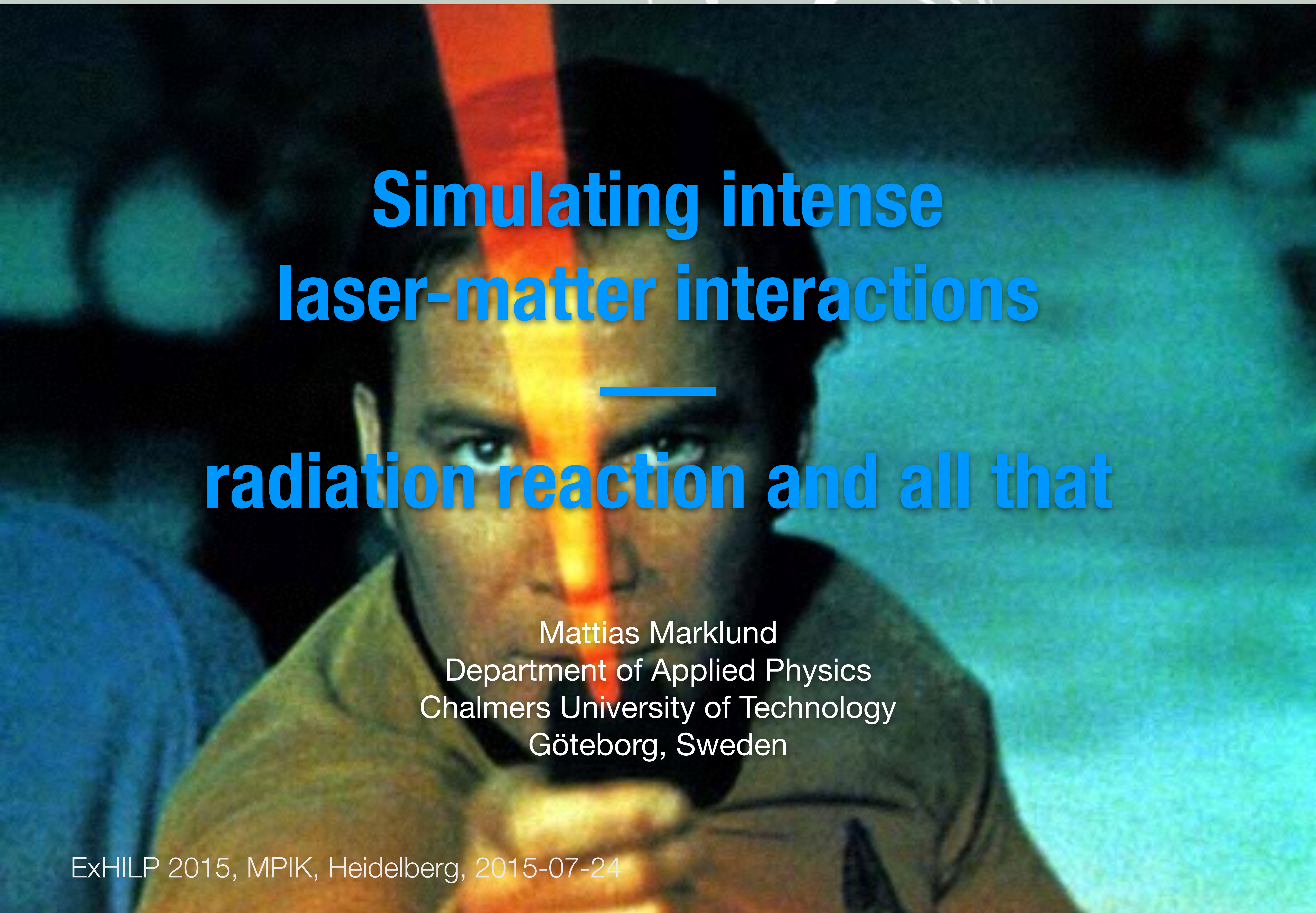


Simulating intense laser-matter interactions

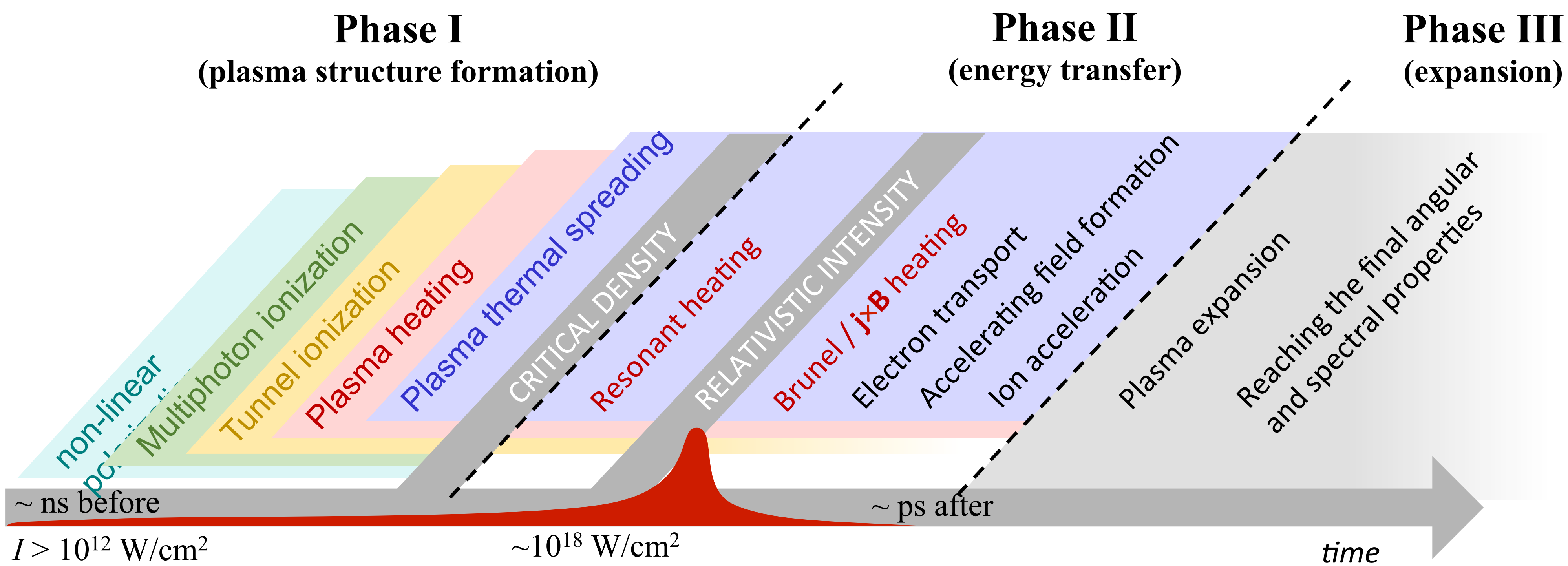
—

radiation reaction and all that

Mattias Marklund
Department of Applied Physics
Chalmers University of Technology
Göteborg, Sweden

ExHILP 2015, MPIK, Heidelberg, 2015-07-24

Processes in plasma formation

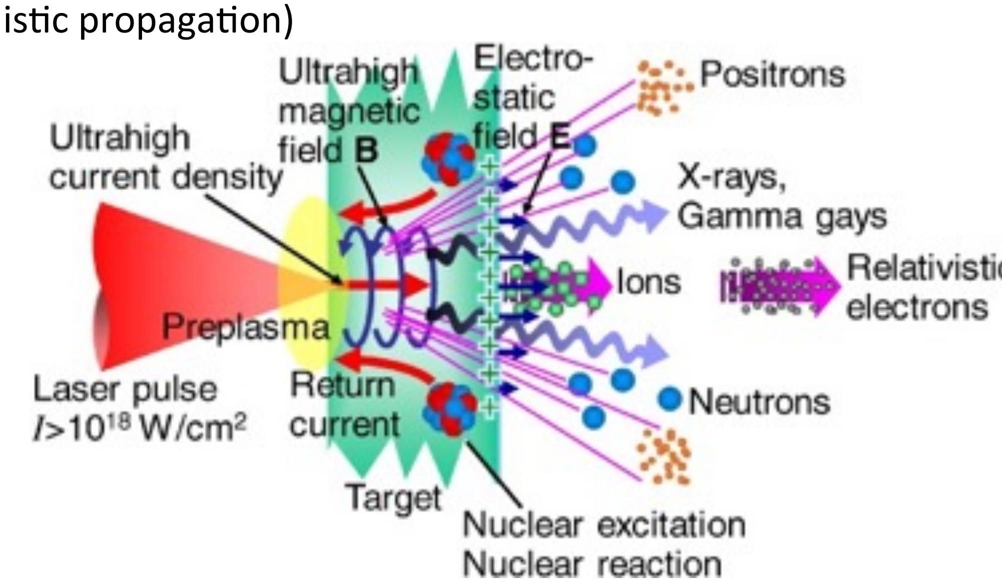


Atoms: TDSE, ionization theoretical/empirical rates

Plasma: Vlasov equation, MHD, other kinetic approaches

Plasma: Particle-In-Cell
- Maxwell's eq. (FFT, FDTD+)
- Particles motion (relativistic solvers)

Particles:
- Maxwell's eq. (FFT, FDTD+)
- Particles (ballistic propagation)



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

Micro- and macroscopic physics

Particle simulation of plasmas

John M. Dawson

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

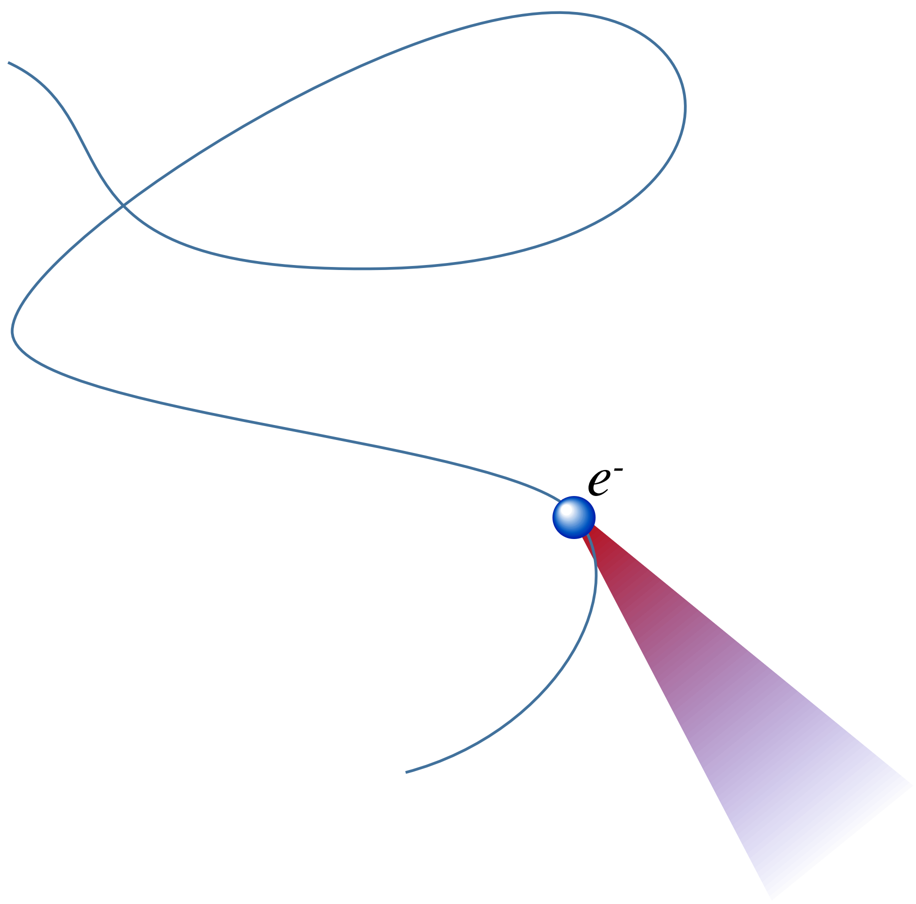
Reviews of Modern Physics, Vol. 55, No. 2, April 1983

”Proper treatment of systems where both the microscopic and macroscopic behavior are important will undoubtedly challenge simulation physicists for many years to come”

- Not only multi-scale, but also different treatment of physical quantities (e.g. EM fields vs. photons),

Synchrotron emission

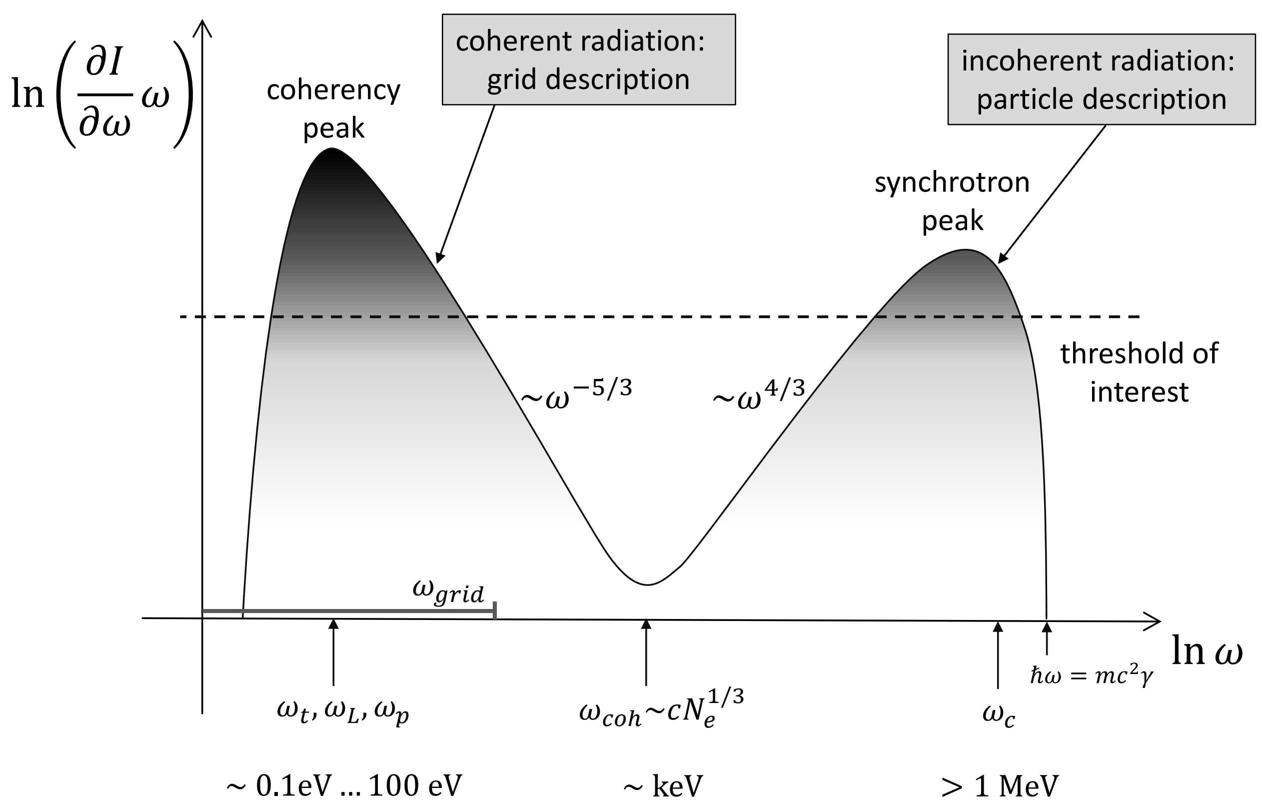
- In the strong acceleration regime, electrons emit large number of high energy photons (in high-*Z* targets, bremsstrahlung is a major contributor for moderate intensities).
- Typical frequency: $\omega_c = \frac{3eH_{\text{eff}}}{2mc}\gamma^2$.
- Making inclusion of synchrotron emission via direct solving of Maxwell's equations impossible in PIC scheme. *Cannot achieve good enough grid resolution.*
- Luckily the power spectra helps us.



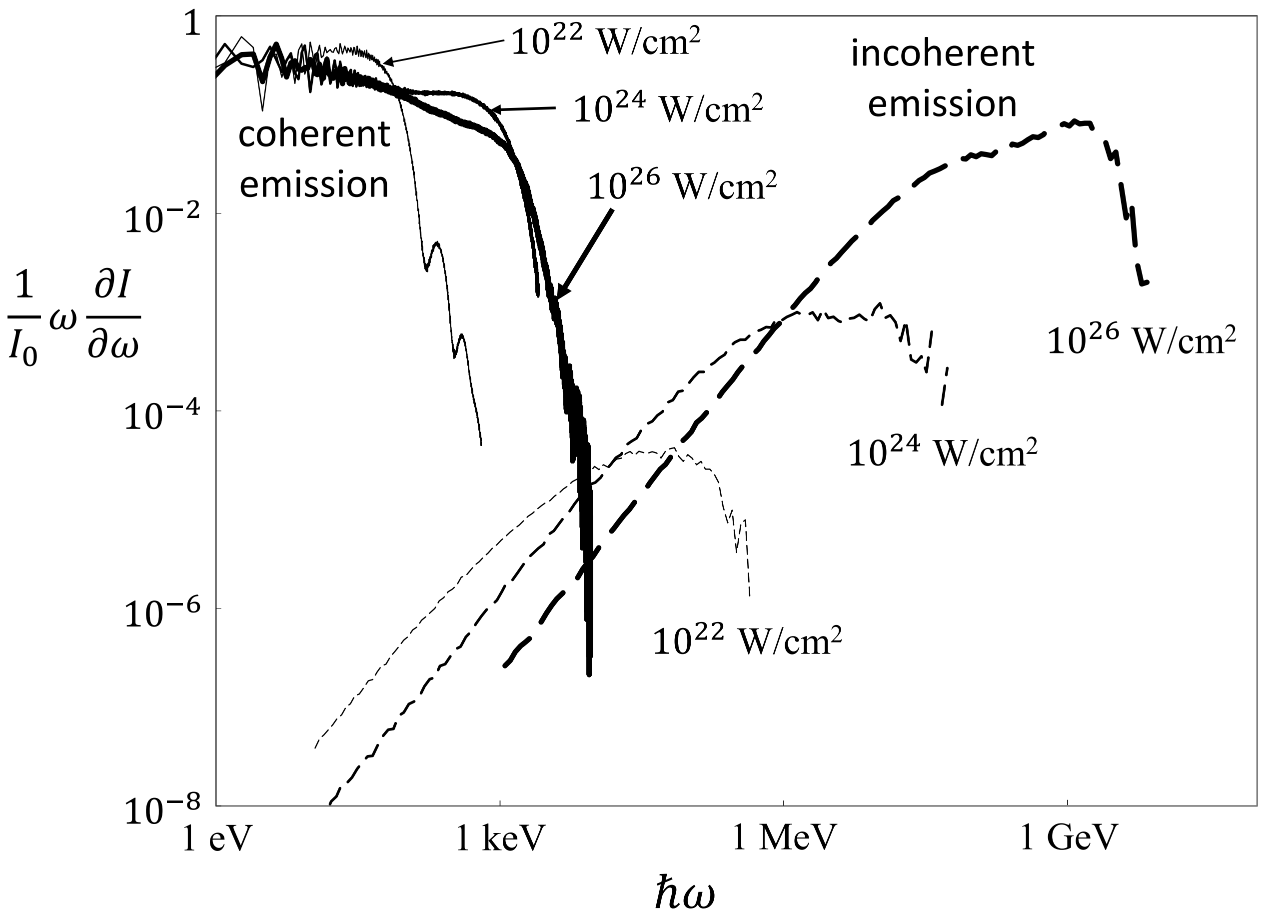
- Classical backreation: $I > 10^{23}$ W/cm^2
- Quantum backreaction: $I > 10^{24}$ W/cm^2

Electromagnetic energy deposition

"Cartoon" based on analytical estimates.



Simulation results from laser interaction with overdense target.



Gonoskov, Bastrakov, Efimenko, Ilderton, Marklund, Meyerov, Muraviev, Surmin & Wallin, PRE, to appear (2015) (arXiv:1412.6426)

Synchrotron emission

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  enough grid resolution.
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- Assuming photons emitted along direction of propagation:

$$\mathbf{f}_{RR}^{cl} = -\frac{2}{3}\frac{e^2m^2c}{\hbar^2}\chi^2\mathbf{v}. \qquad \chi = \gamma\frac{H_{\text{eff}}}{E_S}$$

- Same as ultra-relativistic limit of the Landau-Lifshitz expression.
- Postprocessing: cannot be executed in real time, no feedback.
- On-the-fly: neglect interference between time-steps. Only a small error in regime where radiation reaction important.

Radiation reaction

- **PIC schemes**: ideally fully self-consistent on the classical level.
- **Radiation reaction**: inclusion because of *finite grid size* in PIC codes (see coherency and synchrotron peak).
- **Interesting**? Impurities may limit focal intensities in the future, as acceleration of stray charges gives significant release of high energy photons, thus possible laser depletion. Also possible applications (beam cooling etc.).
- **Extensive literature** on this topic, as well as many different implementations, see, e.g.,

Di Piazza, Lett. Math. Phys. **83**, 305 (2008)
Bell & Kirk, PRL **101**, 200403 (2008)
Di Piazza et al., PRL **105**, 20403 (2010)
Bulanov et al., PoP **17**, 063102 (2010)
Sokolov et al., PoP **18**, 093109 (2011)
Thomas et al., PRX **2**, 041004 (2012)
Di Piazza et al., RMP **84**, 1177 (2012)
Schlegel & Tikhonchuk, NJP **14**, 073034 (2012)
Chen et al., PRSTAB **16**, 030701 (2013)
Mackenroth et al., PPCF **55**, 124018 (2013)
Ilderton & Torgrimsson, PRD **88**, 025021 (2013)
Ridgers et al., J. Comp. Phys. **260**, 273 (2014)
Yoffe et al., NJP **17**, 053025 (2015)
Tamburini et al., PRE **89**, 021201 (2014)
etc…

Radiation reaction/friction

- Classical radiation reaction described using Lorentz-Abraham-Dirac (LAD) theory

$$m\dot{u}^{\mu} = eF^{\mu\nu}u_{\nu} - \frac{2}{3}\frac{e^2}{4\pi}(u^{\mu}\ddot{u}^{\nu} - u^{\nu}\ddot{u}^{\mu})$$

- or the perturbative expansion (lacking runaways etc.) due to Landau & Lifshitz (LL)

$$\dot{u}^{\mu} = \frac{e}{m}F^{\mu\nu}u_{\nu} + \frac{2}{3}\frac{e^2}{4\pi}\left\{\frac{e}{m^2}\dot{F}^{\mu\nu}u_{\nu} + \frac{e^2}{m^3}F^{\mu\alpha}F_{\alpha}{}^{\nu}u_{\nu} - \frac{e^2}{m^3}u_{\alpha}F^{\alpha\nu}F_{\nu}{}^{\beta}u_{\beta}\,u^{\mu}\right\}$$

- Works in classical regime (i.e. current facilities) when $(a_0 = eE/\omega mc)$

$$\chi \equiv \frac{e\hbar\sqrt{(F^{\mu\nu}u_{\nu})^2}}{m^2c^4} \ll 1, \qquad \Longrightarrow \qquad \hbar a_0\gamma\omega \ll mc$$

- QED regime (i.e. next generation regime) when

$$\chi \sim 1 \qquad\qquad \dot{u}^{\mu} = \frac{e}{m}F^{\mu\nu}u_{\nu} + \frac{d^2P}{dt\,d\chi_{\gamma}}$$

Burton & Noble, Contemporary Phys. **55**, 110 (2014)

Including classical radiation reaction in PIC codes

- PIC schemes work with super particles where the charge to mass ratio is kept fixed for each species *q/m.*
- This works because the acceleration due to the Lorentz force depends on *q/m*.
- Not true for RR force. However ⟶

Let us consider a macro particle that represents α electrons. The charge of the macro particle is $e_m = \alpha e$, and the mass is $m_m = \alpha m_e$. For a single particle with the same mass and charge as the macro particle, the radiation reaction would be α times stronger than in the case of a single electron:

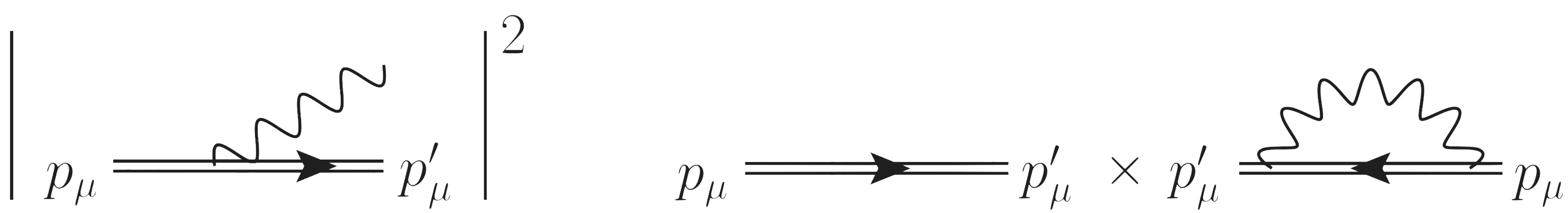
$$\frac{F_{RD}}{F_L} \propto \frac{(\alpha e)^3}{(\alpha m_e)^2} = \alpha \frac{e^3}{m_e^2} \tag{12}$$

and the trajectory of such particle would be different than the trajectory of a single electron (Fig. 1). This result would be equivalent to assuming that α electrons are radiating coherently. As a consequence, the results of a PIC simulation would be qualitatively different for different number of particles per cell or different cell sizes. To obtain the correct dynamics of a macro-particle, it is therefore essential to use the real charge and mass to calculate the correct radiation reaction coefficient for a particular particle species. This approach yields the same result regardless of the macro-particle weight.

Vranic et al., arXiv:1502.02432

Radiation reaction: which model?

- There are a number of classical models in the literature (see also Vranic et al., arXiv:1502.02432).
- Start from QED, take the classical expansion to order e^2

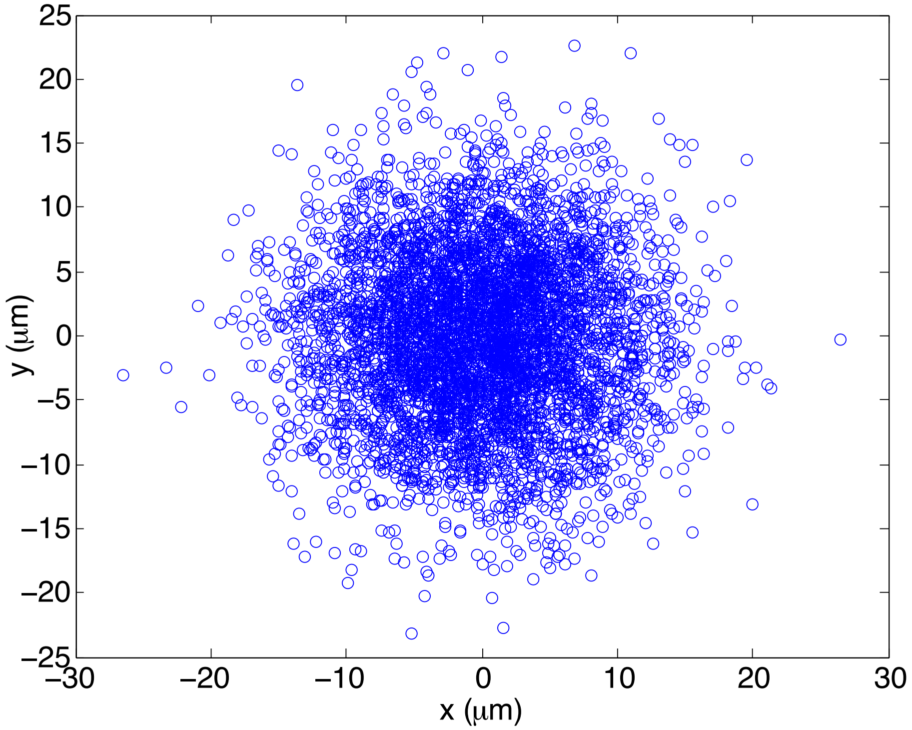


Radiation Reaction	$\mathcal{O}(e^2)$	$\mathcal{O}(e^4)$
Abraham Lorentz Dirac (LAD)	✓	?
Landau Lifshitz (LL)	✓	?
Eliezer Ford O'Connell (EFO)	✓	?

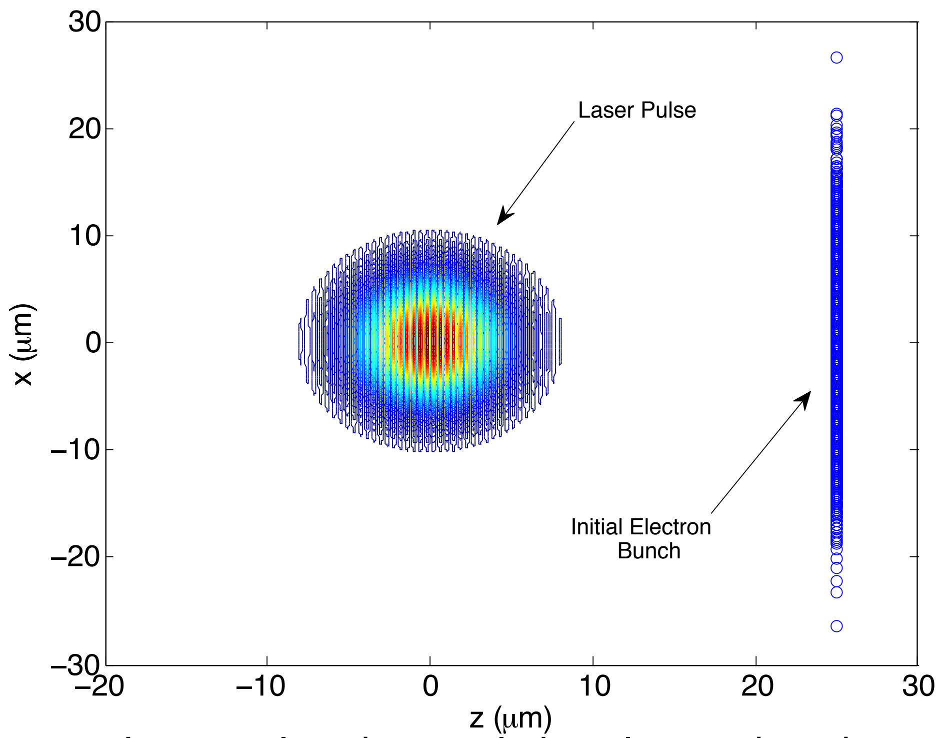
To this order, we could (in principle) distinguish between LAD, LL, EFO

A. Ilderton & G. Torgrimsson, PRD and PRB (2013)

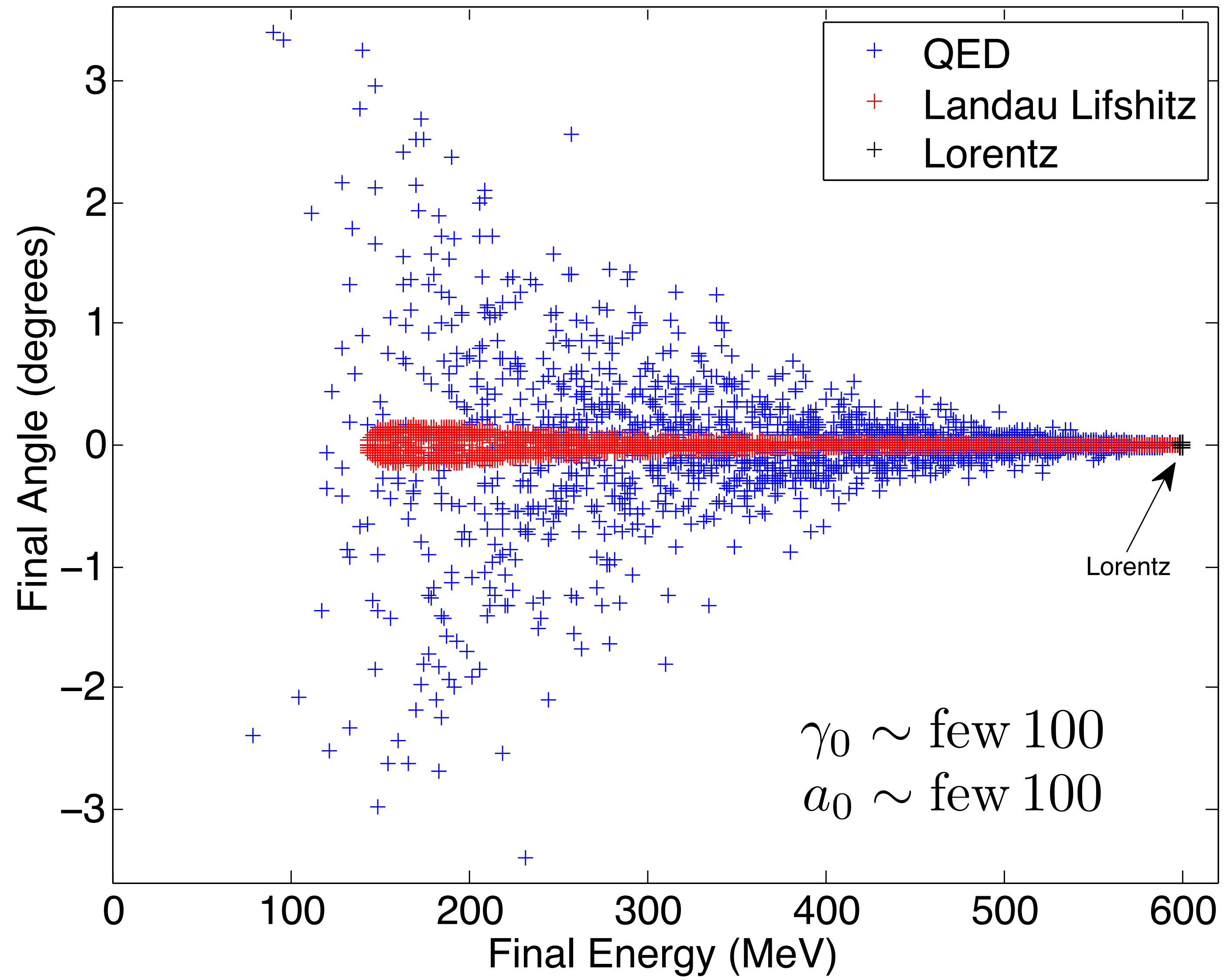
Radiation reaction: electron distribution



Initial spatial spread of electron bunch



Laser pulse shape relative electron bunch



Final angular distribution of electrons

Green & Harvey, PRL **112**, 164801 (2014)
Li, Hatsagortsyan, & Keitel, PRL **113**, 044801 (2014)
Green & Harvey, arXiv:1410.4055
Harvey, Ilderton, & King, arXiv:1409.6187

Radiation reaction: radiation distribution

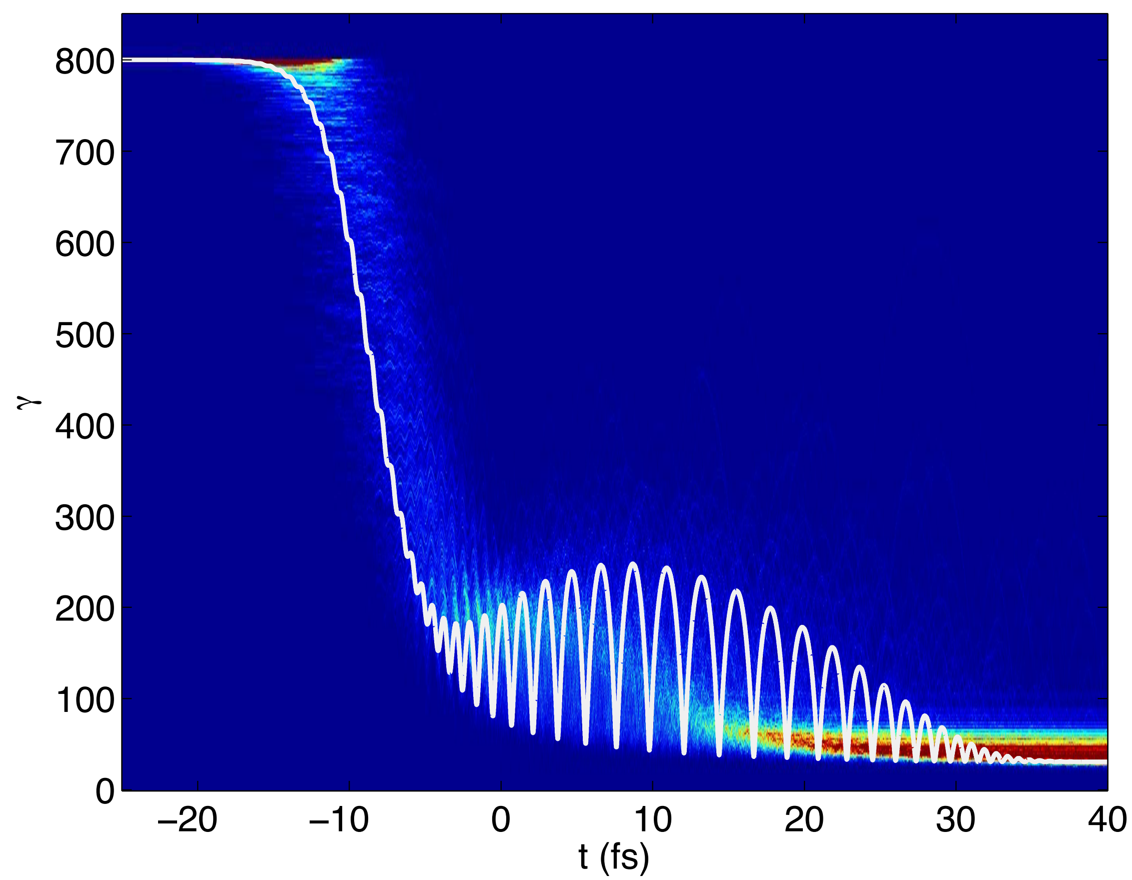


FIG. 4. Density plot showing how the electron γ-factor changes with time (statistical distribution generated by recording the paths of 500 QED electrons all with the same initial condition $\gamma_0 = 800$). Parameters are $a_0 = 200$, $\lambda = 0.8\mu$m and duration 30fs. The white line shows the γ-factor for a classical electron.

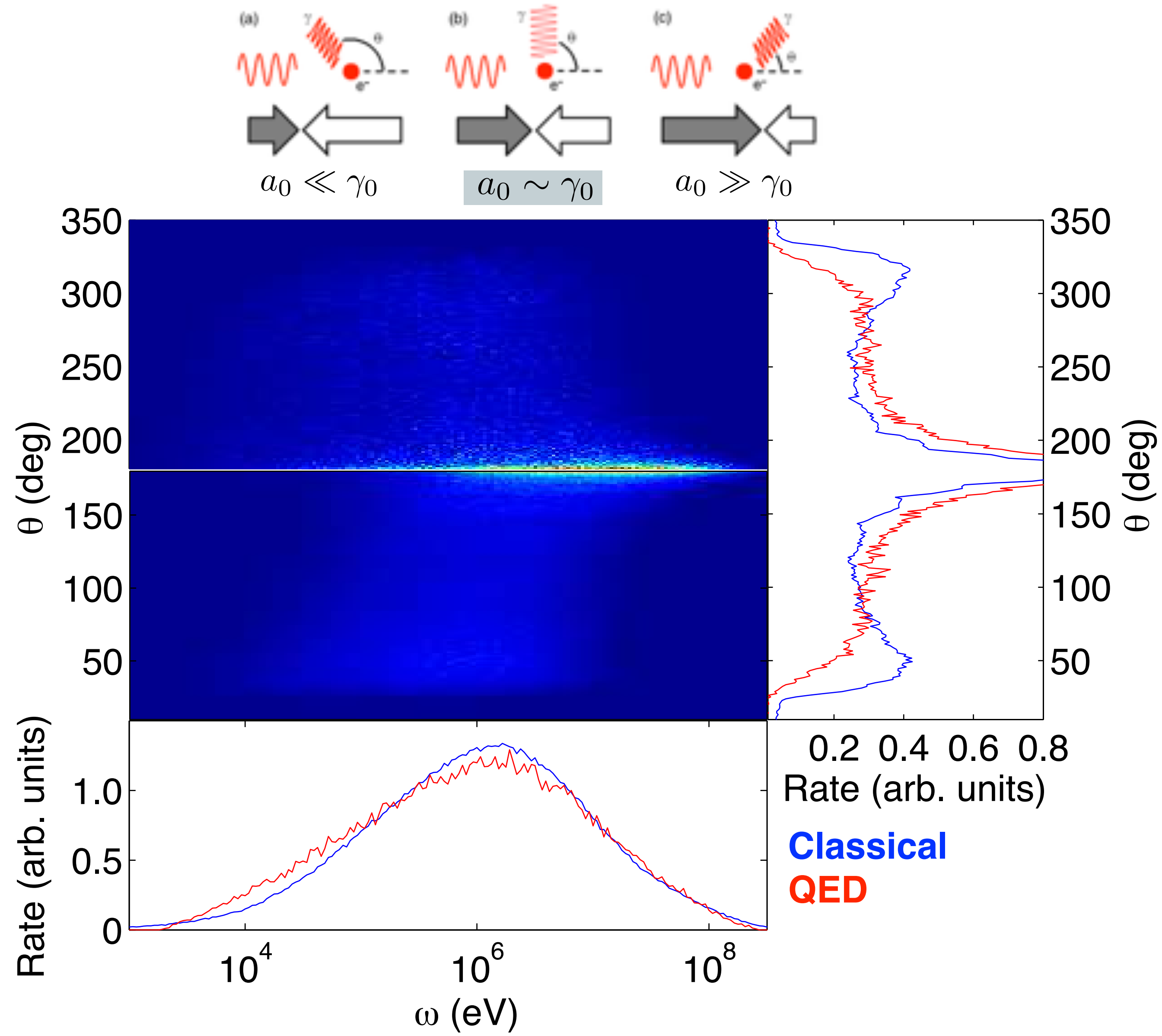


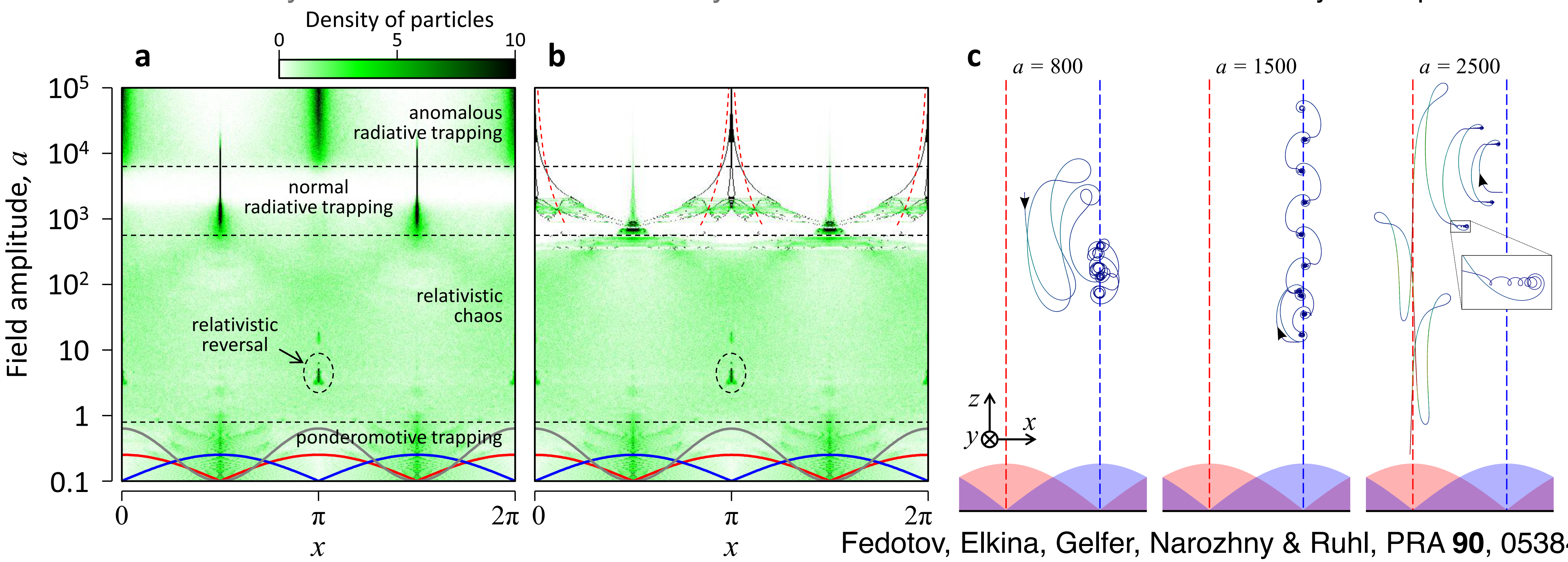
FIG. 6. Emission spectrum for the realistic case ($a_0 = 250$) described in Fig. 5. The centre panel shows the radiation intensity as a function of frequency and angle. This panel is split into two, the top half showing the emissions for the QED simulation and the bottom half the classical. The right hand panel shows the total angular rate summed over all frequencies (both classical and QED for all angles), and the bottom panel the total frequency rate summed over all angles. Red lines: QED. Blue lines: classical.

Harvey, Marklund & Wallin, arXiv:1507.06478 (2015)
Vranic, Martins, Vieira, Fonseca & Silva, PRL **113**, 134801 (2014)
Green & Harvey, PRL **112**, 164801 (2014)
Neitz & Di Piazza, PRL **111**, 054802 (2013)
Li, Hatsagortsyan & Keitel, PRL **113**, 044801 (2014)
Harvey, Heinzl & Ilderton, PRA **79**, 063407 (2009)

Extreme intensities: *Anomalous Radiative Trapping*

- At high intensities, radiation reaction results in *anomalous radiative trapping* (A. Gonoskov et al., PRL **113**, 014801 (2014)).
- Electrons trapped at peak electric field.
- Strongly enhanced hard photon emission.
- Photons with energy > 3 GeV in cyan in animation.
- Pair production will also play a role.
- See also the talks by S.V. Bulanov and T. Grismayer!

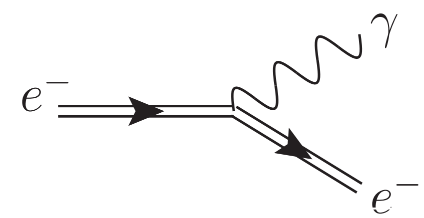
Electron density in e-dipole field



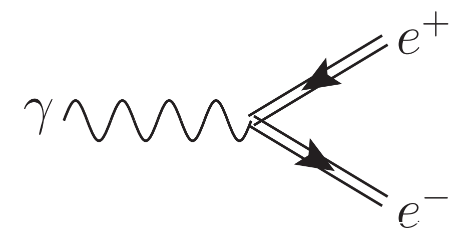
Fedotov, Elkina, Gelfer, Narozhny & Ruhl, PRA **90**, 053847 (2014)
Ji, Pukhov, Kostyukov, Shen & Akli, PRL **112**, 145003 (2014)

Multi-photon processes in intense fields

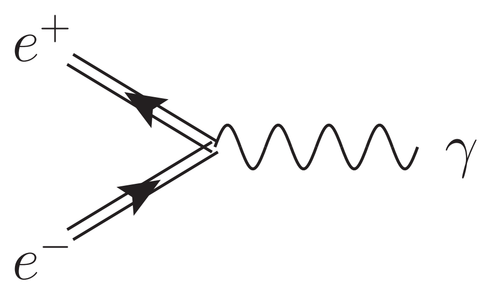
- **Lowest order processes**
  - Nonlinear Compton scattering



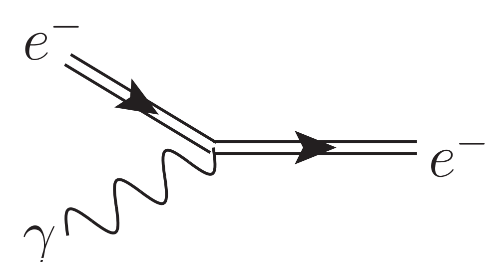
  - Pair production



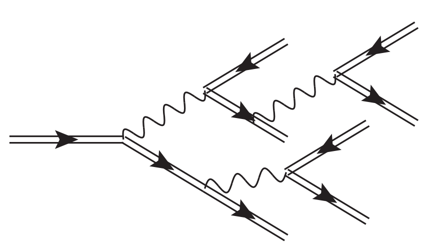
  - Pair annihilation



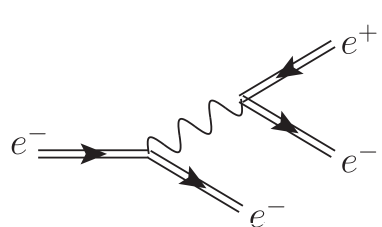
  - One photon absorption



- **Higher order processes (no loop corrections)**
  - Cascading



  - Trident

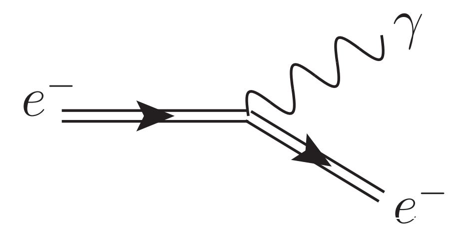


Multi-photon emissions: in high intensity fields (*a* >> 1), multi-photon emission factorized into several single photon events. Captured via synchrotron models. For high energy electrons at low intensity (*a* ~ 1) significant low-frequency contribution from off-shell channels. (Seipt & Kämpfer, PRD **85**, 1019701 (2012); Mackenroth & Di Piazza, PRL **110**, 070402 (2013))

See also: Hu et al., PRL **105**, 080401 (2010);
Ilderton, PRL **106,** 020404 (2011);
King & Ruhl, PRD **88**, 013005 (2013)

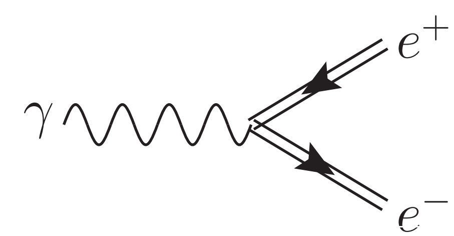
Nonlinear Compton scattering and pair production

- **Nonlinear Compton scattering:**



  - No energy or intensity threshold for channel.
  - Low energy limit: matches spectrum from classical particle with Lorentz force.
  - Classical limit of electron recoil: radiation reaction.

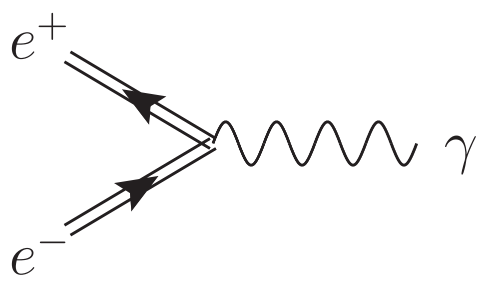
- **Stimulated pair production:**



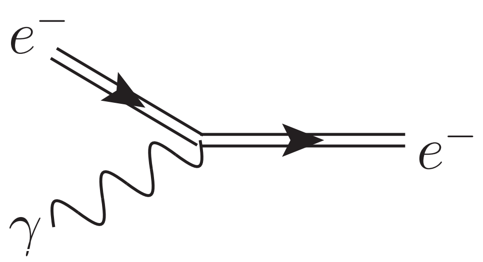
  - Threshold process: probability vanishes in low energy/classical limit.
  - For highly relativistic intensities, the process of pair production takes very small energy from laser as compared to the acceleration of the produced pairs.
  - Thus, the number of pairs needs to be prolific before taking significant energy from laser pulse.

Pair annihiliation and one photon absorption

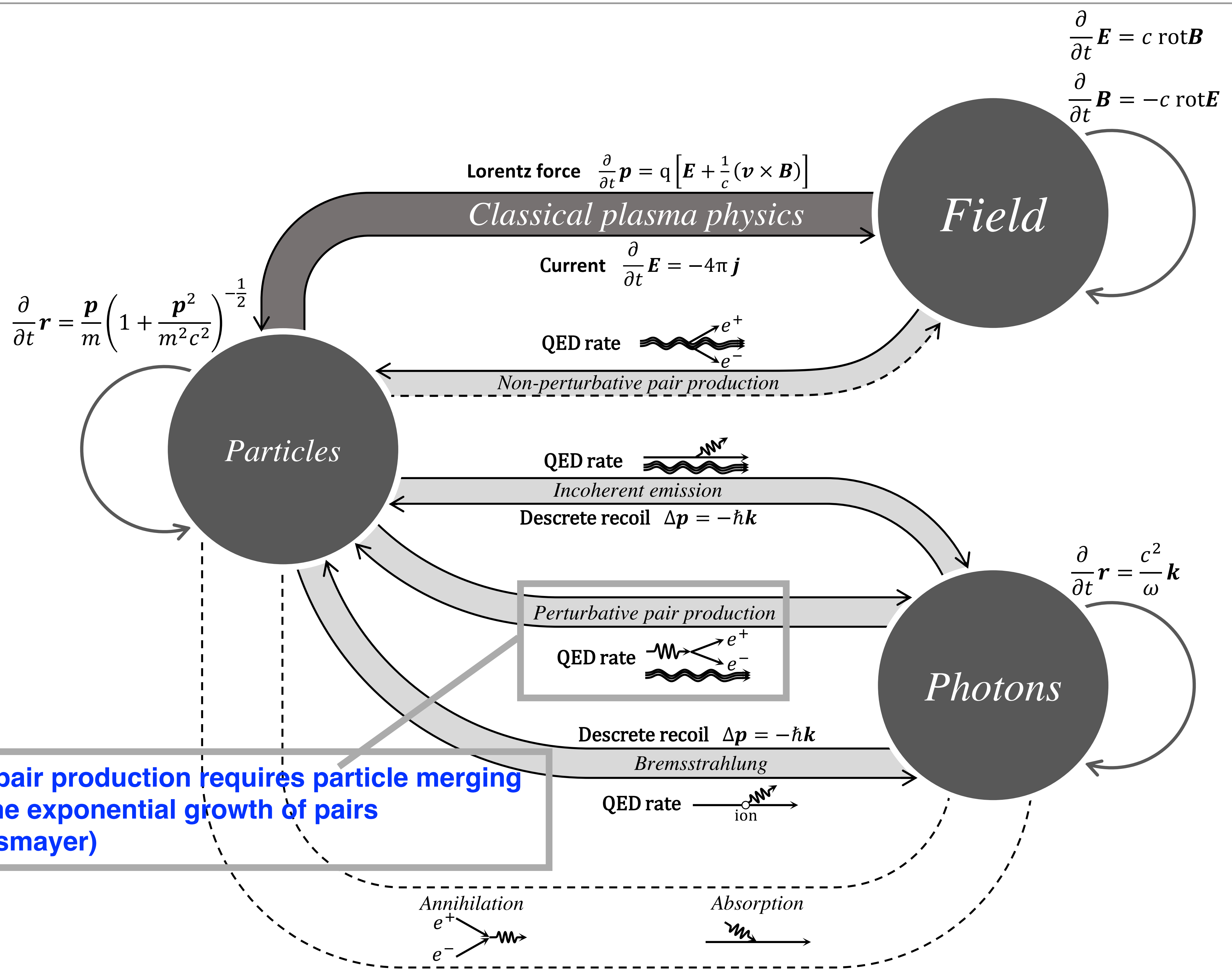
- **Pair annihilation to one photon:**
  - Suppressed by infinite volume factor as compared to the crossing symmetry diagrams above.
  - Energy-momentum conservation —> single four-momentum of photon. final phase space collapses to single point.
  - Ultra-relativistic particles: fine-tuning with pair collision angle ≤ 10^{-5}.
  - *Of importance for approach to equilibrium, or very dense systems.*



- **One photon absorption:**
  - Suppressed as above.



Fields and particles

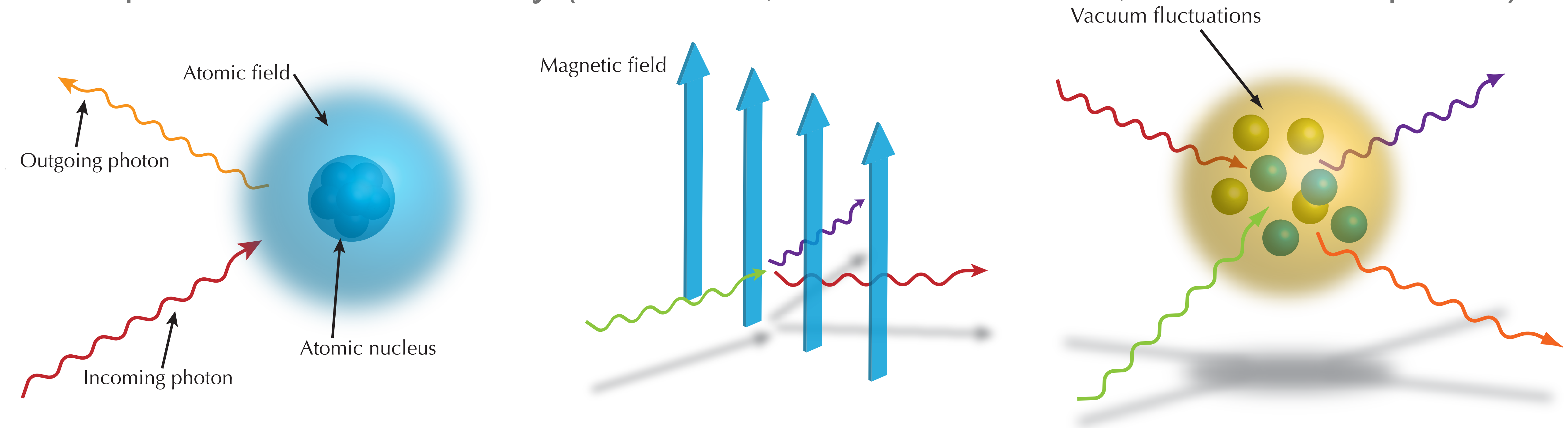


Note that prolific pair production requires particle merging in order to treat the exponential growth of pairs (see talk by T. Grismayer)

Gonoskov, Bastrakov, Efimenko, Ilderton, Marklund, Meyerov, Muraviev, Surmin & Wallin, PRE, to appear (2015) (arXiv:1412.6426)

The nonlinear quantum vacuum

- Special relativity + Heisenberg's uncertainty relation = virtual pair fluctuations.
- Photons can effectively interact via fluctuating electron-positron pairs.
- Astrophysical applications; laboratory tests of high field QED.
- Implemented numerically (Böhl et al., arXiv:1503.05192; P. Carneiro's poster)



Marklund & Shukla, Rev. Mod. Phys. **78** (2006)**;** Marklund, Nature Phot. 4 (2010)

Summary

Complex computational problem:
how to correctly capture many-body physics?

Difficult computational developments.
Necessary?

Energy and intensity

4. QED plasmas

- Many-body physics in strong fields

3. Relativistic plasmas

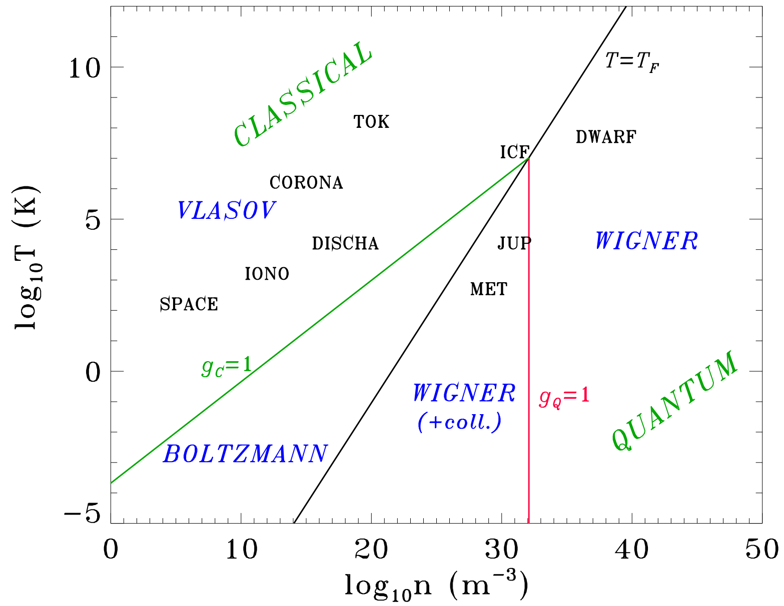
- Fully relativistic plasmas
- Fully quantum mechanical single particle processes

2. Semiclassical plasmas

- Collisional processes.
- Ionization.

1. Classical plasmas

- MHD
- Gyrokinetics/Fokker-Planck
- Particle-in-cell



QED processes in PIC codes

- No trajectories. Instead, scattering probabilities.

1. Calculate the scattering probability in constant crossed fields for given event (Nikishov & Ritus, JETP **19**, 529 + 1191(1964); Ritus, J. Sov. Laser Res. **6**, 497 (1985)).

2. Divide by infinite interaction time to obtain finite rate.

3. Rate assumed to be *local* transition rate using locally constant field approximation.

4. After time step Δt combine rate with statistical event generator, adding or removing particle species as appropriate.