Advanced Quantum Mechanics

Macroscopic Quantum Effects: from Laboratory to Stars

David Blaschke

Institute for Theoretical Physics
University of Wroclaw, Poland

Bogoliubov Laboratory for Theoretical Physics
Joint Institute for Nuclear Research Dubna, Russia

Lectures for PhD students, Winter Semester 2006/2007

Introduction to scientific background

Academic tradition

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

BLTP Bogoliubov Laboratory of Theoretical Physics

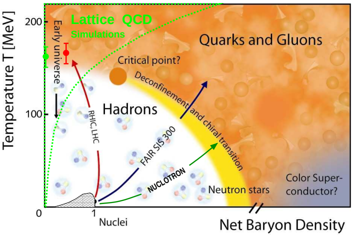
Textbooks

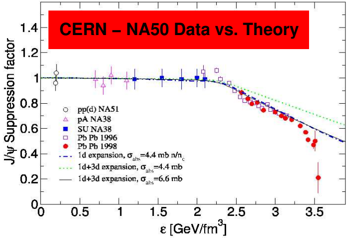
- Bogoliubov/ Shirkov: Quantum Field Theory (1959)
- Zubarev/Morozov/Röpke: Statistical Mechanics of Nonequilibrium Processes (1996)

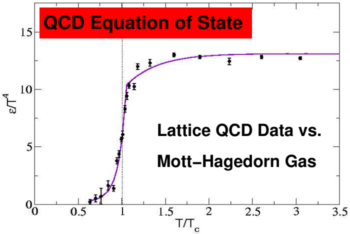
Symmetry Breaking and Restoration

High Temperature

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





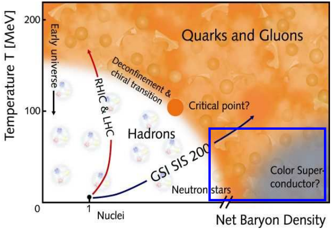


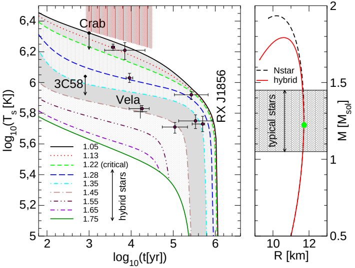
Blaschke, Bugaev: Prog. Part. Nucl. Phys. 53 (2004) 197

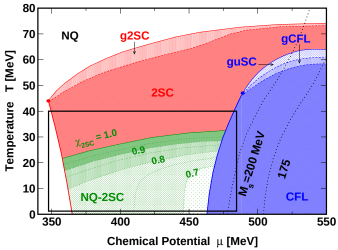
Symmetry Breaking and Restoratoion

High Densities

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



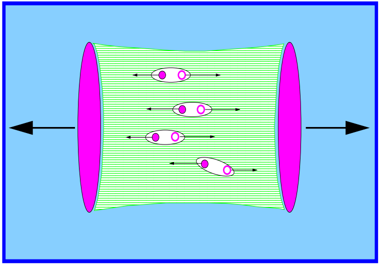


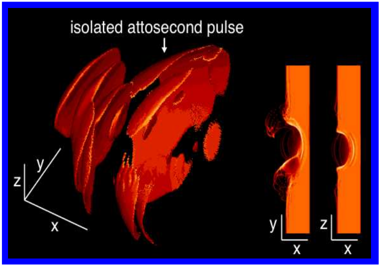


Blaschke, Grigorian, Voskresensky: Phys. Rev. C71 (2005) 045801

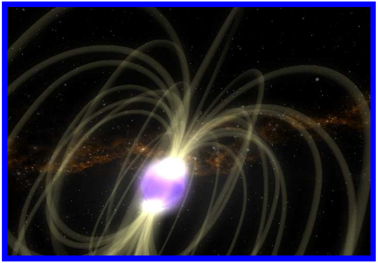
New: Pair Creation in Strong Fields

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



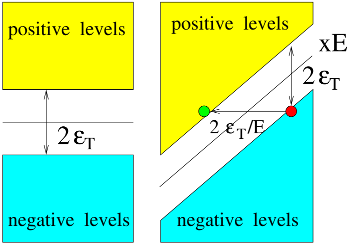


Extreme Light Infrastructure (Project)


Artist view of a Magnetar (NASA)

Schwinger mechanism for pair production

- Pair creation as quantum tunneling



- Schwinger result for pair production rate

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

- 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

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

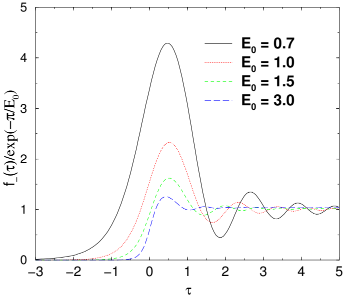
- Emission sufficient for observation when $E \sim E_{\rm crit}$

$$E_{\rm crit} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3\times10^{18}\,{\rm V/m}$$

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

Kinetic fromulation of pair production

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



Schwinger limit (constant field) reproduced

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

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

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

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

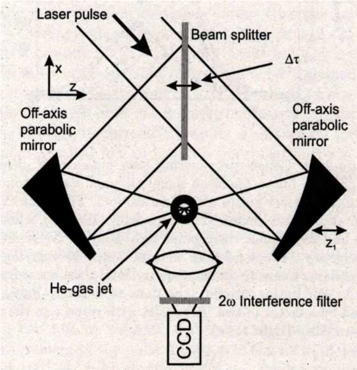
Time-dependent Bogoliubov-transformation

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

Anti-commutating field operators

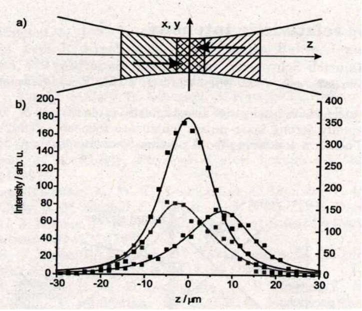
$$\{a_{\bar{p}}(t_0), a^+_{\bar{p}'}(t_0)\} = \{b_{\bar{p}}(t_0), b^+_{\bar{p}'}(t_0)\} = \delta_{\bar{p},\bar{p}'}$$

Laser Experiments: Jena Multi-TW Laser



Colliding laser pulses of a Ti:sapphire laser with

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



Laser diagnostic by nonlinear Thomson scattering off e^- in a He-gas jet
Pulse intensity: $I = 10^{18}$ W/cm^2,
duration: $\tau_L \sim 80 fs$, wavelength: $\lambda = 700$ nm,

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

Heinzl, Sauerbrey, Schwoerer, et al, arXiv:hep-ph/0601076 (2006)

Laser Experiments: Jena Multi-TW Laser

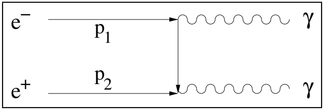
- Analytic estimate for $E_m \ll E_{\rm crit}$, $f \ll 1$

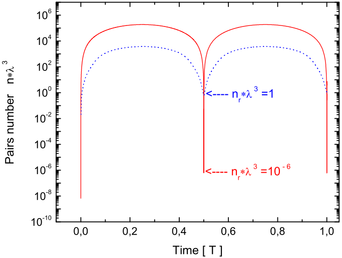
$$n(t) = \frac{1}{2(2\pi)^3} \int d\mathbf{p}\,(m^2 + p_\perp^2) \times \left| \int_{t_0}^{t} dt_1 \frac{eE(t_1)}{\varepsilon^2(t_1)} \exp\left(2i \int_{t_1}^{t} dt_2 \varepsilon(t_2)\right) \right|^2$$

- 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:AlO_3 laser, solid line) and for near-critical field $E_m/E_{\rm crit} = 0.24$, $\lambda = 0.15$ nm (X-FEL, dashed line).

Jena Experiment currently performed

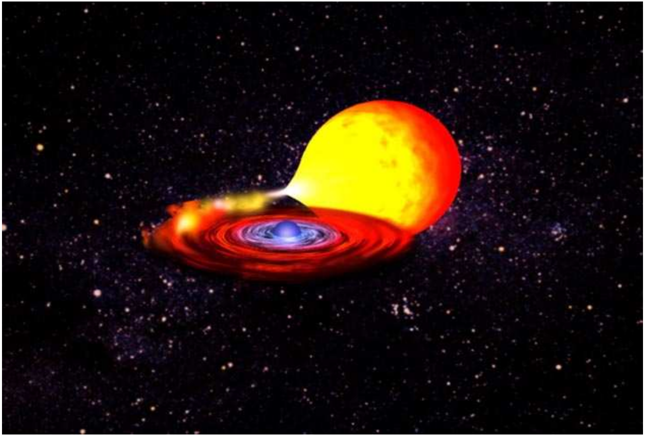
Prediction:

5-10 gamma-pairs per laser pulse !

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

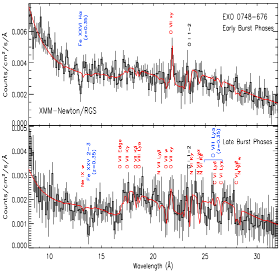
Compact stars: X-ray bursts

A low-mass X-ray binary system

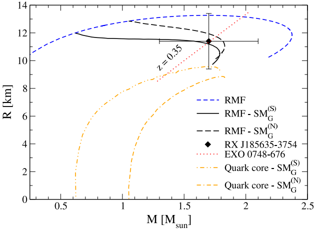


Compact stars: X-ray bursts

- 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

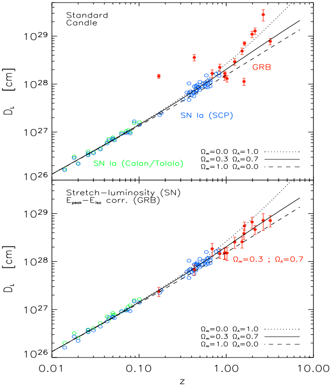
- New constraints to EoS

T. Klähn et al: nucl-th/0602038

Gamma-Ray Bursts: Magnetars or Black holes?

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

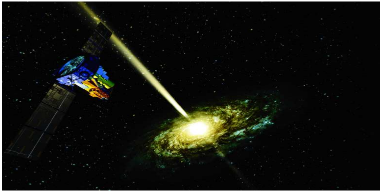
Ghirlanda et al: ApJ 613, L13 (2004)



- 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)

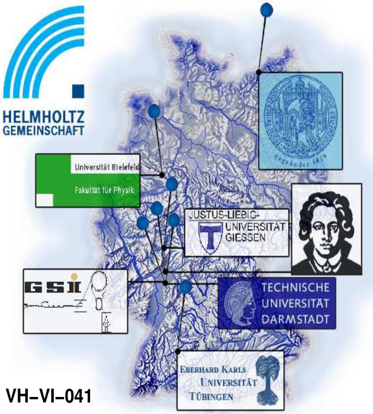
- INTEGRAL and SWIFT missions observe GRB's



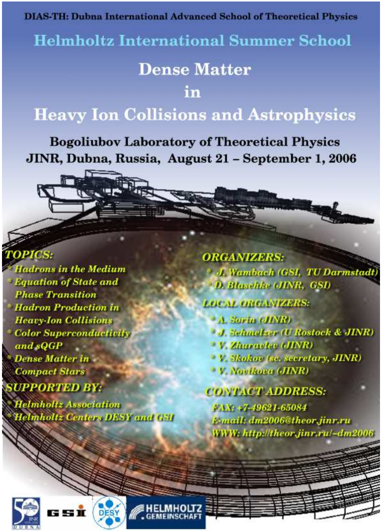
Perspectives

Virtual Institute of the Helmholtz–Association

Dense Hadronic Matter and QCD Phase Transition

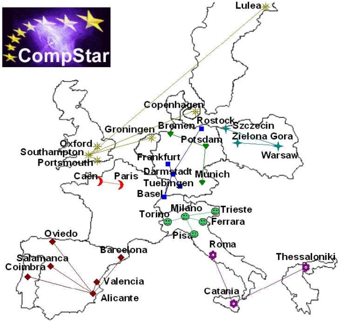


http://theory.gsi.de/Vir-Institute/

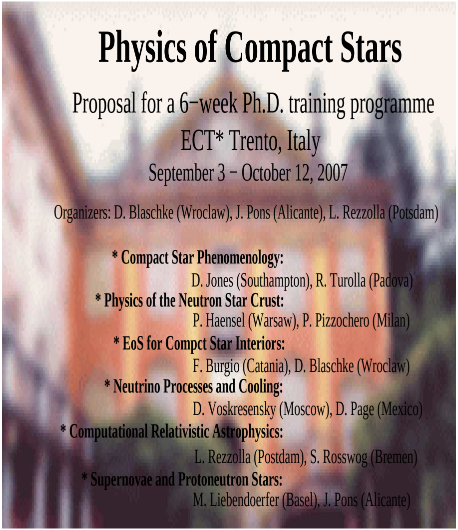


http://thsun1.jinr.ru/∼dm2006/

Perspectives



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



http://www.ect.it

Projects

- 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