Quark Production Far From Equilibrium

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Motivation:

Fermion production plays a crucial role in heavy-ion collisions and early universe!

Heavy-ion collisions:
- production of quarks from highly occupied gauge fields

Cosmology:
- production of fermionic matter from inflaton decay

Non-equilibrium processes!
- real-time description necessary
- initial value problem

Previous studies:
- Dirac equations with homogeneous background fields [6]
  - genuine quantum effects (scattering etc.) not included
  - highly oscillatory spectra

Our approach:
- comparison of 2PI effective action techniques and lattice simulations

First application to a quark-meson model [1] :
- enhancement of boson fluctuations through non-equilibrium instabilities
  - **parametric resonance**
  - spinodal decomposition

Implementation:

We consider a $O(N_s = 4)$ symmetric 3+1 dimensional linear sigma model coupled to $N_f = 2$ massless Dirac fermions

$$-\frac{g}{N_f}\bar{\psi}_i\left((1-\gamma^5)\Phi^\dagger_{ij}+(1+\gamma^5)\Phi_{ij}\right)\psi_j$$

with a non-vanishing expectation value of the sigma meson

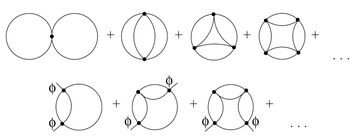
$$\Phi = (\sigma + i\vec{\tau}\vec{\pi})/2 \qquad \phi(t) = \langle \mathrm{Tr}\,\Phi(t,\mathbf{x})\rangle$$

and potential: $V = m^2(\sigma^2+\vec{\pi}^2)/2 + \lambda\left(\sigma^2+\vec{\pi}^2\right)^2/4!N_s$

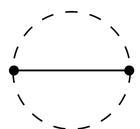
Information about quark production can be extracted from statistical and spectral correlation functions:

$$F(x,y) = \frac{1}{2}\left\langle[\psi(x),\bar{\psi}(y)]\right\rangle \qquad \rho(x,y) = i\left\langle\{\psi(x),\bar{\psi}(y)\}\right\rangle$$

2PI:
- 1/N expansion to NLO in the number of scalar fields N_s [4]:



- coupling expansion to NLO in the Yukawa coupling g [5]:



Lattice:
- fermion determinant integrated out numerically [2]
- efficient ♂/♀ - fermions [3]
- classical-statistical scalar fields

Results:

- **strongly enhanced quark production out of equilibrium**
- quantum effects important for fermion production, even at small couplings
- quark production rate proportional to $\sim \xi = g^2/\lambda$
- quasi-stationary fermion spectra emerge
- thermal occupation number in the infrared
- particle numbers drop at the rescaled initial field amplitude $\phi_0 = \phi(t=0)/\sqrt{6N_s/\lambda}$
- sufficiency of 2PI truncation for small ξ checked with lattice simulations

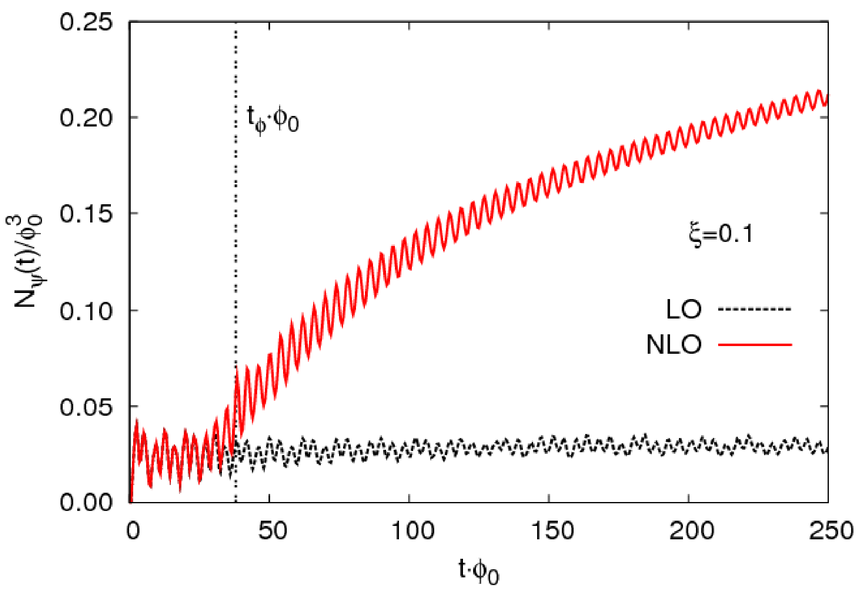


Figure 1: Total number density of fermions

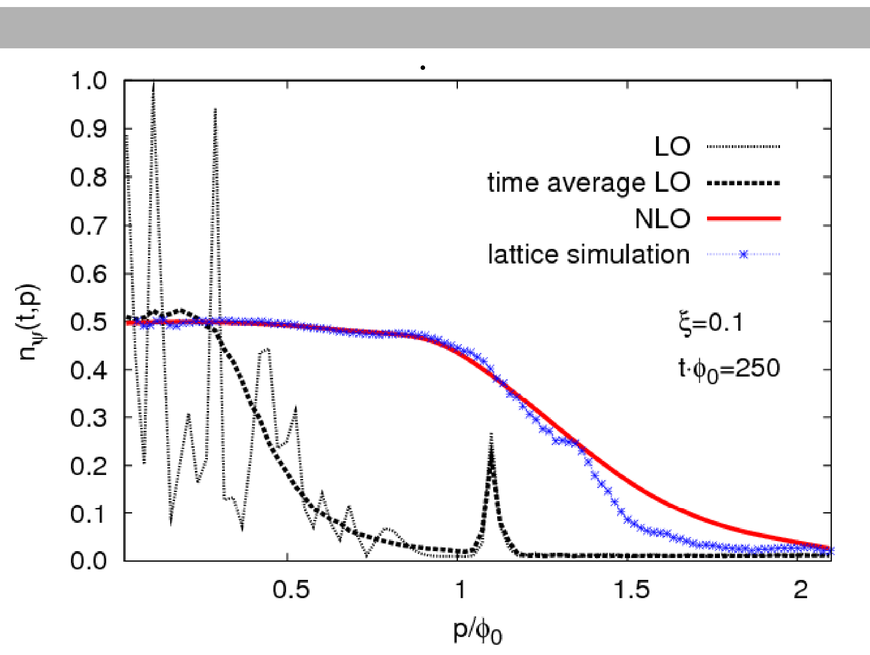


Figure 2: Time-dependent fermion occupation number

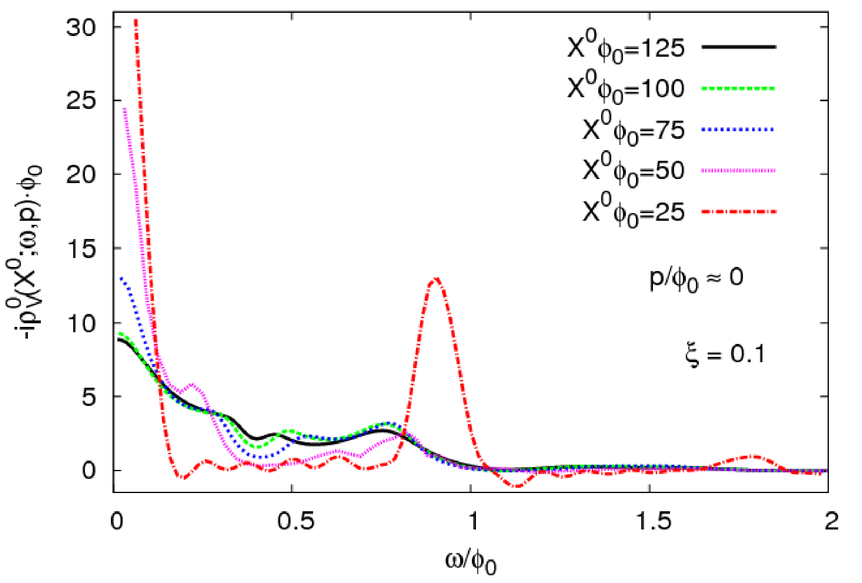


Figure 3: Non-equilibrium fermion spectral function

Outlook:

- explore the strongly-coupled regime with lattice simulations
- study the quark production in QCD

References:

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[2] G. Aarts and J. Smit, Nucl. Phys. B 555 (1999) 355.
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[5] J. Berges, J. Pruschke and A. Rothkopf, Phys. Rev. D 80 (2009) 023522.
[6] F. Gelis, K. Kajantie and T. Lappi, Phys. Rev. Lett. 96 (2006) 032304; P. B. Greene and L. Kofman, Phys. Lett. B 448 (1999) 6; G. F. Giudice, M. Peloso, A. Riotto and I. Tkachev, JHEP 9908 (1999) 014.

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