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Strong Field QED Effects in Lasers-Matter Interactions

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IDEAS

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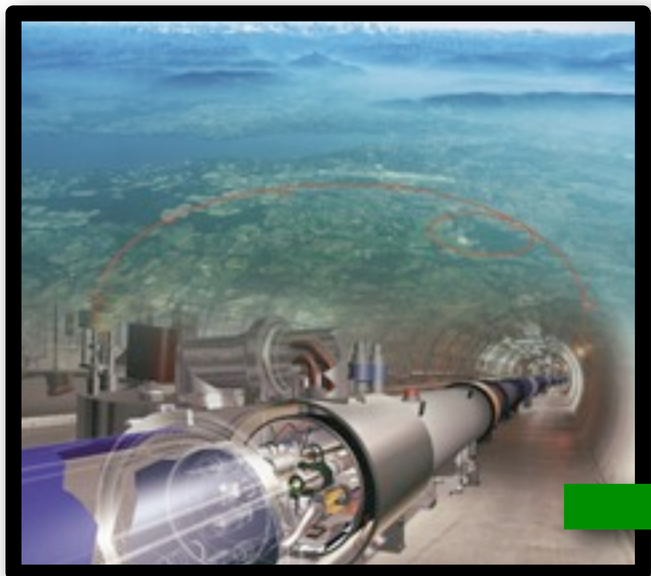
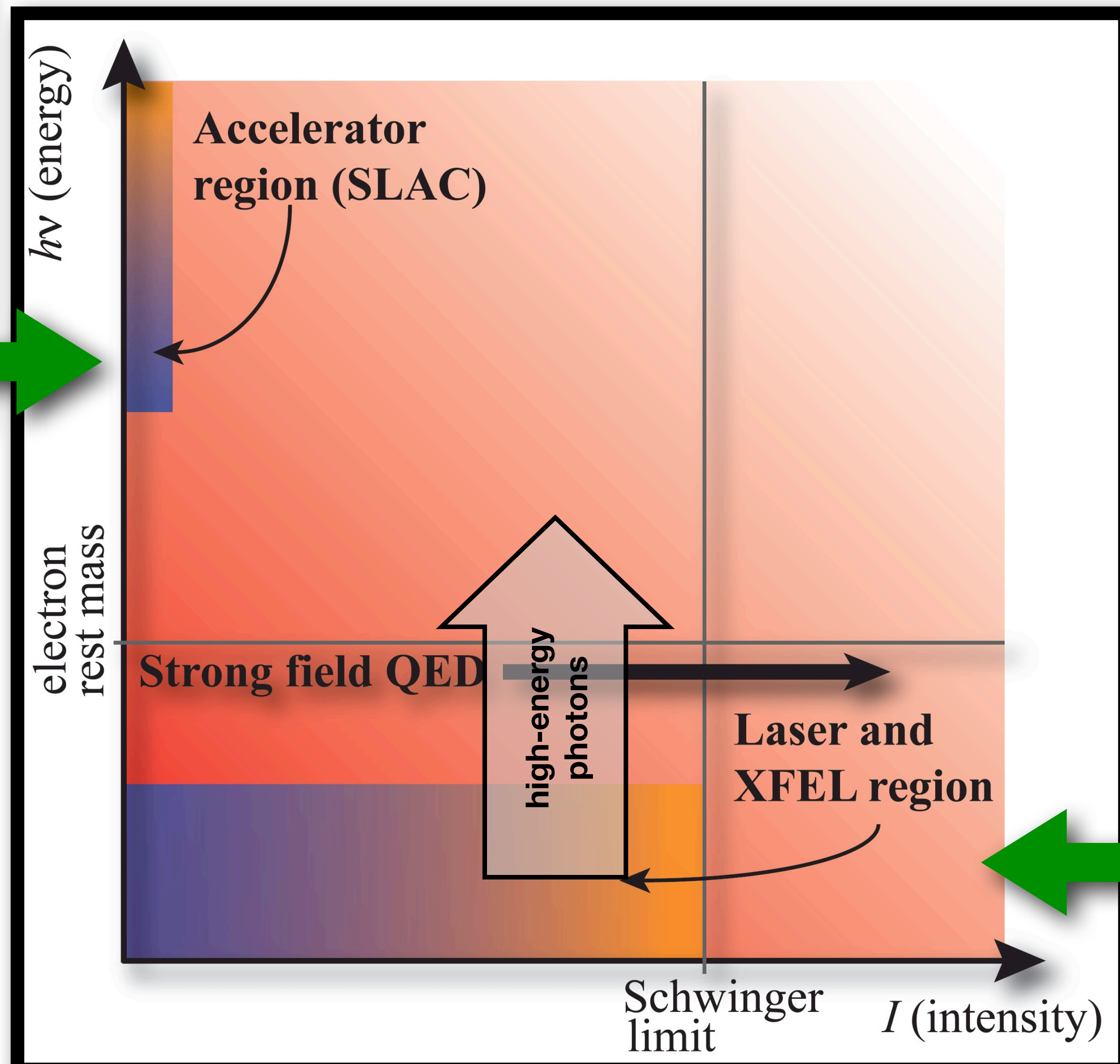
Swedish Research Council

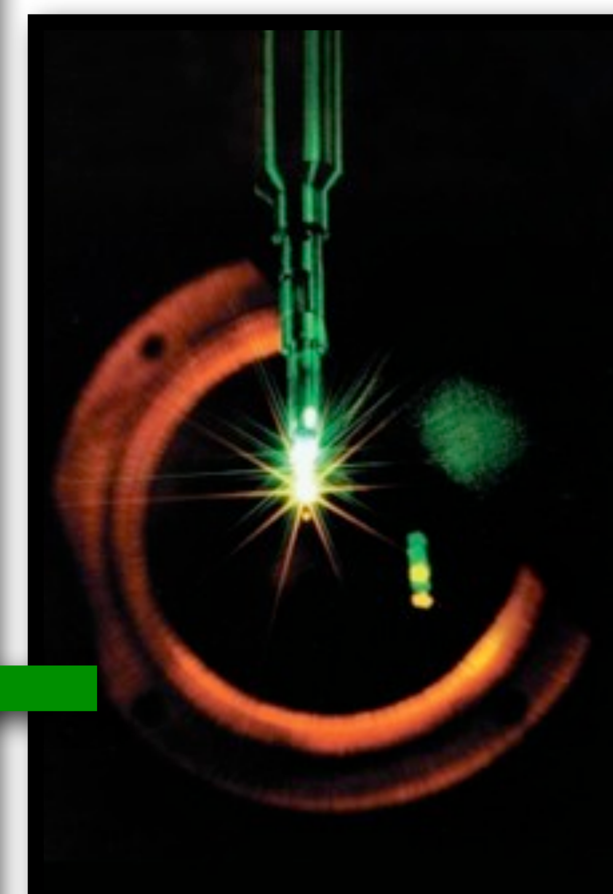
Work done with **A. Ilderton, C. Harvey, A. Gonoskov, A. Korzhimanov, L.O. Silva, T. Grismayer, I. Gonoskov, G. Brodin, A. Kim, A. Sergeev**

FILMITh 2012, MPQ@Garching, 2012-09-21

Background: opportunities with high-power lasers



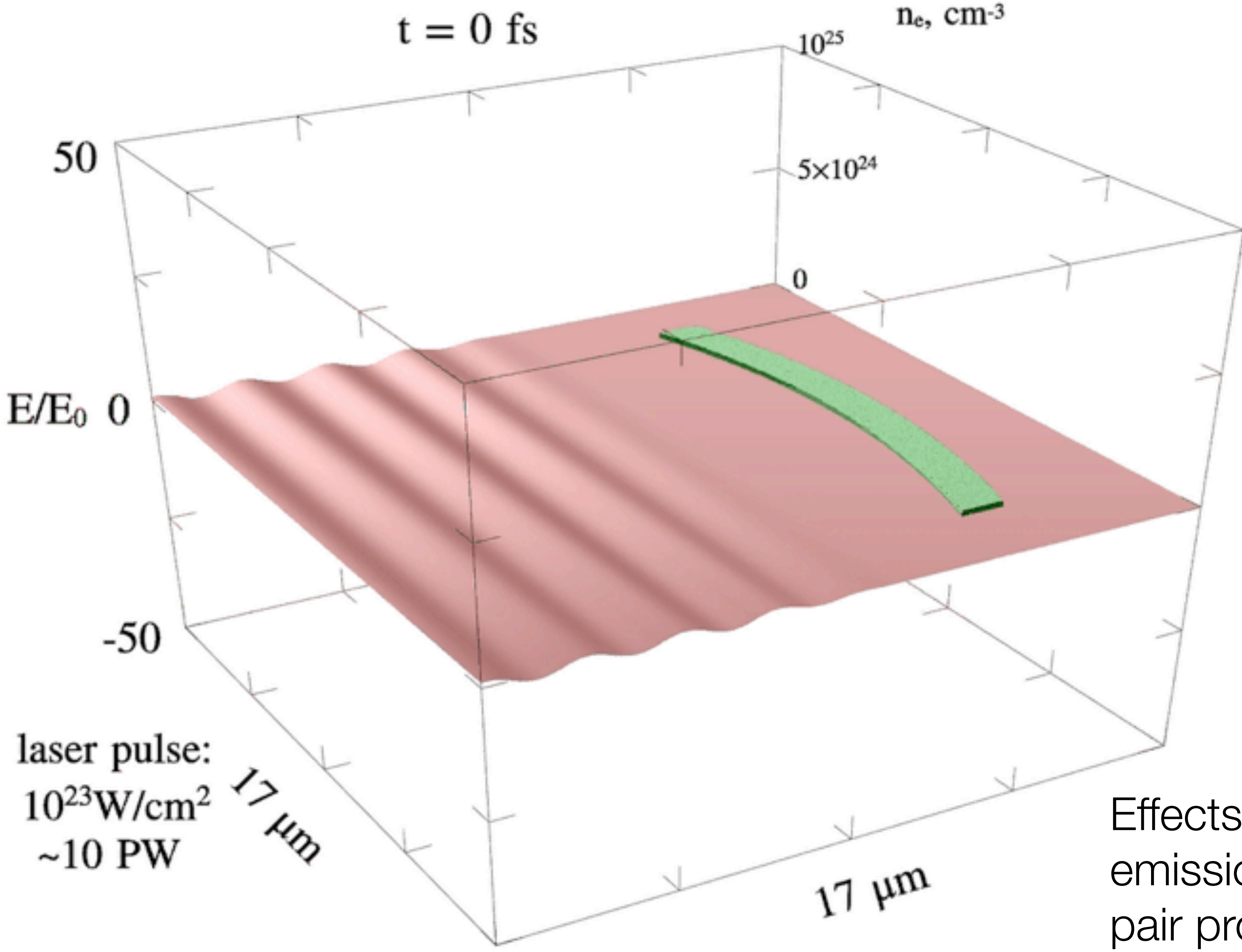


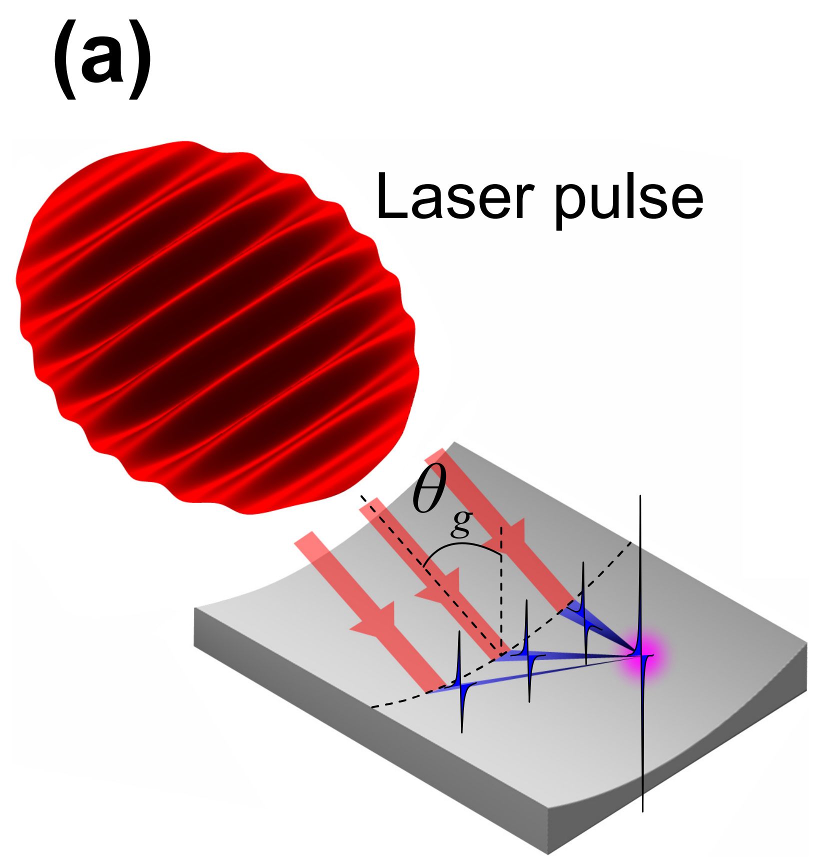


Gies, Europhys. J. D **55** (2009); Marklund & Lundin, Europhys. J. D **55** (2009)

Strong field generation

Some recent simulations on attosecond pulse generation and amplification (Gonoskov et al. 2011)





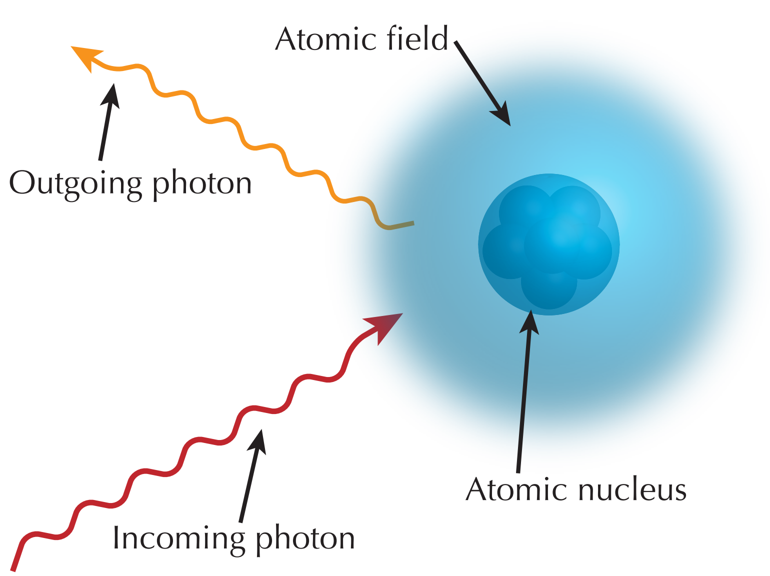
Effects of radiation reaction, gamma-emission, superthermal electrons, pair production... ?

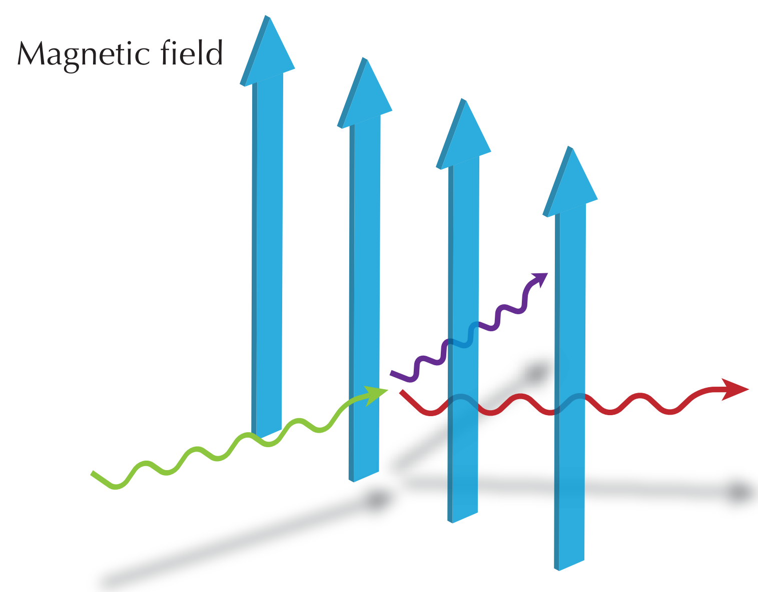
Addendum: strong magnetic field generation

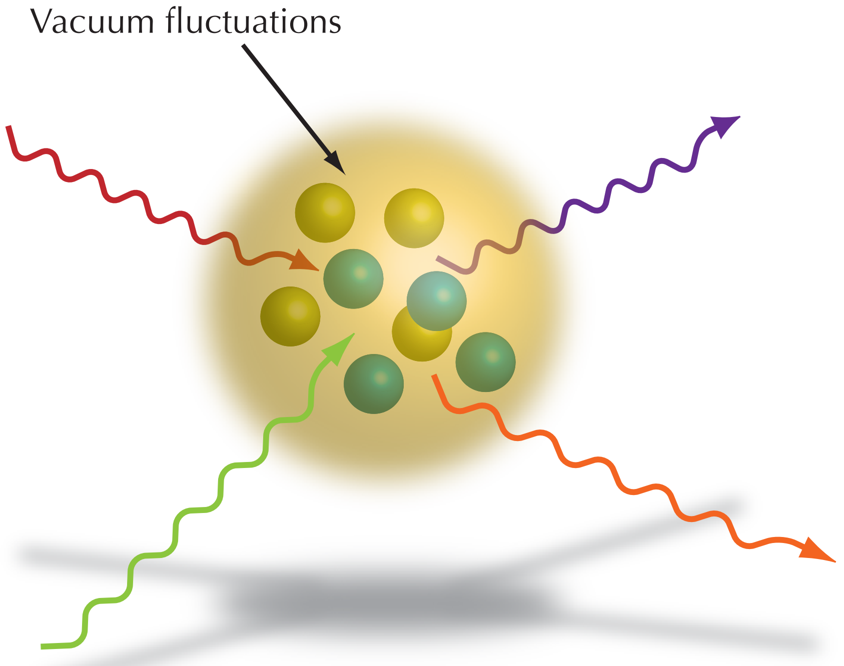
- Laboratory fields from a few tesla to 10^3 tesla, depending on time scaleex. Relatively large scale.
- Relativistic laser-plasma interactions can create fields of the order gigagauss, on micrometer scales, stationary on pikosecond scales. Relative laser pulse of femtosecond, this is a long time.
- Heavy ion collisions, RHIC, produce chiral fields, 10^{17} gauss. However, (probably) on QCD scales, both in time and space.
- Strong fields for lab astrophysics, search for WIMPs, and wakefield acceleration.

The nonlinear quantum vacuum

- Special relativity + Heisenberg's uncertainty relation = virtual pair fluctuations.
- Antimatter from Dirac's relativistics quantum mechanics.
- Properly described by QED.
- Photons can effectively interact via fluctuating electron-positron pairs.



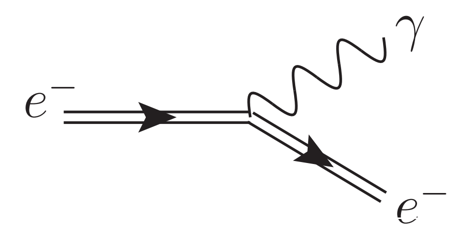




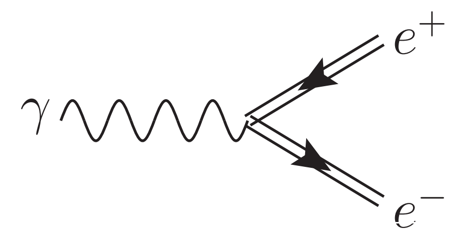
Marklund & Shukla, Rev. Mod. Phys. **78** (2006)**;** Marklund, Nature Phot. 4 (2010)

Multi-photon processes in intense fields

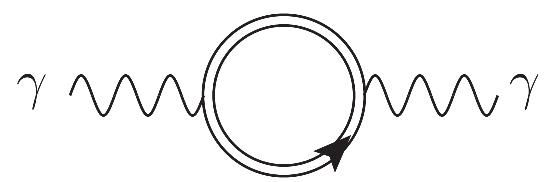
- Nonlinear Compton scattering



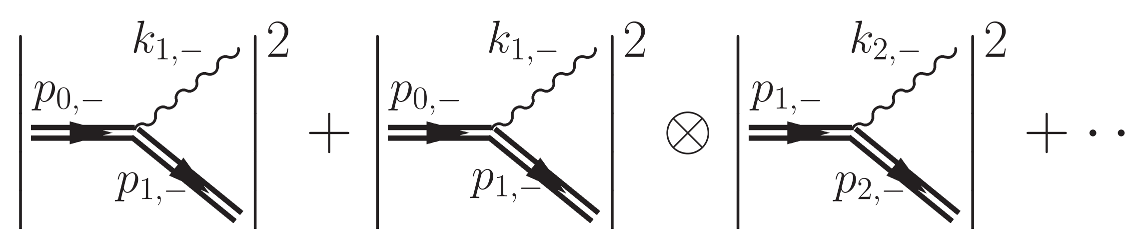
- Stimulated pair production



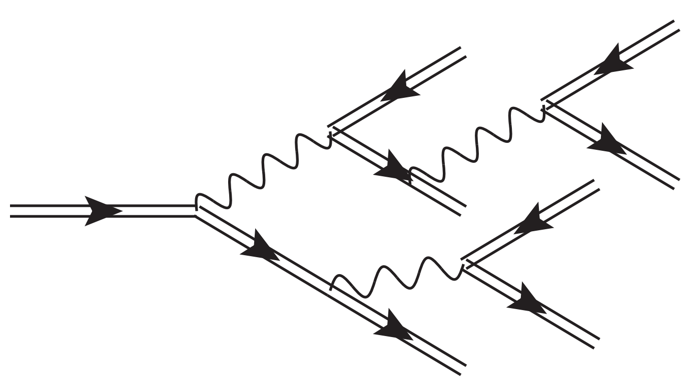
- Birefringence



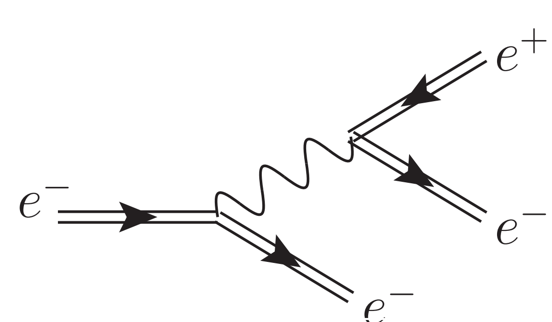
- Radiation reaction (Di Piazza et al. 2011)



- Cascading



- Trident



The Heisenberg-Euler Lagrangian

- Describes the vacuum fluctuations as an effective field theory, fermionic degrees of freedom integrated out.

$$L = -\frac{\alpha}{2\pi}\epsilon_0 E_{\rm crit}^2 \int_0^{i\infty} \frac{dz}{z^3} e^{-z} \times \left[z^2 \frac{ab}{E_{\rm crit}^2} \coth\left(\frac{a}{E_{\rm crit}} z\right) \cot\left(\frac{b}{E_{\rm crit}} z\right) - \frac{z^2}{3}\frac{(a^2-b^2)}{E_{\rm crit}^2} - 1 \right]$$

$$a = \left[(F^2+G^2)^{1/2} + F \right]^{1/2}, \; b = \left[(F^2+G^2)^{1/2} - F \right]^{1/2}$$

$$F \equiv \tfrac{1}{2}(c^2\mathbf{B}^2 - \mathbf{E}^2), \; G \equiv -c\mathbf{E}\cdot\mathbf{B}$$

- Has real and imaginary part. The imaginary part signals depletion, i.e. pair production, the real part defines elastic photon scattering events.

- Can compute equations of motion for test photons in both sub- and super-critical fields.

Effective Maxwell's equations

$$\partial_a F^{ab} = 2\epsilon_0 \kappa \partial_a \left[(F_{cd}F^{cd})F^{ab} + \tfrac{7}{4}(F_{cd}\widehat{F}^{cd})\widehat{F}^{ab} \right]$$

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = -\mu_0 \left[\frac{\partial^2 \mathbf{P}}{\partial t^2} + c^2 \nabla(\nabla \cdot \mathbf{P}) + \frac{\partial}{\partial t}(\nabla \times \mathbf{M}) \right]$$

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = \mu_0 \left[\nabla \times (\nabla \times \mathbf{M}) + \frac{\partial}{\partial t}(\nabla \times \mathbf{P}) \right]$$

$$\mathbf{P} = 2\kappa\epsilon_0^2 \left[2(E^2 - c^2 B^2)\mathbf{E} + 7c^2(\mathbf{E}\cdot\mathbf{B})\mathbf{B} \right]$$

$$\mathbf{M} = 2\kappa\epsilon_0^2 c^2 \left[-2(E^2 - c^2 B^2)\mathbf{B} + 7(\mathbf{E}\cdot\mathbf{B})\mathbf{E} \right]$$

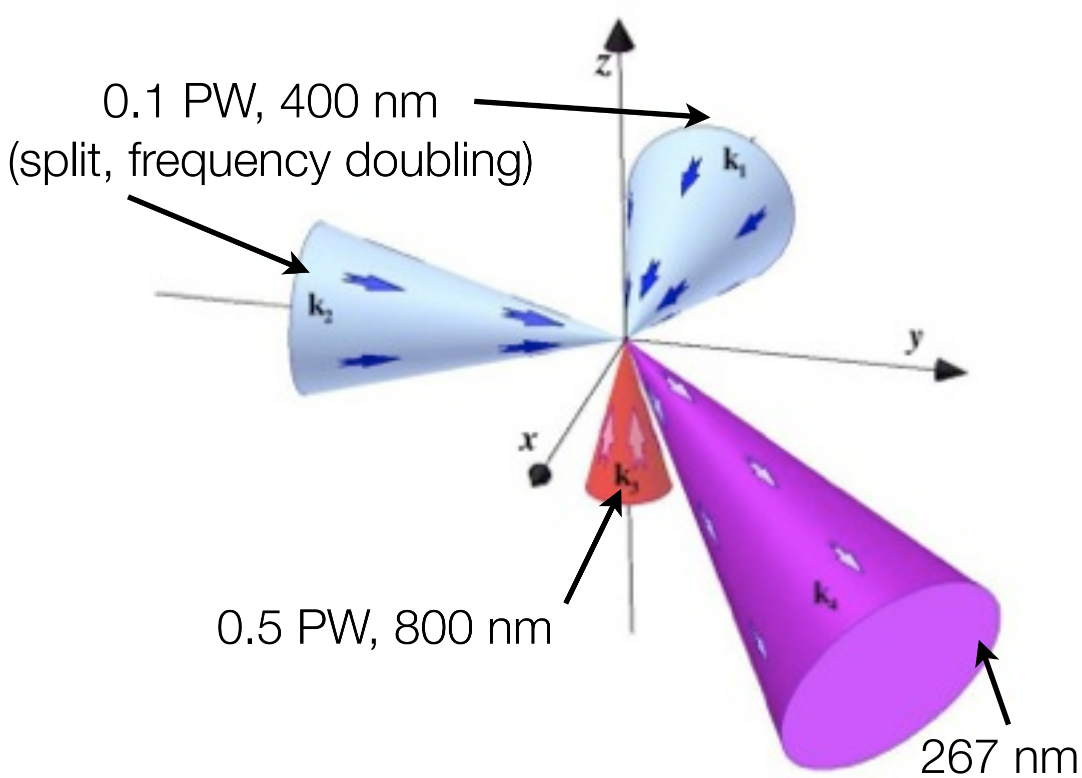
Bialynicka–Birula & Bialynicki–Birula (1970)

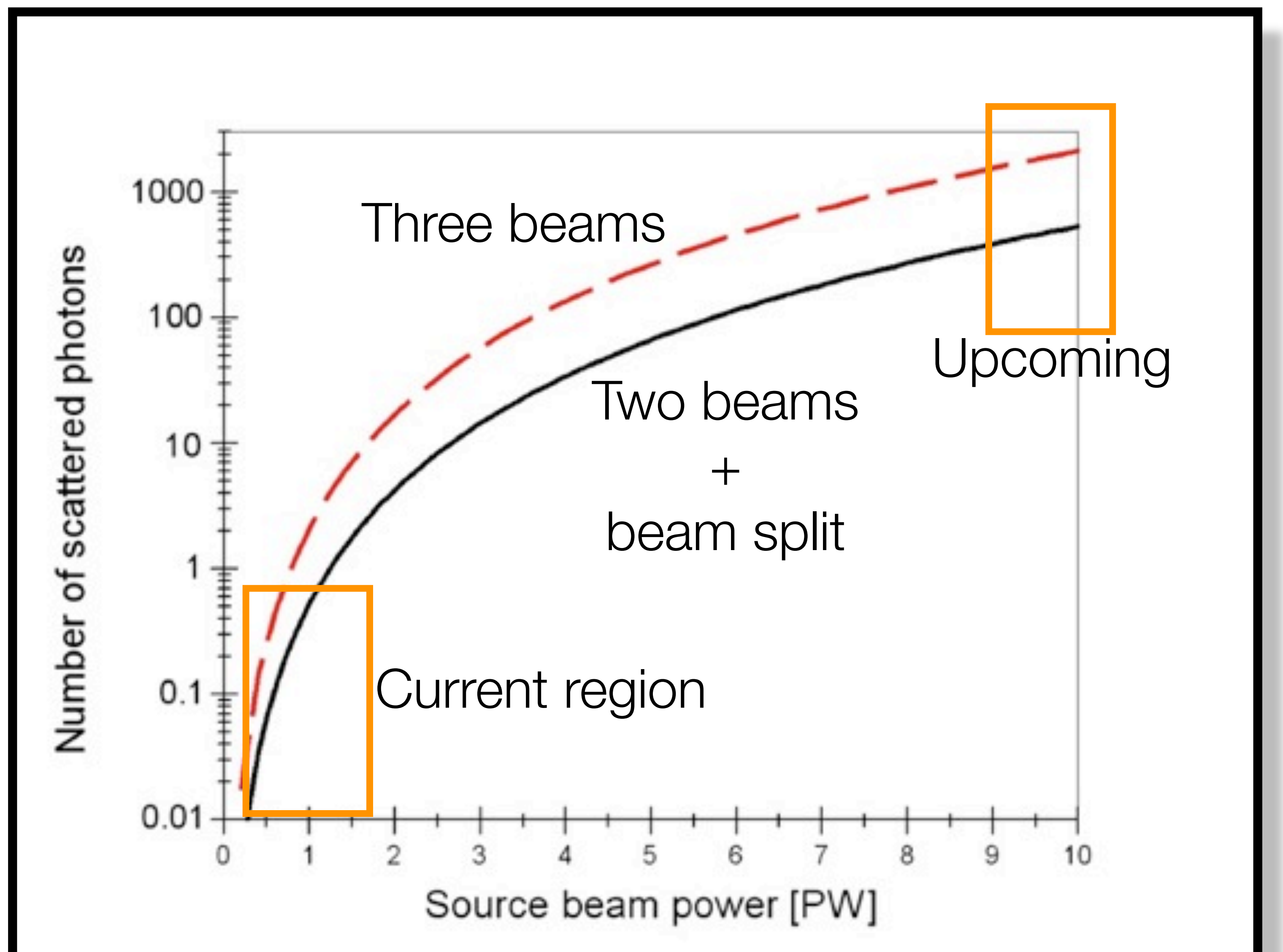
The nonlinear quantum vacuum: photon-photon scattering

- Number of generated photons as a function of beam power.

$$N \approx G \times 10^{-2} \left(\frac{1\,\mu\mathrm{m}}{\lambda_4}\right)^3 \left(\frac{L}{1\,\mu\mathrm{m}}\right) \left(\frac{P_1 P_2 P_3}{1\,\mathrm{PW}^3}\right)$$

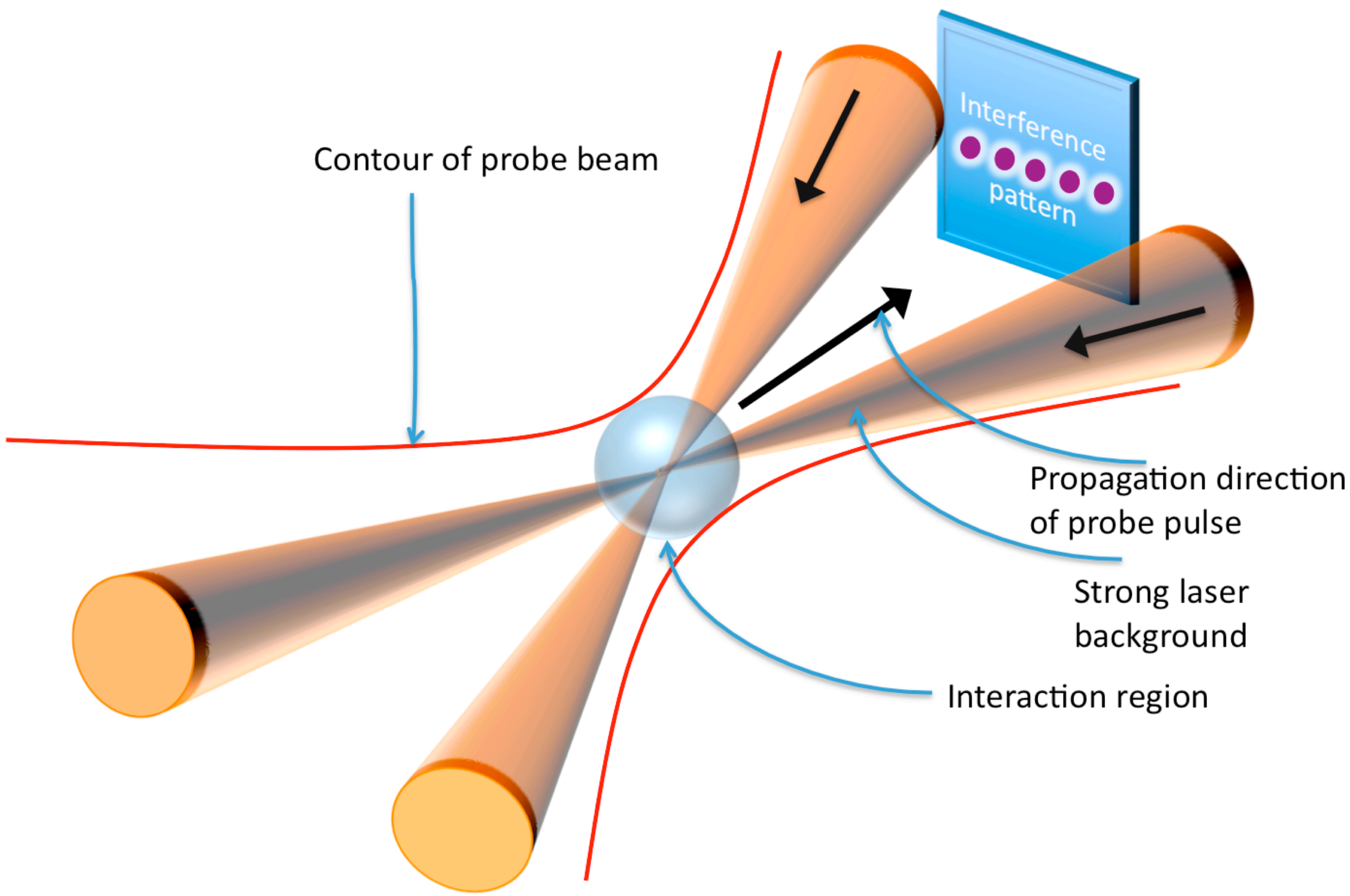
Form factor depending on pulse shape etc. Of order unity





The nonlinear quantum vacuum: photon-photon scattering

- Virtual slit experiments (King et al., Nature Phot. **4** (2010); NJP, (2012))
- Interference pattern, like in double slit experiment.



Pulse collapse?

- Single or colliding pulses, criteria for collapse through nonlinear refractive index

$$4\pi^2 I_{\text{init}} \Delta_{\text{init}}^2 / \lambda^2 > I_{\text{crit}}$$

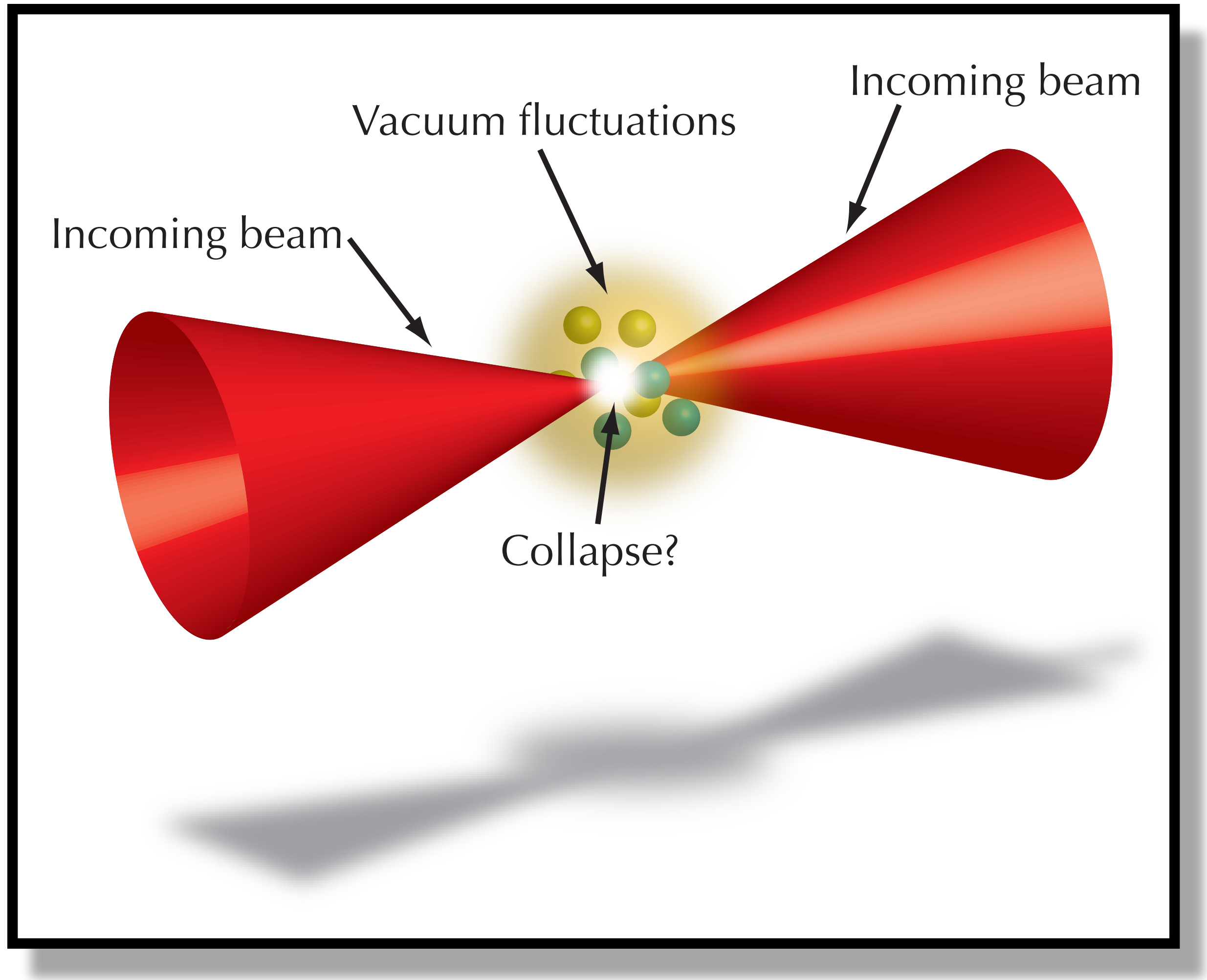
- Diffraction limit: $\Delta_{\text{init}} \sim \lambda$

- For intensities two orders of magnitude below Schwinger intensity

$$I_{\text{init}} \sim 10^{27}\,\text{W/cm}^2$$

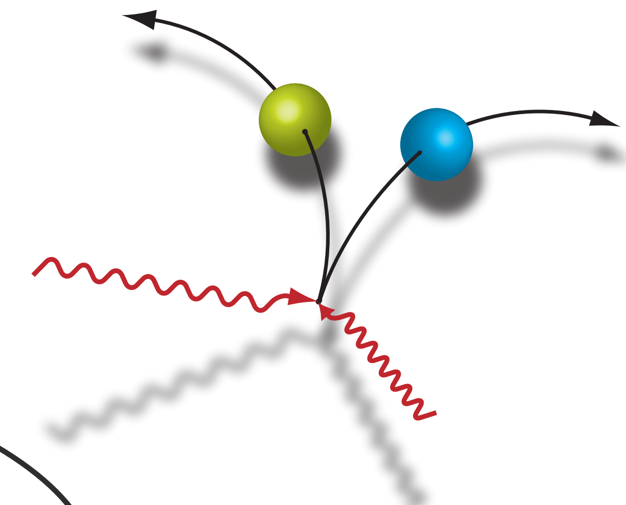
$$P \sim 10\,\text{EW}\ \ (\text{for micron spotsize})$$

- Prefactor changed by field geometry!



Brodin et al., PLA (2003)

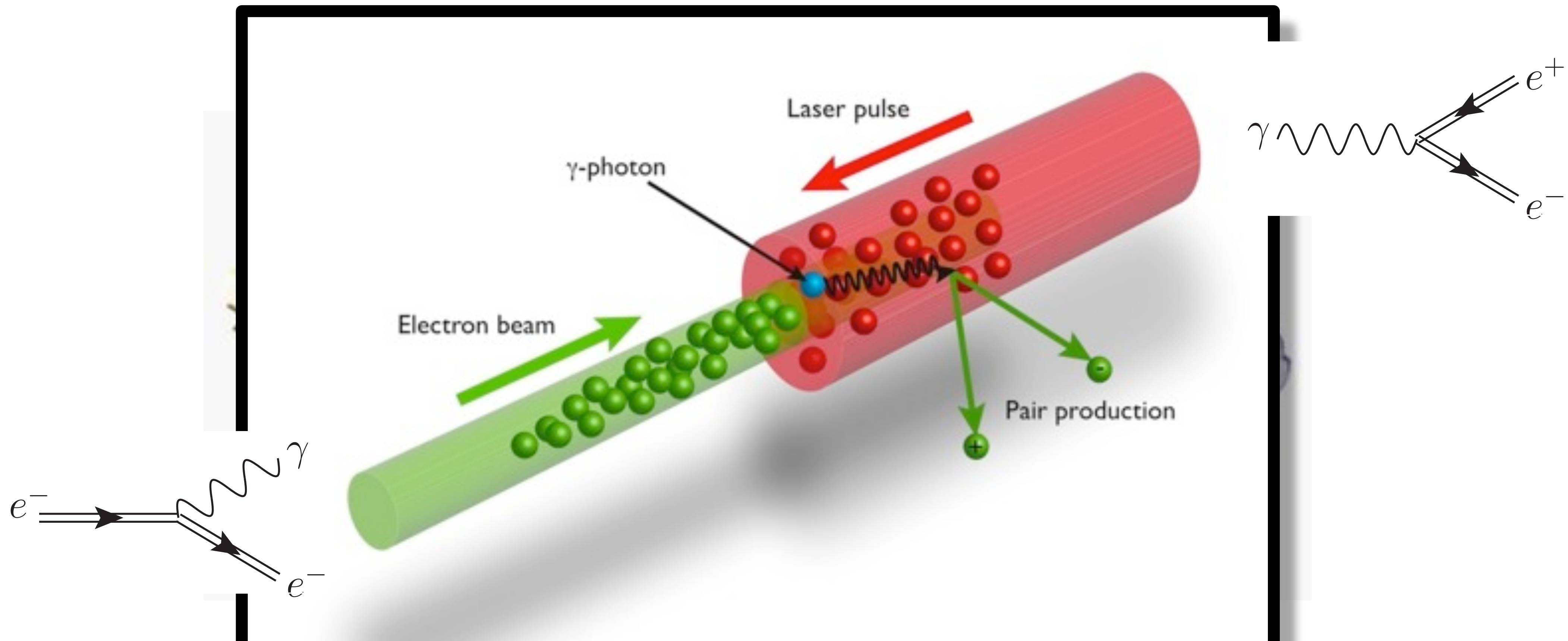
Pair production: trident process and cascading



- Trident: intermediate photon virtual (Ritus (1972); Ilderton, PRL (2010))
- Cascade: intermediate photon = real bremsstrahlung photon (Klepikov (1964); Nikishov & Ritus (1964); Elkina et al. (2011))

Pair production: stimulated process

- The SLAC experiment (see also Bula et al., 1996 and Bamber et al., Phys. Rev. D (1999)). Also all-optical.



Burke et al., PRL **79**, 1626 (1997)

Nonlinear Compton scattering

$$e + n\omega \to e' + \gamma$$

Multi-photon Breit-Wheeler scattering

$$\gamma + n\omega \to e^+ + e^-$$

Radiation reaction/friction

- Classical radiation reaction described using Lorentz-Abraham-Dirac (LAD) theory (supplemented by asymptotic conditions)

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

- or the perturbative expansion 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 $(a_0 = eE/\omega mc)$

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

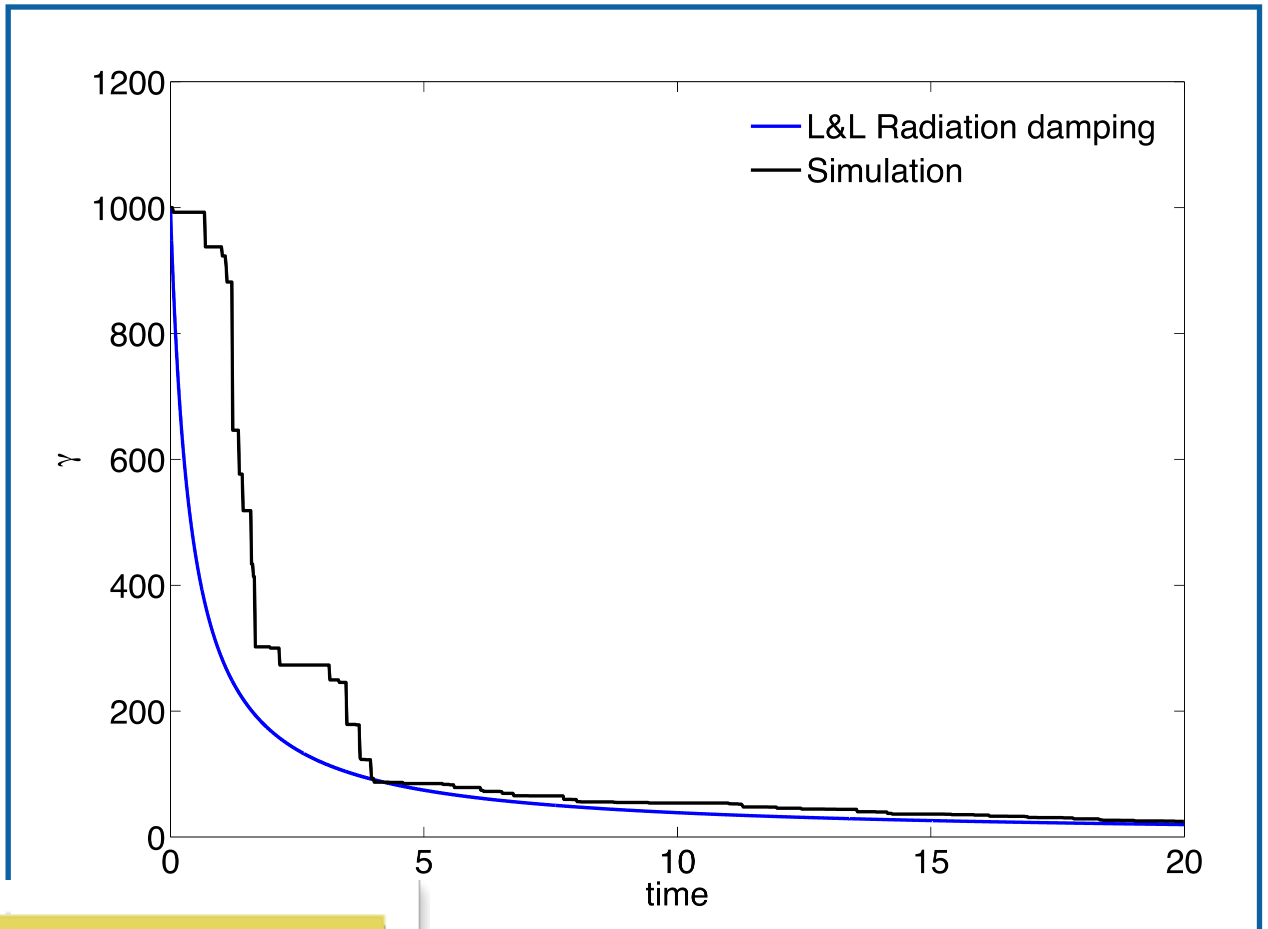
- QED regime (i.e. next generation regime) when

$$\chi \sim 1$$

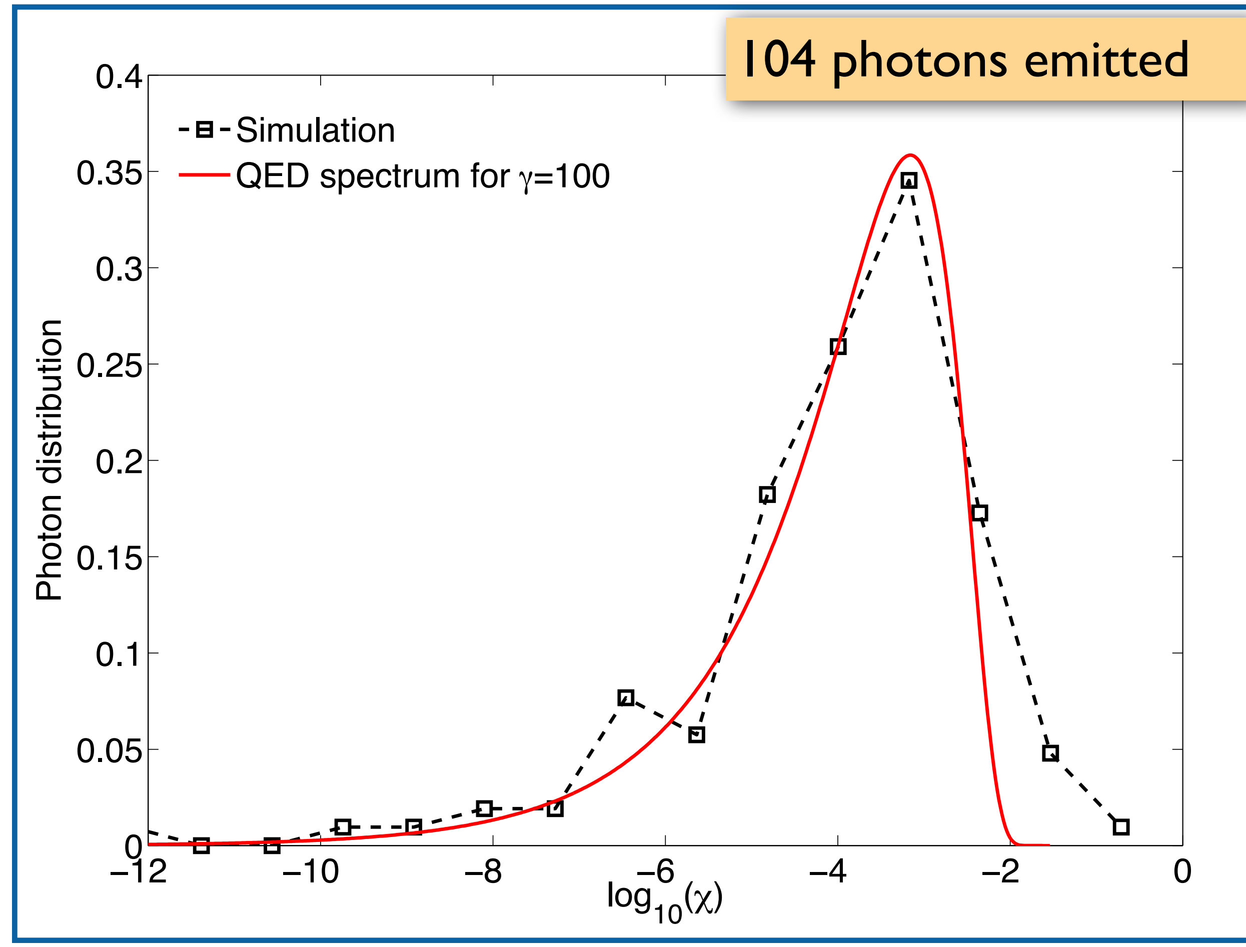
or when the momentum kick is of the order of the mass of the electron...

Synchrotron Radiation Reaction for η = 1

Energy loss



Photon Spectrum



104 photons emitted

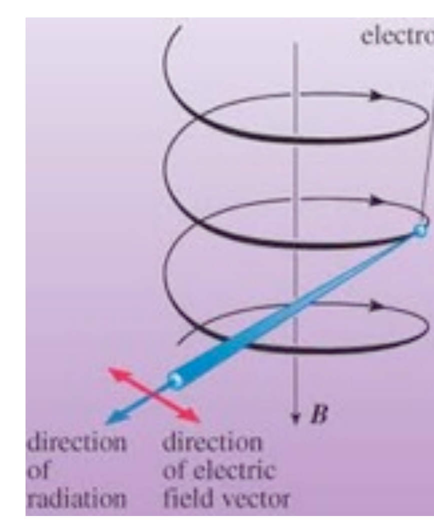
$\gamma = 1000$

$B/B_{crit} = 10^{-3}$

$$\eta = \frac{\gamma B}{B_{crit}}$$

$$\chi = \frac{\hbar k}{mc}\frac{B}{B_{crit}}$$

- **The L&L model breaks down for η ~ 1**
- **The concept of continuous trajectory becomes dubious due to the emission of high energy photons**
- **The final energy remains close in both models**

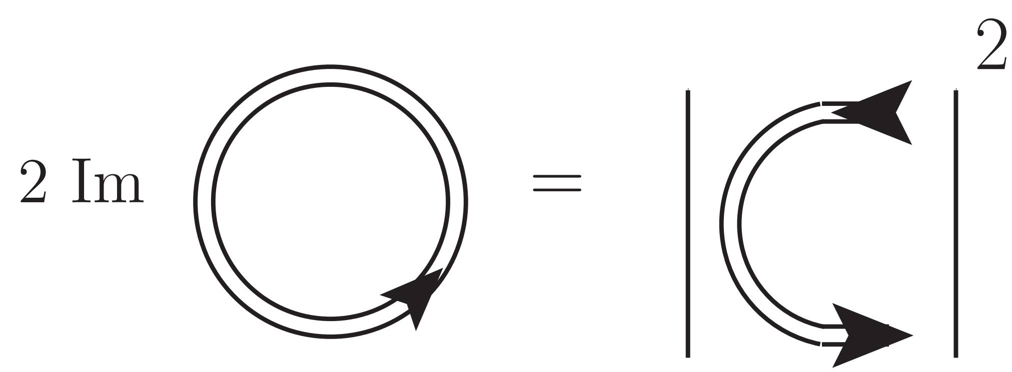


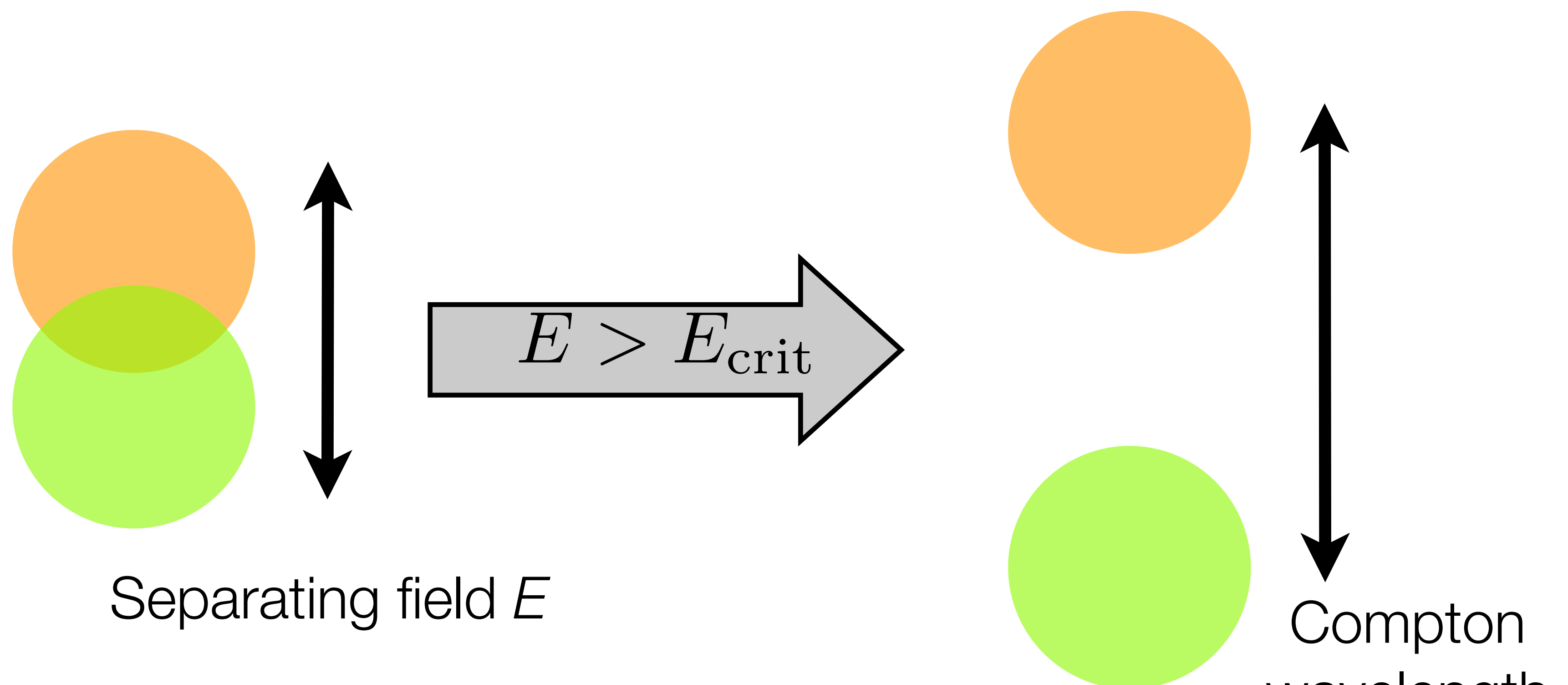
Pair production: radiation reaction

- Interest in cascading and pair production; leads to electron capture and greatly extended interaction time (Harvey & MM, 2011).
- Previously looked at in astrophysical settings (magnetosphere problems).
- Different results in the literature.
- Different intensity values for significant cascading to take place.
- Important implication: could put constraints on achievable intensities.
- Q1: when is a classical treatment possible? (*the transition problem*)
- Q2: when in a relativistic quantum regime, how to treat transitions? (*the dressing-up problem*)
- Q3: when is the division of the pairs into separate e^+ and e^- valid? (*the asymptotic problem*)

Schwinger-Sauter mechanism

- Non-perturbative effect.



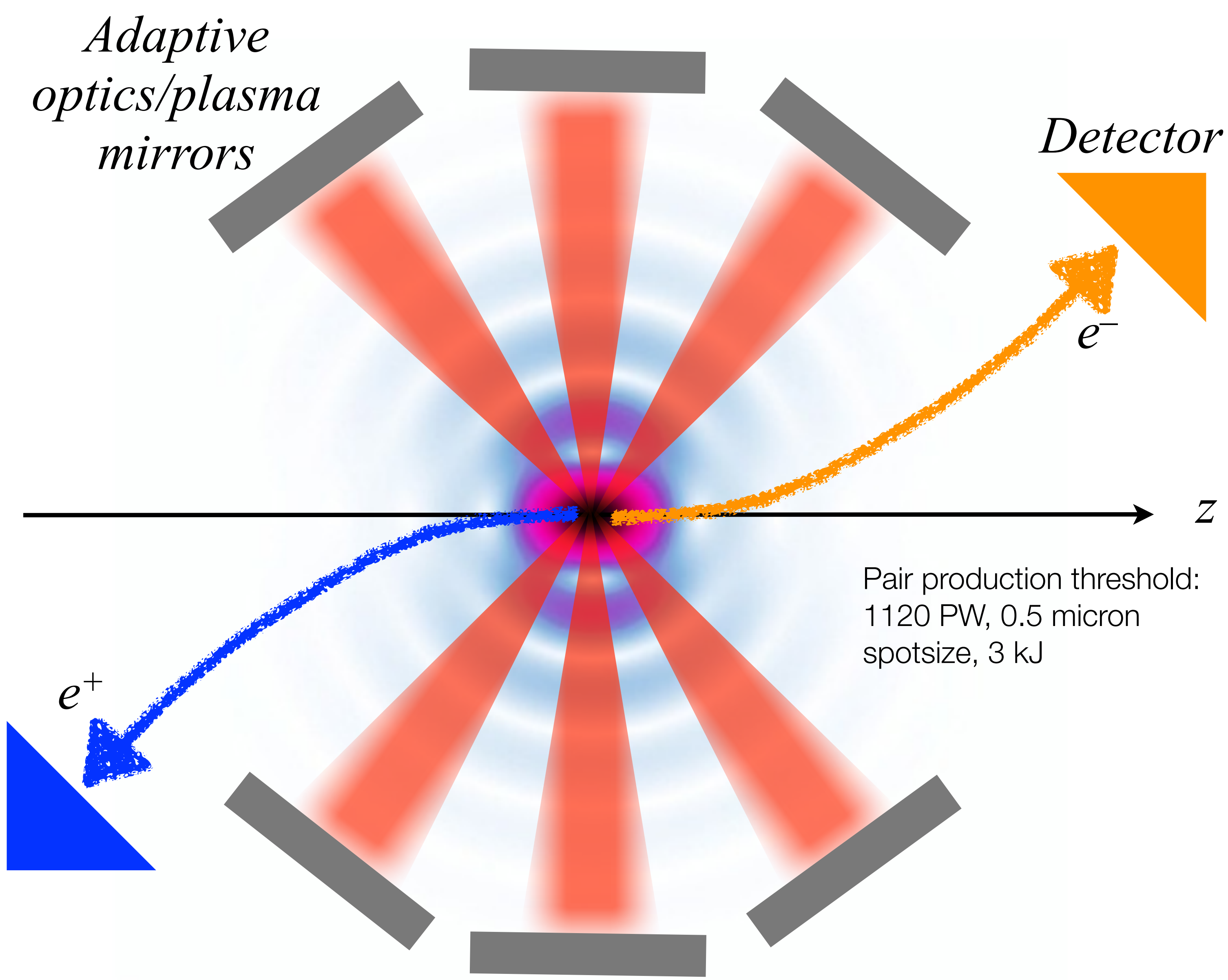


- For general field, we expect pair creation for invariant (crossed field)

$$E^2 - B^2 > E_{\mathrm{crit}}^2$$

- Fight supression by multiple beams/geometry (Bulanov, Narozhny)

Optimizing focusing and pair production



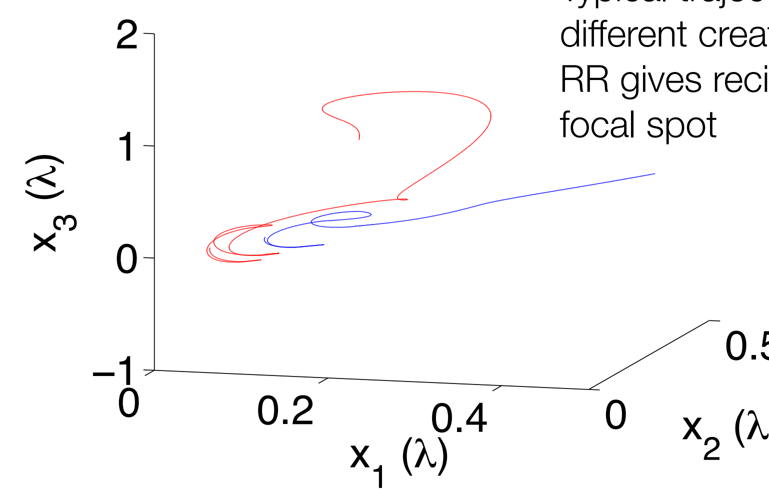
Gonoskov et al., *Maximizing the field amplitude*...to appear (2012). Gonoskov, Harvey, Ilderton, MM, submitted (2012)

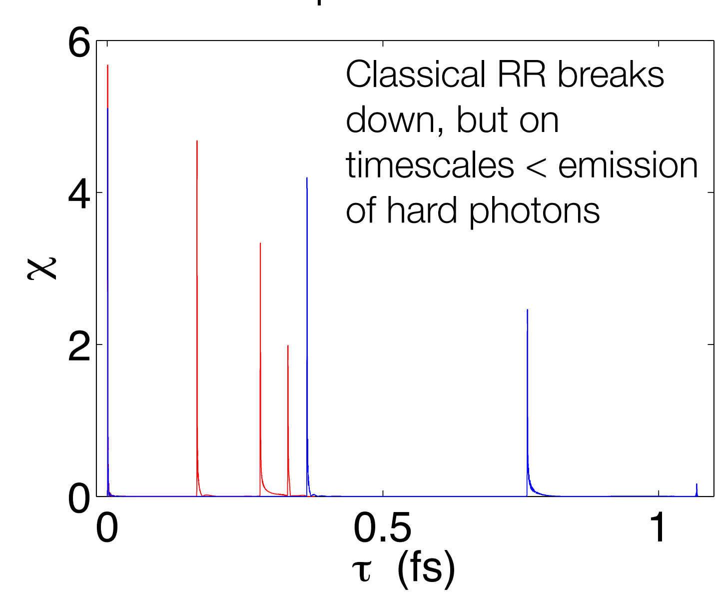
Dipole fields: finite energy non-singular pulses

$$\mathbf{E} = -\nabla \times (\nabla \times \mathbf{Z})$$

$$\mathbf{B} = -\nabla \times \dot{\mathbf{Z}}$$

Typical trajectories for different creation positions: RR gives recirculation at focal spot





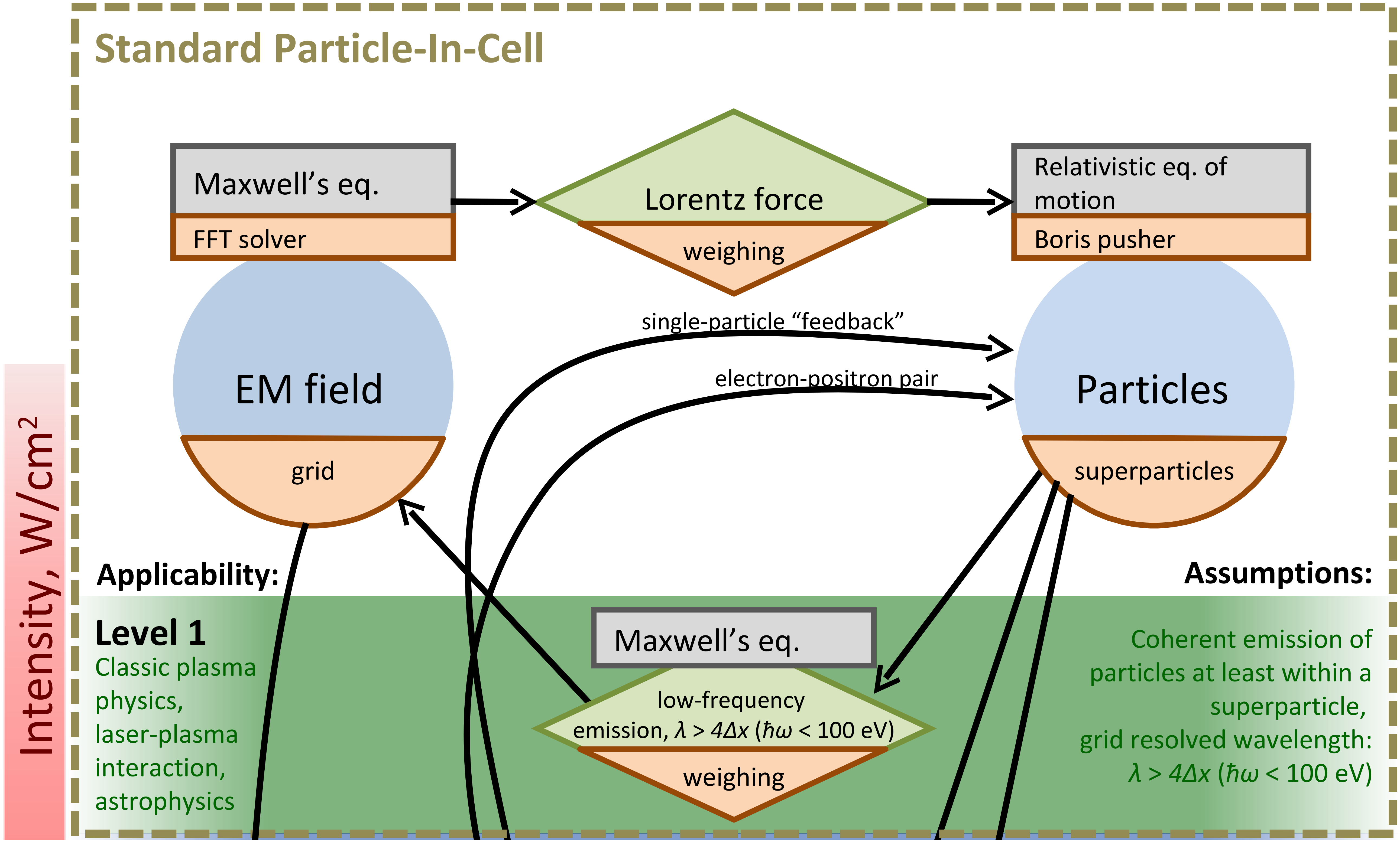
Discerning between processes?

- There are a large number of possible processes that can generate pairs.
- Another example: production from fraction of superthermal electrons in laser-solid target interactions (e.g. Wilks et al. 1998)

$$E \sim \left[\left(1 + \frac{\alpha I \lambda^2}{I_{\text{crit}} \lambda_e^2} \right)^{1/2} - 1 \right] mc^2 = \left[\left(1 + \alpha a_0^2 \right)^{1/2} - 1 \right] mc^2$$

- $a_0 > \sqrt{3/\alpha}$ gives electron energy above rest mass. Can contribute to pair production.
- How to discern between trident, stimulated pair production (cascades) and bremsstrahlung generation, Schwinger mechanism?
- Look at spectral properties of emissions, possible to find unique features?
- Possible to set up experiments that can deal with this?

Principal concept of the QED-PIC code



Is this useful, and what are the applications?

Conclusions

- Ample opportunities for probing new QED physics with high-power laser.
- Requires a strong collaboration between theory, simulations, and experiments.
- Development of advanced codes, but then what. What are the goals? What are the applications?
- The classical-quantum transition of radiation reaction and other events. Mechanisms for pair production.
- How to relate these effects to experiments? How to discern between different mechanisms, producing similar outcomes?

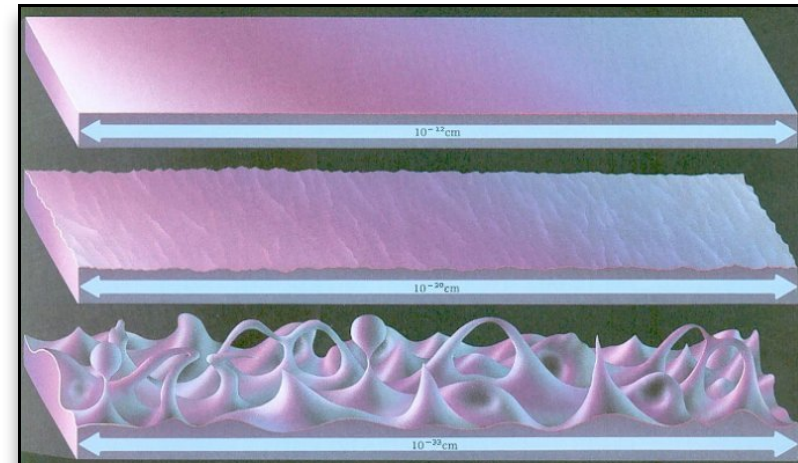
Exotic physics? Possible routes for detection.

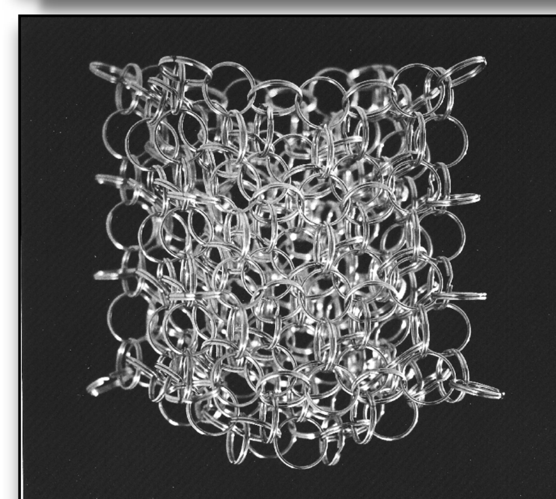
Effects through parametrized generalized Maxwell–Dirac system (Lämmerzahl, Appl. Phys. B, 2006)

- Birefringence.
- Anisotropic speed of light.
- Anisotropy in quantum fields.
- Violations of universality of free fall and the universality of the gravitational redshift.
- Time and space variations of “constants”.
- Charge non-conservations.
- Anomalous dispersion.
- Decoherence and spacetime fluctuations.
- Modified interference.
- Non-localities.

Exotic physics?

- Probing of spacetime structure?
- Noncommutativity (NC) between spacetime coords infered from quantum gravity/string schemes; IR/UV mixing (Amelino-Camelia et al. 2005).
- Noncommuting coordinates implies position uncertainty which eliminates short-distance singularities.
- Analogue: in the plane othogonal to a very strong magnetic field we have coordinate NC (lowest Landau level) [Jackiw, Ann. Henri Poincare (2003)].
- Suggested to be probed using vacuum birefringence experiments (Abel et al. JHEP 2006).





http://www.cpt.univ-mrs.fr/~rovelli/

Noncommutative spacetimes

- Regular quantum mechanics $$[x_a, v_b] = \frac{i\hbar}{m}\delta_{ab} \qquad [x_a, x_b] = 0$$
- Particle in weak magnetic field $$[v_a, v_b] = i\hbar\frac{q}{m^2 c}\epsilon_{abc}B_c$$
- Particle in strong magnetic field ($m \to 0$) $$[x_a, x_b] = \frac{i\hbar}{qB}\epsilon_{ab}$$
- Quantum gravity schemes, emergent quantum mechanics. $[x_\mu, x_\nu] = i\hbar\theta_{\mu\nu}$

Noncommutatitivy: Pair production

- Multi-photon pair production:

$$n\gamma + \gamma' \to e^- + e^+$$

- Threshold number (of laser photons) changes:

$$n_0 \equiv \frac{2m^2(1+a_0^2)}{k.k'} \Rightarrow n_{0,\theta} \equiv \frac{2m^2[1+a_0^2 - a_0^2 \sin^2(k_\mu \theta^{\mu\nu} k'_\nu/2)]}{k.k'}$$

- Threshold is *reduced* in NCQED.

- Moreover, NC breaks azimuthal symmetry around beam axis.

- Look at threshold phenomena, where the NC would push us right over the edge?

Heinzl, Ilderton, MM, PRD (2010)