Probing the Quantum Vacuum at the High-Intensity Frontier

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DFG FOR2783: www.quantumvacuum.org

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Talk title vs. conference title?

Many-particle systems under extreme conditions

A view on the classical vacuum

A view on the classical vacuum

Absence of anything

The birth of the quantum vacuum

- ▷ Field quantization (Born,Heisenberg,Jordan 1925)
- ▷ Dirac's "theory of the positron" (Dirac 1928)
- ▷ Heisenberg-Euler theory (Euler,Kockel 1935; Euler 1936; Heisenberg-Euler 1936)

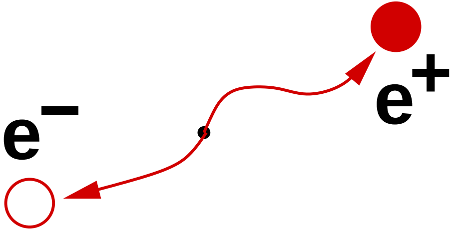
...
Two light quanta can ... be transformed into two other light quanta through the - so to speak - **virtual possibility of pair building** ....
The question ... is principally of **great importance**, ... problem of **how Maxwell's equations are modified** by Dirac's theory.

Heisenberg's evaluation of Euler's thesis

(translation: W. Dttrich 2014)

A view on the quantum vacuum

- Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$



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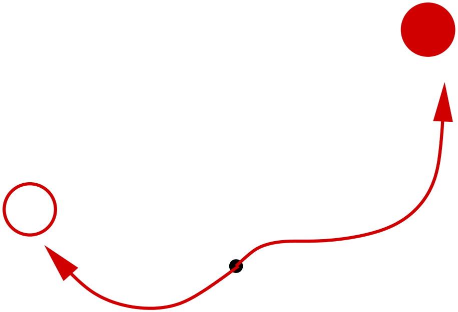

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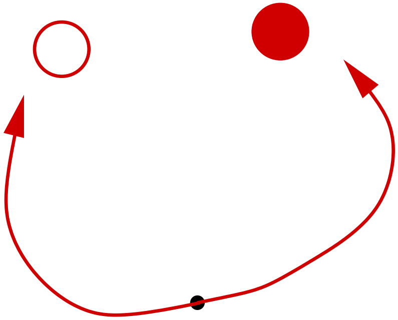

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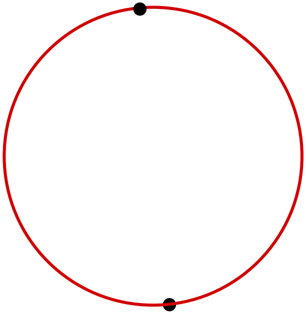

$$\lambda_{\mathrm{C}} = \frac{\hbar}{mc} \approx 3.9 \cdot 10^{-13}\,\mathrm{m}$$

$$\tau_{\mathrm{C}} = \frac{\lambda_{\mathrm{C}}}{c} \approx 1.3 \cdot 10^{-21}\,\mathrm{s}$$

A view on the quantum vacuum

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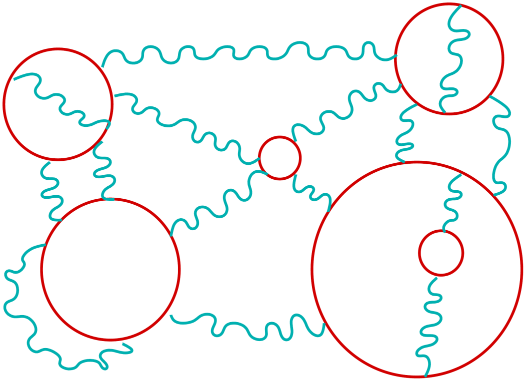
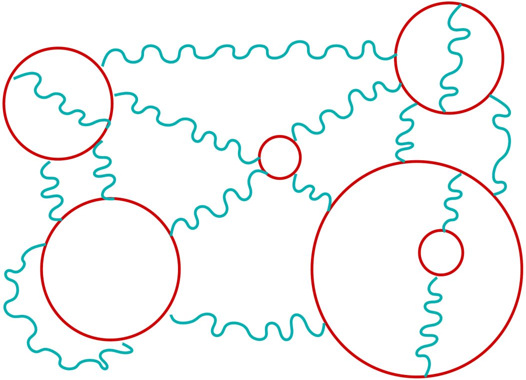


Quantum field theory: possibility of everything

A view on the quantum vacuum

▷ Heisenberg's uncertainty principle, e.g. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$

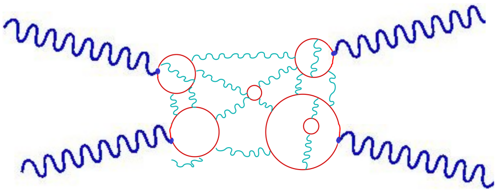


Quantum vacuum $\hat{=}$ Many-particle system ✓

Probing the quantum vacuum

▷ Quantum electrodynamics (QED): e.g., light-by-light scattering*

(Euler, Kockel 1935; Euler 1936)



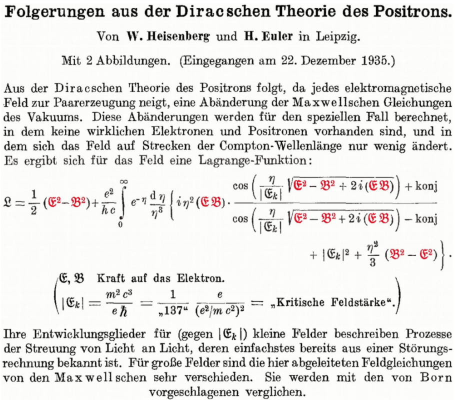
⟹ violation of Maxwell's superposition principle *in vacuo*

* 3) P. Debye, in einer mündlichen Diskussion mit Herrn Prof. Heisenberg.

Probing the quantum vacuum

▷ Heisenberg-Euler effective action

(Heisenberg,Euler 1936; Weisskopf 1936; Schwinger 1951)



Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

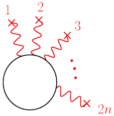
Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2) + \frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot \frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}.$$

$$\left(\begin{array}{l}\mathfrak{E},\mathfrak{B}\ \text{Kraft auf das Elektron.}\\ |\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{„137“}\frac{e}{(e^2/mc^2)^2} = \text{„Kritische Feldstärke“.}\end{array}\right)$$

Ihre Entwicklungsglieder für (gegen $|\mathfrak{E}_k|$) kleine Felder beschreiben Prozesse der Streuung von Licht an Licht, deren einfachstes bereits aus einer Störungsrechnung bekannt ist. Für große Felder sind die hier abgeleiteten Feldgleichungen von den Maxwellschen sehr verschieden. Sie werden mit den von Born vorgeschlagenen verglichen.

$$S_{\text{eff,HE}}[F] = \sum_{n=0}^{\infty}$$



▷ strong field nonlinearities

▷ quantum vacuum

$\simeq$ medium

▷ critical field: extreme conditions!

$$E_{\text{cr}} \simeq 1.3 \times 10^{18}\, V/m$$

▷ vacuum instability:

pair production

Probing the quantum vacuum

▷ Heisenberg-Euler effective action

(Heisenberg,Euler 1936; Weisskopf 1936; Schwinger 1951)

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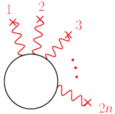
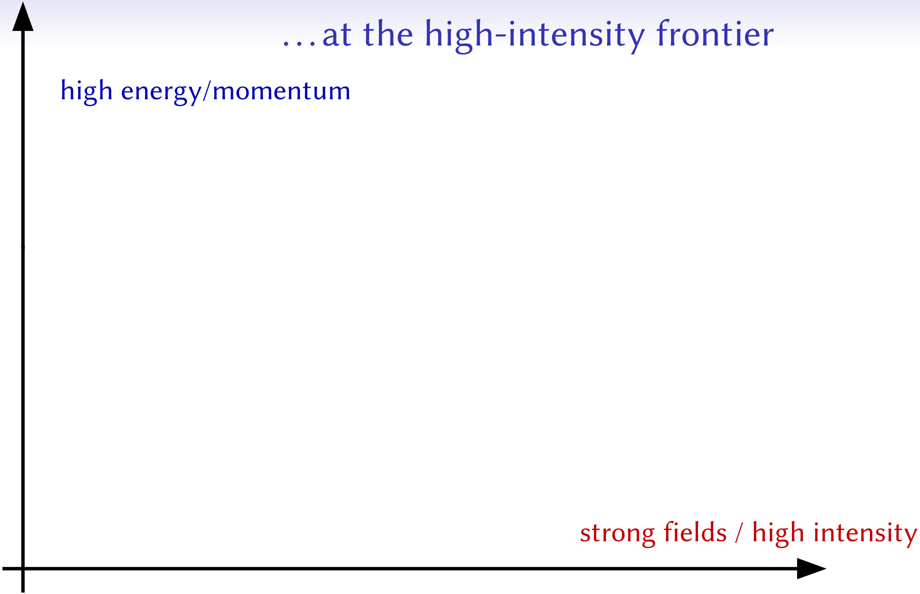
$$S_{\text{eff,HE}}[F] = \sum_{n=0}^{\infty}$$ 

▷ conceptual cornerstone of QFT

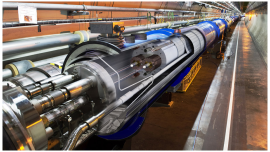
many predicted phenomena still await their discovery

…at the high-intensity frontier



…at the high-intensity frontier

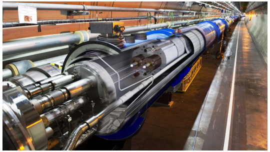
high energy/momentum

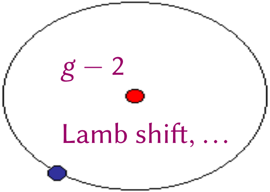


strong fields / high intensity

…at the high-intensity frontier

high energy/momentum





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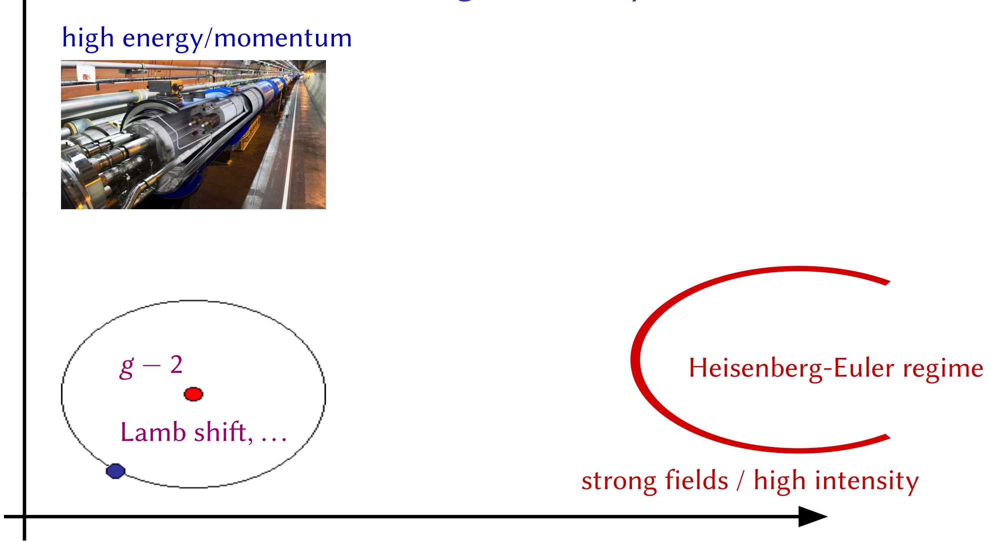


Example: Light Propagation in a B field.

▷ quantum Maxwell equation (Heisenberg,Euler'36;Weisskopf'36)

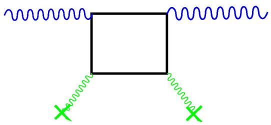
$$0 = \partial_\mu \left(F^{\mu\nu} - \frac{1}{2}\frac{8}{45}\frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} - \frac{1}{2}\frac{14}{45}\frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} \tilde{F}^{\mu\nu} \right)$$

Example: 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



$$v_\| \simeq 1 - \frac{14}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

$$v_\perp \simeq 1 - \frac{8}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

(Toll'54)

(Baier,Breitenlohner'67;Narozhniy'69)

(Adler'71)

(Dittrich,HG'98; Dittrich,HG'00)

$\Longrightarrow$ magnetized quantum vacuum induces birefringence

▷ detection schemes: PVLAS, BMV, Q&A, OSQAR

cf. birefringence in uniaxial cristals

- e.g., calcite

An upcoming experiment

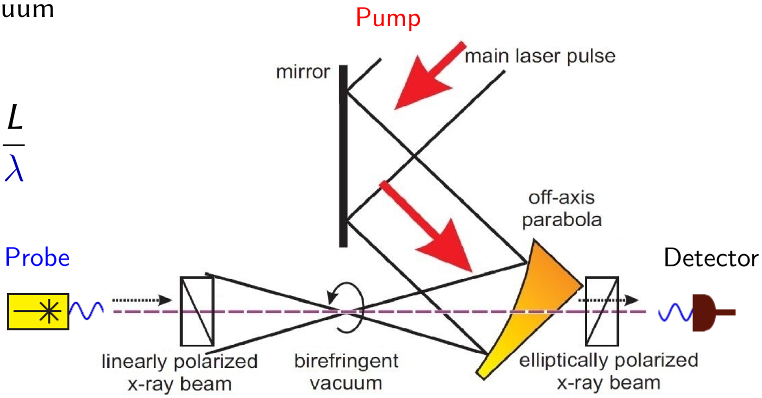
Probing the quantum vacuum at extreme conditions

▷ vacuum birefringence of a probe wave induced by a high-intensity pulse (pump)

Jena SFB-TR18 scheme: (Heinzl,Liesfeld,Amthor,Schwoerer,Sauerbrey,Wipf 2006)

▷ simple estimate: vacuum induced ellipticity

$$\Delta\phi = \frac{4\alpha}{15}\frac{I}{I_c}\frac{L}{\lambda}$$



Vacuum Birefringence: a flagship experiment for

HI JENA HELMHOLTZ

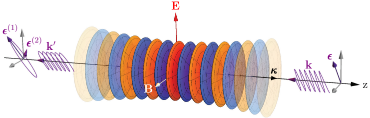
HiBEF

(Schlenvoigt,Heinzl,Schramm,Cowan,Sauerbrey'15)

▷ Theory of pulse collisions

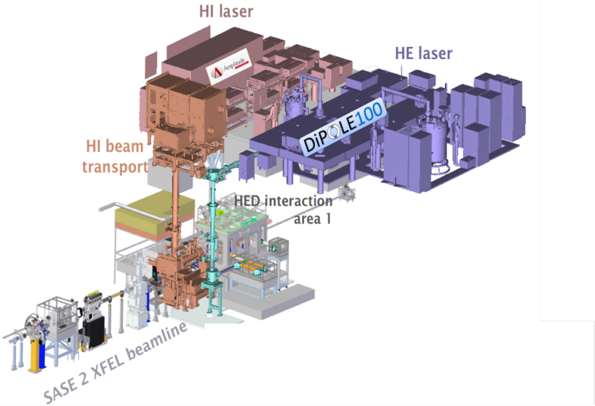
(Karbstein,HG,Reuter,Zepf'15)

(Karbstein,Sundqvist'16; Karbstein,Mosman'21)



▷ High definition X-ray polarimetry

(Marx et al. 2011,Schulze 2015& 2018)



Theory of pulse collisions: discernible Photons

▷ Photons above background (KARBSTEIN,BLINNE,HG,ZEPF 2019)

$$\frac{dN_{\text{signal}}}{d\Omega} \geq \mathcal{P} \frac{dN_{\text{background}}}{d\Omega}$$

...useful tool to identify sweet spots in large parameter space

▷ Signal photons from vacuum emission picture (KARBSTEIN,SHAISULTANOV'15)

$$dN_{\text{signal}} = \frac{d^3k}{(2\pi)^3} |\mathcal{S}_{VE}(\vec{k})|^2$$

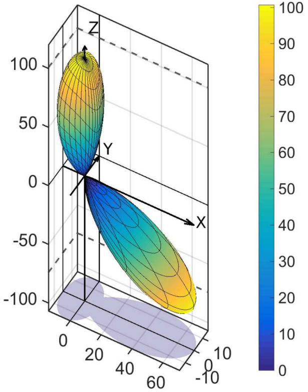
applicable for any pump/probe pulse shapes

amenable to numerical simulations (BLINNE,HG,KARBSTEIN KOHLFÜRST,ZEPF'15)

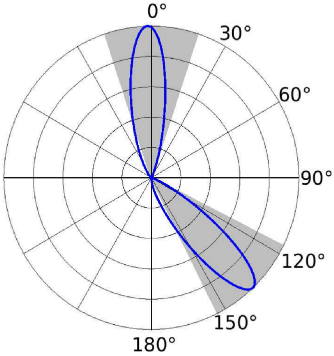
Example: colliding PW-class pulses

- collision under $\vartheta_2 = 135°$ (HG,Karbstein,Kohlfürst'17)

- number density of QED-induced photons



- emission characteristics



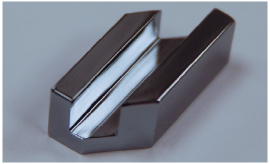
$\sim \mathcal{O}(100)$ γ's

signal γ's swamped by background

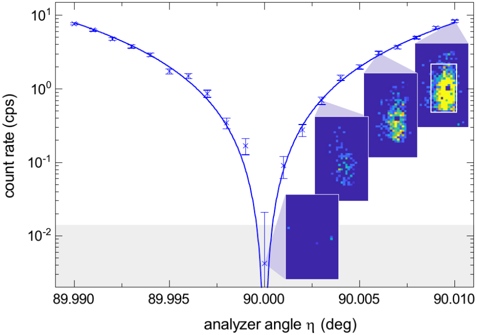
“Canonical approach”: background suppression by X-ray polarimetry

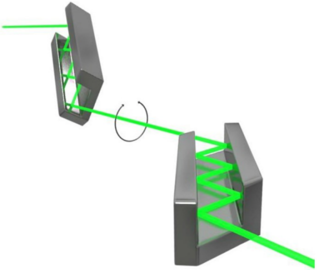
▷ high-definition x-ray polarimetry using Bragg reflections (Marx et al. 2011, Schulze 2015& 2018)

▷ silicon channel cut



Si(800) ∼ 12.914 keV



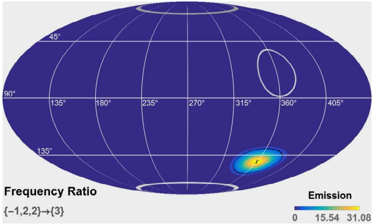


polarization purity (HED@XFEL) 2022: $\mathcal{P} < 8 \times 10^{-11}$

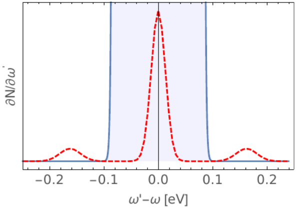
(Schulze et al. 2022)

“3-pulse collision scheme”

optical: (Moulin,Bernard’02; Lundstrom et al.’05; Lundin et al.’06) (HG,Karbstein,Kohlfürst,Seegert’17)

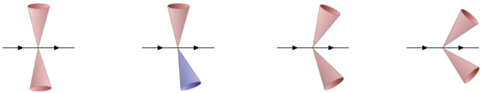


XFEL+optical: (King,Hu,Shen’18)



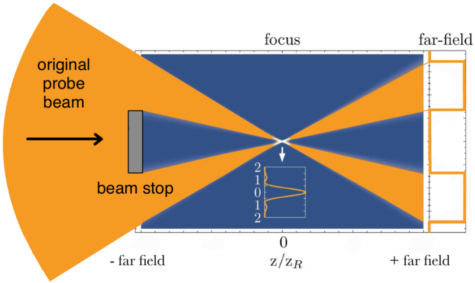
- sizable signal
- $\omega_{\mathrm{signal}} \simeq |\omega_1 \pm \omega_2 \pm \omega_3|$
- angular separation of signal
- prediction for signal divergence
- experimentally more challenging

HIBEF scenarios: (Ahmadiniaz et al’23)

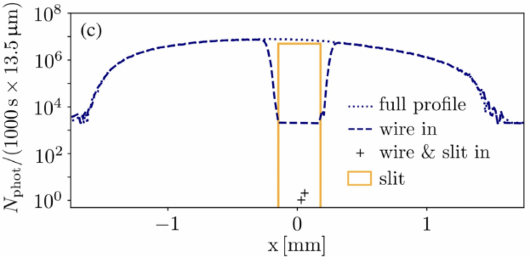


"Dark-field scheme"

▷ annular probe beam (Karbstein,Mosman'20)



- low-background hole in forward direction
- quantum signal maximum on axis



▷ proof of concept experiment: $\mathcal{P} = 10^{-8}$

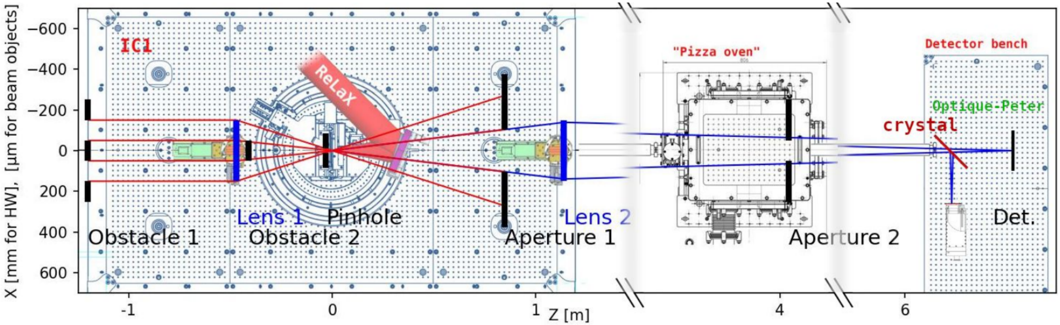
(Karbstein,Ullmann,Mosman,Zepf'22)

$\Longrightarrow$ HIBEF design study

Vacuum Birefringence @ HIBEF/HED collaboration

▷ Dark-field scheme

(Michal Šmíd, et al. 2023)



▷ Simulated shadow factor: $\mathcal{P} = 1.6 \times 10^{-12}$

▷ road map:

- Priority access project 5438: beam time in March 2024, dark-field test X-ray only
- Autumn 2024: combining X-ray with Relax lasers, $\Longrightarrow$ full experiment 2025(?)

Why quantum vacuum physics?

Quantum vacuum physics: emerging opportunities

- Quantum effective actions:

exploring the Heisenberg-Euler paradigm

measuring effective field theories near thresholds

- vacuum birefringence:

fundamental effect of QED

$\sim (g-2)$, Lamb shift, etc.

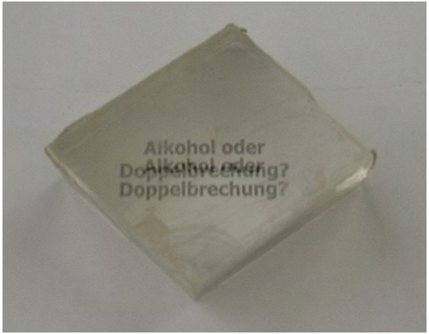
precision explores unknown territory

$$\Delta v \simeq \frac{6}{45}\left(1 + \frac{25}{4}\frac{\alpha}{\pi} + \dots\right)\frac{\alpha^2}{m^4}\, I$$

Quantum vacuum physics: emerging opportunities

▷ quantum vacuum as a building block

"The vacuum is a medium"



Alfvén, magneto-acustic modes

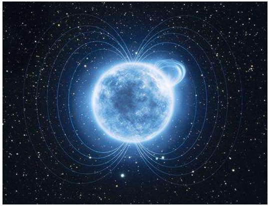
nonlinear/shock-wave propagation

higher-harmonic generation

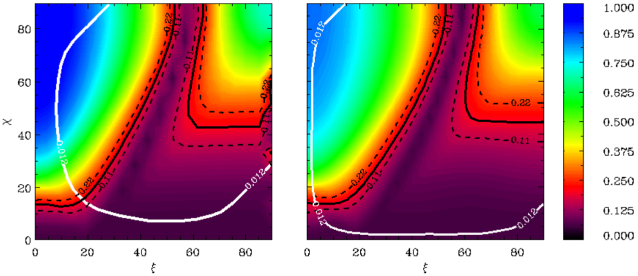
self-focusing

high-intensity metrology

Quantum vacuum physics: emerging opportunities



▷ laboratory tests of astrophysical strong-field environments



(Mignani et al. 2016)

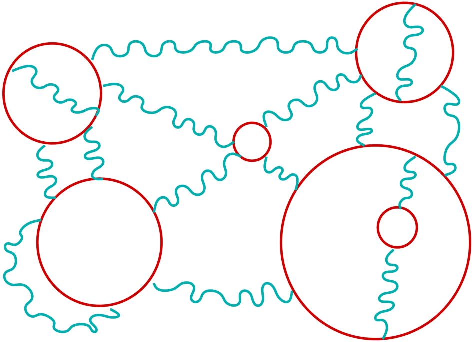
(Capparelli et al. 2017)

polarization properties of pulsars, magnetars, etc.

Quantum vacuum physics: emerging opportunities

- search for "new physics"

all degrees of freedom contribute to the quantum vacuum



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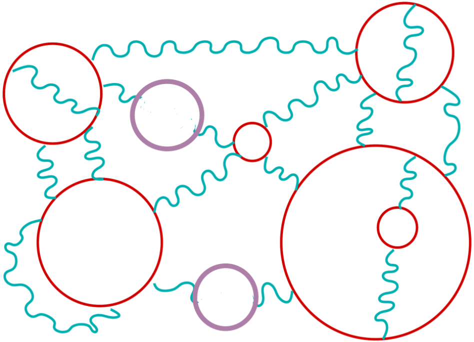

Quantum vacuum physics: emerging opportunities

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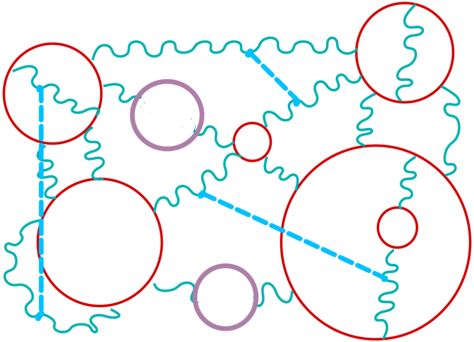


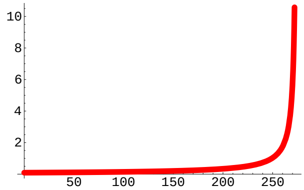
▷ sensitivity to weakly interacting, light particles axions, dark matter candidates …

Going to extremes

Extreme conditions: Strong-field limit?

▷ Leading-log resummation of perturbation theory (Ritus'75;Dittrich,Reuter'85)
1PI Effective action in magnetic fields

$$\Gamma[B] \to \infty, \quad \text{for} \ \frac{\alpha}{3\pi} \ln \frac{eB}{m^2} \to \mathcal{O}(1)$$



LL resummation translates

high-p Landau pole $\to$ high-B

$\Longrightarrow$ artefact of single-scale RG?

Extreme conditions: Strong-field limit?

▷ singularities for large electric field expected

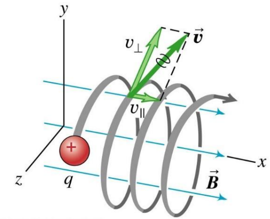
and observed already at 1-loop order: $\mathrm{Im}\Gamma[E] \sim \alpha(eE)^2 e^{-\frac{m^2}{eE}}$

(Sauter'31, Schwinger'51)

▷ BUT (constant) magnetic fields do not transfer energy to charged particles

$\Longrightarrow$ no heuristic physical reason to translate

high-p $\rightarrow$ high-B



Hypothesis: Quantum scale symmetry

(Gell-Mann,Low'54; Weinberg'76; Wetterich'19)

▷ If strong-field limit exists, there will be a regime where

$$eB \ggg m_i^2, \qquad i = e, \mu, \tau, \pi^{\pm}, \ldots$$

▷ This suggests that action density

$$\frac{\Gamma}{\Omega} \;\rightarrow\; \text{scale invariant form in units of an RG scale} \quad k \ggg m_i$$

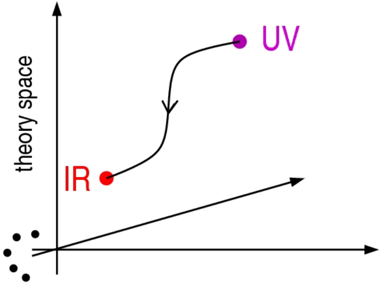
Does such an RG fixed point ("fixed function") exist as a solution to the RG equations?

Functional RG flow equation

▷ Flow equation for the 1PI effective action

(Wetterich'93)

$$k\partial_k \Gamma_k = \frac{1}{2}\,\mathrm{Tr}\; k\partial_k R_k (\Gamma_k^{(2)} + R_k)^{-1}$$



▷ We explore the ansatz (in dim'less quantities)

$$\Gamma = \int_x w_k(\mathcal{F}, \mathcal{G}^2), \quad \mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \; \mathcal{G} = \frac{1}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Evidence for quantum scale symmetry:
$w_k(\mathcal{F}, 0)$ needs to exists globally for $\mathcal{F} > 0$ + RG scale independence

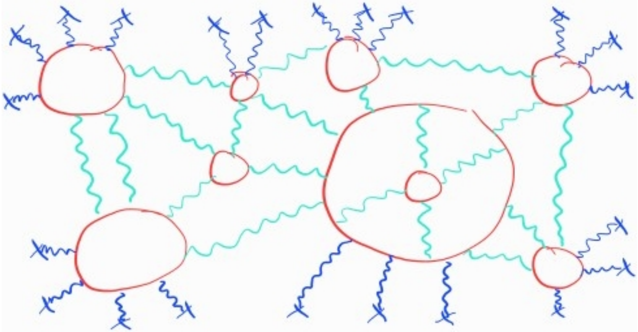
Functional RG flow equation

- ▷ fixed-function equation (Laporte,Locht,Pereira,Saueressig'23; HG,Schirrmeister'23)

$$k\partial_k w_k \overset{!}{=} 0 = -4w_k + (4+\eta)(w_k'\mathcal{F} + 2\dot{w}_k\mathcal{G}^2) - \frac{1}{32\pi^2}\int_y y^2(2y^2 r' + \eta r)Y_k$$

Solutions depend parametrically on photon anomalous dimension η

- ▷ Diagrammar:



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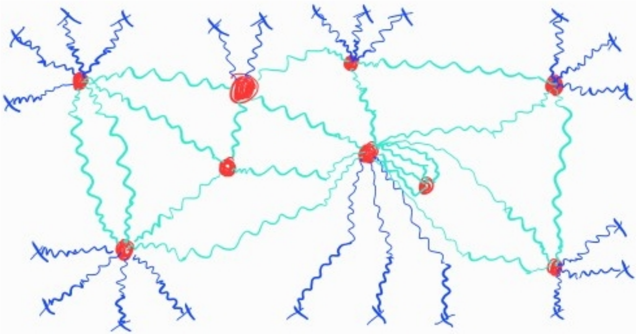
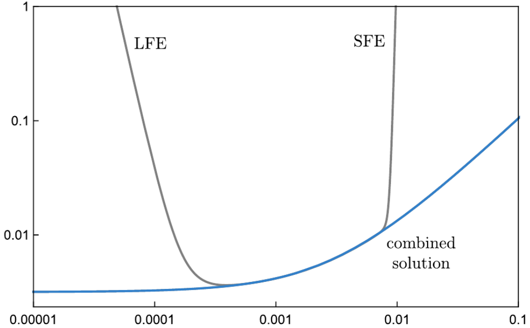


Global fixed function

▷ Constructed from merger of small- and large-field expansions (HG,Schirrmeister'23)



▷ Anomalous dimension

$$w_* \sim \mathcal{F}^{\frac{4}{4+\eta}}$$

$\Longrightarrow$ governs asymptotics.

▷ e.g., QED:

$$\eta = \frac{2\alpha}{3\pi}$$

$\Longrightarrow$ Quantum scale symmetry: self-consistent

scale-invariant solution exists globally

$\Longrightarrow$ Check: perturbative small-η expansion consistent with one-loop strong-field limit.

Conclusions

▷ Probing the quantum vacuum at the high-intensity frontier

- understanding the ground state of nature

“The vacuum is a medium”

- exploring uncharted territory of fundamental physics

…high amplitude vs. high energy

- first discoveries and emerging opportunities

⟹ Golden opportunities for CPA lasers + XFEL!

HiBEF

▷ QED quantum vacuum under ultra-extrem conditions

first nonperturbative evidence for stability (global existence)