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LASER–MATTER INTERACTIONS AT HIGH INTENSITY:

THEORETICAL CHALLENGES

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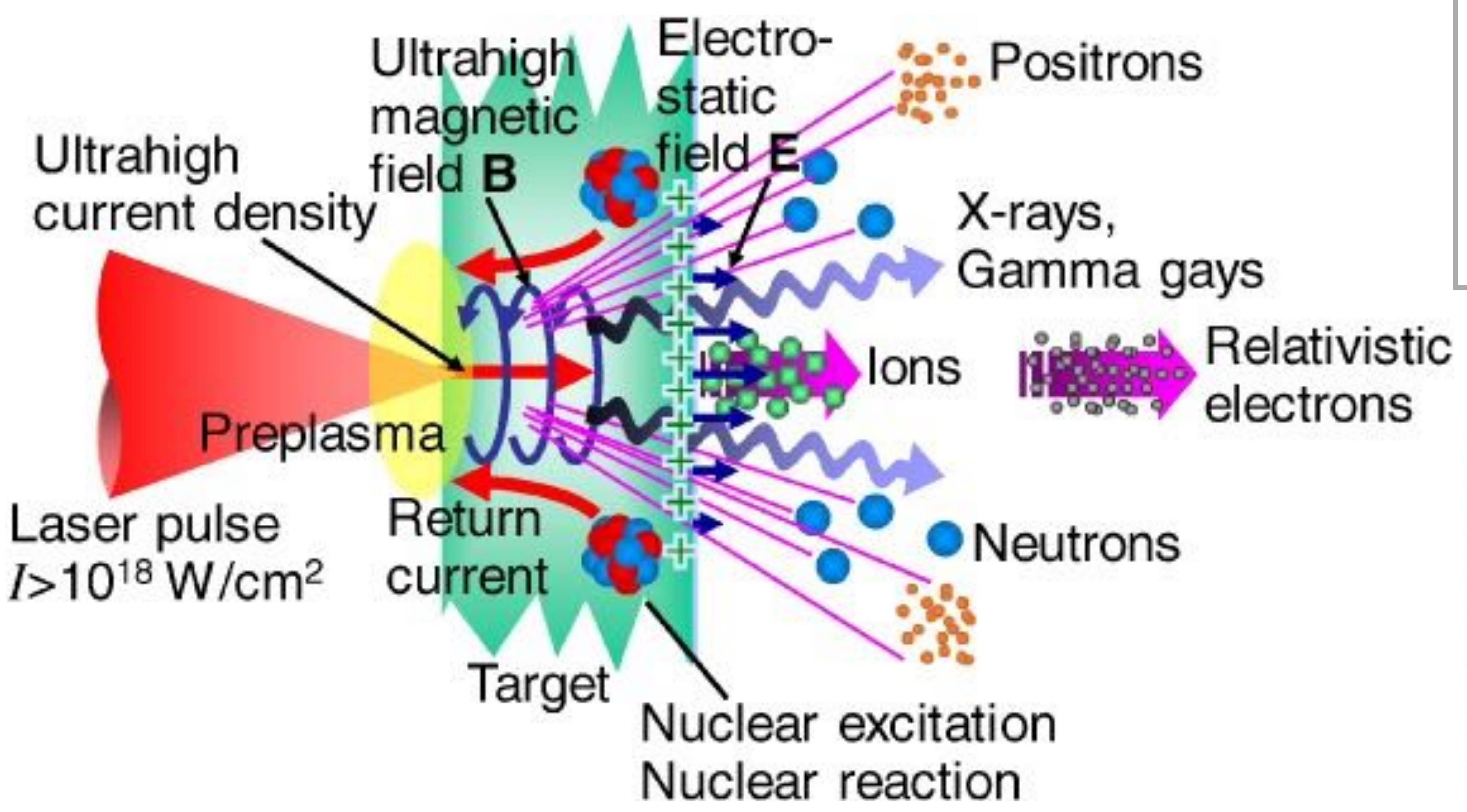
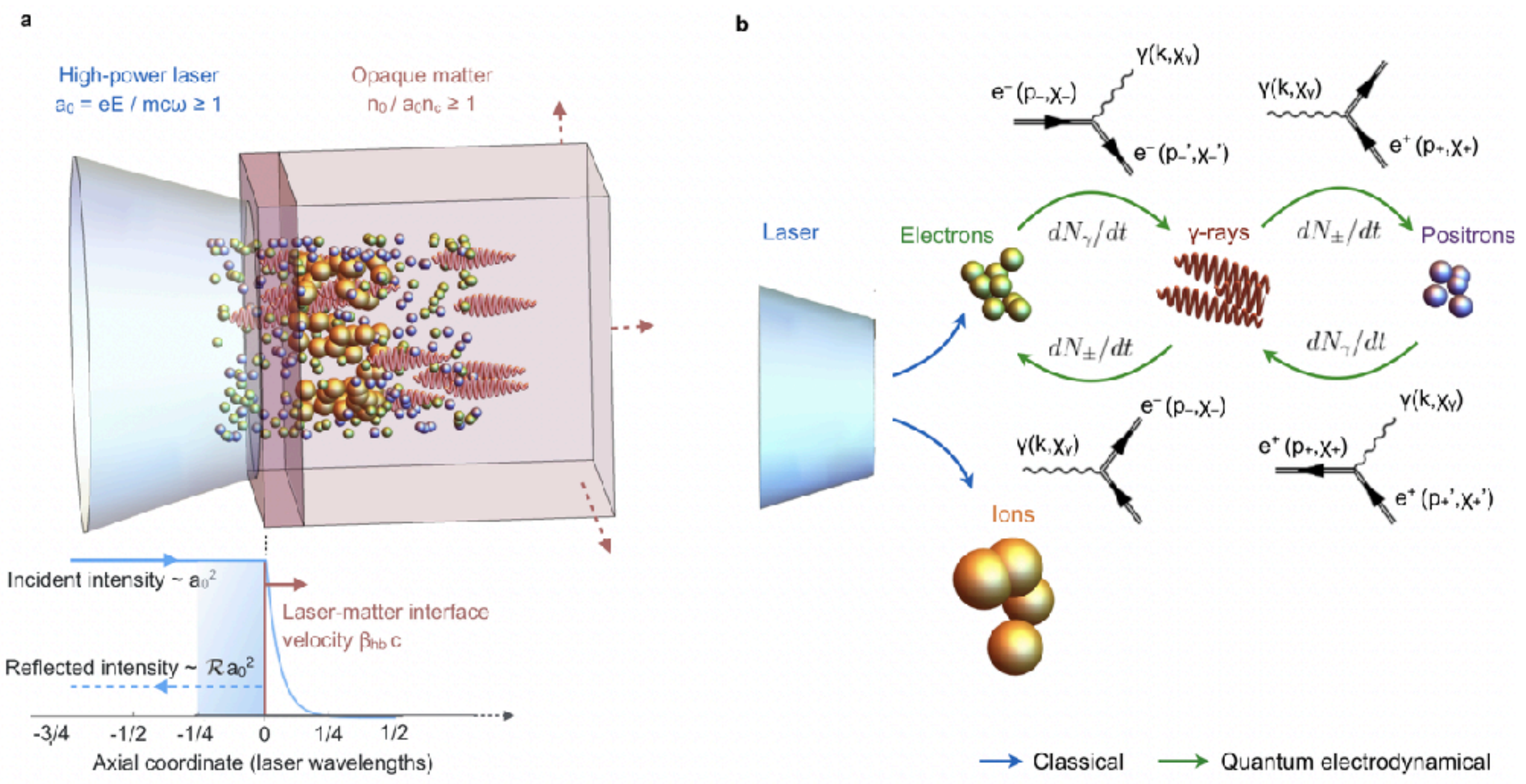
Probing strong-fields QED in electron-photon interactions, DESY, 2018

Plasmas in strong fields



Daido et al., Rep. Prog. Phys. **75**, 056401 (2012)

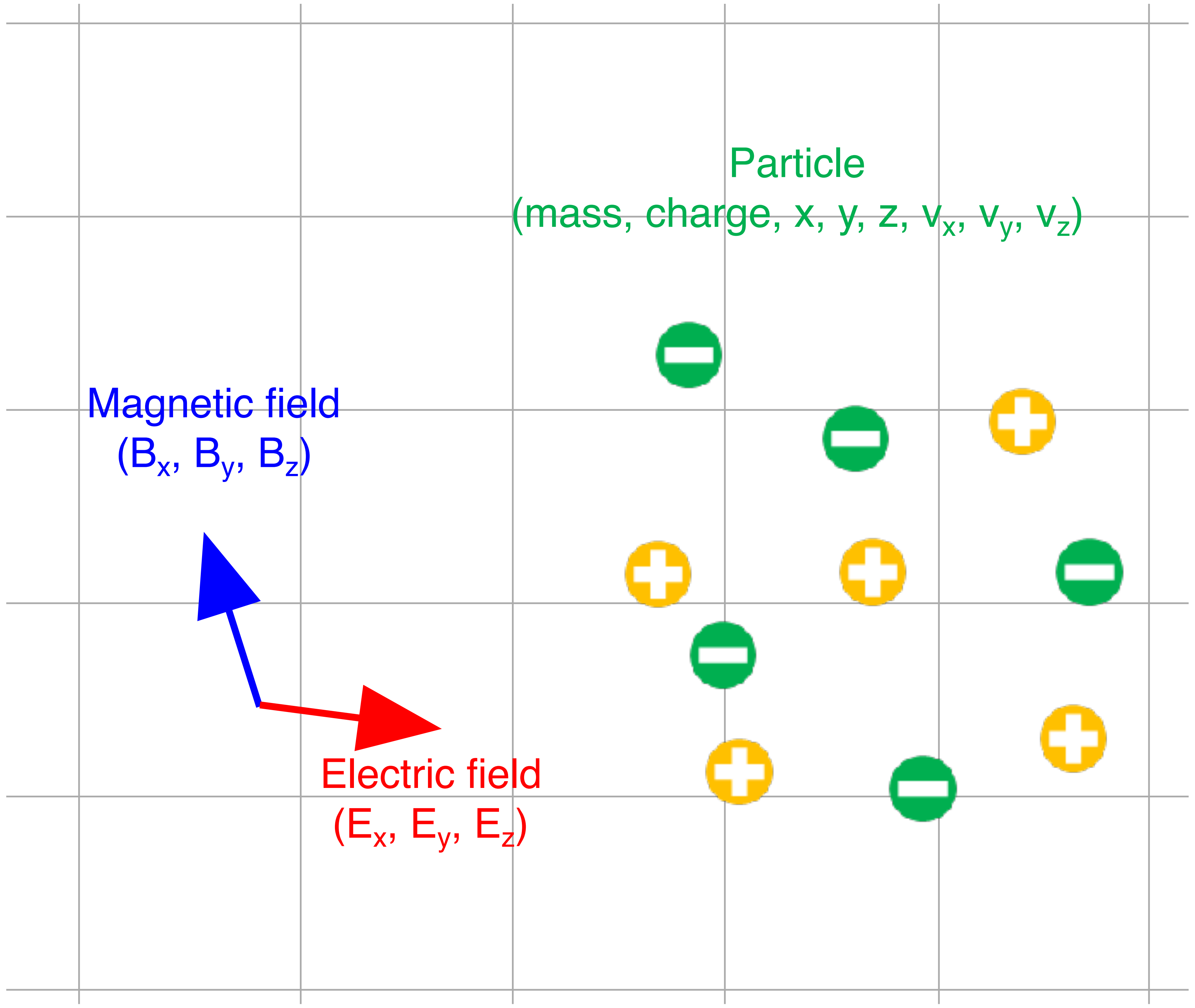
How do we capture all of the physics, contained in such interactions, via analytical or computational schemes?



Levy et al., arXiv:1609.00389 (2016)

Traditional plasma descriptions and computational schemes

- **Single-particle dynamics**: no backreaction, only particle motion in external fields.
- **Kinetic descriptions**: distribution function in phase space describing ensemble of particles, either in external fields or self-consistent.
- **Fluid models**: moments of the distribution function with closure assumptions.
- **Hybrid schemes**: treating plasma as a mixture of kinetic and fluid components.
- For some applications, such as ICF, **strong coupling** effects need to be accounted for (DFT and TDDFT).



- **Particle-in-cell** schemes belong to the kinetic category. Impose a grid structure.

These, and similar, are the methods we will use for assisting experiments!

Micro- and macroscopic physics

Particle simulation of plasmas

John M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

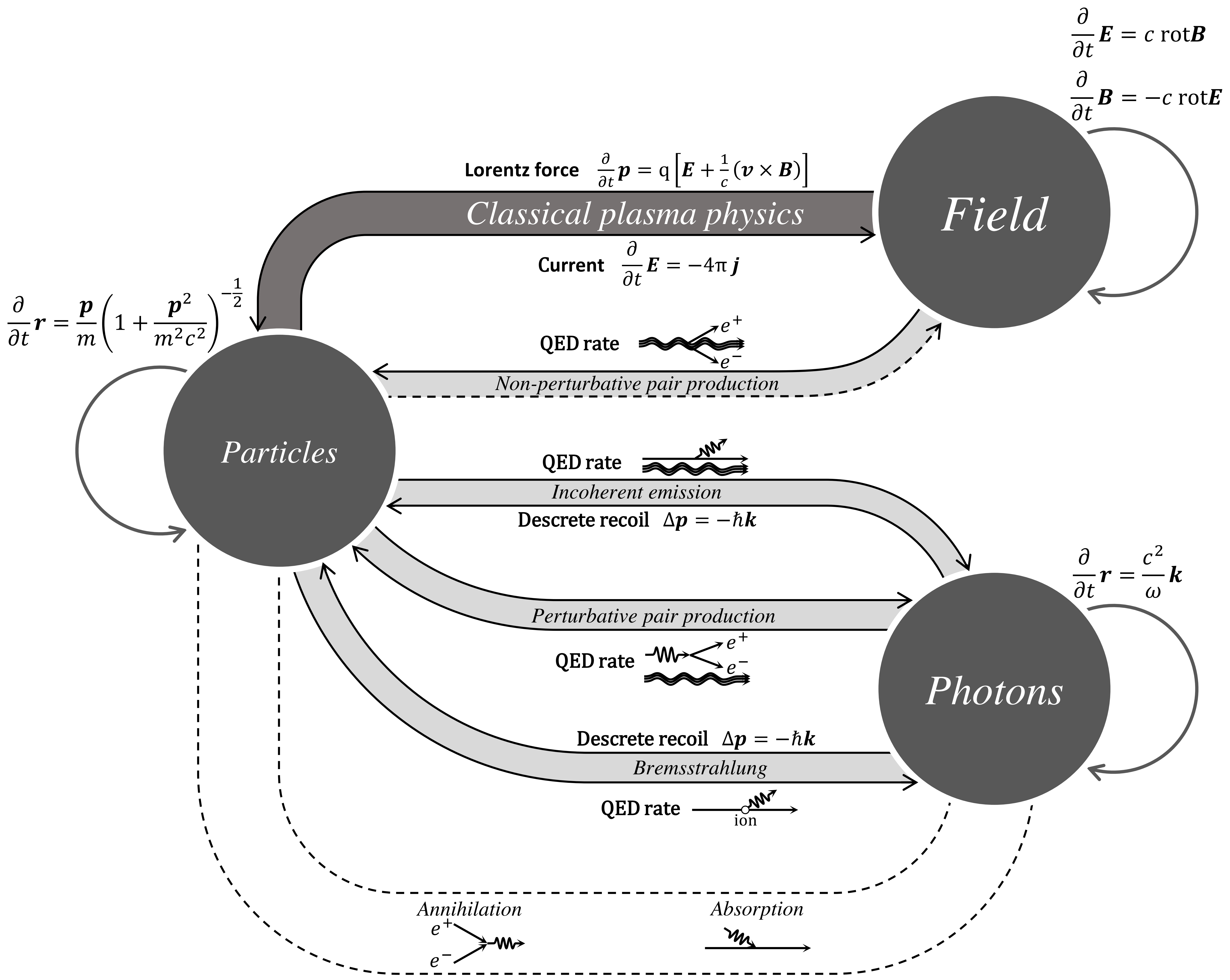
Reviews of Modern Physics, Vol. 55, No. 2, April 1983

> ”Proper treatment of systems where both the microscopic and macroscopic behavior are important will undoubtedly challenge simulation physicists for many years to come”
> (Rev. Mod. Phys.)

Not only multi-scale, but also different treatment of physical quantities (e.g. EM fields vs. photons), collective effect and discrete events etc.

Simpleminded view: as we increase intensity of lasers and energy of particle beams, QED becomes increasingly more important.

QED in particle-in-cell codes



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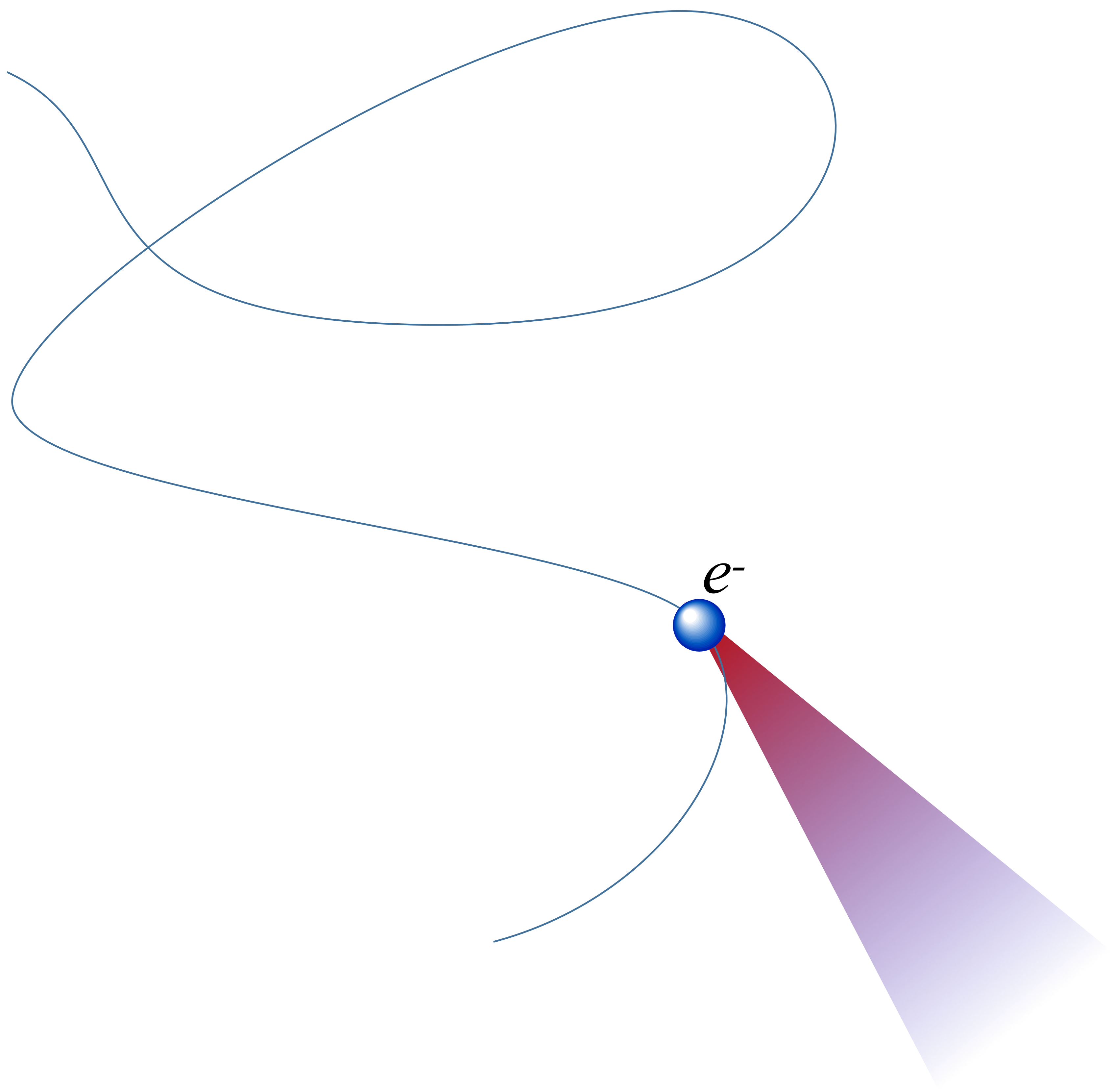
M. Vranic et al., Comp. Phys. Comm. 204, 141 (2016)

Analytical and computational challenges

Prerequisite: our computational tools are only as good as our analytical input. Examples:



- *Locally constant crossed field approximation*: central to almost all analytical work; what is the size of the errors that we make using this approximation?
- *Depletion*: how do we correctly take into account the partition of energy between classical and quantum degrees of freedom, and is it important?
- *S-matrix vs trajectories*: when is it meaningful to talk about trajectories, and when is there a relation between the S-matrix and the classical equations of motion?
- *Many-body quantum systems*: is it computationally viable, and when will it be important?

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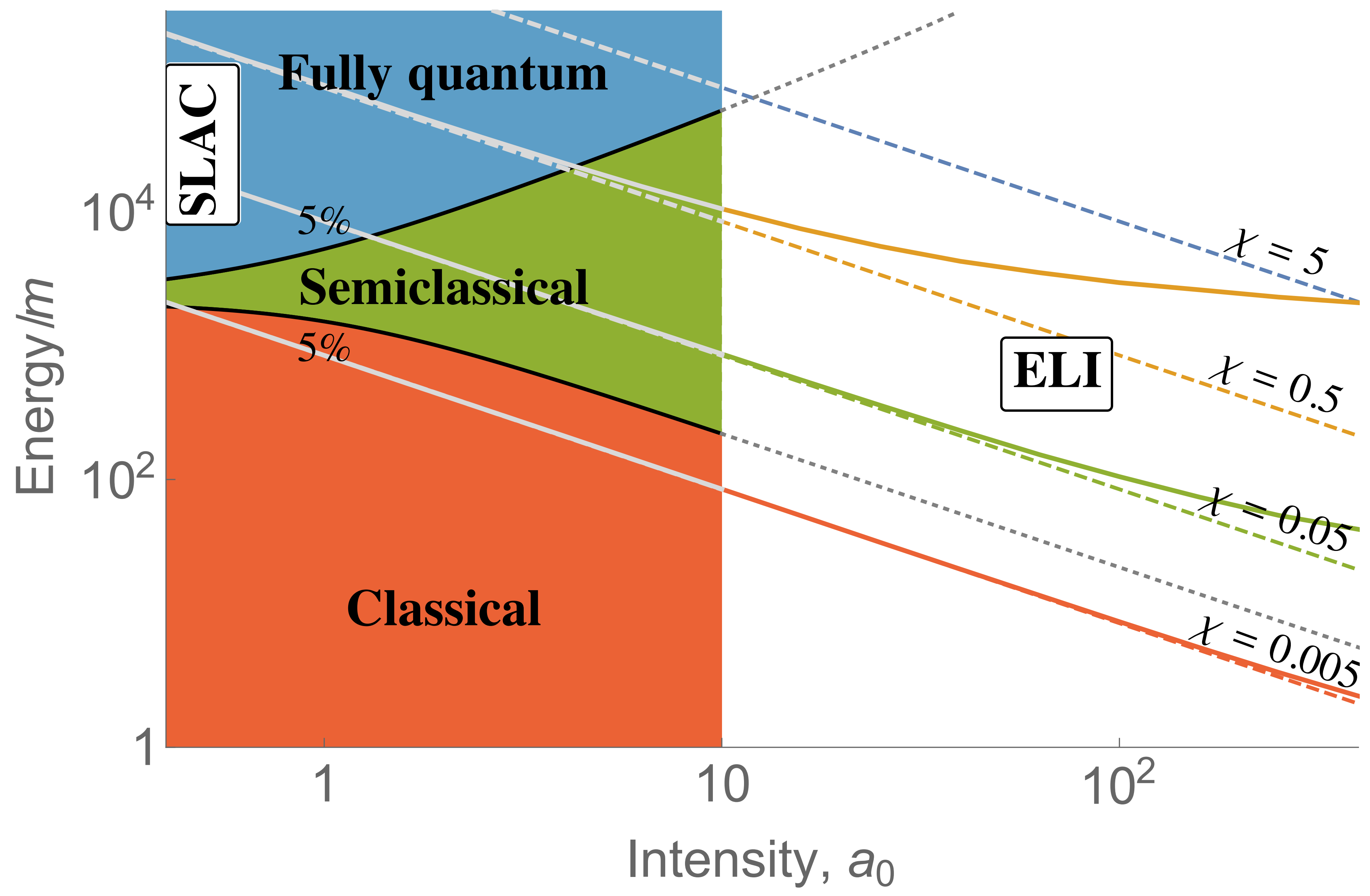
Examples: formation length and coherence

- Quantum radiation reaction: for strong enough fields, the radiation from the accelerated charge is governed by multiphoton emissions.
- Formation length: normally assumed short compared to other scales (in high fields), incoherent events (semiclassical, locally constant).
- However, there are cases when coherent effects dominate (fully quantum).
- Fully quantum calculations are needed (high energy, not ”too high intensity”).



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A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, Phys. Rev. Lett. 105, 220403 (2010)
V. Dinu et al., Phys. Rev. Lett. **116**, 044801 (2016)
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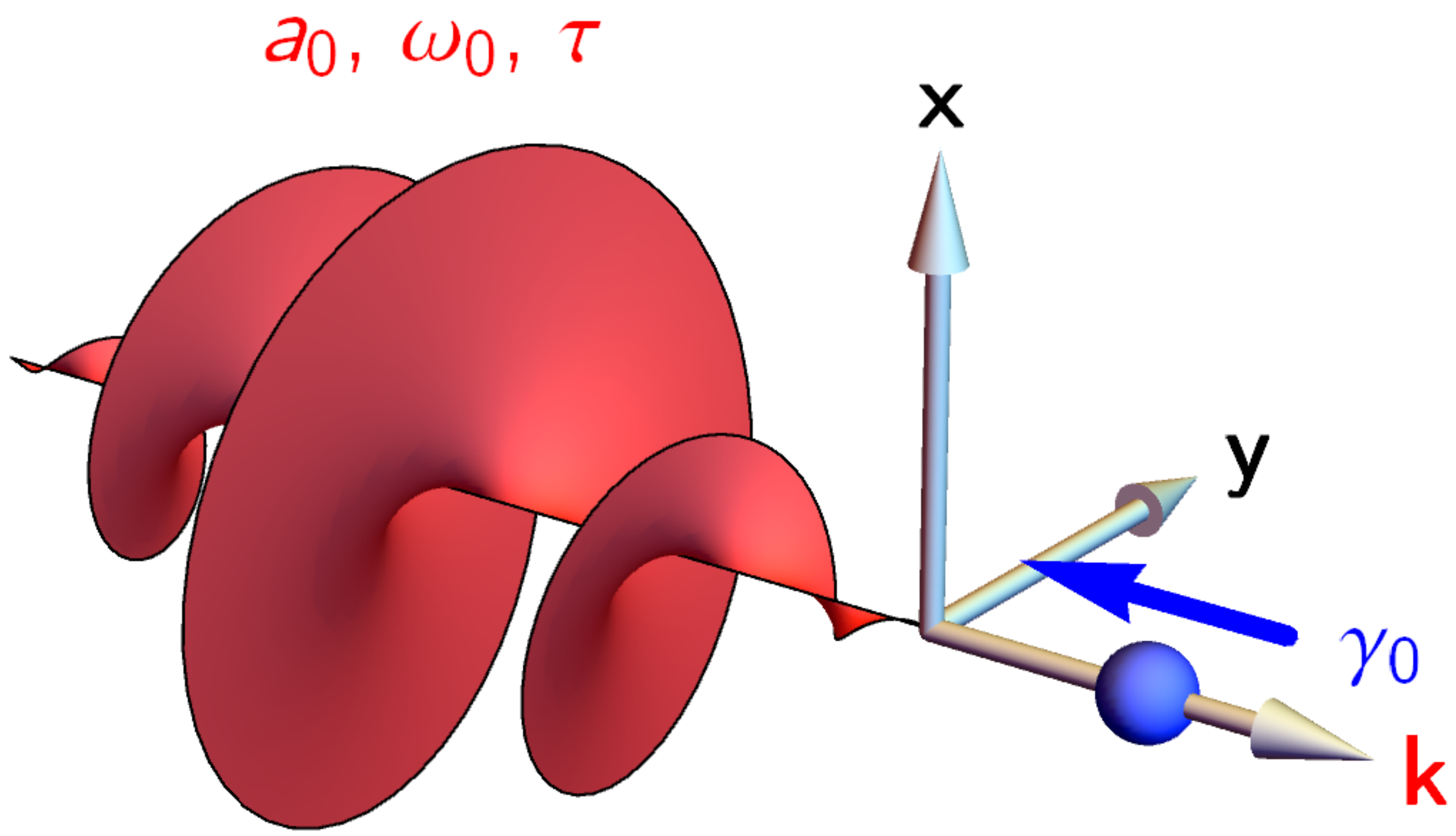
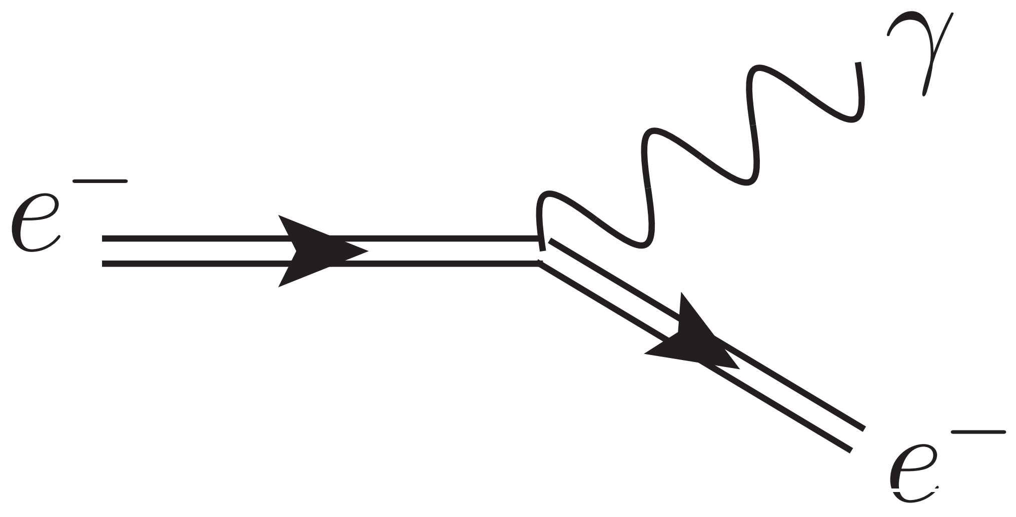
Examples: nonlinear Compton scattering

- Nonlinear Compton scattering: neglecting the external field variations within the formation region of the process.
- Complex field geometries (tight focusing, plasma fields etc) leads to questions about the status of the locally constant field approximation.
- Associating classical trajectories between the events, when does this break down?
- Further benchmarking studies needed: comparing exact calculation in QED with approximate methods.
- Therefore, need further analytical insights for QED in complex geometries.





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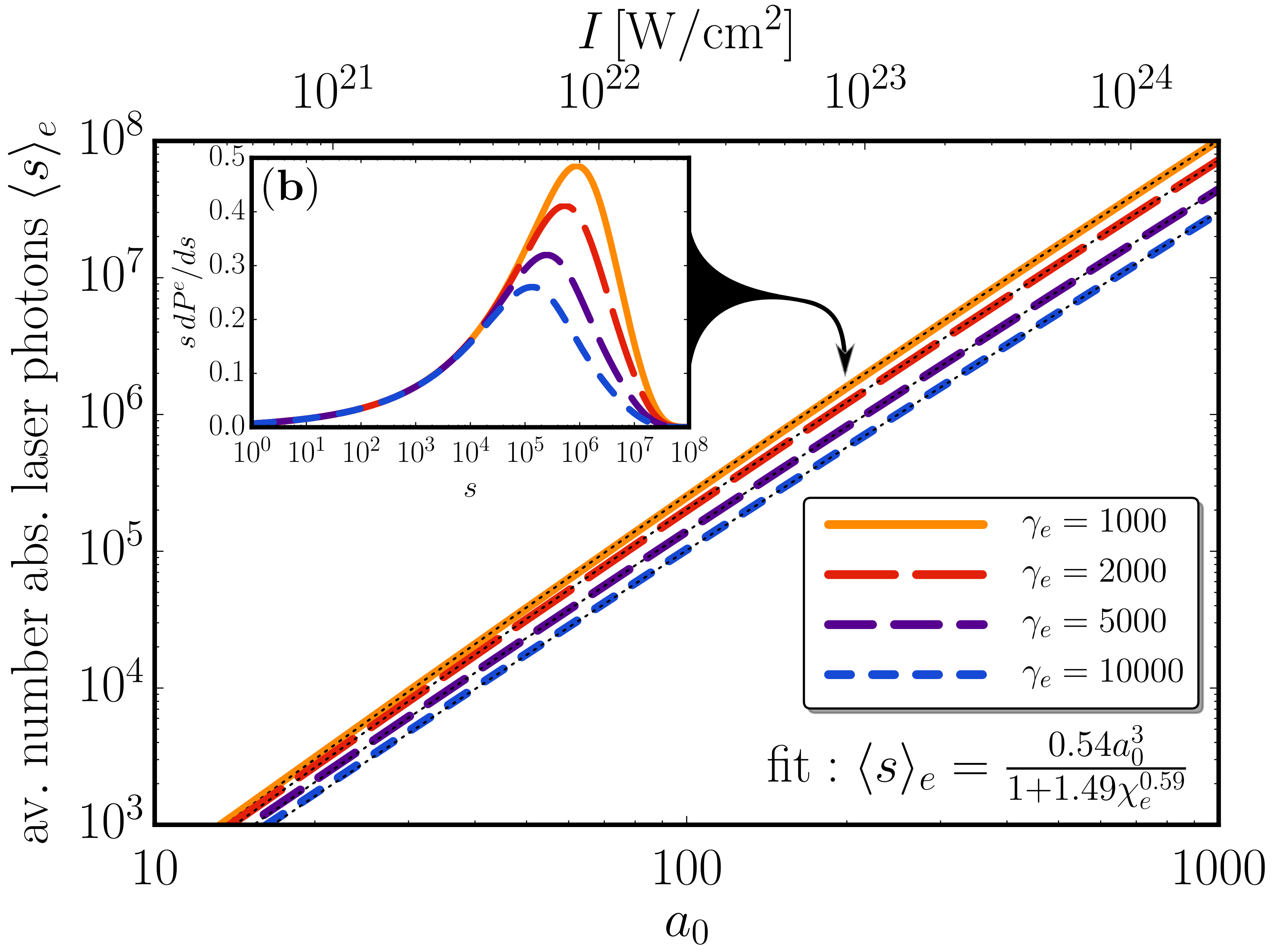
Examples: depletion of the background field

- The interaction of a highly charged electron bunch with an intense laser pulse can lead to significant depletion of the laser pulse energy.
- Depletion normally associated with pair production and the following acceleration and emission.
- Large absorption in nonlinear Compton scattering makes external field approximation problematic.
- What are the effects of depletion on emission probabilities? How are these changes treated in a computational scheme?
- Breakdown of background field approximation may be signalled by the breakdown of the perturbative expansion of the theory. How to incorporate this (see Ilderton and Seipt paper)?



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A. Ilderton and D. Seipt, Phys. Rev. D **97**, 016007 (2018)

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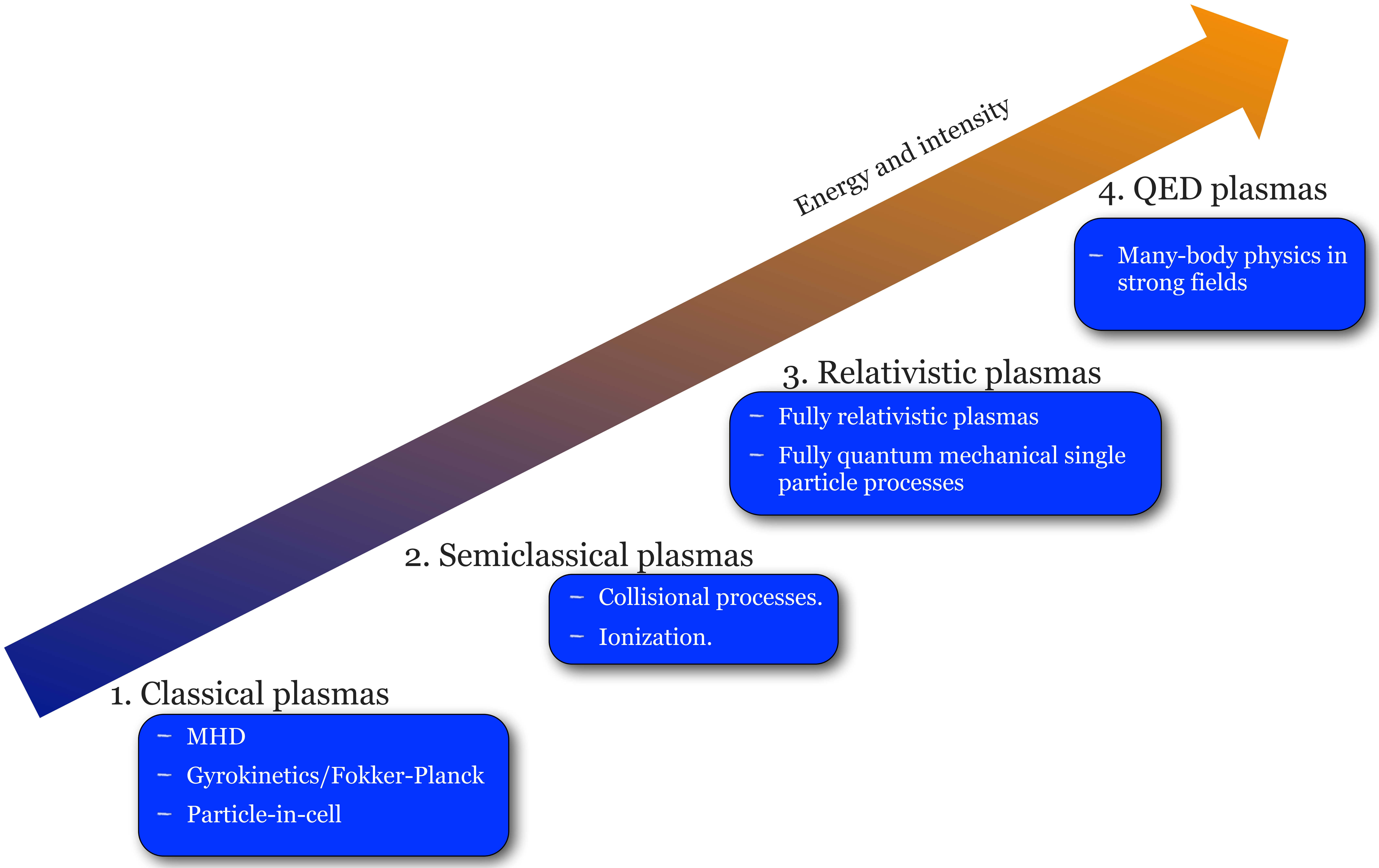
Example: many-body quantum systems



Example: many-body quantum systems

- Full quantum kinetic approach à la de Groot.
- Based on Wigner function for electron state: $\hat{W}_{db}\,(x,p) = \int \frac{d^4y}{(2\pi\hbar)^4}\, e^{-i\frac{p\cdot y}{\hbar}}\, \hat{\Psi}_{db}\left(x+\frac{y}{2}, x-\frac{y}{2}\right)$
- Simplification: Slowly varying classical fields:

$$\left[m\,(\mathbb{1})_{ca} - (\gamma^\mu)_{ca}\left(p_\mu + \frac{i}{2}\left(\partial^x_\mu - e\,F_{\mu\nu}\,(x)\,\partial^\nu_p\right)\right)\right]\hat{W}_{ab}\,(x,p) = 0$$

- Still requires approximations to be computationally viable.
- Other approaches: Schrödinger equation on a grid; path integral approach by multiple weighted classical paths (Dawson). Still principally unsolved.

de Groot & Suttorp (1972); Ruhl & Herzing, arXiv:1611.03892

Summary: some open questions

A. Overcome multiple scale issues (volume, timescale…) for proper experimental analysis.

B. Accurate interplay with experiments (e.g., detailed data input).

C. Computational statistics: requires large scale resources.

D. The breakdown of the locally constant crossed field approximation?

E. The general role of coherent multi-photon effects.

F. Depletion mechanisms of background fields; the breakdown of the background field approximation?

G. The transition between the *S*-matrix approach and equations of motion. No trajectories in QED.

H. Transition times in quantum processes from in and out states? Compare ionization.

I. Non-equilibrium many-body QFT approach. Compare condensed matter, transport theory of solids, and TDFT development.