Photon-Photon Scattering

and related things

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Overview

- **Background.**
- **The quantum vacuum.**
- **Pair production vs. elastic photon-photon scattering.**
- **Why do the experiment?**
- **Other avenues.**
- **New physics?**
- **Conclusions.**

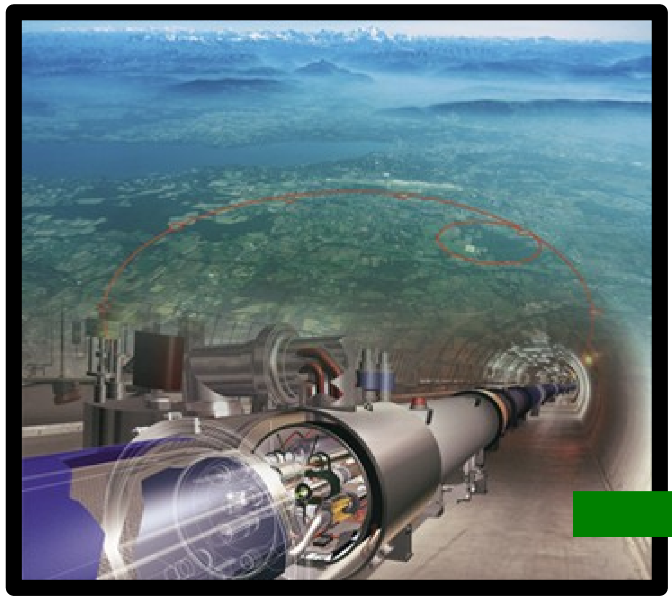
New Physics?

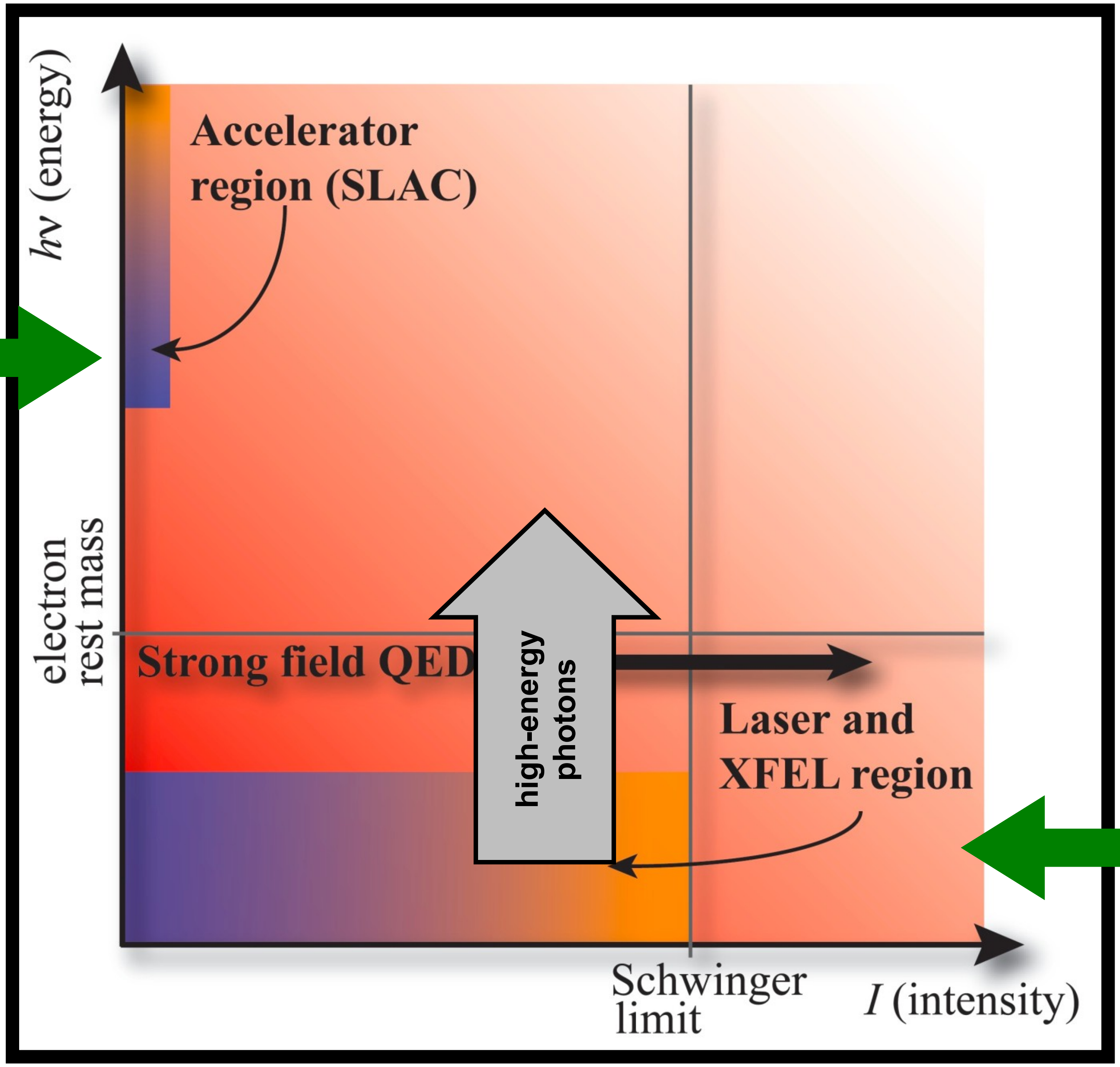
- **The coherent generation of massive amounts of collimated photons opens up a wide range of possibilities.**

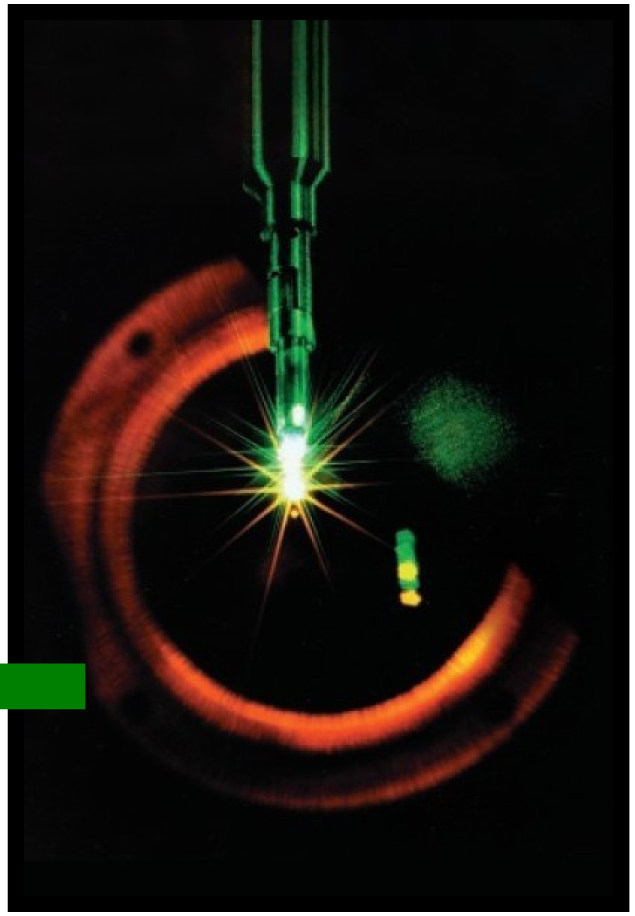
- **Laboratory astrophysics, strongly coupled plasmas, photo-nuclear physics...**

- **Here we will focus on physics connected to the nontrivial quantum vacuum.**

Background: opportunities with high-power lasers



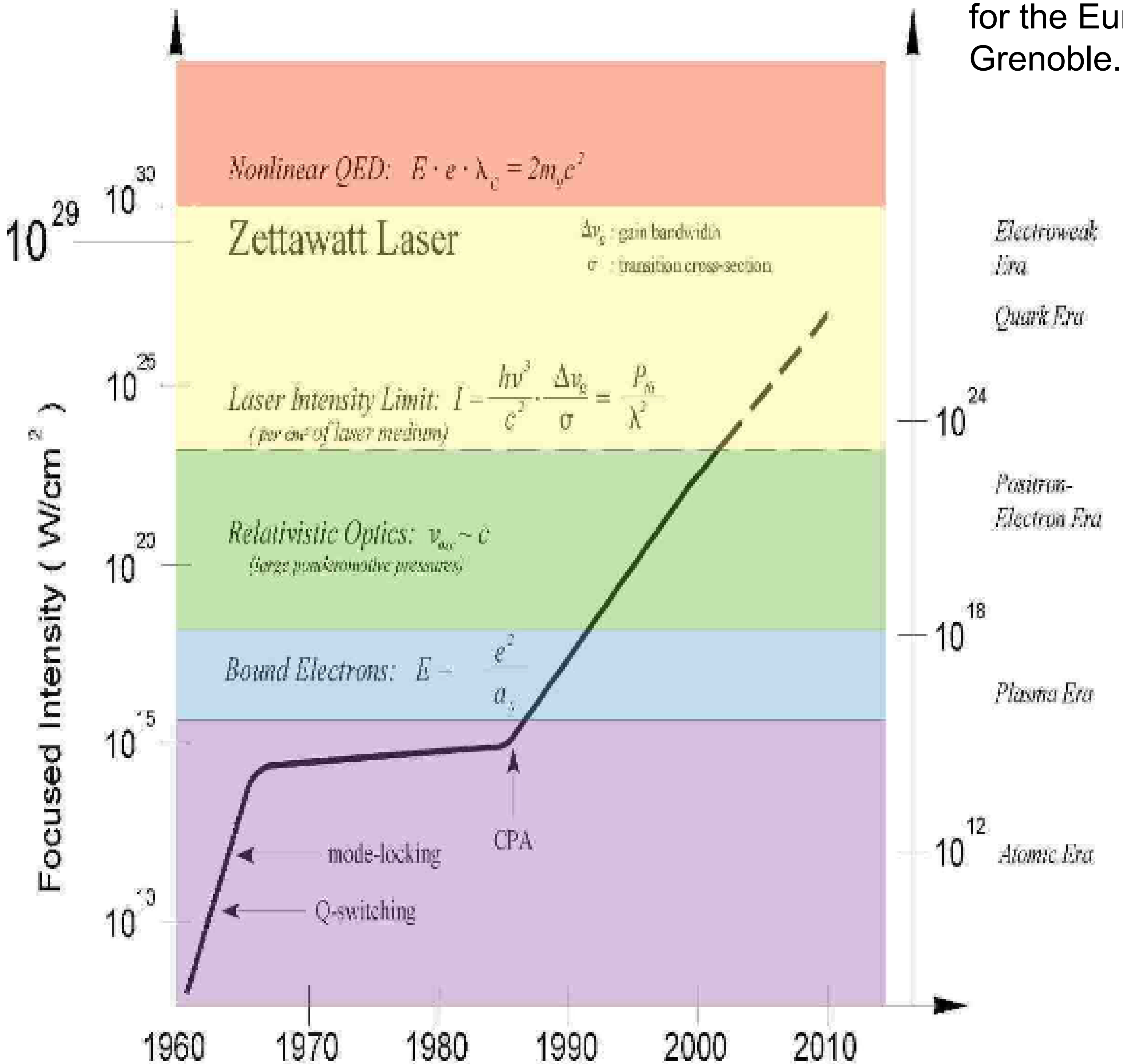


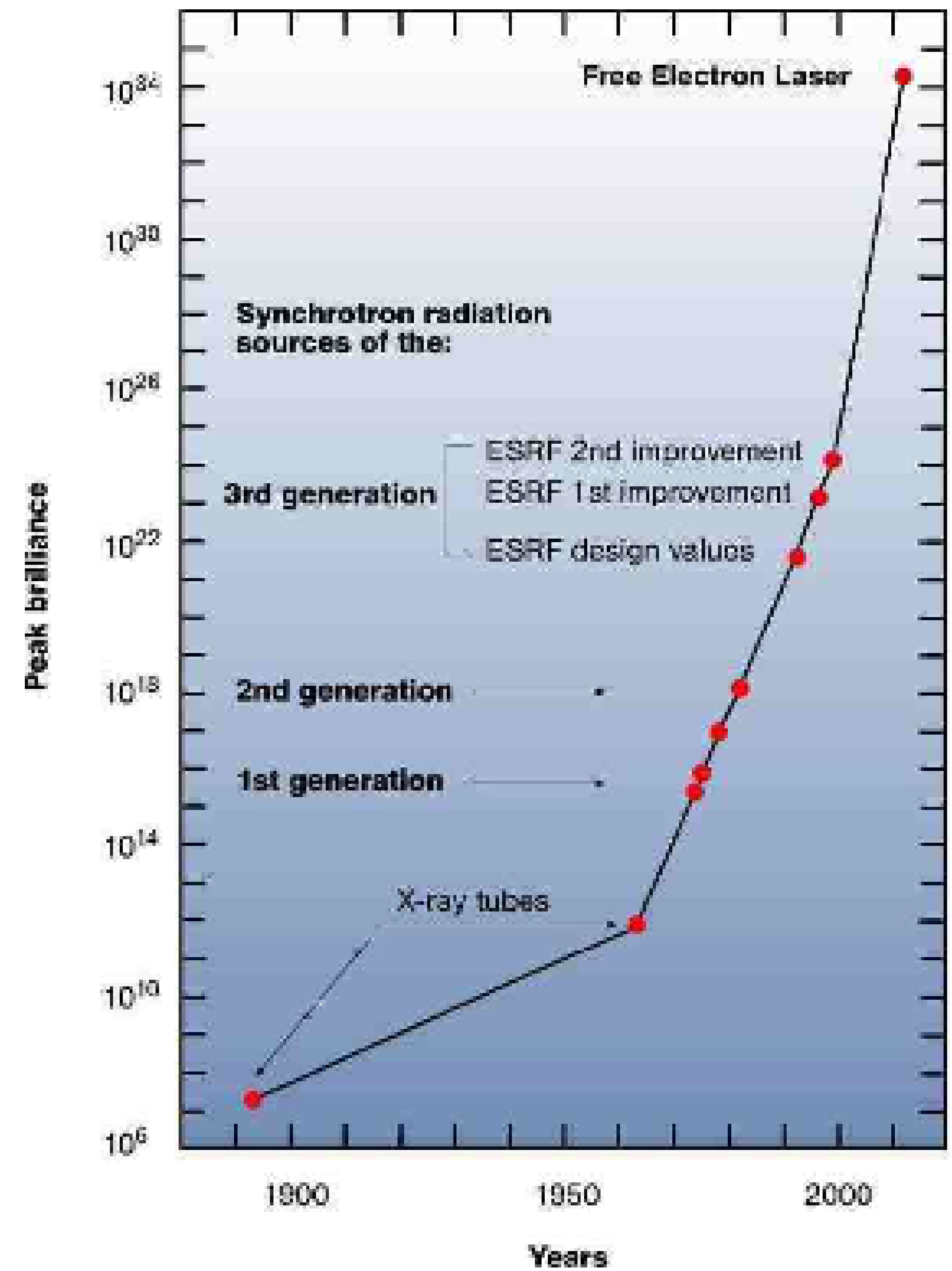


Gies, Europhys. J. D **55** (2009); Marklund & Lundin, Europhys. J. D **55** (2009)

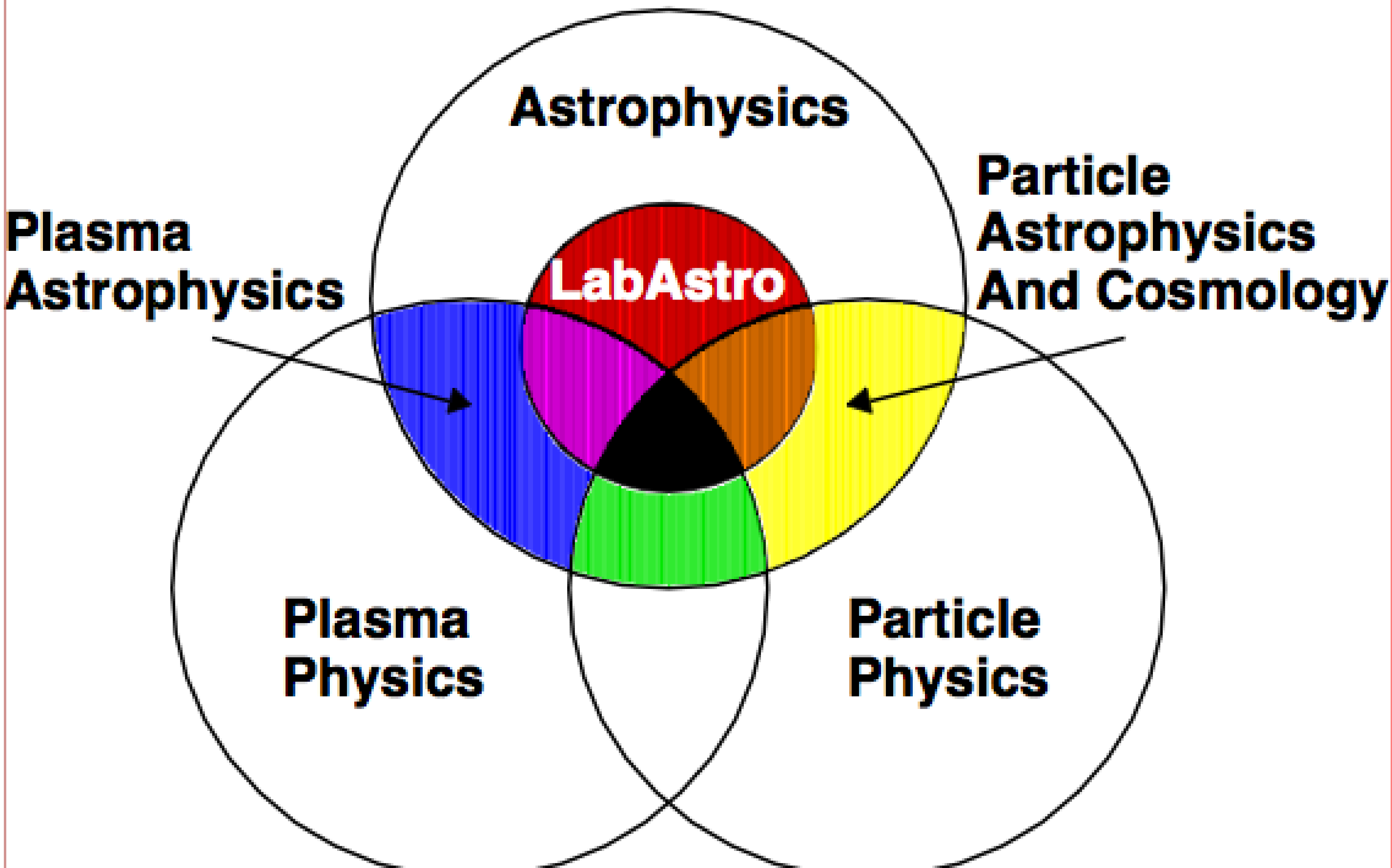
Laser/XFEL development

Evolution of peak brilliance, in units of photons/(s mrad^2 mm^2 0.1 x bandwidth), of X-ray sources. Here, ESRF stands for the European Synchrotron Radiation Facility in Grenoble.





Interdisciplinarity



(Picture by P. Chen)

Probing new regimes

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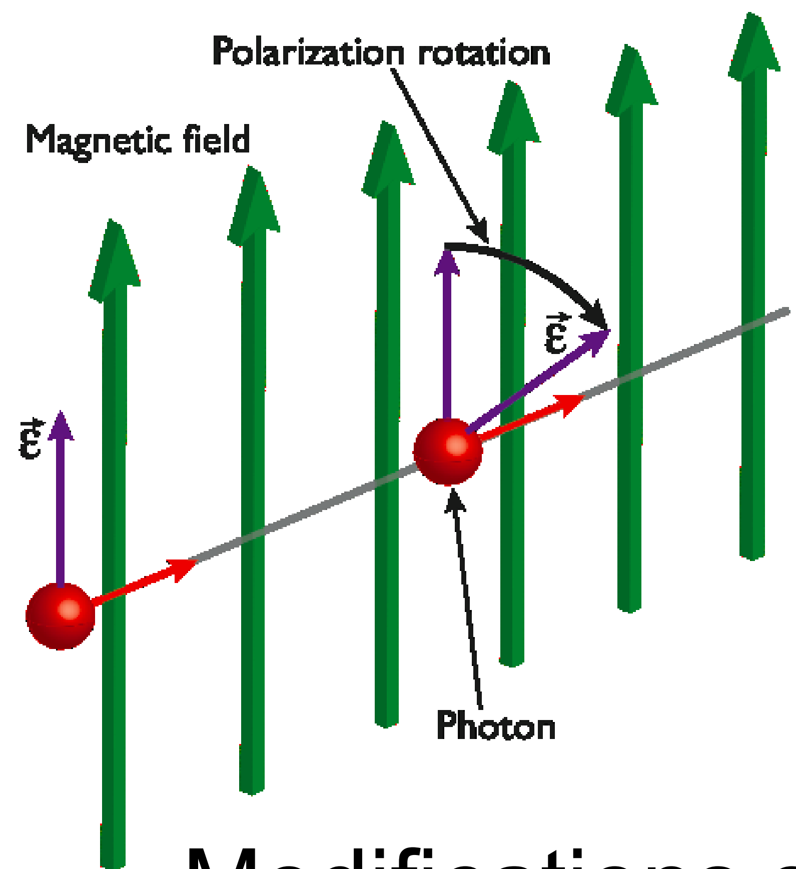
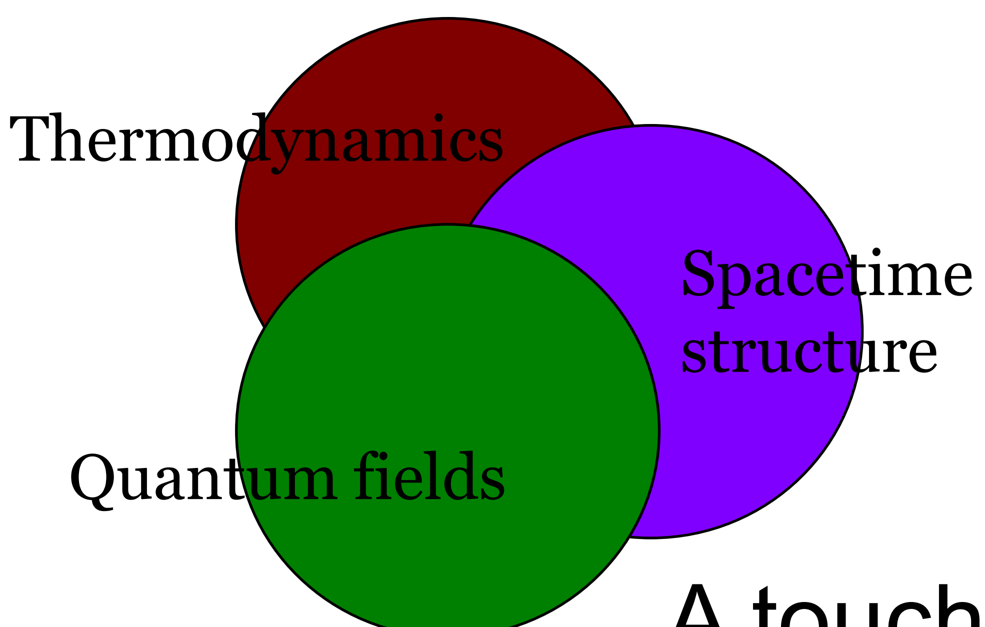


Astrophysics

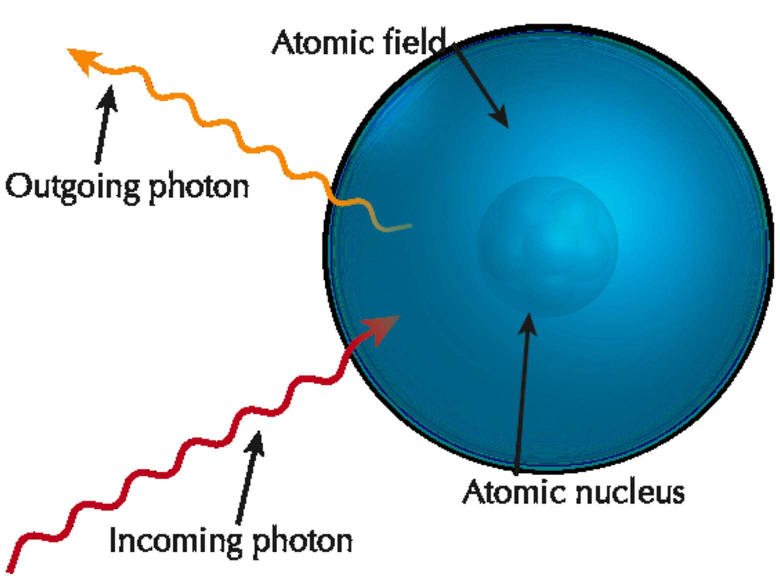


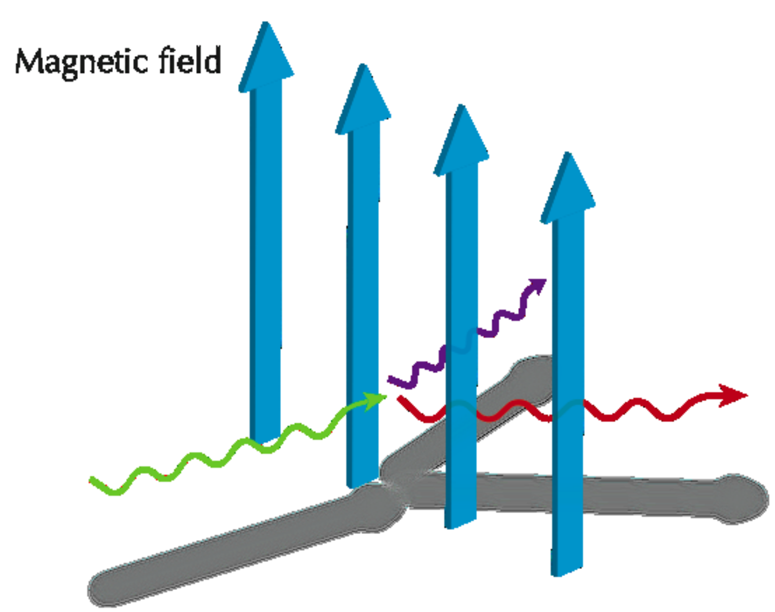
Modifications standard model, e.g. axions

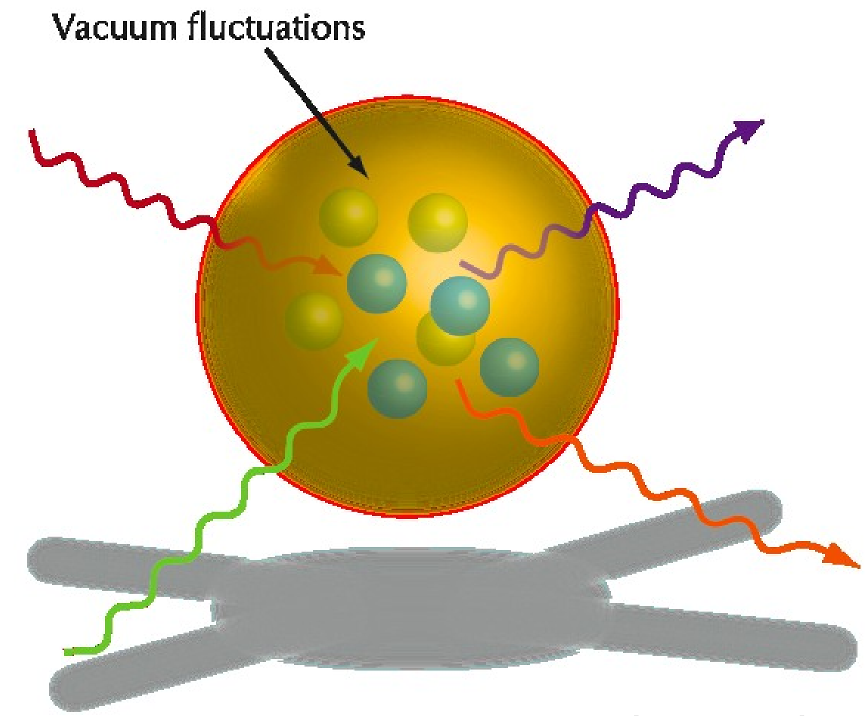
A touch of gravity?

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)

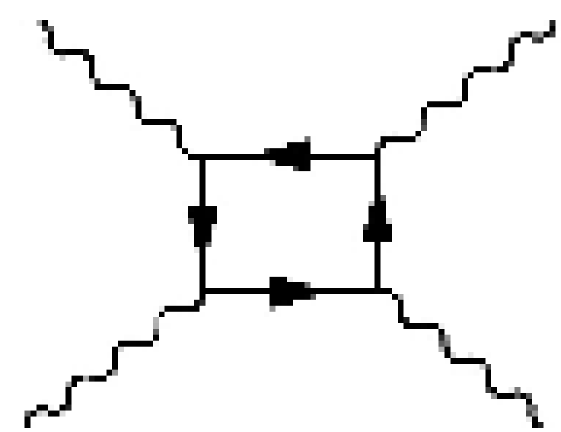
The Heisenberg-Euler Lagrangian

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

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

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

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



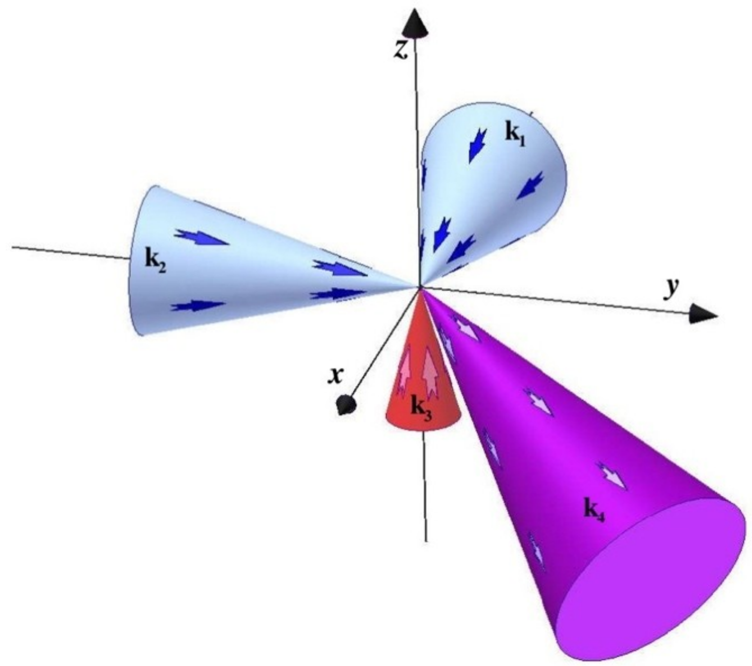
- Has real and imaginary part. The imaginary part signals depletion, i.e. pair production, the real part defines elastic photon scattering events.

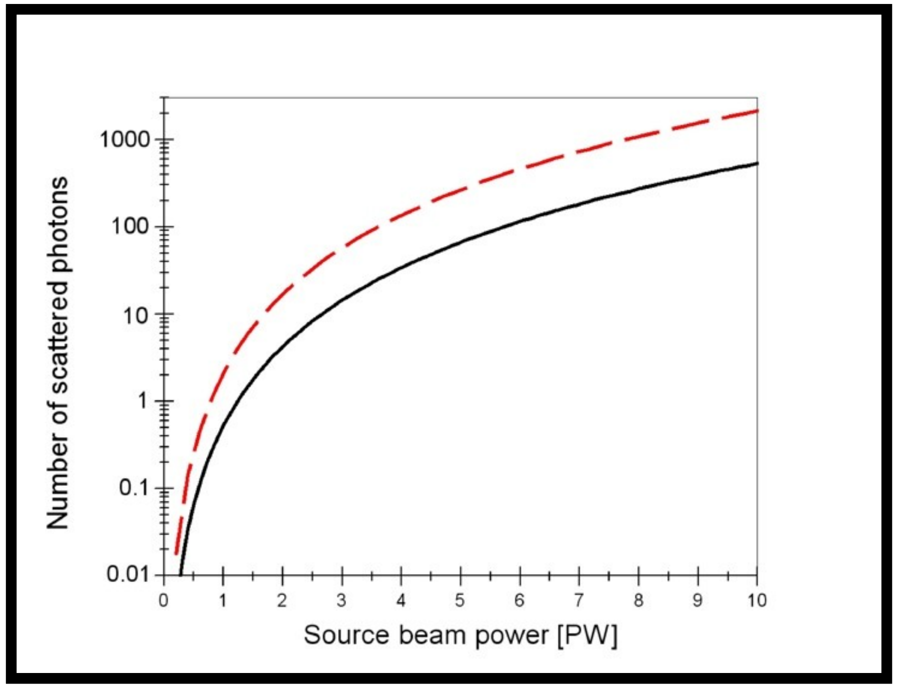
- Dispersion relation for a photon in external field:

$$\omega \approx c|\mathbf{k}|(1 - \tfrac{1}{2}\lambda|\mathbf{Q}|^2) \qquad |\mathbf{Q}|^2 \equiv \epsilon_0|\hat{\mathbf{k}} \times \mathbf{E} + c\hat{\mathbf{k}} \times (\hat{\mathbf{k}} \times \mathbf{B})|^2$$

Photon-photon scattering

- “Clean” experiment on the nonlinear quantum vacuum: four-wave mixing in vacuum, 3D setup (D. Bernard et al., EPJD **10**, 141 (2000); E. Lundström et al., PRL **96**, 083602 (2006)).
- Laser parameters: two 800 nm 15 J pulses of 0.5 PW each, , 0.07 photons/shot.
- Deviations: sign of new physics? (Breaking of Lorentz invariance, axions, low energy quantum gravity effects and extra dimensions (e.g. Davoudiasl, PRD **60**, 084002 (1999)))



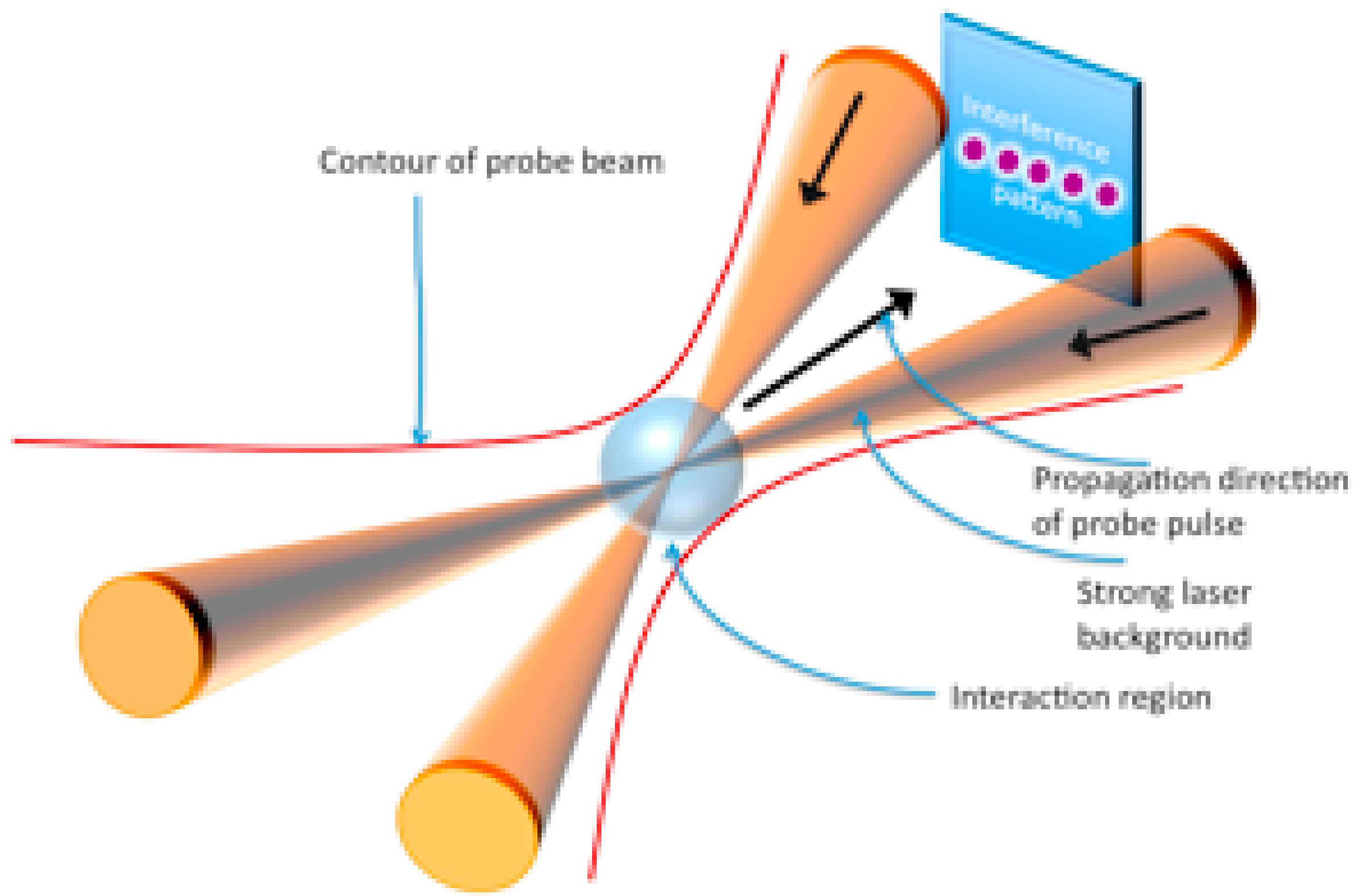


PRL **96**, 083602 (2006)

The nonlinear quantum vacuum

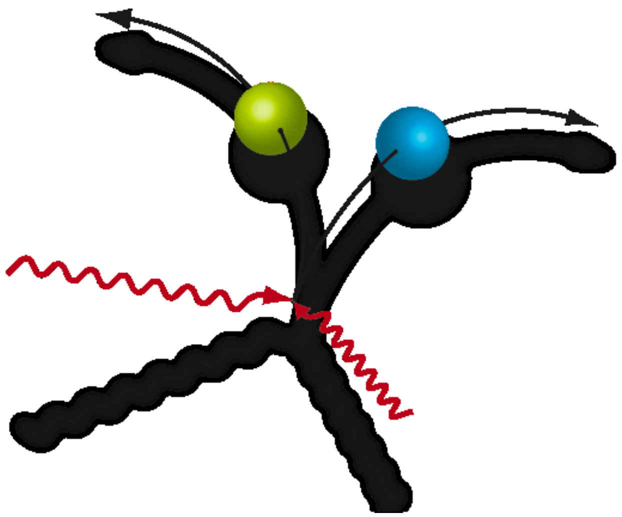
- Photon-photon scattering for low-energy photons: $\hbar\omega \ll 2m_e c^2$

- Could be detectable (Lundström et al., PRL **96** (2006)).



- Virtual slit experiments (King et al., Nature Phot. **4** (2010))

Pair production



- High energy photon may create pairs: $\hbar\omega \geq 2m_e c^2$
- Multiphoton processes:
  - Low-energy photon scatter off electrons, producing h
  - Low-energy photons cause pair production through Sauter-Schwinger mechanism.
- Sauter's resolution to the Klein paradox: static electric field may cause the vacuum to go unstable (Sauter 1931).
- Electrostatic fields under the critical field strength $E_{\mathrm{crit}} \sim 10^{16}\,\mathrm{V/cm}$ is expontially surpressed (Schwinger 1951).
- Relativistic flying/oscillating mirror (Lichters et al., PoP (1996); Bulanov et al, PRL (2003)), relativistic electronic spring (Gonoskov et al., 2010).

Pair production

Some recent simulations on attosecond pulse generation and amplification (Gonoskov et al., submitted (2010))

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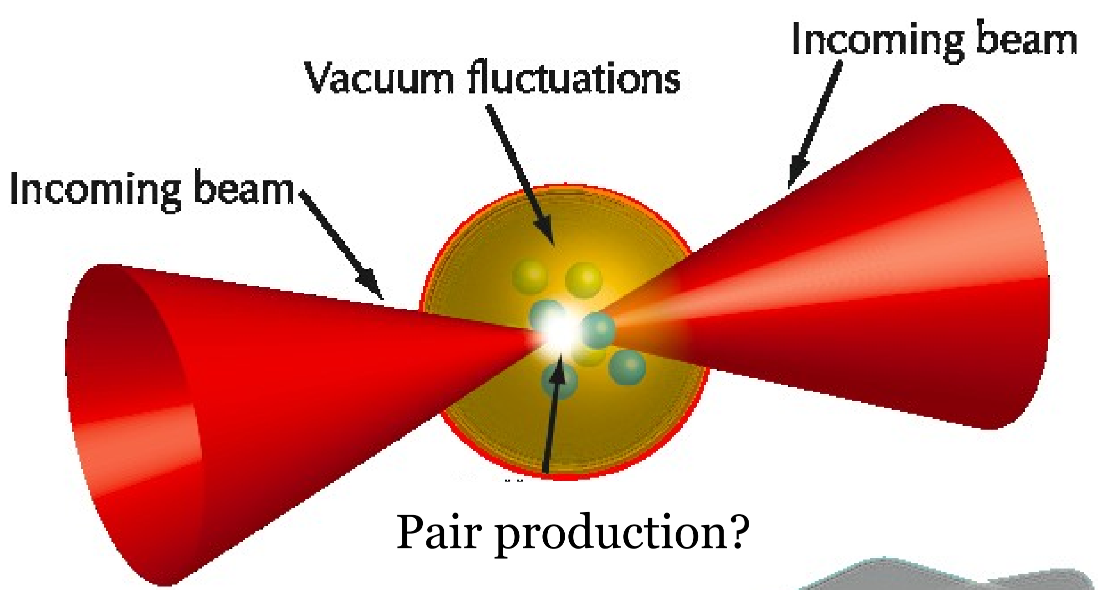
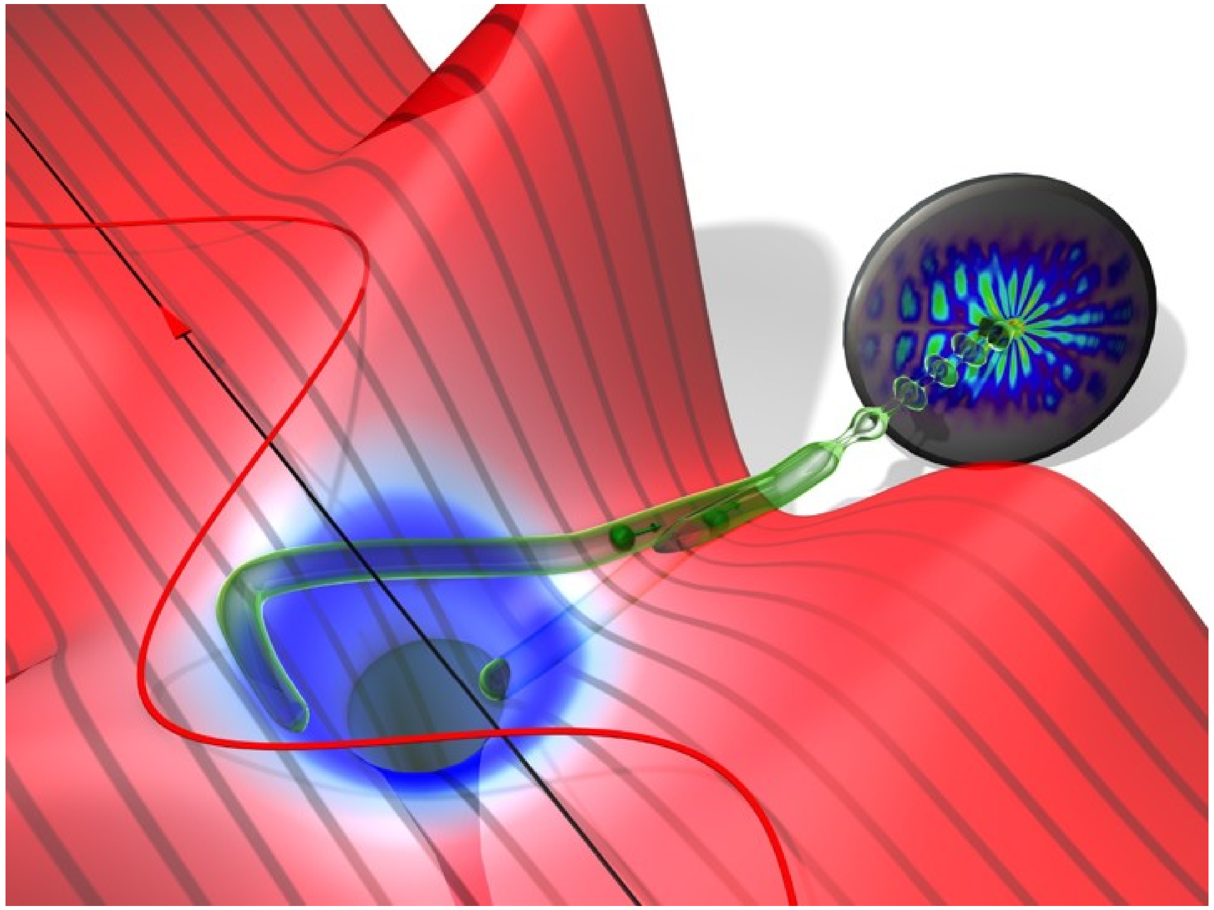
Pair production: the fight against exponential supression

- Using pre-factor [laser four-colume/Compton four-volume ≈ 10^{24}] to increase pair production rate (Narozhny et al., 2004).
- Superimposed oscillatory fields (substructure) gives assisted pair production (Dunne, Gies, Schützhold, 2008, 2009).
- *E* >> *B* for counterpropagating/standing waves (Gregori et al., Astra Gemini/RAL experiment, 2010).
- XFEL-laser interaction for stimulated pair production (Ilderton, Hebenstreit, Marklund (2011)) using quantum kinetics (Wigner form of Dirac theory).
- Complex beam configurations (Bulanov et al.
- Cascading (Ruhl et al., 2010)

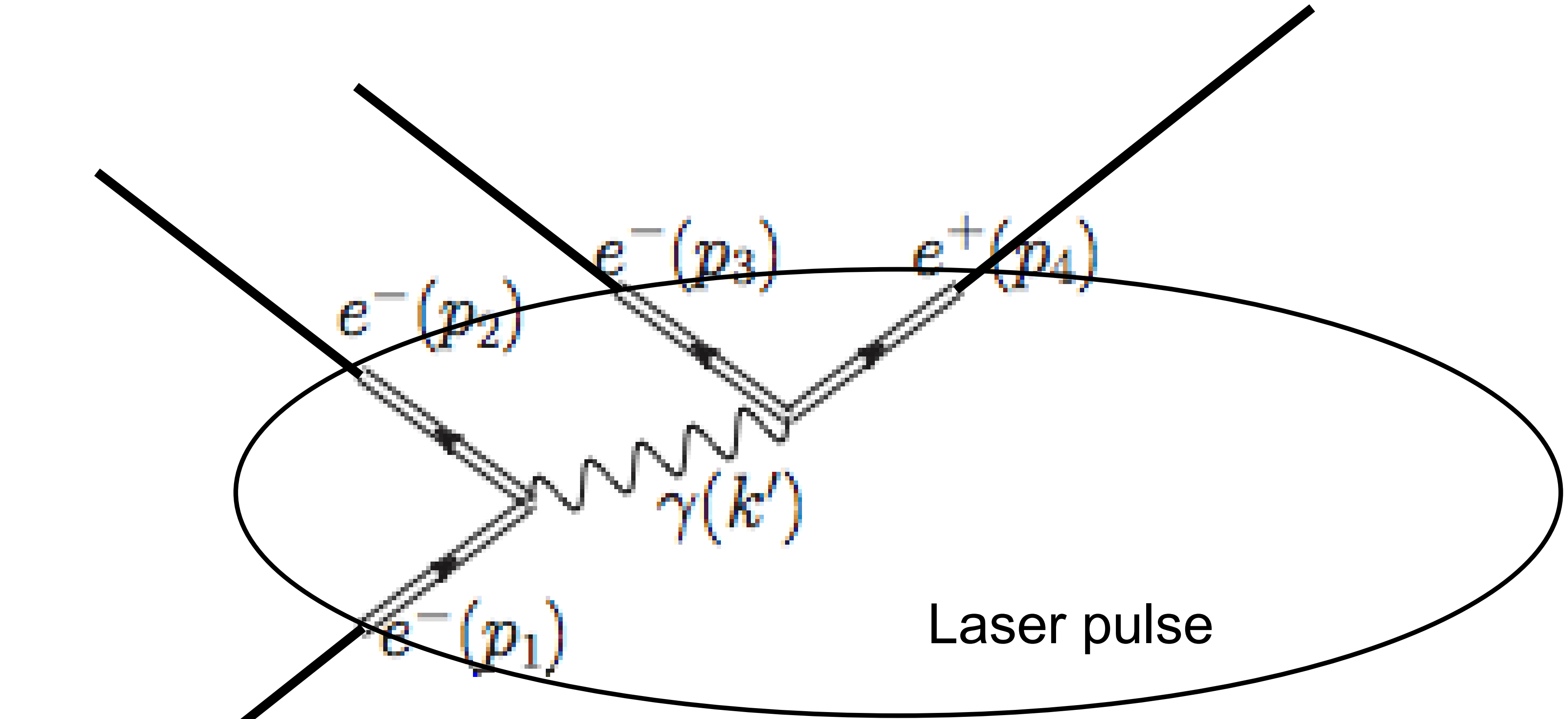


Pair production: importance

- Nonperturbative quantum field theory: truly relativistic quantum field theory.
- Techniques developed for QED pair production useful for QFT in general: MD simulations (e.g. Ruhl), quantum kinetic developments (e.g. Alkhofer, Hebenstreit), world-line and light-cone techniques (Gies, Dunne, Heinzl, Ilderton).
- Similarities to strong field ionization problems (Reiss, PRL 2008; Blaga et al., Nature Phys. 2009).
- Nonlinear scattering events (Heinzl et al., PRA 2010).
- Source of ep-plasma?



The trident process vs. cascading



- Trident: intermediate photon virtual (Ritus (1972); Ilderton, PRL (2010))
- Cascade: intermediate photon real bremsstrahlung photon (Klepikov (1964); Nikishov & Ritus (1964))
- Current work on laser-electron interactions for radiation reaction studies (Harvey, Ilderton, Marklund (2011)): when does the classical theory break down?

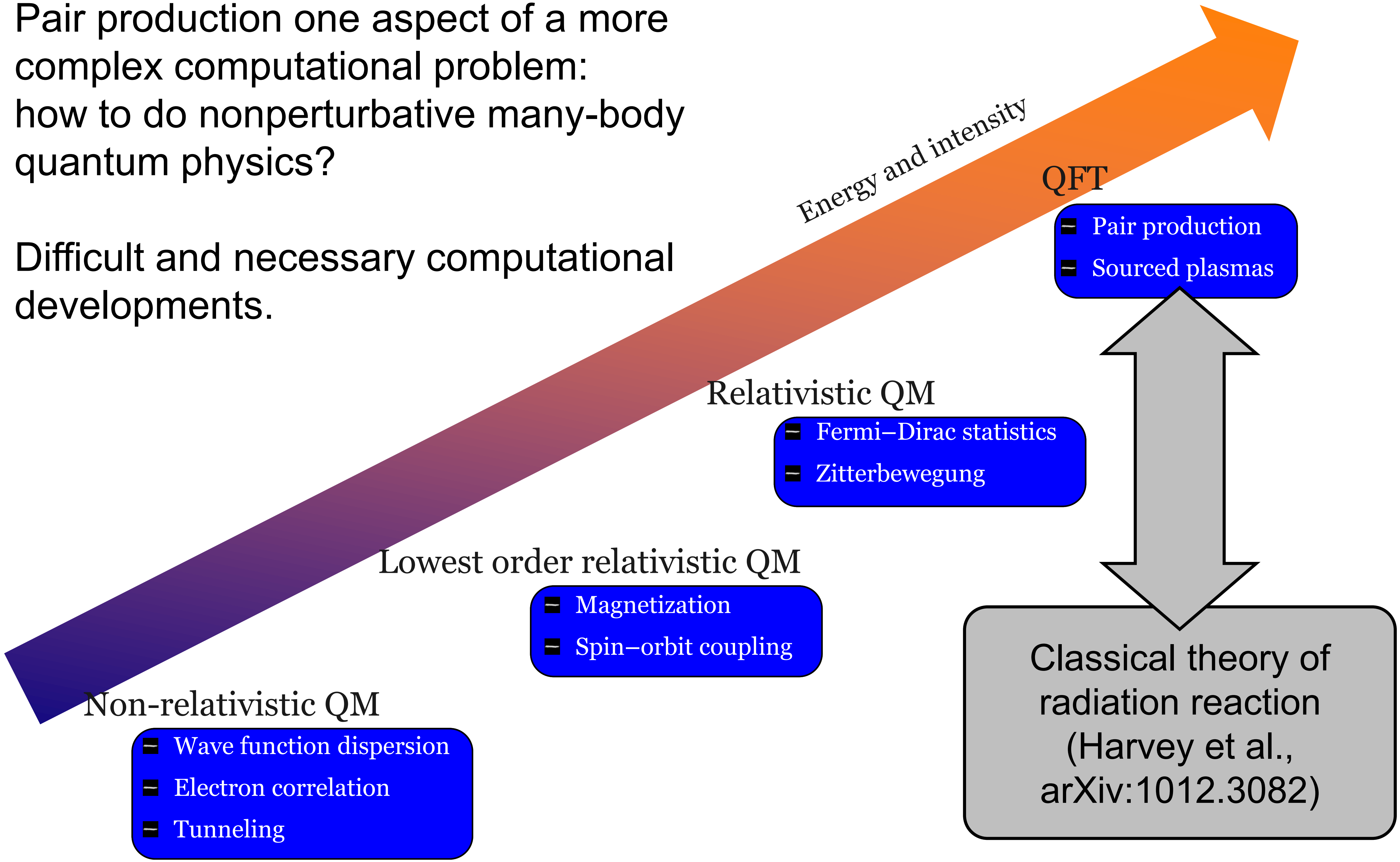
Pair production: radiation reaction/pair cascading

- Recent interest in cascading and pair production (e.g., Bell & Kirk, PRL (2008); Sokolov et al., PRL (2010); Elkina et al, 1010.4528; Duclous et al., 1010.4584).
- Previously looked at in astrophysical settings (magnetosphere problems).
- Seemingly conflicting results in the literature.
- Different intensity values for significant cascading to take place.
- Important issue: 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*)

Pair production: theoretical developments.

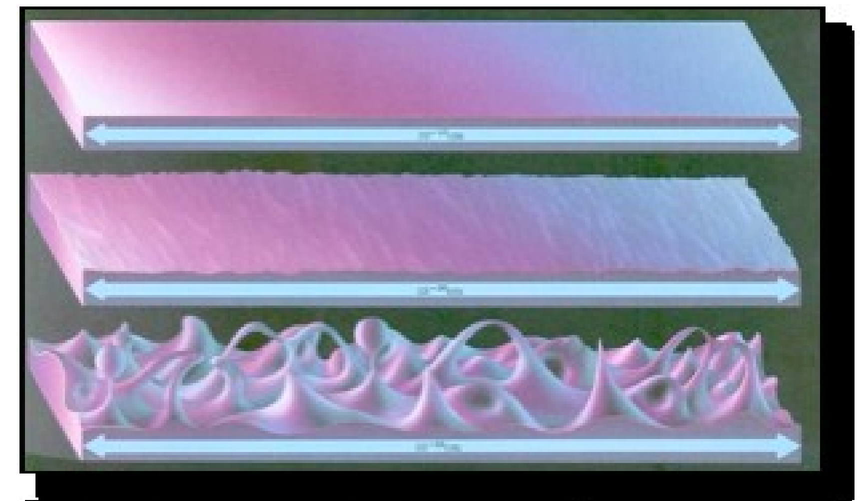
Pair production one aspect of a more complex computational problem: how to do nonperturbative many-body quantum physics?

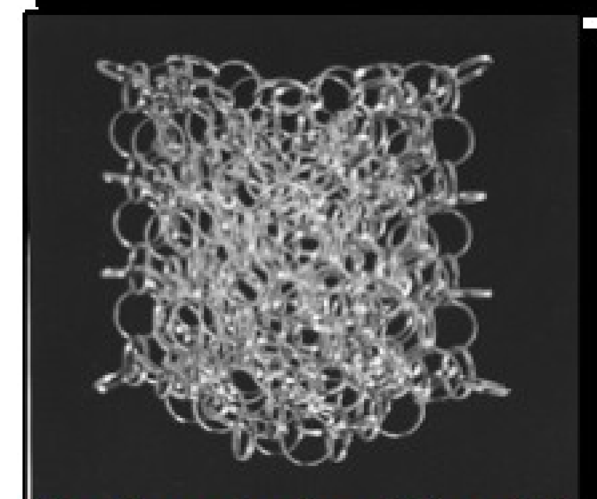
Difficult and necessary computational developments.



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).
- Analogue: in the plane othogonal to a very strong magnetic field we have coord NC.
- Suggested to be probed using vacuum birefringence experiments (Abel et al. JHEP 2006).





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

Exotic physics?

- Noncommuting coordinates $[x^\mu, x^\nu] = i\Theta^{\mu\nu}$
- Laser intensity effects to counter the energy scale (Heinzl et al., PRD 2010).
- Pair production:
  - depends periodically on collision angle,
  - larger cross section,
  - threshold (number of photons, for ELI parameters) lowered from QED value.

$$n_{0,\Theta} \approx n_0 - \frac{2 \times 10^8 m^6}{k \cdot k'} |\Theta|^2$$

- Laser can thus put lower limits on the involved phenomenological parameters.

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.

Conclusions

- Ample opportunities for probing new physics with high-power laser.
- Requires a strong collaboration between theory, simulations, and experiments.
- In particular, still many parts of QED that are not computationally viable, or that need independent verifications.
- The classical-quantum transition of radiation reaction.
- Massive pair production or not in the laboratory?
- Deviations from QED or standard model?