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High Field Physics and Collective Vacuum Effects

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High Field Physics and Collective Vacuum Effects

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Overview

- Why? What are the interesting features of high field physics?
- How? Can we achieve strong enough focal intensities?
- Examples. Some issues regarding quantum field theory are presented.
- Conclusions - what the future might bring.

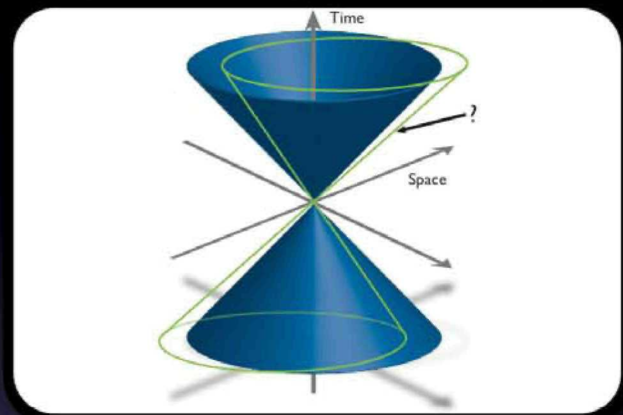
Recent developments

- New developments in extreme plasma systems and lasers. (M. Dunne, Nature Phys. **2**, 2 (2006); M. Buchanan, Nature Phys. **2**, 721 (2006))
- Current divide: relativistic optics & nonlinear QED. (G. Mourou et al., RMP **78**, 309 (2006); M. Marklund & P. K. Shukla, ibid., 591 (2006); Y.I. Salamin, S.X. Hu, K.Z. Hatsagortsyan, & C.H. Keitel, Phys. Rep. **427**, 41 (2006))
- New developments in numerical and experimental tools. (e.g. R.A. Fonseca, Proc. HPCPAST 2002; R. Trines et al., PRL **94**, 165002 (2005))
- Near future importance: laboratory astrophysics, e.g. hydro, nuclear astro. (B.A. Remington et el., RMP **78**, 755 (2006))
- Questions in fundamental physics, e.g.
  - Photon-photon scattering. (J. Schwinger, PR **82**, 664 (1951); D. Bernard et al., Eur. Phys. J. D **10**, 141 (2000); E. Lundström et al., PRL **96**, 83602 (2006))
  - Hawking-Unruh effect. (S.W. Hawking, Nature **248**, 30 (1974); W. Unruh, PRD **14**, 870 (1976); P. Chen & T. Tajima, PRL **83**, 256 (1999); R. Schützhold et al., PRL **97**, 121302 (2006))
  - Axion-like particle searches. (F. Wilczek, PRL 40, 279 (1978); E. Zavattini et al., PRL **96**, 110406 (2006))

Why high field physics?

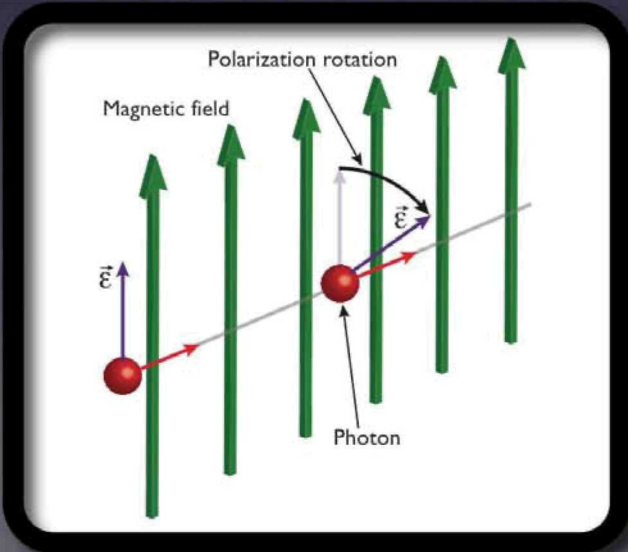
Astrophysical environments

Symmetry breaking?



Modifications of Standard Model

$g\phi\, \boldsymbol{E} \cdot \boldsymbol{B} \Rightarrow$



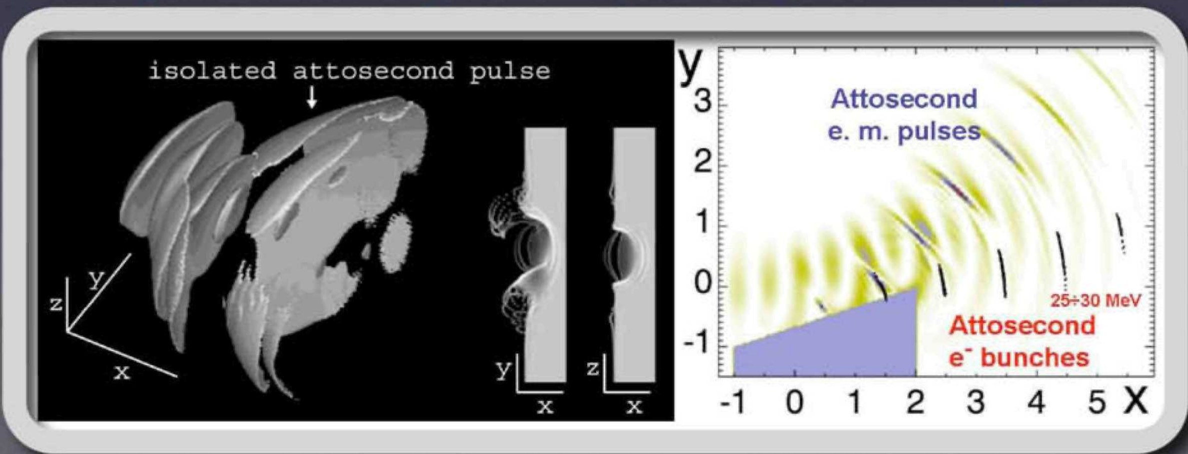
A touch of quantum gravity

- Thermodynamics
- Quantum fields
- Spacetime structure

$\Rightarrow$??

High field generation

- Many high field phenomena directly tractable with next generation laser systems.
- Some phenomena require intensities above current experimental limits.
- Attosecond electron bunches creates mirror (Naumova et al., PRL 92 and 93 (2004); Nees et al., J. Mod. Opt. 52 (2005); Thaury et al., NPhys. (2007)).



Opportunity to reach the Schwinger field $\sim 10^{29}\ \mathrm{W/cm^2}$

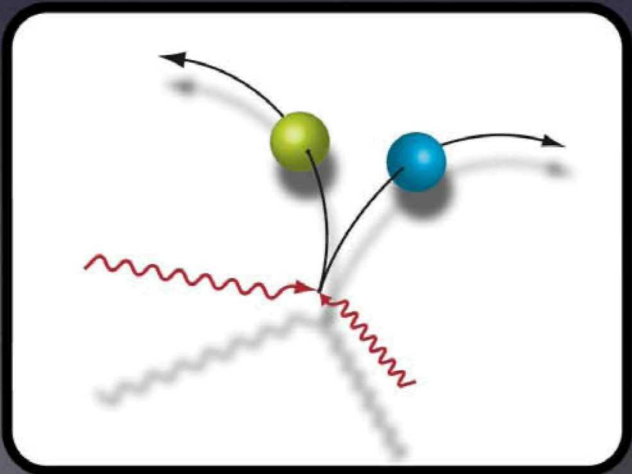
Fundamental physics with lasers

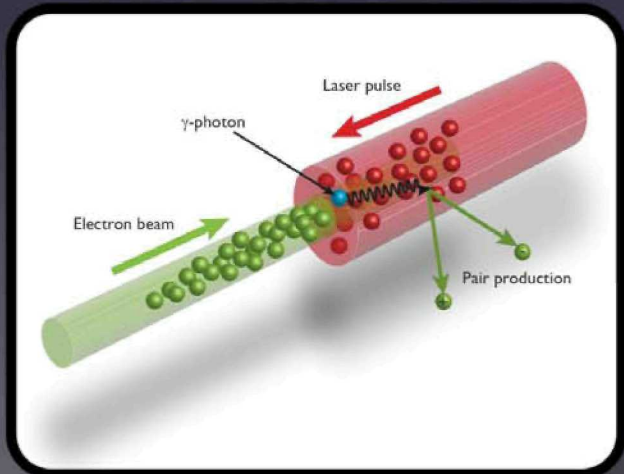
- Relativity + uncertainty principle ⟶ quantum vacuum (virtual pair plasma).
- Coherent photon probe ideal.
- Lowest mass excitation in vacuum: electrons and positrons.
- Even before Schwinger field is reached, vacuum becomes weakly nonlinear.
- Stimulated processes.

Electrostatic potential strong enough to separate virtual pairs a Compton wavelength.

The quantum vacuum

- Classically, photons in vacuum indifferent to each other.
- Quantum field theory: vacuum nontrivial, due to Heisenberg's uncertainty relation and relativistic mass-energy equivalence.
- Pair creation (e.g. Burke et al., PRL **79**, 1626 (1997)), high-frequency or intense photons.
  - Positronium interaction with laser: Small scale muon pair collider! (Müller et al. PRD **74**, 074017 (2006))
  - Gamma source.



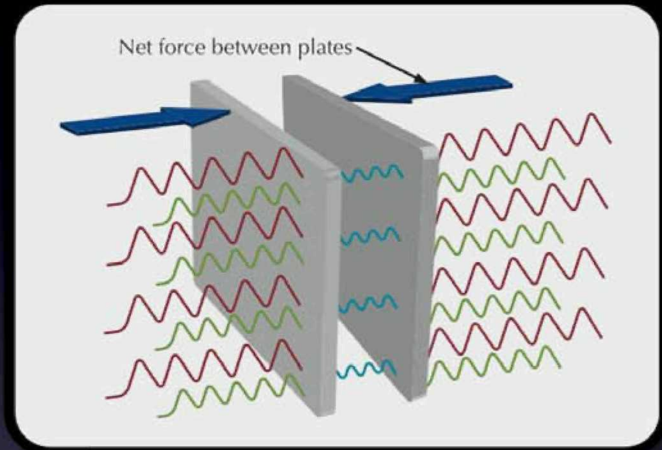


Some vacuum effects

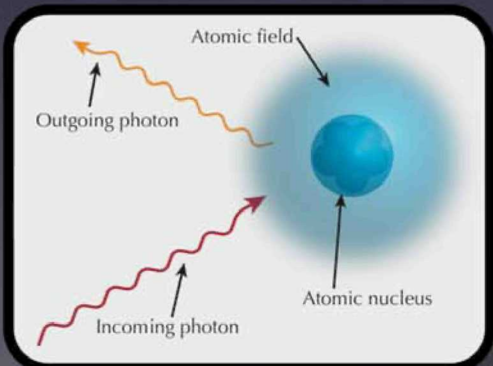
1. Lamb shift and anomalous magnetic moment of electron.

2. Casimir effect:

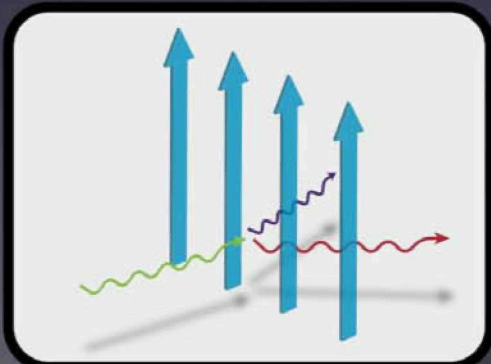
   Predicted 1948, measured 1997.
   1 atm at 10 nm, important in nano-mechanics (T. Emig, PRL **98**, 160801 (2007)).



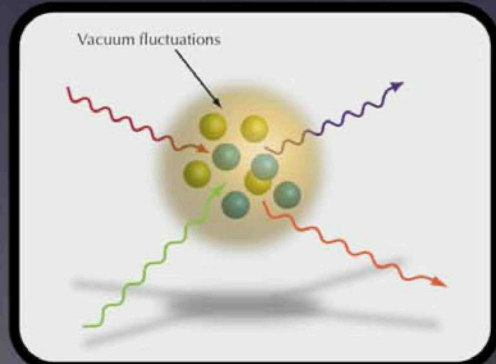
3. Photon interactions.



a. Delbrück scattering



b. Photon splitting



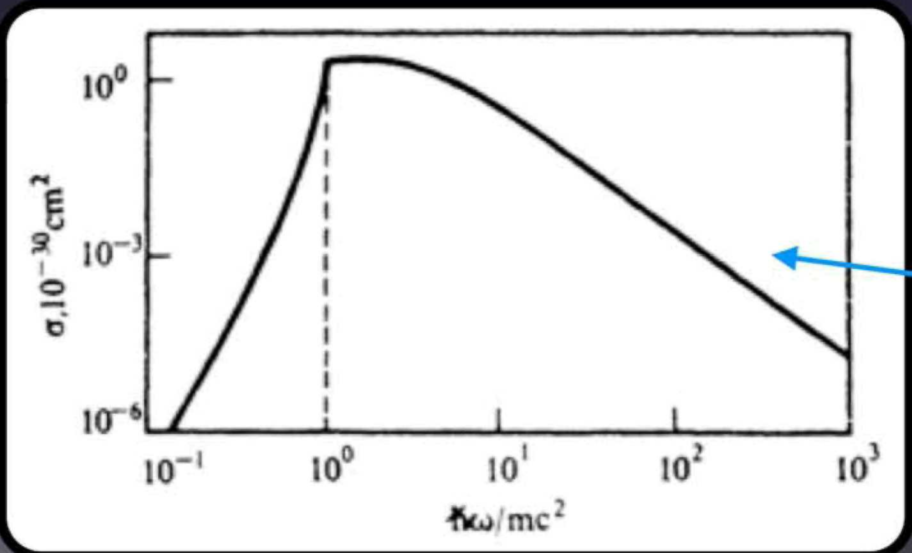
c. Photon-photon scattering?

The quantum vacuum

- Light-by-light scattering: Low-frequency cross-section and lagrangian

$$\sigma_{\gamma\gamma} \approx 0.7 \times 10^{-29} \left(\frac{\hbar\omega}{1\,\mathrm{MeV}} \right)^6 \mathrm{cm}^2$$

$$\mathcal{L} = \mathcal{L}_0 + \frac{\epsilon_0 \alpha}{90\pi E_{\mathrm{crit}}^2} \left[\left(E^2 - c^2 B^2\right)^2 + 7c^2 (\boldsymbol{E} \cdot \boldsymbol{B})^2 \right]$$



$$E_{\mathrm{crit}} \approx 10^{16}\,\mathrm{V/cm} \;\rightarrow\; 10^{29}\,\mathrm{W/cm}^2$$

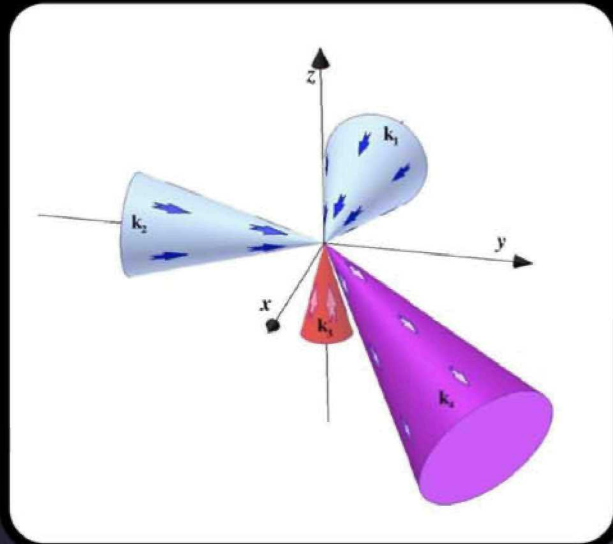
$$eE_{\mathrm{crit}} \times \frac{\hbar}{m_e c} = m_e c^2$$

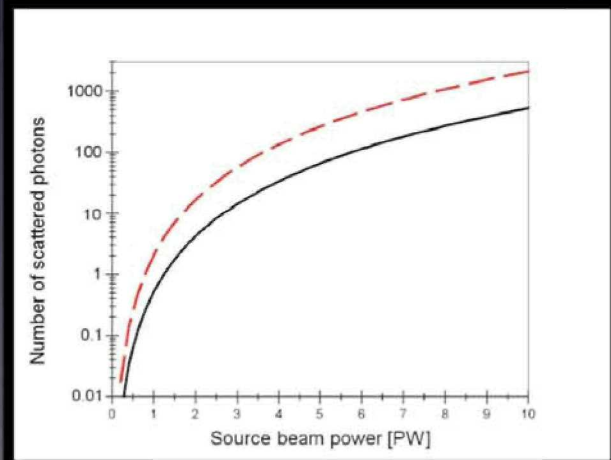
Work times distance = rest mass

Peak in cross-section at electron mass. Cross-section only five orders of magnitude below Thomson. Optical regime ⟶ 40 orders of magnitude smaller than Thomson!

Laser detection schemes

- "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, $10^{22}\ \mathrm{W/cm}^2$, 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)

Colliding light pulses

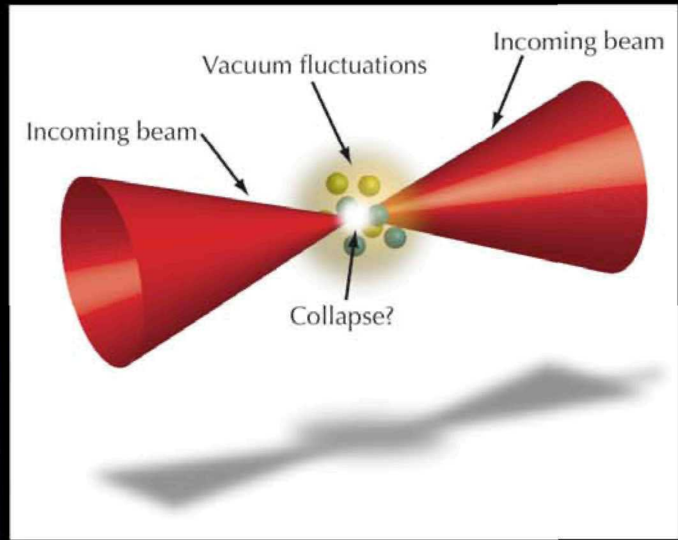
Two light pulses are allowed to collide. Criteria for vacuum collapse:

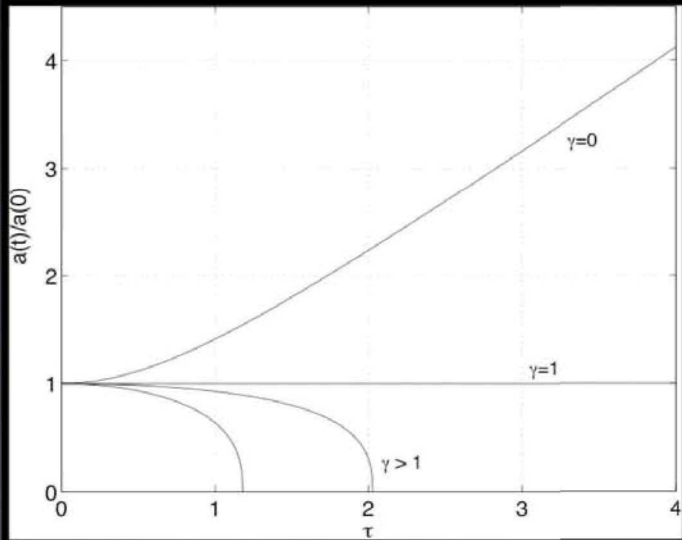
$$\left(\frac{\alpha}{90\pi}\right)^{1/2}\frac{|E|}{E_{\rm crit}} > \frac{r_p}{\lambda_p}$$

which has to be supplemented with

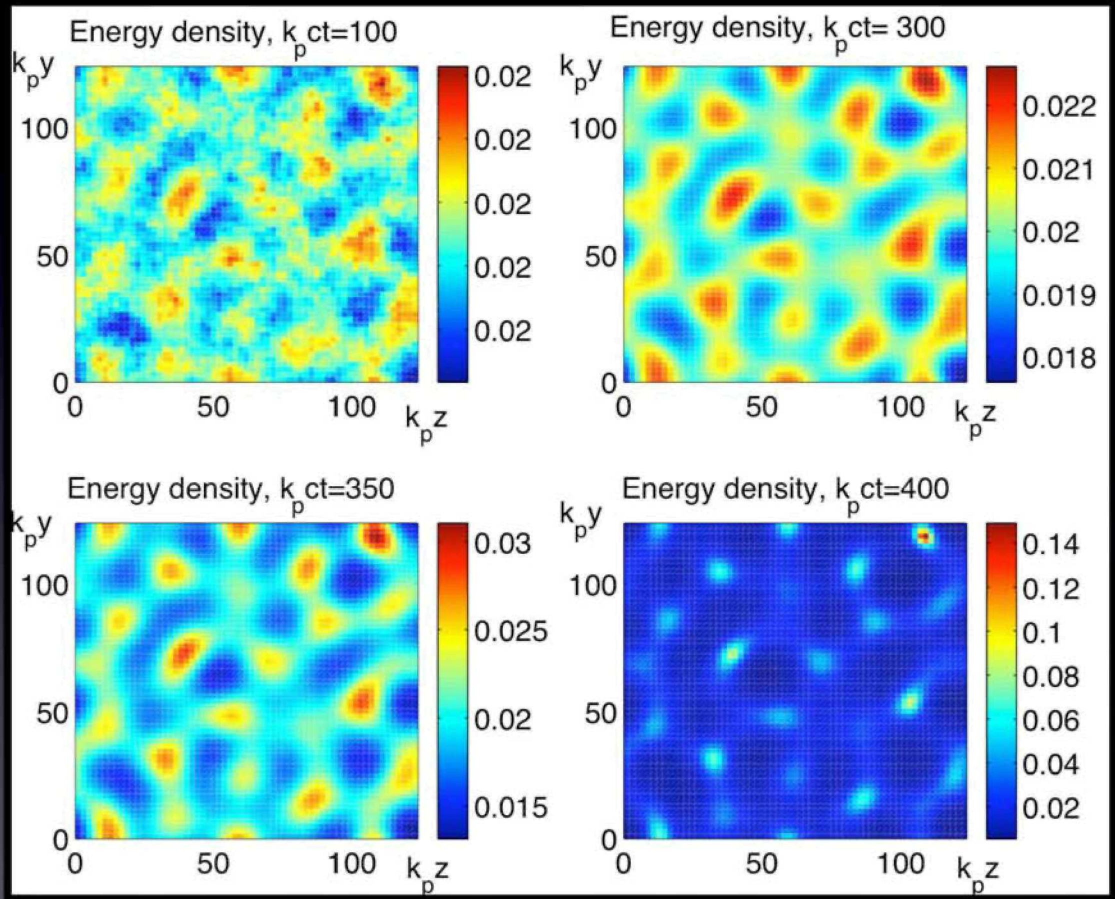
$$\frac{W_p}{\lambda_p r_p^2} > \frac{90\pi}{\alpha}\epsilon_0 E_{\rm crit}^2$$

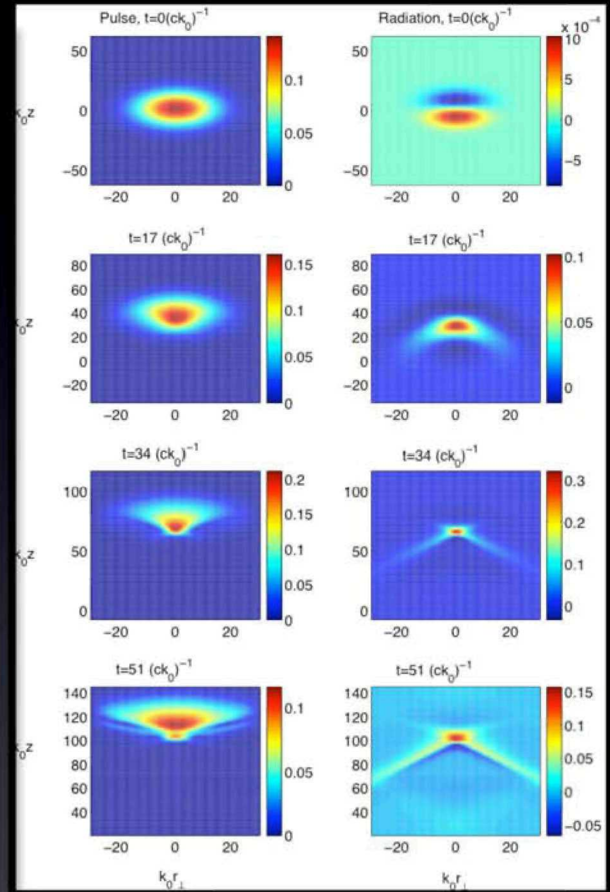
expressing that the pulse length has to be sufficiently long for collapse to occur. See also Kharzeev & Tuchin, PRA **75**, 043807 (2007).





Dynamic vacuum effects

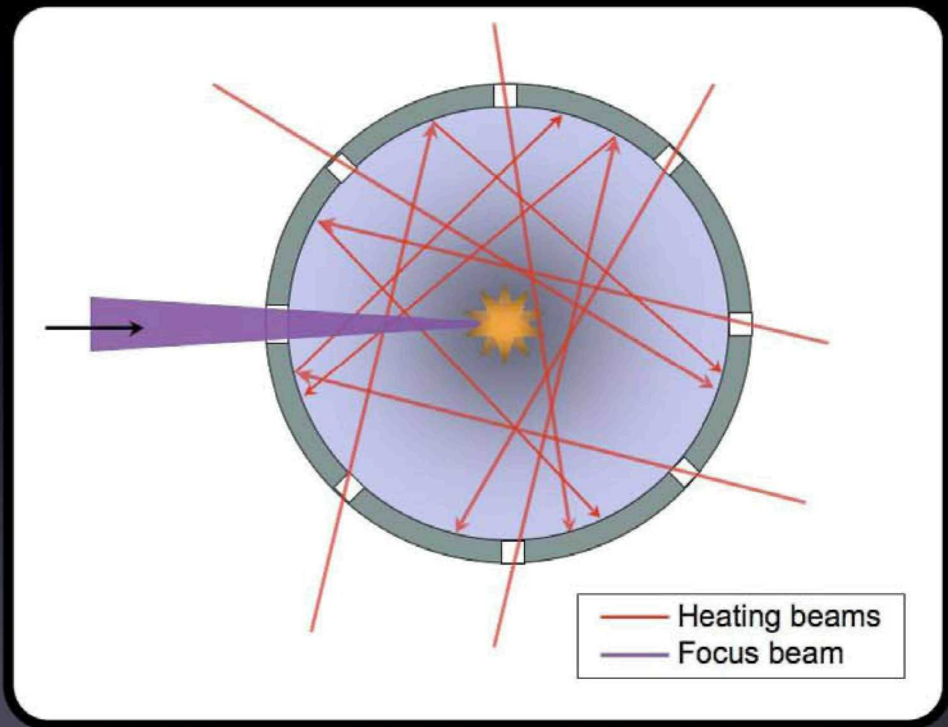




Marklund et al., PRL **91**, 163601 (2003);
P.K. Shukla & B. Eliasson, PRL **92**, 073601 (2004);
Marklund & Shukla, RMP **78**, 591 (2006)

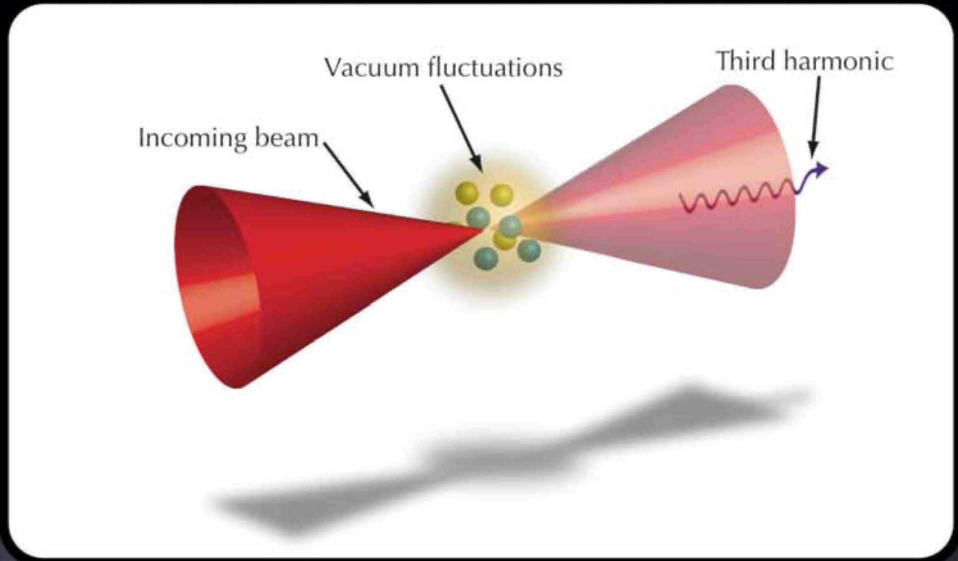
Possible future studies

- Although speculative, collective incoherent quantum vacuum effects could possibly be studied using extremely heated cavities.
- Generation of radiation gas focal spot.
- Why? Approaching the Schwinger intensity: truly nonlinear QED vacuum.
- Could detect vacuum effects in incoherent system.



Harmonic generation

- Third harmonic generation from laser focusing in QED vacuum. (Fedotov & Narozhny, PLA **362**, 1 (2007))



- Considered as a possible source of pair plasma. (N.B. Narozhny et al., PLA **330**, 1 (2004))
- New nonlinear physics (as in laser-plasma case), higher harmonics?

Gravity and QFT

- Unruh-effect (W. Unruh, PRD **14**, 870 (1976)):

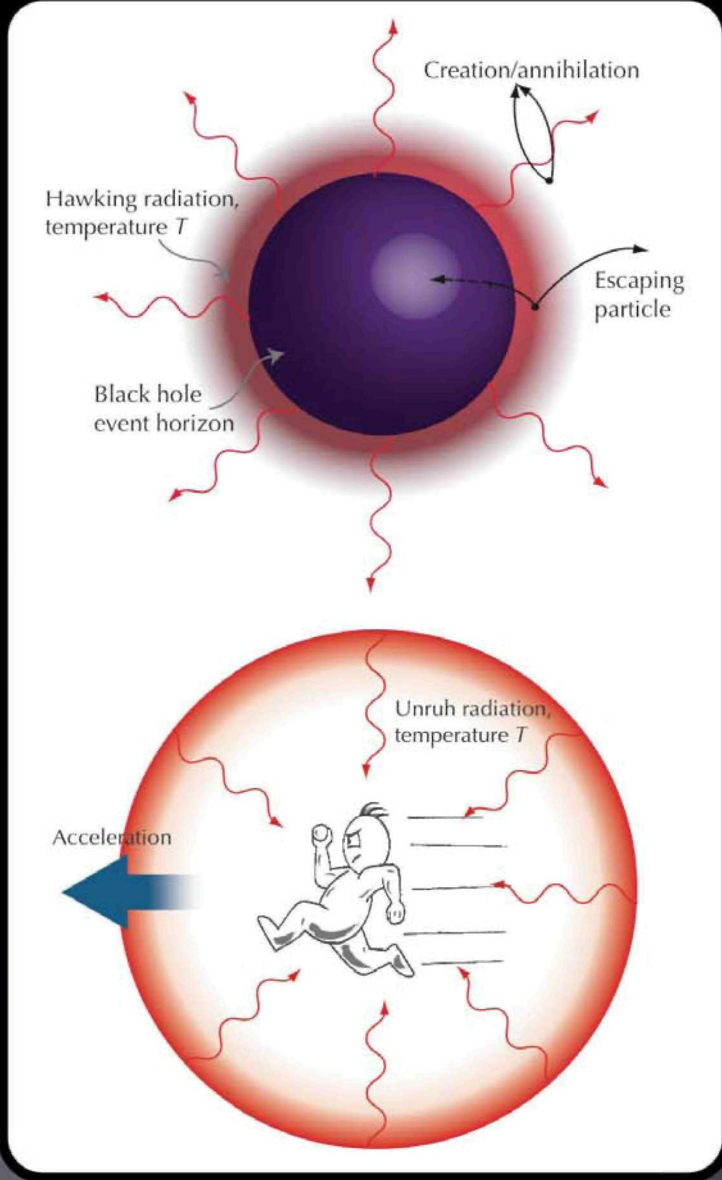
$$k_B T_U = \frac{\hbar a}{2\pi c}$$

- Test of curved spacetime effects in quantum field theory.

- Insight into Hawking radiation and black holes? (S.W. Hawking, Nature **248**, 30 (1974))

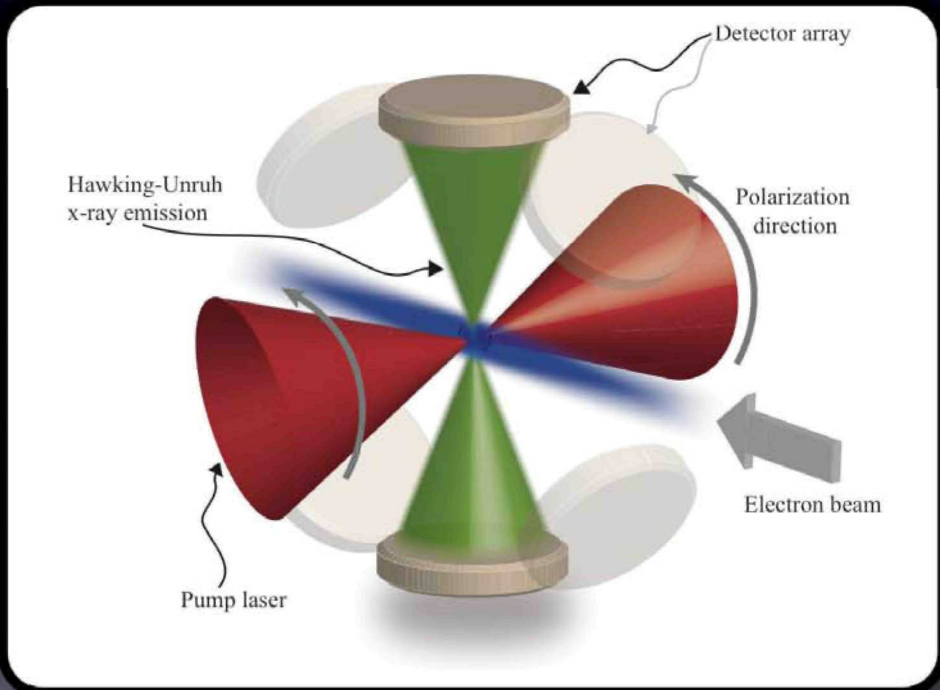
$$k_B T_H = \frac{\hbar g}{2\pi c}$$

- $T_H \leftrightarrow T_U$: Experiment? (Chen & Tajima, PRL **83**, 256 (1999); Schützhold *et al.*, PRL **97**, 121302 (2006))
    - Charged particles in intense laser field; window in Larmor radiation.



Detection of Unruh effect

- Experimental idea: use spectral properties of Unruh radiation (G. Brodin et al., submitted to PRL (2007)).



- Unique soft x-ray signature.

Conclusions

- Possible to experimentally probe uncharted quantum field theory sectors.
- Laser probes of photon-photon scattering.
  - Clean experiment, benchmark experiment?
  - Enhancement in plasma environments?
  - Low energy quantum gravity test.
- Interesting future possibilities:
  - Collective quantum vacuum effects.
  - Higher harmonic generation.
  - Hawking-Unruh tests and spacetime effects in quantum field theory.
  - Small scale particle colliders.
  - Pair production and coherent gamma sources.