

# Quantum vacuum phenomena in Strong Fields

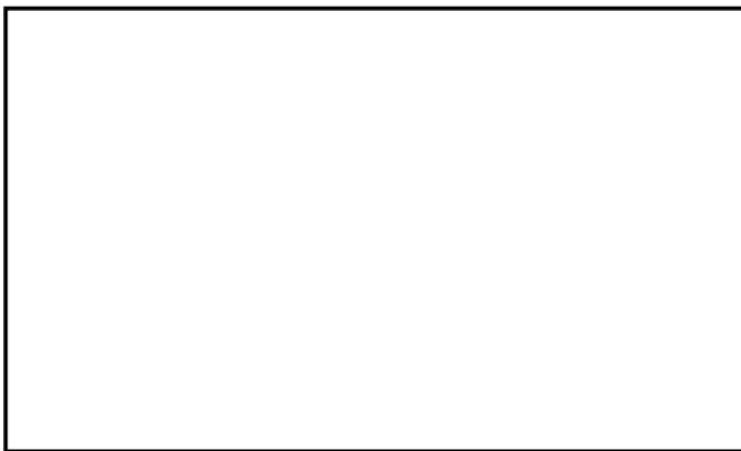
Holger Gies

Friedrich-Schiller-Universität Jena

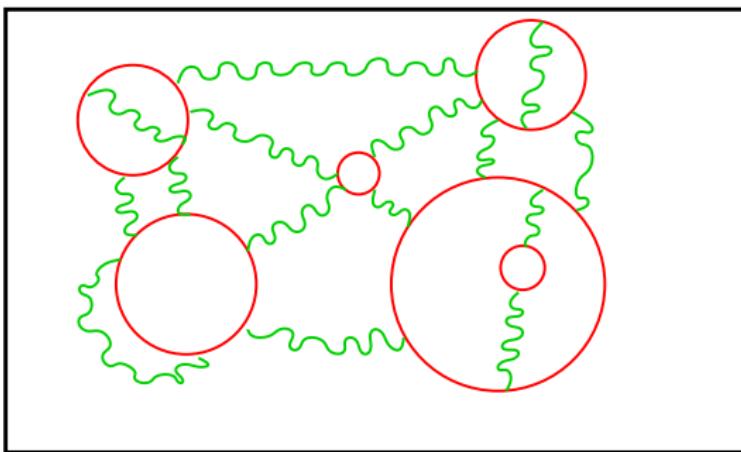


A view on the quantum vacuum.

# A view on the quantum vacuum.



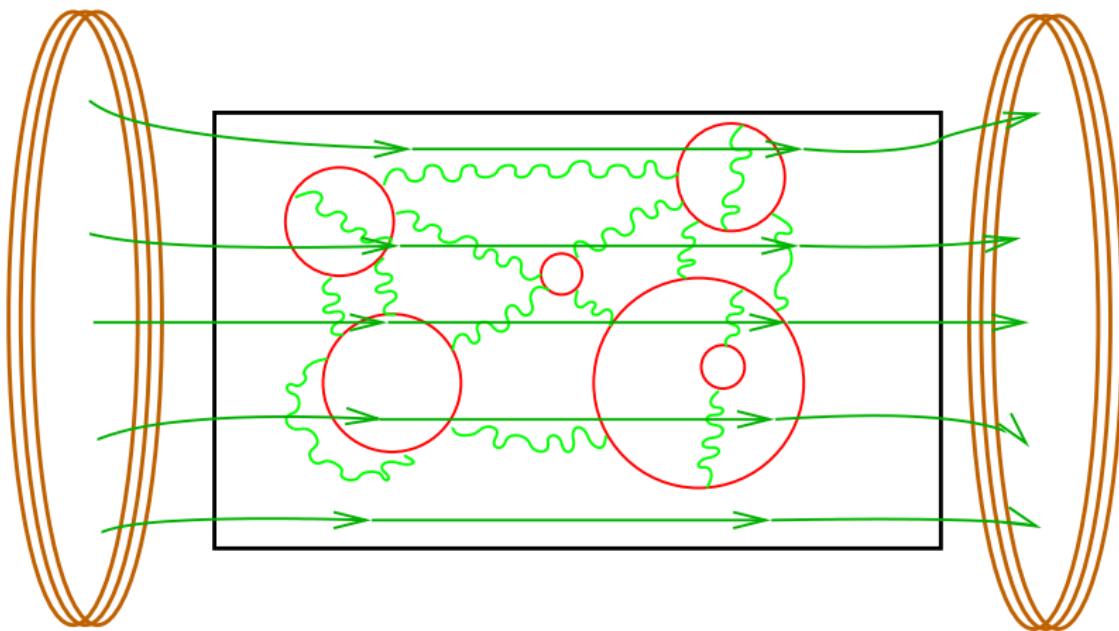
## A view on the quantum vacuum.



► QFT: quantum fluctuations

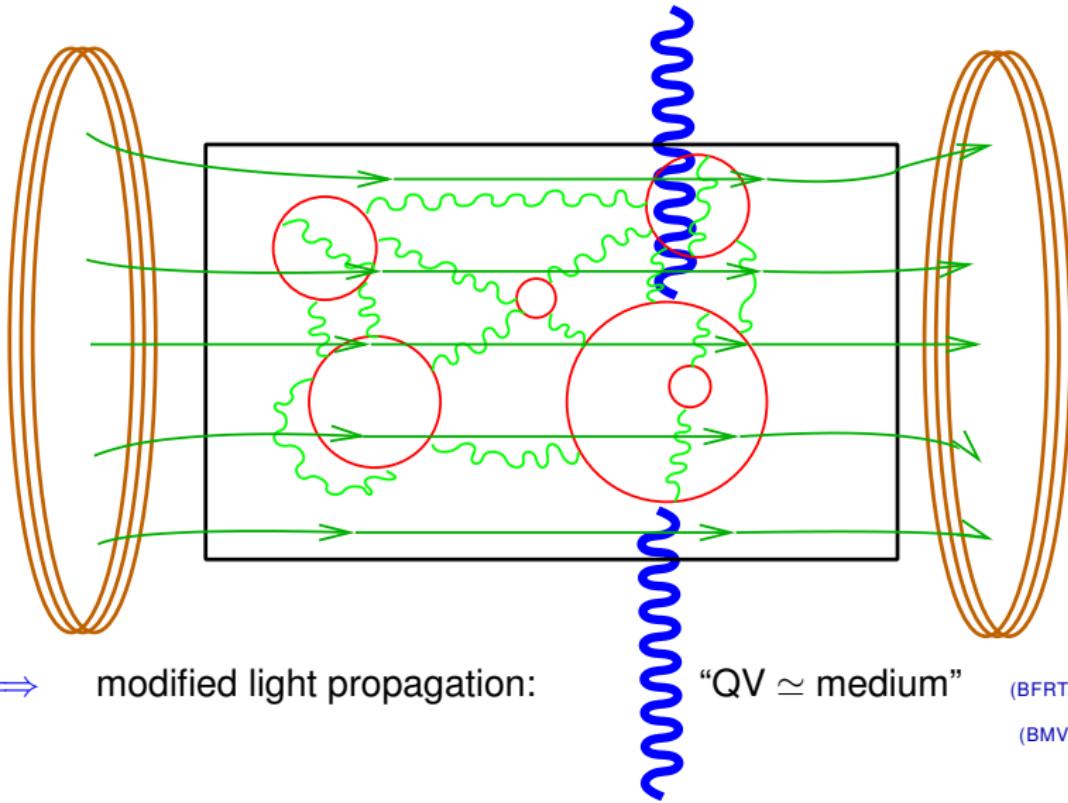
BUT: ... just a picture !

# A view on the quantum vacuum.



- ▷ External fields: Heisenberg-Euler effective action

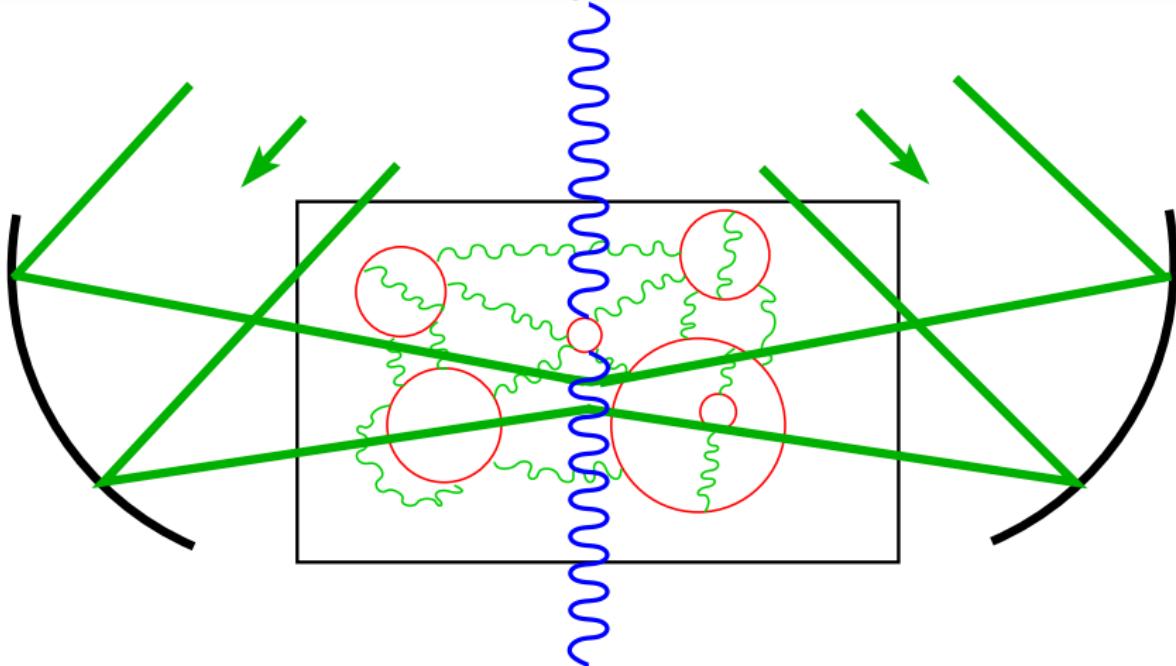
# A view on the quantum vacuum.



(BFRT,PVLAS,Q&A)

(BMV,OSQAR)

# A view on the quantum vacuum.



⇒ modified light propagation:

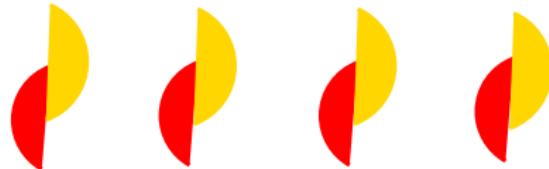
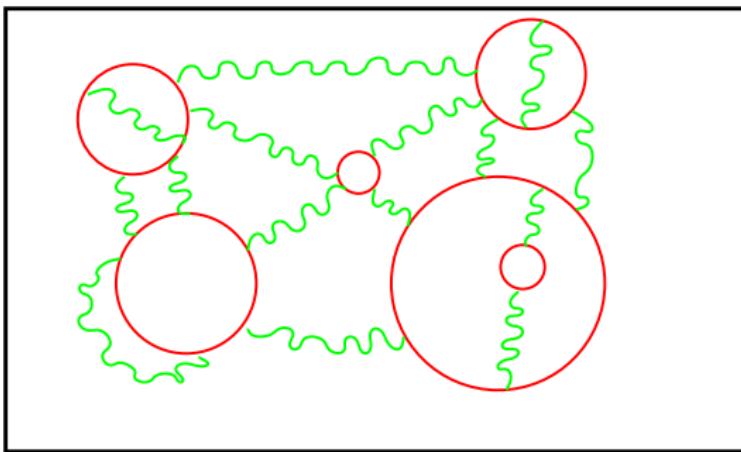
" $QV \simeq \text{medium}$ "

(POLARIS@JENA)

(HEINZL ET AL.'06)

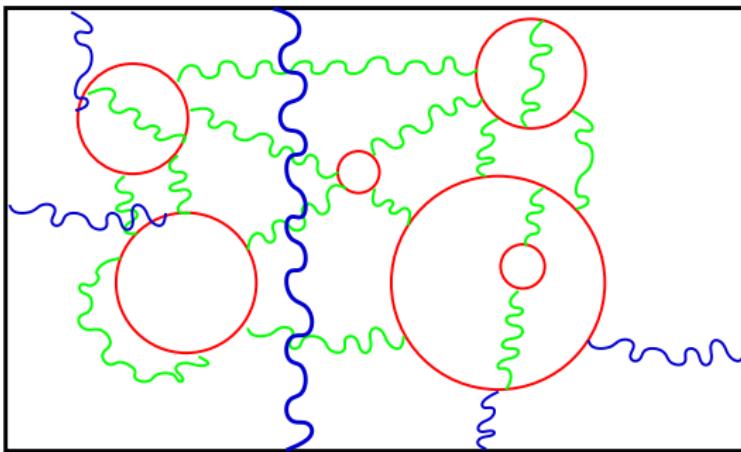
(B7@SFB-TR18)

# A view on the quantum vacuum



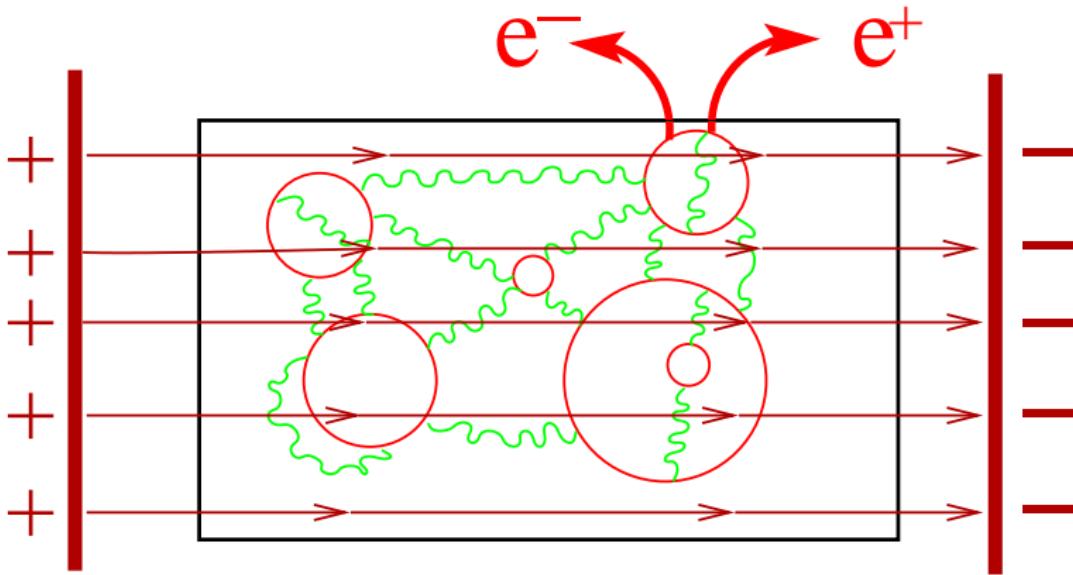
- ▷ Heat bath: quantum & thermal fluctuations

# A view on the quantum vacuum



- ▷ Boundary conditions: Casimir effect

# A view on the quantum vacuum



- ▶ electric fields: Schwinger pair production      “vacuum decay”

# Effective action

for the electromagnetized quantum vacuum

# Light Propagation

- ▶ classical Maxwell equation in vacuo

(MAXWELL 1861, 1865)

$$S = - \int d^4x \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \implies 0 = \partial_\mu F^{\mu\nu}$$

- ▶ velocity of a plane-wave solution:

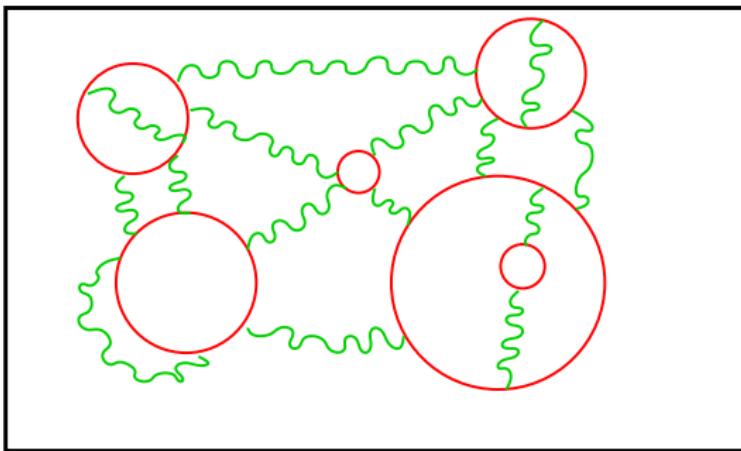
$$v = 1 \quad (= c)$$

- ▶ superposition principle

$$F^{\mu\nu} = F_1^{\mu\nu} + F_2^{\mu\nu}$$

⇒ no self-interactions

# Self-interactions from the Quantum Vacuum



Mind the  $e^+e^-$  fluctuations

## Electron mass scale

▷ the electron ...

$$\textcolor{red}{m} \simeq 511 \text{ keV} \simeq 9 \cdot 10^{-31} \text{ kg}$$

... is very heavy!

▷  $\hbar = 1 = c$

- $E_{\text{cr}} \simeq 1.3 \cdot 10^{18} \text{ Volt/m}$
- $m \simeq 7.6 \cdot 10^{11} \text{ GHz}$
- $m \simeq 6 \cdot 10^9 \text{ Kelvin}$
- $m^2 \simeq 1.3 \cdot 10^9 \text{ Tesla}$

**m**

# Electron mass scale

▷ the electron ...

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... is very heavy!

▷  $\hbar = 1 = c$

- $E_{\text{cr}} \simeq 1.3 \cdot 10^{18} \text{ Volt/m}$        $I_{\text{cr}} \equiv E_{\text{cr}}^2 \simeq 4.4 \times 10^{29} \text{ W/cm}^2$
- $m \simeq 7.6 \cdot 10^{11} \text{ GHz}$        $\Rightarrow$  Polaris:       $\sim 1\% \text{ } \textcolor{red}{m}$
- $m \simeq 6 \cdot 10^9 \text{ Kelvin}$        $\Rightarrow$  ELI:       $\sim 25\% \text{ } \textcolor{red}{m}$
- $m^2 \simeq 1.3 \cdot 10^9 \text{ Tesla}$        $\Rightarrow$  U ion:       $\sim 138\% \text{ } \textcolor{red}{m}$

# From QED to Nonlinear ED

- ▶ mass scale  $m$  divides quantum fluctuations in

hard  $|p^2| > m^2$

(photons and electrons)

soft  $|p^2| < m^2$

(only photons =EM fields)

## Physics of the soft fields:

average over  $\int$  (integrate out) hard modes

⇒ Heisenberg-Euler effective action  $\Gamma$

## Heisenberg-Euler Effective Action

- ▷ vacuum energy

$$E = \frac{1}{2} \hbar \omega$$

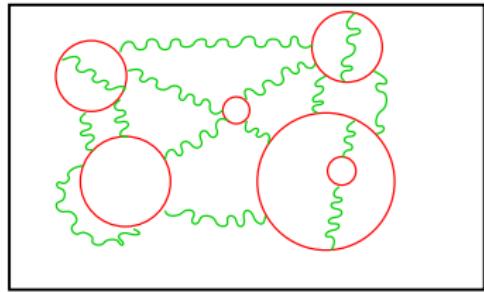
# Heisenberg-Euler Effective Action

- ▷ vacuum energy

$$E = \frac{1}{2} \hbar \sum_n \omega_n$$

- ▷ electron modes

$$\omega_n = \sqrt{\vec{p}^2 + m^2}$$



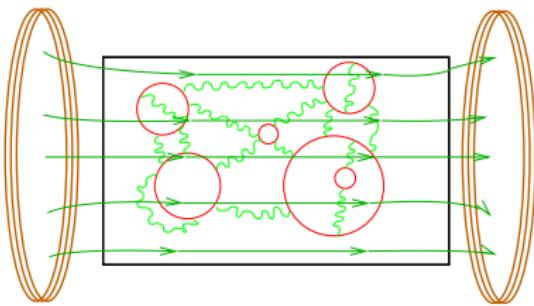
# Heisenberg-Euler Effective Action

- ▷ vacuum energy

$$E = \frac{1}{2} \hbar \sum_n \omega_n$$

- ▷ electron modes

$$\omega_n = \sqrt{p_{\parallel}^2 + m^2 + eB(2n+1 \pm 1)}$$



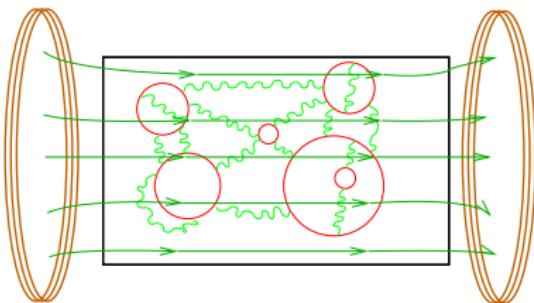
# Heisenberg-Euler Effective Action

- ▷ vacuum energy

$$E = \frac{1}{2} \hbar \sum_n \omega_n$$

- ▷ electron modes

$$\omega_n = \sqrt{p_{\parallel}^2 + \cancel{m^2} + eB(2n+1 \pm 1)}$$



- ▷ Heisenberg-Euler effective action  $\Gamma$

(HEISENBERG & EULER '36; WEISSKOPF '36)

$$\begin{aligned}\frac{\Gamma^1}{L_t} &= -\Delta E(\cancel{B}) = -\frac{1}{2} \hbar \sum_n (\omega_n(\cancel{B}) - \omega_n(\cancel{B}=0)) \\ &= \frac{1}{8\pi^2} \int_0^\infty \frac{ds}{s^3} e^{-\cancel{m^2}s} \left( \frac{eBs}{\tanh eBs} - 1 \right) \quad (\text{unrenormalized})\end{aligned}$$

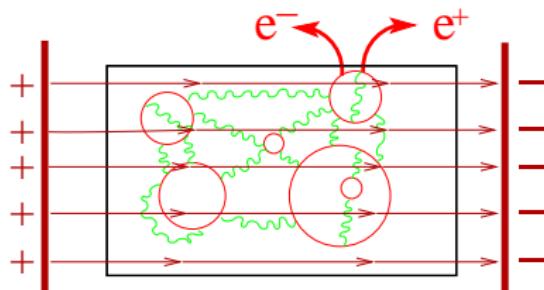
# Heisenberg-Euler Effective Action

- ▷ vacuum energy

$$E = \frac{1}{2} \hbar \sum_n \omega_n$$

- ▷ electric fields

$$B \rightarrow iE$$



- ▷ Heisenberg-Euler effective action  $\Gamma$

(HEISENBERG & EULER'36; WEISSKOPF'36)

$$\frac{\Gamma^1}{L_t} = \frac{1}{8\pi^2} \int_0^\infty \frac{ds}{s^3} e^{-m^2 s} \left( \frac{eEs}{\tan eEs} - 1 \right) \quad (\text{unrenormalized})$$

$$\Rightarrow \text{Im}\Gamma[E] \neq 0 \quad (\text{SAUTER'31})$$

- ▷ vacuum persistence probability:

$$P = \exp(-2 \text{Im}\Gamma)$$

# Heisenberg-Euler Effective Action.

(EULER, KOCKEL'35; HEISENBERG, EULER'36; WEISSKOPF'36; SCHWINGER'51; RITUS'76)

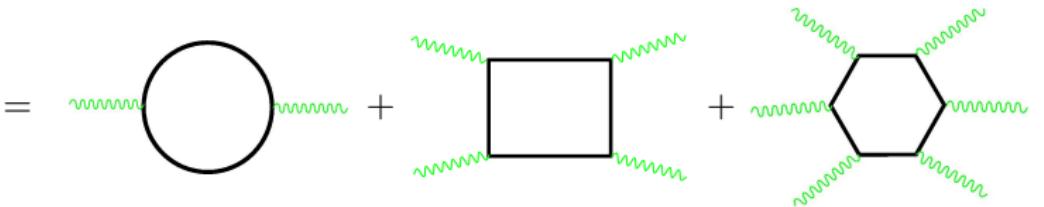
$$\begin{aligned}\Gamma &= \text{wavy line} + \text{loop with wavy lines} + 1\% \text{ loop with wavy lines and blue wavy line} + \dots \\ &= - \int \mathcal{F} + \frac{1}{8\pi^2} \int_X \int \frac{ds}{s} e^{-im^2 s} \left[ (es)^2 |\mathcal{G}| \cot(es\sqrt{\sqrt{\mathcal{F}^2 + \mathcal{G}^2} + \mathcal{F}}) \right. \\ &\quad \left. \times \coth(es\sqrt{\sqrt{\mathcal{F}^2 + \mathcal{G}^2} - \mathcal{F}}) \right] \dots\end{aligned}$$

Conventions:  $\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}(B^2 - E^2)$ ,  $\mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = -B \cdot E$

# Heisenberg-Euler Effective Action.

(EULER, KOCKEL'35; HEISENBERG, EULER'36; WEISSKOPF'36; SCHWINGER'51; RITUS'76)

▷ weak-field expansion

$$\Gamma = \int \left\{ -\mathcal{F} + \frac{8}{45} \frac{\alpha^2}{m^4} \mathcal{F}^2 + \frac{14}{45} \frac{\alpha^2}{m^4} \mathcal{G}^2 + \mathcal{O}(\mathcal{F}^6) \right\}$$
$$= \text{circle diagram} + \text{square diagram} + \text{hexagon diagram} \dots$$


Conventions:  $\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} (B^2 - E^2)$ ,  $\mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = -B \cdot E$

# Light Propagation.

- ▶ classical Maxwell equation in vacuo

(MAXWELL 1861, 1865)

$$0 = \partial_\mu \textcolor{green}{F}^{\mu\nu}$$

- ▶ velocity of a plane-wave solution:

$$v = 1 \quad (= \textcolor{blue}{c})$$

# Light Propagation in a $B$ field.

▷ quantum Maxwell equation

(HEISENBERG,EULER'36;WEISSKOPF'36)

$$0 = \partial_\mu \left( F^{\mu\nu} - \frac{1}{2} \frac{8}{45} \frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} - \frac{1}{2} \frac{14}{45} \frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} \tilde{F}^{\mu\nu} \right)$$

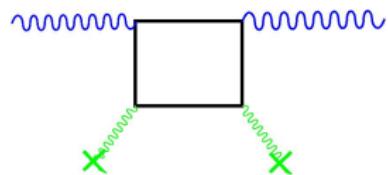
# Light Propagation in a $B$ field.

- ▷ quantum Maxwell equation for a “light probe”  $f^{\mu\nu}$

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45} \frac{\alpha^2}{m^4} F_{\alpha\beta} F^{\mu\nu} \partial_\mu f^{\alpha\beta} - \frac{14}{45} \frac{\alpha^2}{m^4} \tilde{F}_{\alpha\beta} \tilde{F}^{\mu\nu} \partial_\mu f^{\alpha\beta}$$

## Phase and group velocity

$$\begin{aligned} v_{\parallel} &\simeq 1 - \frac{14}{45} \frac{\alpha^2}{m^4} B^2 \sin^2 \theta_B \\ v_{\perp} &\simeq 1 - \frac{8}{45} \frac{\alpha^2}{m^4} B^2 \sin^2 \theta_B \end{aligned}$$



(TOLL'54)

(BAIER, BREITENLOHNER'67; NAROZHNIY'69)

(BIALYNICKA-BIRULA, BIALYNICKI-BIRULA'70)

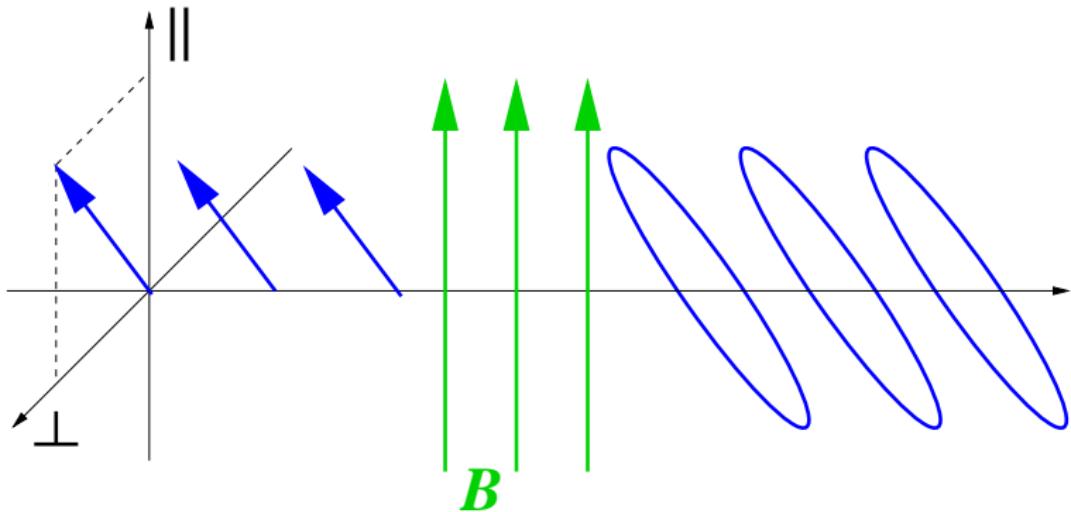
(ADLER'71)

⇒ magnetized quantum vacuum induces birefringence

- ▷ detection schemes: PVLAS, BMV, Q&A, OSQAR, TR18-B7

# Light Propagation in a $B$ field.

- ▷ observable: birefringence induces ellipticity



- ▷ ellipticity:

$$\Delta\phi = \pi \frac{L}{\lambda} \Delta v \sin 2\theta, \quad \Delta v(5.5T) \simeq 10^{-22}$$

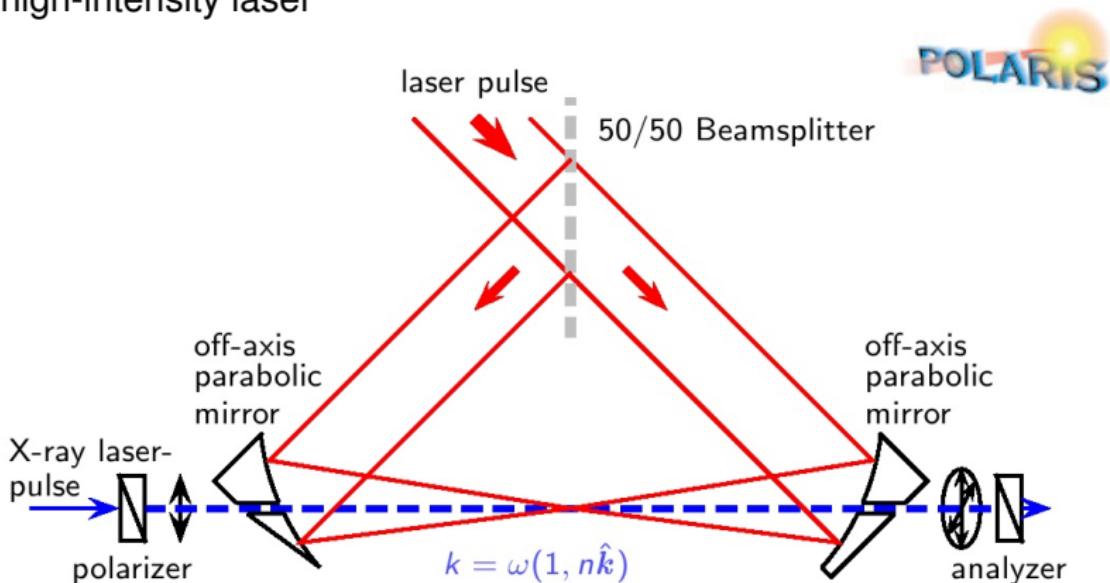
# Quantum Vacuum@Jena

- ▷ birefringence at a photon collider

(HEINZL,LIESFELD,AMTHOR,SCHWOERER,SAUERBREY,WIPF'06)

(SFB-TR18-PROPOSAL: HG,KALUZA,WIPF,PAULUS'08)

- ▷ high-intensity laser



# Birefringence@Jena

(Koch,Heinzl,Wipf'05)

- ▷ back-scattered Thomson photons

$$\omega \simeq 2 \times 10^{-3} m$$

- ▷ intensity

$$I = 2 \times 10^{-8} I_{\text{cr}} \simeq 10^{22} \text{W/cm}^2$$

- ▷ parameters ( $\omega$  in keV,  $\lambda$  in nm,  $z_0$  in  $\mu\text{m}$ )

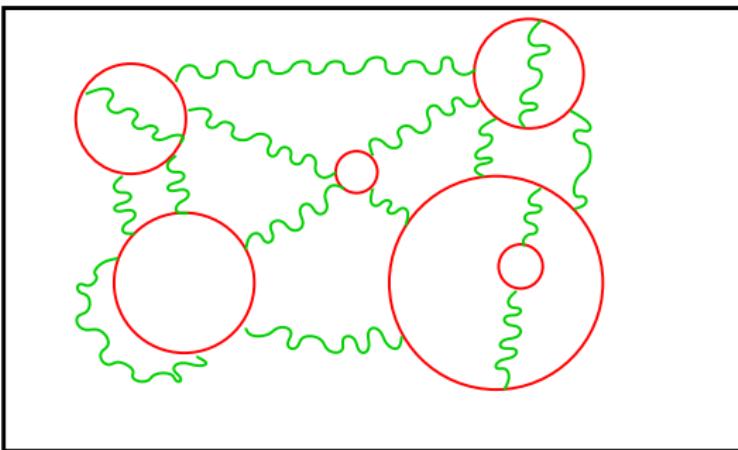
	$\omega$	$\lambda$	$L$	$\Delta\phi$ (rad)
Polaris	1	1.2	10	$1.2 \times 10^{-6}$
	12	0.1	10	$1.4 \times 10^{-5}$
XFEL	15	0.08	25	$4.4 \times 10^{-5}$

- ▷ vacuum: pre-pulse?

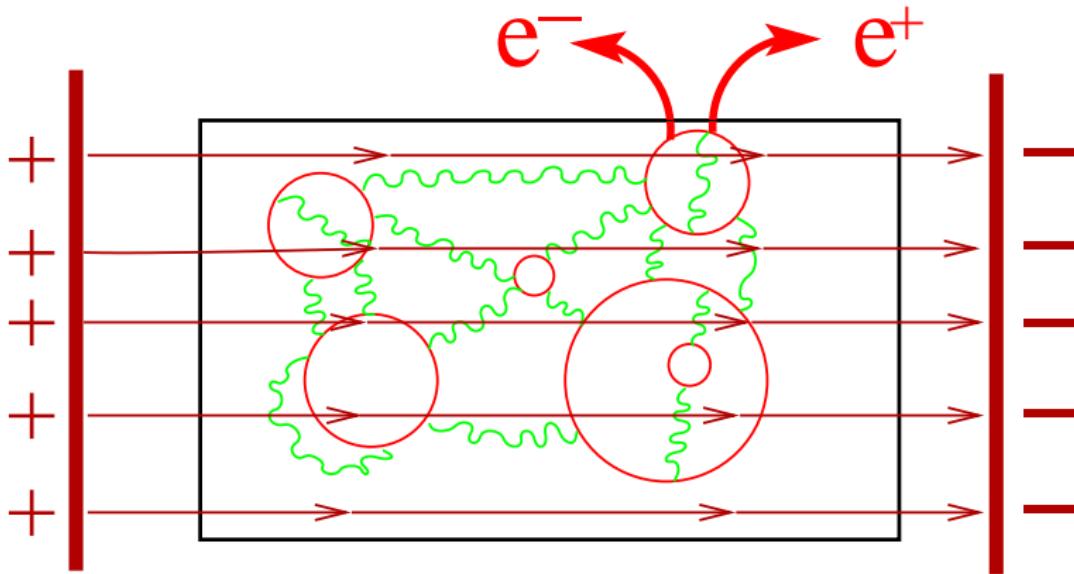
- ▷ x-ray optics, in principle  $\Delta\phi \simeq 6 \times 10^{-6}$  ?

(Alp et al.'00)

# Quantum vacuum



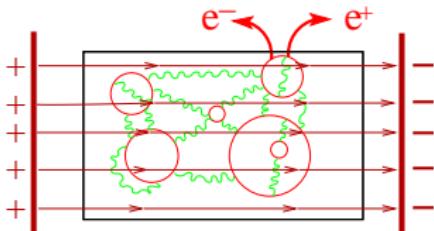
# Quantum vacuum



- ▶ electric fields: Schwinger pair production      “vacuum decay”

# Schwinger pair production

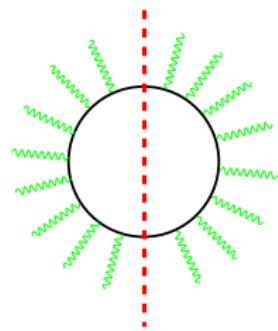
(SAUTER'31; HEISENBERG, EULER'36; SCHWINGER'51)



▷ production rate  $(E_{\text{cr}} = \frac{m^2}{e})$

$$\mathcal{W} = \frac{(eE)^2}{4\pi^3} \exp\left(-\frac{m^2}{e} \frac{\pi}{E}\right)$$

“nonperturbative” phenomenon

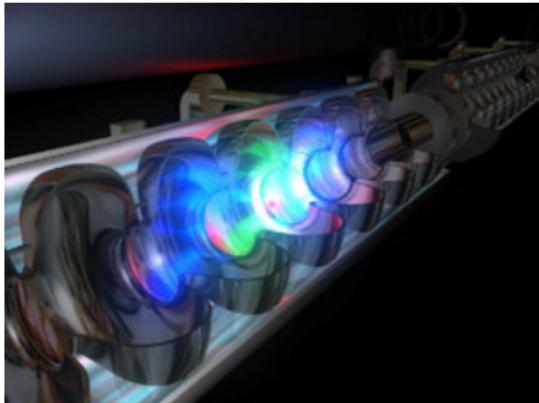


# Schwinger pair production

- ▷ e.g., pair production in RF cavities

$$E \simeq 100 \text{ MV/m}$$

$$\text{Vol} \simeq 1 \text{ m}^3$$



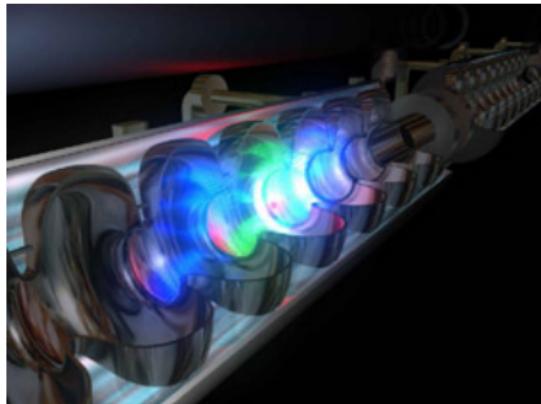
- ▷ vacuum decay time  $\Leftrightarrow$  production time of 1 pair:

## Schwinger pair production

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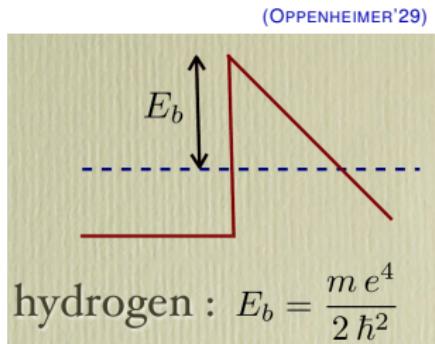
- ▷ vacuum decay time  $\Leftrightarrow$  production time of 1 pair:

$$\tau \sim 10^{5000000000} \text{ s}$$

# Pair Production as Tunneling

▷ cf. atomic ionization as tunneling:

$$P \sim \exp \left[ -\frac{4}{3} \frac{\sqrt{2m} E_b^{3/2}}{eE} \right]$$
$$\sim \exp \left[ -\frac{2}{3} \frac{m^2 e^6}{eE} \right]$$



▷ pair production as tunneling:

(SAUTER'31; HEISENBERG,EULER'36)

$$P \sim \exp \left[ -\frac{\pi m^2}{eE} \right] \quad E_b = 2m$$
$$\sim \exp \left[ -\frac{2}{3} \frac{m^2 e^6}{eE} \times \frac{3\pi}{2\alpha^3} \right] \quad \text{factor } \sim 10^7$$

# Schwinger Pair Production?

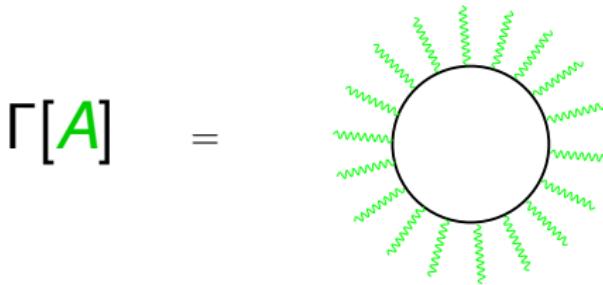
- Are there mechanisms to enhance pair production?  
*... nonperturbative QFT, ~ Hawking radiation ...*
- $E$  fields with spatial and temporal inhomogeneities?  
*... quantum energies, Casimir phenomena ...*
- Real-time evolution and momentum distributions?  
*... non-equilibrium QFT: early universe, HIC, baryogenesis ...*

# Inhomogeneous Fields

# Effective action $\Gamma$ in inhomogeneous fields

Remember ...

- ▷ quantum energies  $E = \frac{1}{2} \sum_n \omega_n[A]$ ,  $E = \frac{\Gamma}{T}$
- ▷ effective action:

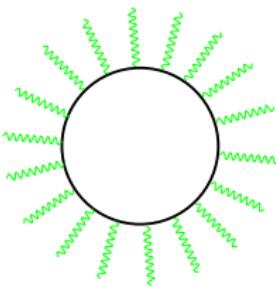


Problem solved, “in principle”

- find spectrum  $\omega_n[A]$  for a given background  $A$
- sum over spectrum

# Effective action $\Gamma$ in inhomogeneous fields

$$\Gamma[A] = \frac{T}{2} \sum_n \omega_n[A]$$



BUT:

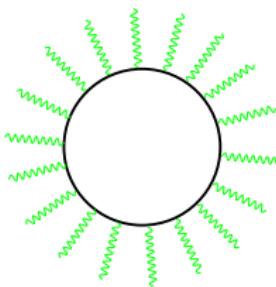


In general practice:

- spectrum  $\{\omega_n[A]\}$  not known analytically
- spectrum  $\{\omega_n[A]\}$  not bounded
- $\sum_n \rightarrow \infty$  (regularization)
- renormalization

# Effective action $\Gamma$ in inhomogeneous fields

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In general practice:

- spectrum  $\{\omega_n[A]\}$  not known analytically
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# Worldline representation of $\Gamma$

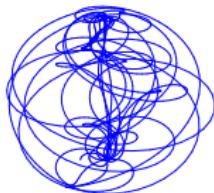
$$\Gamma[A] = \int_{1/\Lambda^2}^{\infty} \frac{dT}{T} e^{-m^2 T} \mathcal{N} \int \mathcal{D}\mathbf{x}(\tau) e^{-\int_0^T d\tau \left( \frac{\dot{\mathbf{x}}^2}{4} + ie \dot{\mathbf{x}} \cdot A(\mathbf{x}_\tau) \right)}$$

(FREYMAN'50)

(BERN&KOSOWER'92; STRASSLER'92)

(SCHMIDT&SCHUBERT'93)

$$x(T) =$$



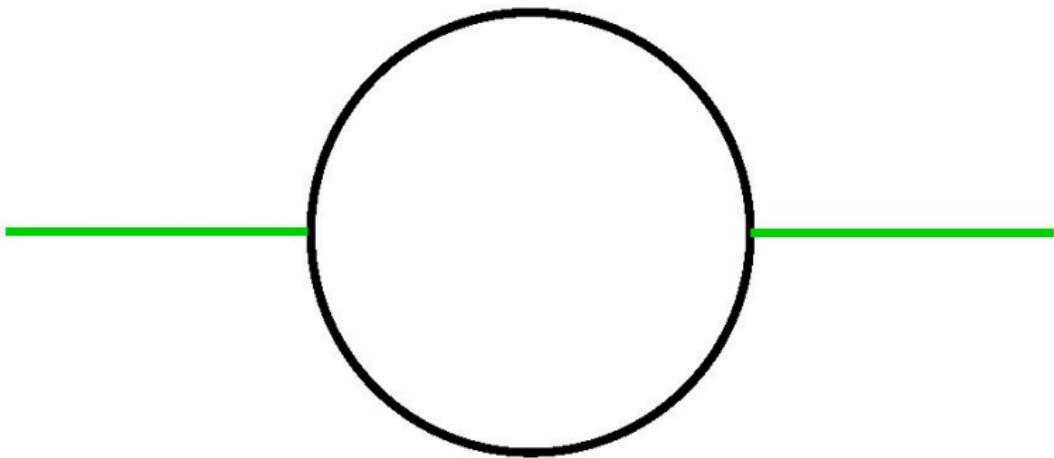
(HG&LANGFELD'01)

## Worldline approach:

- effective action  $\Gamma \sim \int$  closed worldlines  $x(\tau)$
- worldline  $\sim$  spacetime trajectory of  $\phi$  fluctuations
- gauge-field interaction  $\sim$  “Wegner-Wilson loop”
- finding  $\{\omega_n[A]\}$  and  $\sum_n$  done in one finite (numerical) step

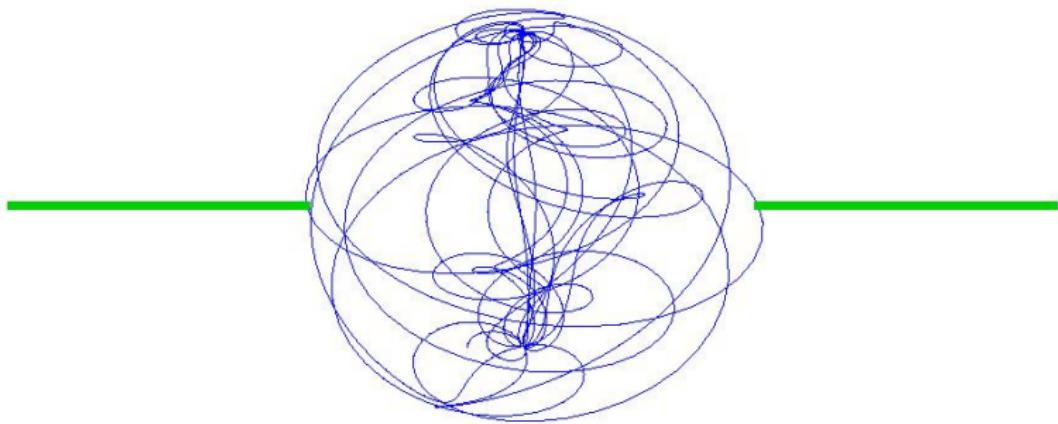
## Trajectory of a Quantum Fluctuation.

- ▷ Feynman diagram (conventionally in momentum space)



# Trajectory of a Quantum Fluctuation.

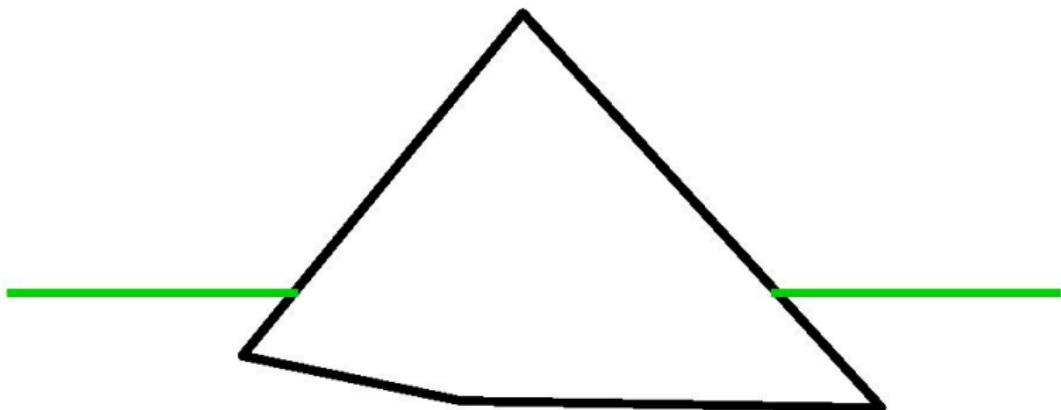
- ▷ worldline (artist's view)



# Trajectory of a Quantum Fluctuation.

► worldline numerics:

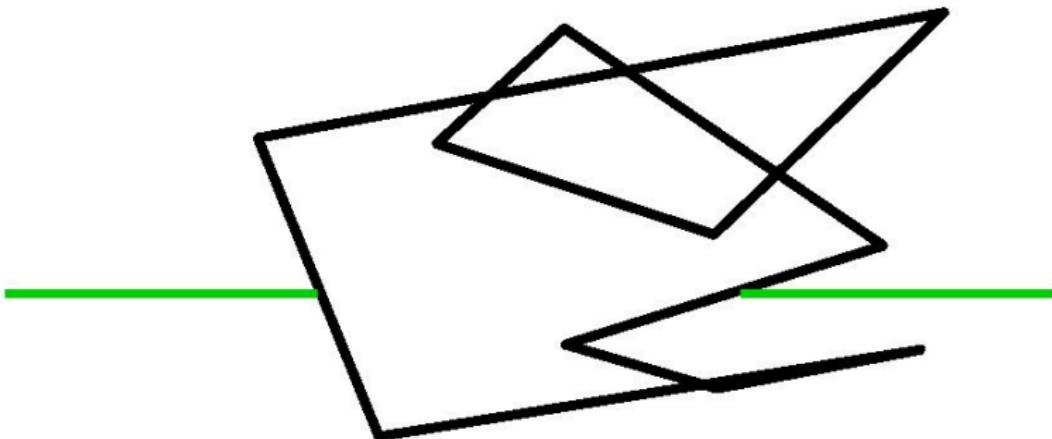
$N = 4$  points per loop (ppl)



# Trajectory of a Quantum Fluctuation.

► worldline numerics:

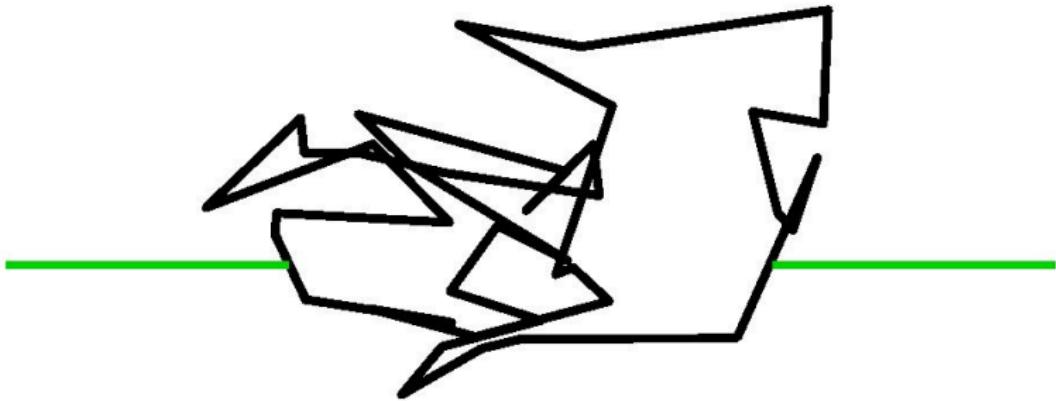
$N = 10$  points per loop (ppl)



# Trajectory of a Quantum Fluctuation.

► worldline numerics:

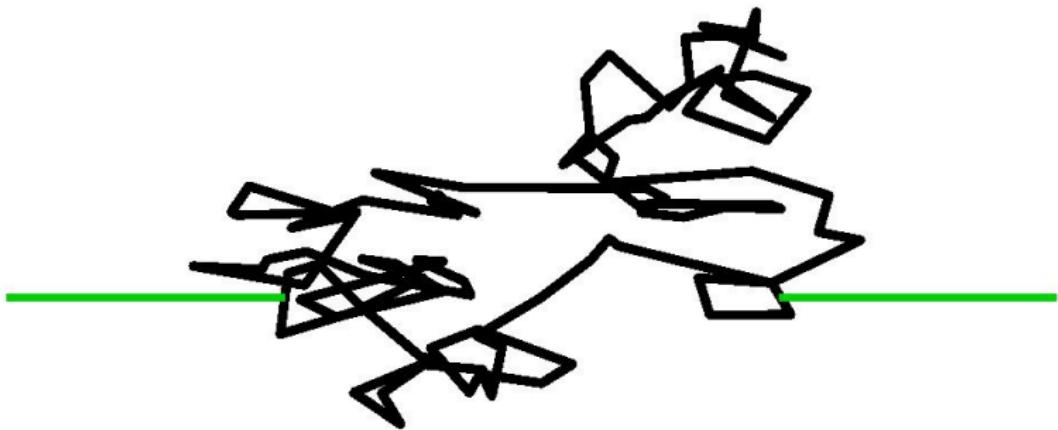
$N = 40$  points per loop (ppl)



# Trajectory of a Quantum Fluctuation.

► worldline numerics:

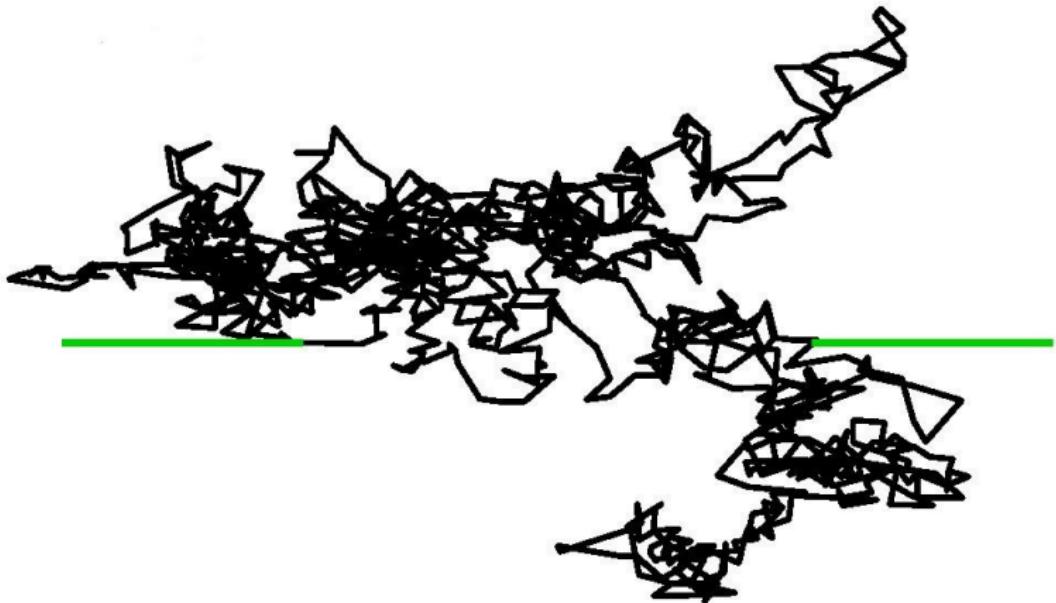
$N = 100$  points per loop (ppl)



# Trajectory of a Quantum Fluctuation.

► worldline numerics:

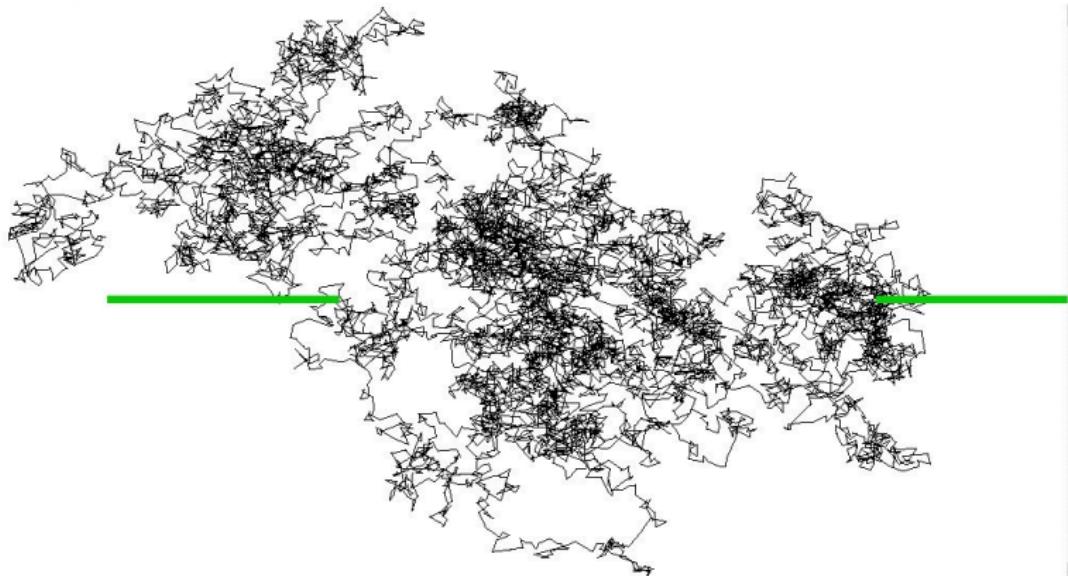
$N = 1000$  points per loop (ppl)



# Trajectory of a Quantum Fluctuation.

► worldline numerics:

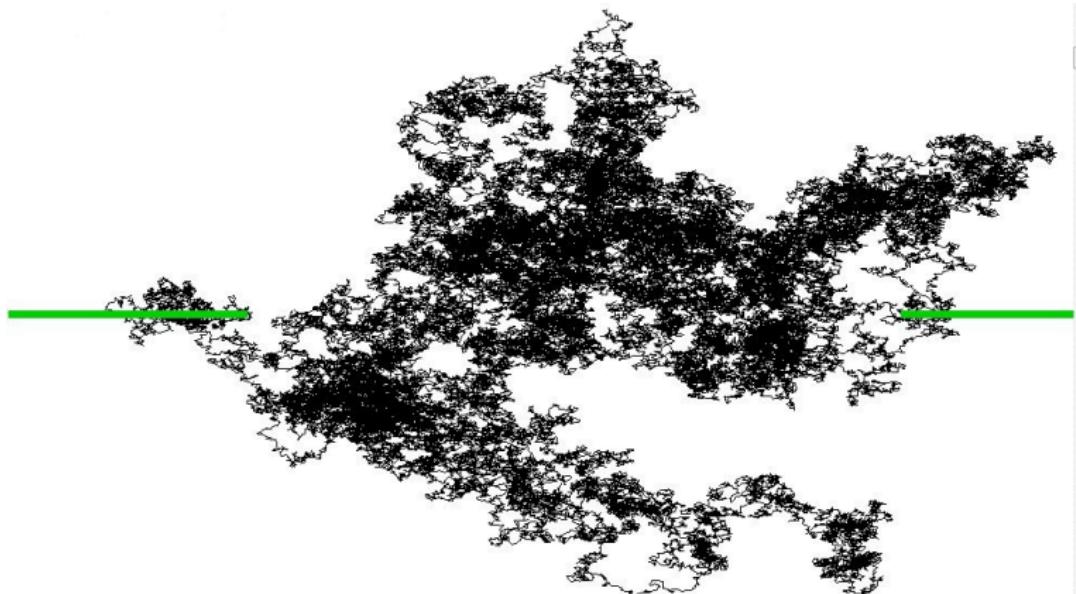
$N = 10000$  points per loop (ppl)



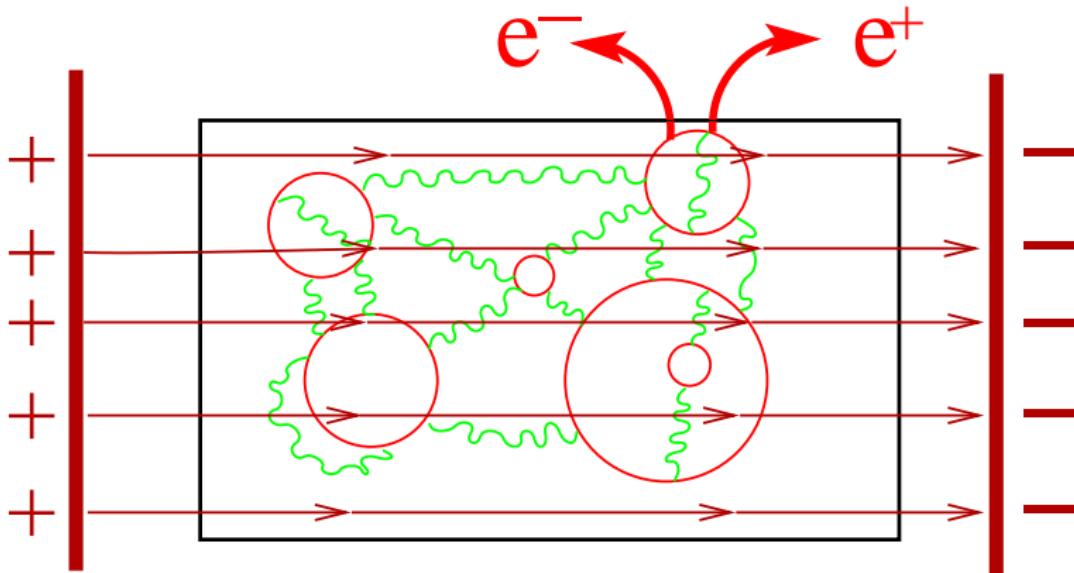
# Trajectory of a Quantum Fluctuation.

► worldline numerics:

$N = 100000$  points per loop (ppl)



# Quantum vacuum

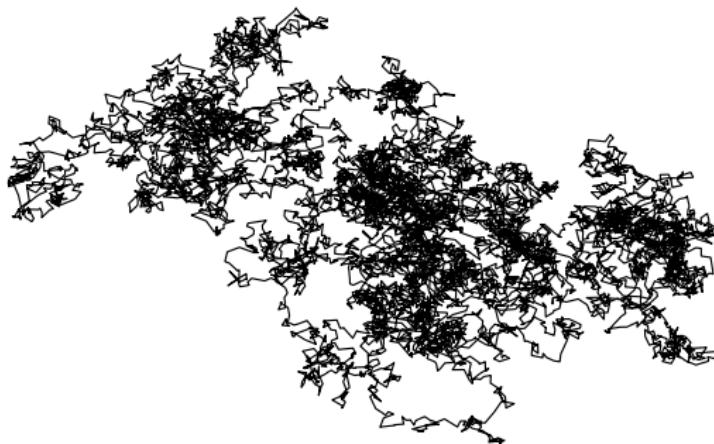


- ▶ electric fields: Schwinger pair production      “vacuum decay”

# Schwinger pair production

► worldline picture

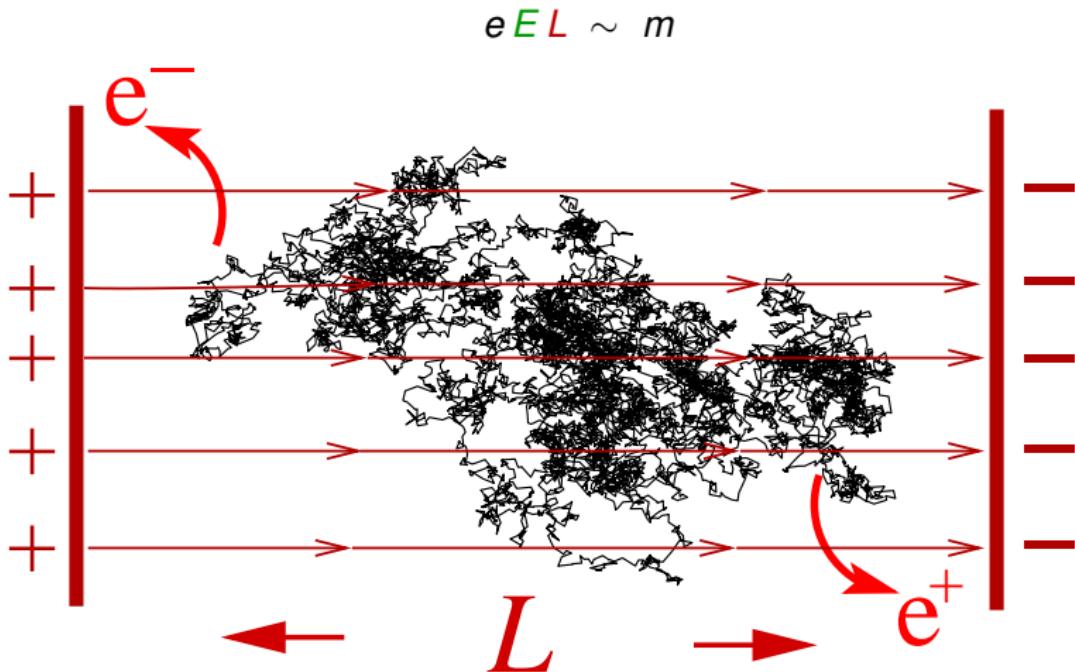
(HG,KLINGMULLER'05)



# Schwinger pair production

▷ worldline picture

(HG,KLINGMULLER'05)

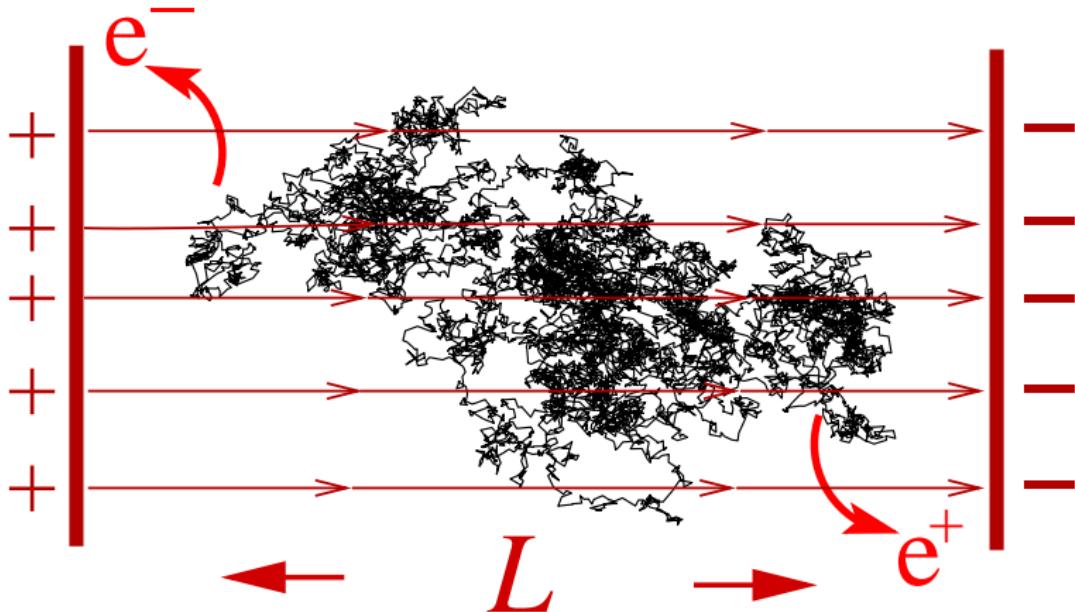


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▷ worldline picture

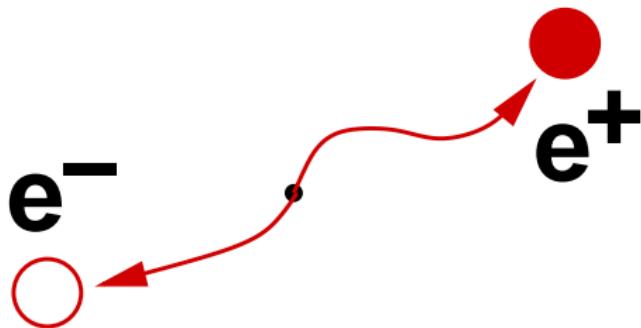
(HG,KLINGMULLER'05)

$$L \sim \frac{1}{m}: \quad E_{\text{cr}} = \frac{m^2}{e} \simeq 1.3 \times 10^{18} \text{V/m}$$



## $e^+ e^-$ pair production

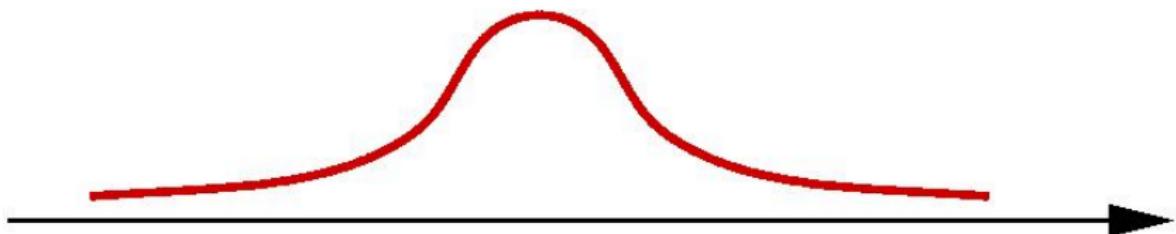
- ▶ Pair production requires delocalization !



$$e \int d\mathbf{s} \cdot \mathbf{E} > 2m$$

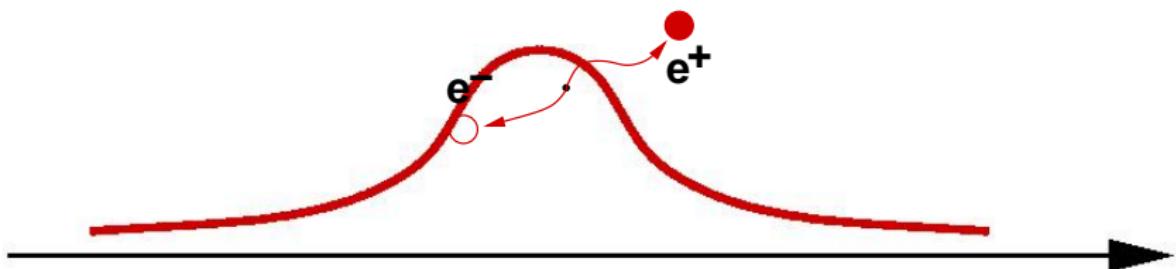
## $e^+ e^-$ pair production

- ▷ e.g., a localized field  $E \sim \text{sech}^2 kx$ :



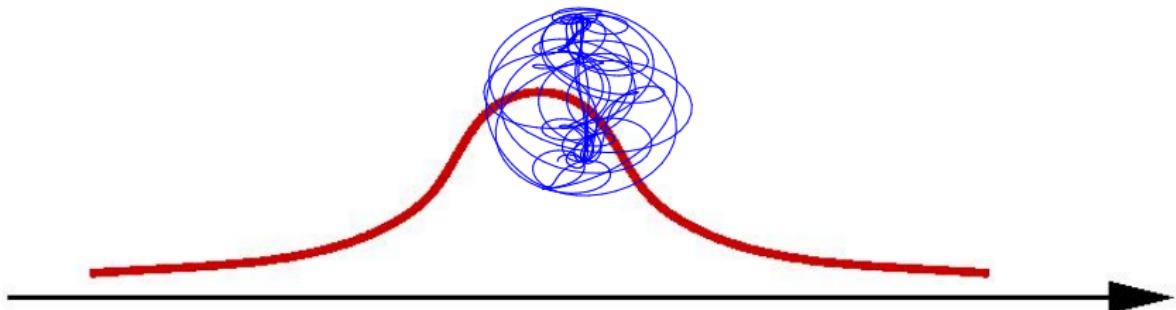
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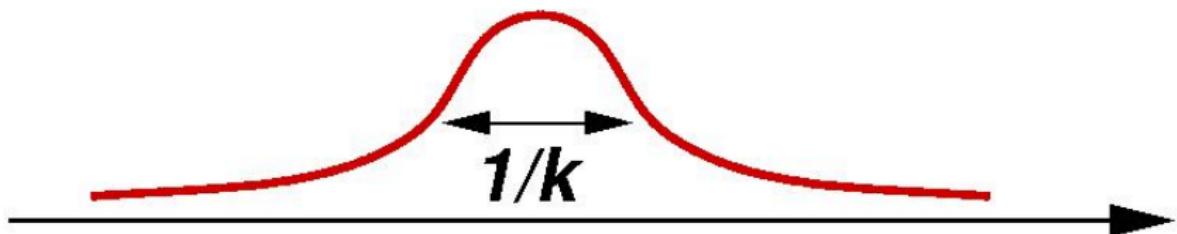
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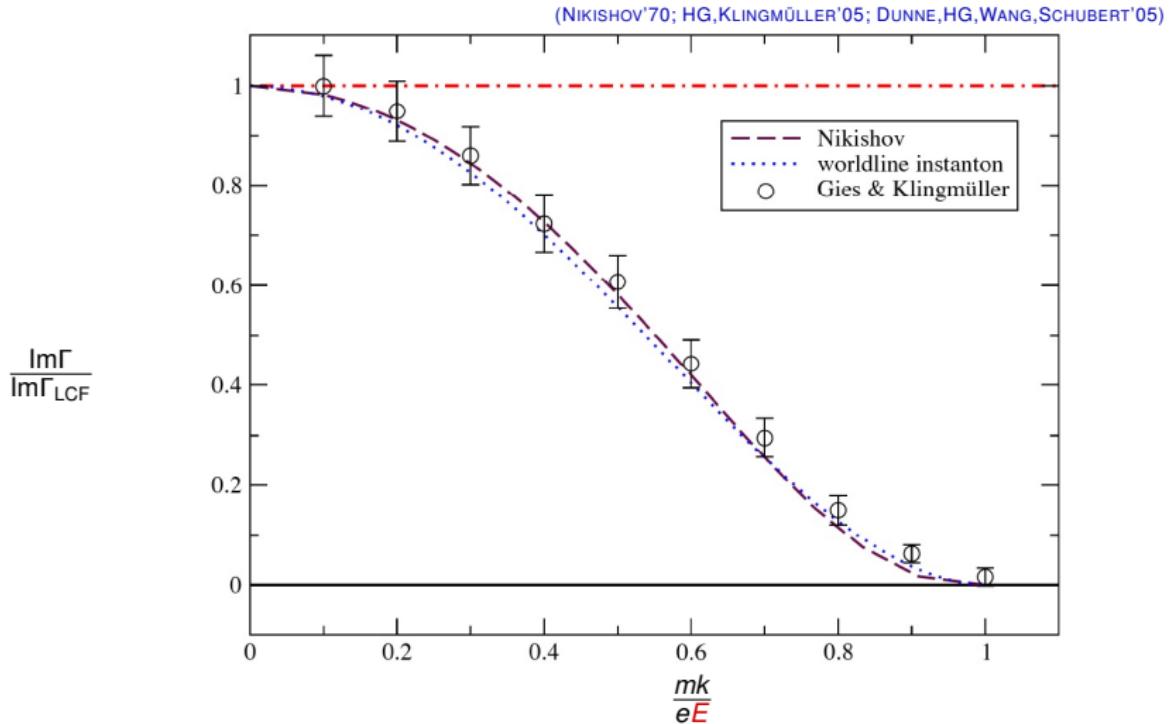
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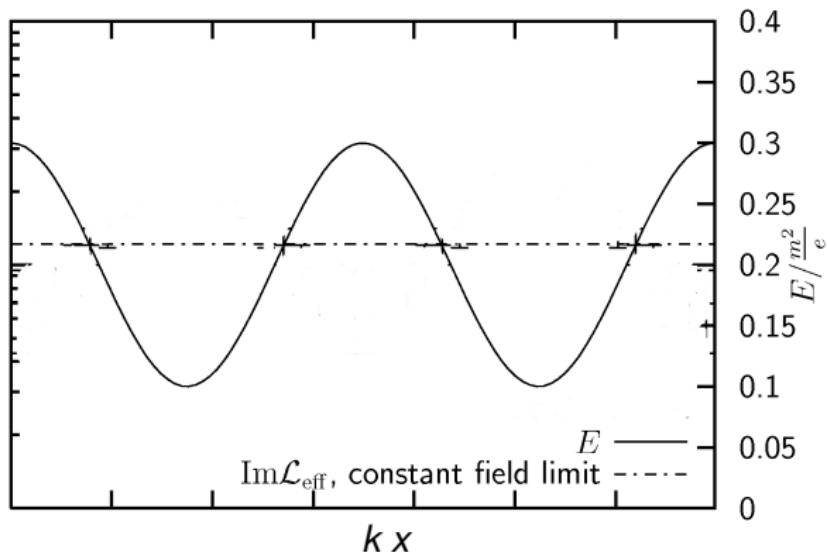
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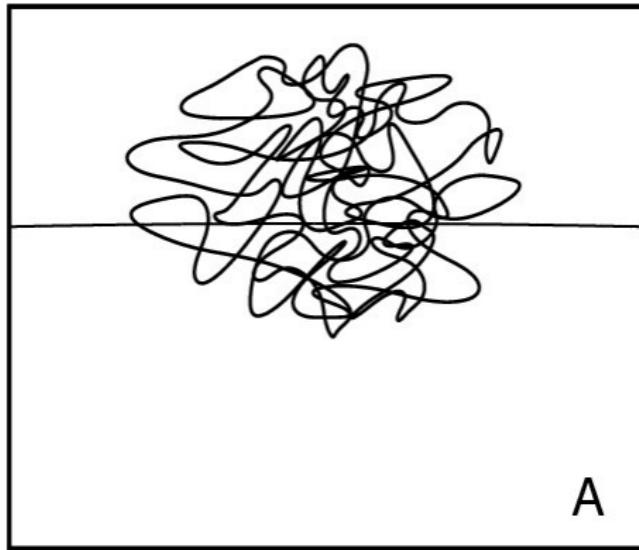
## $e^+ e^-$ pair production

- ▷ sine-modulated field:  $E(x) = E_0 + E_1 \sin kx$



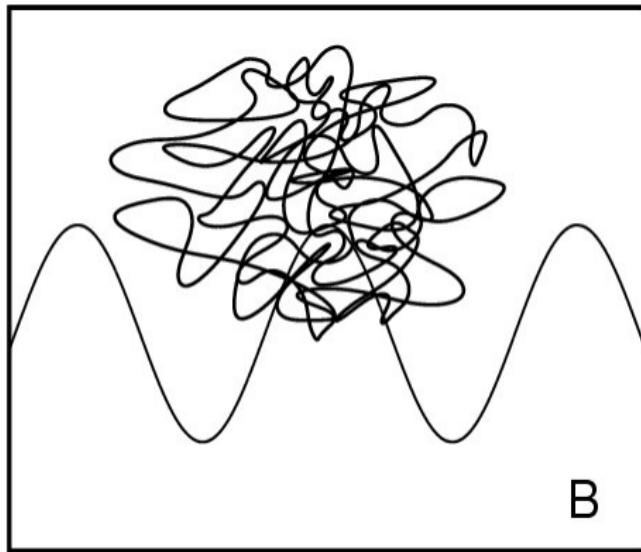
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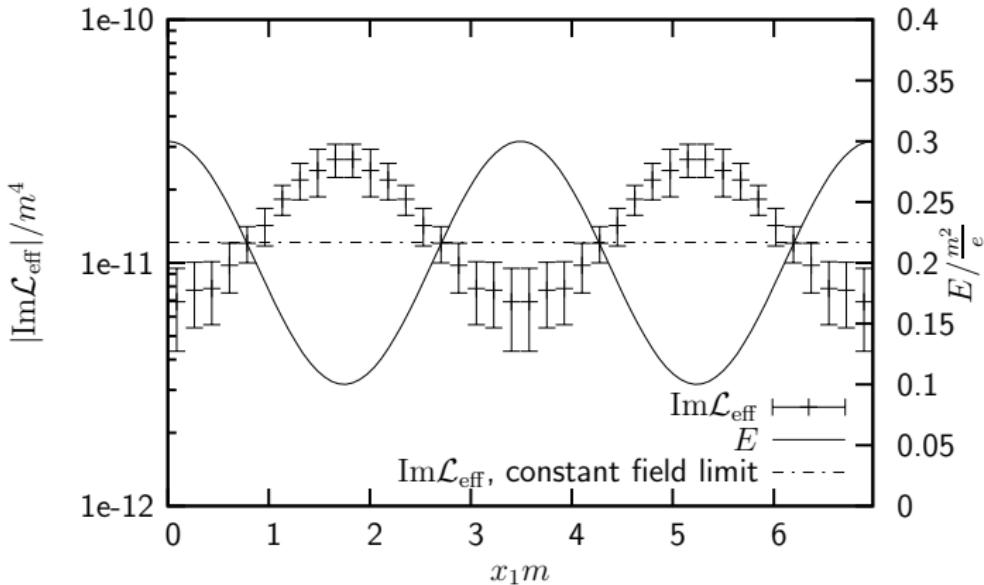
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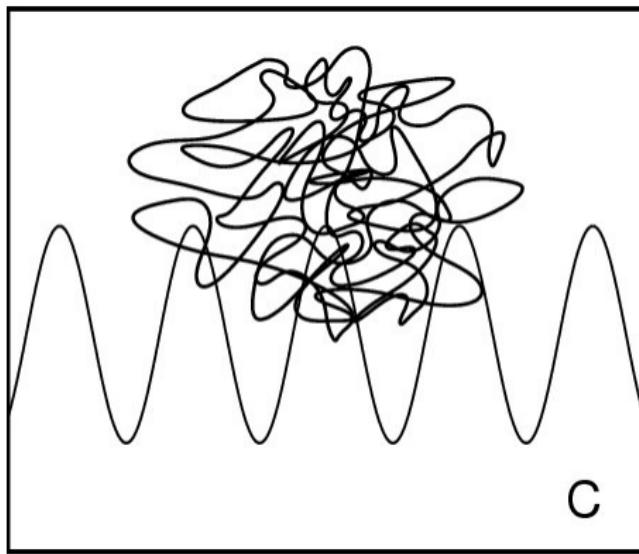
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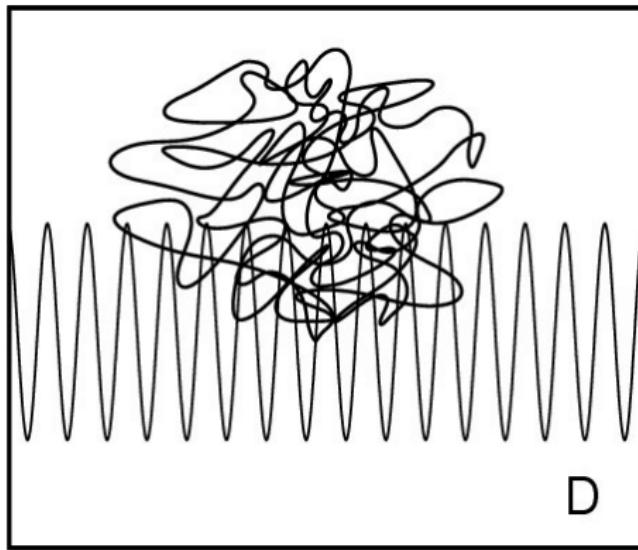
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## $e^+ e^-$ pair production

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# $e^+ e^-$ pair production

Pair production in spatially inhomogeneous fields:

- slowly varying fields,  $k \ll m$ :

$$\text{Im}\Gamma = \int d^4x \text{Im}\mathcal{L}_{\text{Schwinger}}(\textcolor{red}{E}(x))$$

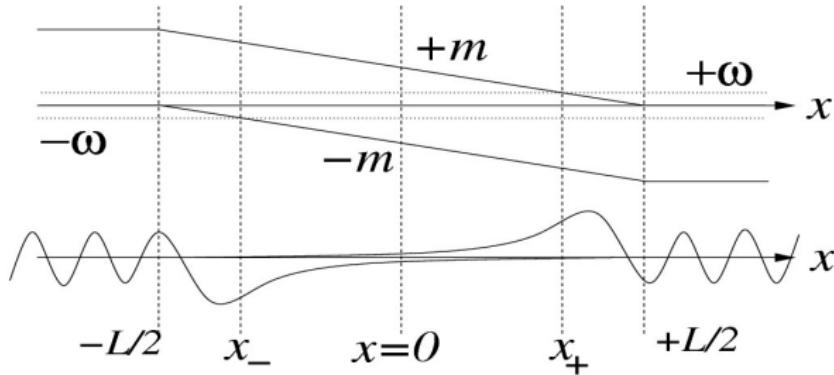
- rapidly varying fields,  $k \gg m$ :

$$\text{Im}\Gamma = \text{Im}\Gamma_{\text{Schwinger}}(\bar{E}), \quad \bar{E} = \frac{1}{V} \int d^3x \textcolor{red}{E}(x)$$

# Pair Production with Taylored Pulses

(SCHÜTZHOLD,HG,DUNNE'08)

- ▶ how to beat  $\tau \sim 10^{5000000000} \text{ s} \dots ?$



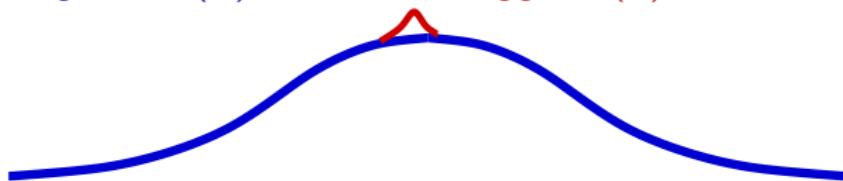
- ▶ temporal inhomogeneities at frequency  $\omega$

⇒ dynamically assisted pair production

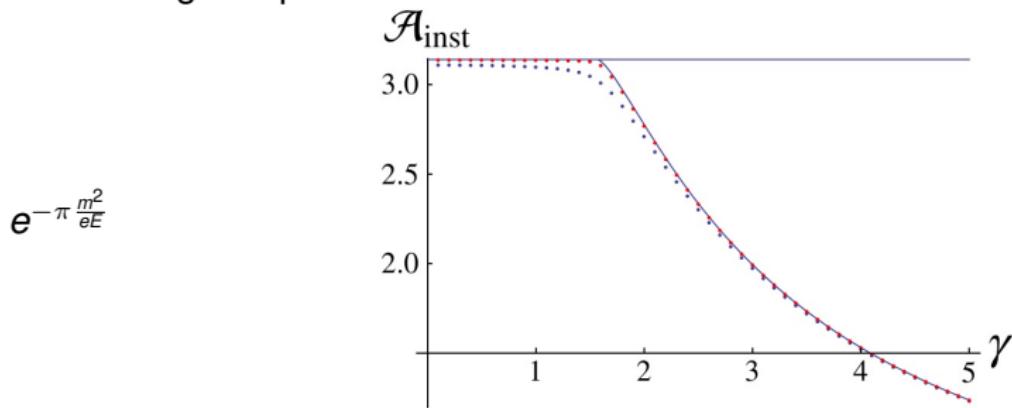
# Pair Production with Taylored Pulses

(SCHÜTZHOLD,HG,DUNNE'08)

- ▷ slow strong field  $E(\Omega)$  + fast weak wiggles  $\epsilon(\omega)$



- ▷ Schwinger exponent:



combined Keldysh parameter:  $\gamma = \frac{m\omega}{eE}$

# Real-Time Evolution

# Real-time evolution of pair production

▷ one-loop QED → quantum kinetic equation

(SMOLYANSKY ET AL'97; KLUGER,MOTTOLA,EISENBERG'98;SCHMIDT ET AL'98)

$$\frac{d\mathbf{f}(\vec{k}, t)}{dt} = \frac{1}{2} \frac{eE(t)\epsilon_{\perp}}{\omega^2(\vec{k}, t)} \int_{-\infty}^t dt' \frac{eE(t')\epsilon_{\perp}}{\omega^2(\vec{k}, t')} [1 - 2\mathbf{f}(\vec{k}, t')] \cos \left[ 2 \int_{t'}^t d\tau \omega(\vec{k}, \tau) \right]$$

where

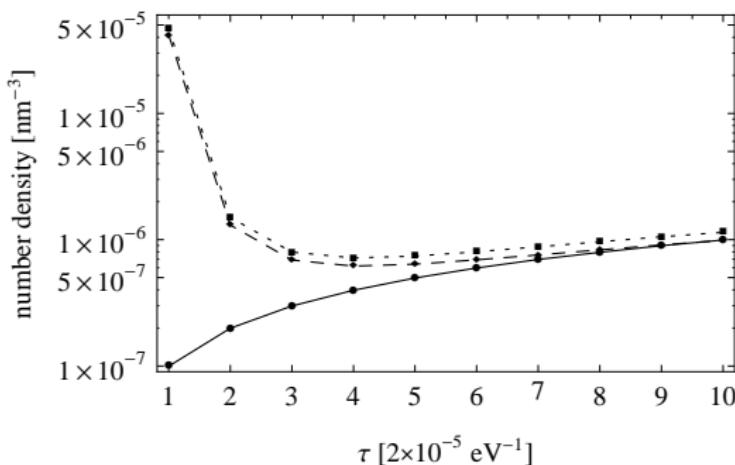
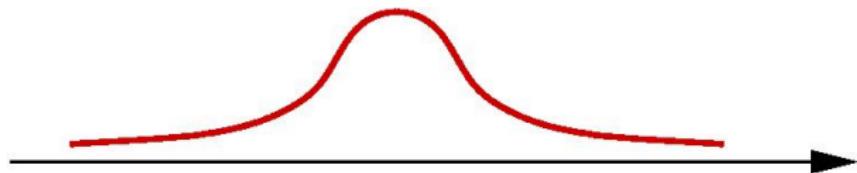
$$\epsilon_{\perp}^2 = m^2 + k_{\perp}^2, \quad \omega^2 = \epsilon_{\perp}^2 + [k_3 - eA(t)]^2$$

- non-Markovian (memory effects)
- statistics (Pauli blocking)
- back-reactions can be included (BLOCH ET AL.'99)

# $e^+ e^-$ pair production

(NIKISHOV'70; DUNNE,HALL'98; HEBENSTREIT,ALKOFER,HG'08)

- ▷ e.g., a temporally localized field  $E \sim \text{sech}^2 \frac{t}{\tau}$ :



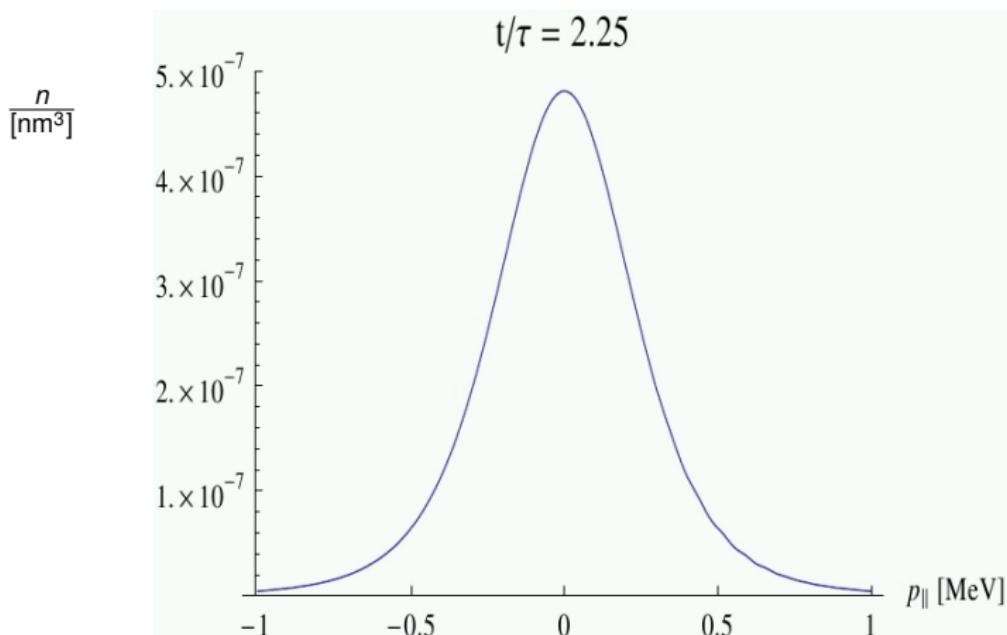
enhancement for

$$\gamma = \frac{m}{\tau e E} \sim 1$$

Keldysh parameter

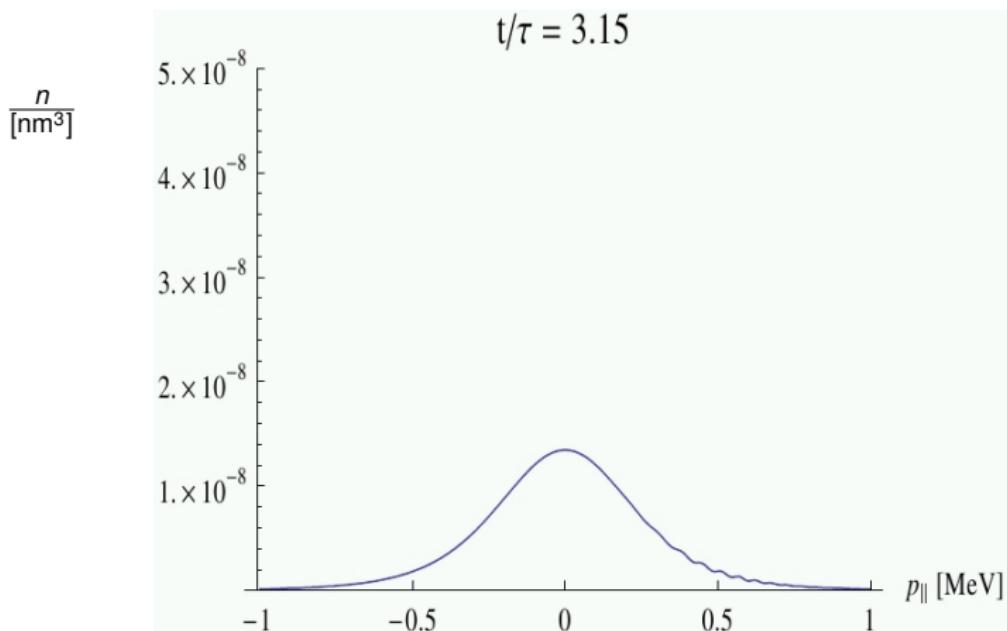
# Real-time evolution of pair production

- ▷ particle density  $n$ : virtual excitations vs. asymptotic real pairs  
(e.g.,  $E = 0.1E_{\text{cr}}$ ,  $\tau = 2 \times 10^{-5}\text{eV}^{-1}$ ,  $k_{\perp} = 0$ ):



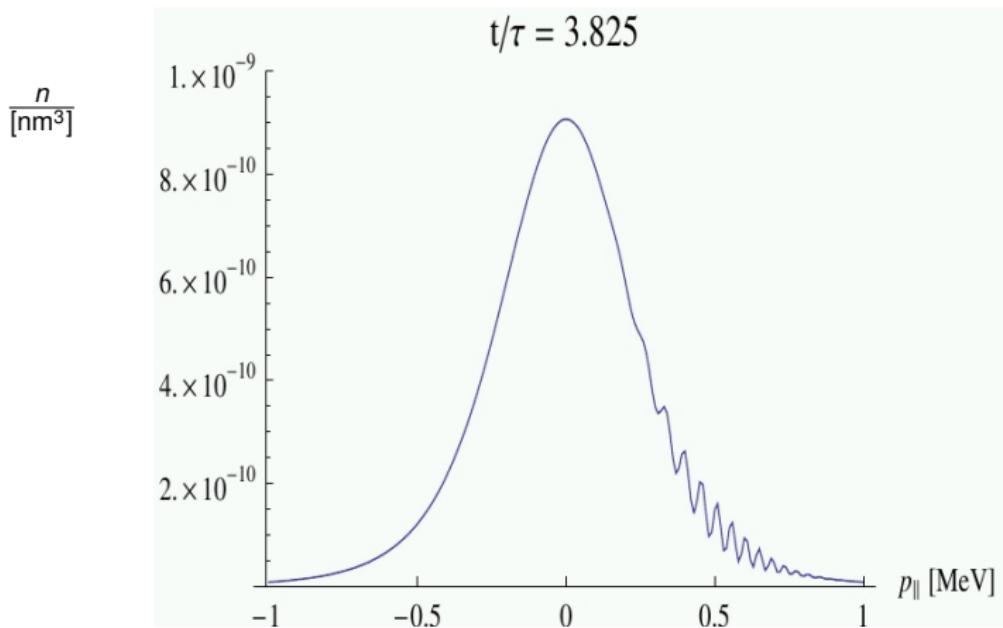
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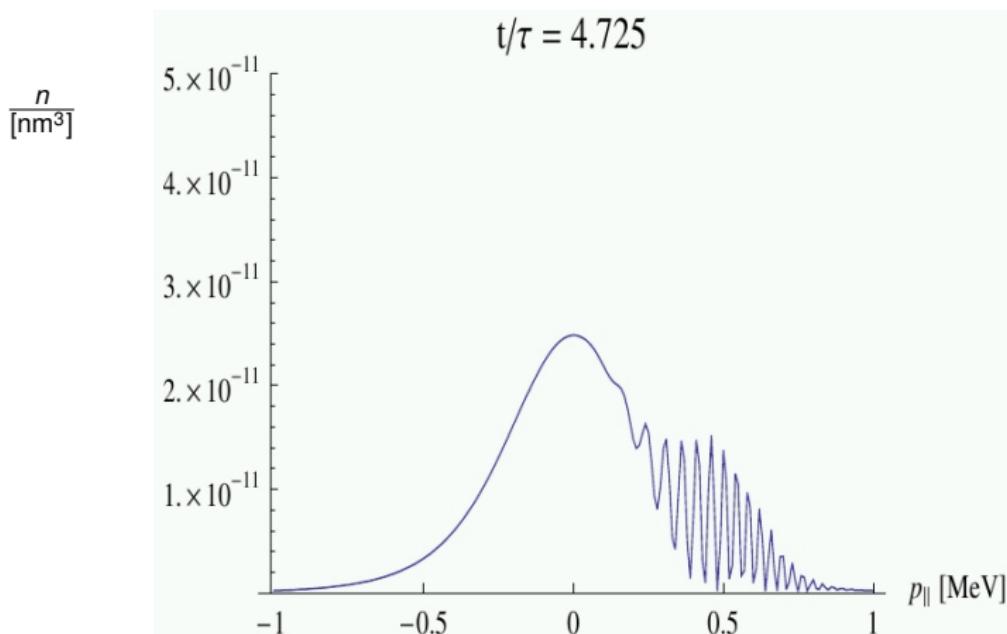
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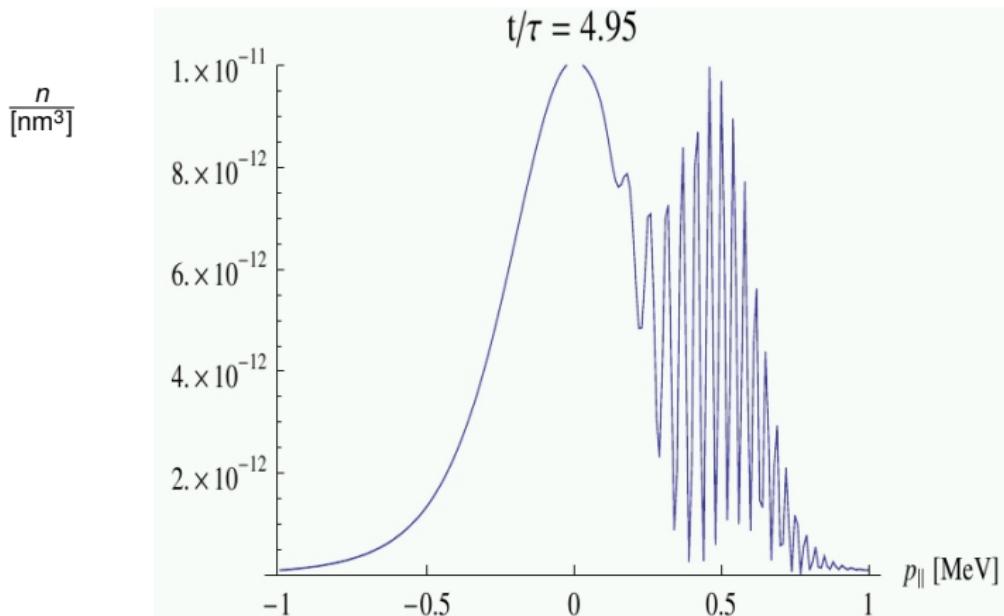
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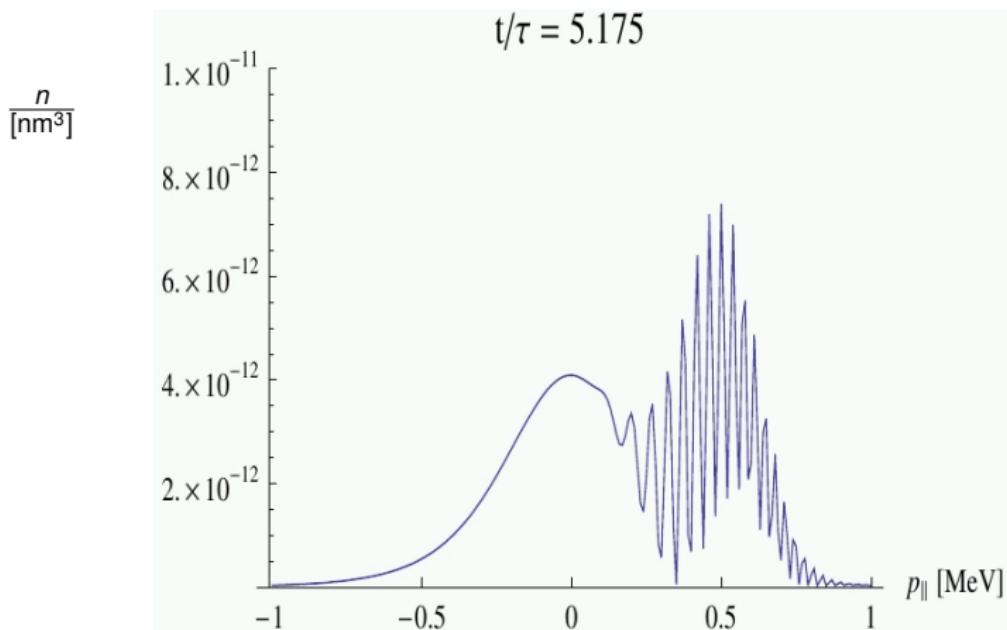
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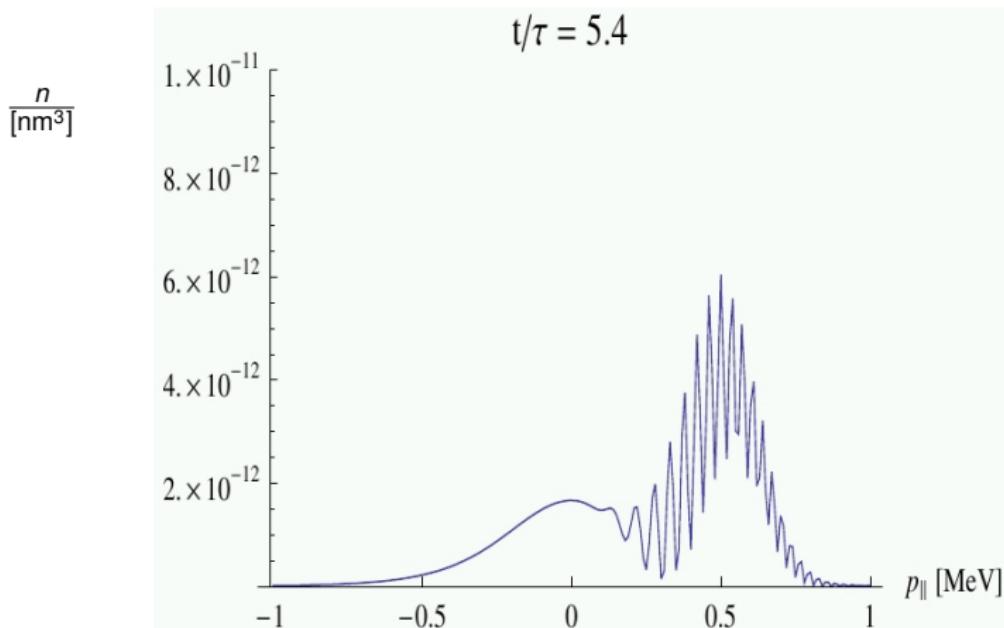
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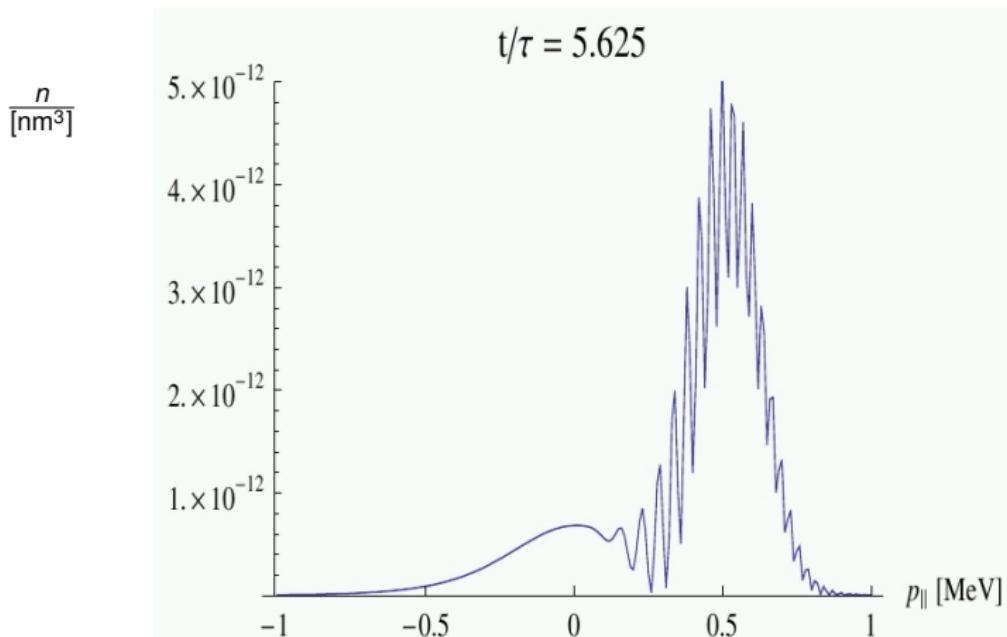
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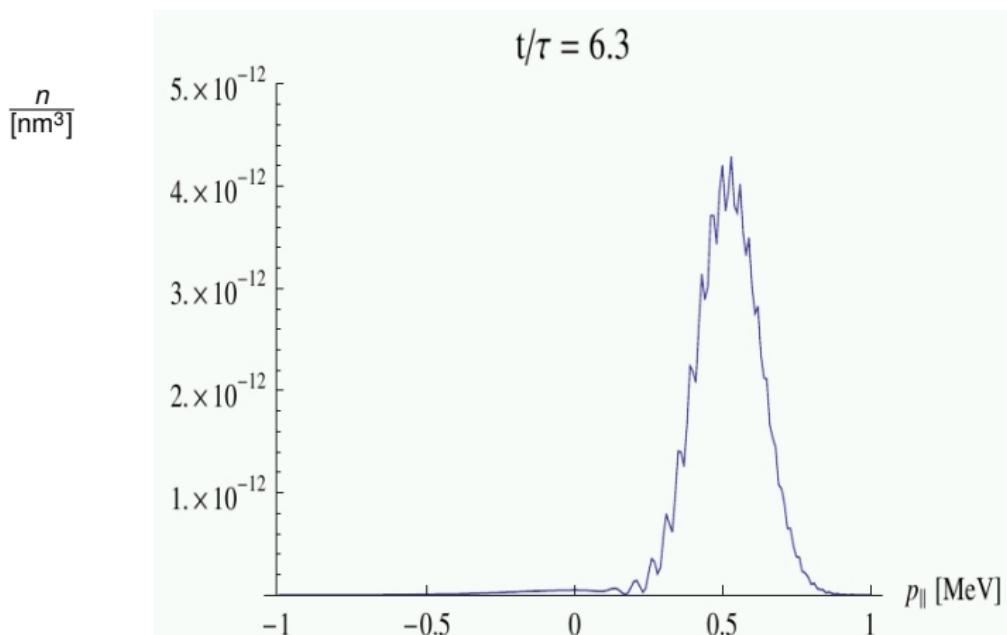
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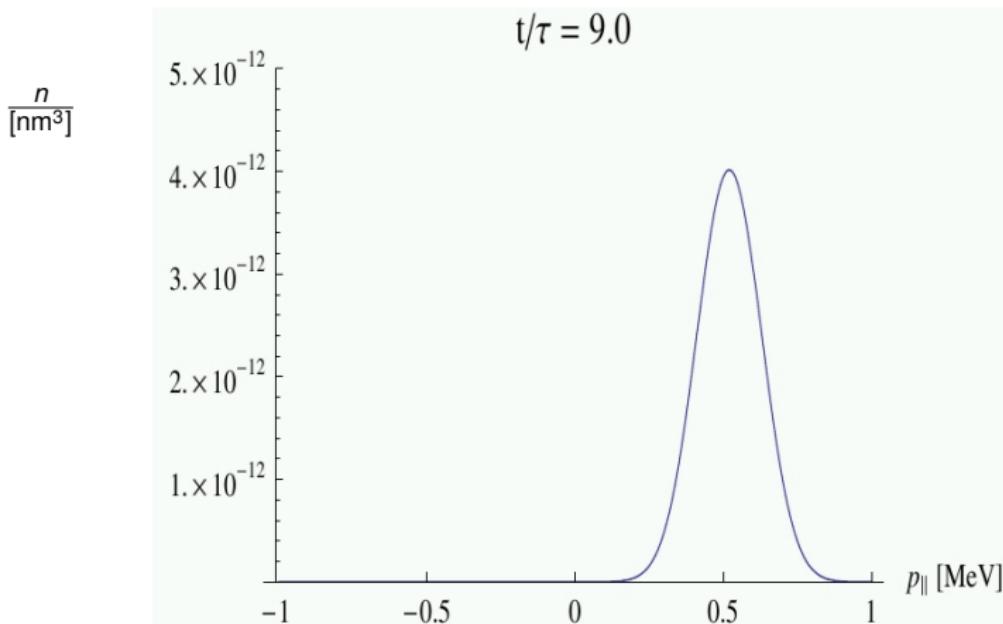
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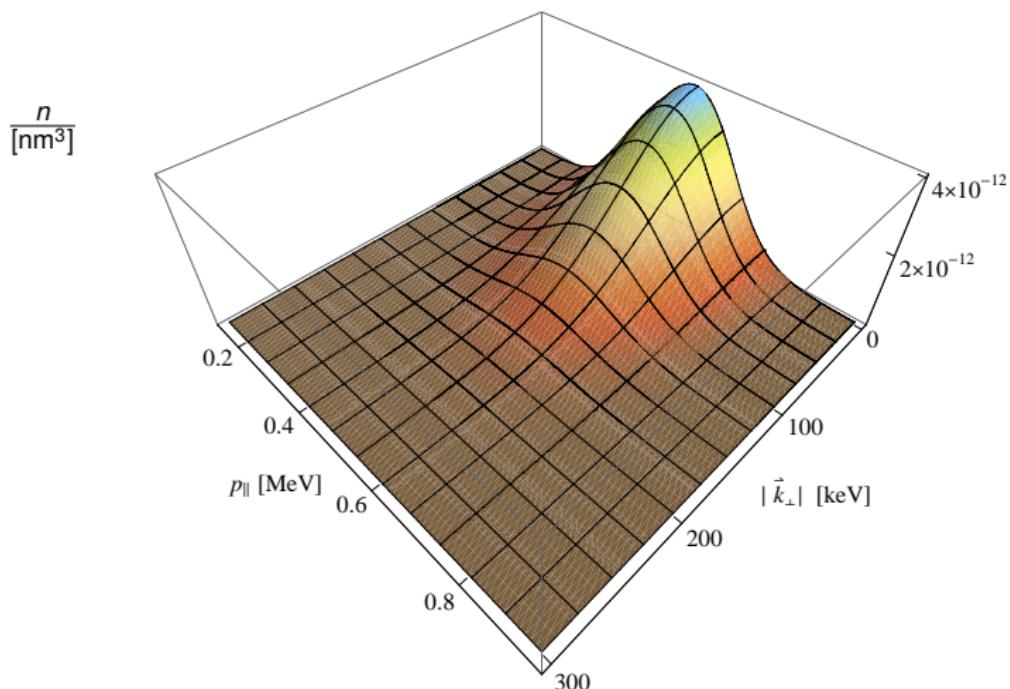
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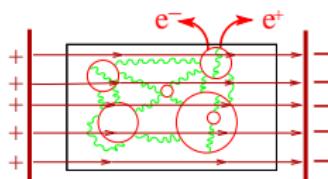
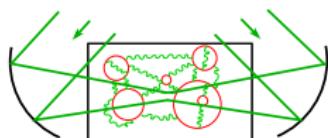
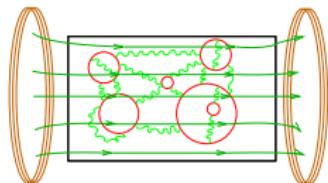


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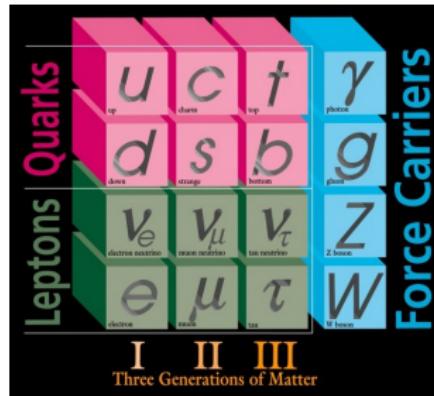


# Why quantum vacuum physics?

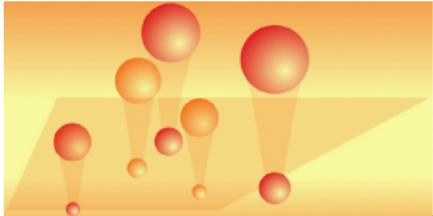


- Heisenberg-Euler/Casimir in mathematical physics
  - QFT in strong fields or with boundaries
  - functional determinants
- applied quantum vacuum physics
  - quantum fluctuations as a building block
  - dispersive forces in micro/nano machinery
- fundamental effect of QFT
  - ( $\sim$  Lamb shift,  $g - 2, \dots$ )
- fundamental physics
  - search for new physics
  - new particles or forces

# Discovery Potential



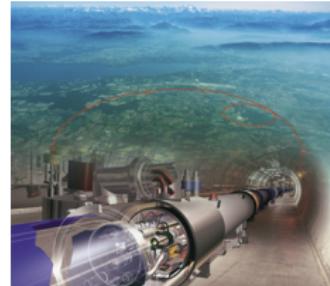
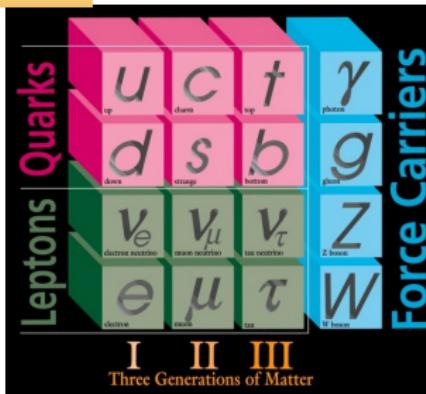
# Discovery Potential



beyond SM

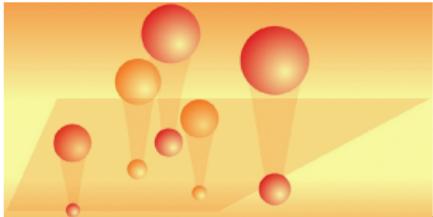
e.g. SUSY

[ZMS.DESY.DE]



[WWW.CERN.DE]

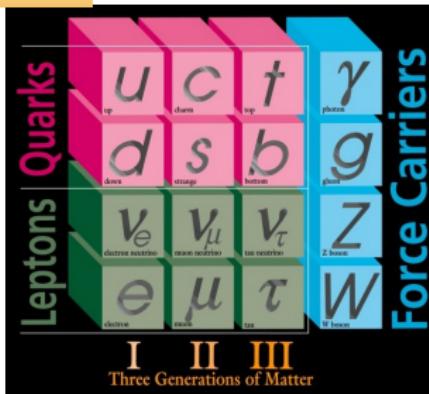
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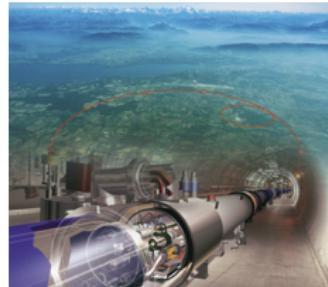
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[ZMS.DESY.DE]



[AHLERS@DESY]



[WWW.CERN.DE]



Hidden Sector

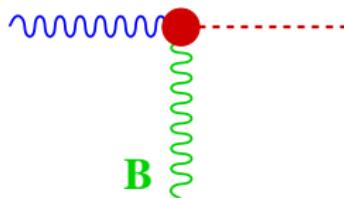


Optical Experiments

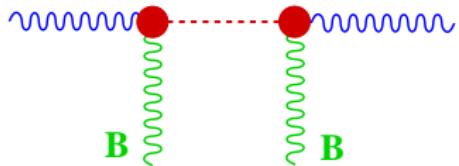
# Hidden Sector

(MAIANI, PETRONZIO, ZAVATTINI'86; RAFFELT, STODOLSKY'88)

- ▷ e.g., new scalar/pseudo-scalar particle  
(e.g., axions, cosmological scalars, etc.):



- photon loss / rotation:



- birefringence / ellipticity:

- ▷ or **MiniC**harged **P**articles

(HG, JAECKEL, RINGWALD'06)

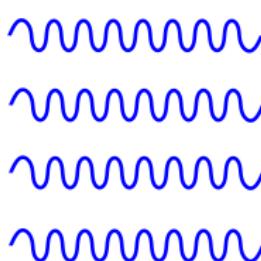
- ▷ or U(1) paraphotons

cf. intersecting-brane models

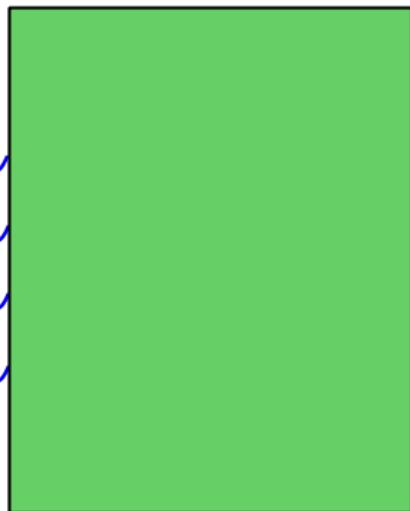
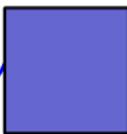
(MASSO, REDONDO'05; AHLERS, HG, JAECKEL, REDONDO, RINGWALD'07)

# Optical Experiments

$N_\gamma \sim 10^{24}$



$N_d \sim 1$



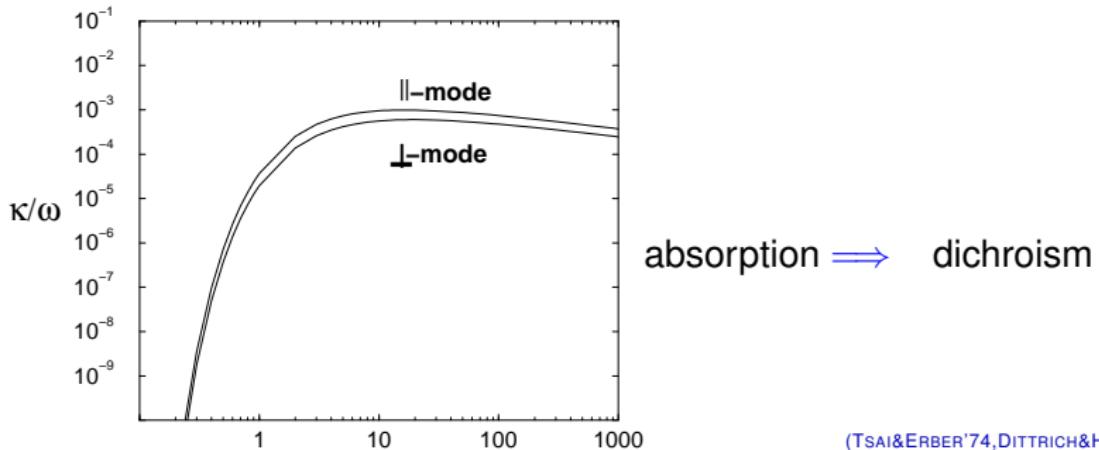
← L →

$$L = \mathcal{O}(10\mu\text{m} - \text{km})$$
$$I = 10^{22}\text{W/cm}^2$$

# Light Propagation in a $B$ field.

- absorption: in QED only above pair-production threshold  $\omega > 2m$

$$\kappa_{\parallel,\perp} = -\frac{1}{\omega} \operatorname{Im} \Pi_{\parallel,\perp}$$

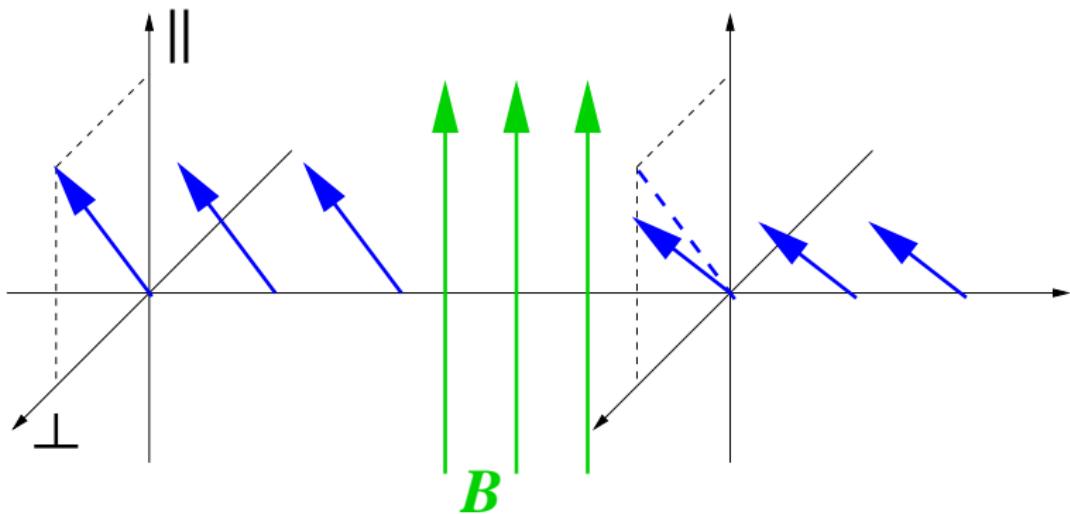


(TSAI&ERBER'74, DITTRICH&HG'00)

$$\frac{3}{2} \frac{eB}{m^2} \frac{\omega}{m} \sin \theta$$

# Light Propagation in a $B$ field.

- ▷ observable: dichroism induces rotation



$$\text{rotation: } |\Delta\theta| \simeq \frac{1}{4} \Delta\kappa l \sin 2\theta$$

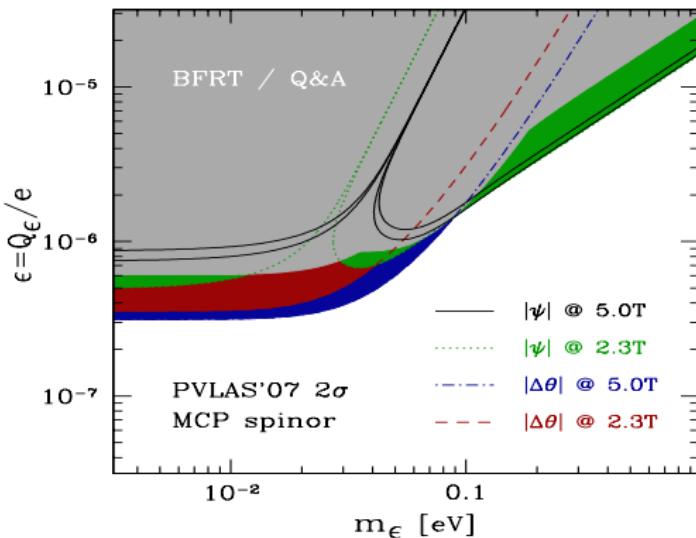
# Results from Birefringence Data

▷ PVLAS'07: (ZAVATTINI ET AL.'07)

(cf. BFRT (CAMERON'93), Q&A (CHEN'06))

birefringence:  $\Delta\nu \leq 1.1 \times 10^{-19}/\text{pass}$  at  $B = 2.3\text{T}$

dicroism:  $\Delta\kappa \leq 5.4 \times 10^{-15}\text{cm}^{-1}$  at  $B = 5.5\text{T}$



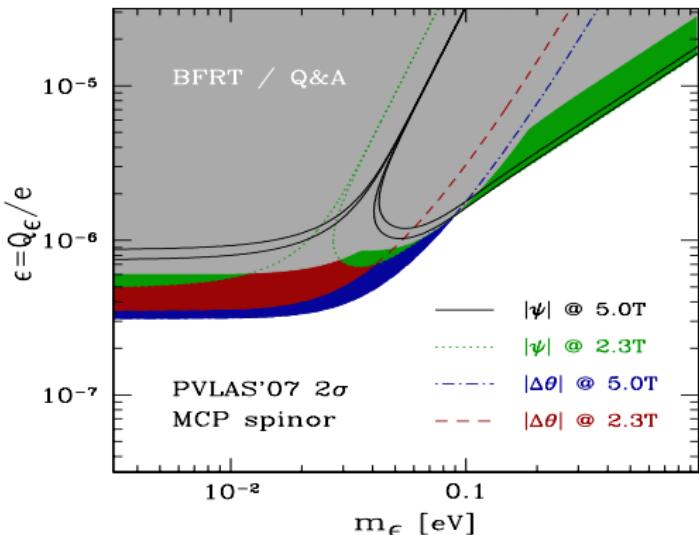
(HG,JAECKEL,RINGWALD'06; AHLERS,HG,JAECKEL,REDONDO,RINGWALD'08)

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Lamb shift



(MITSUI'93)

(DAVIDSON ET AL.'00)

~ new CMB  
bounds

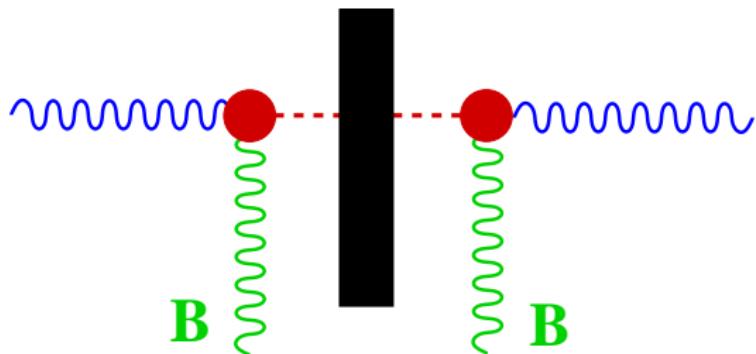
(MELCHIORRI ET AL.'07)

model-dependent  
astro-bounds ↓

(HG,JAECKEL,RINGWALD'06; AHLERS,HG,JAECKEL,REDONDO,RINGWALD'08)

# ALP: Light-Shining-Through-Walls Experiments

(SIKIVIE'83; ANSELM'85; GASPERINI'87; VAN BIBBER ET AL.'87)

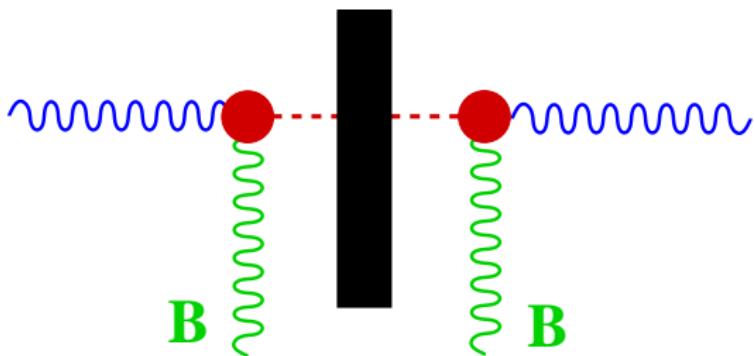


▷ photon regeneration:

$$n_{\text{out}} = n_{\text{in}} \left\lfloor \frac{N_{\text{pass}} + 1}{2} \right\rfloor \frac{1}{16} (gB L \cos \theta)^4 \left( \frac{\sin(\frac{Lm_\phi^2}{4\omega})}{\frac{Lm_\phi^2}{4\omega}} \right)^4$$

# ALP: Light-Shining-Through-Walls Experiments

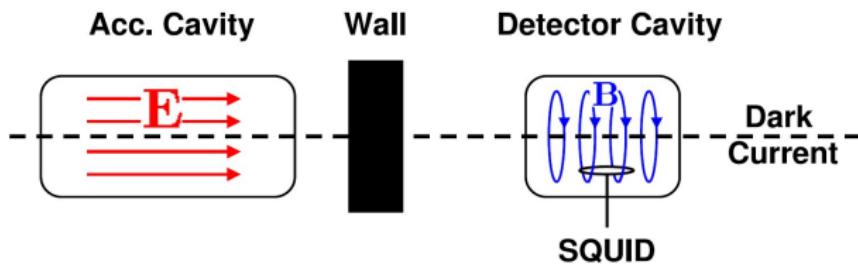
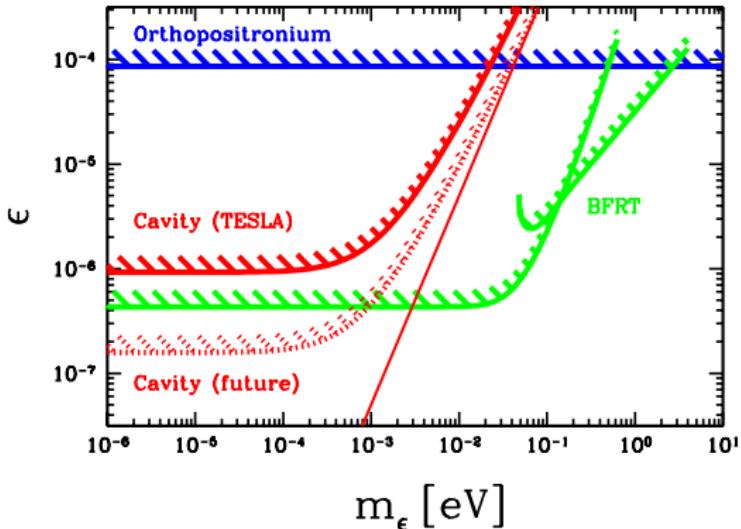
(SIKIVIE'83; ANSELM'85; GASPERINI'87; VAN BIBBER ET AL.'87)



- BMV (Toulouse) 1st run: 2006; 1st data: Oct 2007
  - LIPSS (JLAB) 1st run: Mar 2007; 1st data: Apr 2008
  - OSQAR (CERN) 1st run: Jun 2007; 1st data: Nov 2007
  - GammeV (Fermilab) 1st run: Jul 2007; 1st data: Jan 2008
  - ALPS (DESY) 1st run: Sep 2007; 1st data: soon

# Future Experiments: MCPs

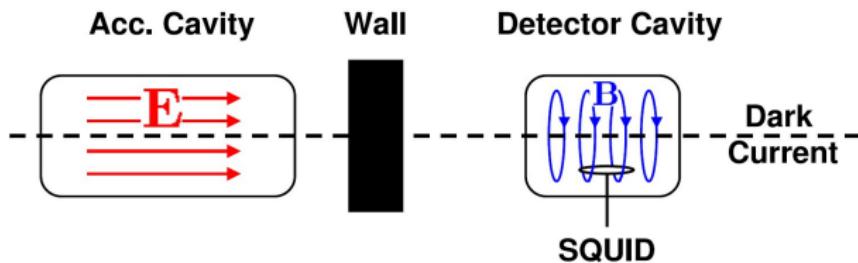
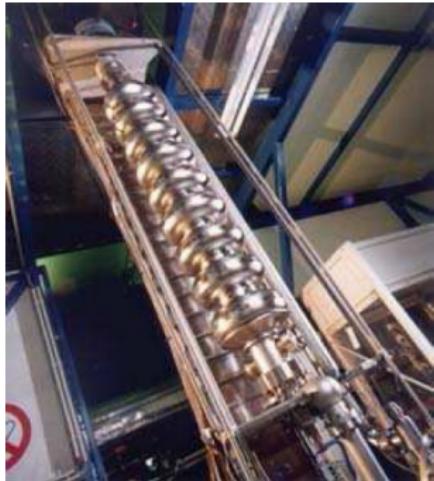
- ▷ MCP pair production  
in strong electric fields:  
(Schwinger mechanism)



(HG, JAECKEL, RINGWALD'06)

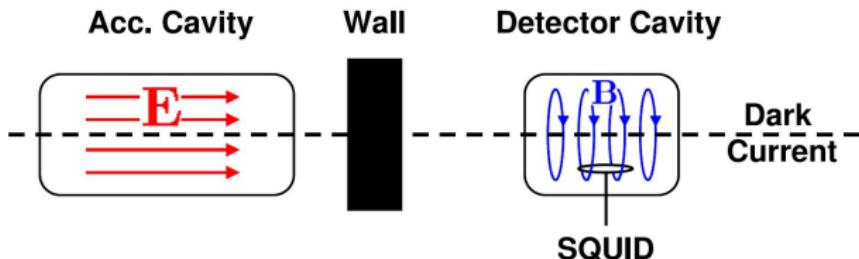
# Future Experiments: MCPs

A  
C  
D  
C  
accelerator  
avity  
ark  
urrent



# Future Experiments: MCPs

A  
C  
D  
C  
accelerator  
cavity  
dark  
current



# Conclusions

## ▷ Why strong-field physics . . . ?

- “ . . . exploring some issues of fundamental physics that have eluded man’s probing so far”

(TAJIMA’01)

- **QFT**: high energy (momentum)      vs.      high amplitude
- **Pair production**: ideal model system  
(nonperturbative QFT, quantum energies, non-equilibrium QFT)
- “**Fundamental-Physics**” discovery potential:
  - ALPs: hypothetical NG bosons (axion, majoron, familon, etc.)
  - MCPs: minicharged particles
  - paraphotons
  - sub-millimeter forces
  - ...