



Advanced Quantum Mechanics

Macroscopic Quantum Effects: from Laboratory to Stars

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Lectures for PhD students, Winter Semester 2006/2007



- 1** Introduction
- 2** Symmetry Breaking and Restoration
 - High Temperatures
 - High Densities
 - Strong Fields
- 3** Problem: Particle Production
 - Schwinger mechanism
 - Kinetic equation for particle production
- 4** Applications
 - Optical and X-ray Laser Experiments
 - Compact Astrophysical Objects
- 5** Perspectives
- 6** Projects





Introduction to scientific background

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Astrophysics

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Academic tradition

- Bogoliubov
 - Shirkov
 - Zubarev
 - Röpke
 - Smolyansky
 - Tavkhelidze



Textbooks

- Bogoliubov/ Shirkov: Quantum Field Theory (1959)
- Zubarev/Morozov/Röpke: Statistical Mechanics of Nonequilibrium Processes (1996)



Symmetry Breaking and Restoration

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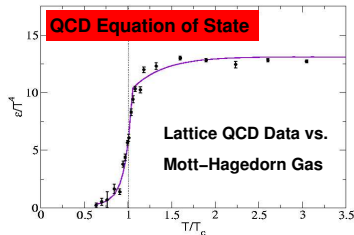
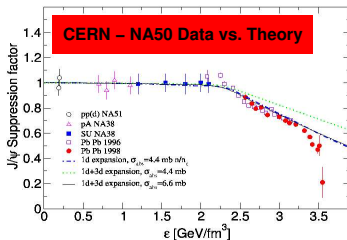
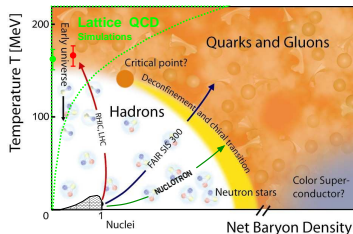
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High Temperature

- Deconfinement at $T_c \sim T_H$
- Strongly interacting QGP in Heavy ion collisions
- Signal: J/ψ suppression



Blaschke, Bugaev: Prog. Part. Nucl. Phys. 53 (2004) 197



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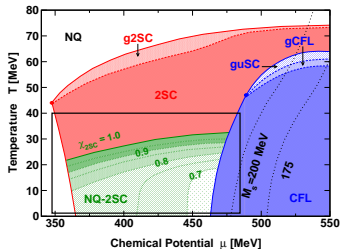
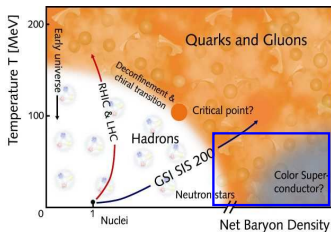
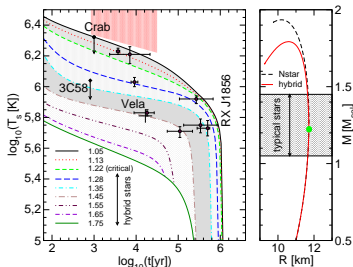
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High Densities

- Quark matter phases at 3-5 nuclear densities
- Color superconductivity
- Interiors of Compact Stars
- Cooling of Compact Stars



Blaschke, Grigorian, Voskresensky: Phys. Rev. C71 (2005) 045801



New: Pair Creation in Strong Fields

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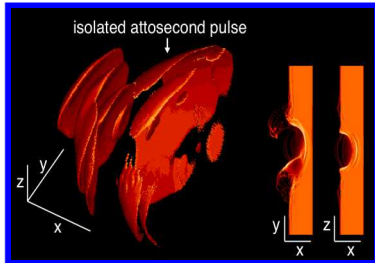
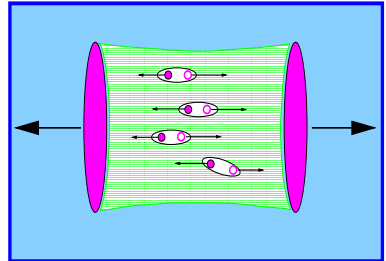
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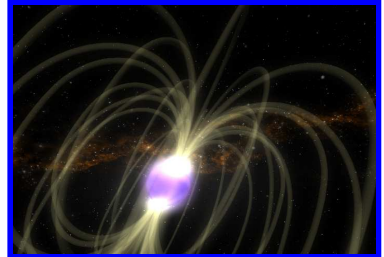
Perspectives

Projects

- Heavy Ion Collisions
- Magnetars: $B \sim 10^{15} \text{ G}$
- Optical and X-Ray Lasers:
 $E \sim 10^{15} \div 10^{17} \text{ V/m}$



Extreme Light Infrastructure (Project)

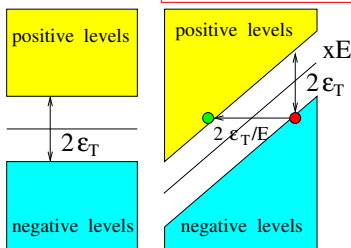


Artist view of a Magnetar (NASA)

Schwinger mechanism for pair production



- Pair creation as **quantum tunneling**



- Schwinger result for pair production rate

$$\frac{dN}{d^3x dt} = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_{\text{crit}}}{E}\right)$$

- J. Schwinger: On Gauge Invariance and Vacuum Polarization, Phys. Rev. 82 (1951) 664**

- To 'materialize' a virtual e^+e^- pair in a constant electric field E the separation d must be sufficiently large

$$eEd = 2mc^2$$

- Probability for separation d as quantum fluctuation

$$P \propto \exp\left(-\frac{d}{\lambda_c}\right) = \exp\left(-\frac{2m^2c^3}{e\hbar E}\right) \\ = \exp\left(-\frac{2E_{\text{crit}}}{E}\right)$$

- Emission sufficient for observation when $E \sim E_{\text{crit}}$

$$E_{\text{crit}} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{18} \text{ V/m}$$

- For time-dependent fields: Kinetic Equation approach from Quantum Field Theory



Kinetic formulation of pair production

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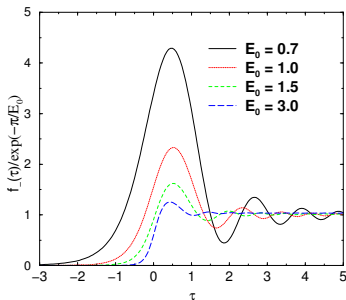
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Kinetic equation for the distribution function $f(\vec{P}, t) = \langle 0 | a_{\vec{p}}^+(t) a_{\vec{p}}(t) | 0 \rangle$



Schwinger limit (constant field) reproduced

$$f(\tau \rightarrow \infty) = \exp\left(\frac{-\pi}{E_0}\right)$$

Schmidt, Blaschke, Smolyansky et al:
Non-Markovian effects in strong-field pair creation,
Phys. Rev. D 59 (1999) 094005

$$\begin{aligned} \frac{df_{\pm}(\vec{p}, t)}{dt} &= \frac{\partial f_{\pm}(\vec{p}, t)}{\partial t} + eE(t) \frac{\partial f_{\pm}(\vec{p}, t)}{\partial p_{\parallel}(t)} \\ &= \frac{eE(t)\varepsilon_{\perp}}{2\omega^2(t)} \int_{-\infty}^t dt' \frac{eE(t')\varepsilon_{\perp}}{\omega^2(t')} \\ &\times [1 \pm 2f_{\pm}(\vec{p}, t')] \cos\left[\int_{t'}^t d\tau \omega(\tau)\right] \end{aligned}$$

Kinematic momentum $\vec{p} = (p_1, p_2, p_3 - eA(t))$,

Time-dependent Bogoliubov-transformation

$$\begin{aligned} a_{\vec{p}}(t) &= \alpha_{\vec{p}}(t) a_{\vec{p}}(t_0) + \beta_{\vec{p}}(t) b_{-\vec{p}}^+(t_0) \\ b_{\vec{p}}(t) &= \alpha_{-\vec{p}}(t) b_{\vec{p}}(t_0) - \beta_{-\vec{p}}(t) a_{-\vec{p}}^+(t_0) \end{aligned}$$

Anti-commuting field operators

$$\{a_{\vec{p}}(t_0), a_{\vec{p}'}^+(t_0)\} = \{b_{\vec{p}}(t_0), b_{\vec{p}'}^+(t_0)\} = \delta_{\vec{p}, \vec{p}'}$$



Laser Experiments: Jena Multi-TW Laser

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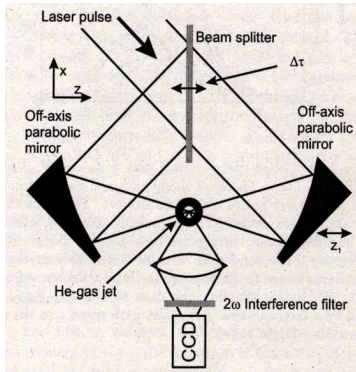
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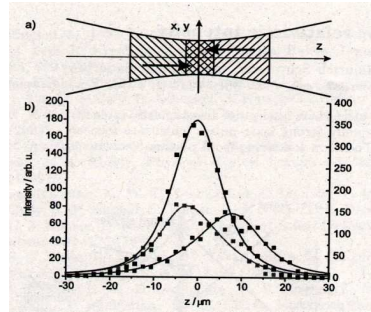
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Colliding laser pulses of a Ti:sapphire laser with

$$E_m/E_{\text{crit}} \approx 1.5 \cdot 10^{-6} \text{ and } \nu/m = 2.84 \cdot 10^{-6}$$



Laser diagnostic by nonlinear Thomson scattering off e^- in a He-gas jet

Pulse intensity: $I = 10^{18} \text{ W/cm}^2$,

duration: $\tau_L \sim 80 \text{ fs}$, wavelength: $\lambda = 700 \text{ nm}$,

cross-size: $z_0 = 9 \mu\text{m}$

Heinzl, Sauerbrey, Schworer, et al, [arXiv:hep-ph/0601076](https://arxiv.org/abs/hep-ph/0601076) (2006)

Laser Experiments: Jena Multi-TW Laser

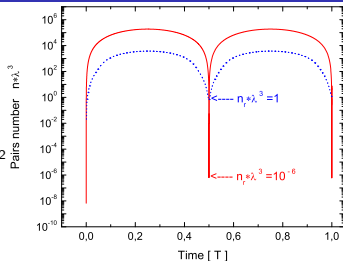
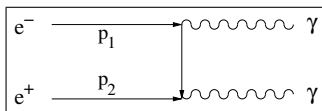
- Analytic estimate for $E_m \ll E_{\text{crit}}$, $f \ll 1$

$$n(t) = \frac{1}{2(2\pi)^3} \int d\mathbf{p} (m^2 + p_{\perp}^2) \times \left| \int_{t_0}^t dt_1 \frac{eE(t_1)}{\varepsilon^2(t_1)} \exp\left(2i \int_{t_1}^t dt_2 \varepsilon(t_2)\right) \right|^2$$

- Mean pair density (low frequency limit $\nu \ll m$)

$$\langle n \rangle \approx 1.6 \times 10^{-3} \frac{(eE)^2}{m} = \left(\frac{m}{\nu}\right)^2 n_r$$

- Observable signal: two-photon annihilation!



Number of e^+e^- pairs in the volume λ^3 for a weak field (Jena Ti:AlO₃ laser, solid line) and for near-critical field $E_m/E_{\text{crit}} = 0.24$, $\lambda = 0.15$ nm (X-FEL, dashed line).

Jena Experiment currently performed

Prediction:

5-10 gamma-pairs per laser pulse !

Blaschke, Prozorkevich, Roberts, Schmidt, Smolyansky: PRL 96, 140402 (2006).



Compact stars: X-ray bursts

A low-mass X-ray binary system

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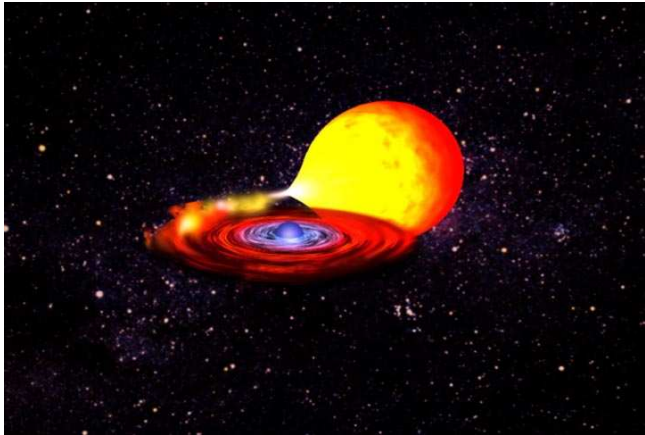
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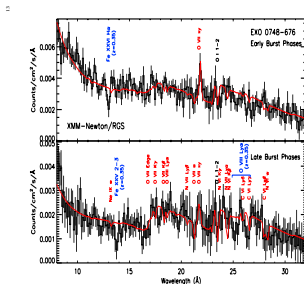
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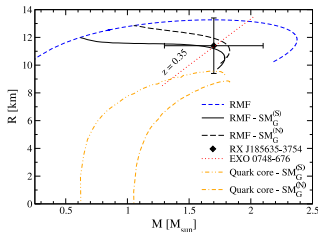
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- RXTE observes burst spectra of EXO 0748-676 with redshifted Fe-lines
- Quark matter core is not excluded.



- Observation of redshift $z=0.35$ puts constraints on compactness M/R , i.e. on neutron star EoS



Grigorian, Blaschke, Aguilera,
Phys. Rev. C 69 (2004) 065802

- New constraints to EoS
T. Klähn et al: nucl-th/0602038



Gamma-Ray Bursts: Magnetars or Black holes?

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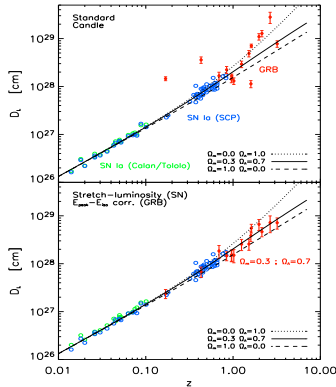
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- GRB's as new 'standard candles' to measure the space-time structure of the Universe

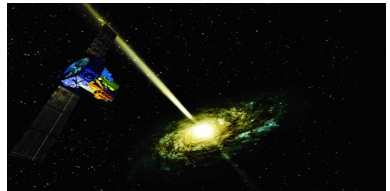
Ghirlanda et al: *ApJ* 613, L13 (2004)



- Understanding GRB's is a challenge to QFT under extreme conditions!
- Relation to kinetic theory of pair production in strong fields

Ruffini et al: *astro-ph/0410233* (2004)

- INTEGRAL and SWIFT missions observe GRB's





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Virtual Institute of the Helmholtz-Association Dense Hadronic Matter and QCD Phase Transition



VH-VI-041

<http://theory.gsi.de/Vir-Institute/>

DIAS-TH: Dubna International Advanced School of Theoretical Physics

Helmholtz International Summer School

Dense Matter in Heavy Ion Collisions and Astrophysics

Bogoliubov Laboratory of Theoretical Physics
JINR, Dubna, Russia, August 21 – September 1, 2006



TOPICS:

- Hadrons in the Medium
- Equation of State and Phase Transition
- Hadron Production in Heavy-Ion Collisions
- Color Superconductivity and sQGP
- Dense Matter in Compact Stars

SUPPORTED BY:

- Helmholtz Association
- Helmholtz Centers DESY and GSI

ORGANIZERS:

- J. Wambach (GSI, TU Darmstadt)
- D. Blaschke (JINR, GSD)

LOCAL ORGANIZERS:

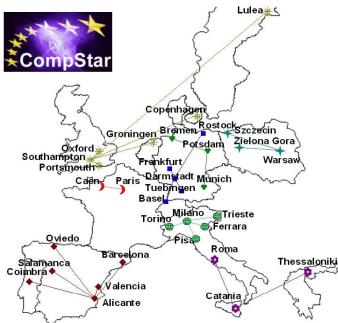
- A. Sarti (JINR)
- J. Schmeiser (U Rostock & JINR)
- V. Zhuravley (JINR)
- V. Skokov (ex. secretary, JINR)
- V. Novikova (JINR)

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<http://luth.obspm.fr/%7ecarter/CompStar/>

Physics of Compact Stars

Proposal for a 6-week Ph.D. training programme

ECT* Trento, Italy

September 3 – October 12, 2007

Organizers: D. Blaschke (Wroclaw), J. Pons (Alicante), L. Rezzolla (Potsdam)

* **Compact Star Phenomenology:**

D. Jones (Southampton), R. Turolla (Padova)

* **Physics of the Neutron Star Crust:**

P. Haensel (Warsaw), P. Pizzochero (Milan)

* **EoS for Compact Star Interiors:**

F. Burgio (Catania), D. Blaschke (Wroclaw)

* **Neutrino Processes and Cooling:**

D. Voskresensky (Moscow), D. Page (Mexico)

* **Computational Relativistic Astrophysics:**

L. Rezzolla (Postdam), S. Rosswog (Bremen)

* **Supernovae and Protoneutron Stars:**

M. Liebendoerfer (Basel), J. Pons (Alicante)

<http://www.ect.it>

Projects



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- First Project:
Symmetry breaking. Goldstone theorem. Higgs-effect
- Second Project:
Bose condensation. Superconductivity. Superfluidity
- Third Project:
Pair production in strong fields. Schwinger mechanism
- Fourth Project:
Hawking radiation. Unruh effect
- Fifth Project:
Confinement of Quarks and Gluons

