Radiation Reaction and Nonlinear Compton Scattering in Intense Laser Interactions with Relativistic Electrons

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10/15/2019

Outline

- How does RR that affect plasma dynamics at extreme light intensities?
- How can RR be measured: High-power laser experiments
- How to simulate RR effects in laser-plasma interactions?
- Narrowband Compton backscattering at high intensity
- What's next: Radiative electron spin polarization with lasers

Radiation Back-Reaction

- What is the correct equation of motion for a charged particle?
- Nonrelativistic force

$$m\ddot{\boldsymbol{x}} = e\boldsymbol{E}$$

- Larmor's equation for radiated power

$$P = \frac{2}{3}\ddot{\boldsymbol{d}}^2 = -\frac{2}{3}e^2\dot{\boldsymbol{x}}\cdot\dddot{\boldsymbol{x}} = \dot{\boldsymbol{x}}\cdot\boldsymbol{f}_{RR}$$

- Lorentz-Abraham equation

$$m\ddot{\boldsymbol{x}} = e\boldsymbol{E} + \boldsymbol{f}_{RR} = e\boldsymbol{E} - \frac{2}{3}\alpha\dddot{\boldsymbol{x}}$$

Abraham, Ann. Phys. 1904, Klepikov Phys Uspekh 1985, Hammond EJTP 2010

- ... has problems like runaway solutions $\Rightarrow$ reduce order: Landau Lifshitz equation

Invariant Strong Field Parameters

1. Classical nonlinearity parameter

$$a_0 = \frac{eA}{m} = \frac{eE}{m\omega} \simeq 8.5\lambda_{\mu\mathrm{m}}\sqrt{I_{20}} \rightsquigarrow 100$$

   - Energy density of the laser as seen in the electron rest frame
   - Normalized average quiver momentum
   - Relativistic optics, large amplitude plasma waves, ...
   - Multi-photon effects

2. Quantum nonlinearity/efficiency parameter for a probe particle

$$\chi = \frac{e}{m^3}\sqrt{|F_{\mu\nu}p^\nu|^2} = \frac{E_{\mathrm{rf}}}{E_{\mathrm{QED}}} \sim 2\gamma\frac{E}{E_{\mathrm{QED}}} \rightsquigarrow \gamma \times 6 \times 10^{-4}$$

   - QED experiments with present day lasers by colliding GeV electrons
   - Self-accelerated regime $\gamma \sim a_0$

- Longer wavelength: $a_0 \uparrow$ and $\chi \downarrow$; Shorter wavelength $a_0 \downarrow$ and $\chi \uparrow$

Radiation Back-Reaction

- Average radiation power: Larmor formula

$$\mathbb{I} = \frac{d\varepsilon}{dt} = -\frac{2\alpha}{3}\dot{u}\cdot\dot{u} \sim \alpha m^2\chi^2 \sim \alpha\omega^2\gamma^2 a_0^2$$

- Compare radiated energy $\Delta\varepsilon = \mathbb{I}T$ to the particle energy $m\gamma$

$$\frac{\mathbb{I}T}{m\gamma} \sim \alpha\frac{\omega}{m}\gamma a_0^2\,(\omega T) \sim \alpha\chi a_0\,(\omega T)$$

- Radiation dominated regime

$$R_C = \alpha\chi a_0 \sim 1$$

  e.g. $a_0 \sim 100$, $\chi \sim 1$: GeV electrons colliding with PW pulse

- **Classical vs. quantum** radiation reaction: Average energy of emitted photon

$$\frac{\langle\omega\rangle}{m\gamma} \simeq 0.46\chi$$

Modeling of Quantum Effects in RR

- Semi-classical radiation reaction

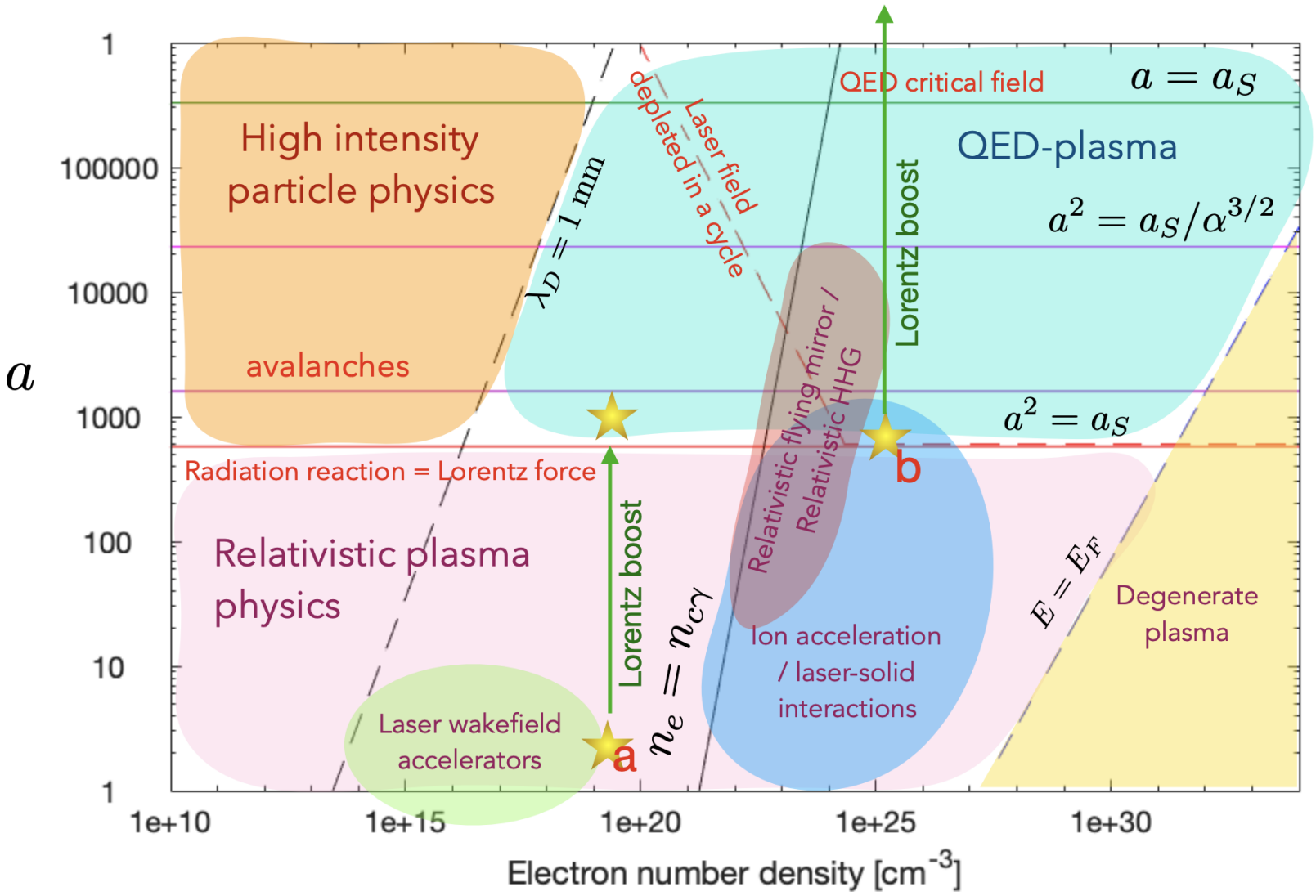
$$\frac{du^\mu}{d\tau} = f^{\mu\nu} u_\nu + \epsilon_{rad}\, g(\chi_e)\, [\eta^{\mu\nu} - u^\mu u^\nu] f_{\nu\kappa} f^{\kappa\lambda} u_\lambda$$

- Gaunt-factor models reduced radiated power

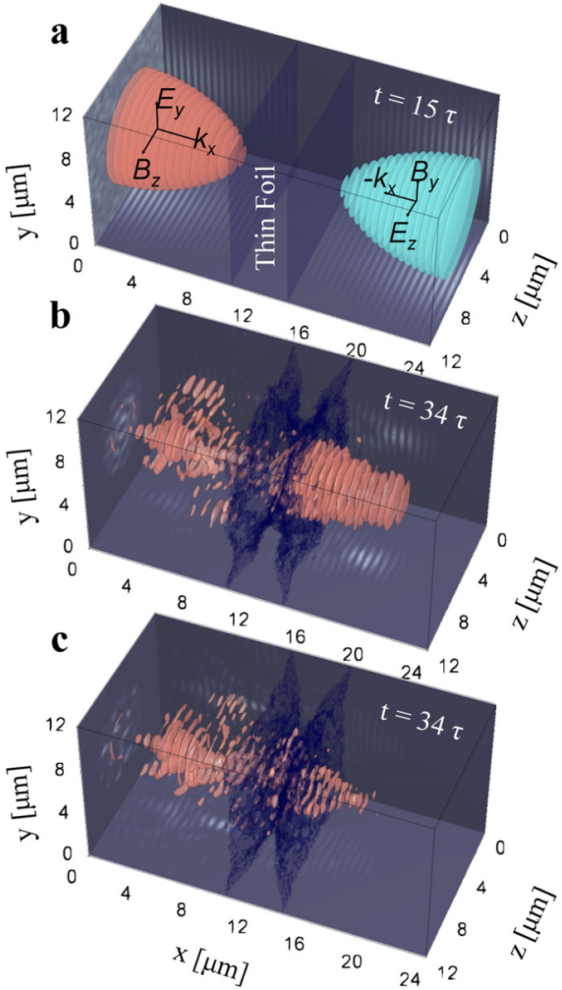
$$g(\chi_e) = \frac{\mathbb{I}(\chi_e)}{\mathbb{I}_{\text{class}}} \approx [1 + 4.8(1+\chi_e)\ln(1+1.7\chi_e) + 2.44\chi_e^2]^{-2/3}$$

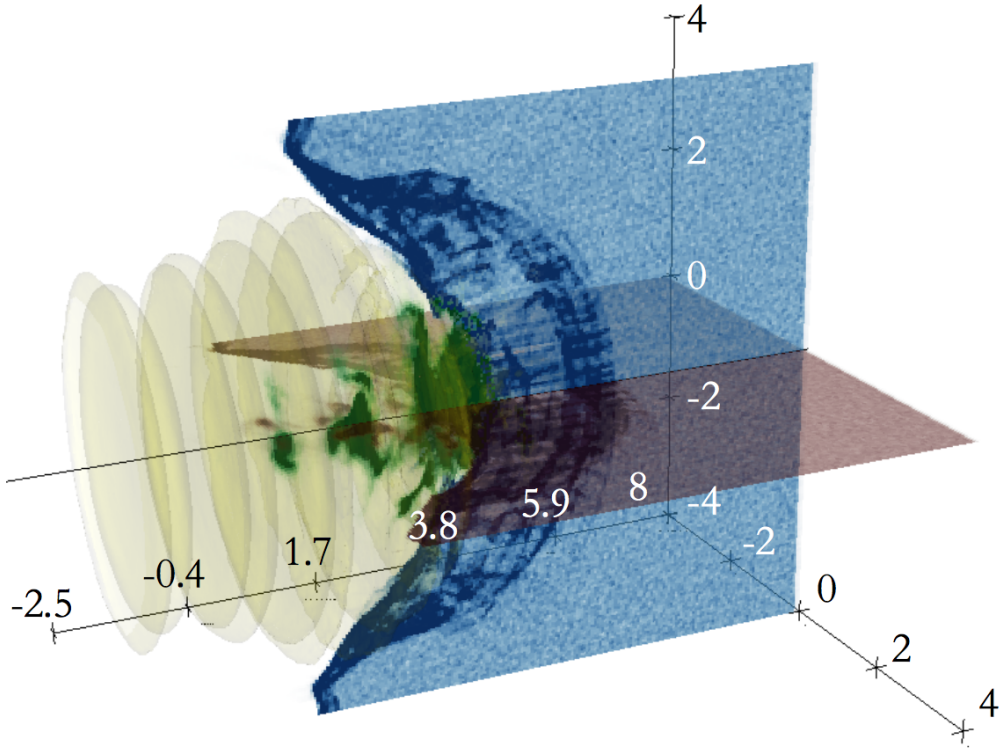
- Quantum Regime: Emitted photons have quantum parameter $\chi_\gamma \lesssim \chi_e$
- Pair production effective for $\chi_\gamma \gtrsim 0.1$

Regimes of High-Intensity Plasma Interactions



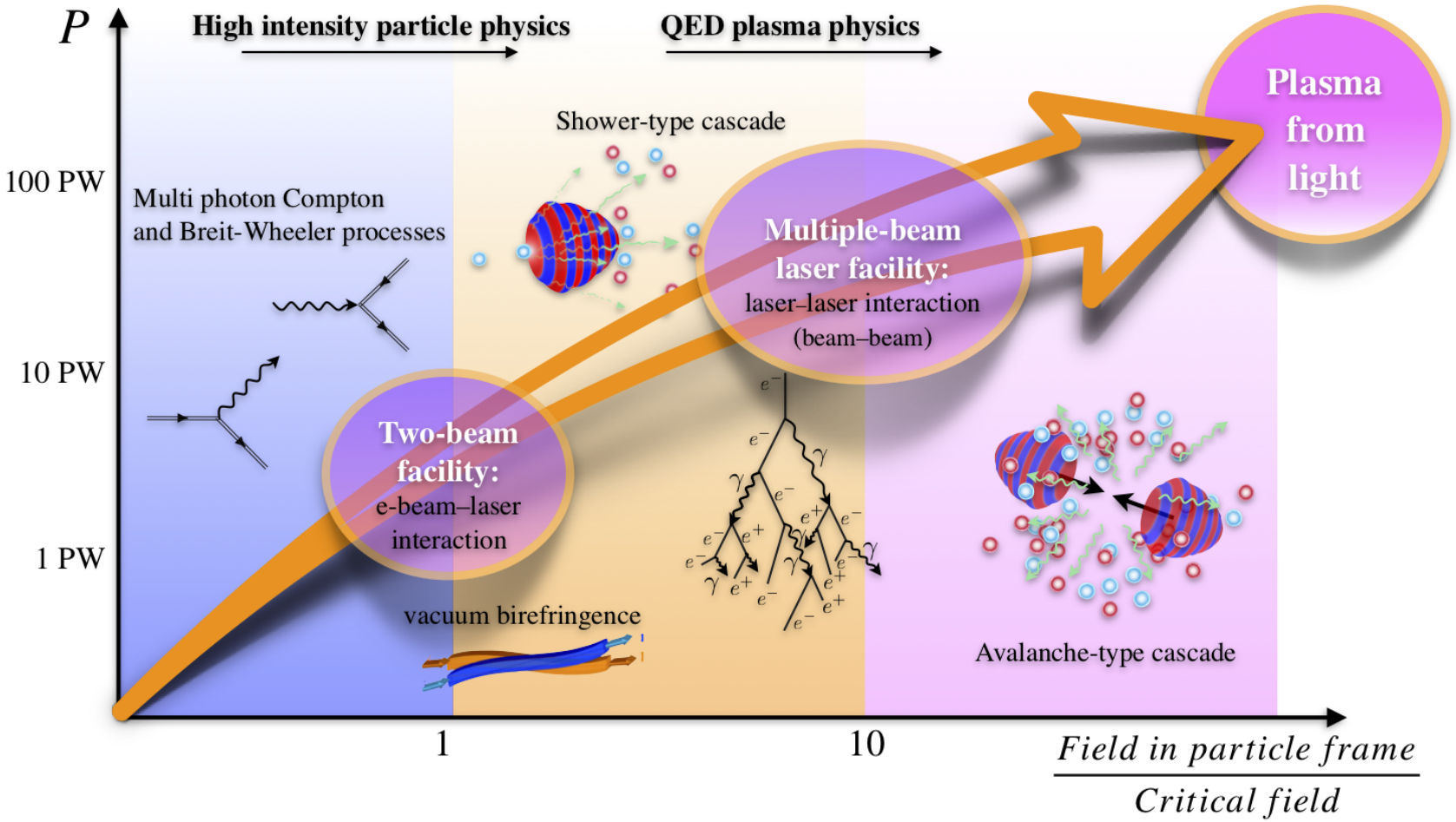
Radiation Dominated High-Intensity Plasma Physics



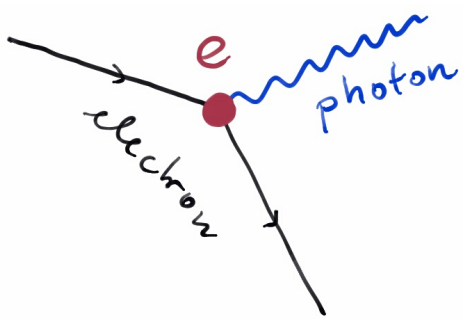


Zhang NJP 2015,Del Sorbo NJP 2018

High-Intensity Regimes



Quantum Field Theory in Strong Fields



- $L = \underbrace{\bar{\psi}(i\partial\!\!\!/ - m)\psi}_{e^+/e^-} - \underbrace{\frac{1}{4}\mathrm{tr}\, F^2}_{\text{photons}} - \underbrace{eA_\mu\bar{\psi}\gamma^\mu\psi}_{\text{interaction}}$
- Strong field = many photons $N_\gamma \gg 1$
- Bose enhancement factor $e \to e\sqrt{N_\gamma} \sim e\sqrt{\lambda\lambda_C^2 n_\gamma} = a_0$
- a_0 is effective interaction strength — A. Fedotov, arXiv:1612.02038
- Transition to the Furry picture $A \to \mathcal{A} + A_{ext}$: — W. H. Furry, PR **81**, 115 (1951)
- $L = \underbrace{\bar{\psi}(i\partial\!\!\!/ - m - eA\!\!\!/_{ext})\psi}_{\text{laser dressed } e^+/e^-} - \underbrace{\frac{1}{4}\mathrm{tr}\, F^2}_{\text{photons}} - \underbrace{e\mathcal{A}_\mu\bar{\psi}\gamma^\mu\psi}_{\text{interaction}}$
- Calculation of quantum processes using laser-dressed **Volkov states**

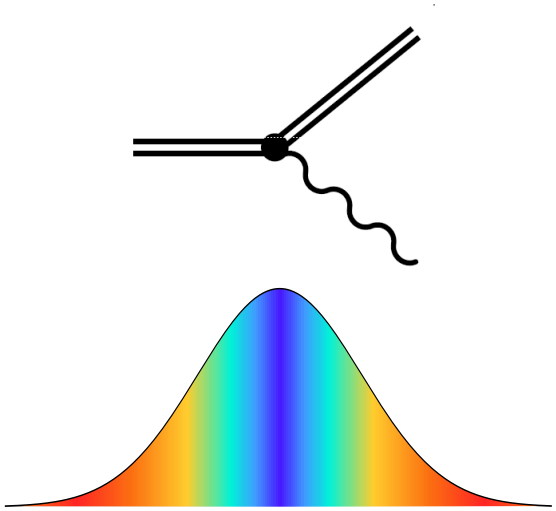
D. M. Volkov, Z. Phys. **94**, 250 (1935)

Compton Backscattering at $a_0 \sim 1$

Goal: Narrowband, intense, short-pulse, collimated, bright γ-rays

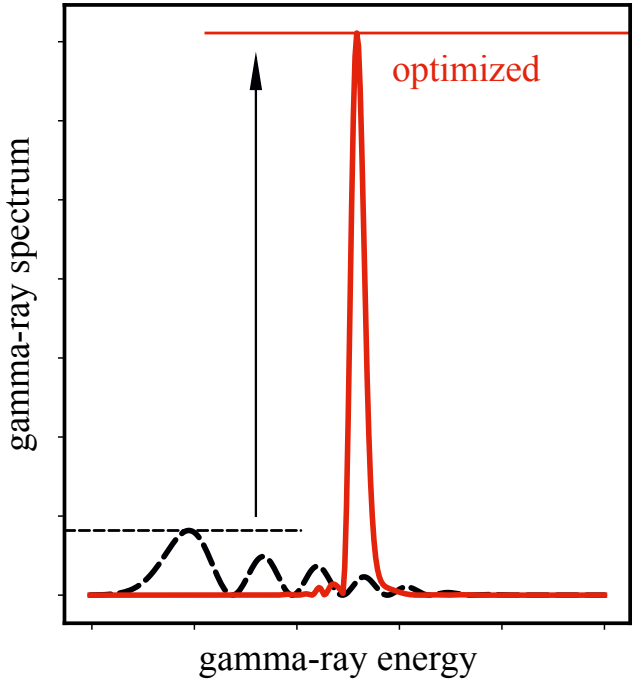
Problem: γ yield $\propto I_L$, ponderomotive broadening as $a_0 \sim 1$

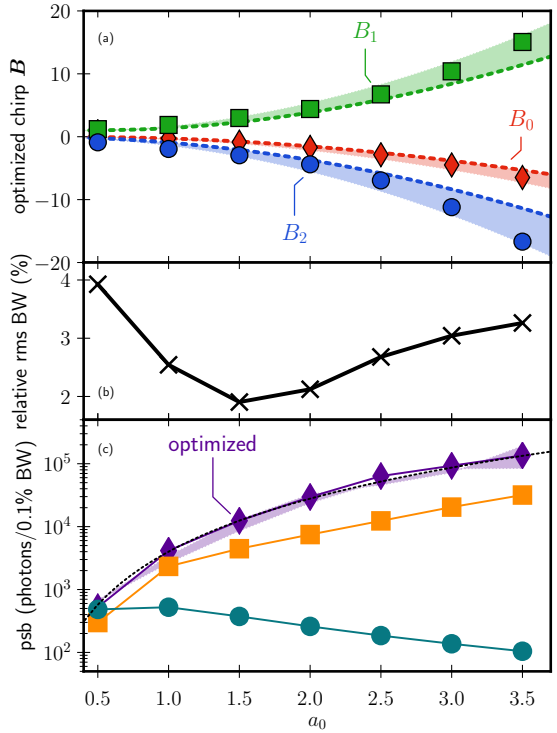
Solution: Use optimized chirped pulses to compensate a_0-dep. red-shift



blue-shift at large intensity

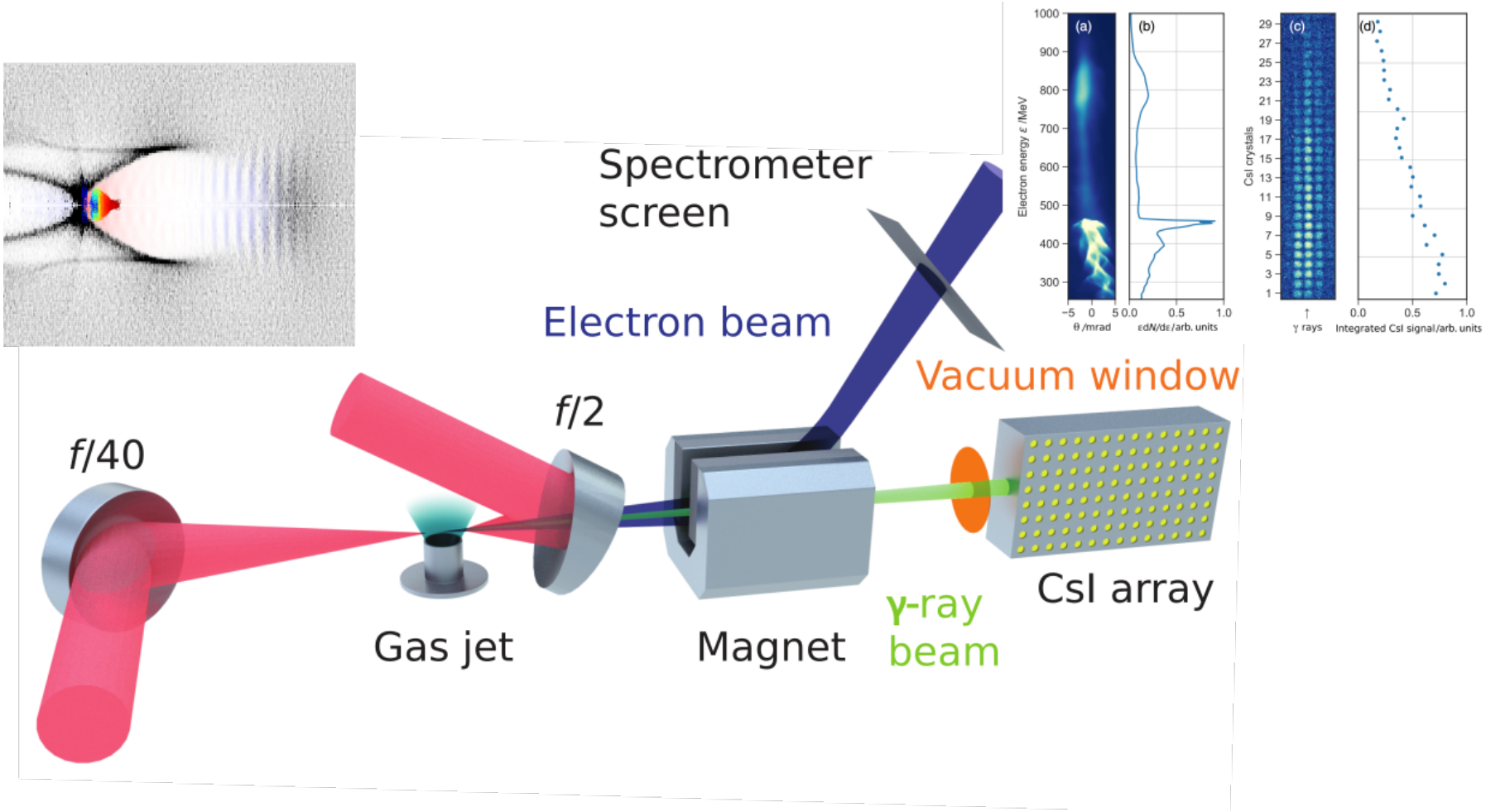
$\omega(\varphi) \propto 1 + a^2(\varphi)$





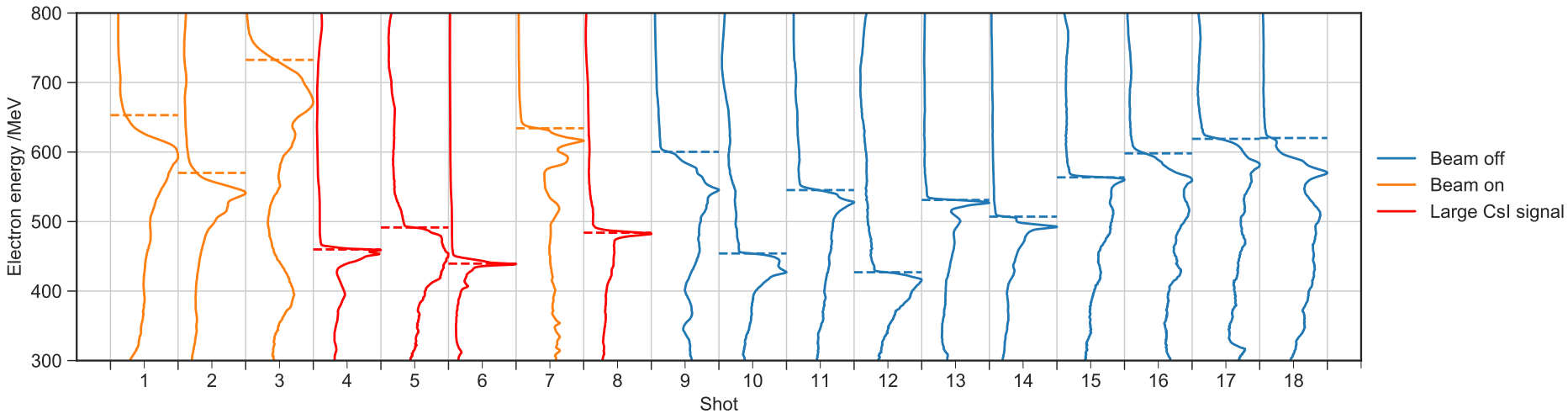
Seipt et al, PRL 122, 204802 (2019), Kharin, et PRL 120, 044802 (2018)

Radiation Reaction Experiment @ RAL-Gemini



J. Cole et al, PRX **8**, 011020 (2018); K. Behm et al, Review of Scientific Instruments 89, 113303 (2018)

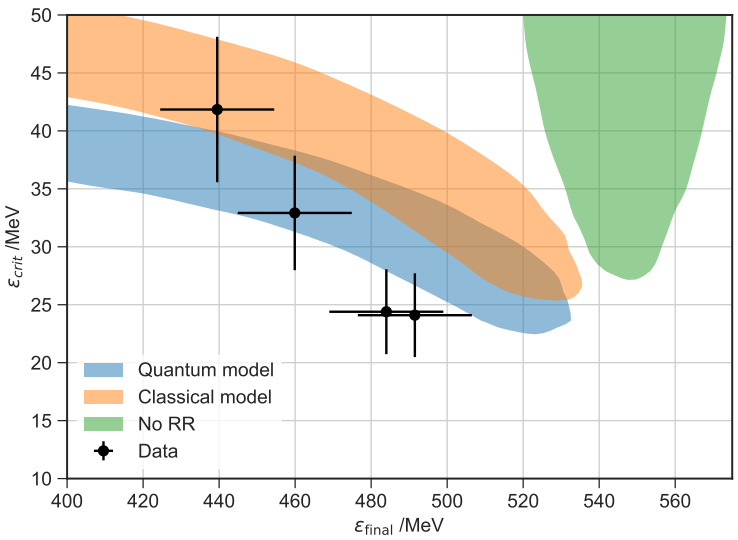
RR Experiment @ RAL-Gemini

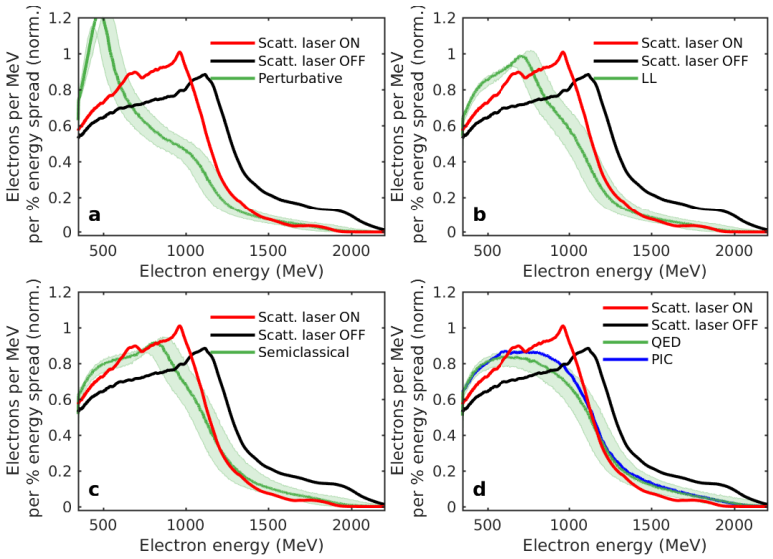


- No monochromatic electron beams, but characteristic *edge feature*
- γ-ray spectrum is synchrotron-like: Fit of critical energy
- Correlation between electron and γ signal

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

RR Experiment contd





- Experimental results incompatible with "No RR"
- Cannot yet decide on classical/quantum emission regime
- UMich's Hercules laser is getting upgrade to 500 TW

\+ New 3PW Zeus laser @ Michigan will enable additional experiments

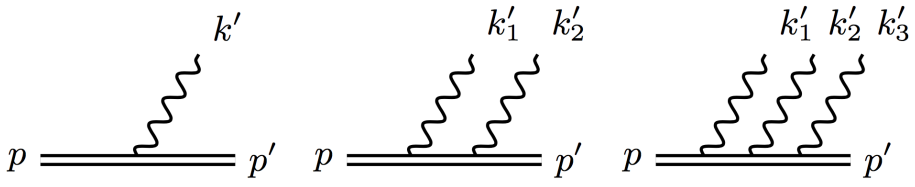
J. Cole et al, PRX **8**, 011020 (2018), Poder et al, PRX (2018)

Theory and Simulation: Non-linear Compton

- Quantum electrodynamics in strong background fields

$$L = \bar{\Psi}(i\partial\!\!\!/ - e\cancel{A} - m)\Psi - \frac{1}{4}F^2 - e\bar{\Psi}\gamma_\mu\Psi\mathcal{A}^\mu$$

- Each electron emits many photons



- Fully coherent quantum calculation impossible
- At high-intensity and for relativistic particle short formation length

  $\Rightarrow$ Locally constant crossed field approximation (LCFA)

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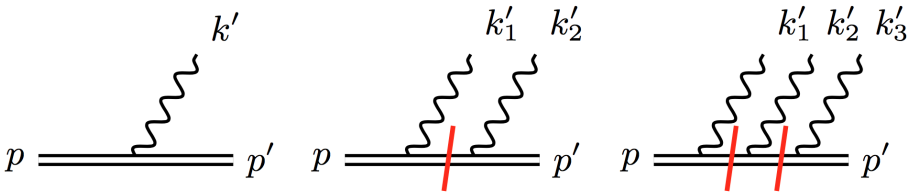

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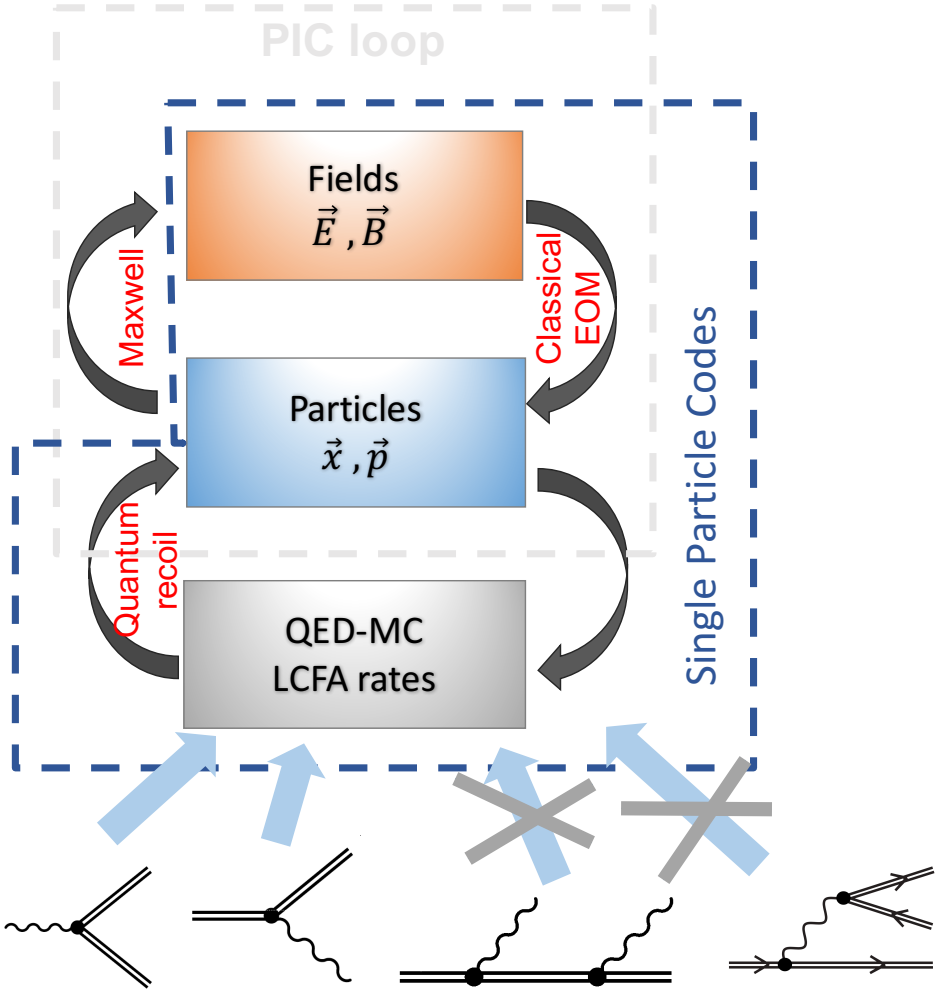
Modelling of RR Effects in Plasma Simulations



- Quantum emission rates in locally constant crossed field $d\mathbb{R}/dk$, emission directed along the electron velocity
- Classical propagation between emissions
- Quantum corrected EOM

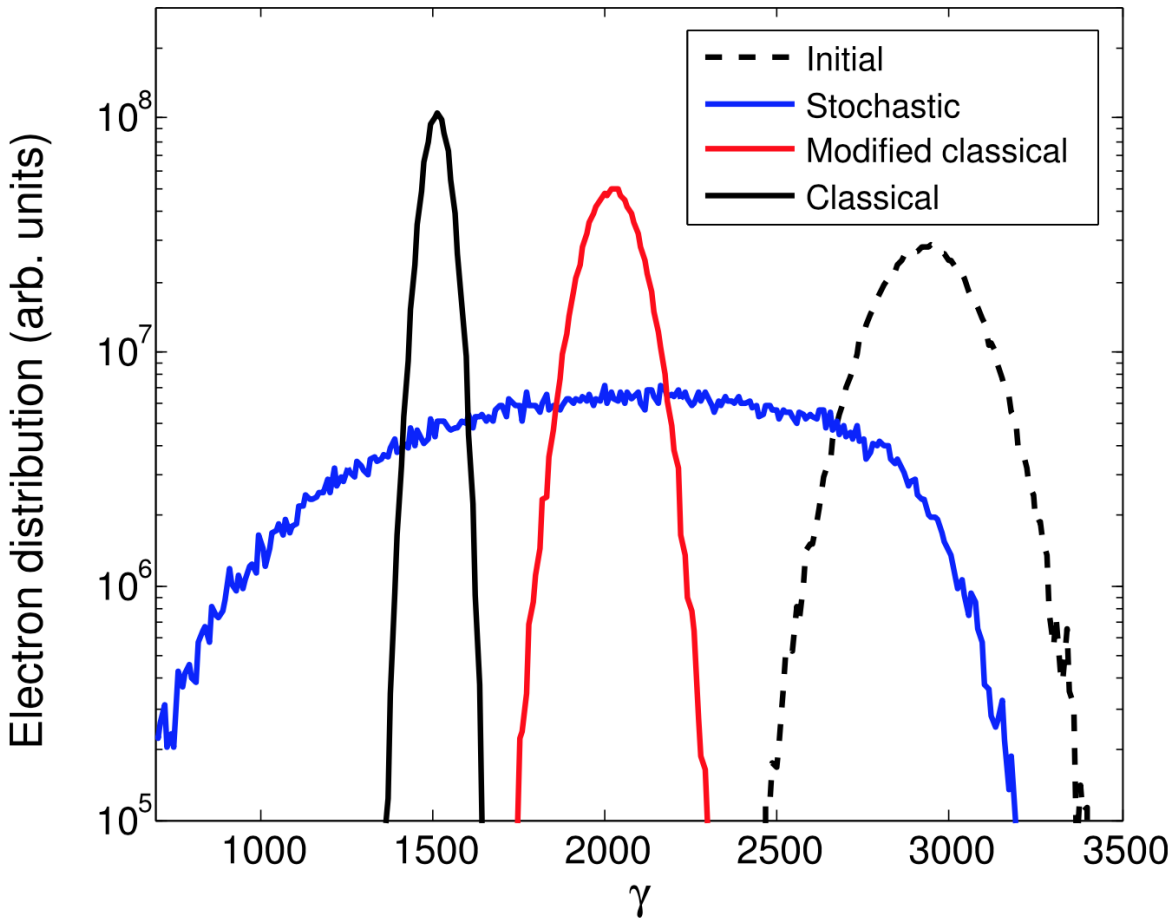
$$\frac{d\bar{\boldsymbol{p}}_{rad}}{dt} = -g(\chi)P_{class}\hat{\boldsymbol{p}}\,,$$

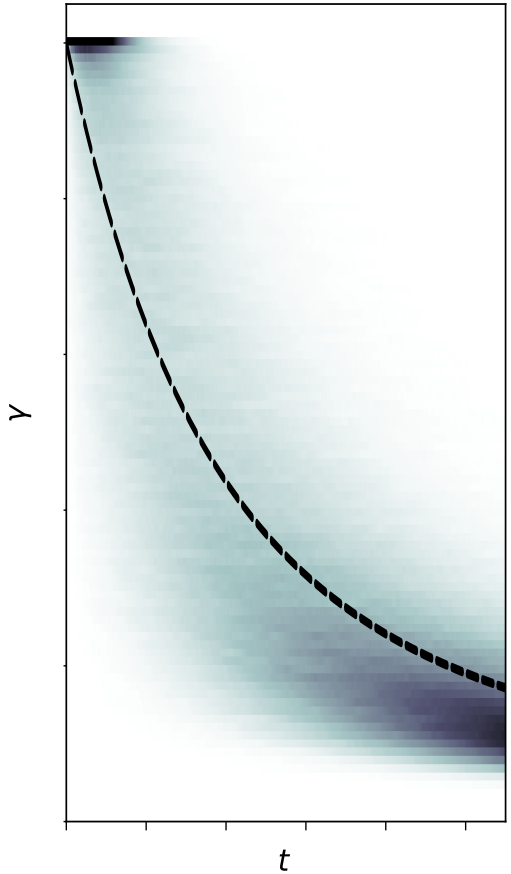
- Spreading of distribution

$$\frac{d\sigma^2}{dt} = \frac{\langle S\rangle}{m^2} - \frac{\Delta\gamma g(\chi)P_{class}}{m}$$

Ridgers [...] AGR Thomas, JPP 2017, ...

Classical vs. Quantum RR

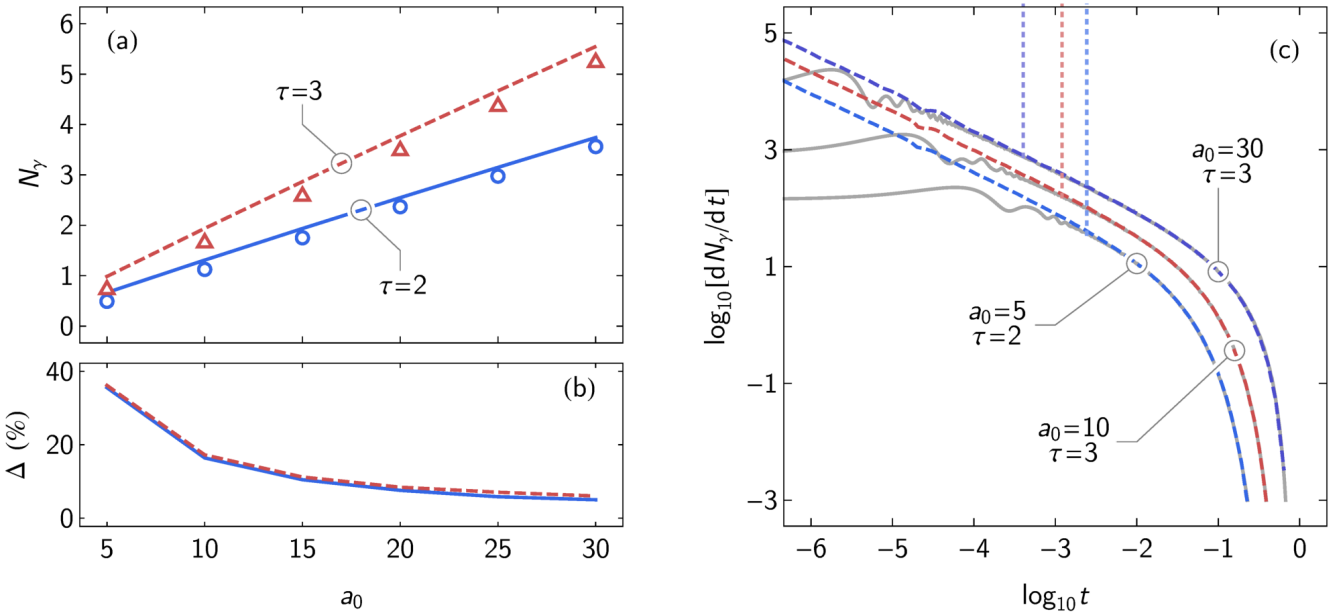




Ridgers [...] AGR Thomas, JPP 2017

Benchmarking of MC-LCFA vs. Full QED

- How good are the LCFA rates for finite $a_0 \sim 5...10$?

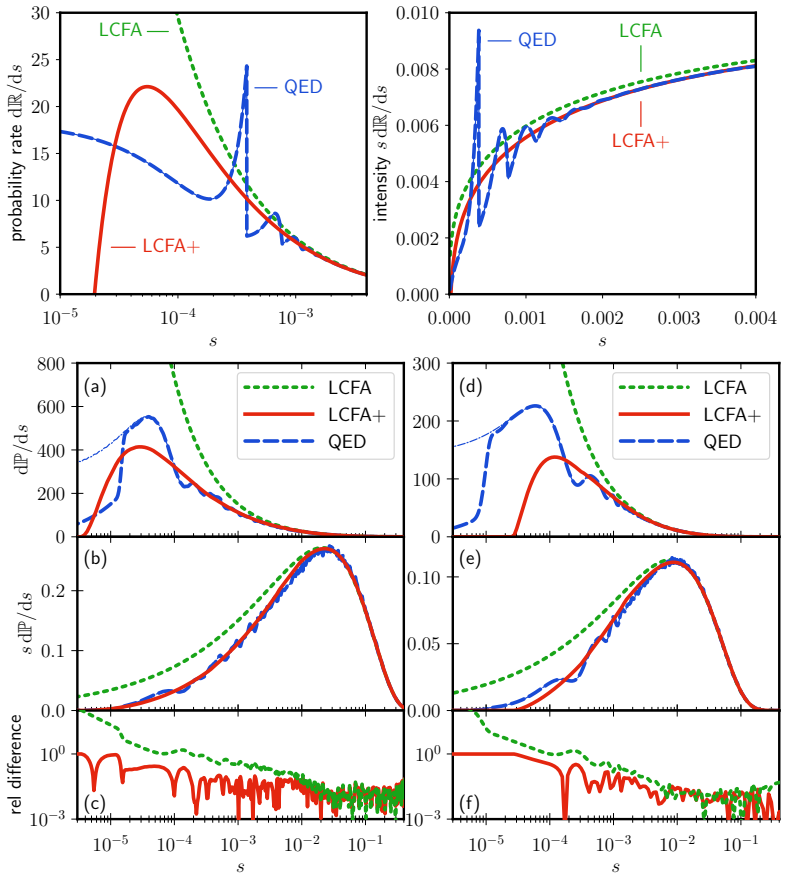


1. Strong-field QED calculation of the NLC spectra
2. Monte-Carlo simulation using LCFA rates with post-selection of single-emission orbits

T. Blackburn, D. Seipt et al, Phys. Plas. **25**, 083108 (2018).

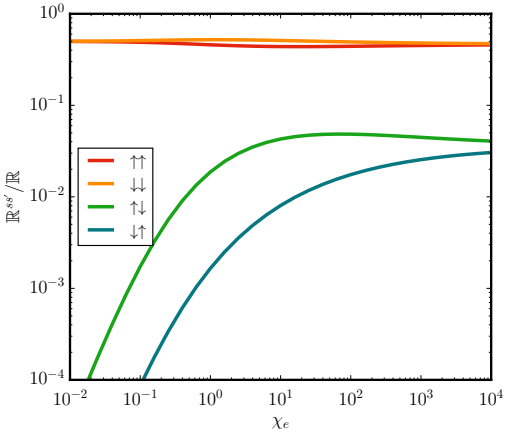
Improved LCFA Rates

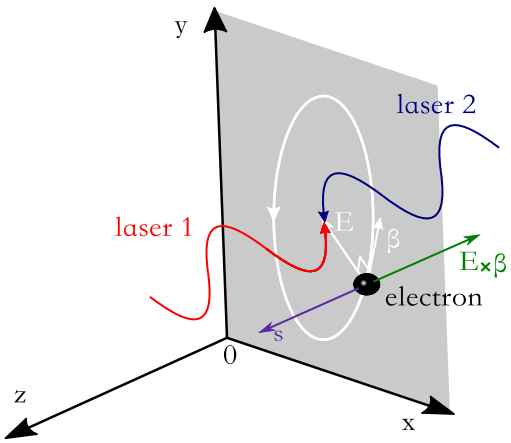
- LCFA is the leading asymptotic approximation for $a_0 \gg 1$, can we do better?
- Yes! Calculate next-to-leading term: Corrections $\propto 1/a_0^2$ due to field gradients.
- Problems at low energies and low intensities, which can been cured.
- Excellent agreement with QED even for $a_0 = 2$

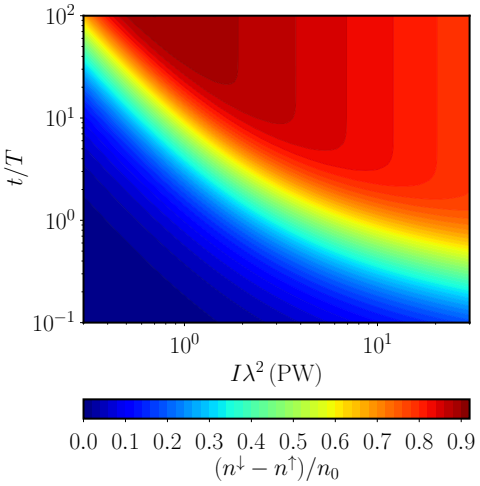


Ilderton, King, Seipt, PRA 2019

Radiative Spin-Polarization







Del Sorbo PRA 2017, PPCF 2018

- Radiative spin-polarization because spin-flip rates $\mathbb{R}^{\uparrow\downarrow} > \mathbb{R}^{\downarrow\uparrow}$
- Sokolov-Ternov effect

Sokolov & Ternov, "Synchrotron Radiation"

- Well known from storage rings ($\chi \ll 1$) ...
- ... occurs on femtosecond time-scales with PW lasers ($\chi \sim 1$)

Spin-Polarization in PW–Laser Plasma Interactions

1. Laser wakefield accelerators for lepton–lepton colliders
   - ⊗ HEP collider experiments need highly polarized beams

   Moortgat-Pick, Phys. Reports 2008

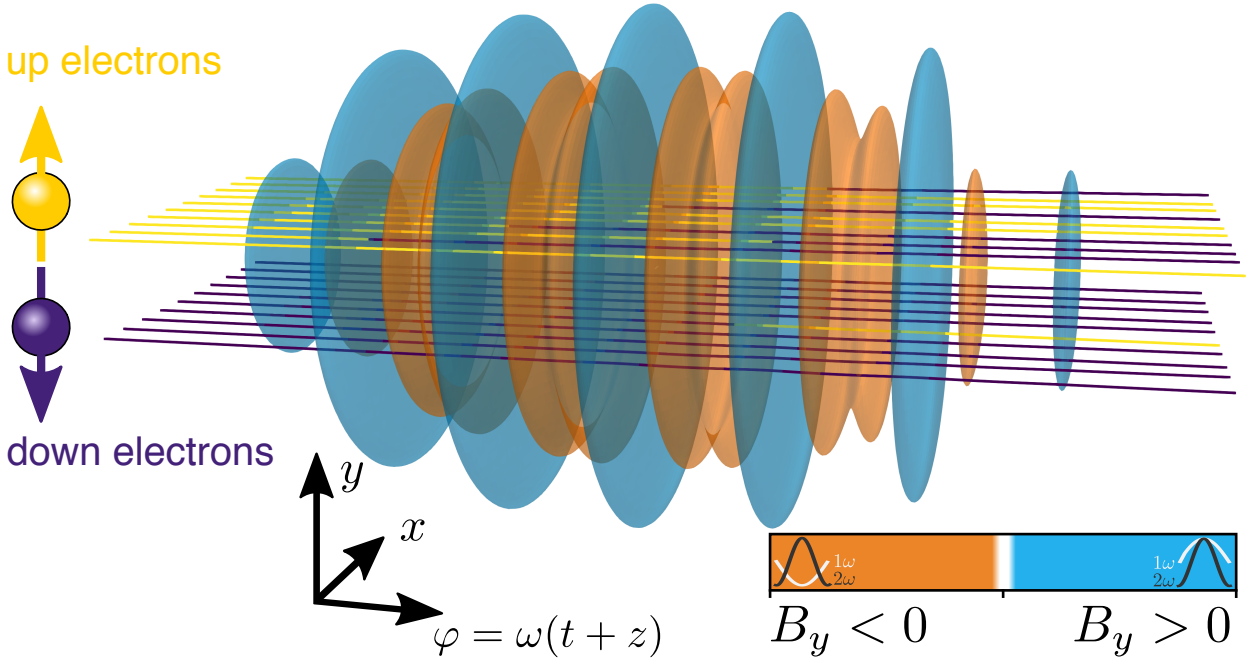
2. Studies of quantum radiation reaction
   - ⊗ Radiation emission spin-polarizes electrons
   - ⊗ Radiative losses are polarization-dependent

   Cole PRX 2018, Poder PRX 2018

3. Radiation and QED dominated collective plasma dynamics
   - ⊗ Extreme intensities, absorption, cascades, rad. trapping, ...

   Bell & Kirk PRL 2008, Fedotov PRL 2010, Esirkepov PRA 2015, Magnusson 2018, Yakimenko PRL 2019, ..., ...

Polarizing Electrons w/ Bi-Chromatic Laser Pulses



- Oscillating field: Spin polarization averages to zero
- 1ω–2ω add constructively: larger $\chi \Rightarrow$ more spin flips when $\downarrow \equiv -\boldsymbol{e}_y$
- **8 GeV electrons collide with 1 PW laser: $\sim$ 10 % polarization**

Seipt et al arXiv:1904.12037, PRA accepted

Summary

- Radiation dominated particle and plasma dynamics at high intensity
- Experiments for distinguishing quantum and classical regimes of radiation reaction possible with present day high-power lasers
- Narrowband Inverse Compton γ-ray sources by optimized chirped laser pulse to overcome ponderomotive broadening limit
- Radiative polariztion of electron beams

Thanks for Listening!