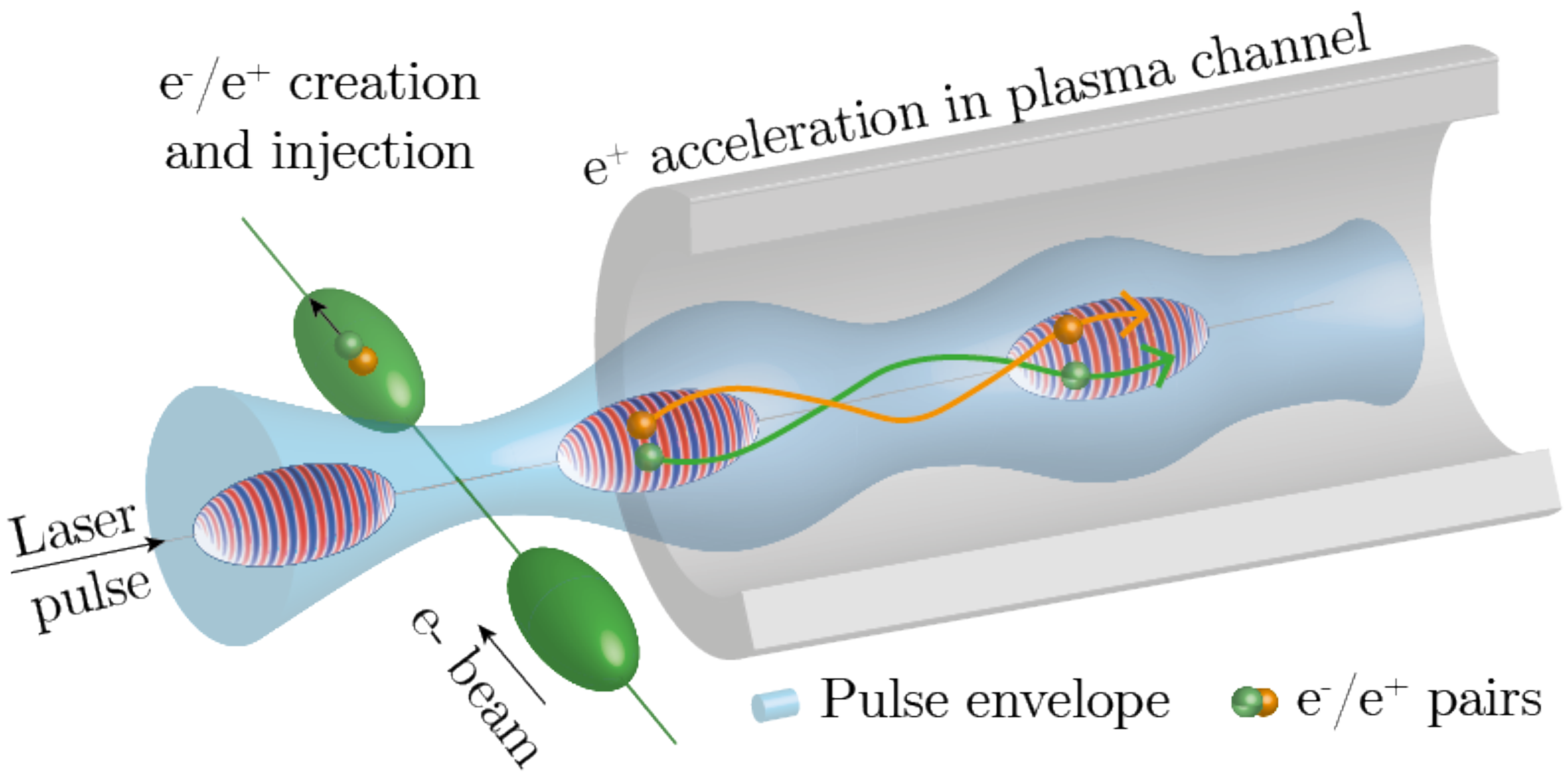
Image credit to M. Vranic et al., SR **8**, 4702 (2018)

2D and/or staged simulations → no quantitative estimate
Short acceleration distance $\sim 50\,\mu\mathrm{m}$

[1] M.J. Hogan et al., PRL **90**, 205002 (2003)
[2] B.E. Blue et al., PRL **90**, 214801 (2003)
[3] S. Corde et al., Nat. **524**, 442-445 (2015)
[4] N. Jain et al., PRL **115**, 195001 (2015)
[5] S. Gessner et al., NC **7**, 11785 (2016)
[6] A. Doche et al., SR **7**, 14180 (2017)
[7] C. Lindstrom et al., PRL **120**, 124802 (2018)
[8] M. Vranic et al., SR **8**, 4702 (2018)
[9] Z. Xu et al., CP **3**, 191 (2020)
[10] Y. He et al., CP **4**, 139 (2021)

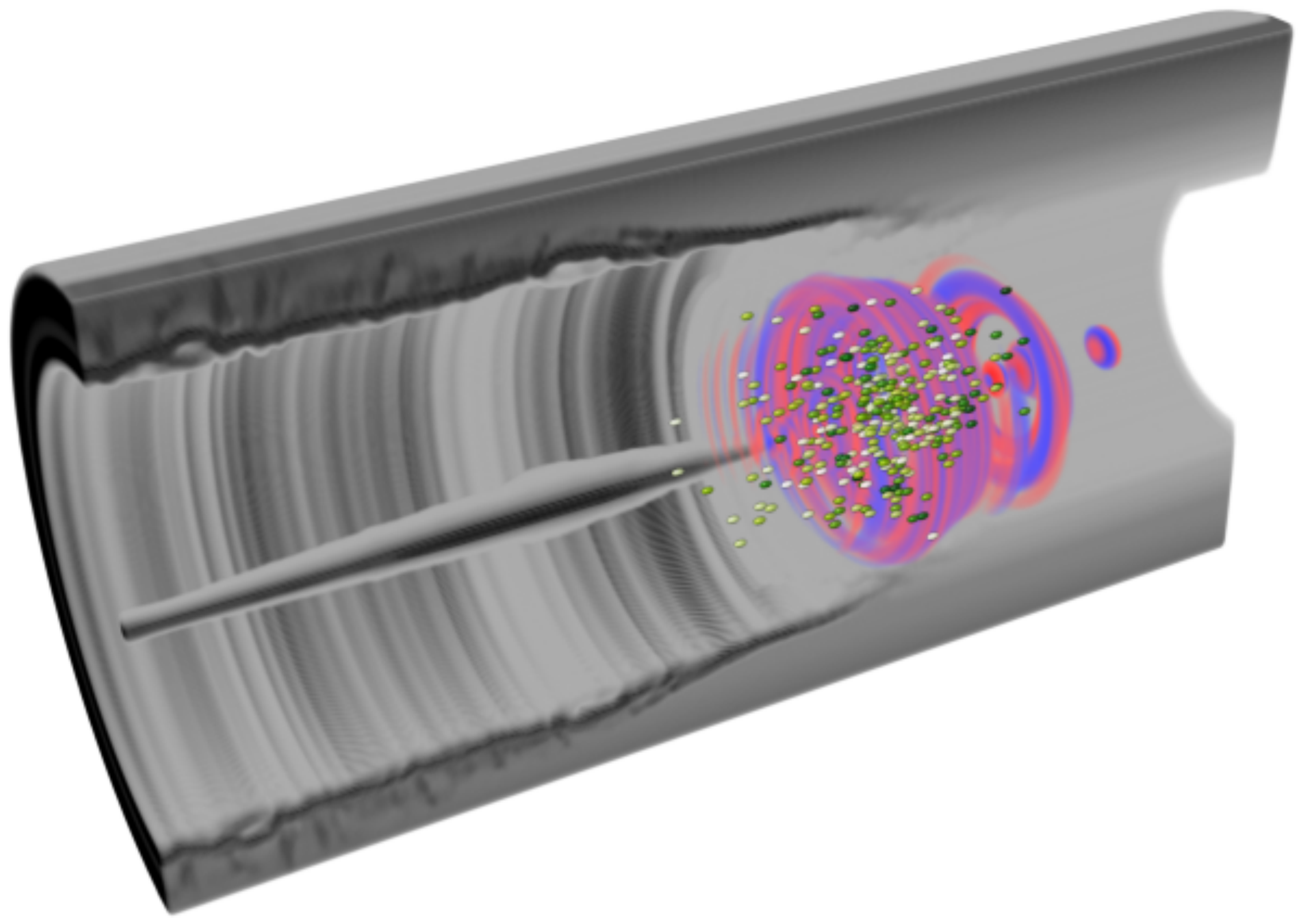
Outline

Paper available arXiv:2207.08728



Numerical modelling and theory

- Implementation: Quasi-3D decomposition with QED processes
- How can we guide positrons in a plasma channel ?

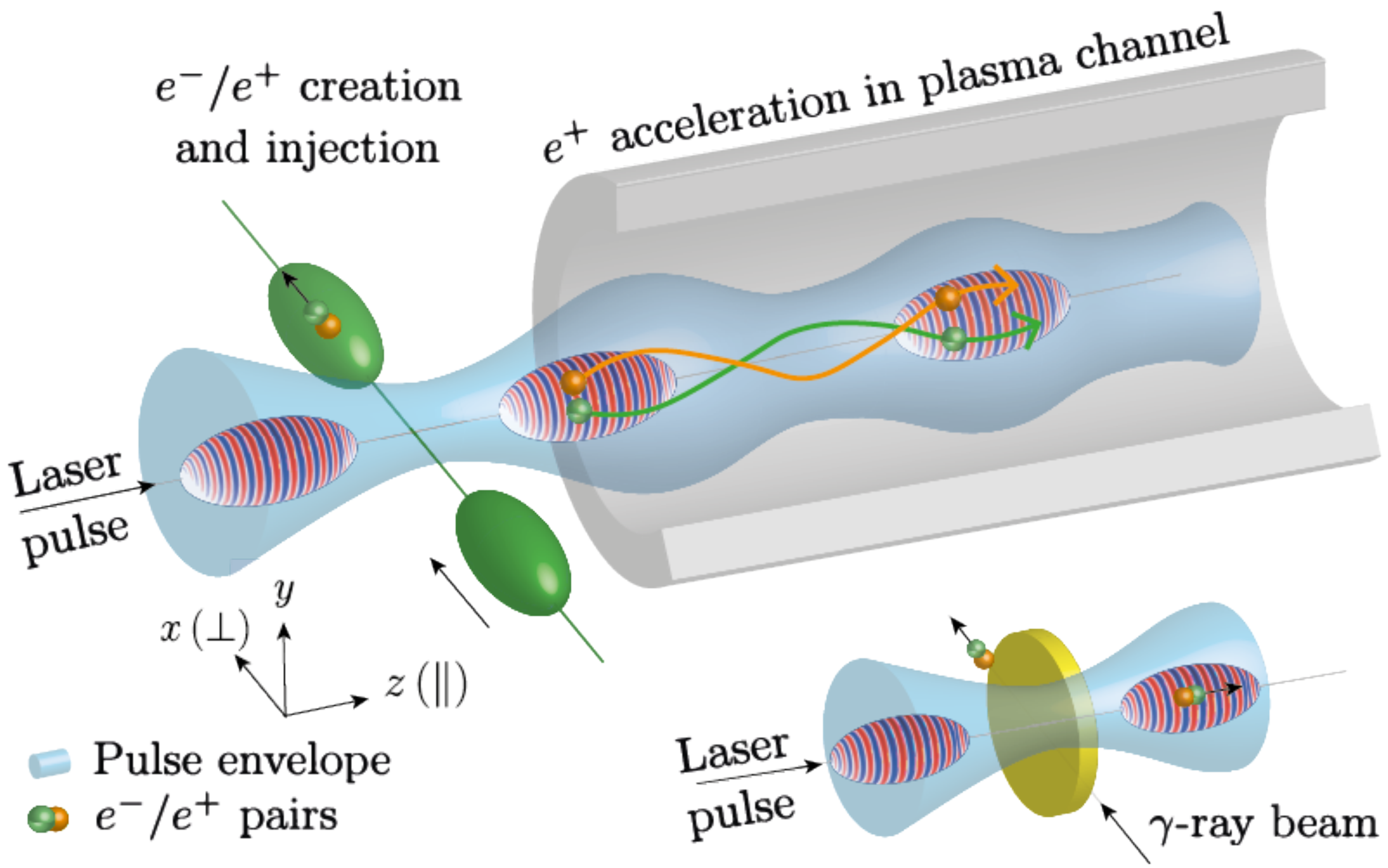


One-to-one full-scale numerical simulations

- Positron guiding via a self-loaded dense electron beam
- Direct laser acceleration of positron

Modelling geometry: quasi-3D

3D modelling of the laser guiding is necessary, but out of reach for super computers



Quasi-3D: Fourier decomposition in azimuthal modes[1,2]

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

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

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

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

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

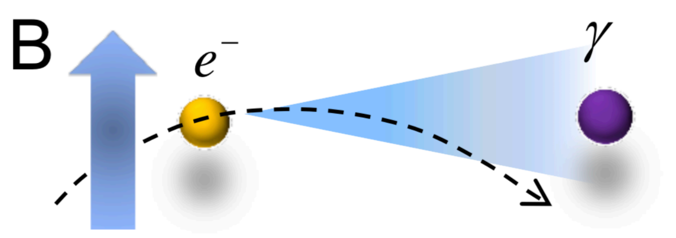
[1]A. Lifschitz et al., JCP **228**(5), 1803-1814 (2009)

[2]A. Davidson et al., JCP **281**, 1063-1077 (2015)

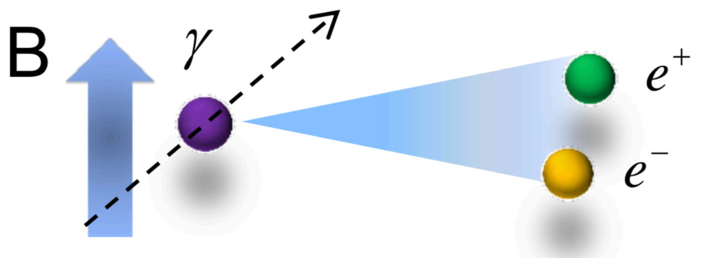
Requirements in terms of numerical implementations

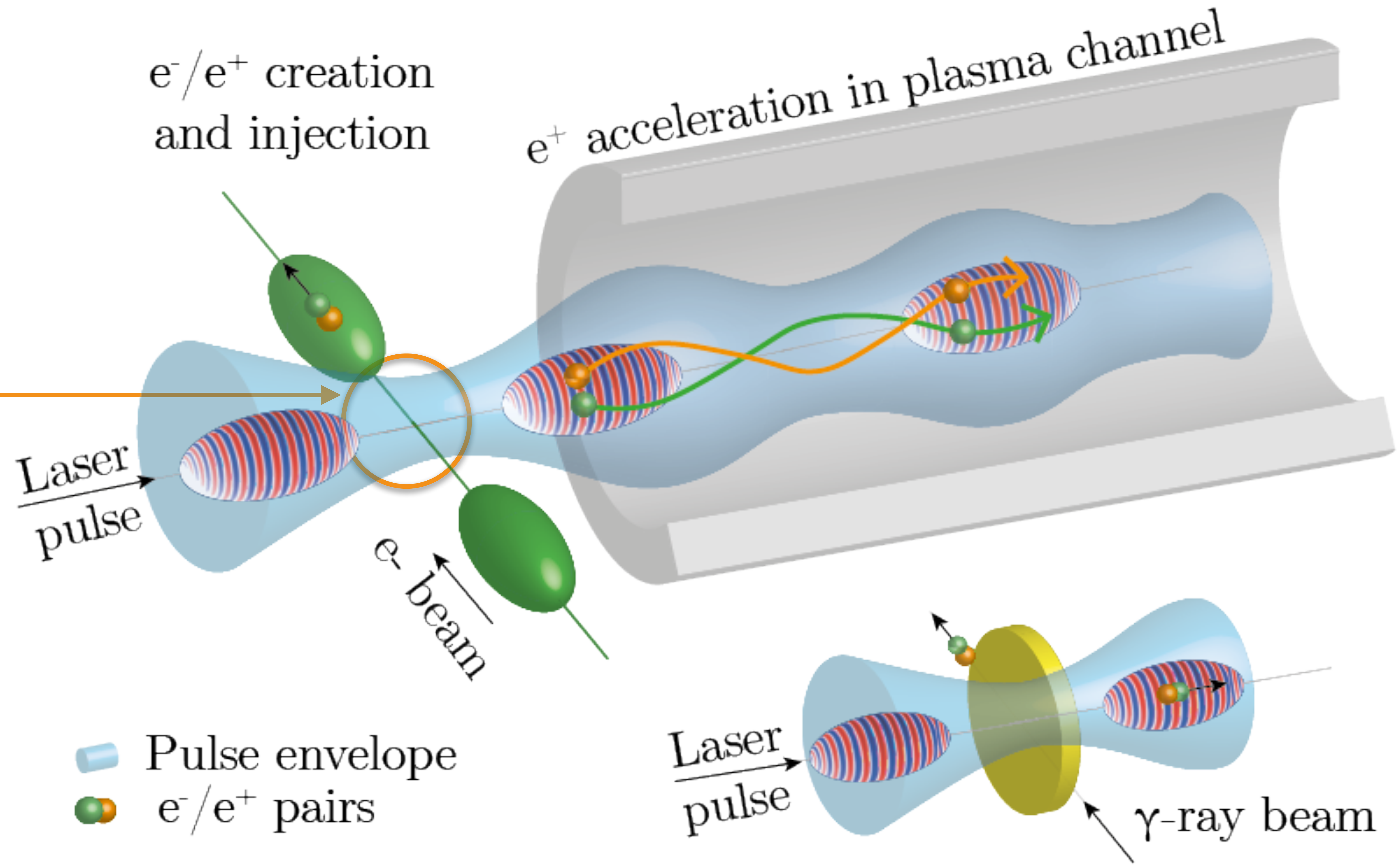
We need to account for QED processes taking place at the focal plane[1]

Non-Linear Compton scattering



Breit-Wheeler pair production





[1] R. A. Fonseca et al., in ICCS, LNCS **2331** 342 –351 (2002)
[2] A. Davidson et al., JCP **281**, 1063-1077 (2015)
[3] B. Martinez et al., arXiv 2207.08728 (2022)

Overview on the Particle-in-cell method[1]

Fields are discretised on a grid

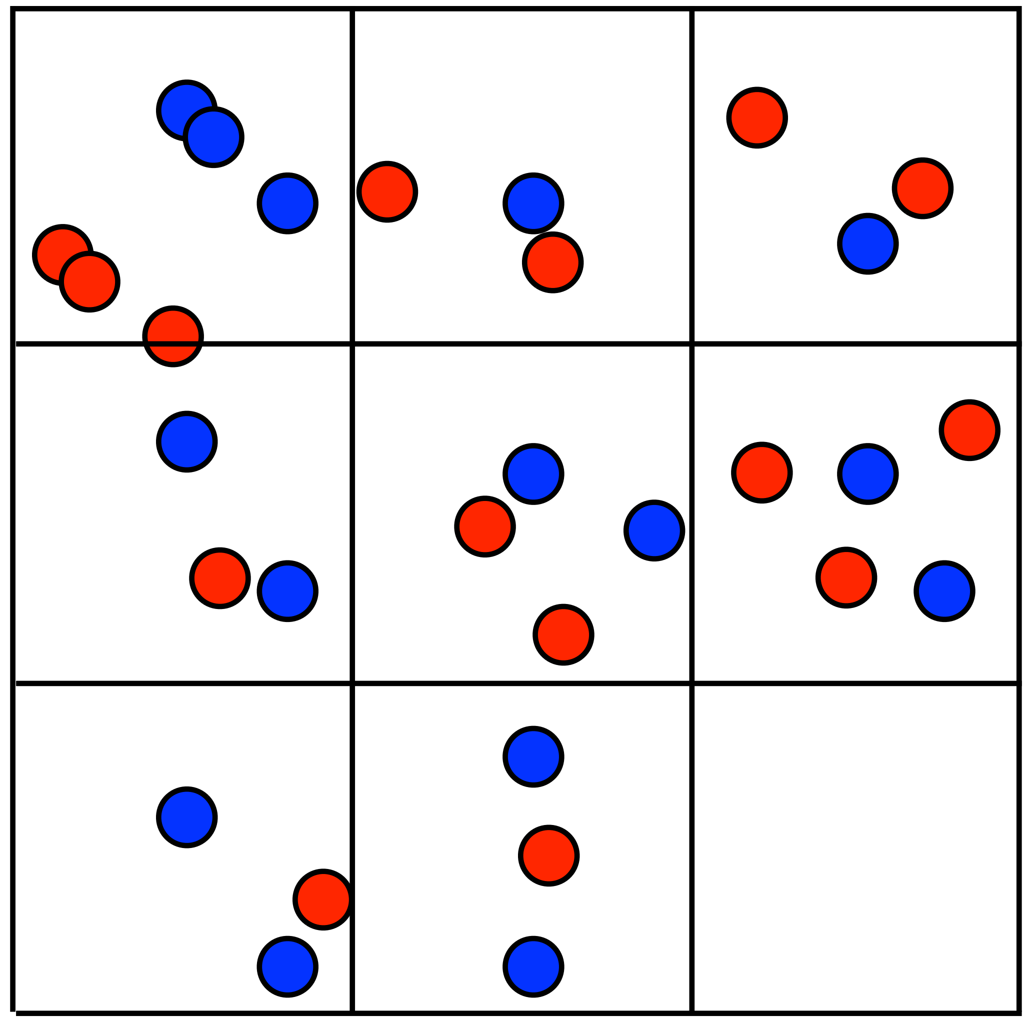
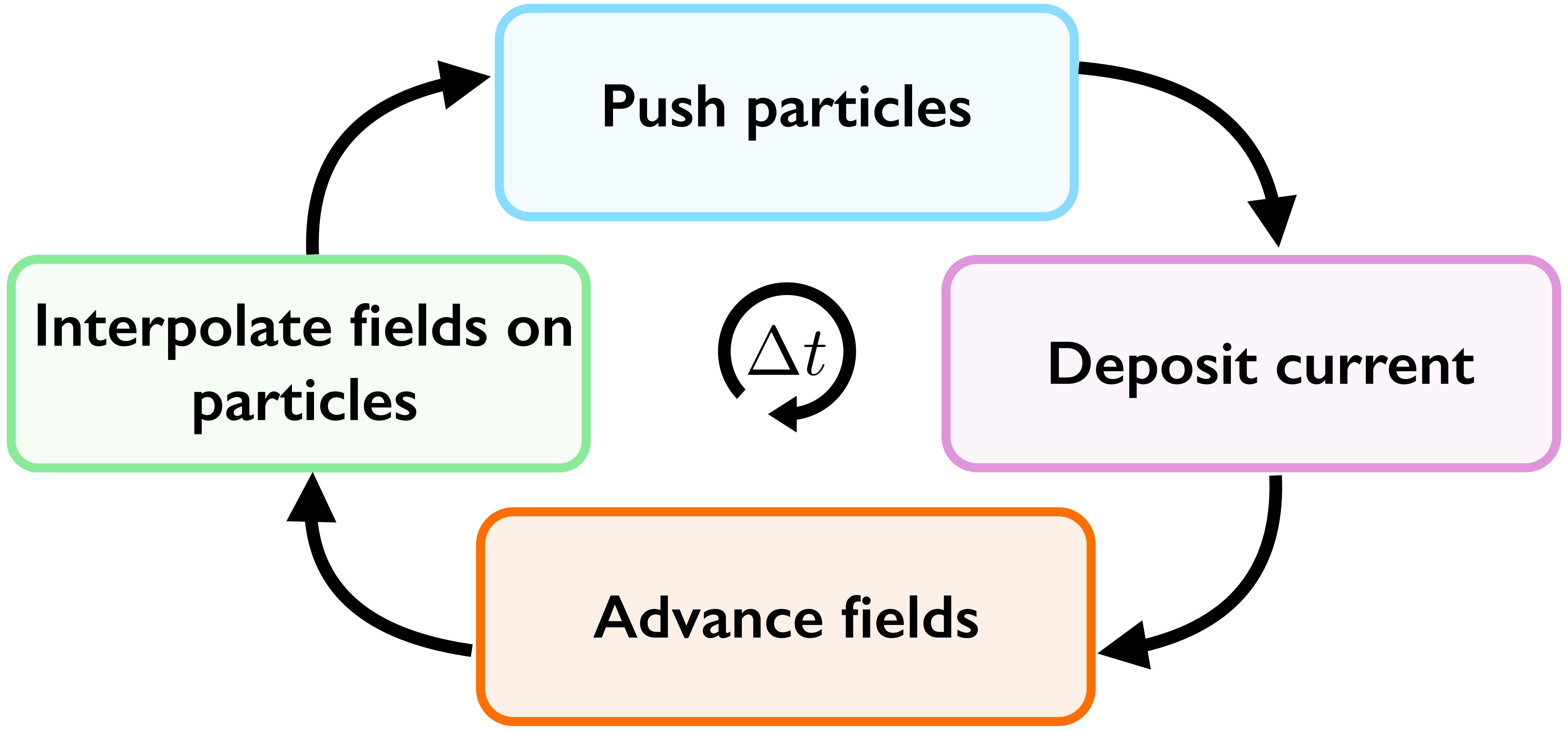


Image credit to L.O. Silva

The Particle-In-Cell method



[1] C.K. Birdsall, and A. B. Langdon, *Plasma Physics via Computer Simulation* (1991)

Fields are discretised on a grid

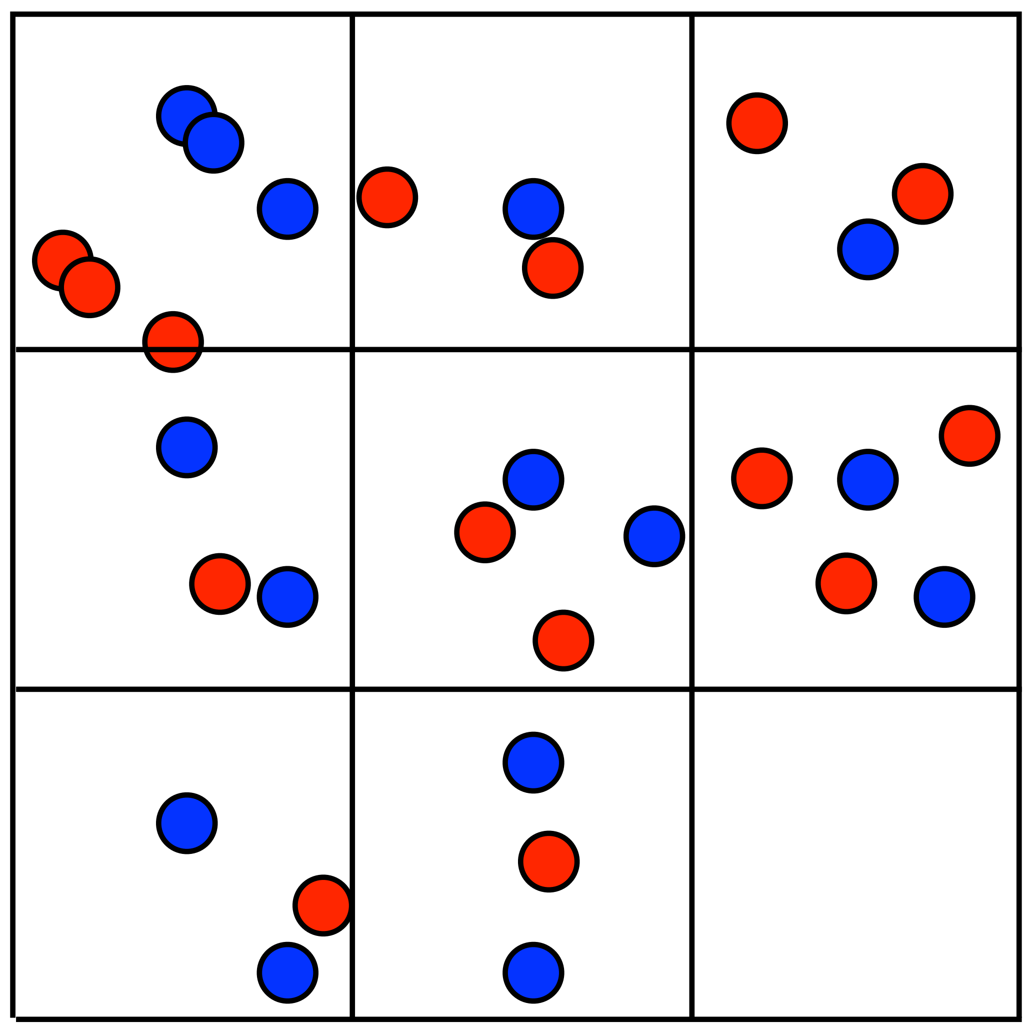
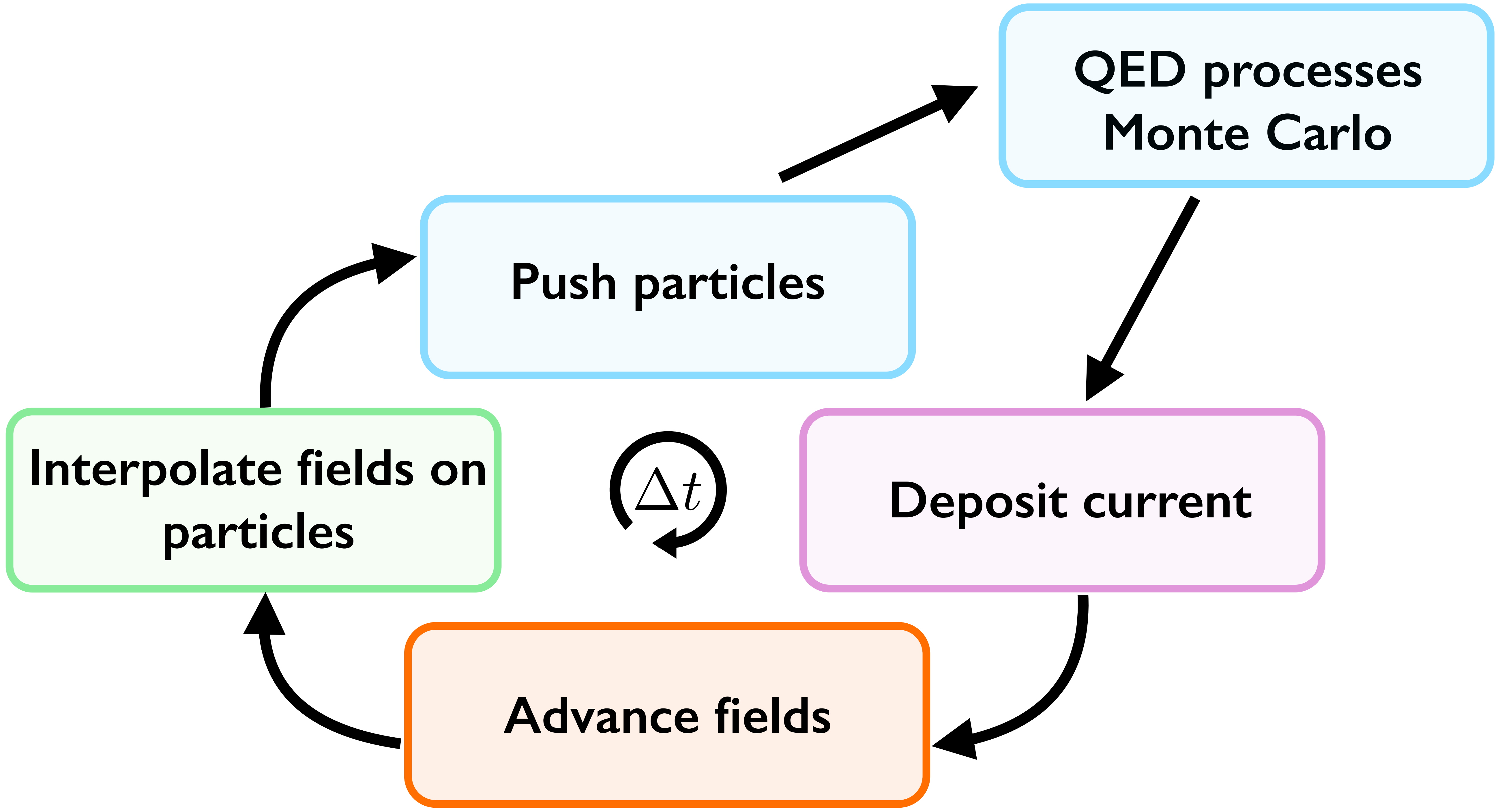


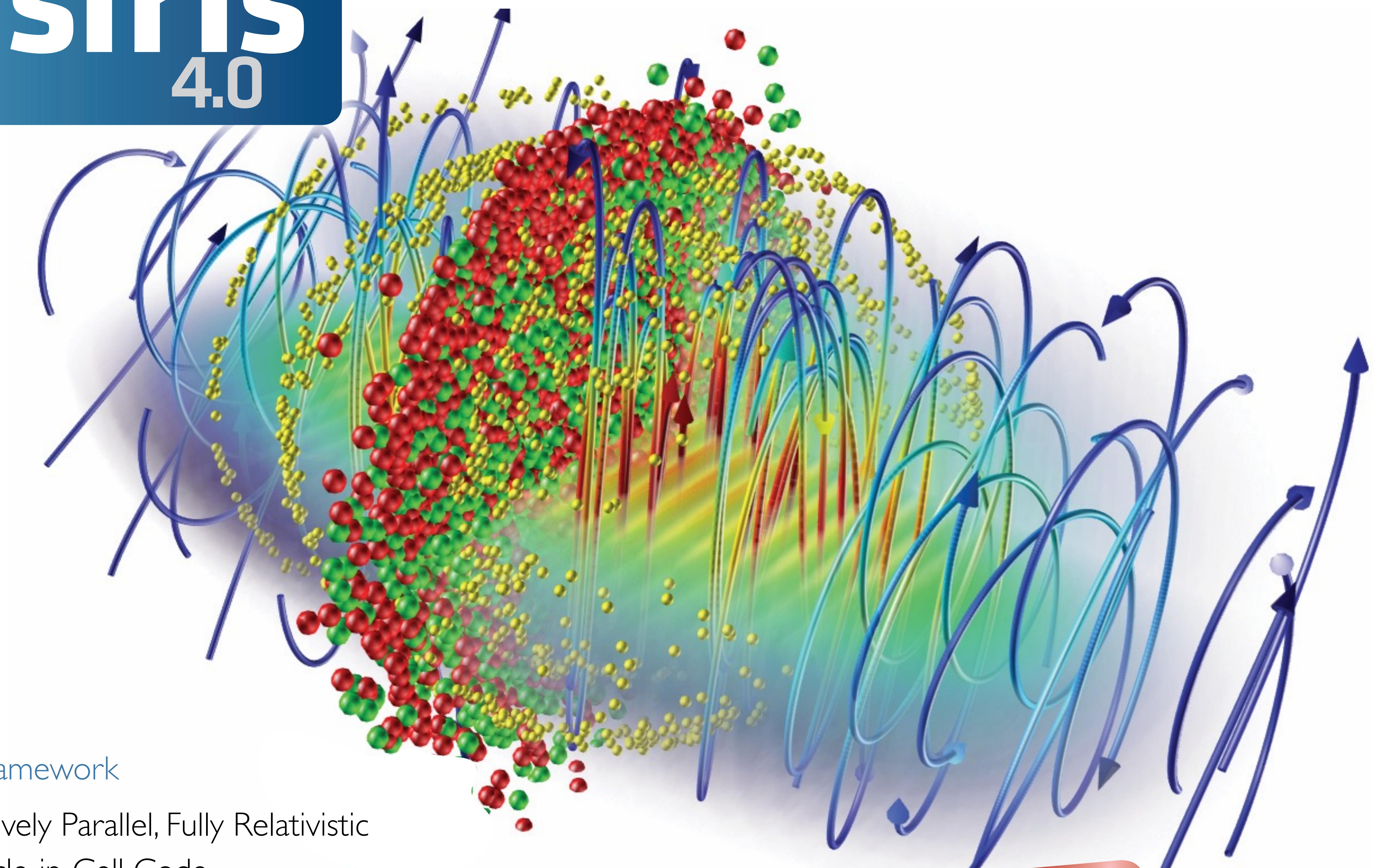
Image credit to L.O. Silva

The Particle-In-Cell method with QED processes



[1] A. Zhidkov et al., PRL **88**, 18 (2002)
[2] C.P. Ridgers et al., PRL **108**, 165006 (2012)

OSIRIS 4.0



Open-access model

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

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at: epp.tecnico.ulisboa.pt/osiris

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

VisXD

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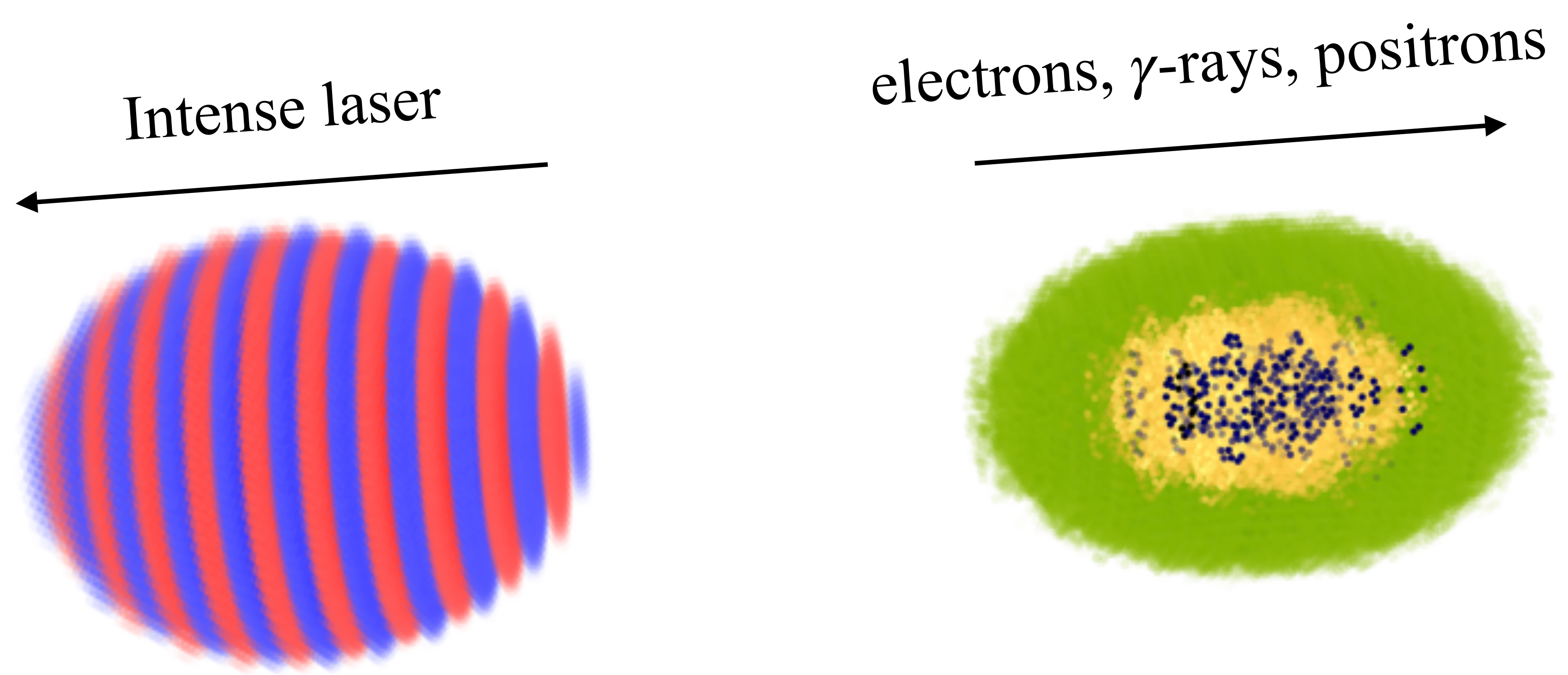
Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

Osiris Quasi-3D: implementation of γ-ray and $e^{\pm}$ pair creation

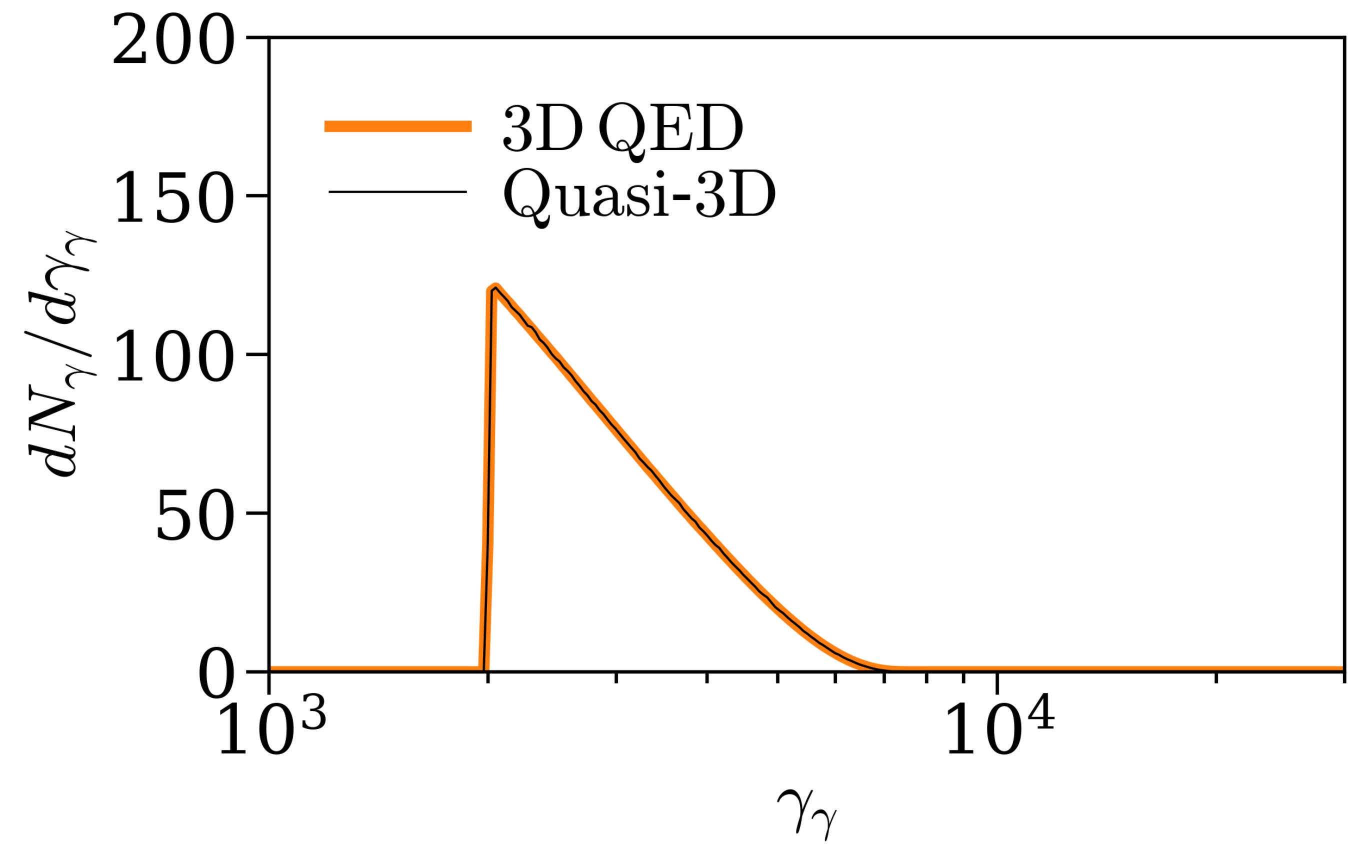
Laser pulse colliding with a relativistic electron beam



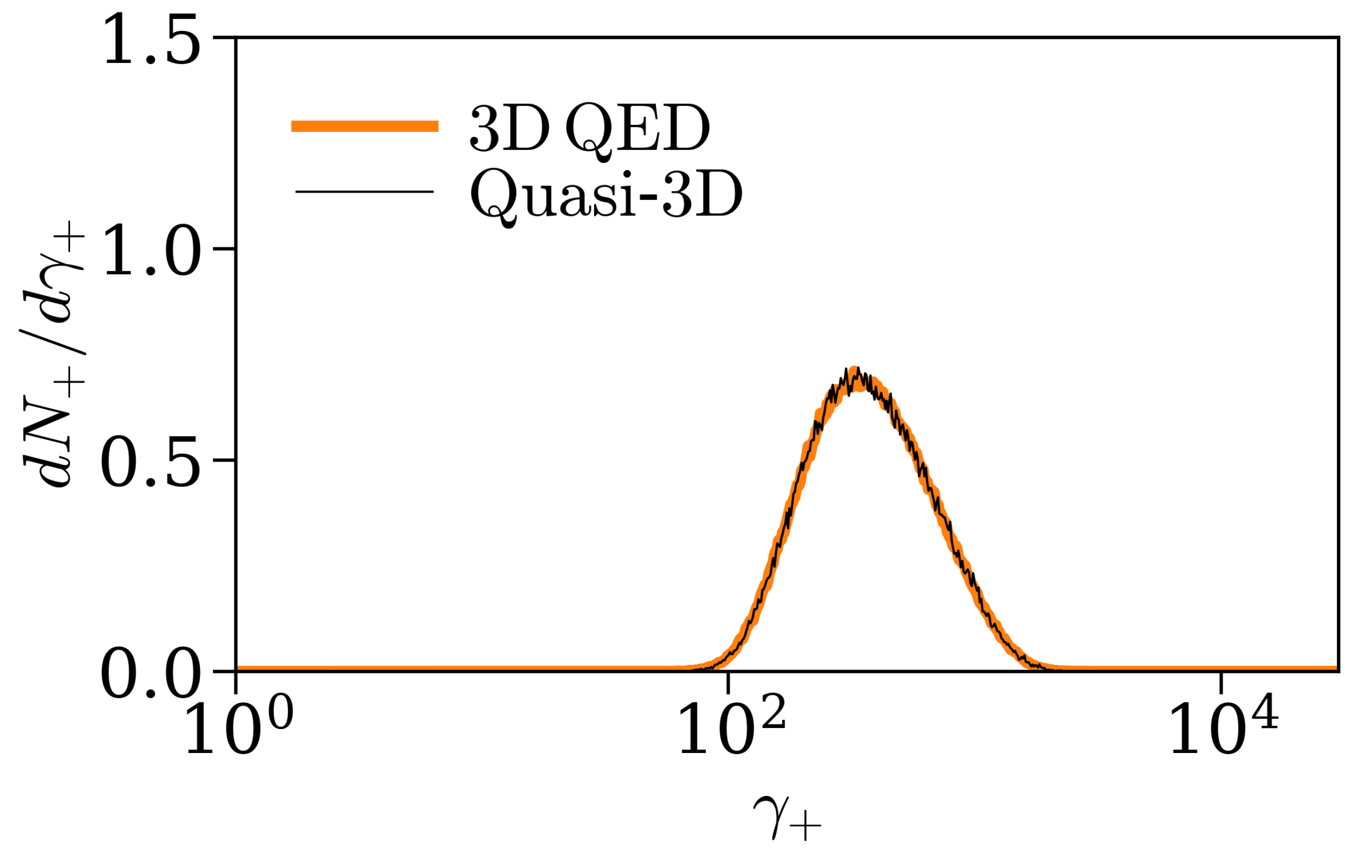
3D QED → Quasi-3D
Computational gain is reduced by a factor ~ 400
80 kCPU.hours → 0.2 kCPU.hours

Pair production is the same in 3D and Quasi-3D

Energy spectrum of photons



Energy spectrum of positrons



Simulation of single-stage positron acceleration

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Consistent simulation of positron creation and acceleration

Laser pulse[1-3] (red/blue)

$80\,\mathrm{PW}$ and $12\,\mathrm{kJ}$

$150\,\mathrm{fs}$ duration, peak amplitude $5 \times 10^{23}\,\mathrm{W/cm^2}$

Photon beam[4-5]

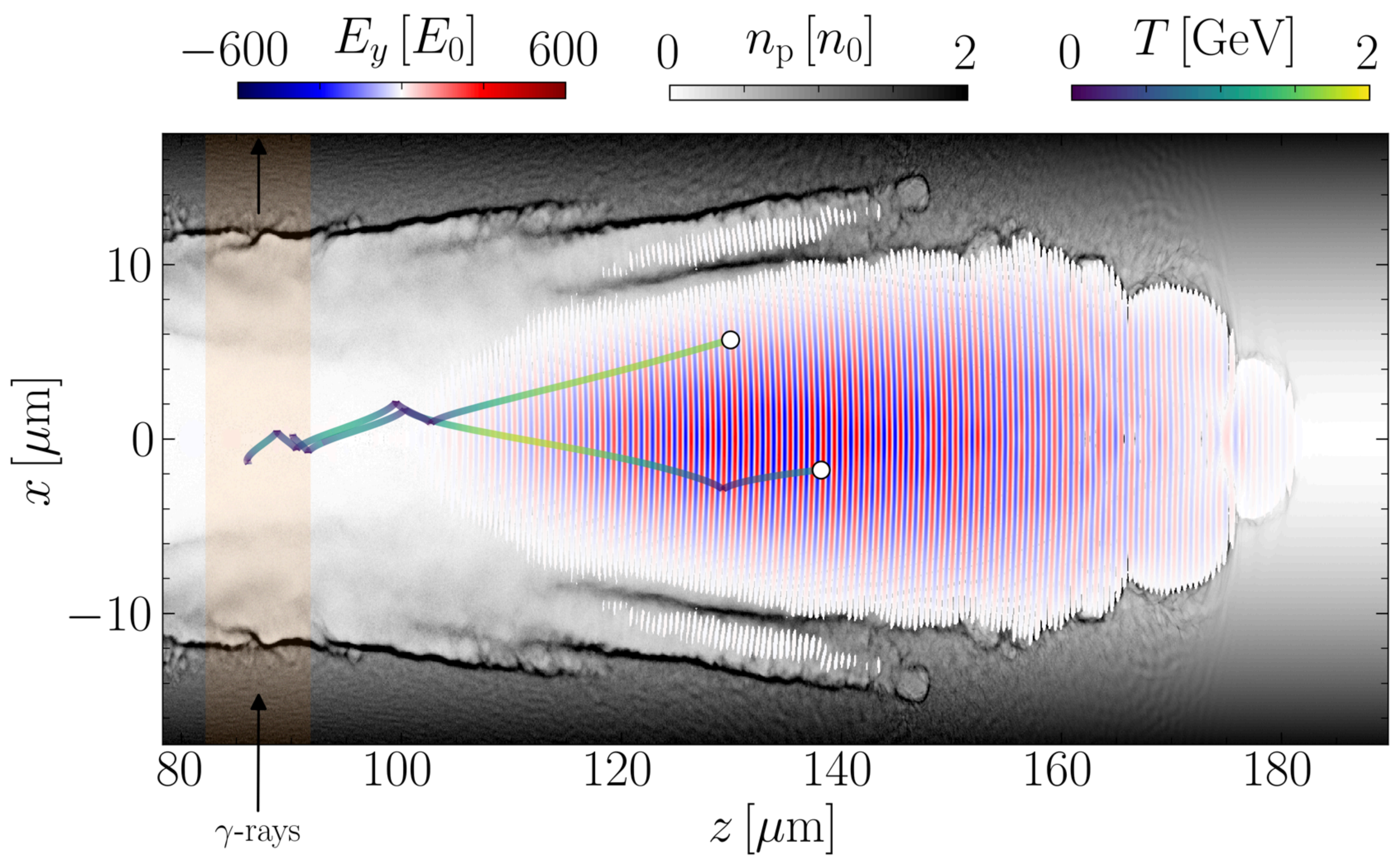
Synchrotron energy profile

Transverse periodic boundary condition

Submillimeter dense plasma channel[6] (gray)

Transverse density profile is parabolic

Plasma gradient at the boundary



B. Martinez et al., arXiv 2207.08728 (2022)

[1] J. Bromage et al., HPLSE **7**, e4 (2019)
[2] G. Mourou et al., ELI Whitebook (2011)
[3] B. Shao et al., OL **45**, 2215 (2020)
[4] A.J. Gonçalves et al., PRL **122**, 084801 (2019)
[5] H.T. Kim et al, SR **7**, 10203 (2017)
[6] F. Sylla et al., RSI **83**, 033507 (2012)

Positron are guided by a dense and self-loaded electron beam

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How are positrons focused ?

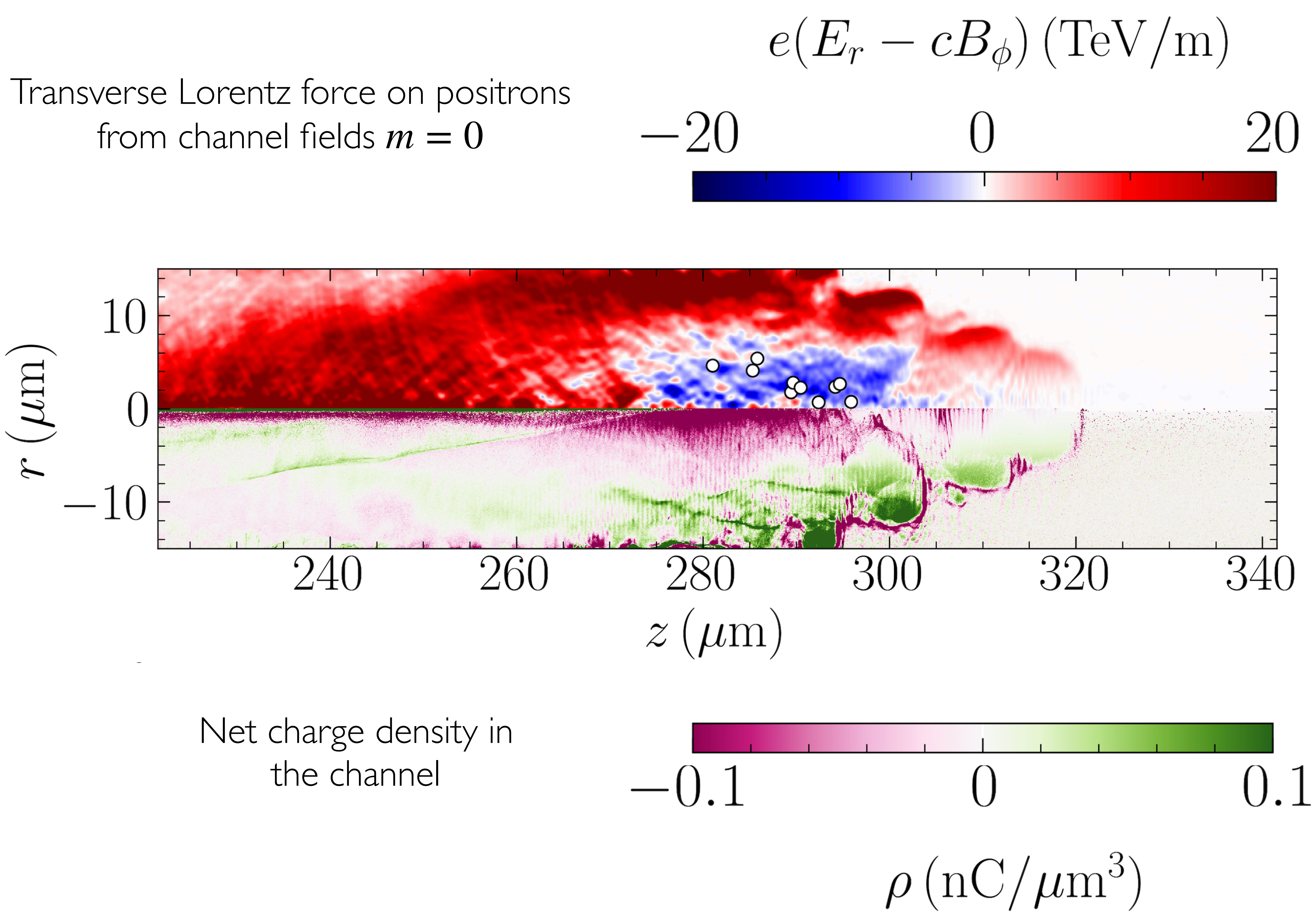
B. Martinez et al., arXiv 2207.08728 (2022)

Large e^- density in channel walls
+ ion motion[1,3,4] + radiation reaction[1,2]

Large central e^-beam loading (800 nC)

Positron focusing fields

Transverse Lorentz force on positrons from channel fields $m = 0$



Net charge density in the channel

[1] L. L. Ji et al., PRL **112**, 145003 (2014)
[2] M. Vranic et al., PPCF **60**, 034002 (2018)
[3] T. Wang et al., PPCF **61**, 084004 (2019)
[4] E.G. Gelfer et al., NJP **23**, 095002 (2021)

Charge content and the energy spectrum of the positron beam[I]

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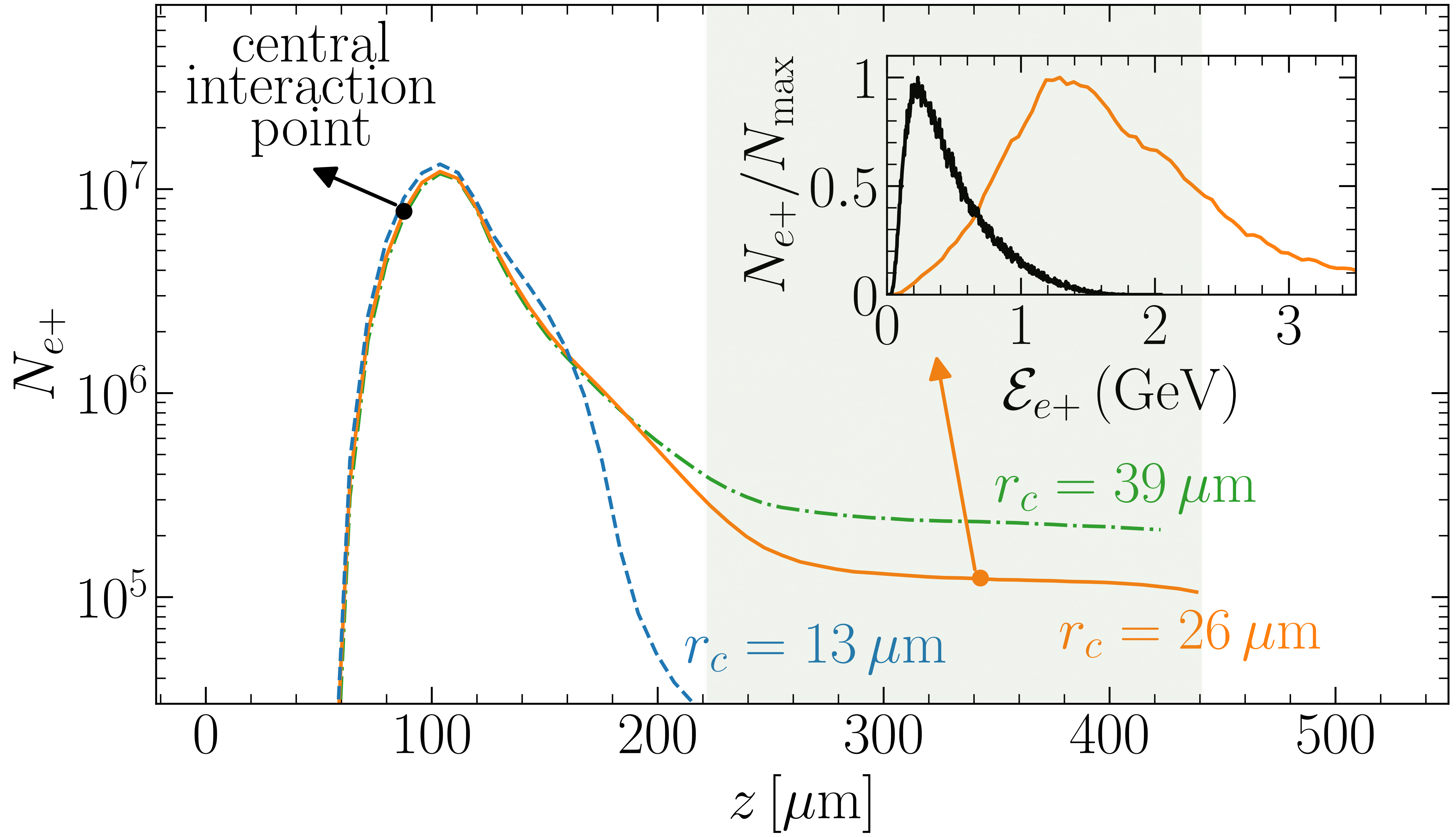
About the focusing structure

Number of positrons as a function of the laser propagation distance for different channel widths.



About the guiding structure

- It starts after ~200 μm
- It is sustained for ~200 μm

After ~ 400 μm of propagation

- Total charge 17 fC
- Energy gain $0.22 \rightarrow 1.3$ GeV (6-fold increase)
- Inset: $N_{\max} = 6$ pC/GeV and 12 fC/GeV

[I] B. Martinez et al., arXiv 2207.08728 (2022)

Positrons gain energy through direct laser acceleration[1]

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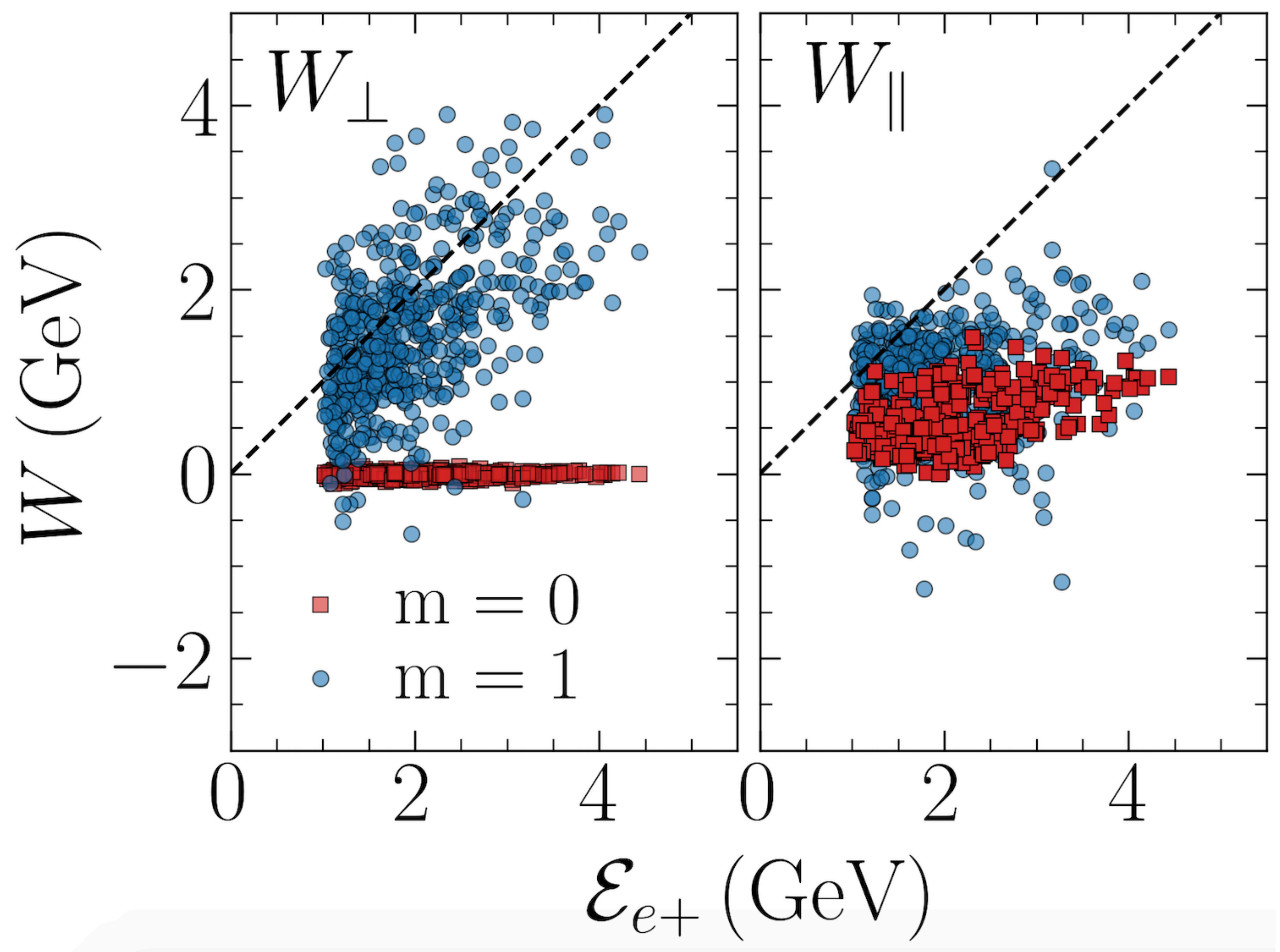
Summary of work performed by different field components towards positron acceleration (500 trajectories)

Energy gain in different field components



A recall of the coordinate system

x(⊥) : polarisation

z(‖) : propagation

Work from channel field $\rightarrow m = 0$

Work from laser field $\rightarrow m = 1$

Dashed line = limit where energy gain equals the final energy

Main energy gain from the laser field in its polarisation direction

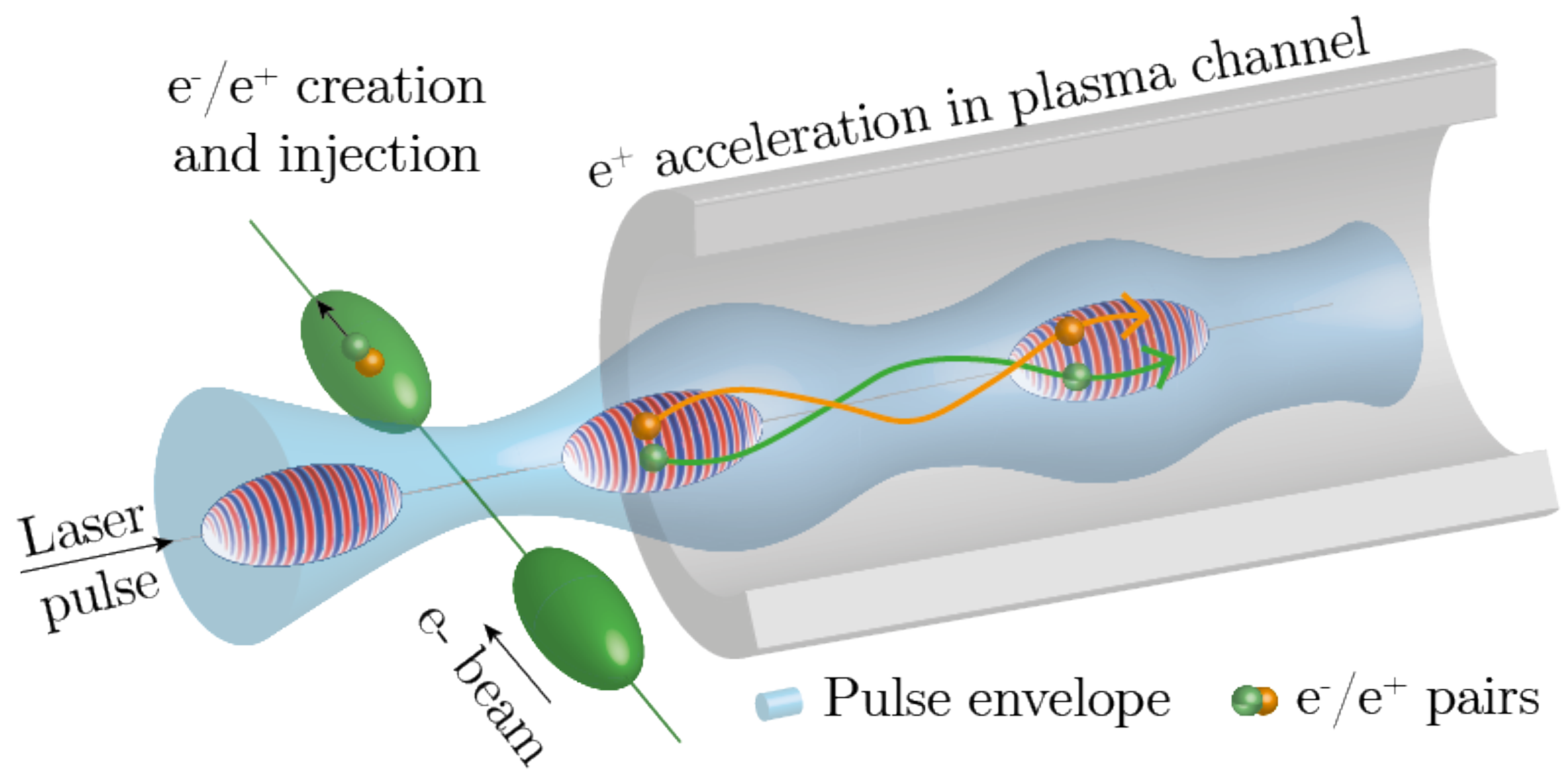
→ signature of direct laser acceleration

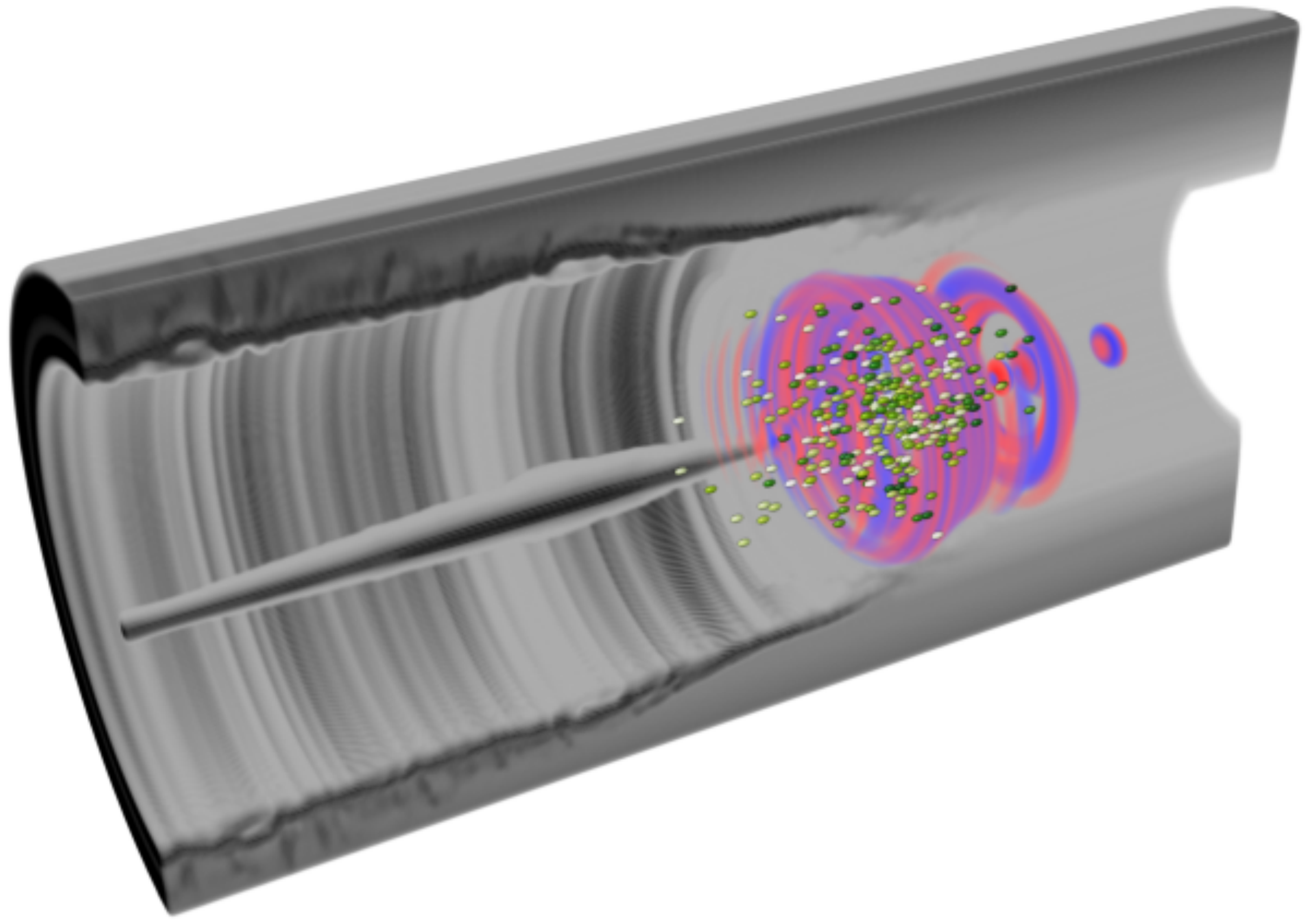
Longitudinal energy gain from channel and laser fields

→ the dephasing length of positrons is longer

[1] B. Martinez et al., arXiv 2207.08728 (2022)

Outline of our work[1]





Conclusions

- Implementation: Quasi-3D decomposition with QED processes
- Positron creation and acceleration in a single stage

Perspective 1: inject more positrons

- Use a higher charge electron beam[2,3] $10\,\mathrm{pC} \rightarrow 100\,\mathrm{nC}$

Perspective 2: decrease the laser power

- Combine the scheme with the Bethe-Heitler pair creation

[1] B. Martinez et al., arXiv 2207.08728 (2022)
[2] O.N. Rosmej et al., MRE **6**, 048401 (2021)
[3] A.E. Hussein et al., NJP **23**, 023031 (2021)

Discussion

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What future developments are needed ?

- Take advantage of new parallelisation methods (GPU, vectorisation)
- Particle pushers to handle high-amplitude fields
- Implement and handle more radiative/QED processes and particles

Do the planned activities address the requirements from funded projects

- It belongs to the 2020 Roadmap on plasma accelerators[1]
- It is not part of AWAKE, nor EuPRAXIA

Does simulation/theory require its own roadmap ?

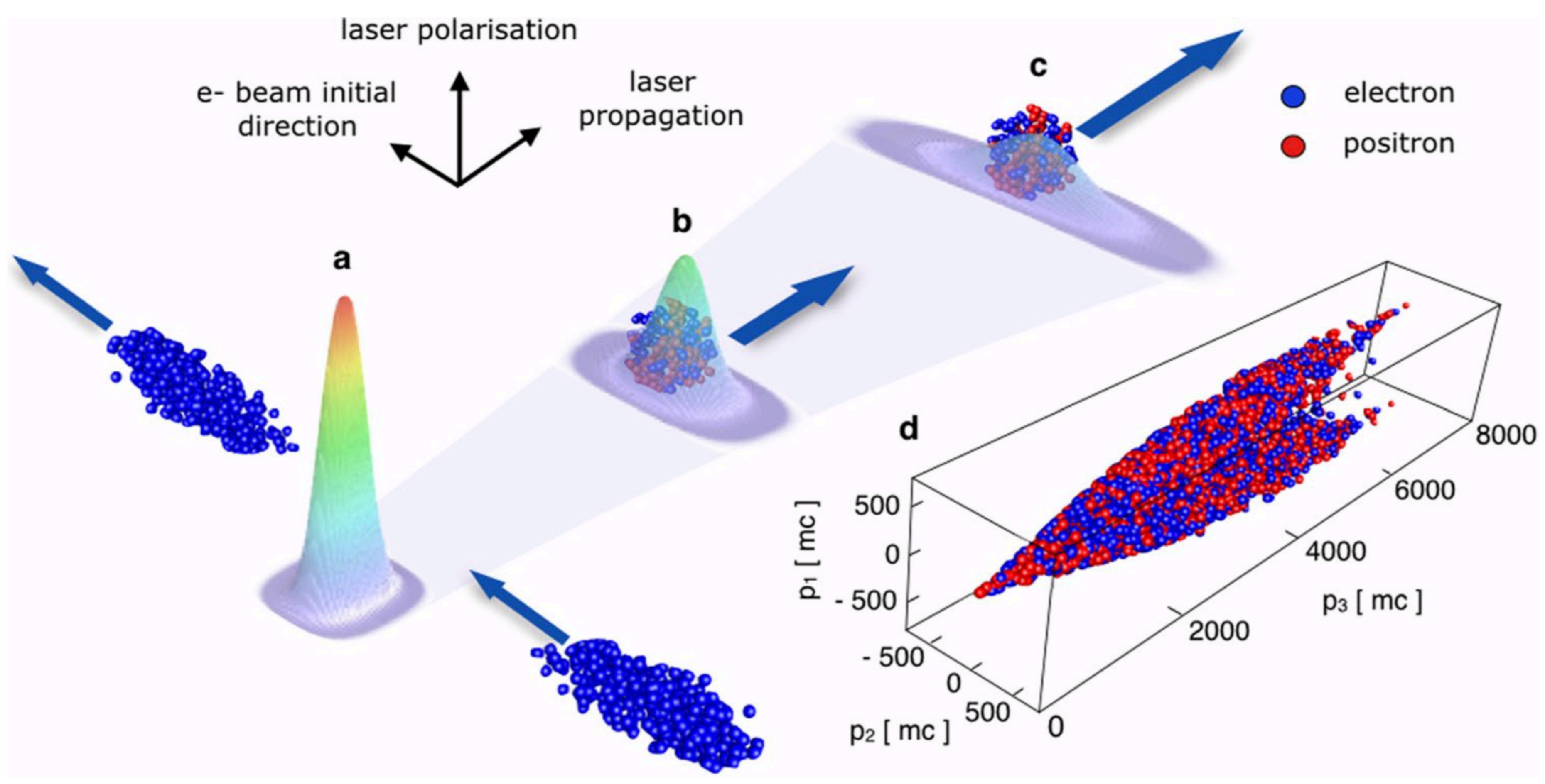
- Yes, multi-scale physics requires more developments
- It requires a roadmap, and also dedicated programs/fundings

[1] F. Albert et al., New J. Phys. **23**, 031101 NJP (2021)

Slides for questions

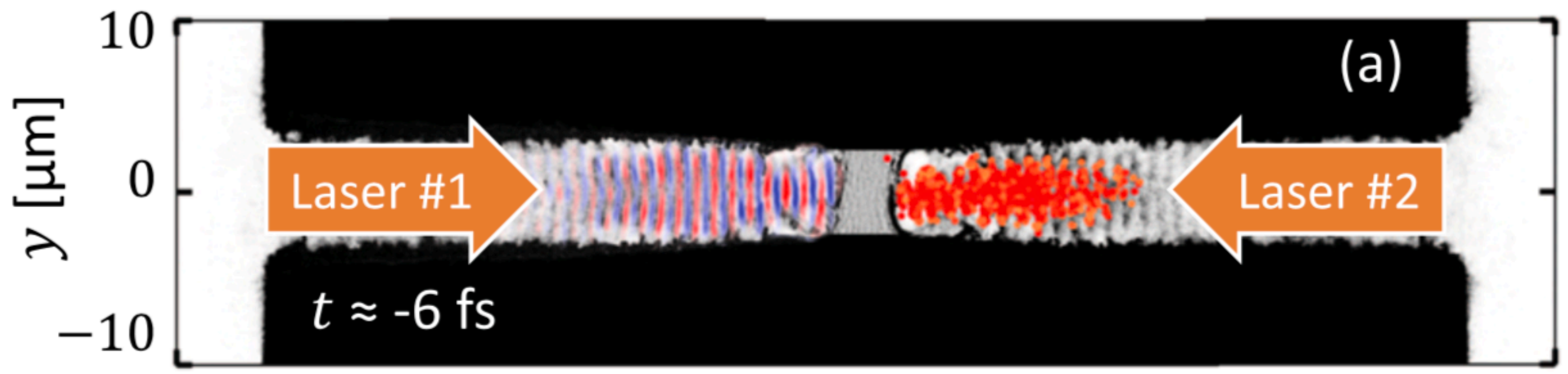
With multi-PW lasers, we can create, inject and accelerate positrons

Laser-electron beam scattering[1]



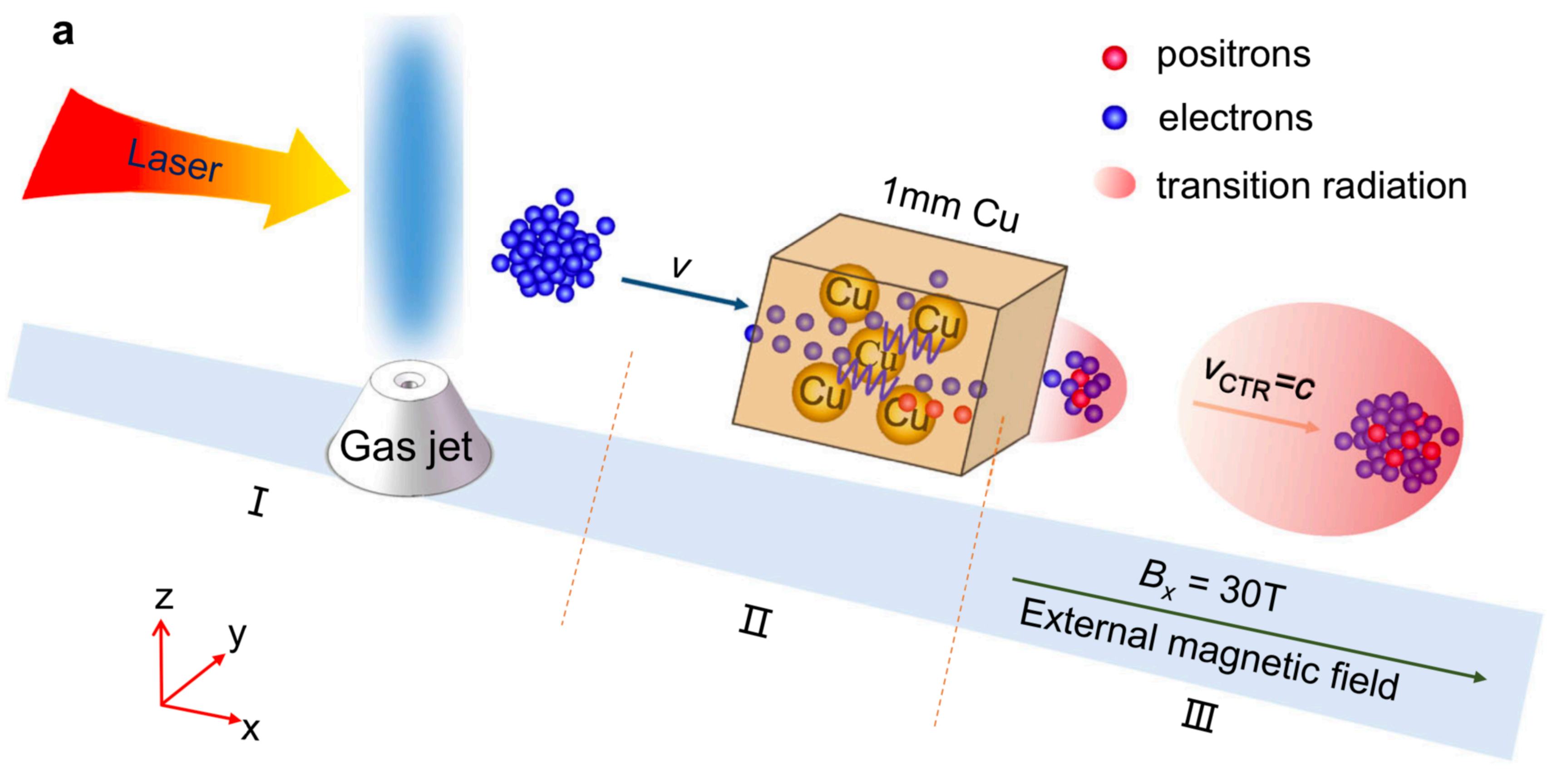
[1]M.Vranic et al, SR 8, 4702 (2018)

Two lasers in a dense and short channel[2]



[2]Y. He et al., 4, 139 (2021)

Acceleration in Coherent Transition Radiation fields[3]



[3]Z. Xu et al., CP, 3, 191 (2020)

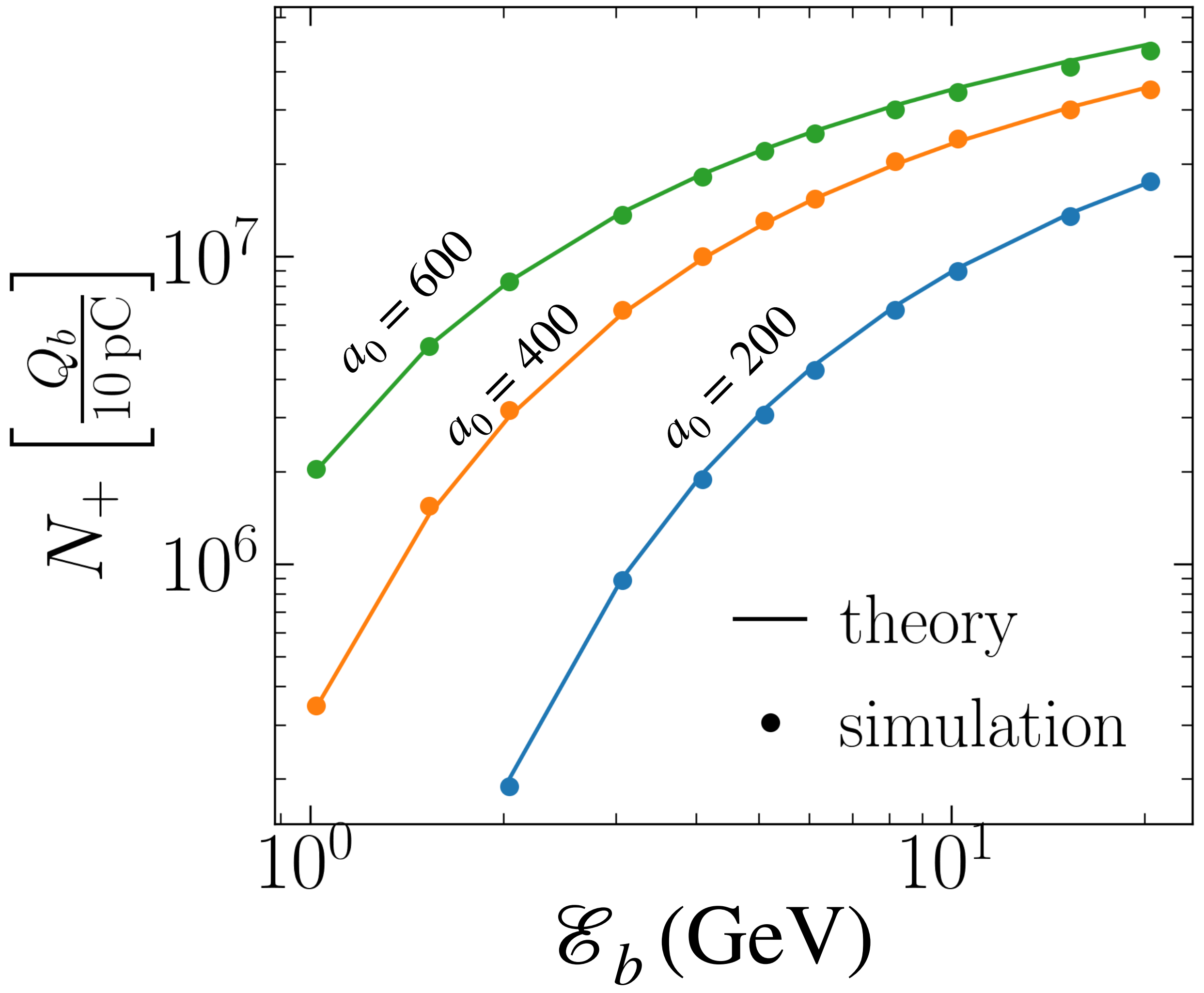
Weakness: 2D and/or staged simulations → No quantitative estimates !

Strength: Compactness, all-optical positron creation and acceleration

Positron creation can be quantified precisely

Estimate for the number of positrons created

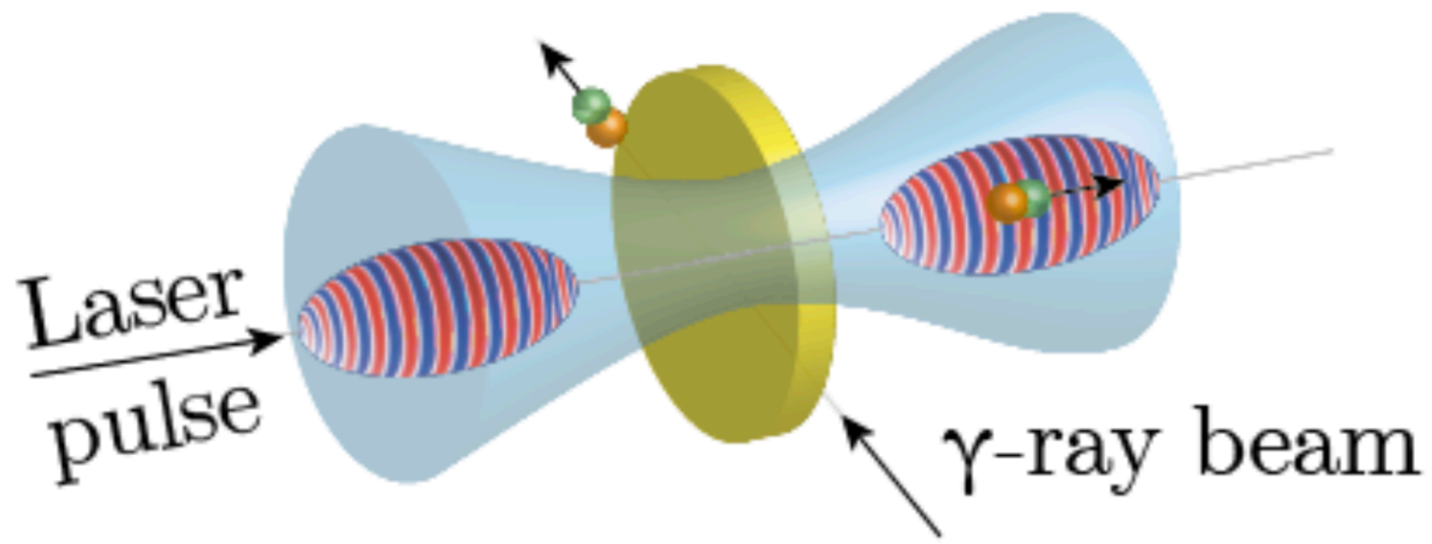
Number of positrons as a function of laser intensity and electron beam energy



We can quantify precisely how many positrons are created the laser focus

Derivation of the estimate[1]

Modelling of the problem



γ-rays beam = cylinder with infinite radius

Semi-analytical estimate for the number of positrons

$$N_+ = \int_2^{\gamma_e} d\gamma_\gamma \boxed{\frac{dN}{dt d\gamma_\gamma}} \times \int_0^{a_L} da \boxed{\frac{dN}{da}} \times \boxed{P_\pm(\gamma_\gamma, a, \tau_L)}$$

Decay probability for one photon in a plane wave[1]

Synchrotron energy distribution

a is the maximum field amplitude a photon will experience[2,3]

[1]T.G. Blackburn et al., PRA **96**, 022128 (2017)

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

[3]A. Mercuri-Baron et al., NJP **23** 085006 (2021)

What is the optimal electron beam energy for injecting most positrons?

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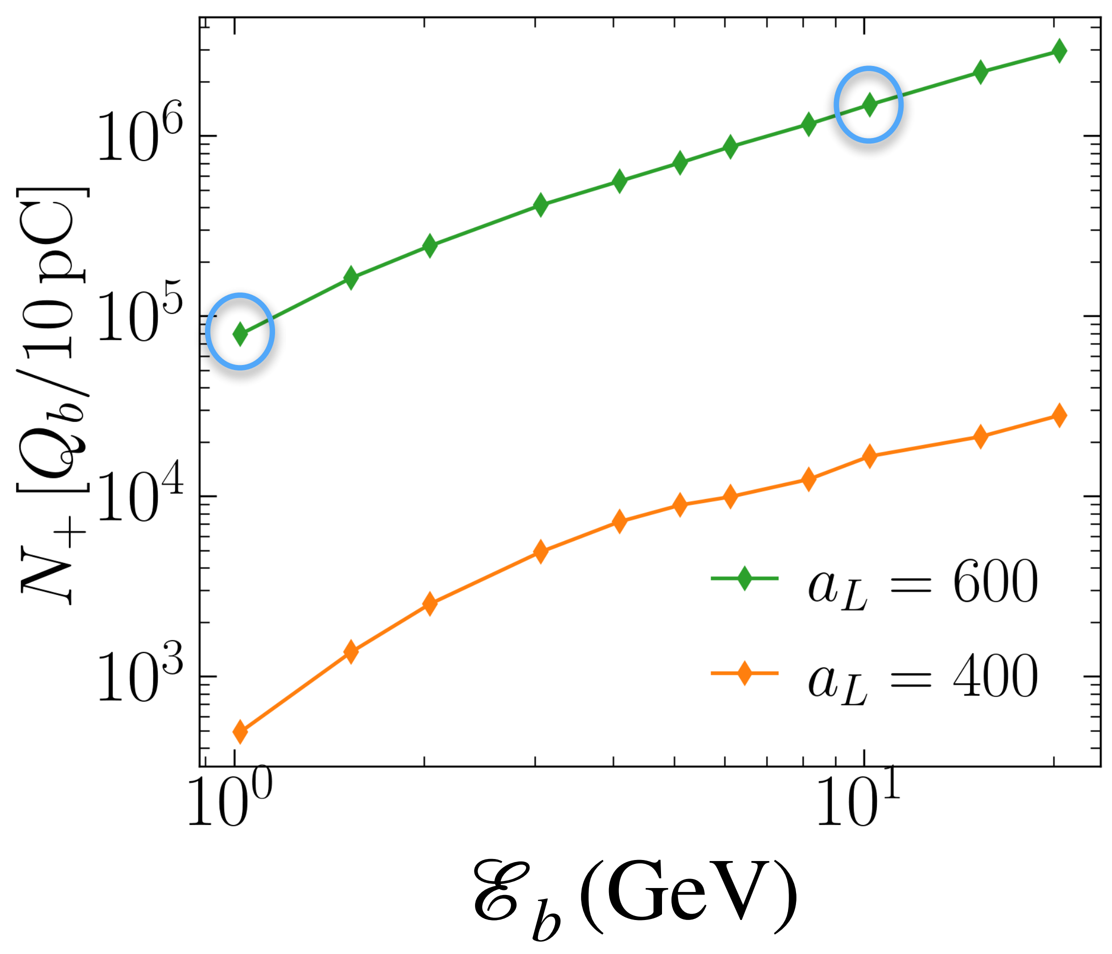
There is a trade-off between having more positrons overall and the injection efficiency

Higher energy electron beams are better…

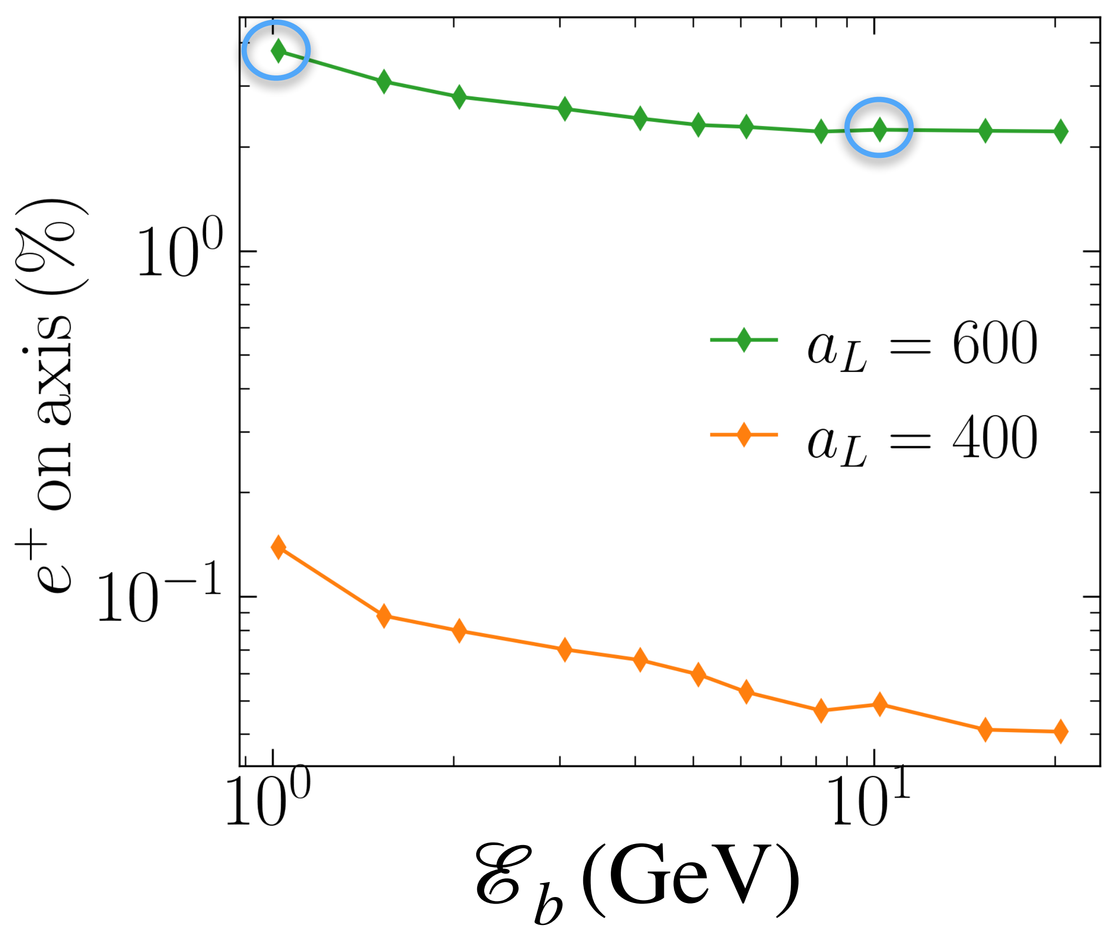
Number of deflected positrons as a function of laser intensity and electron beam energy



One can inject 10 times more positrons by increasing $\mathscr{E}_b$ from 1 to 10 GeV

… but less efficient

Fraction of positrons deflected as a function of laser intensity and electron beam energy



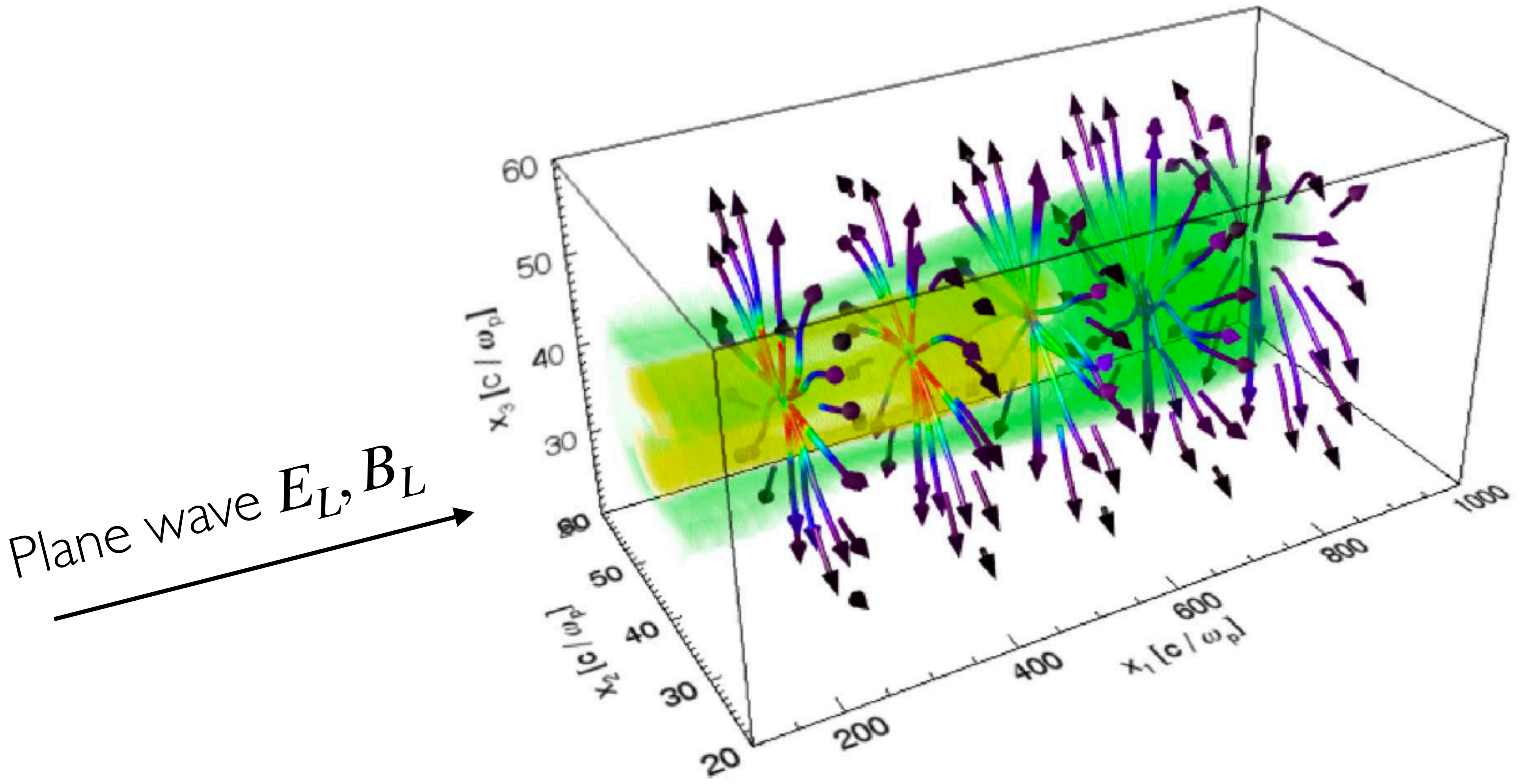
The efficiency of injection decreases from 4% to 2% by increasing E_b from 1 to 10 GeV

A good compromise is to choose a 2 GeV electron beam, which is also available in experiments

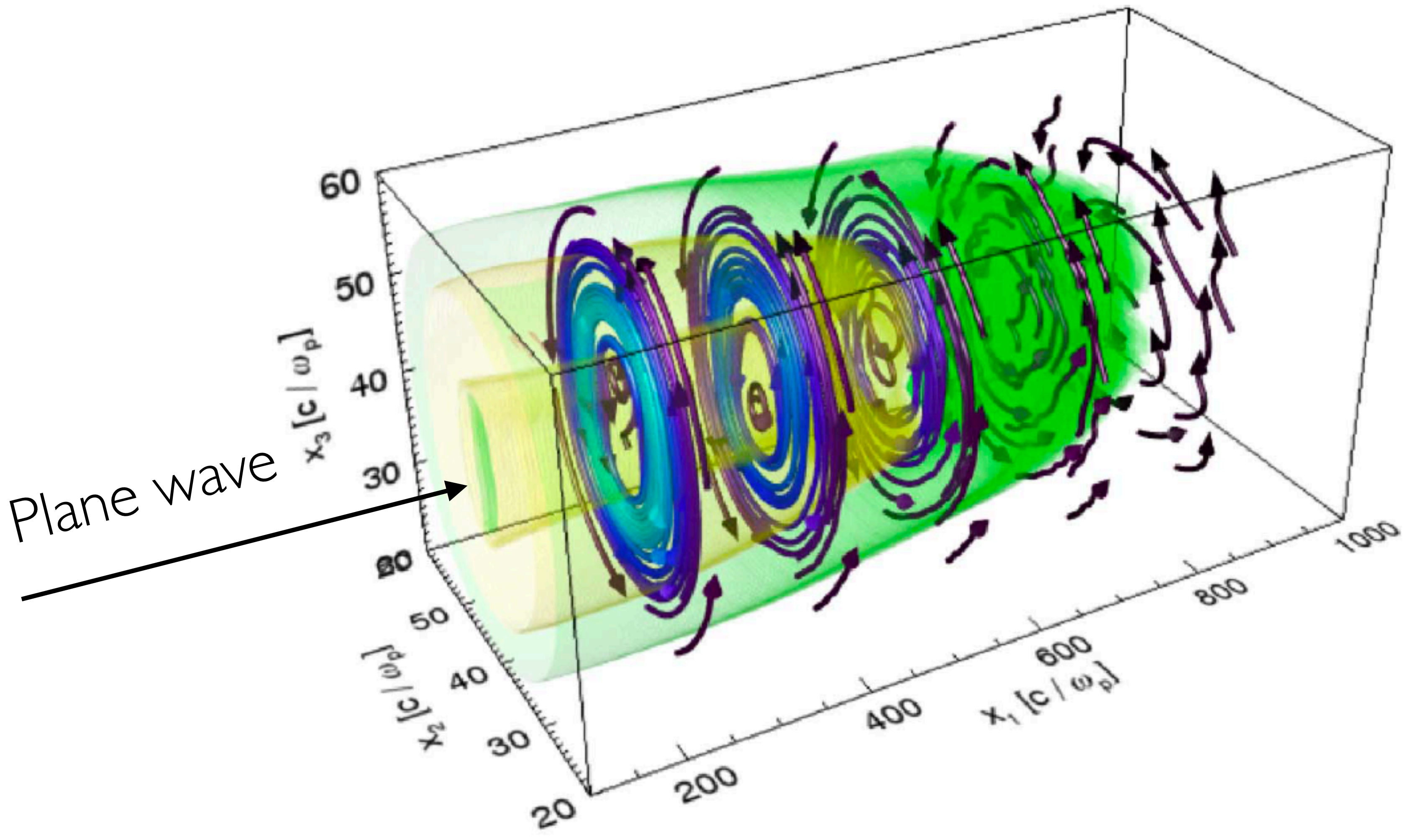
What we know about direct laser acceleration of electrons[1,2]

Electrons interacting with a laser inside a channel

Ponderomotive expulsion of electrons
→ Radial electric field $E_y = \kappa_E y > 0$



Current of accelerated electrons
→ Azimuthal magnetic field $B_z = -\kappa_B y < 0$



Electrons oscillate

in laser fields E_L, B_L at a frequency ω_L

in channel fields E_y, B_z at a frequency ω_β

A coupling and energy gain is possible if $\omega_L \simeq \omega_\beta/(1 - v_x/c)$

[1] A. Pukhov et al., PoP **6**, 2847 (1999)
[2] M. Vranic et al., PPCF **60**, 034002 (2018)

Direct laser acceleration of positrons is possible only if we can invert the background field direction

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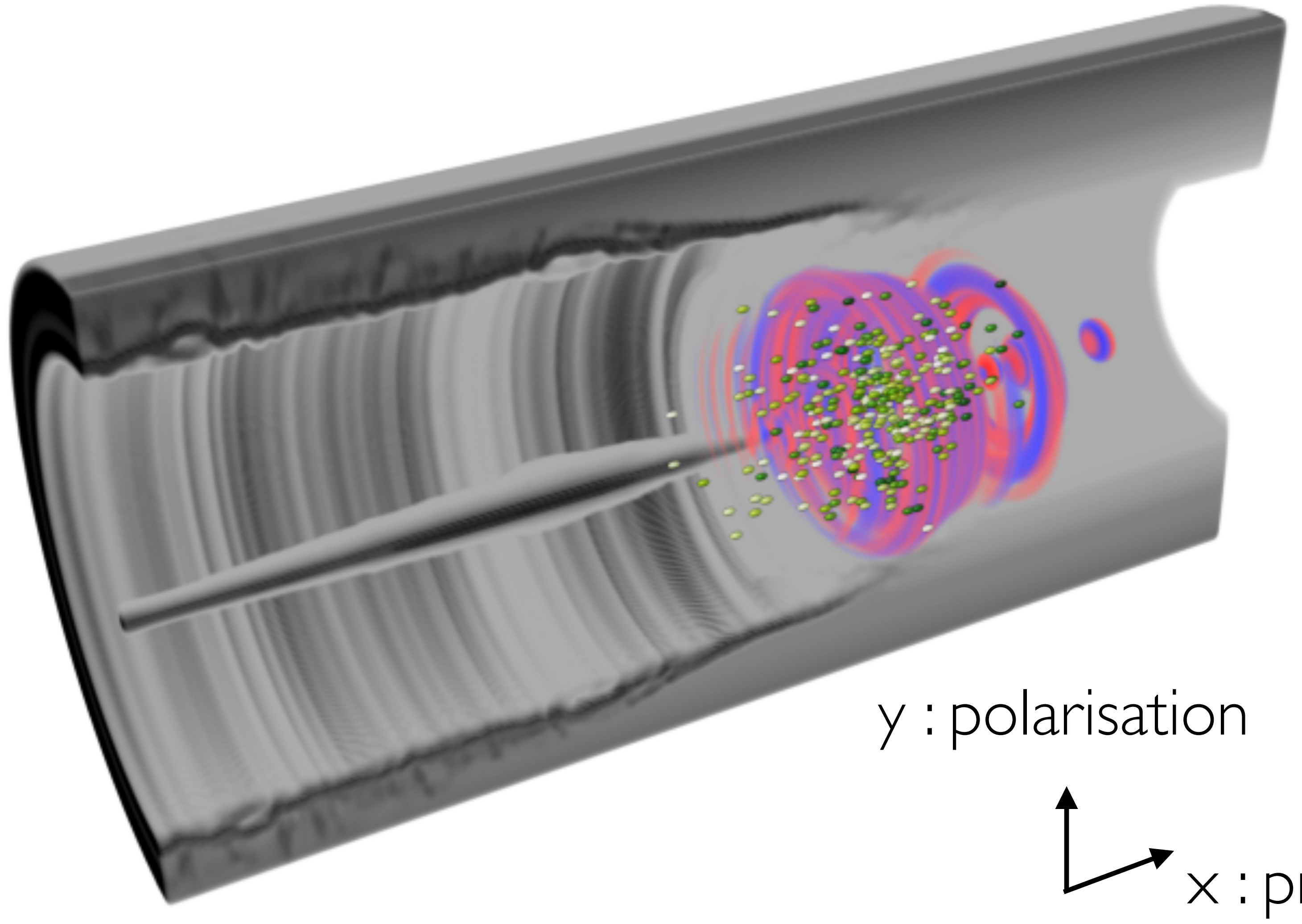
Modelling in a simplified framework

Assumption: we have a self-loaded electron beam at the channel center

Self-loaded electron beam at the channel center (gray)

→ The radial channel field $E_y = \kappa_E y > 0 \rightarrow E = \kappa_E y < 0$



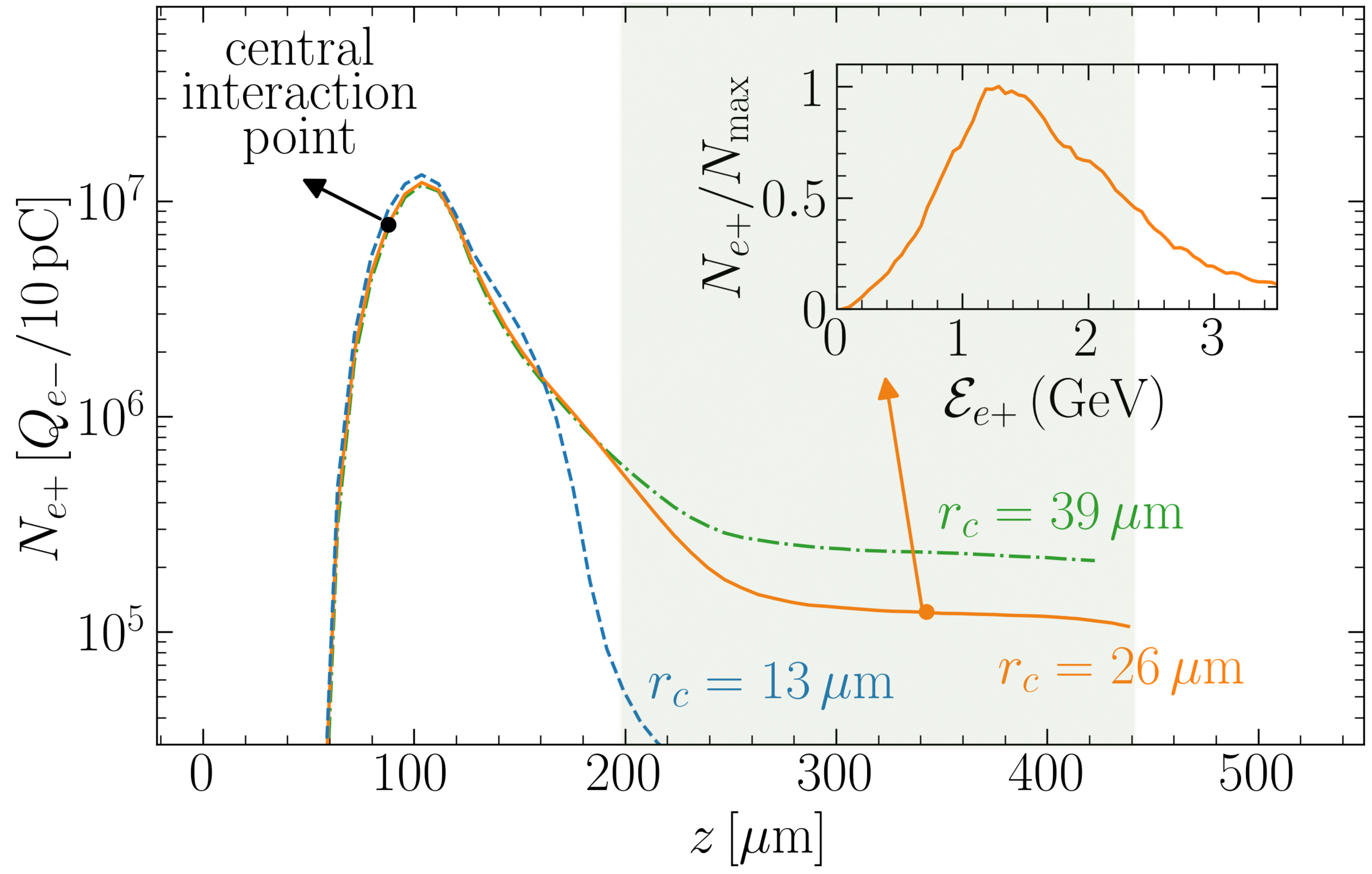
Equation for the transverse coordinate y of the positron $\rightarrow y'' - \frac{\kappa_E + c\kappa_B}{\gamma} y = -\left[\frac{E_L}{\gamma}\left(v_y^2 - 1 + \frac{v_x}{c}\right) + v_y^2 \frac{\kappa_E y}{\gamma}\right]$

Since $\kappa_E < 0$, we can have $-\frac{\kappa_E + c\kappa_B}{\gamma} > 0 \rightarrow$ positrons can oscillate at the betatron frequency defined by $\omega_\beta^2 = -\frac{\kappa_E + c\kappa_B}{\gamma}$

Charge content and the energy spectrum of the positron beam

About the focusing structure

Number of positrons as a function of the laser propagation distance for different channel widths.



About the guiding structure

- It starts after ~200 µm
- It is sustained for ~200 µm

After ~ 400 µm of propagation

Total charge $17\ \mathrm{fC}$

The spectrum is peaked $\sim 1.3\ \mathrm{GeV}$ since low energy positrons are expelled away

Energy conversion efficiencies

laser pulse $\rightarrow e^+$ beam: 10^{-9}

Emittance $\epsilon_{\mathrm{rms}} = 0.5\ \mathrm{mm\,.\,mrad}$

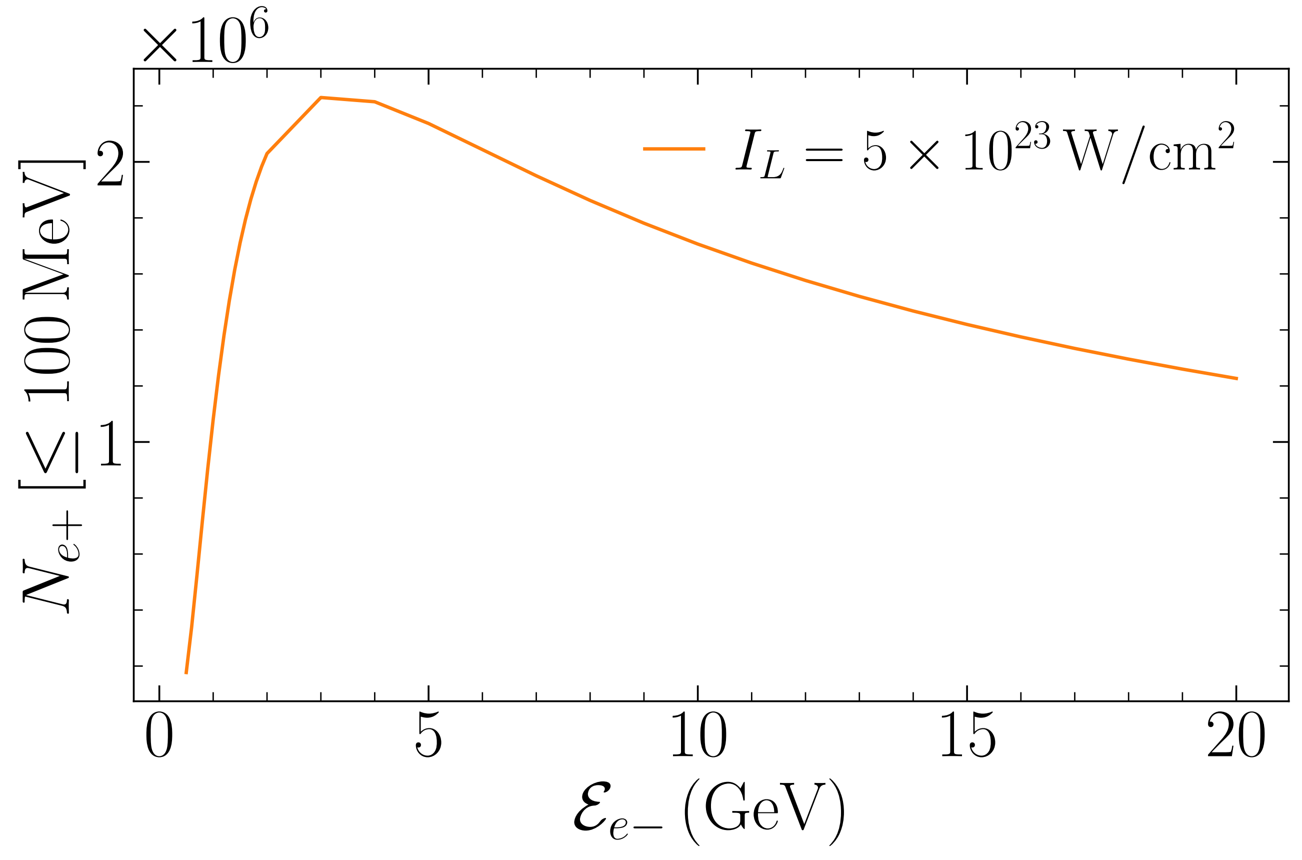
normalised emittance $\epsilon_{\mathrm{n,rms}} = 1000\ \mathrm{mm\,.\,mrad}$

Divergence $\pm 100\ \mathrm{mrad}$

Number of positrons deflected toward the channel axis[1]

Theory: the number of low-energy positrons

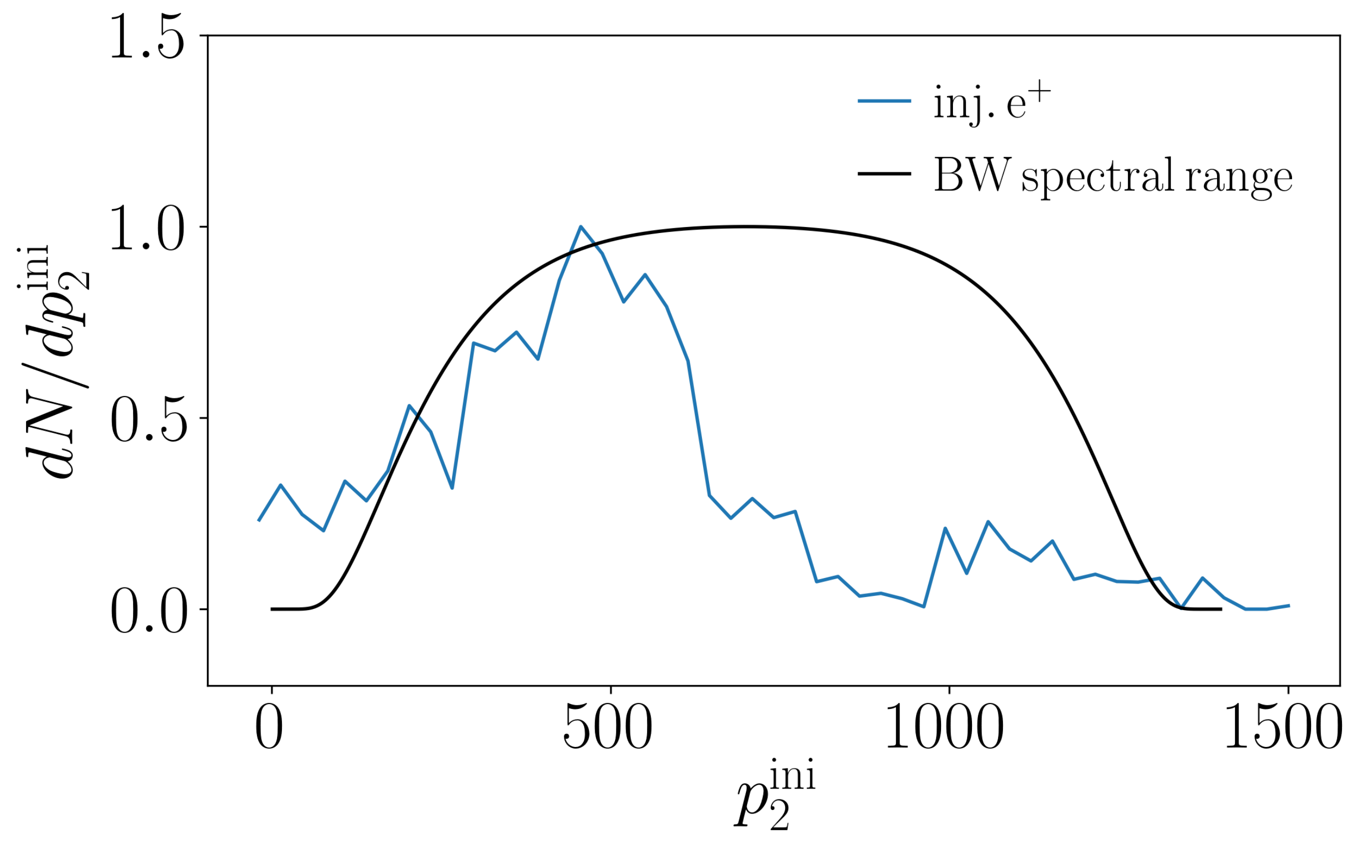
Number of positrons with an energy below $100\,\mathrm{MeV}$



Positrons are emitted when $\boldsymbol{E}_y$ is maximum and $\boldsymbol{B}_z$ is minimum

Simulation: only "low" energy positron are accelerated

Initial transverse momentum distribution of accelerated positrons



Positrons are efficiently deflected if their initial transverse momentum is low enough

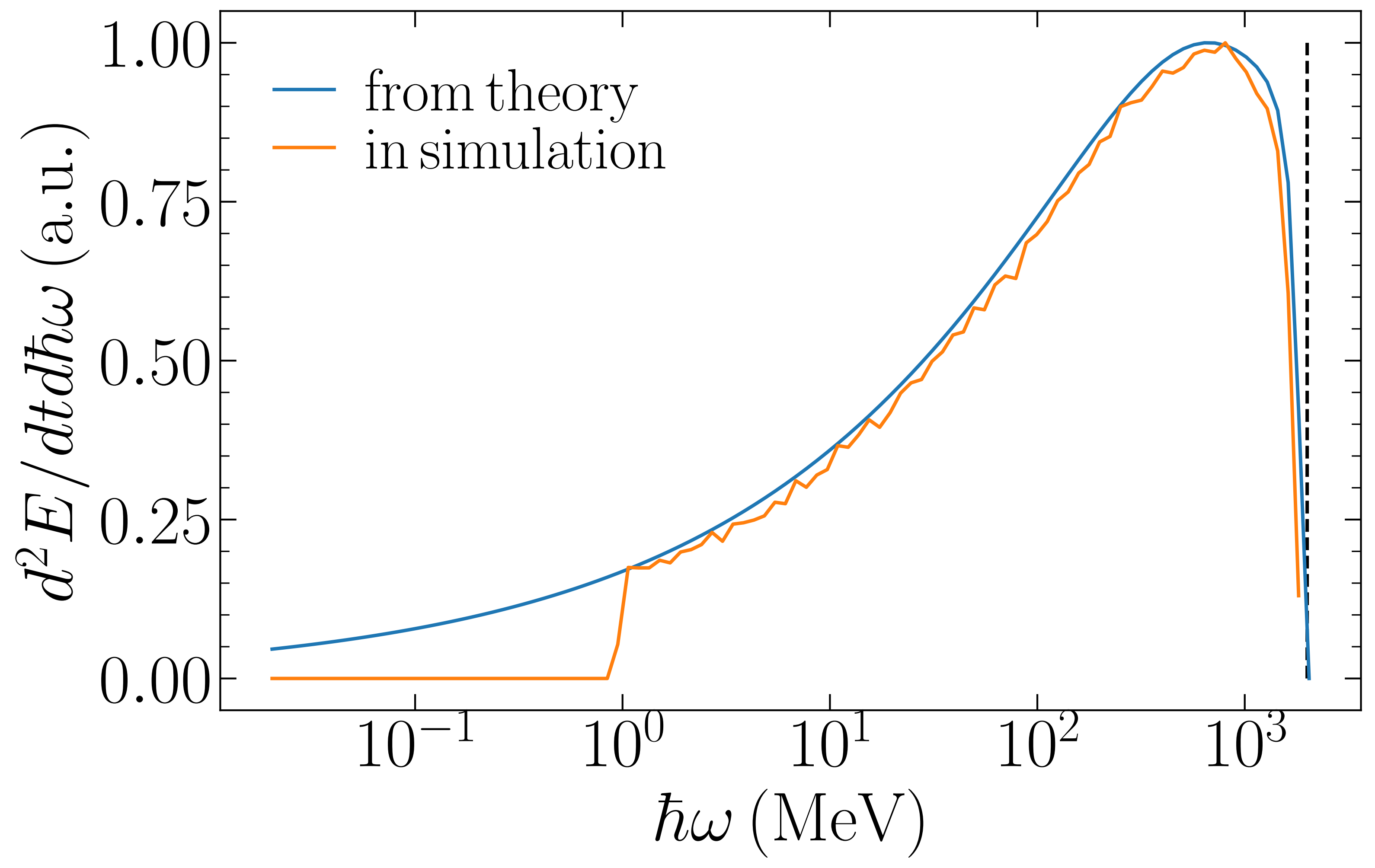
Work with Bernardo Barbosa to get the number of "low" energy positrons with a semi-analitycal estimate

[1] B. Martinez et al., arXiv 2207.08728 (2022)

Initial distribution of gamma-rays

Energy spectrum of gamma-rays

Theoretical synchrotron spectrum from Ref[1]

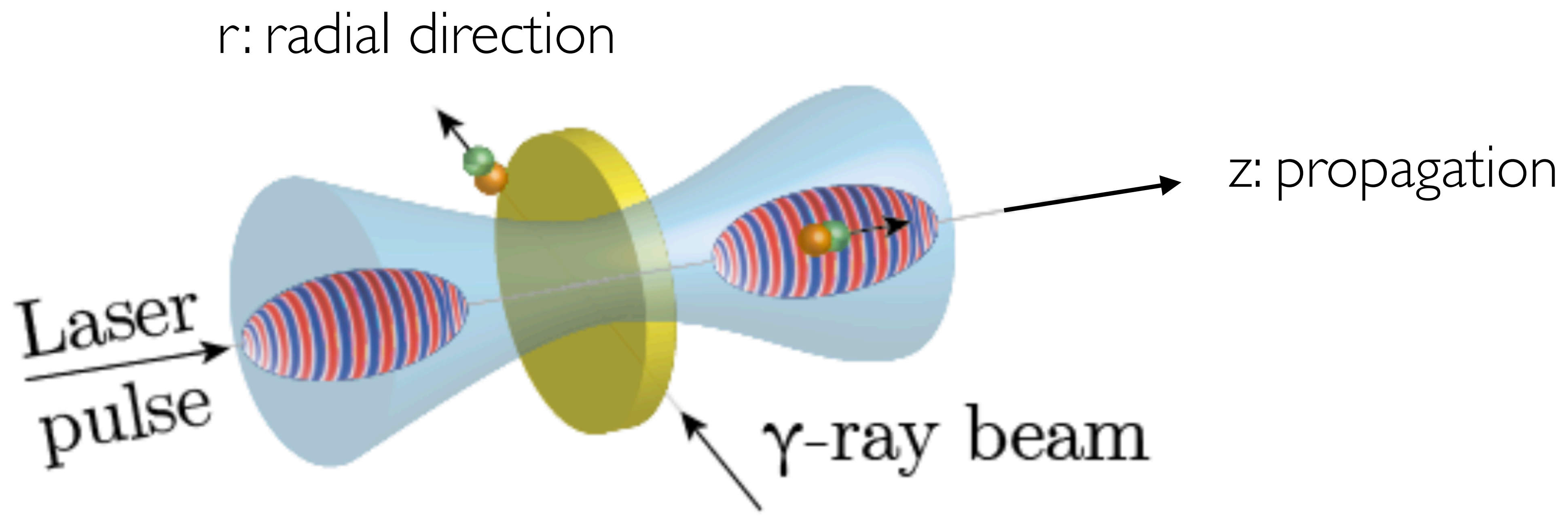


Definition $\chi_e = a_0\gamma_e/E_s$

Electrons will not experience the peak field

→ Assumption $a_0 \rightarrow a_0/2$

Spatial distribution of gamma-rays for simulations[2]



Due to Quasi-3d, we have to

→ initialise photons instead of electrons

→ use a uniform distribution

Number density $10^{17}/\mathrm{cm}^3$

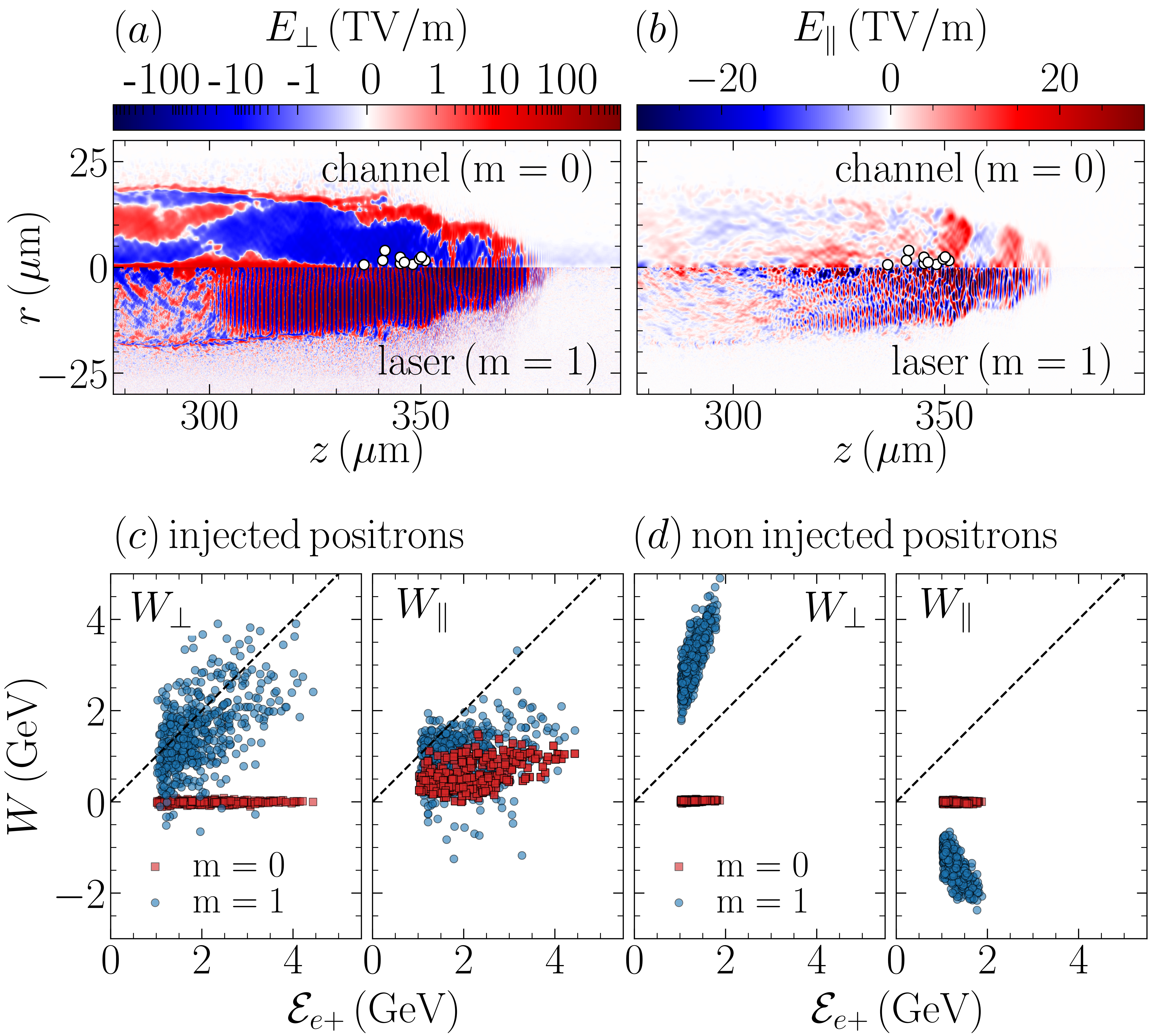
direction z: Gaussian with FWHM of $3\ \mu\mathrm{m}$

direction r: uniform

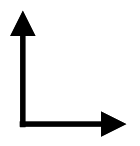
[1]T. Erber, RMP **38**, 4 (1966)

[2]B. Martinez et al., arXiv 2207.08728 (2022)

Fields in the plasma channel

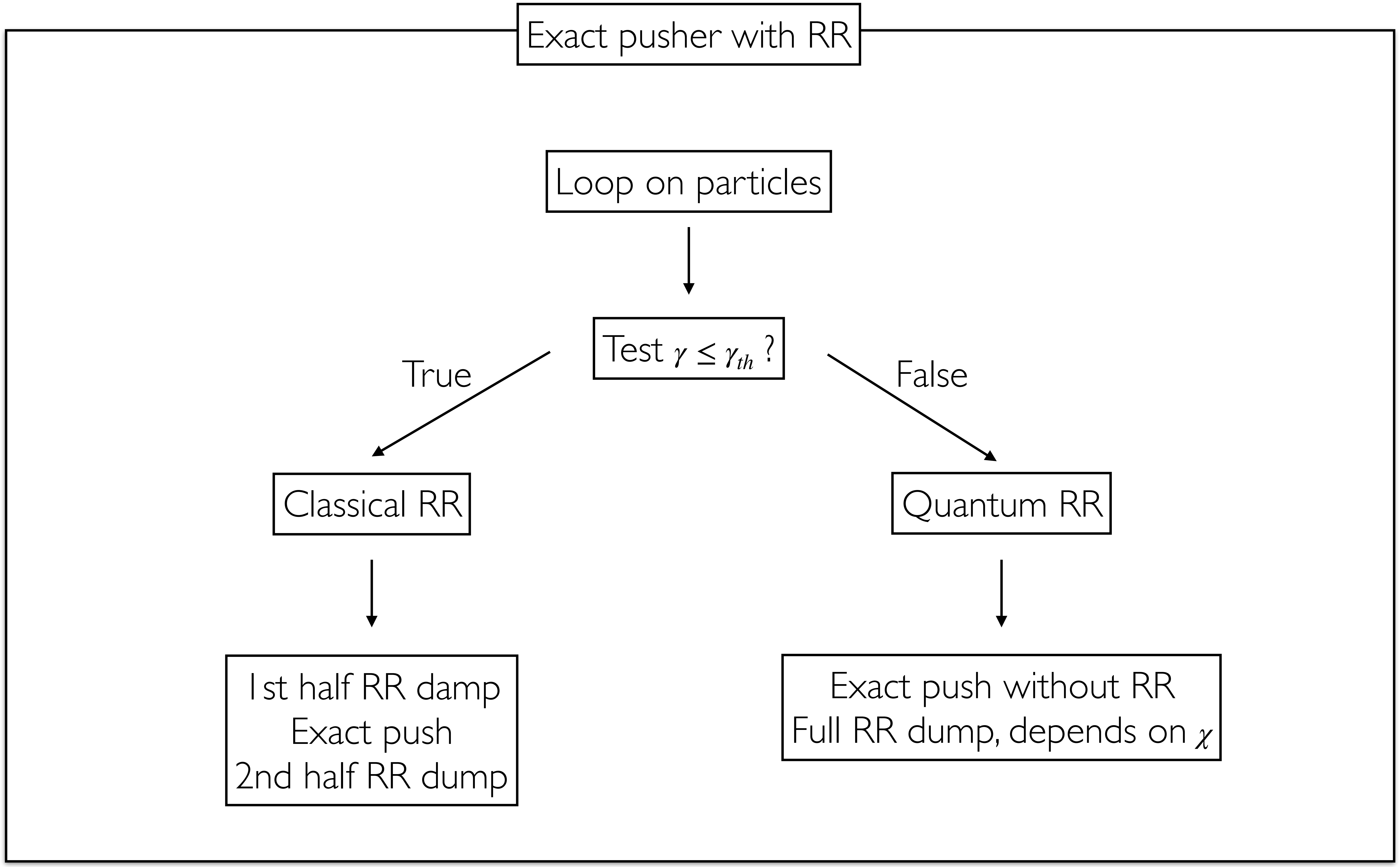


A recall of the coordinate system



Slides for implementation

Exact pusher in quantum regime



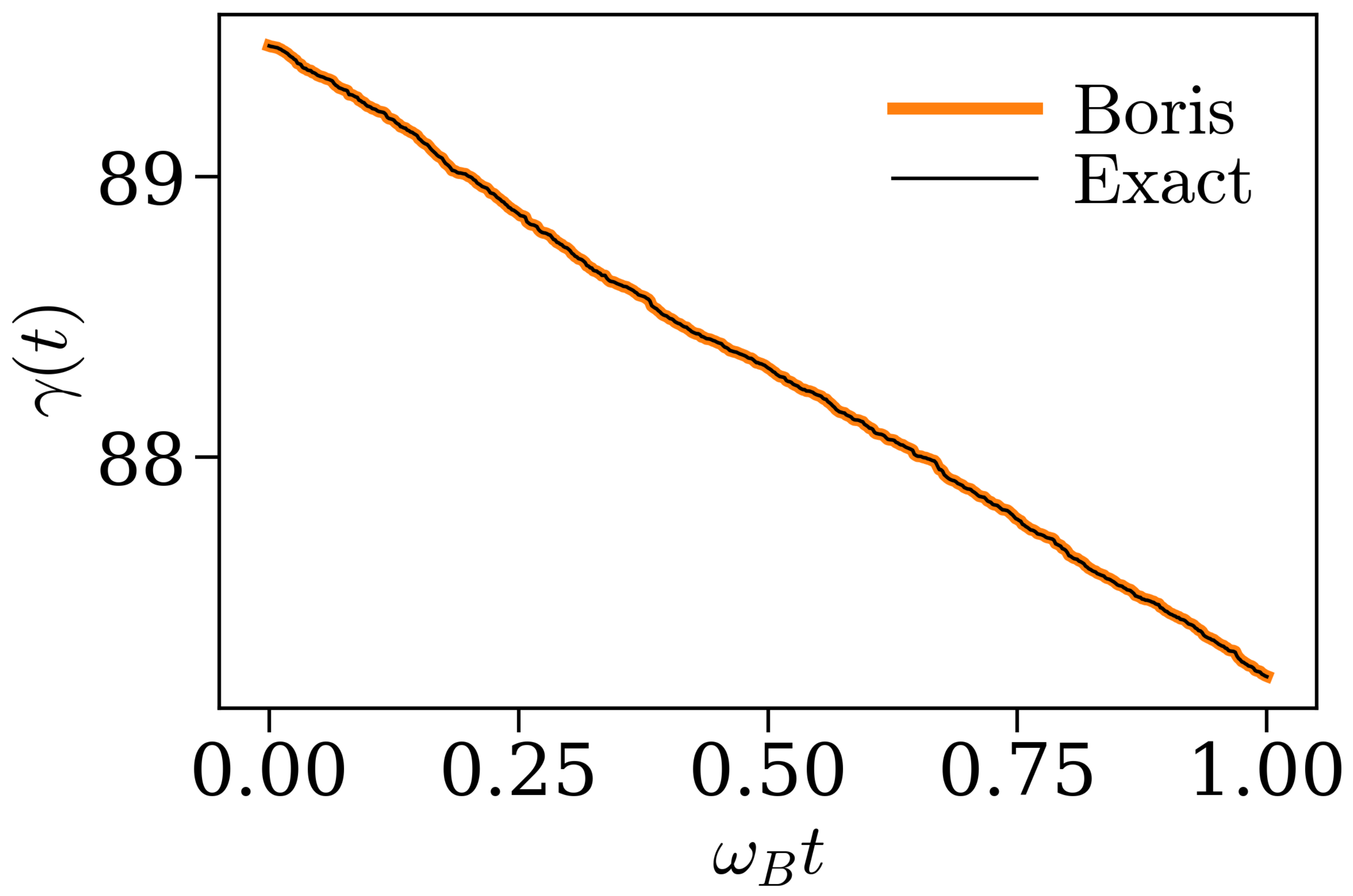
In the classical case, we do not modify the pre-existing routine
In the quantum regime, we combine the exact push with the quantum RR damp

Exact pusher in "qed" algorithm

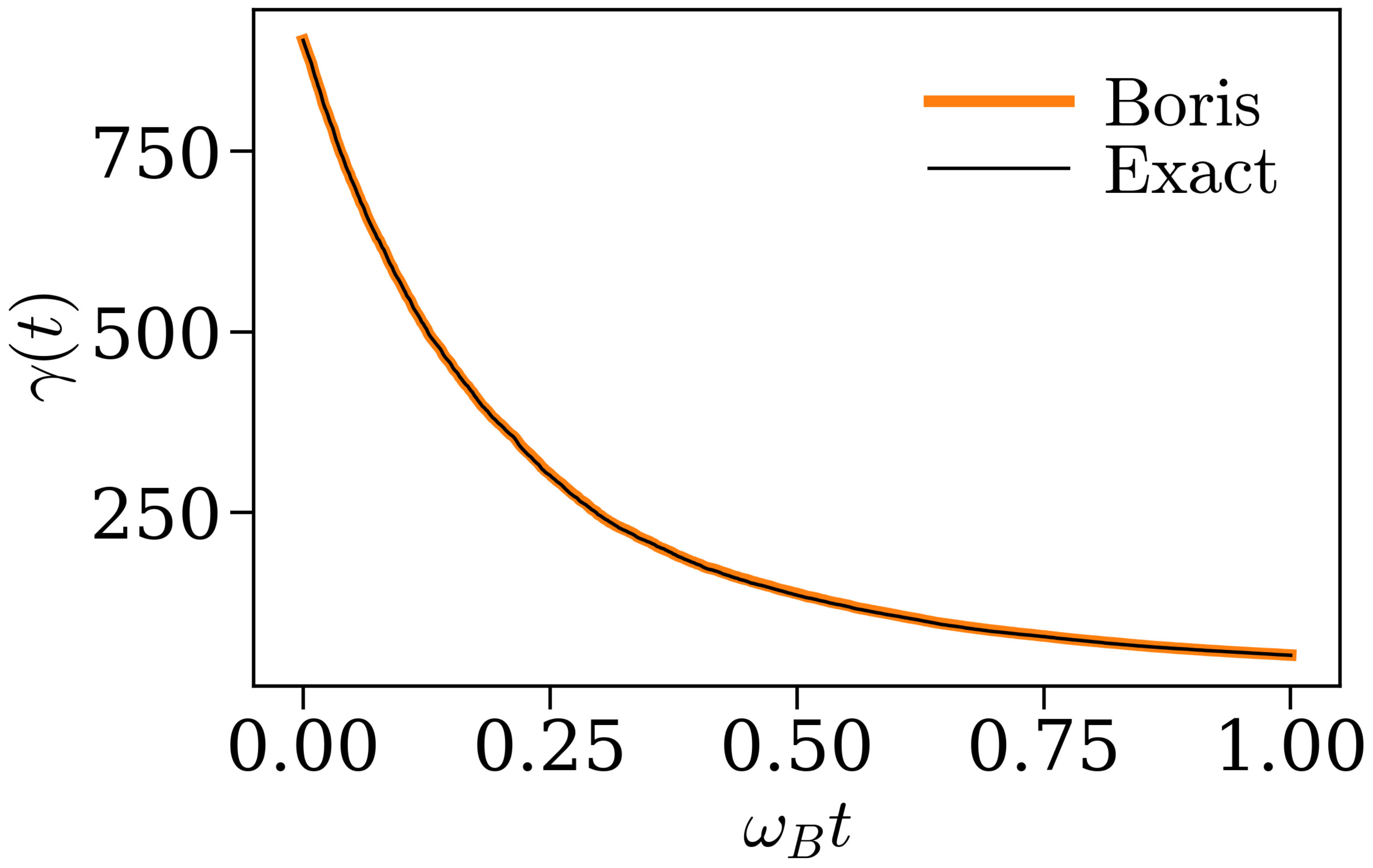
Agreement between Boris and exact quantum pushers

Setup : e^- rotating in a uniform B field
Average on 1000 trajectories

e^- energy for $\chi = 0.01$



e^- energy for $\chi = 1$

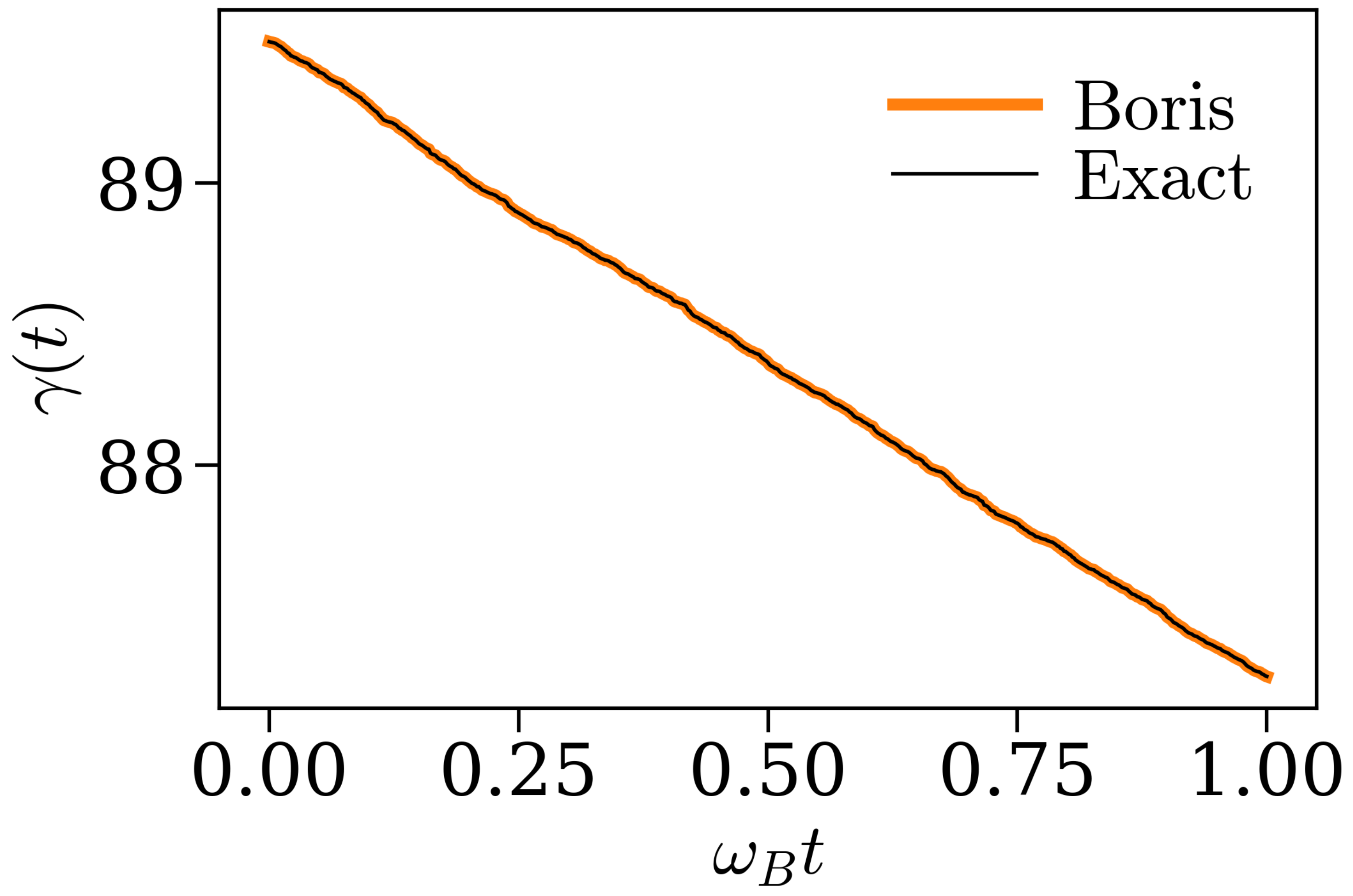


Exact pusher in "qed-cyl" algorithm

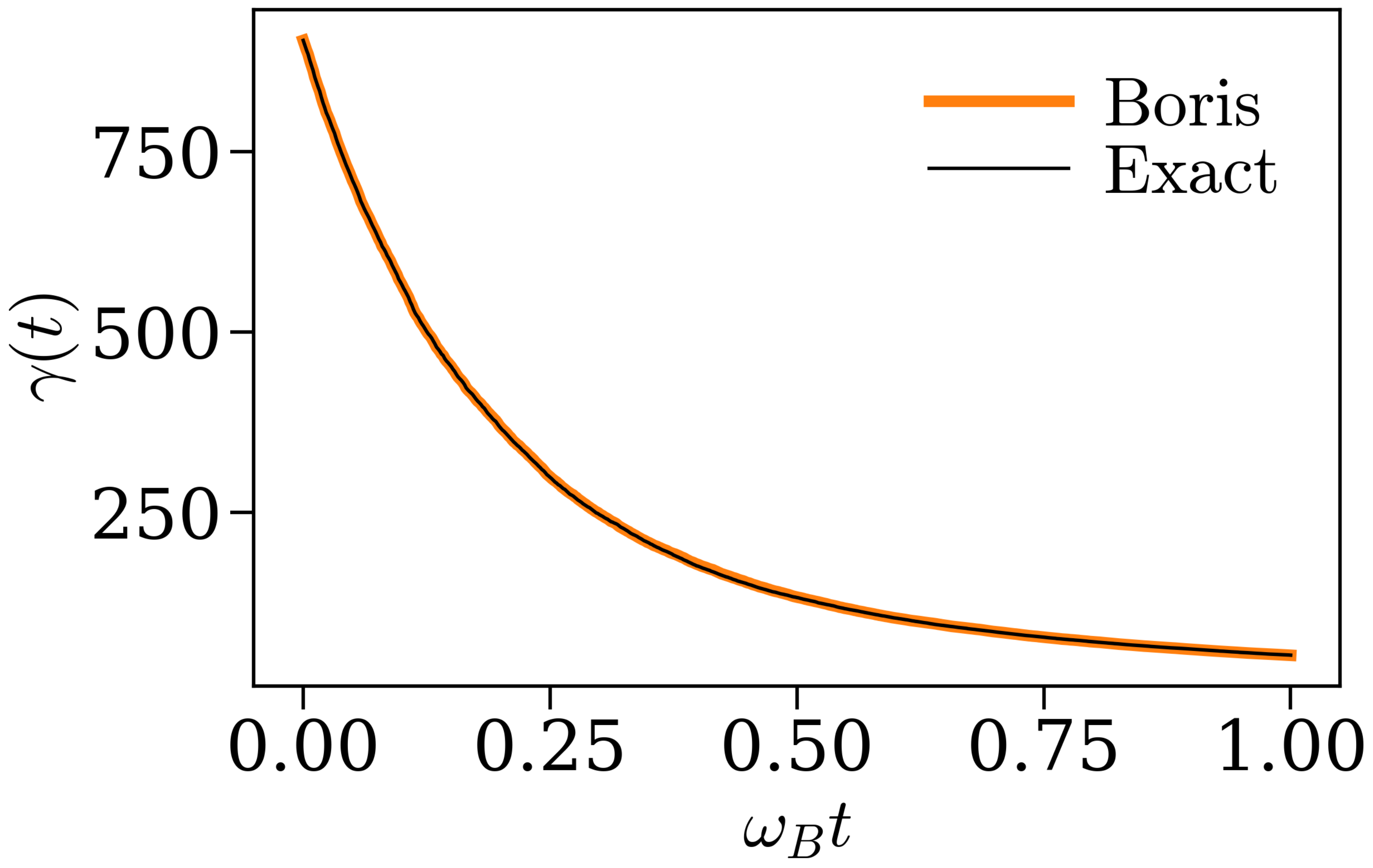
Agreement between Boris and exact quantum pushers

Setup : e^- rotating in a uniform B field
Average on 1000 trajectories

e^- energy for $\chi = 0.01$



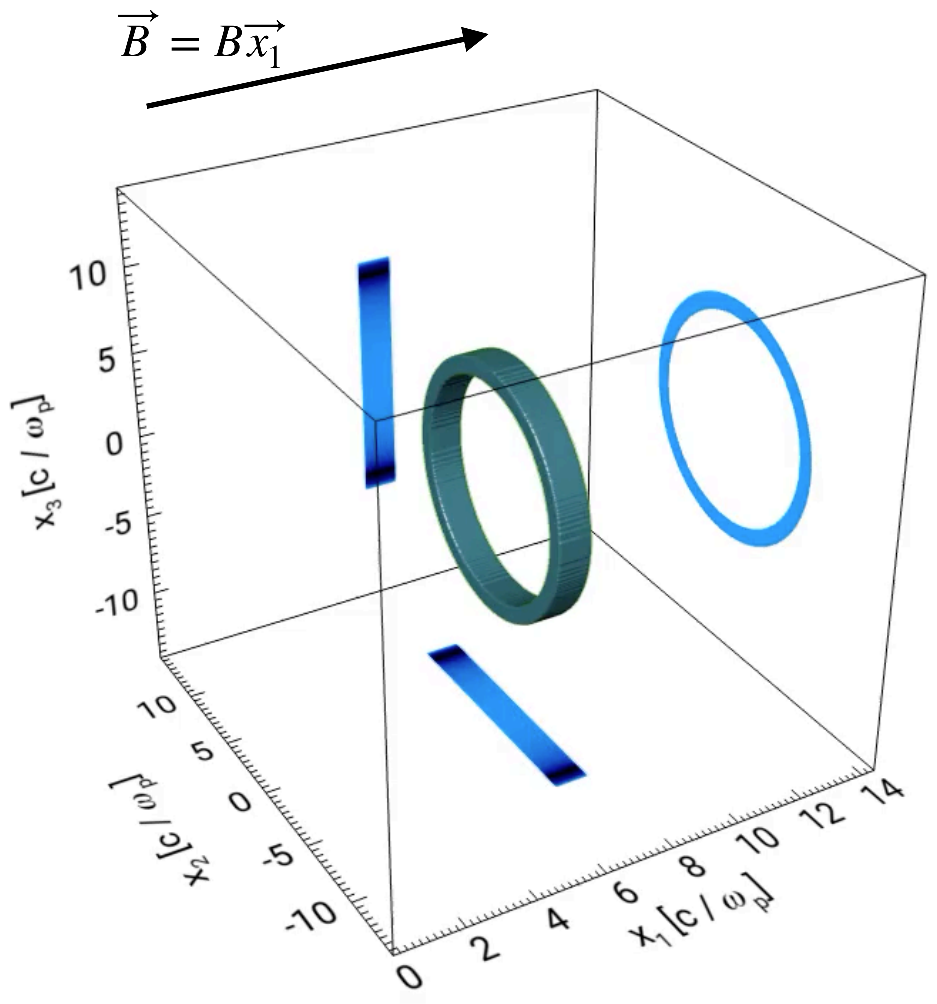
e^- energy for $\chi = 1$



Setup I : e^- rotating in a uniform B field

3D view of the setup

e^- rotating in a uniform B field



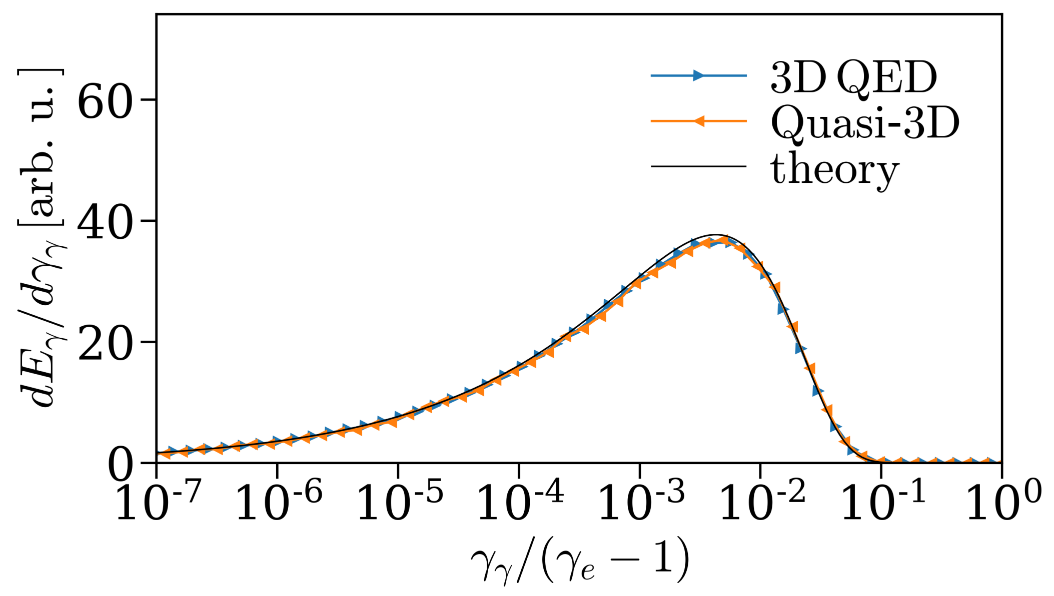
Validation

Spectra of the energy radiated by electrons

Agreement between 3D, quasi-3D and theory

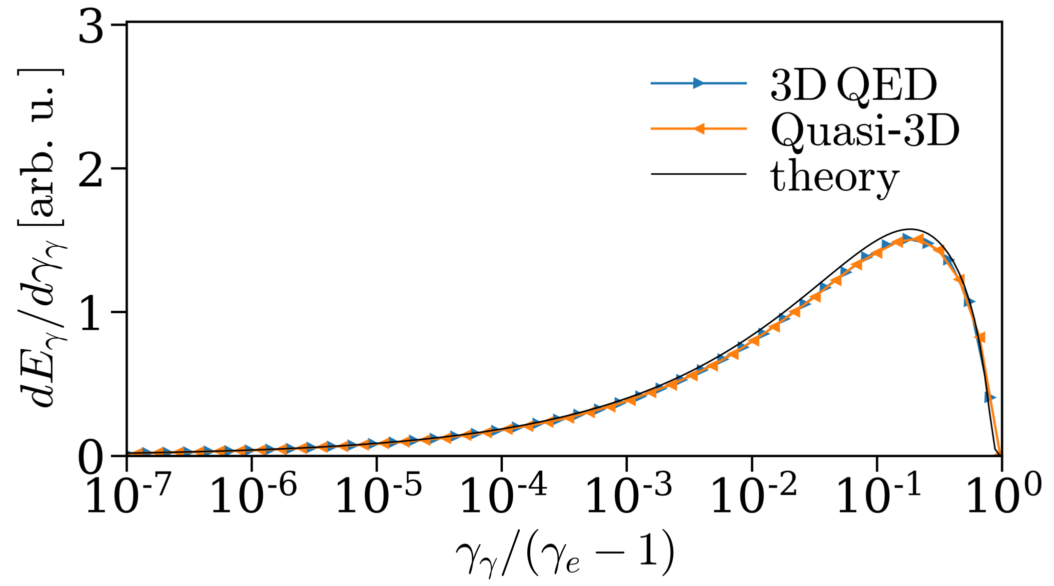
Validation was done for the range $\eta \in (0.01, 1)$

$\eta = 0.01$



η : quantum parameter of the electron

$\eta = 1$



Setup 2 : Laser beam interaction

TÉCNICO LISBOA

Electron beam

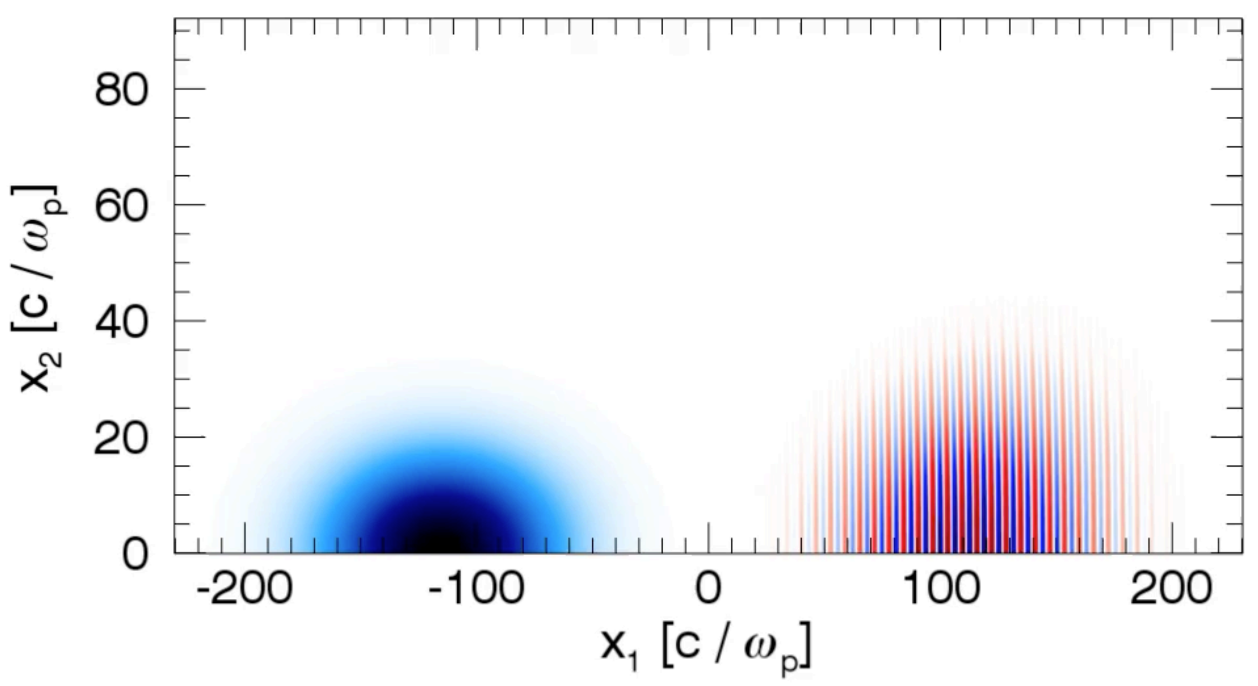
$9 \times 3 \times 3$ micron FWHM size in x, y and z
4 GeV and mono energetic
Density $\simeq 2 \times 10^{18}\,\mathrm{cm}^{-3}$

Laser pulse

0.8 micron wavelength
Linearly polarised, $a_0 = 50$
30 fs FHWM duration
2.5 micron transverse FWHM at focus

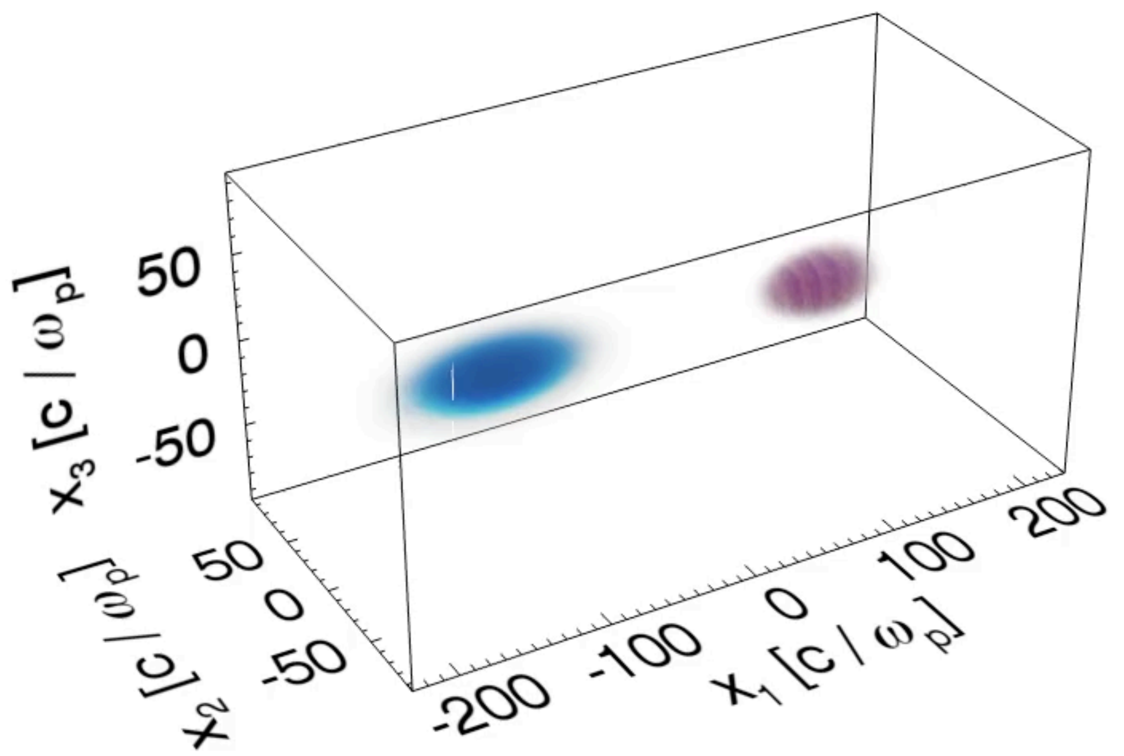
Simulation setup in quasi 3D and in 3D

Quasi 3D simulation



211 hours = 4.4 hours × 48 processors
52 points per laser wavelength
250 points per laser period

3D simulation



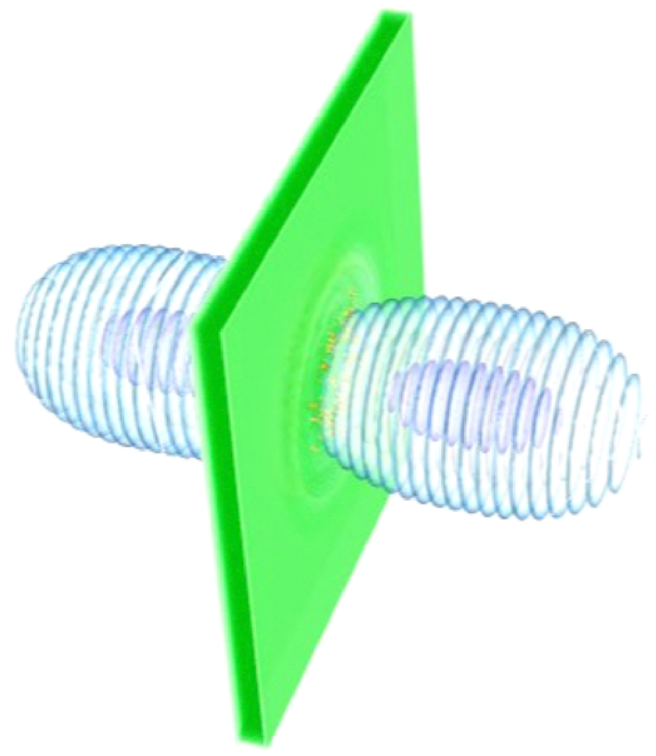
84480 hours = 14.4 hours × 19200 processors
52 points per laser period
314 points per laser period

$\times 400$

Setup 3 :A more complex scenario

3D view of the setup

Two laser pulses and a target



$n = 10\ n_c \quad d = 1\ \mu\text{m}$

$\lambda = 1\ \mu\text{m} \quad W_0 = 3\ \mu\text{m}$

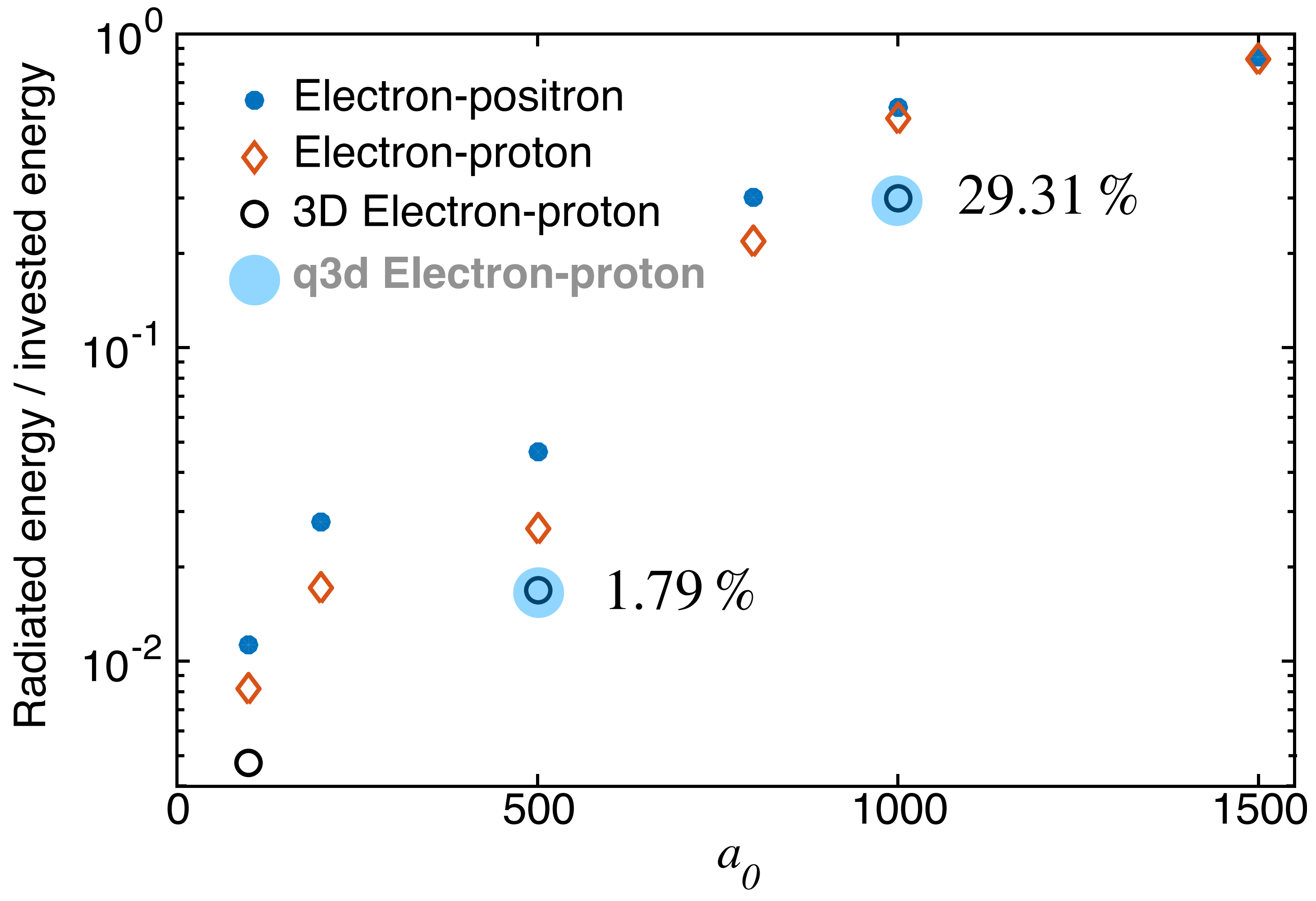
$t = 25\ \text{fs}$

Validation

Agreement 3D and quasi-3D

On the radiative conversion efficiency

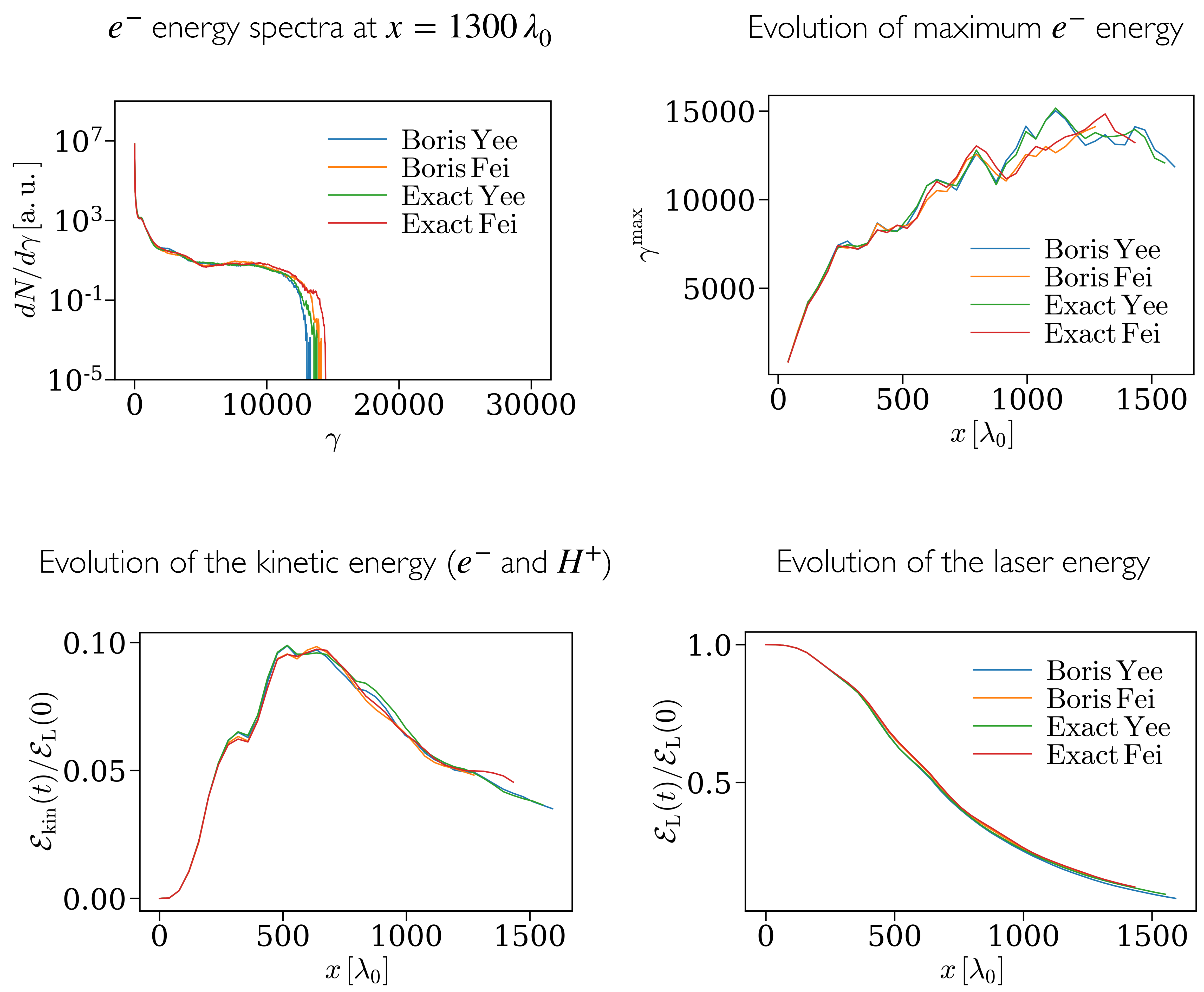
$$\text{radiative efficiency} = \frac{\text{photon energy}}{\text{laser energy}}$$



M.Vranic et al, Phys. Plasmas 26, 053103 (2019)

Choice of solver and pusher

Simulation results with various solver/pusher combinations



Motivations for testing solvers/pushers

Why should we test the field solver of Fei ?

Laser propagation in an under-dense plasma

Precision on the transverse Lorentz force is required

Why should we test the the exact pusher from Fei ?

Pair propagation and deflection in strong fields

No significant difference on global energy balance

Identical maximum energy for pairs