External and Dynamic Gauge Fields in Strong-Field QED

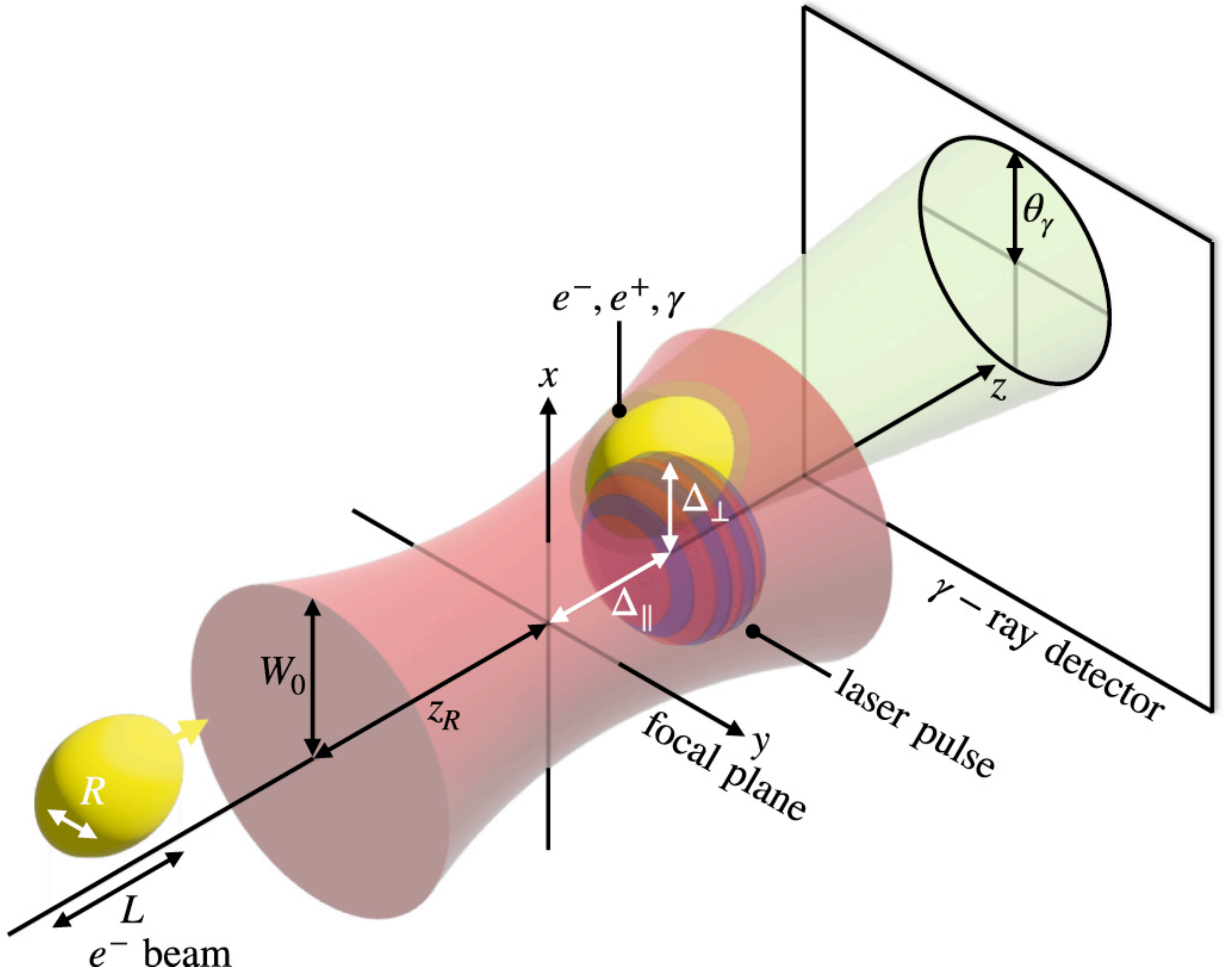
+SIGN25+

Óscar Amaro [1]

Co-authors:
Marija Vranic [1]
João Pinto Barros [2]
Marina Marinkovic [2]

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

[2] Institute for Theoretical Physics, High Performance Computational Physics, ETH Zürich, Switzerland



golp GROUP FOR LASERS AND PLASMAS | ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR | TÉCNICO LISBOA | fct Fundação para a Ciência e a Tecnologia | ETH zürich

Acknowledgments

Collaborations with **ETHZ** (João Pinto Barros, Marina Marinkovic).

This work was supported by the European Research Council (ERC-2015-AdG Grant No. 695088) and Portuguese Science Foundation (FCT) Grants No. CEECIND/01906/2018, PTDC/FIS-PLA/3800/2021, and UI/BD/153735/2022.

Simulation results obtained at the Accelerates cluster (IST), and local desktop.

Outline

TÉCNICO LISBOA

Introduction
Extreme Plasma Physics, intense lasers, and the path to SFQED

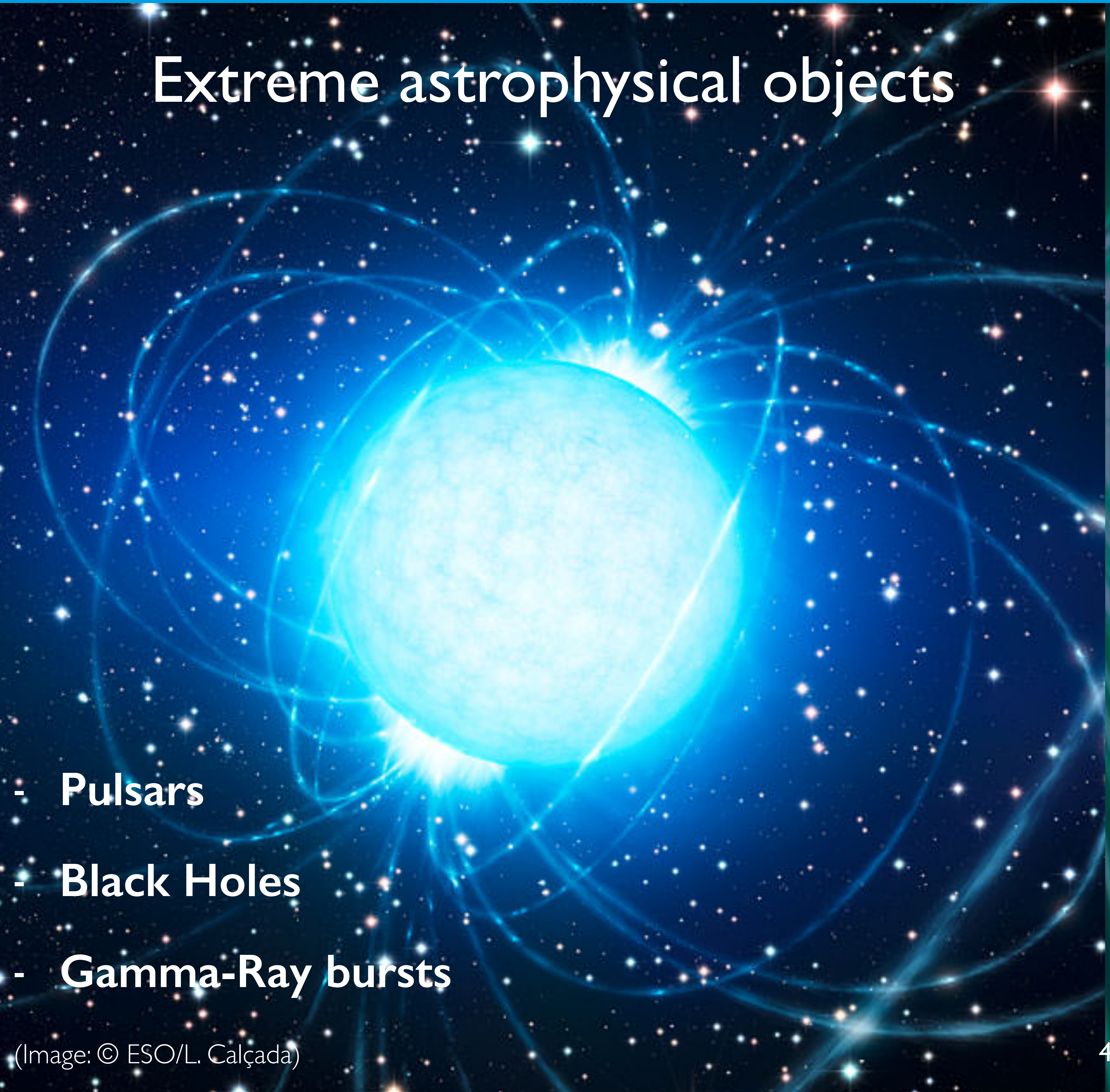
Regimes of plasma dynamics
Electron-positron density and field strength, back-reaction on fields

Kinetic, $\mathbb{Z}_n$ and axial-gauge approaches
First comparisons

Conclusions and Future directions
Particle-scattering, SFQED-cascades

Extreme Plasma Physics, intense lasers, and the path to SFQED

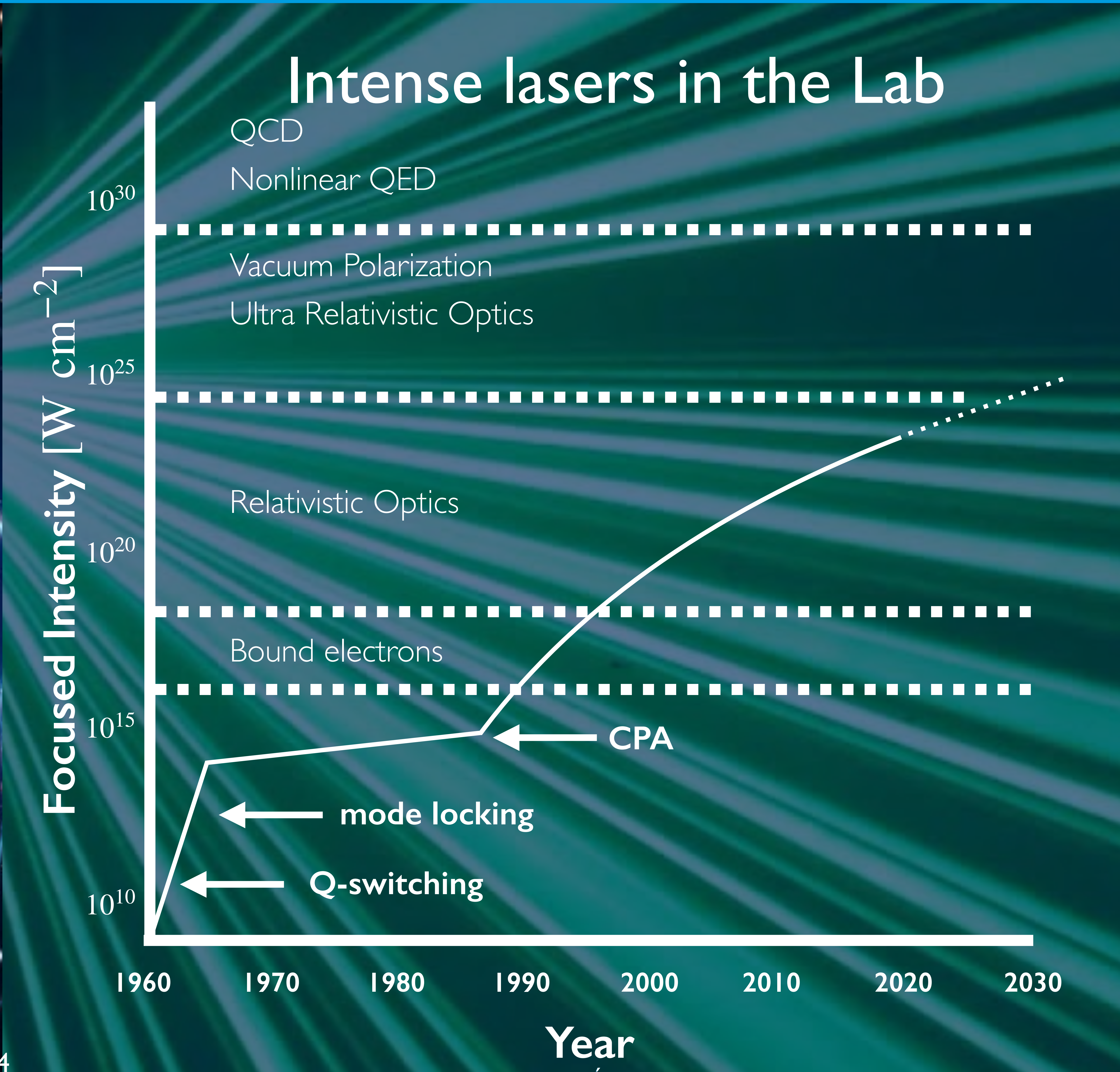
Extreme astrophysical objects



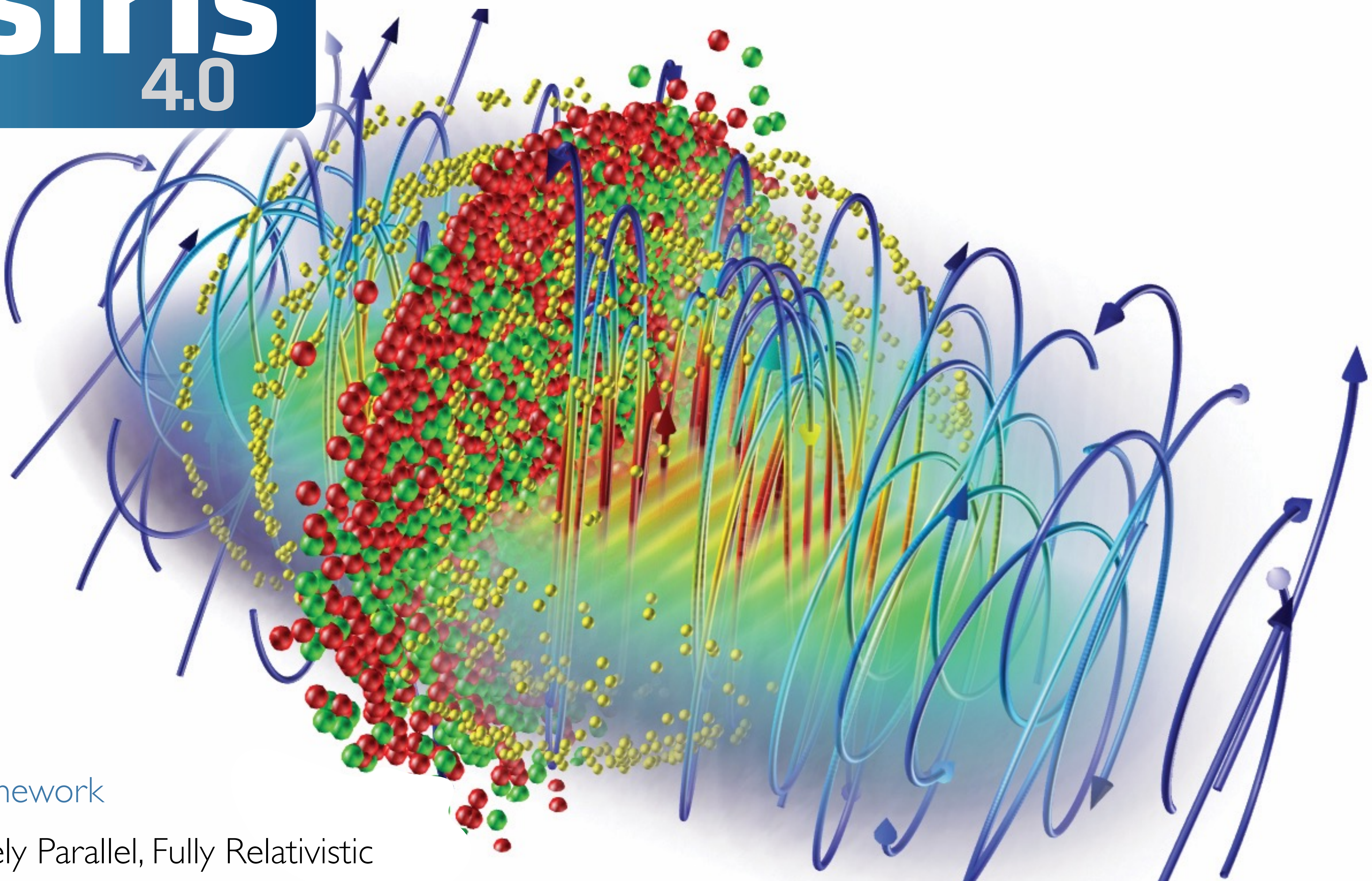
- Pulsars
- Black Holes
- Gamma-Ray bursts

(Image: © ESO/L. Calçada)

Intense lasers in the Lab



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 - **QED and particle merging**

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**

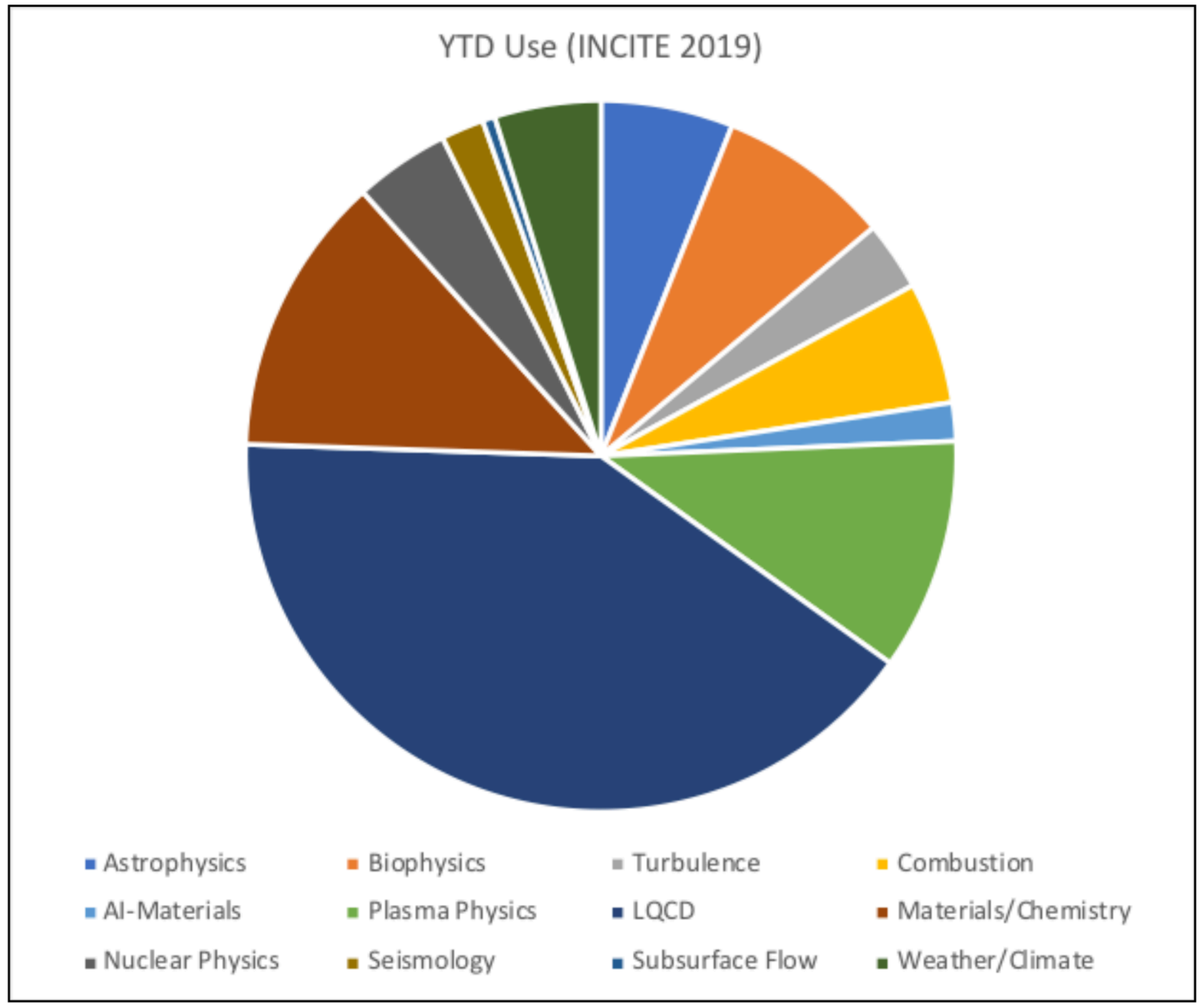
visXD

UCLA TÉCNICO LISBOA

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

Plasma Physics requires extensive computational resources

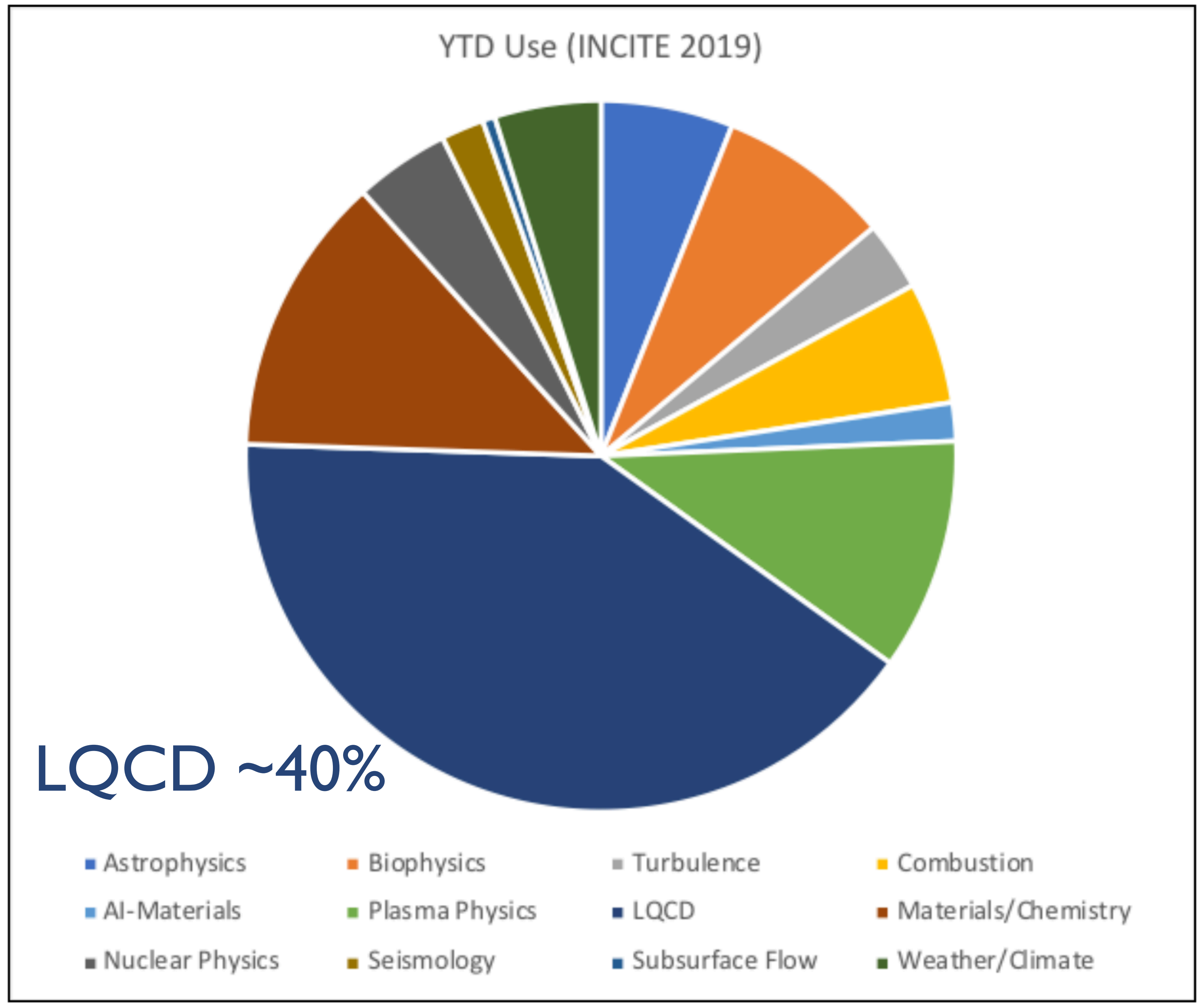
(classical) High Performance Computing



* Figure credit Jack Wells, Kate Clark, *Supercomputer usage for different fields (INCITE 2019)*

Plasma Physics requires extensive computational resources

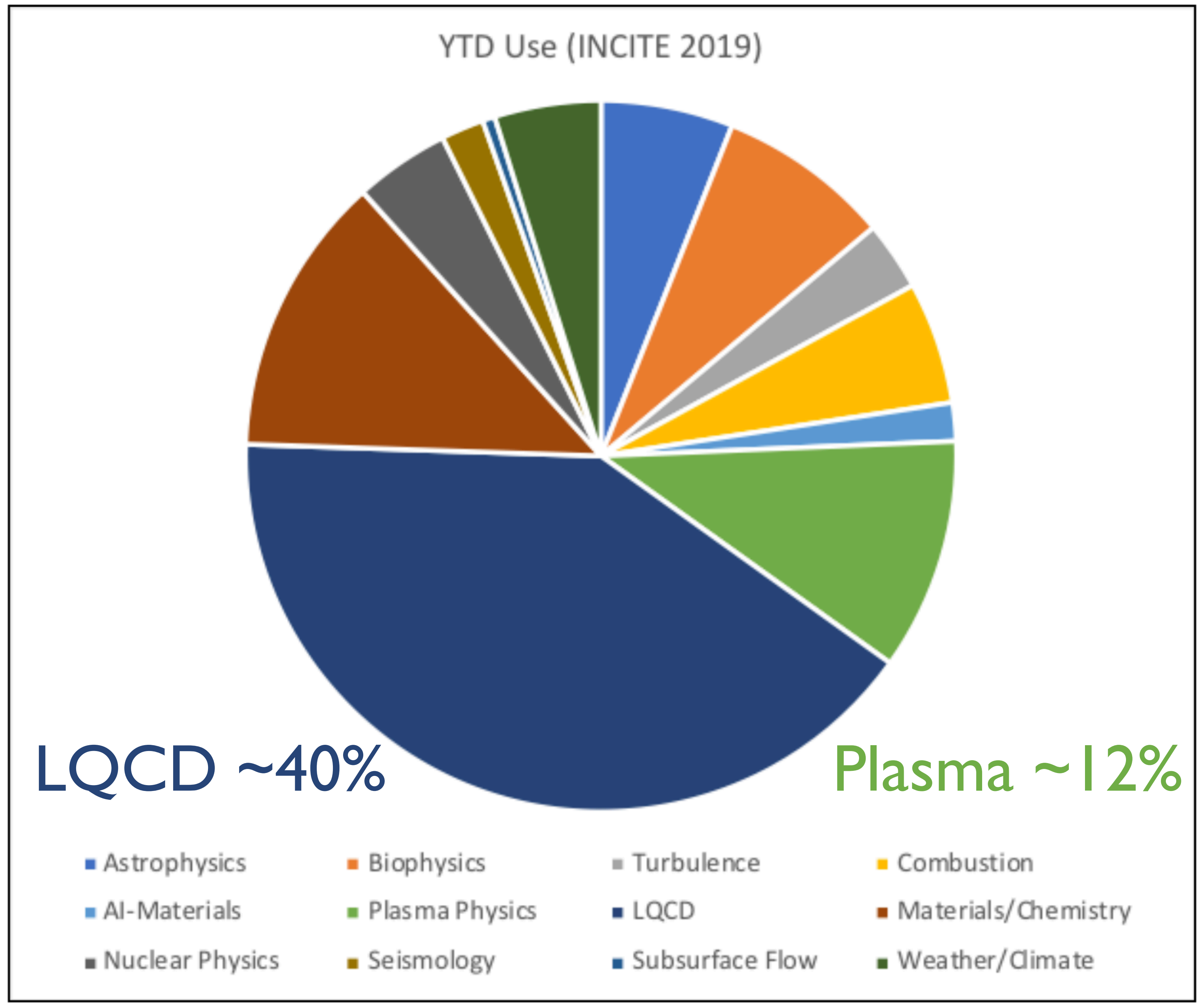
(classical) High Performance Computing



* Figure credit Jack Wells, Kate Clark, *Supercomputer usage for different fields (INCITE 2019)*

Plasma Physics requires extensive computational resources

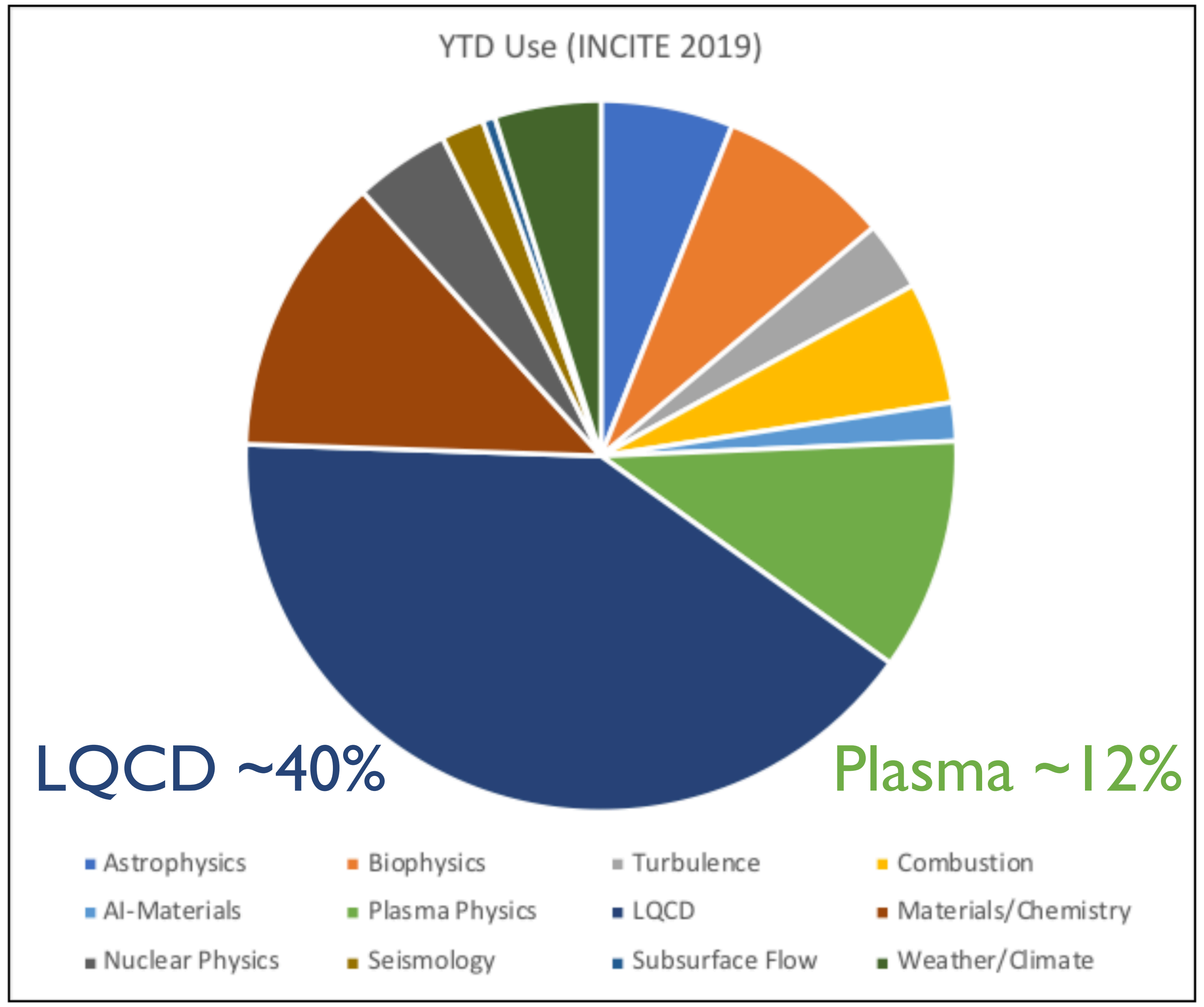
(classical) High Performance Computing



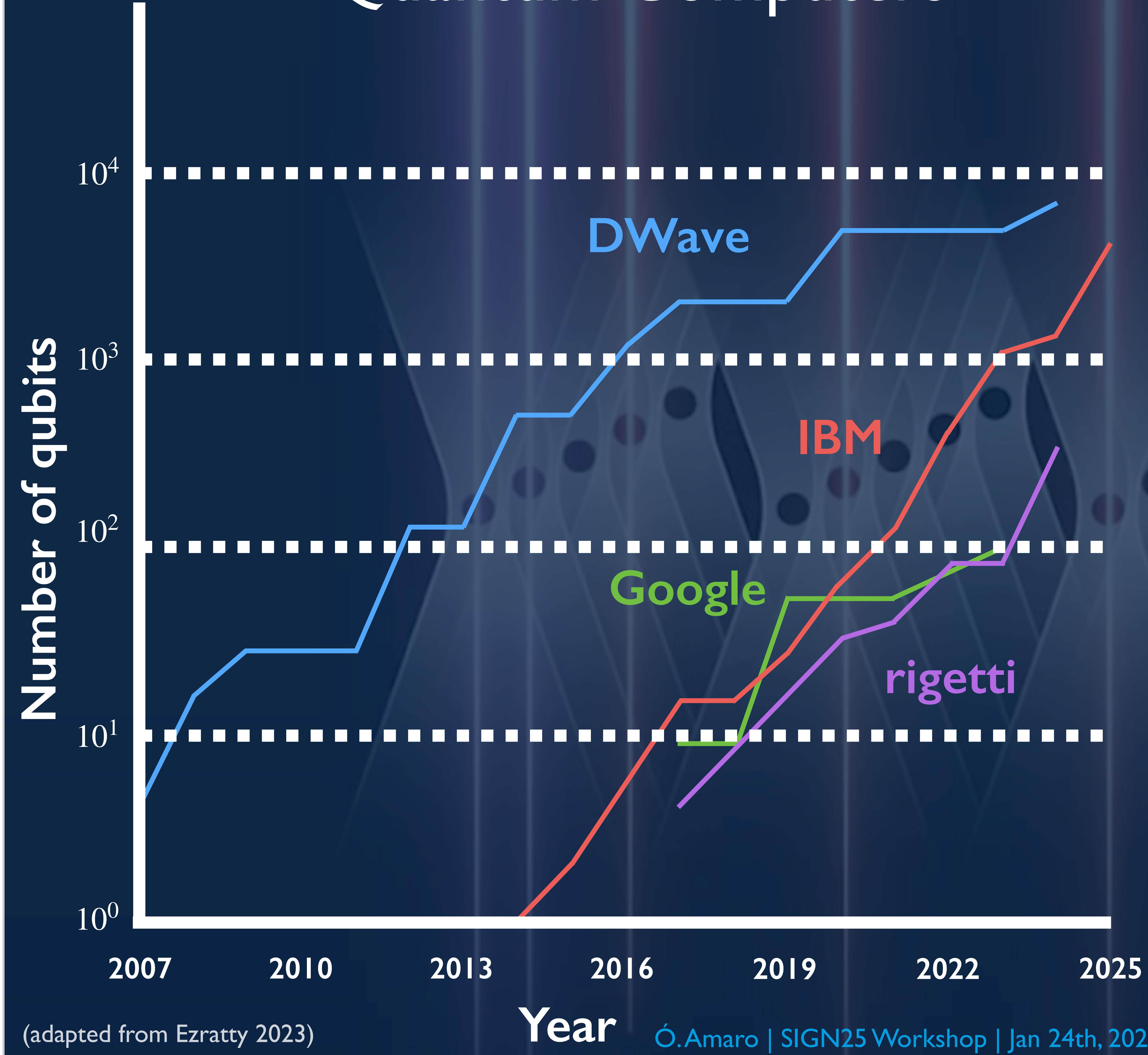
* Figure credit Jack Wells, Kate Clark, *Supercomputer usage for different fields (INCITE 2019)*

Plasma Physics requires extensive computational resources

(classical) High Performance Computing



Quantum Computers

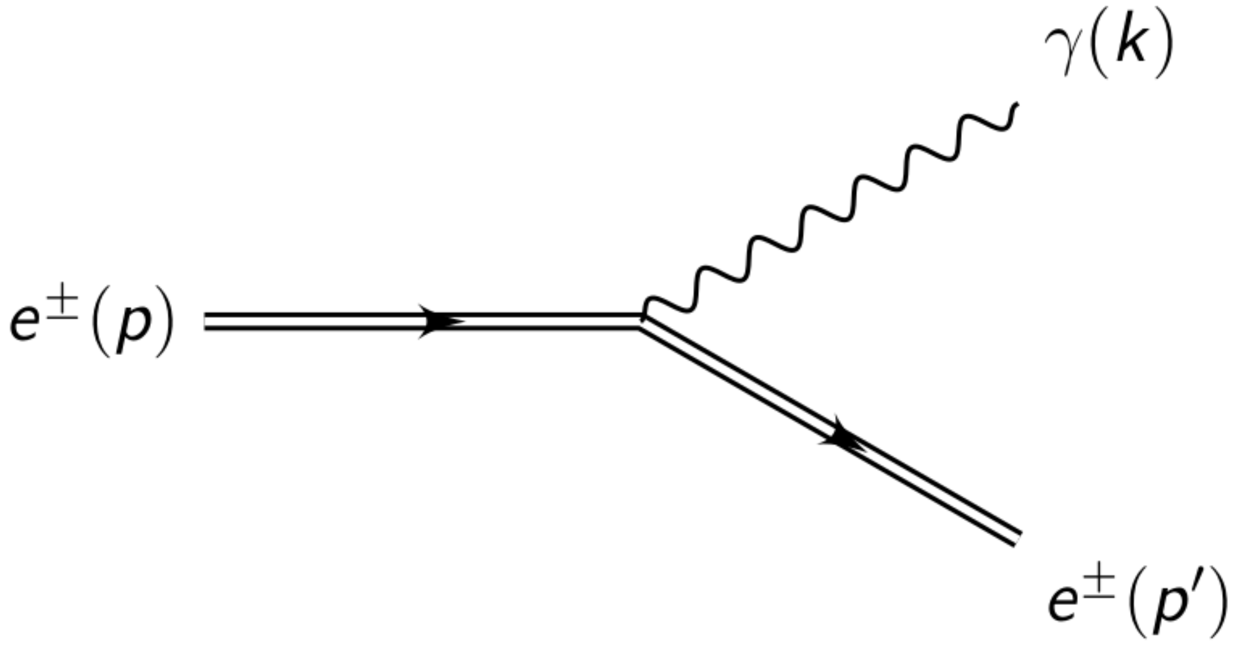


* Figure credit Jack Wells, Kate Clark, *Supercomputer usage for different fields (INCITE 2019)*

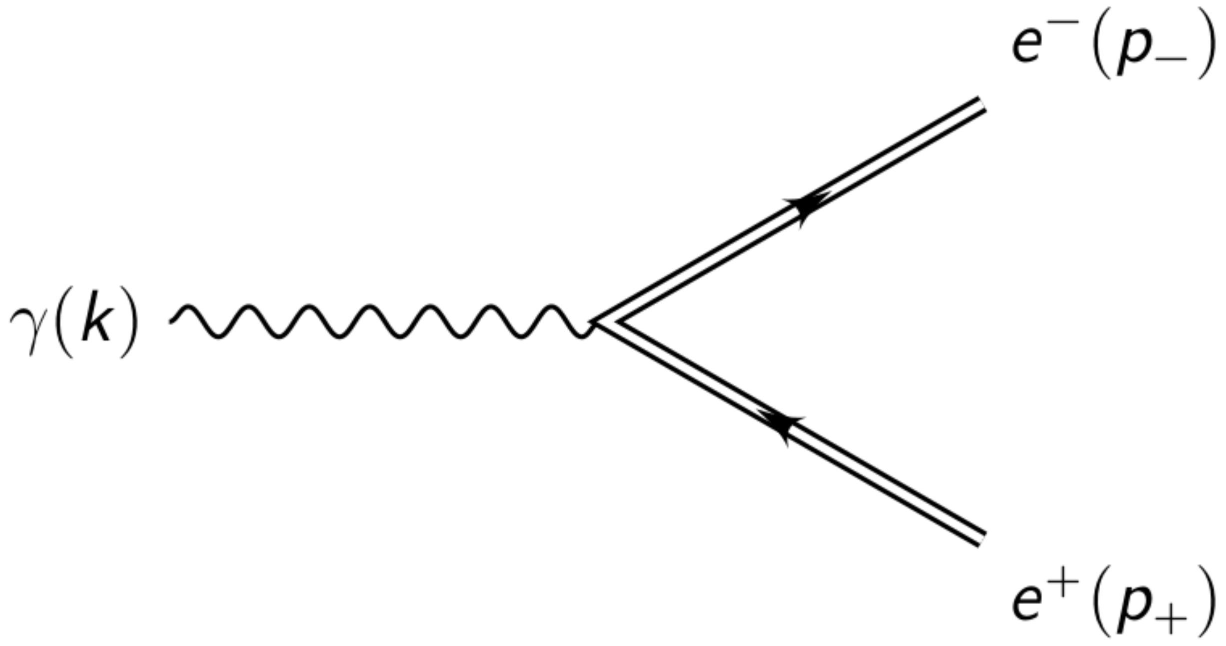
(adapted from Ezratty 2023)

Electron beam - laser collision: setup and experiment

Nonlinear Compton scattering (γ emission)



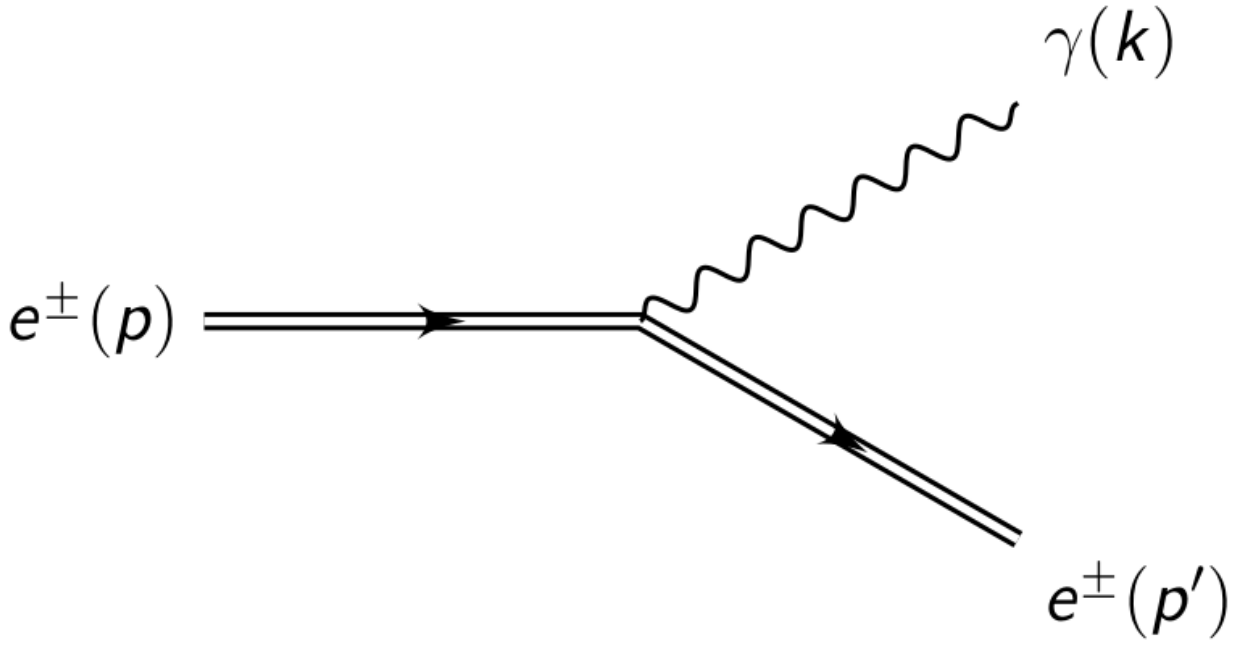
Nonlinear Breit-Wheeler (e^+e^- production)



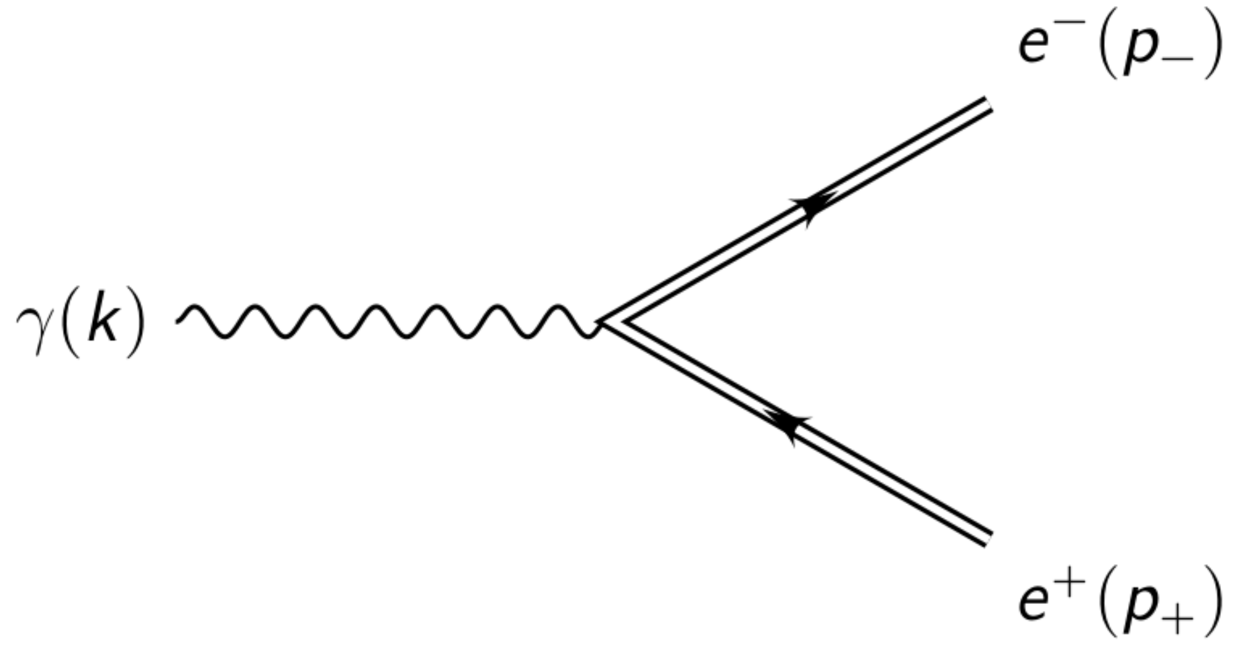
* OA, MV, PPCF 66 045006 (2024), † M Mirzaie, OA, MV, et al, Nature Photonics (2024)

Electron beam - laser collision: setup and experiment

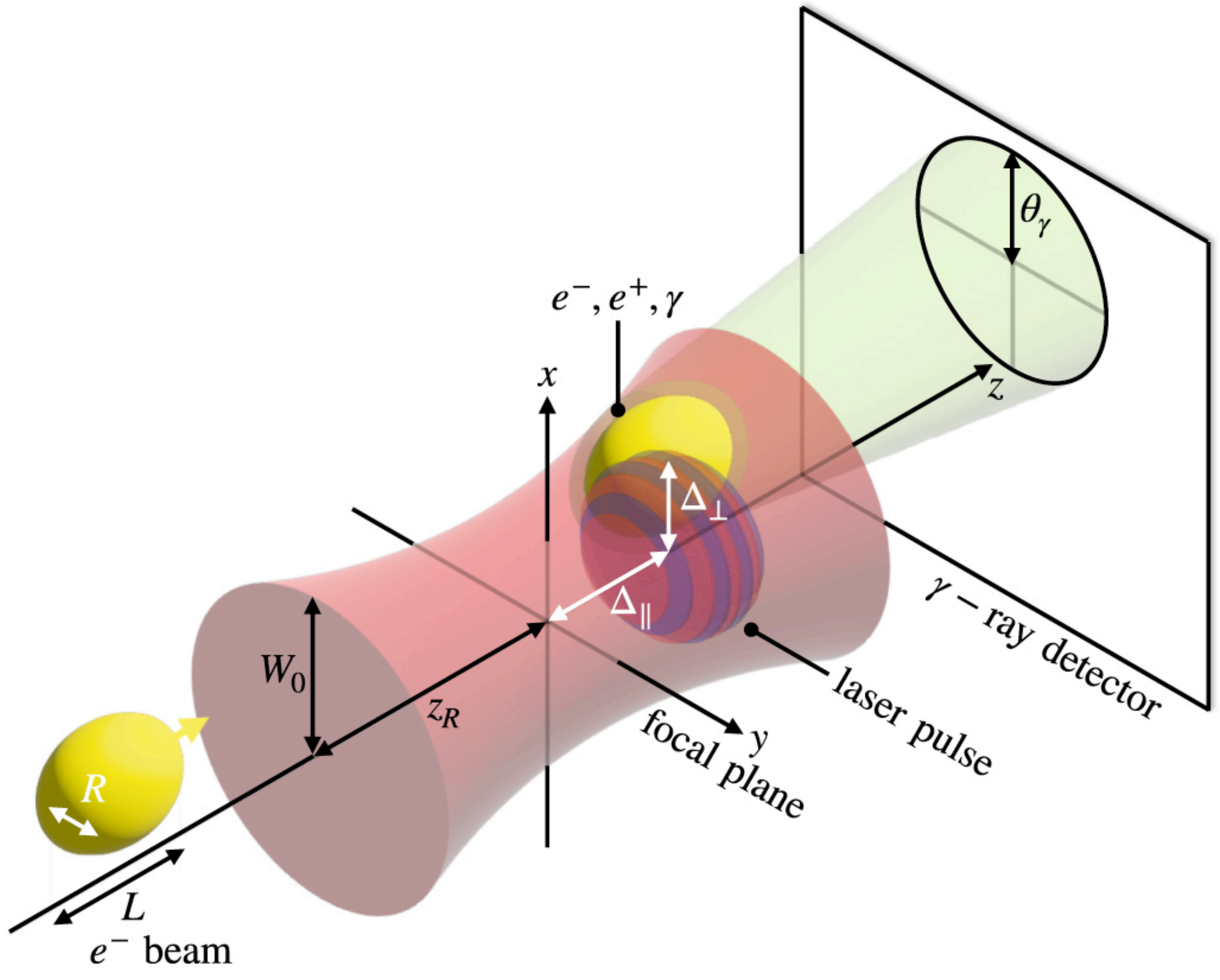
Nonlinear Compton scattering (γ emission)



Nonlinear Breit-Wheeler (e^+e^- production)



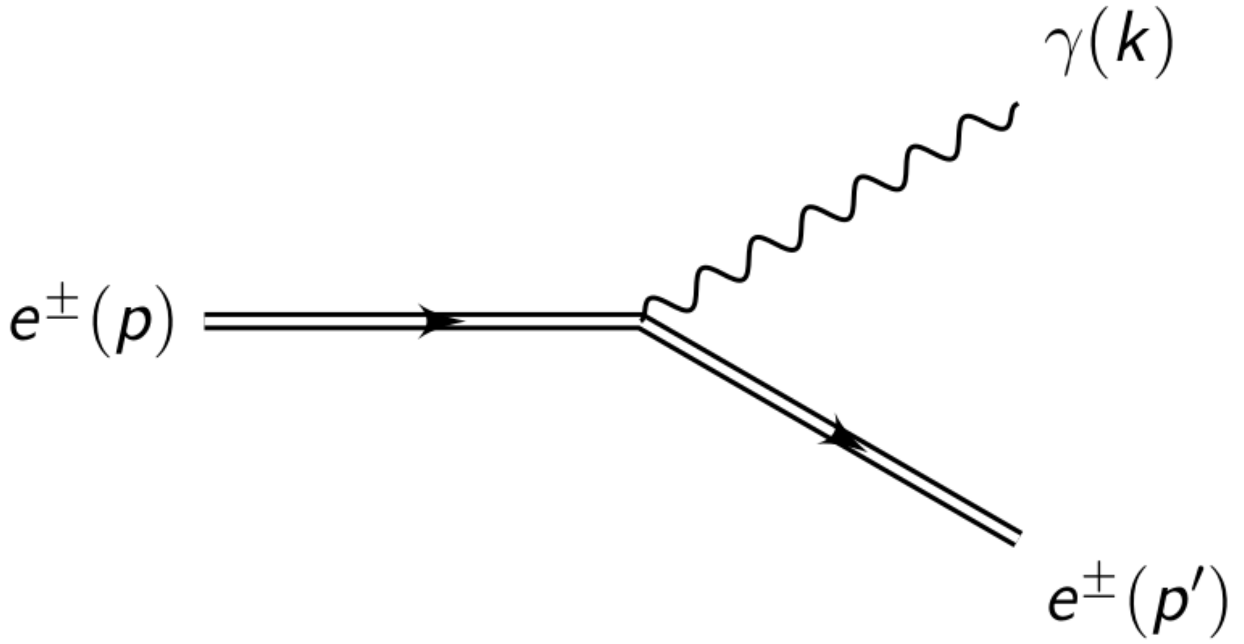
*



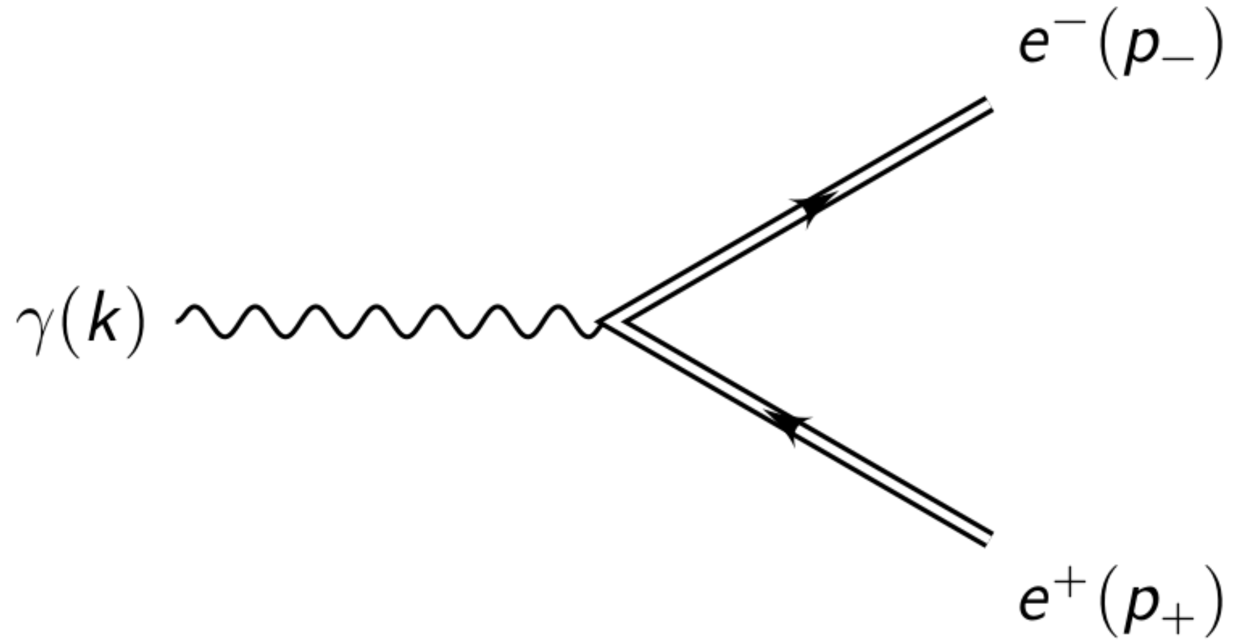
Electron beam - laser collision: setup and experiment

TÉCNICO LISBOA

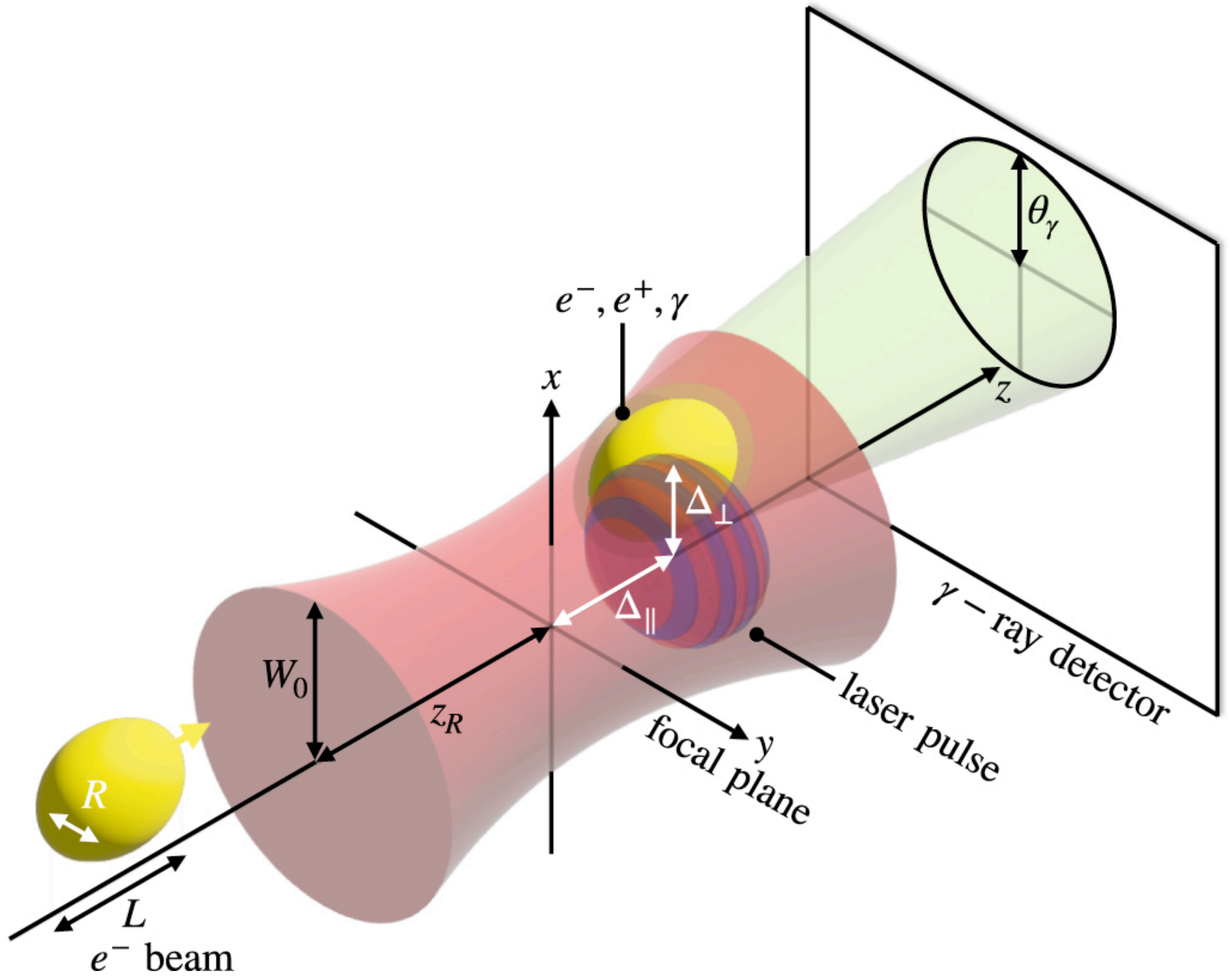
Nonlinear Compton scattering (γ emission)



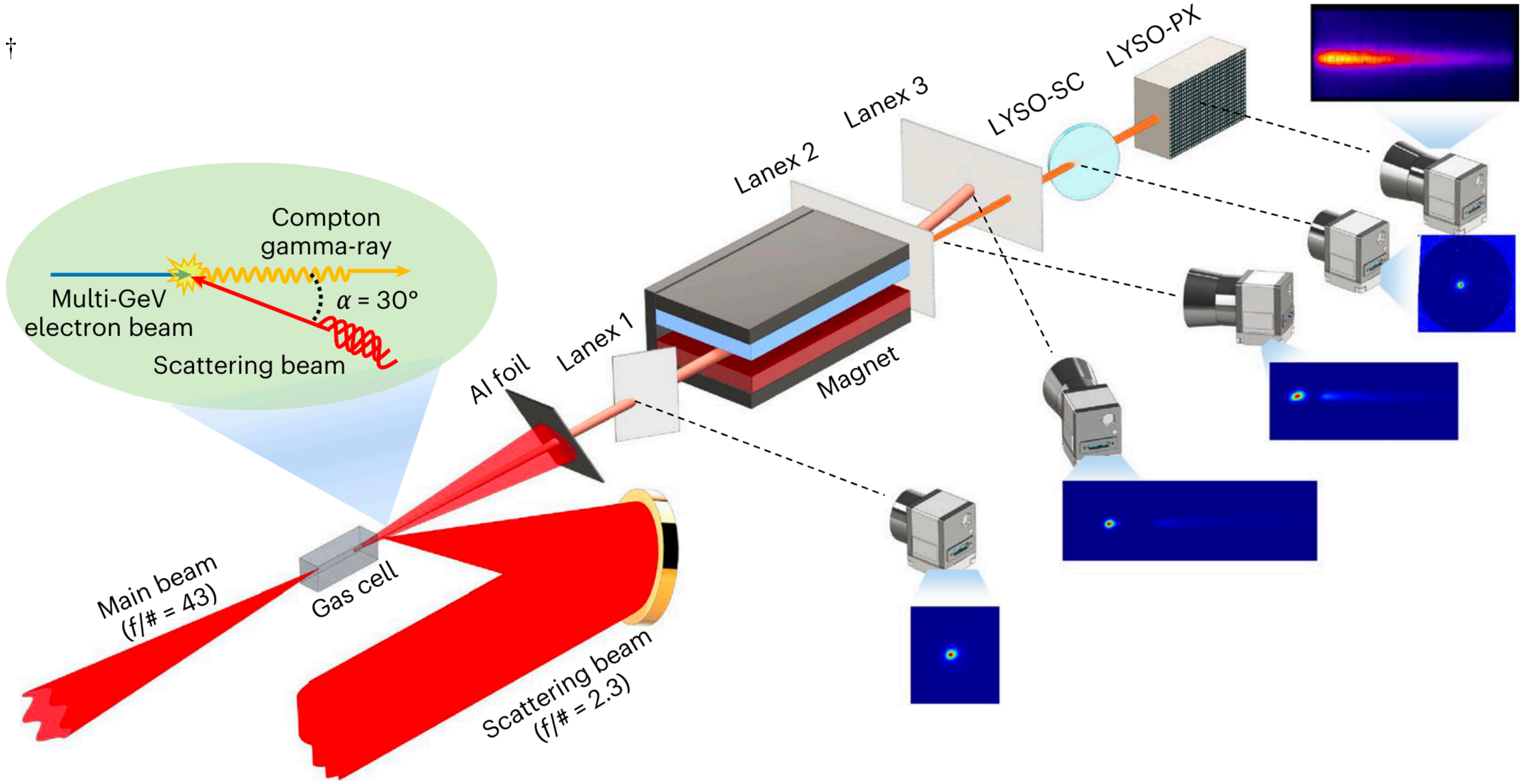
Nonlinear Breit-Wheeler (e^+e^- production)



*



†

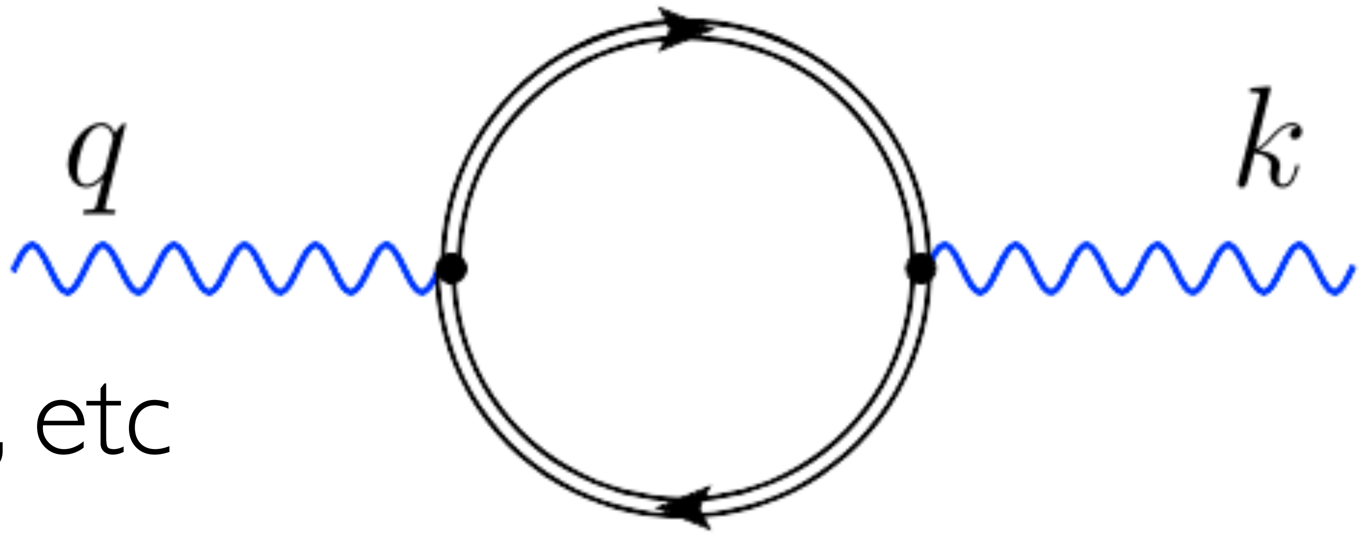


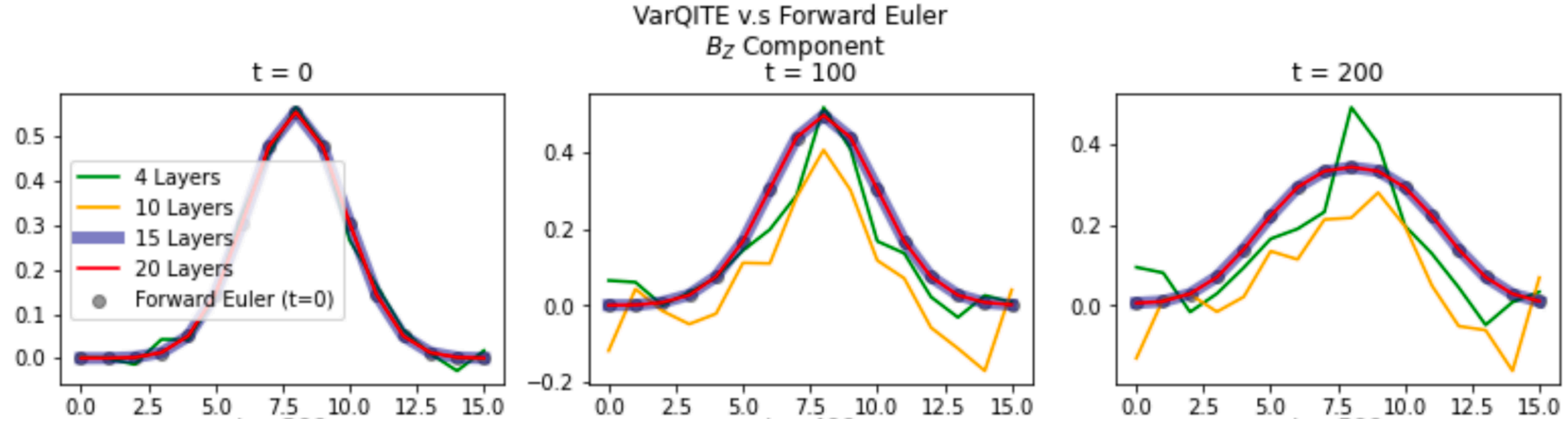
* OA, MV, PPCF 66 045006 (2024), † M Mirzaie, OA, MV, et al, Nature Photonics (2024)

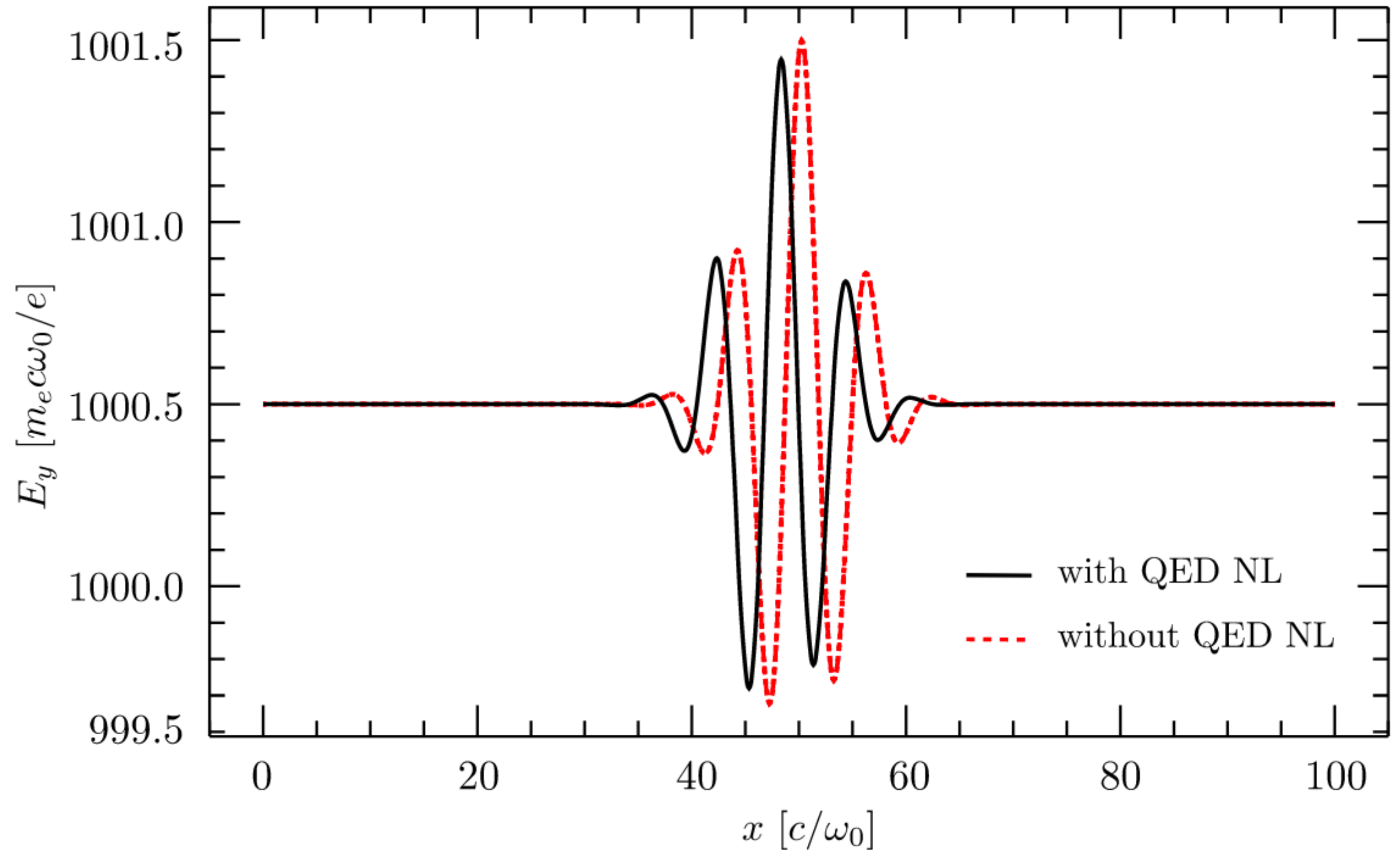
Intense lasers: Maxwell's equations and Nonlinear QED

Strong electromagnetic fields can lead to nonlinear phenomena.

The "vacuum" effectively behaves like a material medium: bi-refringence, etc







E/E_c

Linear Maxwell's *

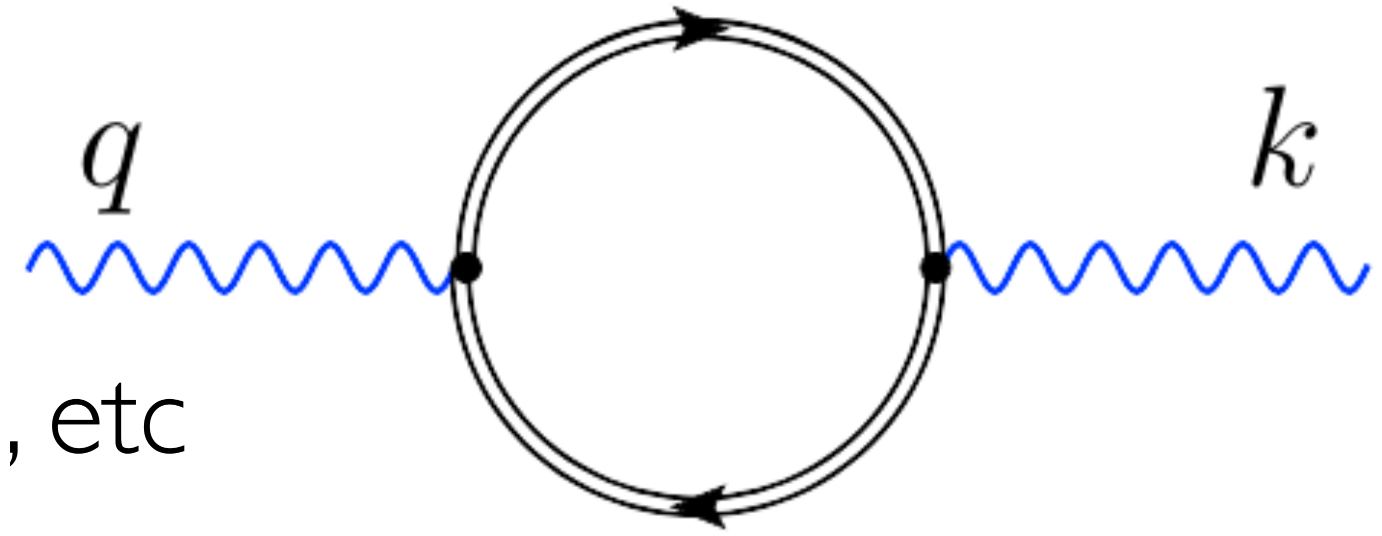
Euler-Heisenberg effective Lagrangian †

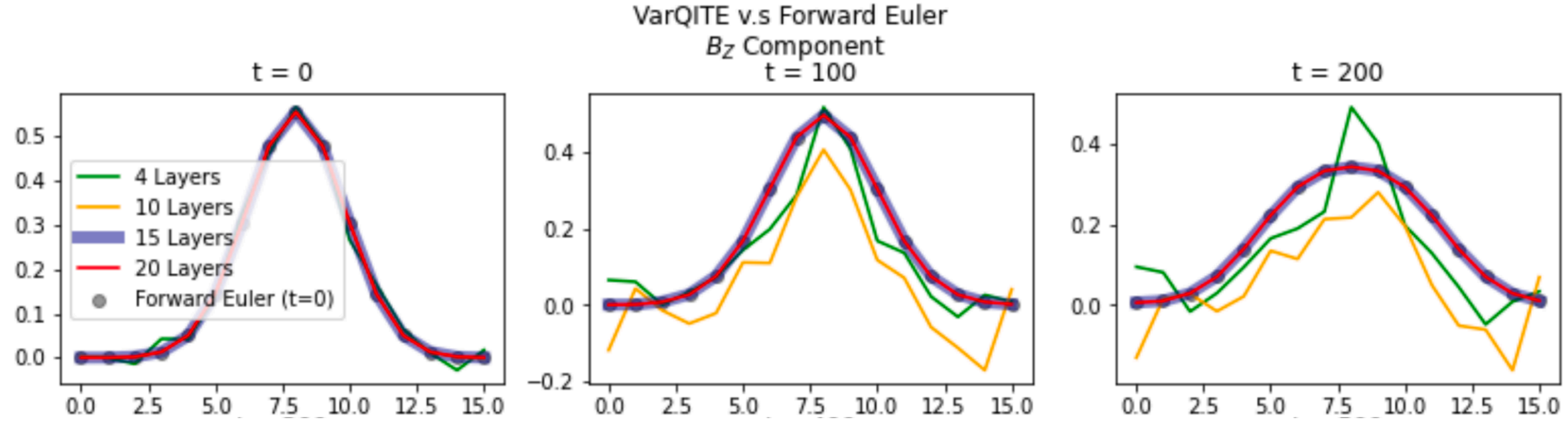
* Costa et al, PRA 99, 012323 (2019), Nguyen 2402.12156 (2024), † Grismayer NJP 2021

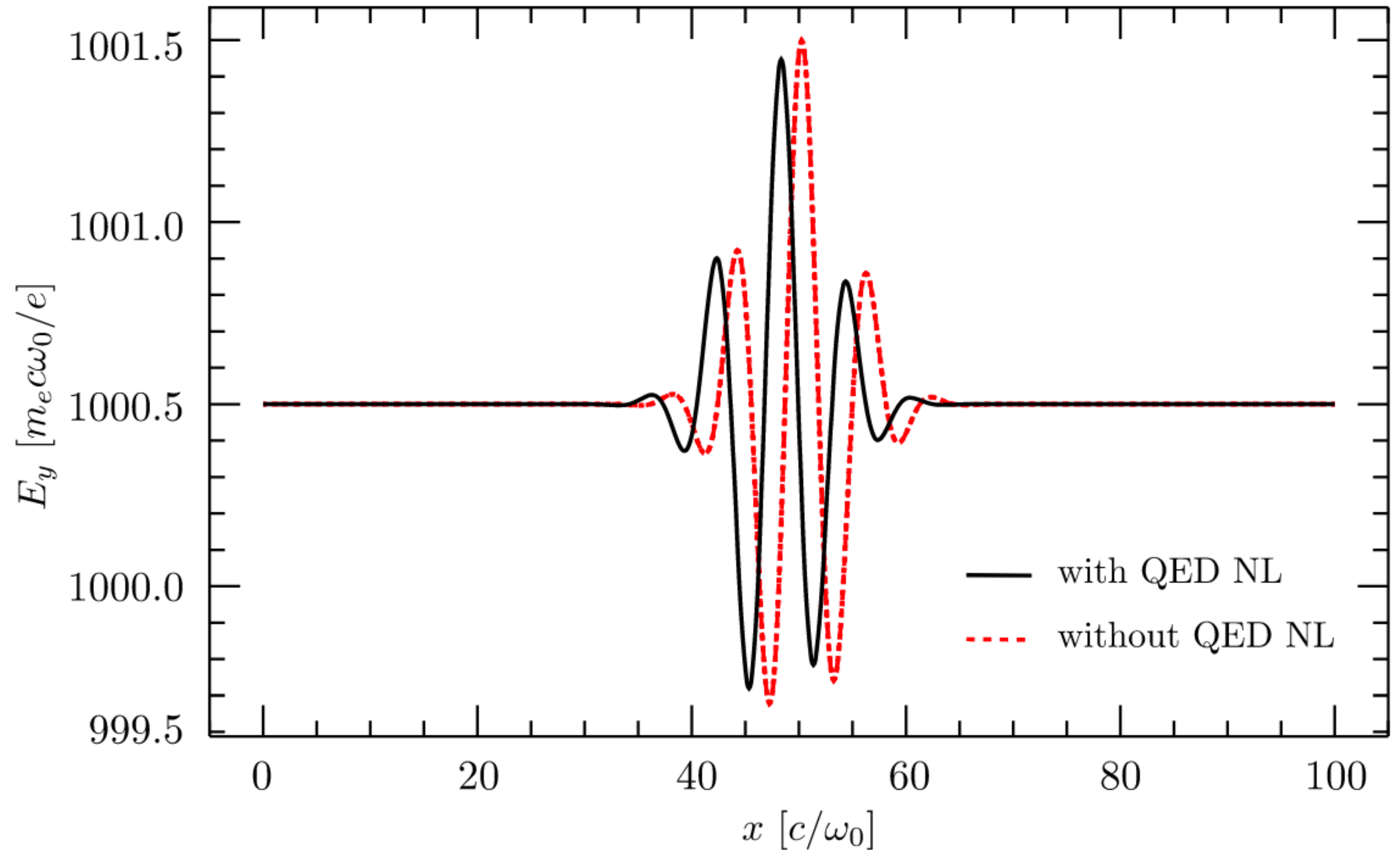
Intense lasers: Maxwell's equations and Nonlinear QED

Strong electromagnetic fields can lead to nonlinear phenomena.

The "vacuum" effectively behaves like a material medium: bi-refringence, etc







E/E_c

Linear Maxwell's *

Euler-Heisenberg effective Lagrangian †

No implemented algorithm for self-consistent nonlinear dynamics of plasma + EM fields yet!

* Costa et al, PRA 99, 012323 (2019), Nguyen 2402.12156 (2024), † Grismayer NJP 2021

Intense lasers + plasmas: regimes of Strong-Field Plasma dynamics

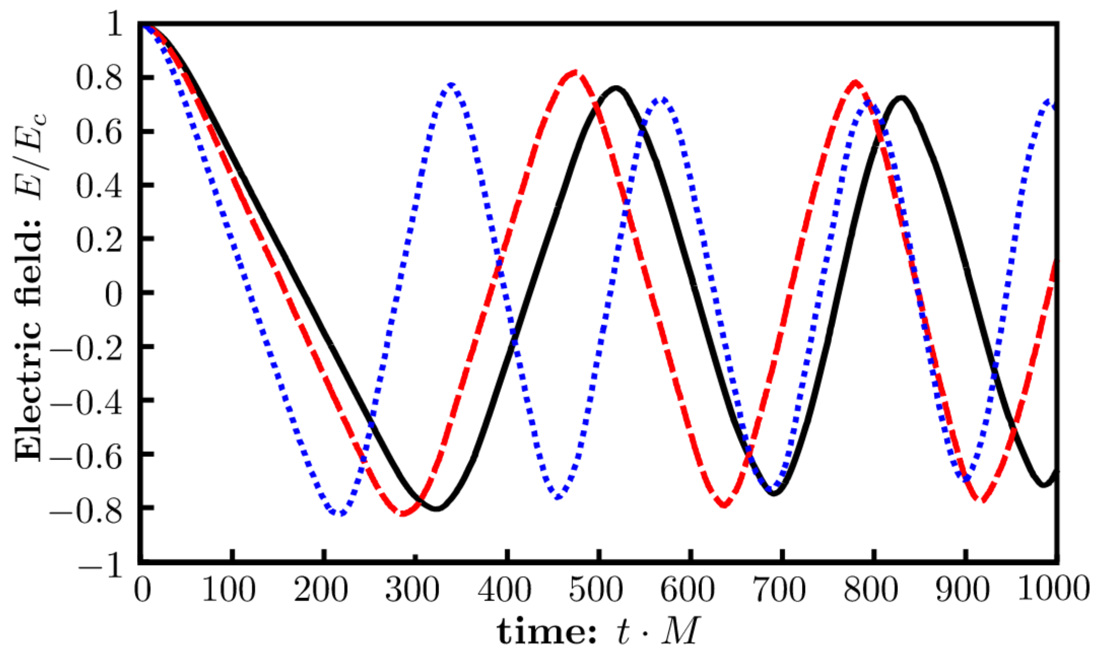
TÉCNICO LISBOA

n/n_c

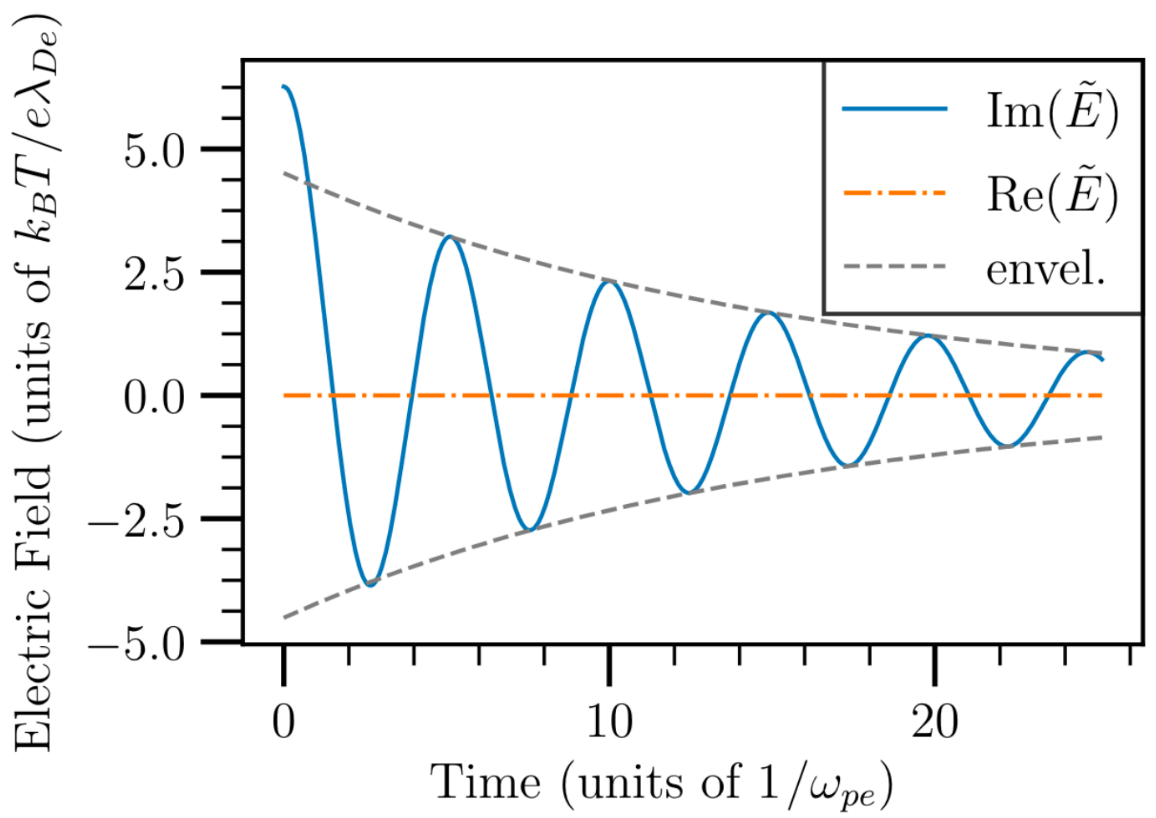
Back-reaction, screening, collective modes, quantum spin statistics

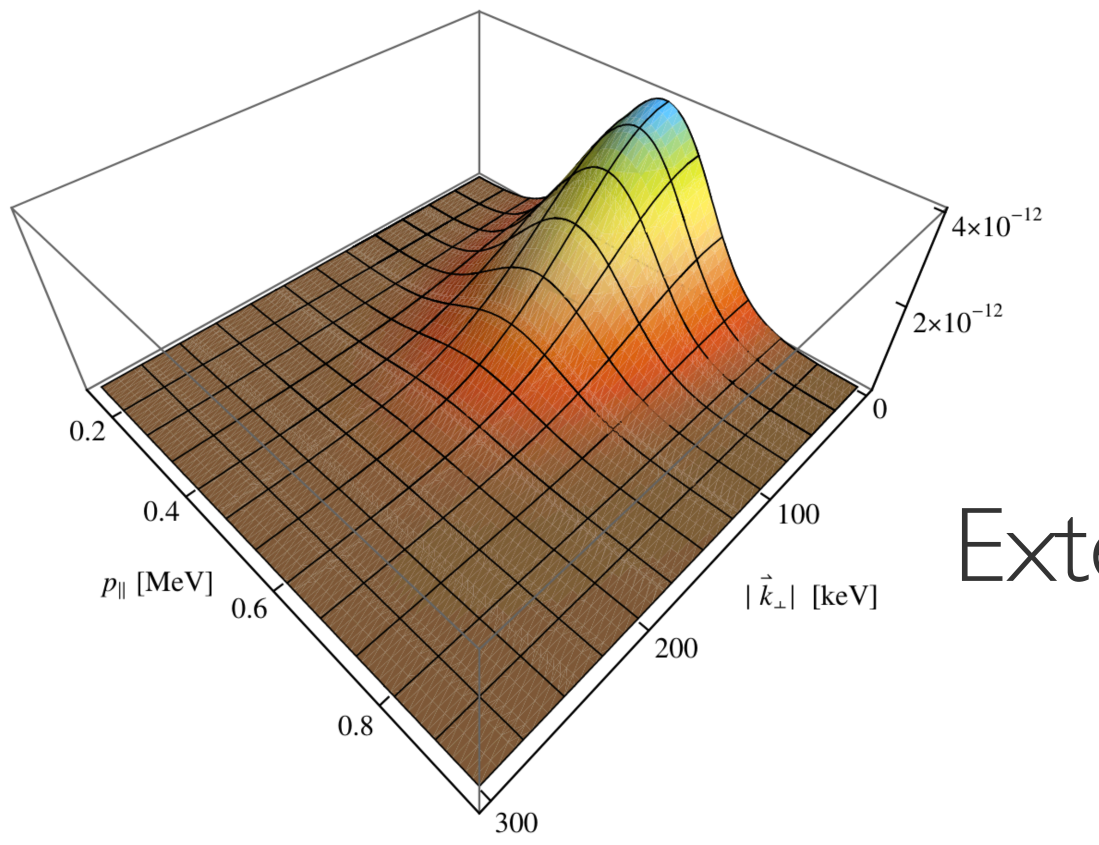
Pauli-blocked plasmas

Full QED cascade/avalanche ‡



e^- Landau damping *





External-field Schwinger pair-production †

Low-density approximations

Linear Maxwell's eqs

EH Lagrangian

E/E_c

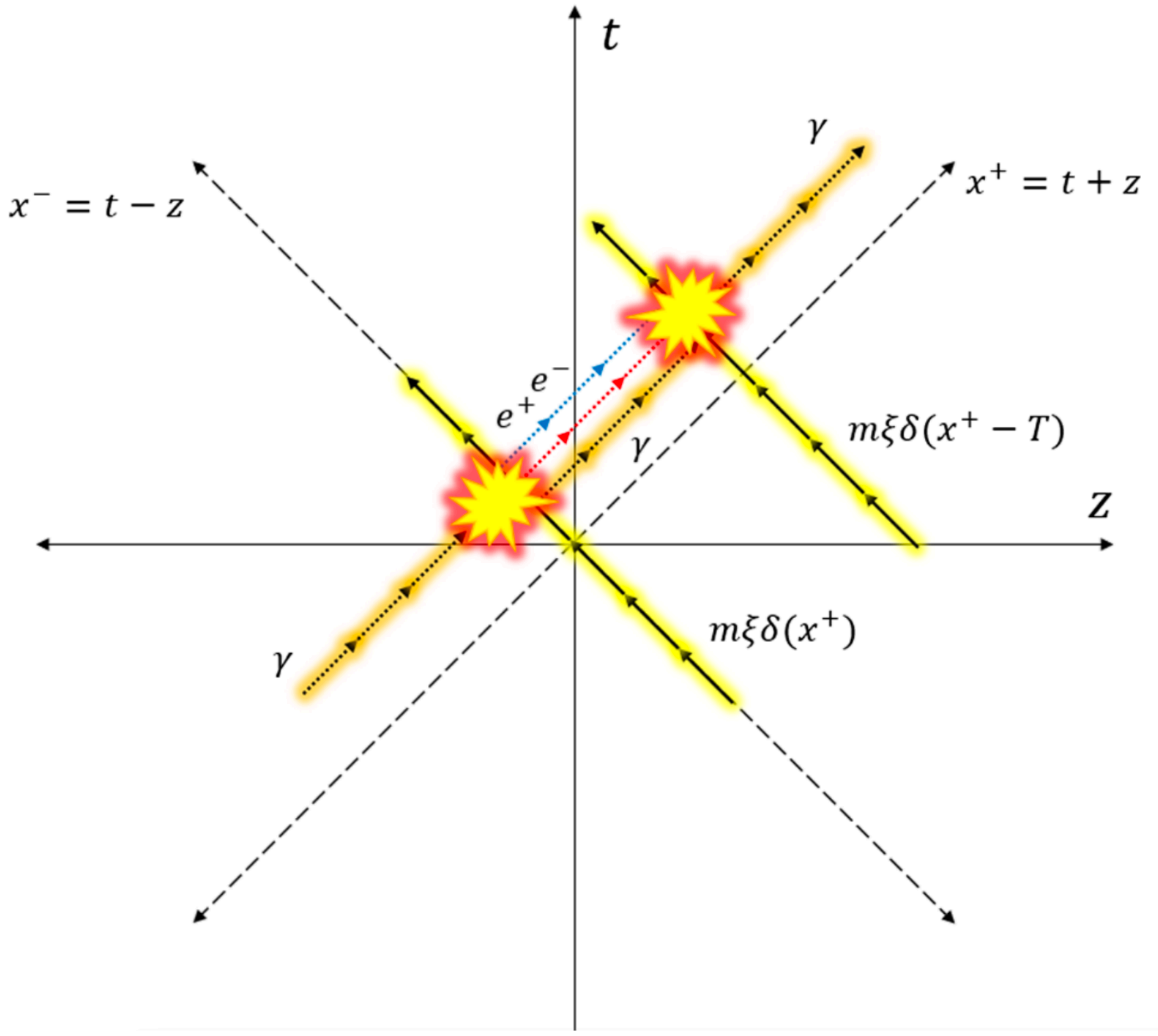
No pair-production | $E/E_c \ll 1$ | $E/E_c \sim 0.1$ | $E/E_c > 1$

* Engel PRA 2019, † Hebenstreit PRD 2008, ‡ Kasper PhysLetB 2016

Pair production in scattering and Schwinger mechanism

Scattering $E < E_c$ †

- Initial state is not the vacuum/Ground-State, but a particle beam (relativistic fermions or photons)
- Light-front coordinates, momentum/Fock-space
- Sequence of laser pulses
- Usually limited pair production → no significant back-reaction on strong EM field
- Asymptotic free-particle states well defined
- More closely connected to experimental setups

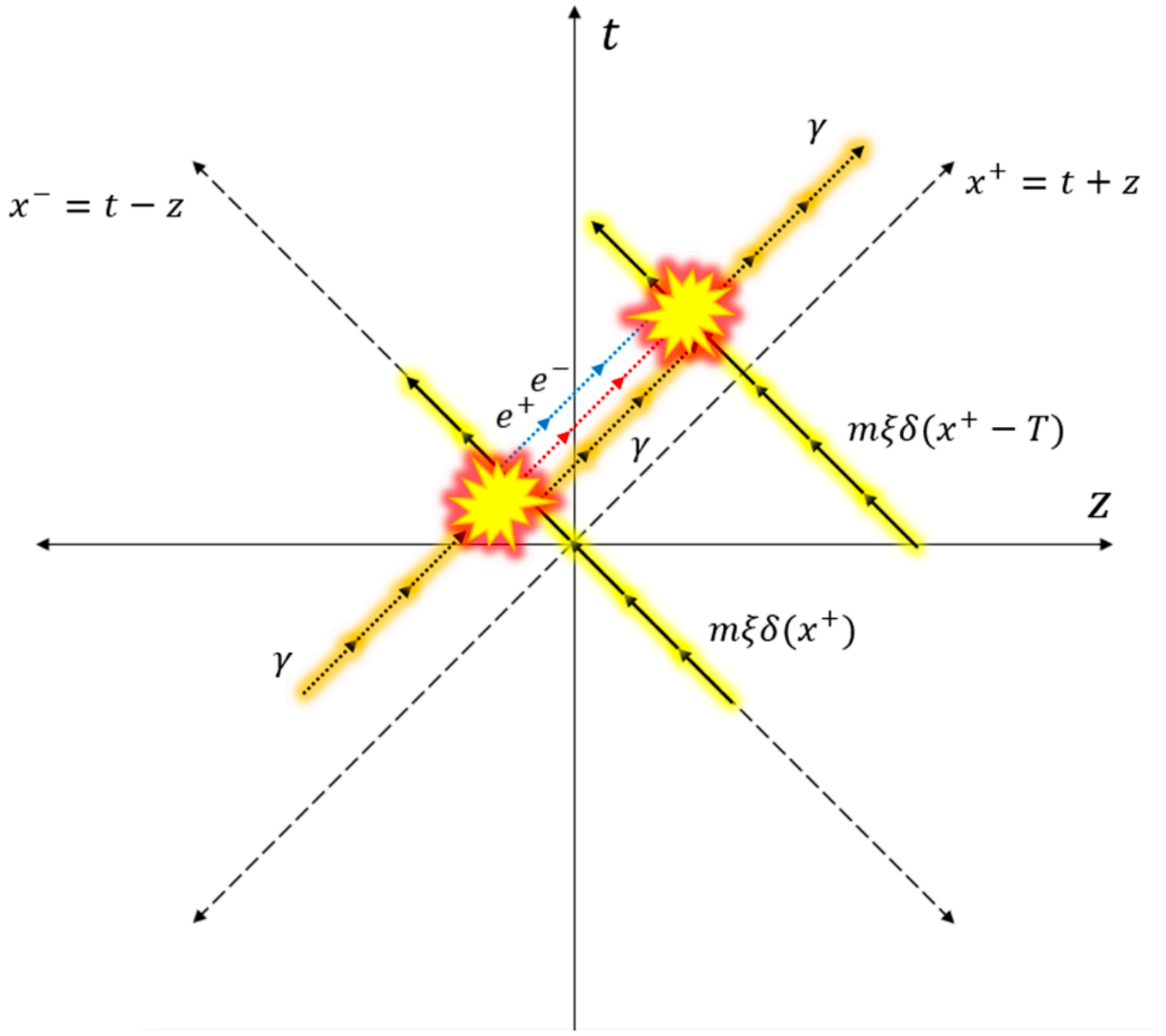


* Hidalgo PRD 2024, † Kasper PhysLetB 2016, ‡ Grismayer PoP 2016

Pair production in scattering and Schwinger mechanism

Scattering $E < E_c$ [†]

- Initial state is not the vacuum/Ground-State, but a particle beam (relativistic fermions or photons)
- Light-front coordinates, momentum/Fock-space
- Sequence of laser pulses
- Usually limited pair production → no significant back-reaction on strong EM field
- Asymptotic free-particle states well defined
- More closely connected to experimental setups

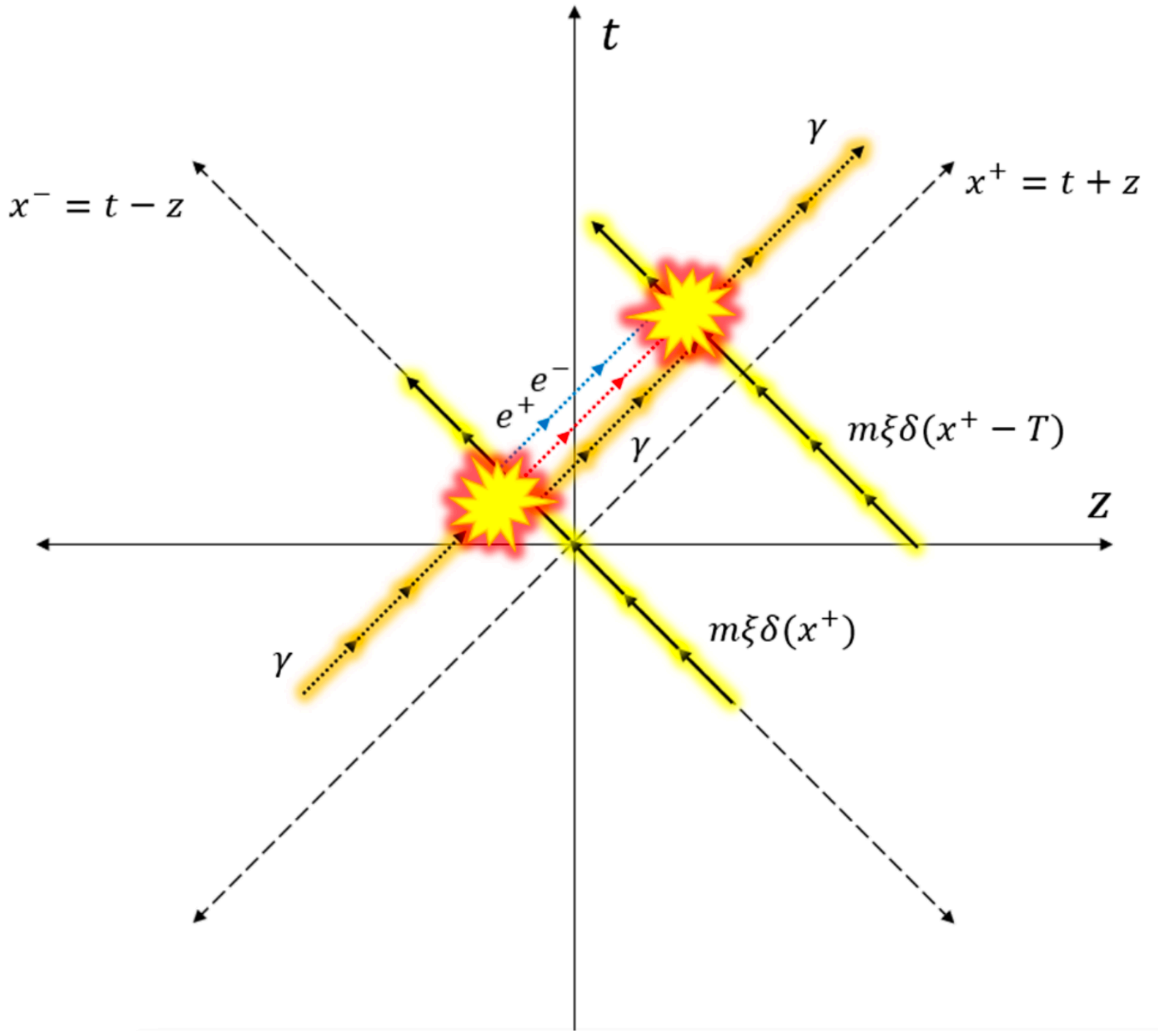


* Hidalgo PRD 2024, † Kasper PhysLetB 2016, ‡ Grismayer PoP 2016

Pair production in scattering and Schwinger mechanism

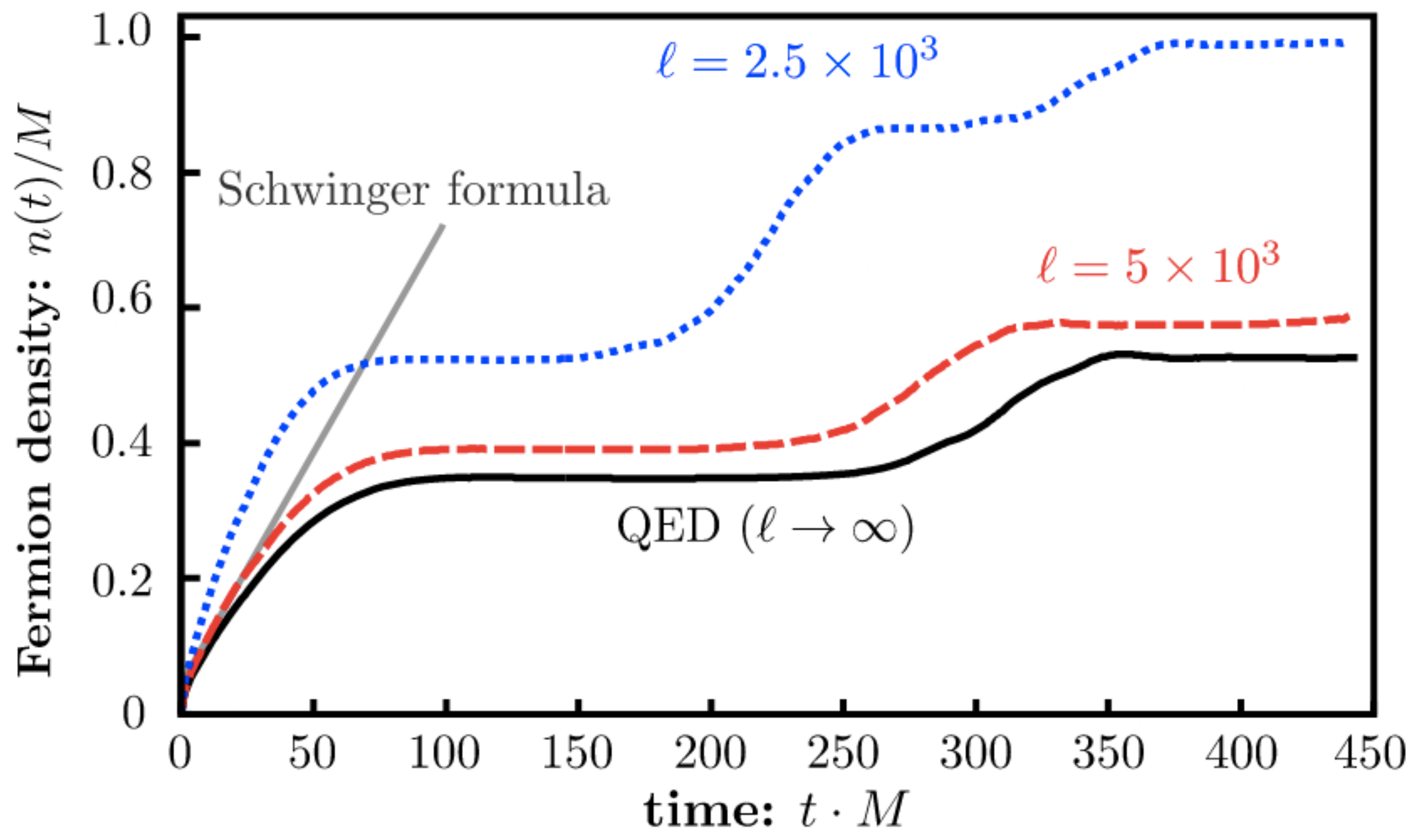
Scattering $E < E_c$ †

- Initial state is not the vacuum/Ground-State, but a particle beam (relativistic fermions or photons)
- Light-front coordinates, momentum/Fock-space
- Sequence of laser pulses
- Usually limited pair production → no significant back-reaction on strong EM field
- Asymptotic free-particle states well defined
- More closely connected to experimental setups



Schwinger mechanism $E \sim E_c$ *

- Initial state is the vacuum of the theory
- Usually simulation in real coordinate space
- Background strong electric field (can be made localized and space/time-dependent)
- Electrical current feedback from pairs leads to damping and oscillation of electric field
- Quantum kinetic approach well studied



* Hidalgo PRD 2024, † Kasper PhysLetB 2016, ‡ Grismayer PoP 2016

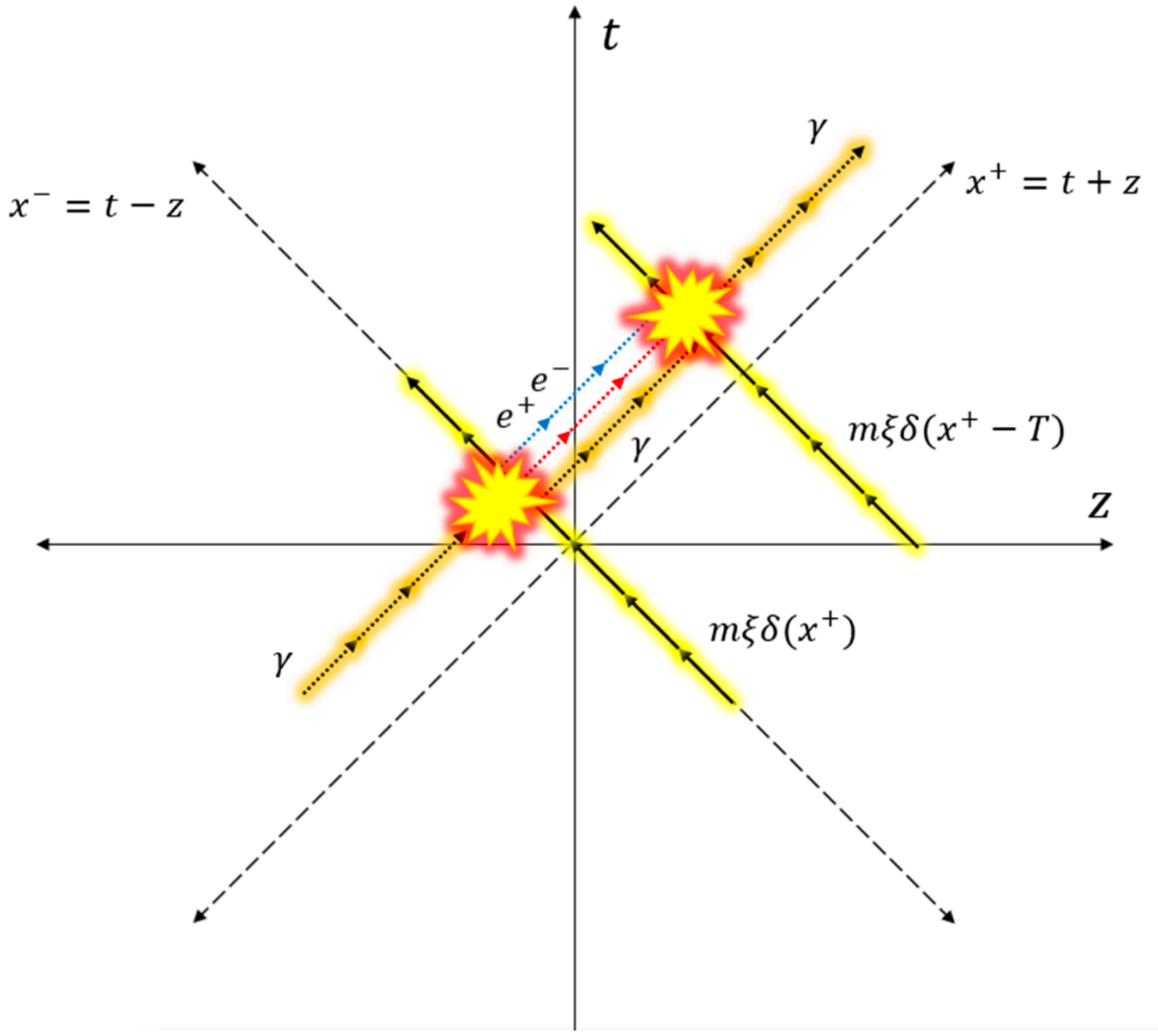
Pair production in scattering and Schwinger mechanism

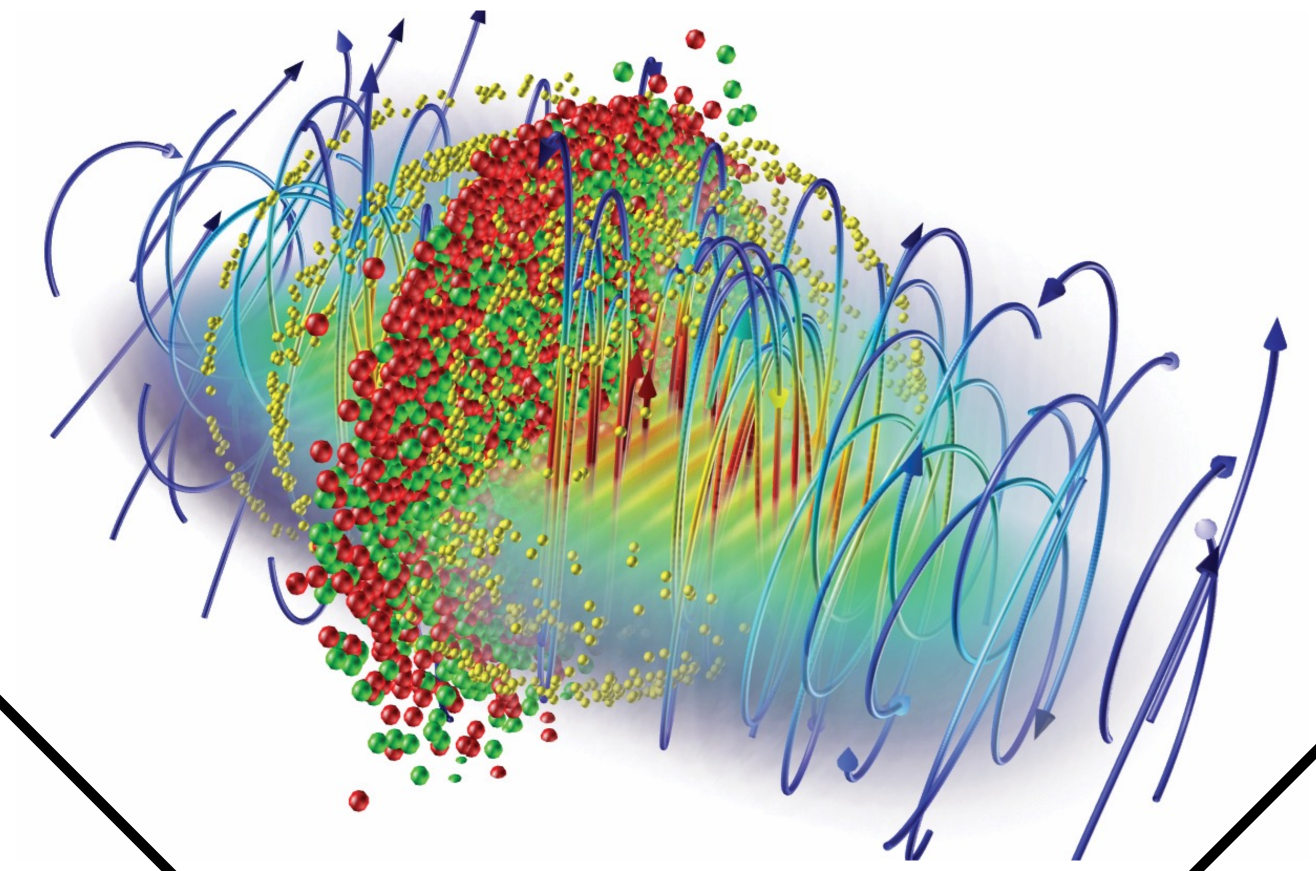
Scattering $E < E_c$ †

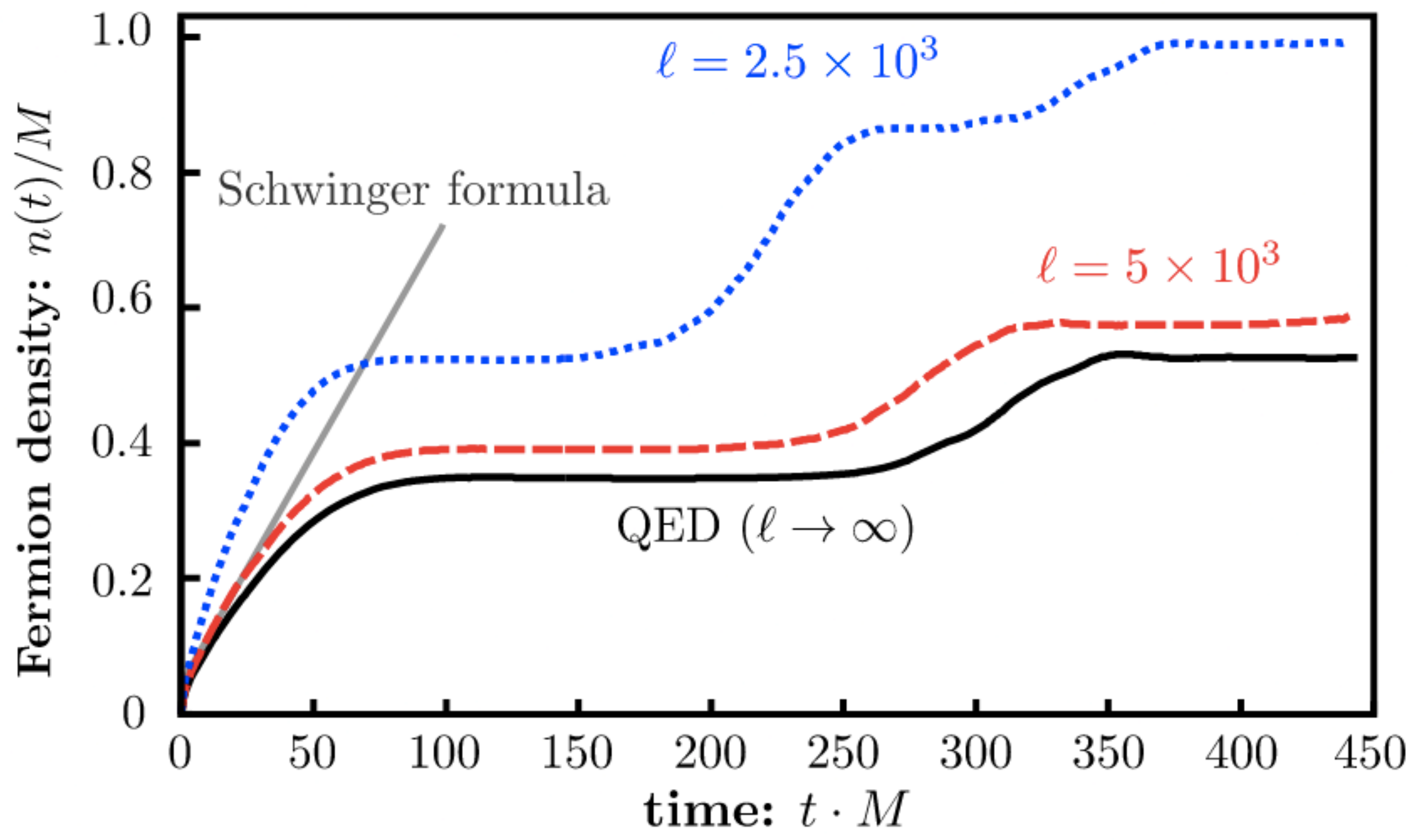
- Initial state is not the vacuum/Ground-State, but a particle beam (relativistic fermions or photons)
- Light-front coordinates, momentum/Fock-space
- Sequence of laser pulses
- Usually limited pair production → no significant back-reaction on strong EM field
- Asymptotic free-particle states well defined
- More closely connected to experimental setups

Schwinger mechanism $E \sim E_c$ *

- Initial state is the vacuum of the theory
- Usually simulation in real coordinate space
- Background strong electric field (can be made localized and space/time-dependent)
- Electrical current feedback from pairs leads to damping and oscillation of electric field
- Quantum kinetic approach well studied







SFQED-cascades ‡

Radiation Reaction of electrons in a strong field - kinetic approach

Fokker-Planck equation for the energy distribution:

$$\frac{\partial f}{\partial t}(t,\gamma) = \frac{\partial}{\partial \gamma}\left[S(\chi)\, f\right] + \frac{1}{2}\frac{\partial^2}{\partial \gamma^2}\left[R(\chi,\gamma)\, f\right]$$

* OA, MV, L Gamiz, arXiv.2411.17517 (2024)

Radiation Reaction of electrons in a strong field - kinetic approach

TÉCNICO LISBOA

Fokker-Planck equation for the energy distribution:

$$\frac{\partial f}{\partial t}(t,\gamma) = \frac{\partial}{\partial \gamma}\left[S(\chi)\, f\right] + \frac{1}{2}\frac{\partial^2}{\partial \gamma^2}\left[R(\chi,\gamma)\, f\right]$$

Encoding particle distribution in quantum circuit.

Evolution of variational parameters through VarQITE.

* OA, MV, L Gamiz, arXiv.2411.17517 (2024)

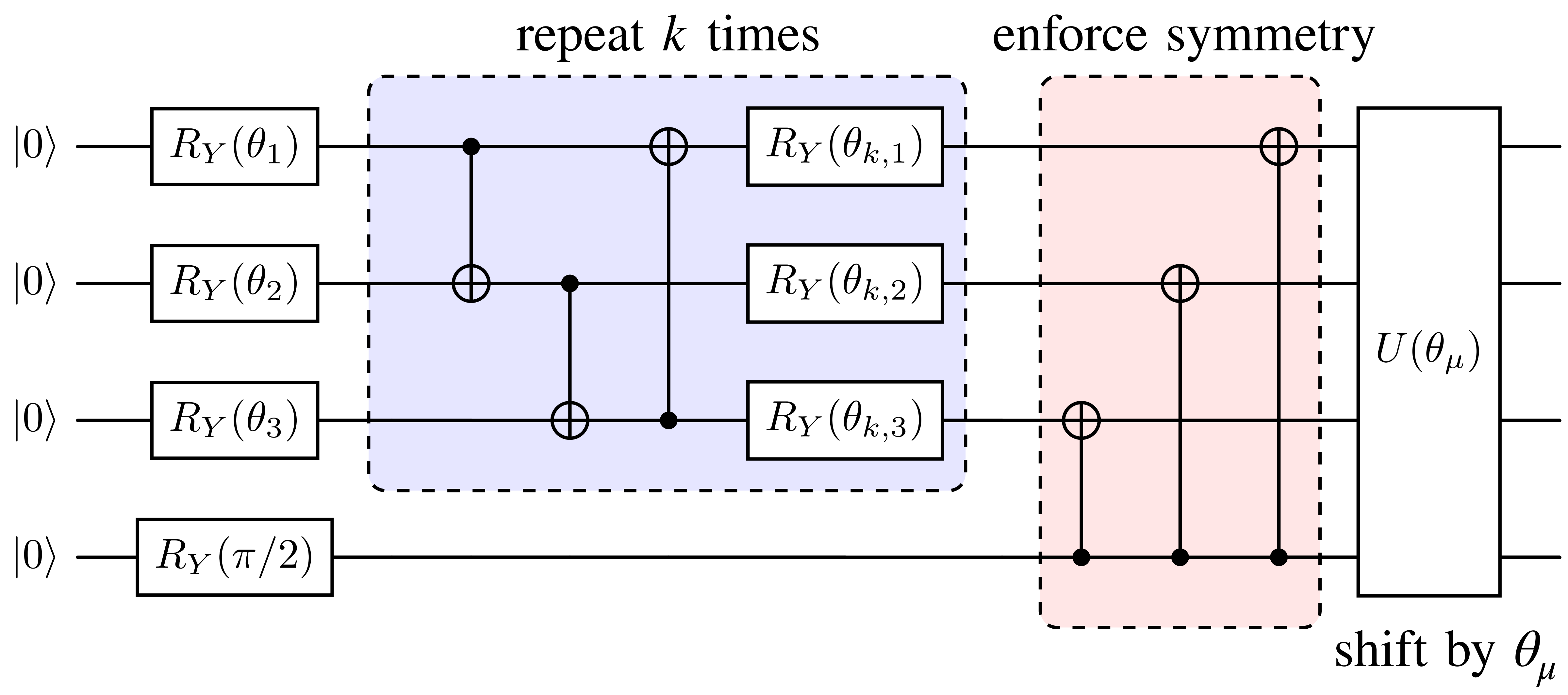
Radiation Reaction of electrons in a strong field - kinetic approach

Fokker-Planck equation for the energy distribution:

$$\frac{\partial f}{\partial t}(t,\gamma) = \frac{\partial}{\partial \gamma}\left[S(\chi)\, f\right] + \frac{1}{2}\frac{\partial^2}{\partial \gamma^2}\left[R(\chi,\gamma)\, f\right]$$

Encoding particle distribution in quantum circuit.

Evolution of variational parameters through VarQITE.



* OA, MV, L Gamiz, arXiv.2411.17517 (2024)

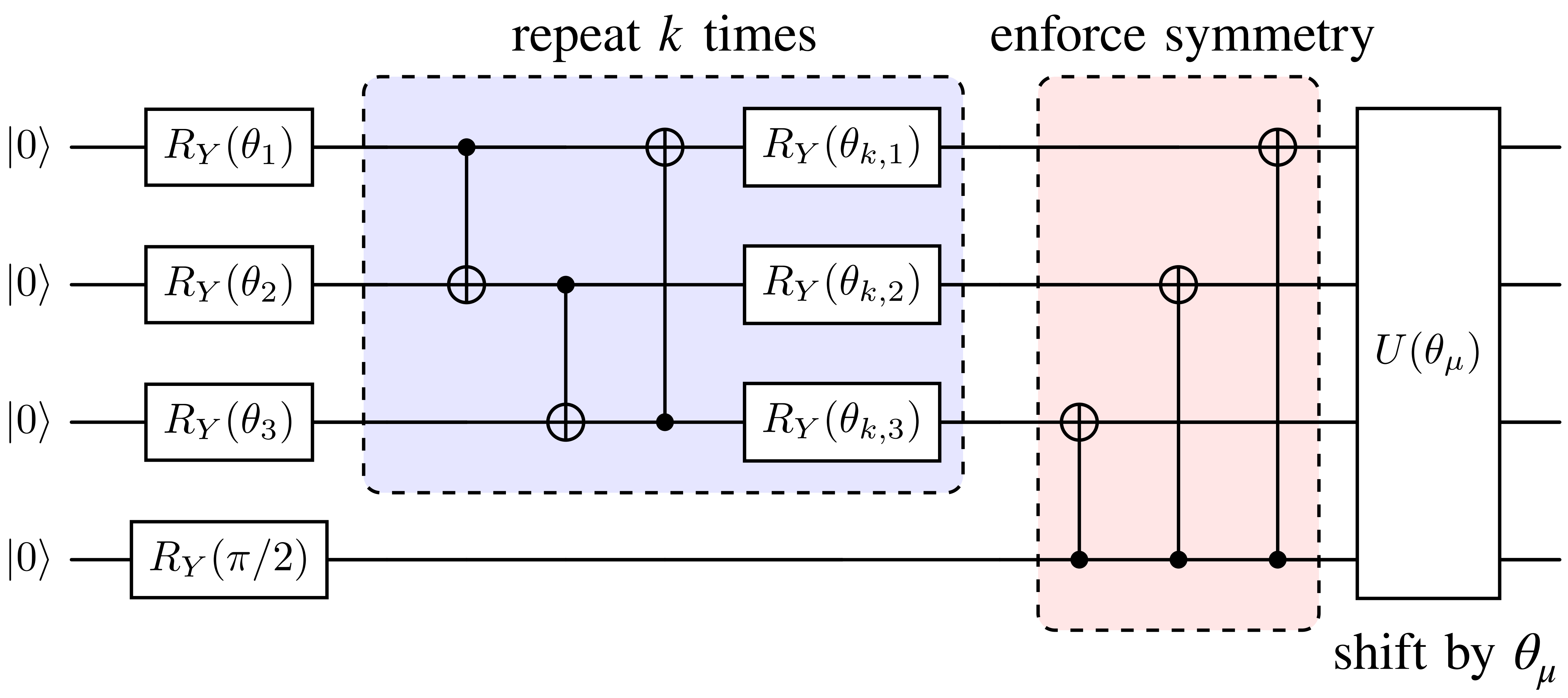
Radiation Reaction of electrons in a strong field - kinetic approach

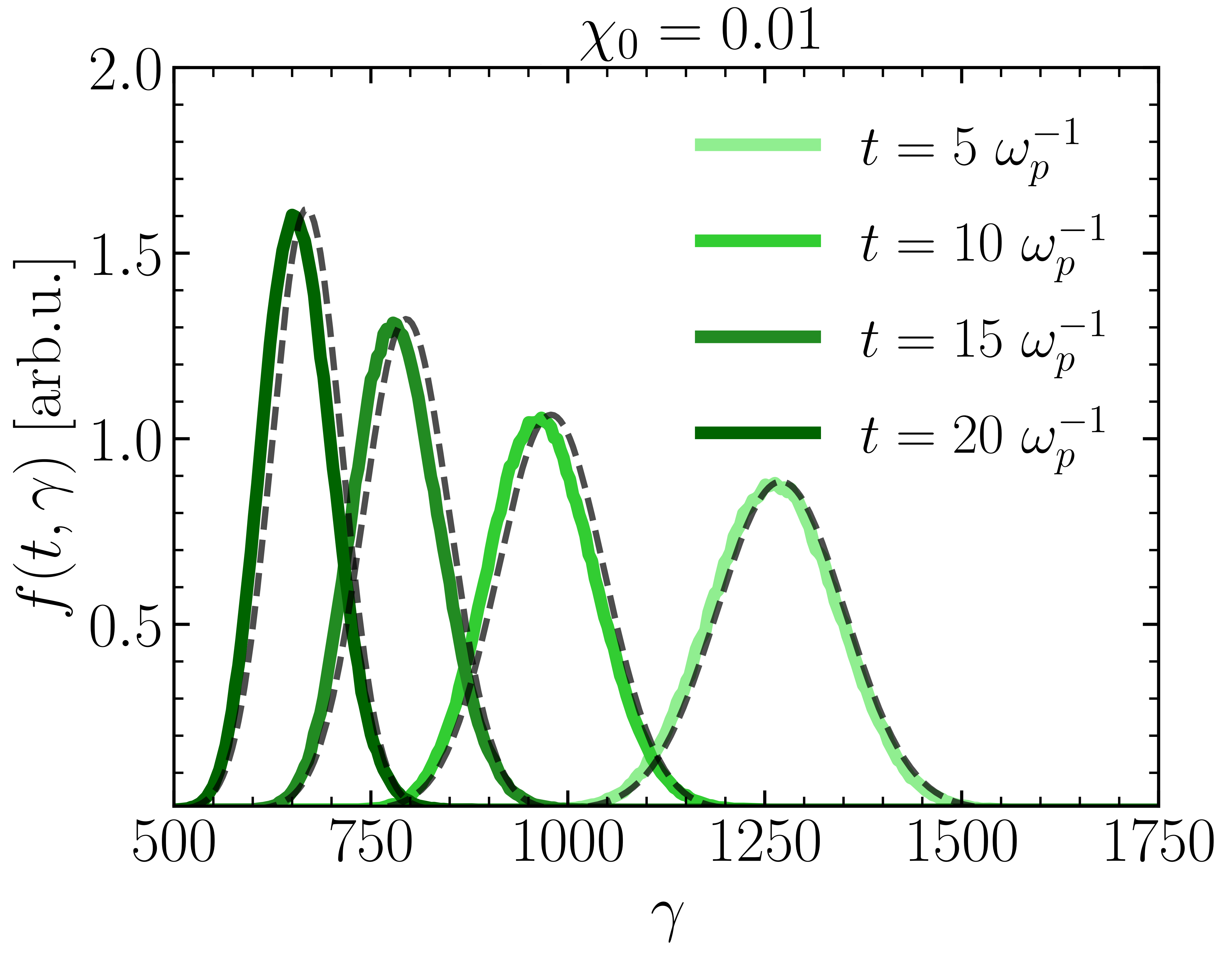
Fokker-Planck equation for the energy distribution:

$$\frac{\partial f}{\partial t}(t,\gamma) = \frac{\partial}{\partial \gamma}\left[S(\chi)\, f\right] + \frac{1}{2}\frac{\partial^2}{\partial \gamma^2}\left[R(\chi,\gamma)\, f\right]$$

Encoding particle distribution in quantum circuit.

Evolution of variational parameters through VarQITE.

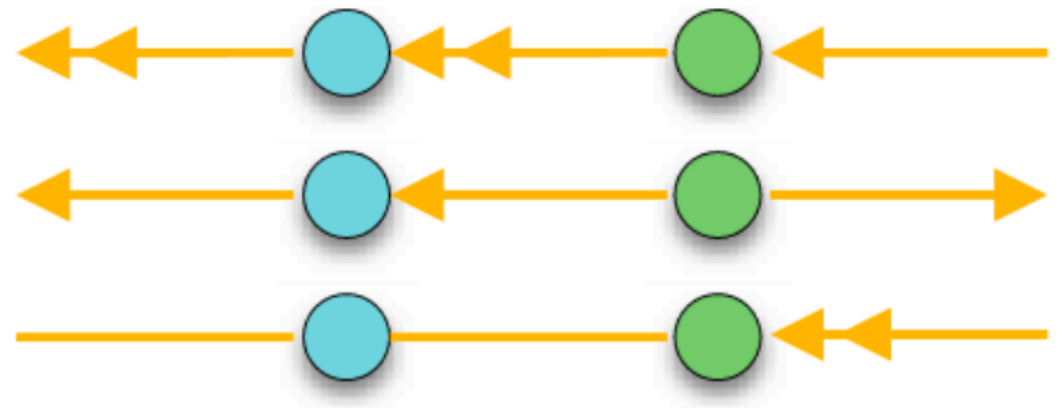




* OA, MV, L Gamiz, arXiv.2411.17517 (2024)

Types of Electromagnetic fields in classical/quantum simulations

Separation of scales leads to different approaches to the EM fields:



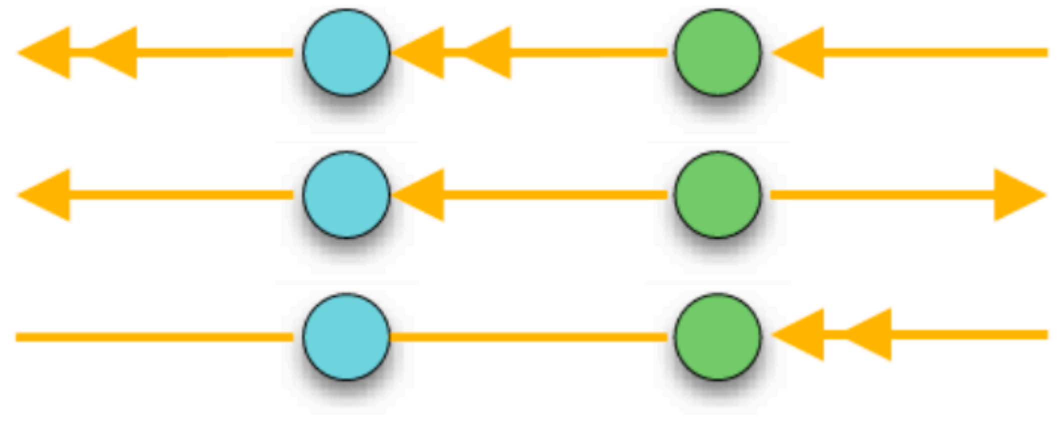
- Dynamical gauge: self-consistent, generated EM fields E_{dyn}
  - Are updated through quantum Hamiltonian or Maxwell's eqs on PIC grid.

* Hidalgo PRD 2024, † Kasper PhysLetB 2016, ‡ Grismayer PoP 2016

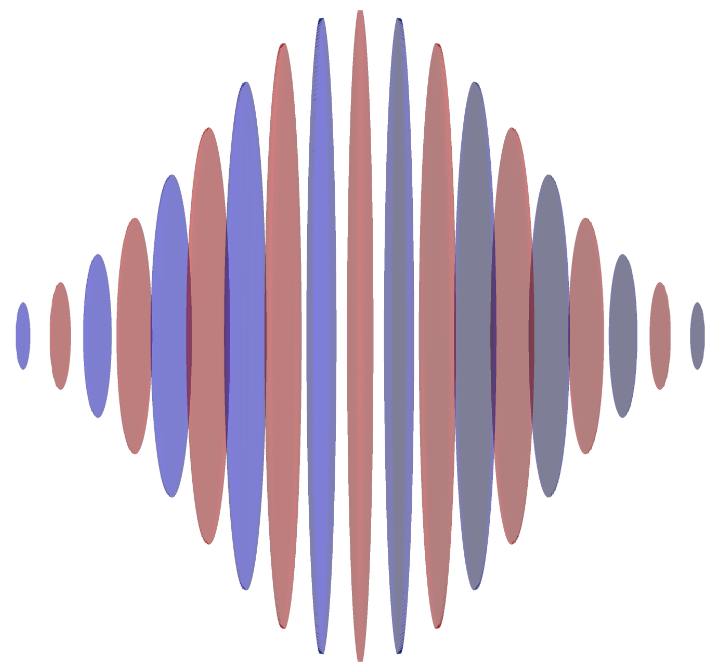
Types of Electromagnetic fields in classical/quantum simulations

Separation of scales leads to different approaches to the EM fields:

- Dynamical gauge: self-consistent, generated EM fields E_{dyn}
  - Are updated through quantum Hamiltonian or Maxwell's eqs on PIC grid.



- External/background semiclassical fields E_{ext}
  - Imposed on fermions (eg. strong laser fields)

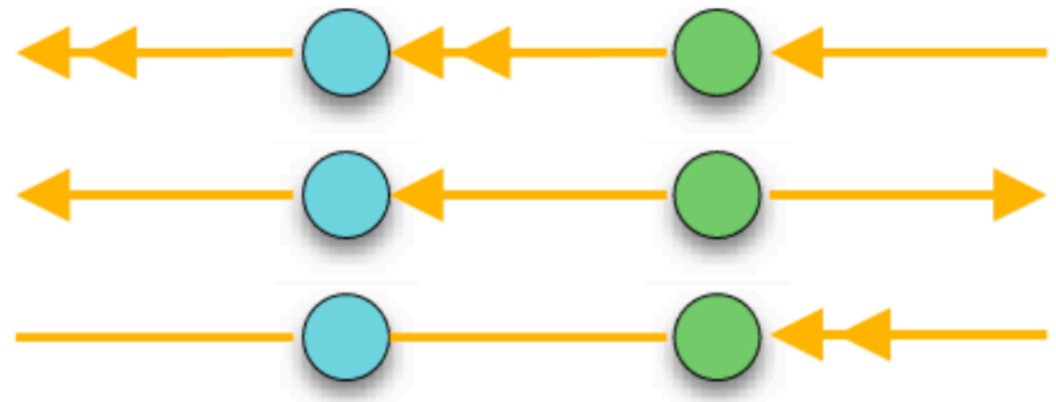


* Hidalgo PRD 2024, † Kasper PhysLetB 2016, ‡ Grismayer PoP 2016

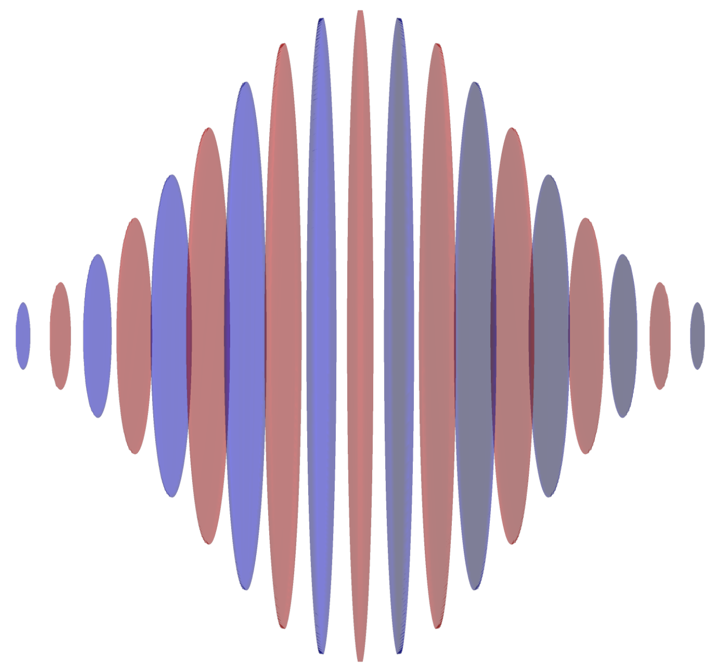
Types of Electromagnetic fields in classical/quantum simulations

Separation of scales leads to different approaches to the EM fields:

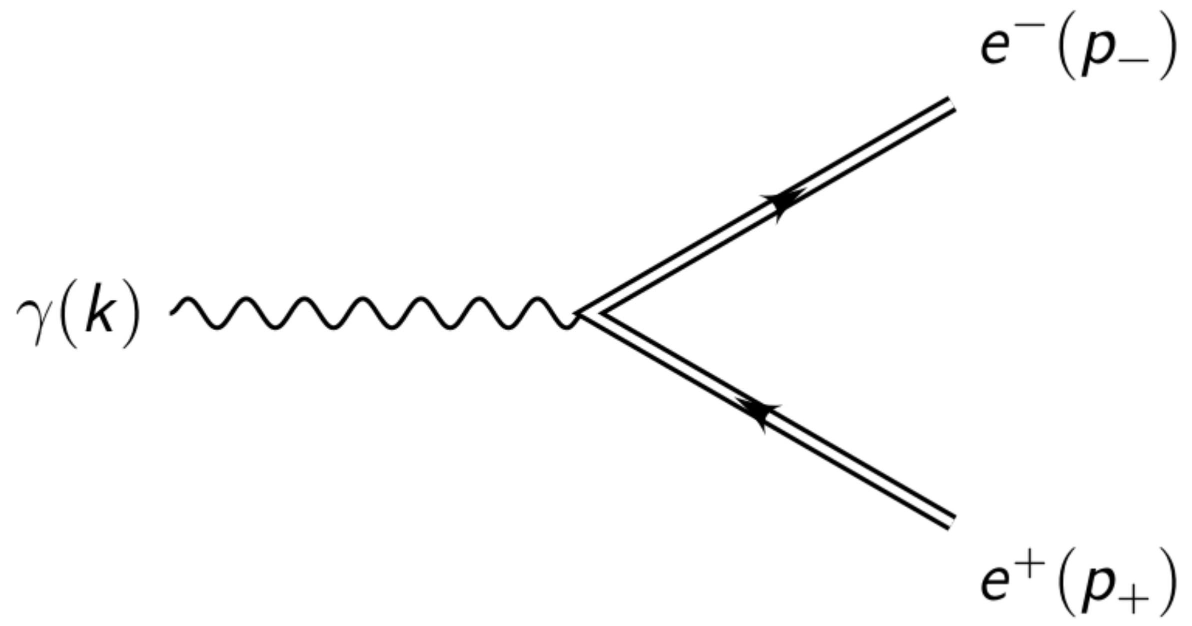
- Dynamical gauge: self-consistent, generated EM fields E_{dyn}
  - Are updated through quantum Hamiltonian or Maxwell's eqs on PIC grid.



- External/background semiclassical fields E_{ext}
  - Imposed on fermions (eg. strong laser fields)



- High-energy photons that cannot be resolved on the grid E_{γ}
  - Can be taken as macroparticles in PIC or using momentum Fock states



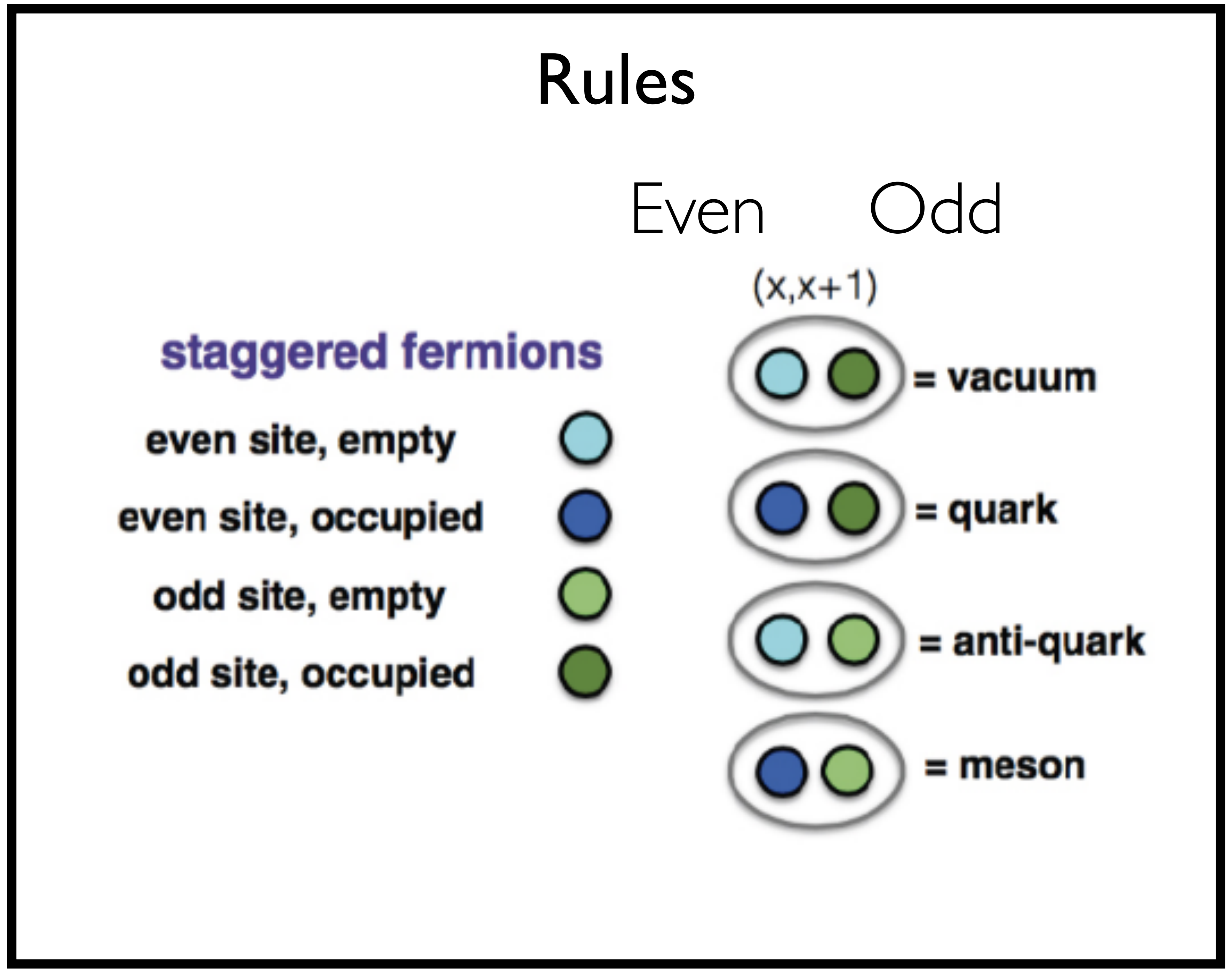
* Hidalgo PRD 2024, † Kasper PhysLetB 2016, ‡ Grismayer PoP 2016

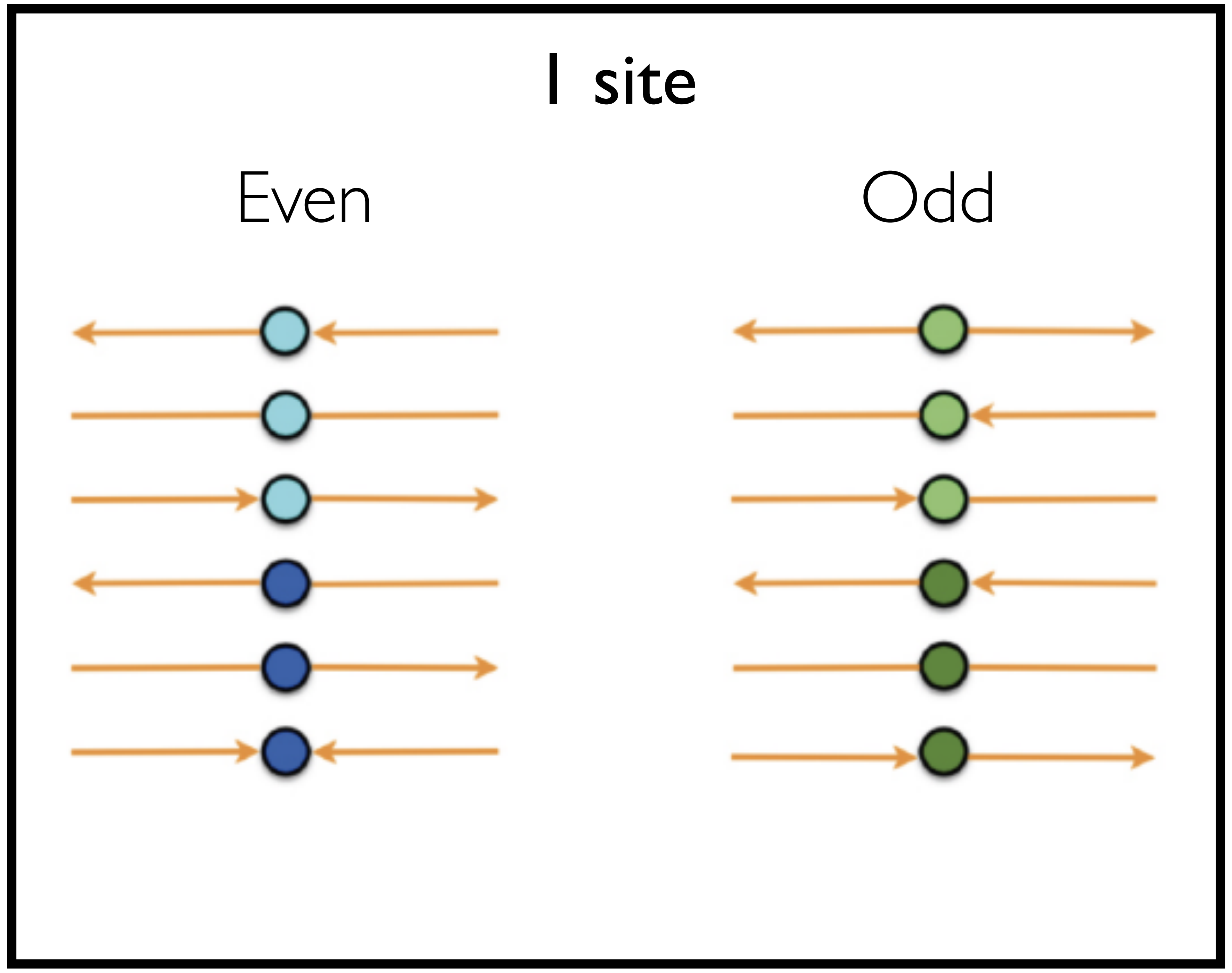
Relevant observables and metrics in QED_{1+1}

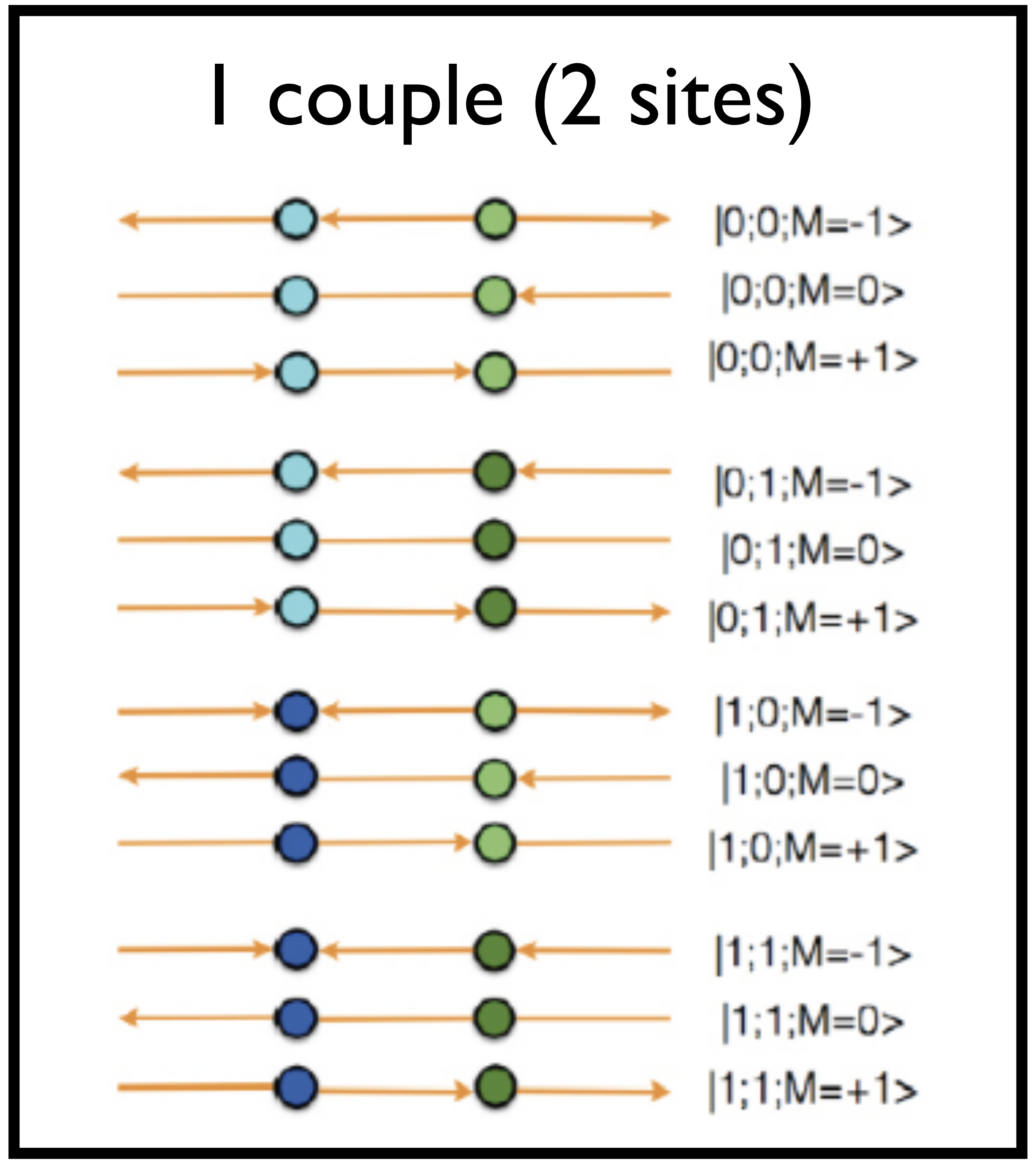
Model metrics:

- Vacuum persistence probability: $P_{\mathrm{vac}} \equiv \mathcal{G}(t) = \langle GS \,|\, \psi(t) \rangle$
- Electric charge: $Q \equiv \frac{1}{N} \sum_{n=0}^{N-1} \langle Z_n \rangle_t$
- Average gauge dynamical electric field: $\mathcal{E}(t) \equiv \frac{g}{2N} \left(\sum_{i=0}^{n-1} \sum_{k=0}^{i} \langle Z_k \rangle + (-1)^k \right) + g\ q$
- Chiral condensate: $\langle \bar{\psi}\psi \rangle \equiv \Sigma(t) = \frac{g}{2wN} \sum_{i=0}^{n-1} (-1)^i \langle Z_k \rangle$
- Logarithmic negativity (a metric for entanglement-entropy): $E_N \equiv \log_2(||\rho^{\Gamma_A}||_1)$, partial transpose with respect to half of the spin chain

$\mathbb{Z}_3$ Approach to QED_{1+1}







Gauss' law in 1+1D allows integrating out either fermions or electric field.

Certain states of fields and particles are not physical, but Hilbert space still grows exponentially,

Observables/metrics: fermion density, electric field, entanglement, etc.

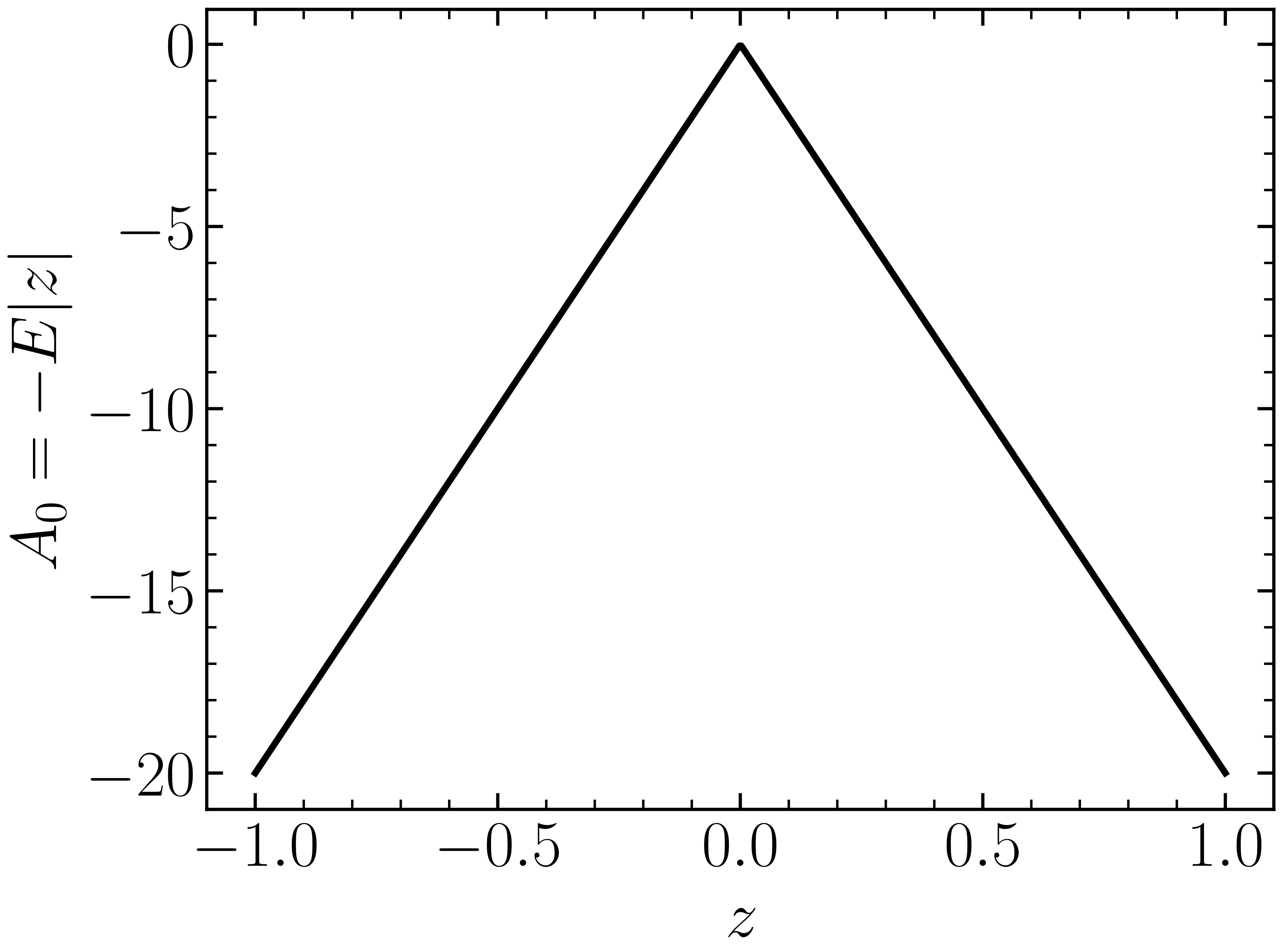
Strong-Field QED will require in general resolving both low and high energy state dynamics.

H_X - axial-gauge external-field Hamiltonian

- Axial-gauge Hamiltonian (local/short-range, no $J = g^2 a/2$ coupling)

$$H_X = \frac{1}{2a}\sum_{i=0}^{n-2}\big(\sigma_+(i)\sigma_-(i+1) + \sigma_+(i+1)\sigma_-(i)\big)(\delta_{i,0}\sqrt{2} + (1-\delta_{i,0})) + \frac{1}{2}\sum_{i=0}^{n-1}((-1)^i m + eEai)\sigma_3(i)$$

- Parameters: a - lattice spacing, no connection between spin $n-2$ and $n-1$.
- Axial gauge $A_0 = -E|z|$ to enforce uniform electric field



- Free bare-mass Hamiltonian $H_X^{0,m} = \frac{1}{2}\sum_{i=0}^{n-1}(-1)^i m\ \sigma_3(i)$
  - Grounds-State (GS) is then $|10(10)..1\rangle$
  - The GS of the free Hamiltonian with kinetic term can be prepared with VQE

* Xu, Xue, Phys. Rev. D 106, 116007 (2022)

Schwinger pair-production rate: w vs Γ

Rates (external eE-field × charge, mass m) *

- Vacuum persistence probability $P_{\text{vac}}^{1+1} = \exp(-w^{1+1}Lt), \quad w^{1+1}(m, eE) = -\frac{eE}{2\pi}\log\left[1 - \exp\left(-\frac{\pi m^2}{eE}\right)\right]$

- Pair production density rate $\dot{\rho} = d\rho/dt = \Gamma_{1+1}(m, eE) = \frac{eE}{2\pi}\exp\left(-\frac{\pi m^2}{eE}\right)$

* Cohen&McGady PRD 2008

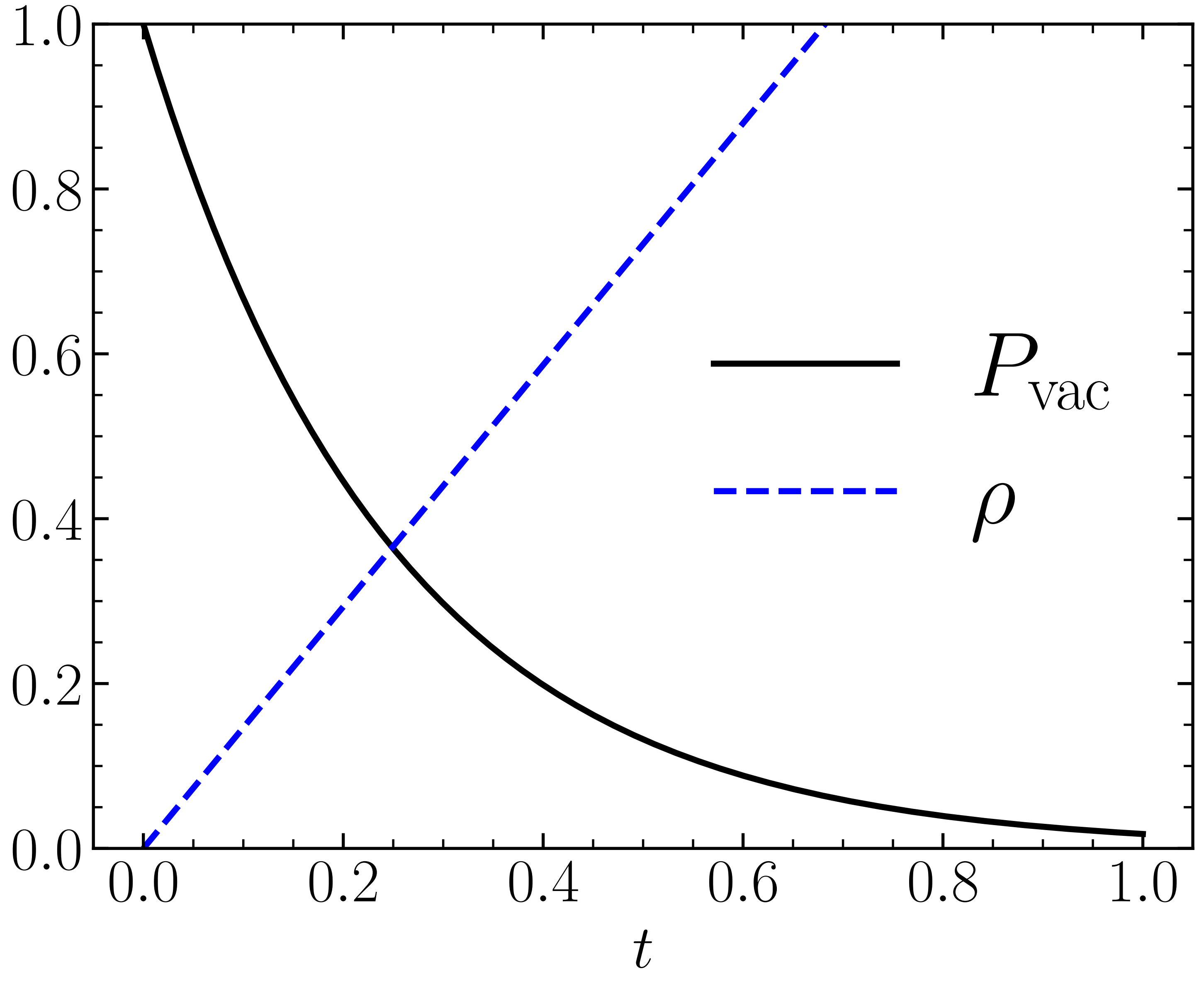
Schwinger pair-production rate: w vs Γ

Rates (external eE-field × charge, mass m) *

- Vacuum persistence probability $P_{\text{vac}}^{1+1} = \exp(-w^{1+1}Lt)$, $\;w^{1+1}(m, eE) = -\frac{eE}{2\pi}\log\left[1-\exp\left(-\frac{\pi m^2}{eE}\right)\right]$
- Pair production density rate $\dot{\rho} = d\rho/dt = \Gamma_{1+1}(m, eE) = \frac{eE}{2\pi}\exp\left(-\frac{\pi m^2}{eE}\right)$

For early-time evolution:

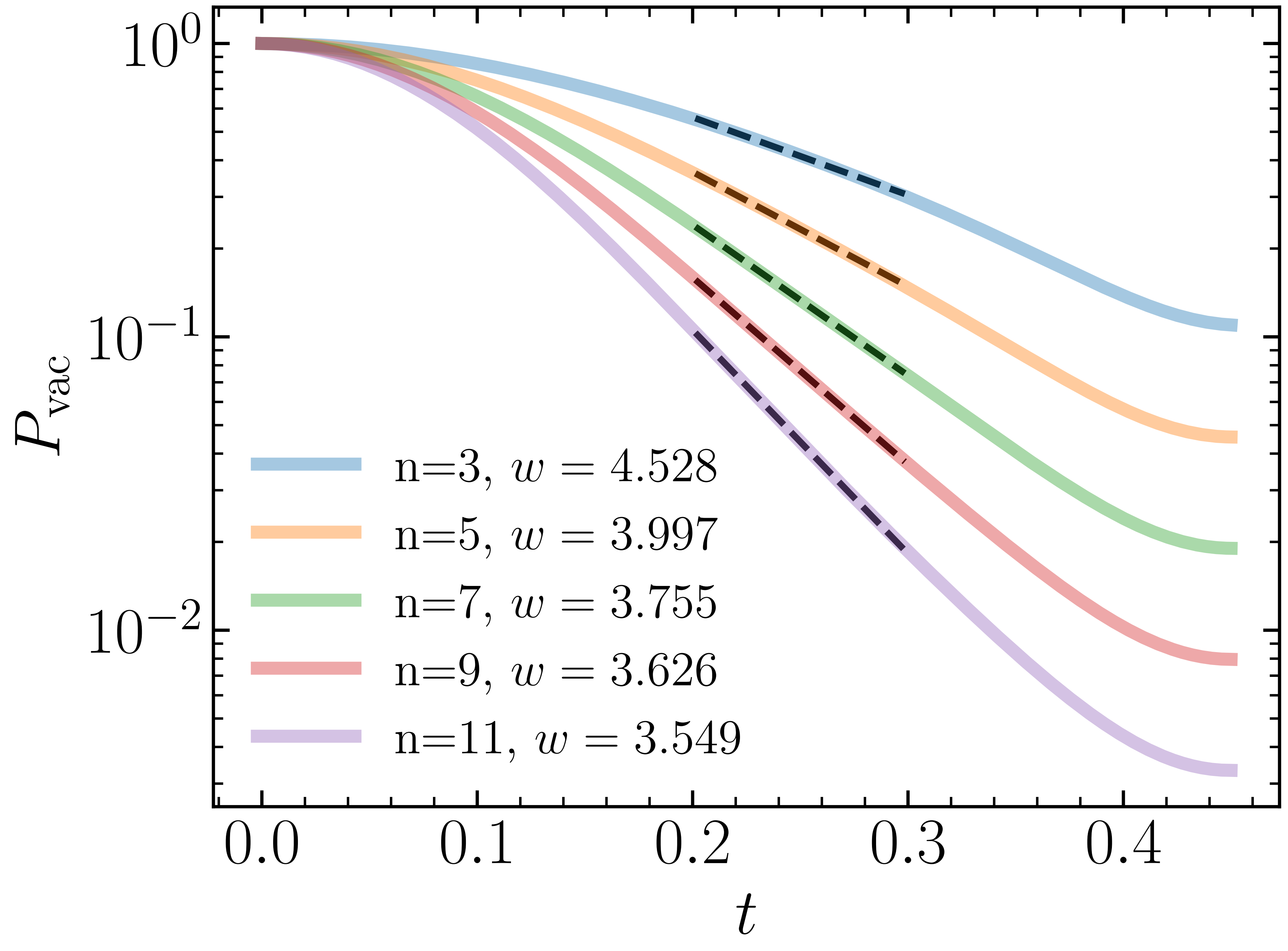
- Starting with the vacuum/GS, the probability of finding the system in this state decreases exponentially
- The increase of electric charge is approximately linear

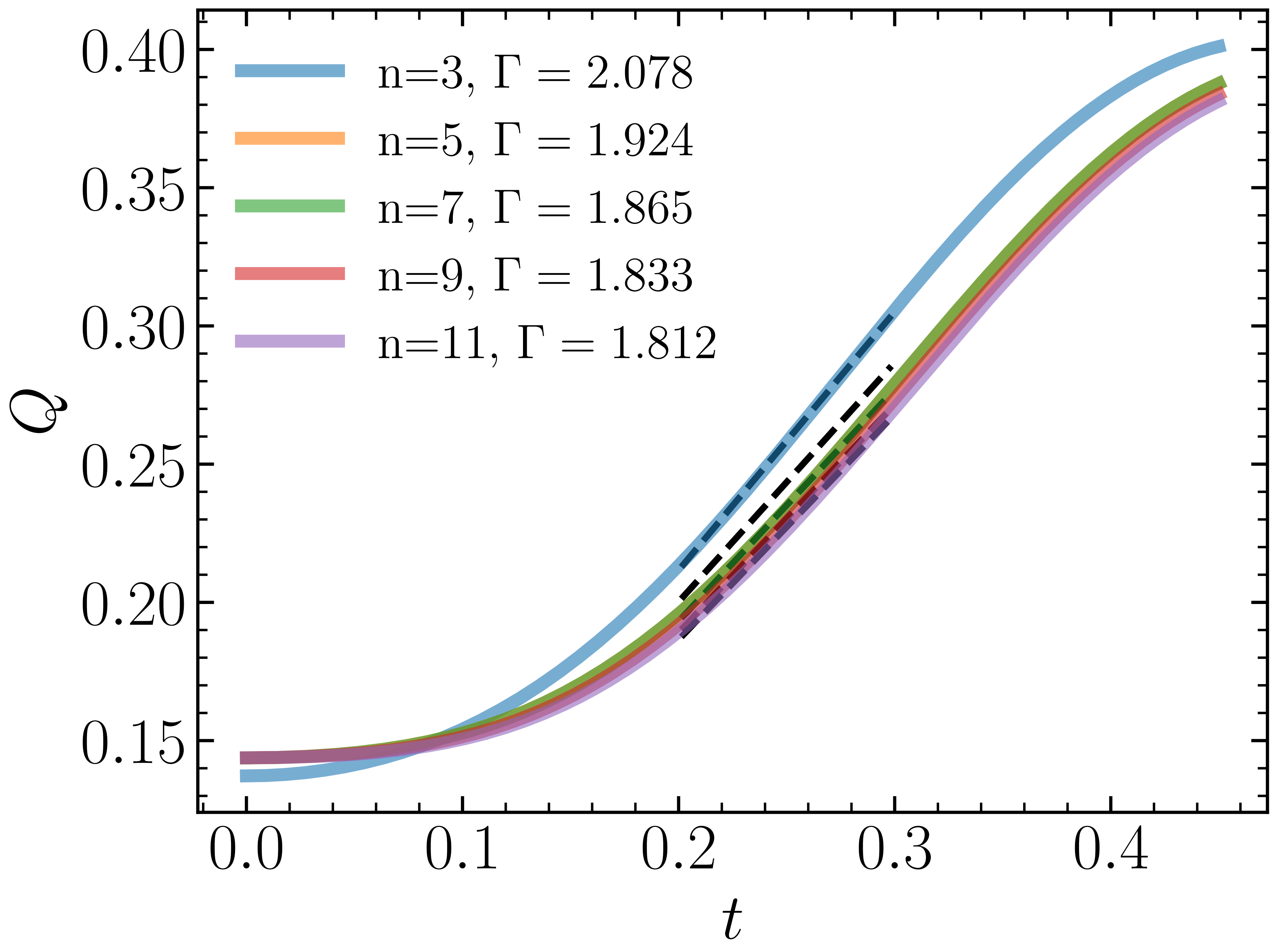


* Cohen&McGady PRD 2008

Extracting the Schwinger pair production rate from simulation

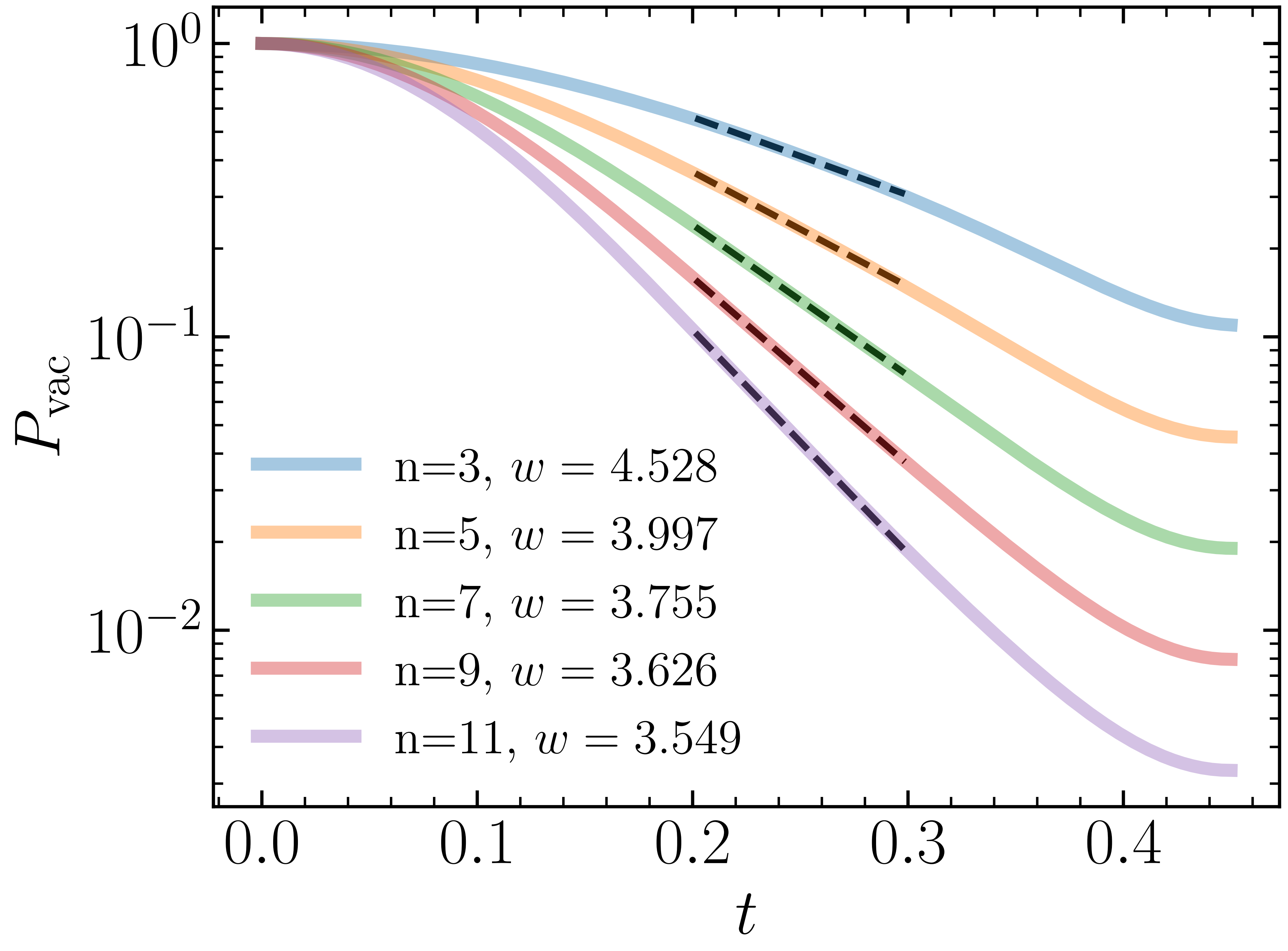
- Fitting $P_{\text{vac}}(t) \sim c^{te} \exp(-w(m', eE) \times an \times t)$ and $\rho \sim c^{te} + t \times \Gamma(m', eE)$ to extract the rates (w, Γ)
- Convergence study with increasing number of qubits n

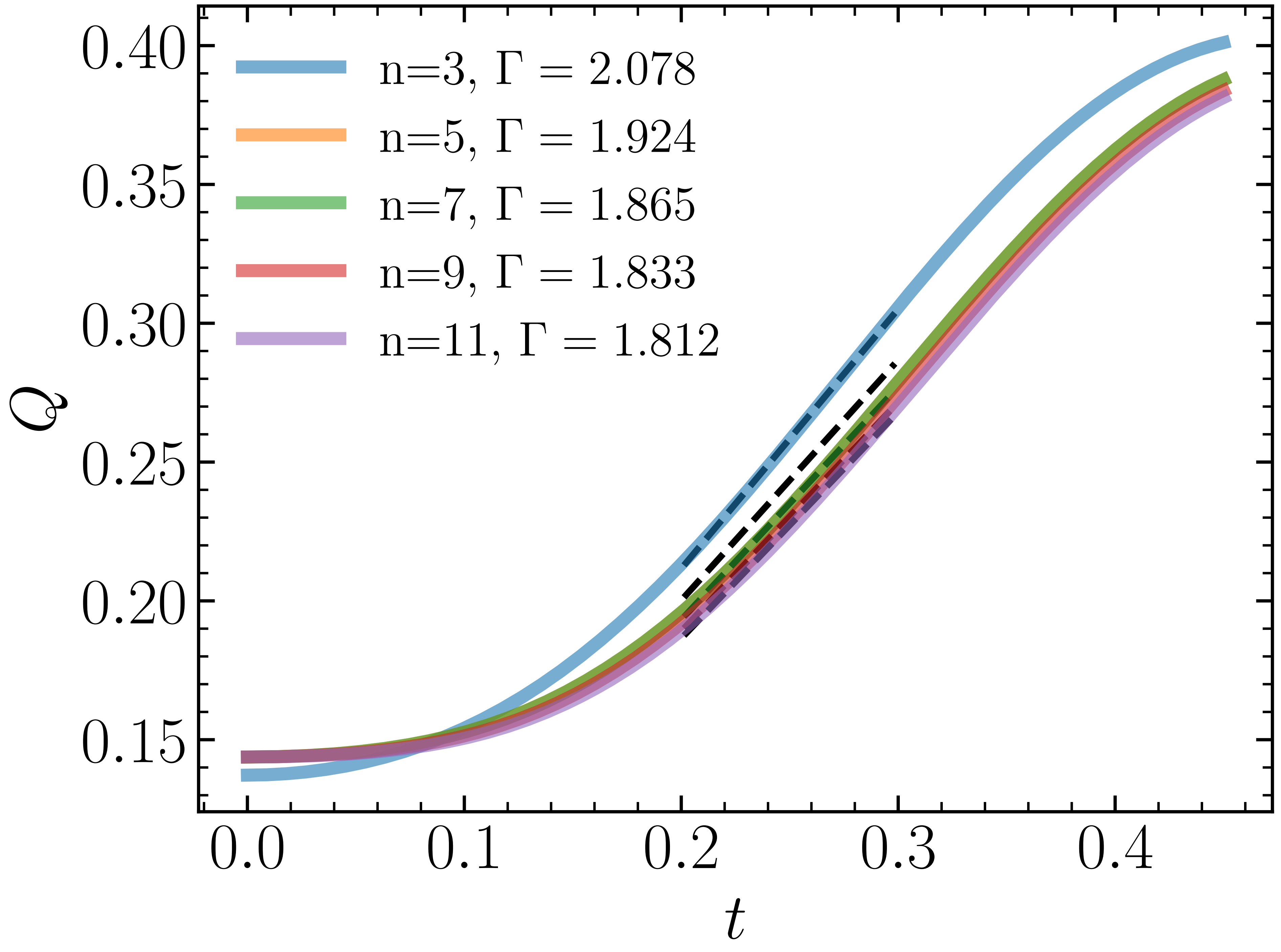




Extracting the Schwinger pair production rate from simulation

- Fitting $P_{\text{vac}}(t) \sim c^{te} \exp(-w(m', eE) \times an \times t)$ and $\rho \sim c^{te} + t \times \Gamma(m', eE)$ to extract the rates (w, Γ)
- Convergence study with increasing number of qubits n





- What other physical observables can we retrieve from $\mathbb{Z}_n$ and axial H_X that are useful to SFQED + plasmas?

Future work: long-term research directions

- **Towards full $2/3+1$ D simulations of Schwinger pair production**
  - Higher dimensionality/volume simulations, different topologies, back-reaction on fields

Future work: long-term research directions

- **Towards full $2/3 + 1$ D simulations of Schwinger pair production**
  - Higher dimensionality/volume simulations, different topologies, back-reaction on fields

- **First-principles simulations of SFQED scattering**
  - Scaling of higher-loop / higher-multiplicity processes
  - Can we inform classical kinetic/fluid simulations with more accurate rates?
  - Quantum states of light vs classical background fields

Future work: long-term research directions

- **Towards full $2/3+1$ D simulations of Schwinger pair production**
  - Higher dimensionality/volume simulations, different topologies, back-reaction on fields

- **First-principles simulations of SFQED scattering**
  - Scaling of higher-loop / higher-multiplicity processes
  - Can we inform classical kinetic/fluid simulations with more accurate rates?
  - Quantum states of light vs classical background fields

- **Quantum simulation of SFQED cascades**
  - Connection with real world physics: laser experiments and astrophysical models

Future work: long-term research directions

- **Towards full $2/3+1$ D simulations of Schwinger pair production**
  - Higher dimensionality/volume simulations, different topologies, back-reaction on fields

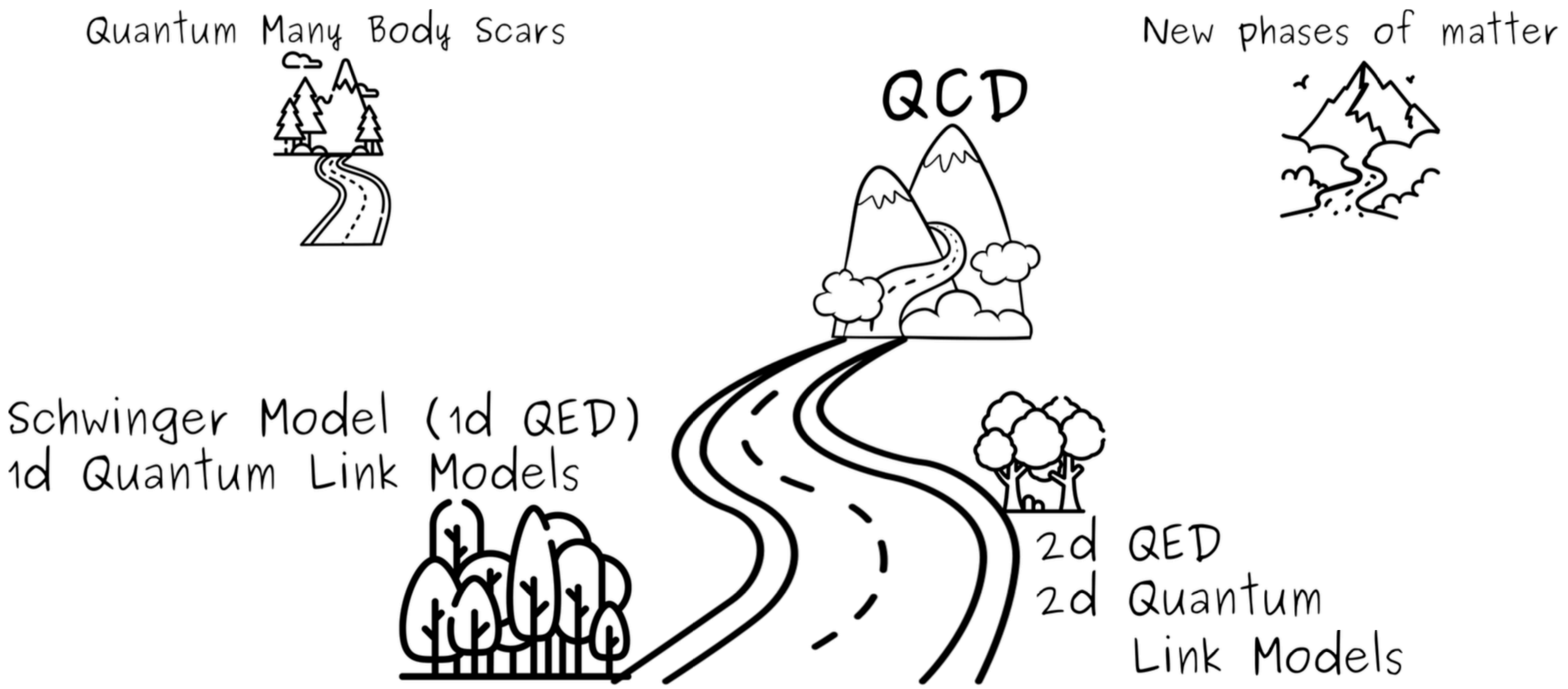
- **First-principles simulations of SFQED scattering**
  - Scaling of higher-loop / higher-multiplicity processes
  - Can we inform classical kinetic/fluid simulations with more accurate rates?
  - Quantum states of light vs classical background fields

- **Quantum simulation of SFQED cascades**
  - Connection with real world physics: laser experiments and astrophysical models

- **Self-consistent focused, ultra-short laser field structure**
  - Open question: is there a maximum achievable laser power, bounded by the Schwinger pair production mechanism (laser depletion and screening)

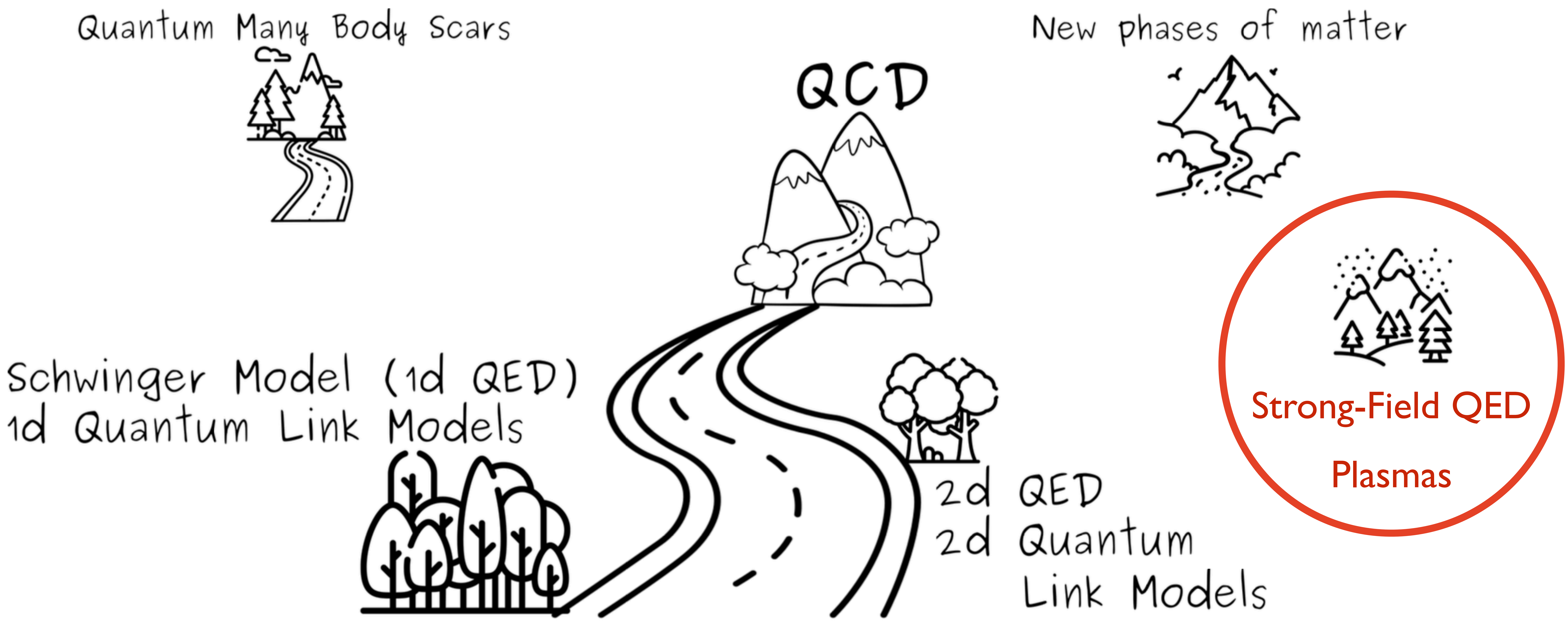
SFQED in the landscape of Quantum Many Body simulations

TÉCNICO LISBOA



* adapted from *JP Barros, MK Marinkovic, Quantum Simulations of Gauge Theories, HS2023 ETHZ*

SFQED in the landscape of Quantum Many Body simulations



* adapted from *JP Barros, MK Marinkovic, Quantum Simulations of Gauge Theories, HS2023 ETHZ*

Conclusions

Why Strong-Field QED is worth studying

Highly non-perturbative, collective plasma dynamics. First-principles simulations lacking

Conclusions

Why Strong-Field QED is worth studying

Highly non-perturbative, collective plasma dynamics. First-principles simulations lacking

First comparisons between QED_{1+1} models towards SFQED regime

Need further studies to understand the role of back-reaction on the background fields

What are the minimal (quantum) computational resources to study quantum plasma physics

Conclusions

TÉCNICO LISBOA

Why Strong-Field QED is worth studying

Highly non-perturbative, collective plasma dynamics. First-principles simulations lacking

First comparisons between QED_{1+1} models towards SFQED regime

Need further studies to understand the role of back-reaction on the background fields

What are the minimal (quantum) computational resources to study quantum plasma physics

A Living Review of Quantum Computing for Plasma Physics

Quantum Computing promises accelerated simulation of certain classes of problems, in particular in plasma physics. The goal of this document is to provide a comprehensive list of citations for those developing and applying these approaches to experimental or theoretical analyses. As a living document, it will be updated as often as possible to incorporate the latest developments. Suggestions are most welcome.

download review

Living review:

Github webpage: https://qppqlivingreview.github.io/review/

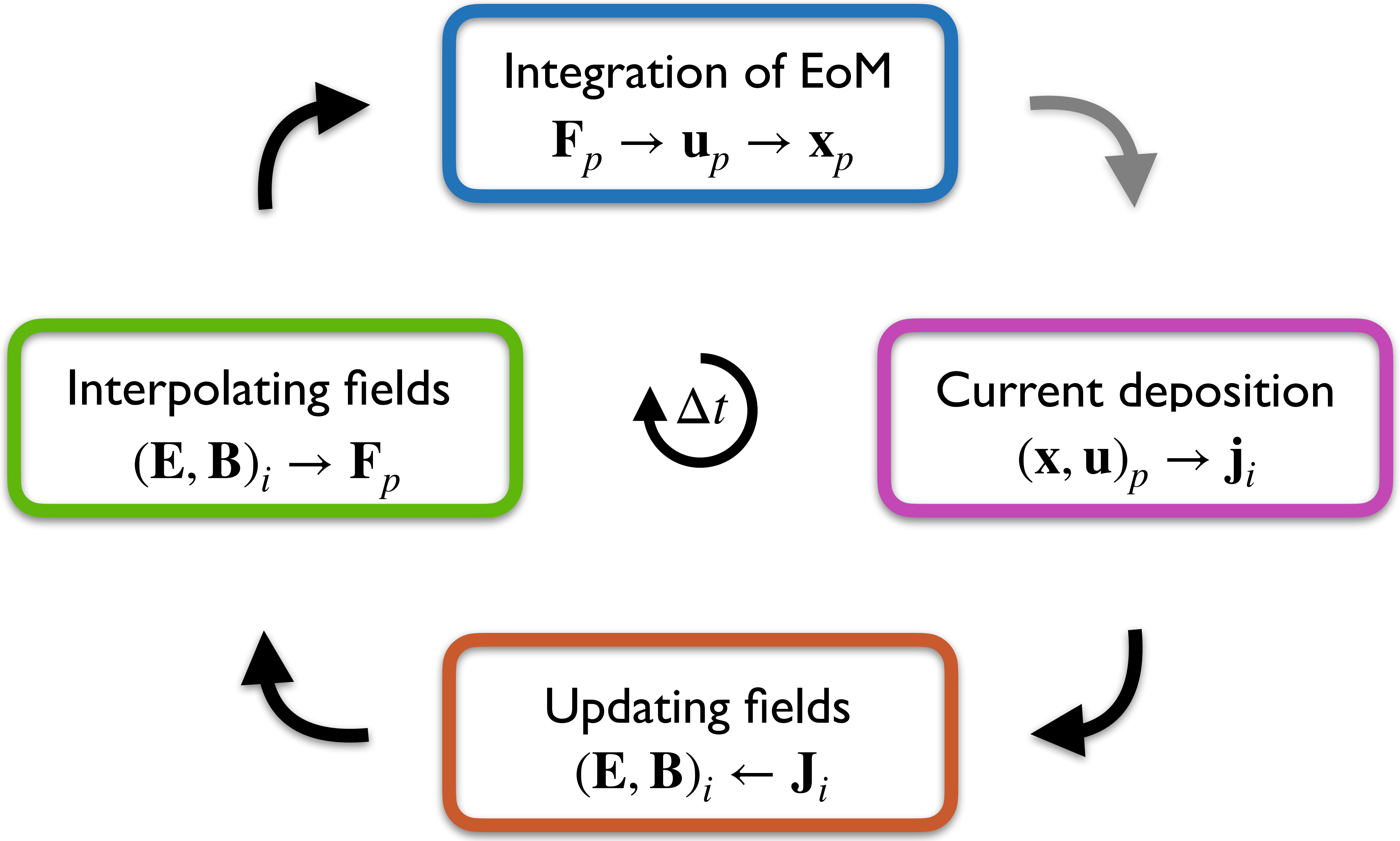
arXiv pre-print: https://arxiv.org/abs/2302.00001

EXTRA SLIDES

PIC loop and the standard Monte Carlo routine

Standard (+ MC) steps of the PIC algorithm

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \frac{d^2P}{dt d\chi}$$

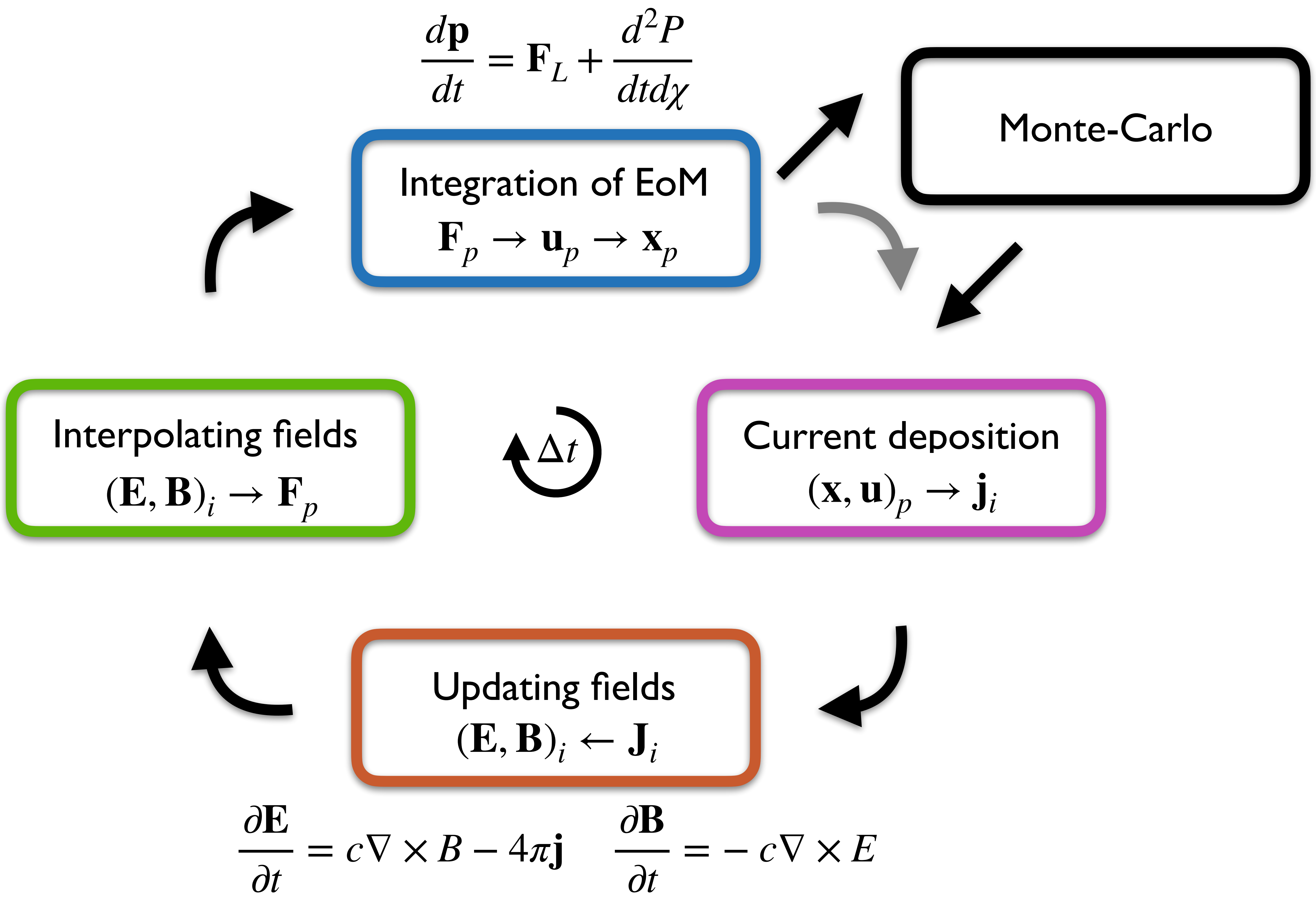


$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times B - 4\pi\mathbf{j} \qquad \frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times E$$

PIC loop with Monte Carlo module

PIC loop and the standard Monte Carlo routine

Standard (+ MC) steps of the PIC algorithm

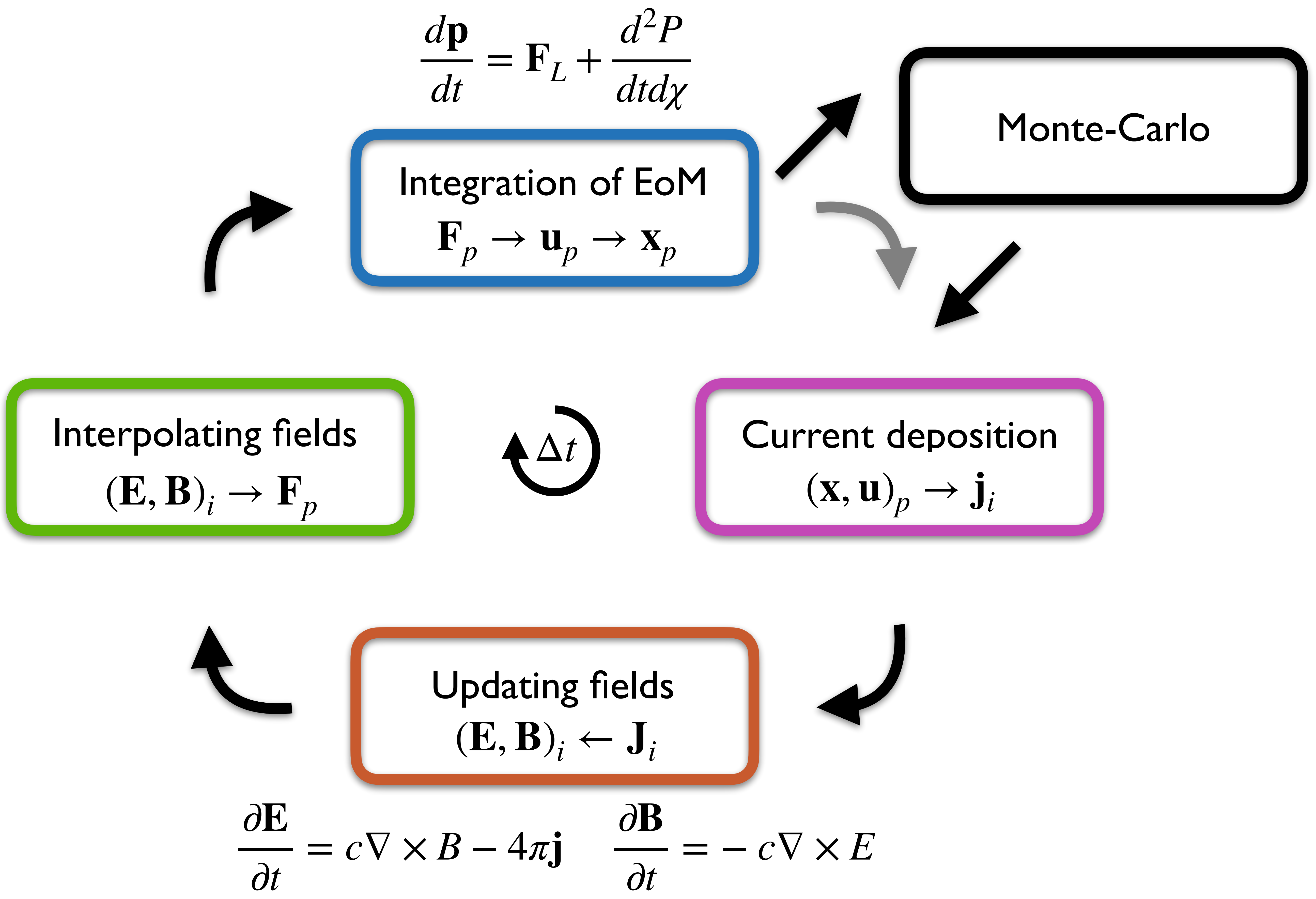


PIC loop with Monte Carlo module

PIC loop and the standard Monte Carlo routine

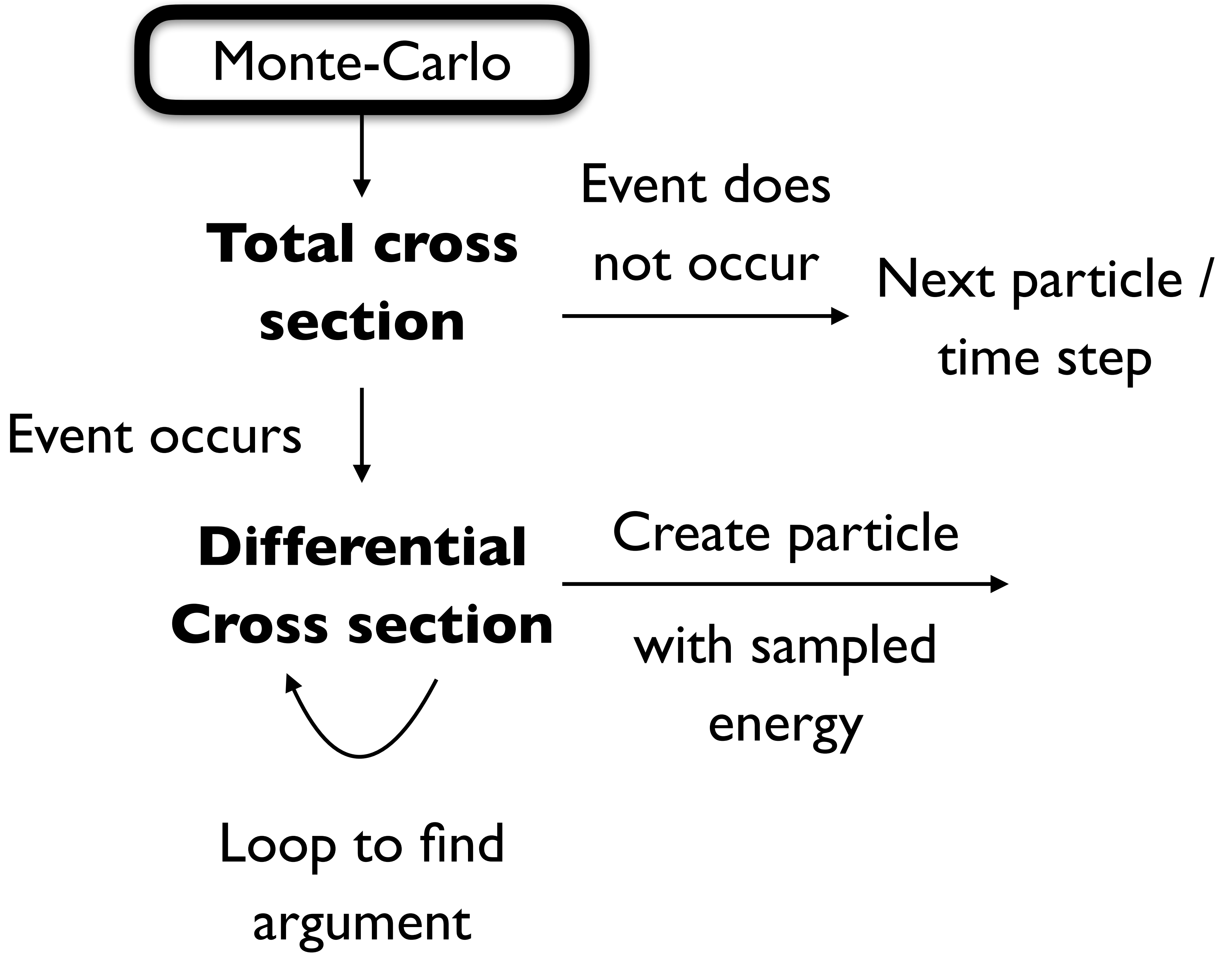
TÉCNICO LISBOA

Standard (+ MC) steps of the PIC algorithm



PIC loop with Monte Carlo module

Two steps of the Monte-Carlo routine



Computing the total or differential cross sections by table/Chebyshev/Neural Network