News from Bosonization

Stefan Flörchinger (Heidelberg)

Work in collaboration with C. Wetterich

FOR 723 Workshop, ReisensbuRG 2009

Introduction

- We want to describe a system of *fermionic* fields ψ.

Introduction

- We want to describe a system of *fermionic* fields ψ.
- At low temperature we expect some kind of order.

Introduction

- We want to describe a system of *fermionic* fields ψ.
- At low temperature we expect some kind of order.
- Order parameter is a *bosonic* field φ.

Fermions or bosons?

- Purely fermionic description (1-PI)

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated
- Also purely bosonic description is possible (2-PI)

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated
- Also purely bosonic description is possible (2-PI)
  - has advantages in ordered regime

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated
- Also purely bosonic description is possible (2-PI)
  - has advantages in ordered regime
  - infared properties well described

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated
- Also purely bosonic description is possible (2-PI)
  - has advantages in ordered regime
  - infared properties well described
  - technically more complicated

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated
- Also purely bosonic description is possible (2-PI)
  - has advantages in ordered regime
  - infared properties well described
  - technically more complicated
  - formalism is nonlocal (bilocal)

Fermions or bosons?

- Purely fermionic description (1-PI)
  - most convenient in symmetric regime
  - many channels can be followed
  - becomes difficult in ordered regime
  - infrared properties (critical phenomena) complicated
- Also purely bosonic description is possible (2-PI)
  - has advantages in ordered regime
  - infared properties well described
  - technically more complicated
  - formalism is nonlocal (bilocal)
- Partial bosonization combines advantages of both approaches.

Notation

- Fermion field ψ_α

Notation

- Fermion field ψ_α
- Abstract index α labels continuous and discrete degrees of freedom.

Notation

- Fermion field ψ_α
- Abstract index α labels continuous and discrete degrees of freedom.
- For example: Matsubara frequency ω_n, momentum $\vec{q}$ and spin i

$$\alpha = (\omega_n, \vec{q}, i)$$

Notation

- Fermion field ψ_α
- Abstract index α labels continuous and discrete degrees of freedom.
- For example: Matsubara frequency ω_n, momentum $\vec{q}$ and spin i

$$\alpha = (\omega_n, \vec{q}, i)$$

- α differentiates also between particles ψ and holes ψ^* (or antiparticles $\bar{\psi}$).

Microscopic model

$$S = \frac{1}{2}\psi_\alpha \, P_{\alpha\beta} \, \psi_\beta + \frac{1}{4!}\lambda_{\alpha\beta\gamma\delta} \, \psi_\alpha\psi_\beta\psi_\gamma\psi_\delta$$

- Inverse propagator P

Microscopic model

$$S = \frac{1}{2}\psi_\alpha \, P_{\alpha\beta} \, \psi_\beta + \frac{1}{4!}\lambda_{\alpha\beta\gamma\delta} \, \psi_\alpha\psi_\beta\psi_\gamma\psi_\delta$$

- Inverse propagator P
- Fermion-fermion interaction λ

Microscopic model

$$S = \frac{1}{2}\psi_\alpha \, P_{\alpha\beta} \, \psi_\beta + \frac{1}{4!}\lambda_{\alpha\beta\gamma\delta} \, \psi_\alpha\psi_\beta\psi_\gamma\psi_\delta$$

- Inverse propagator P
- Fermion-fermion interaction λ
- Examples: Hubbard model, BCS-model, NJL-model,...

Hubbard-Stratonovich transformation

- Add Gaussian functional integral over boson field φ

$$\int D\varphi\, e^{-\frac{1}{2}(\varphi-\chi Q^{-1})Q(\varphi-Q^{-1}\chi)}$$

Hubbard-Stratonovich transformation

- Add Gaussian functional integral over boson field φ

$$\int D\varphi \, e^{-\frac{1}{2}(\varphi-\chi Q^{-1})Q(\varphi-Q^{-1}\chi)}$$

- Operator χ quadratic in fermion field

$$\chi_\epsilon = H_{\epsilon\alpha\beta}\,\psi_\alpha\psi_\beta.$$

Hubbard-Stratonovich transformation

- Add Gaussian functional integral over boson field φ

$$\int D\varphi \, e^{-\frac{1}{2}(\varphi - \chi Q^{-1}) Q (\varphi - Q^{-1}\chi)}$$

- Operator χ quadratic in fermion field

$$\chi_\epsilon = H_{\epsilon\alpha\beta} \, \psi_\alpha \psi_\beta .$$

- Choose H and Q such that λ-term is cancelled

$$\frac{1}{4!}\lambda_{\alpha\beta\gamma\delta} + \frac{1}{2}(HQ^{-1}H)_{\alpha\beta\gamma\delta} = 0.$$

Hubbard-Stratonovich transformation

- Add Gaussian functional integral over boson field φ

$$\int D\varphi\, e^{-\frac{1}{2}(\varphi-\chi Q^{-1})Q(\varphi-Q^{-1}\chi)}$$

- Operator χ quadratic in fermion field

$$\chi_\epsilon = H_{\epsilon\alpha\beta}\,\psi_\alpha\psi_\beta.$$

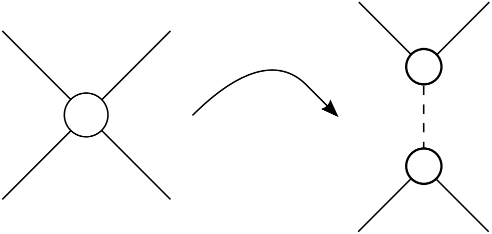
- Choose H and Q such that λ-term is cancelled

$$\frac{1}{4!}\lambda_{\alpha\beta\gamma\delta} + \frac{1}{2}(HQ^{-1}H)_{\alpha\beta\gamma\delta} = 0.$$

- Arrive at theory for fermions and bosons

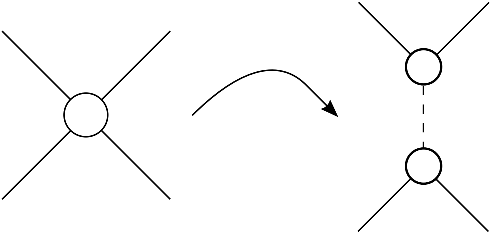
$$S = \frac{1}{2}\psi P\psi + \frac{1}{2}\varphi Q\varphi - \varphi H\psi\psi.$$

Hubbard-Stratonovich II



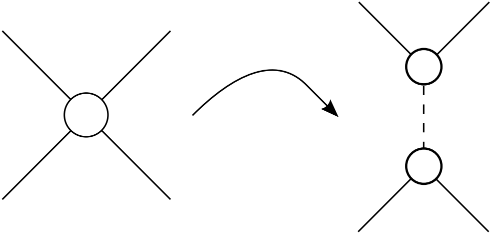
- Fermion interaction is expressed as boson exchange.

Hubbard-Stratonovich II



- Fermion interaction is expressed as boson exchange.
- Need boson field for every channel!

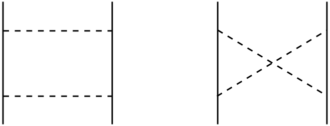
Hubbard-Stratonovich II



- Fermion interaction is expressed as boson exchange.
- Need boson field for every channel!
- Divergence in λ corresponds to order parameter $\langle \varphi \rangle \neq 0$.

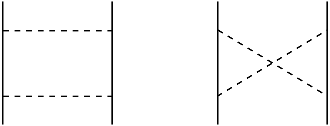
Rebosonization

- Fermion coupling λ is regenerated by renormalization flow.



Rebosonization

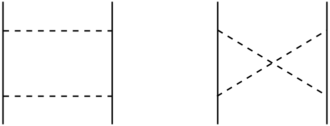
- Fermion coupling λ is regenerated by renormalization flow.



- Gies & Wetterich (2001): Use scale dependent boson fields $\varphi_k[\psi]$ to have $\lambda = 0$ on all scales.

Rebosonization

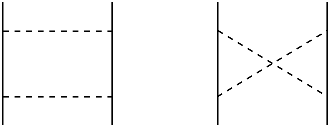
- Fermion coupling λ is regenerated by renormalization flow.



- Gies & Wetterich (2001): Use scale dependent boson fields $\varphi_k[\psi]$ to have $\lambda = 0$ on all scales.
- Related work: Pawlowski (2007).

Rebosonization

- Fermion coupling λ is regenerated by renormalization flow.



- Gies & Wetterich (2001): Use scale dependent boson fields $\varphi_k[\psi]$ to have $\lambda = 0$ on all scales.
- Related work: Pawlowski (2007).
- We will present an exact and simple one-loop flow equation for this task.
(S. Floerchinger and C. Wetterich, arXiv:0905.0915)

Nonlinear field transformation

Consider flow equation (Wetterich 1993)

$$\partial_k \Gamma_k[\psi, \varphi]\big|_{\varphi} = \frac{1}{2}\mathsf{STr}\left\{(\Gamma_k^{(2)} + R_k)^{-1}\partial_k R_k\right\}$$

with k-dependent change of variables $\varphi = \varphi[\bar{\varphi}]$

$$\partial_k \Gamma_k\big|_{\bar{\varphi}} = \partial_k \Gamma_k\big|_{\varphi} - \int_q \frac{\delta \Gamma_k}{\delta \bar{\varphi}} \partial_k \bar{\varphi}\big|_{\varphi}.$$

- $\partial_k \bar{\varphi} \sim \psi\psi$ allows for "rebosonization".

Nonlinear field transformation

Consider flow equation (Wetterich 1993)

$$\partial_k \Gamma_k[\psi, \varphi]\big|_{\varphi} = \frac{1}{2}\mathsf{STr}\left\{(\Gamma_k^{(2)} + R_k)^{-1}\partial_k R_k\right\}$$

with k-dependent change of variables $\varphi = \varphi[\bar{\varphi}]$

$$\partial_k \Gamma_k\big|_{\bar{\varphi}} = \partial_k \Gamma_k\big|_{\varphi} - \int_q \frac{\delta \Gamma_k}{\delta \bar{\varphi}} \partial_k \bar{\varphi}\big|_{\varphi}.$$

- $\partial_k \bar{\varphi} \sim \psi\psi$ allows for "rebosonization".
- $\Gamma_k^{(2)}$ and R_k transform as tensors of rank two.

Nonlinear field transformation

Consider flow equation (Wetterich 1993)

$$\partial_k \Gamma_k[\psi, \varphi]\big|_{\varphi} = \frac{1}{2}\mathsf{STr}\left\{(\Gamma_k^{(2)} + R_k)^{-1}\partial_k R_k\right\}$$

with k-dependent change of variables $\varphi = \varphi[\bar{\varphi}]$

$$\partial_k \Gamma_k\big|_{\bar{\varphi}} = \partial_k \Gamma_k\big|_{\varphi} - \int_q \frac{\delta \Gamma_k}{\delta \bar{\varphi}} \partial_k \bar{\varphi}\big|_{\varphi}.$$

- $\partial_k \bar{\varphi} \sim \psi\psi$ allows for "rebosonization".
- $\Gamma_k^{(2)}$ and R_k transform as tensors of rank two.
- Connection terms $\sim \frac{\delta^2 \varphi}{\delta\bar{\varphi}\delta\bar{\varphi}}$ destroy one-loop structure.

Nonlinear field transformation

Consider flow equation (Wetterich 1993)

$$\partial_k \Gamma_k[\psi, \varphi]\big|_{\varphi} = \frac{1}{2}\mathsf{STr}\left\{(\Gamma_k^{(2)} + R_k)^{-1}\partial_k R_k\right\}$$

with k-dependent change of variables $\varphi = \varphi[\bar{\varphi}]$

$$\partial_k \Gamma_k\big|_{\bar{\varphi}} = \partial_k \Gamma_k\big|_{\varphi} - \int_q \frac{\delta \Gamma_k}{\delta \bar{\varphi}} \partial_k \bar{\varphi}\big|_{\varphi}.$$

- $\partial_k \bar{\varphi} \sim \psi\psi$ allows for "rebosonization".
- $\Gamma_k^{(2)}$ and R_k transform as tensors of rank two.
- Connection terms $\sim \frac{\delta^2 \varphi}{\delta \bar{\varphi} \delta \bar{\varphi}}$ destroy one-loop structure.
- $\Gamma_k[\bar{\varphi}] := \Gamma_k[\varphi[\bar{\varphi}]]$ has different properties than $\Gamma_k[\varphi]$.

Scale-dependent bosonization

- Hubbard-Stratonovich transformation with k-dependent Q ("boson propagator") and H ("Yukawa interaction").

Scale-dependent bosonization

- Hubbard-Stratonovich transformation with k-dependent Q ("boson propagator") and H ("Yukawa interaction").
- Scale-dependent Schwinger functional

$$e^{W_k[\eta,j]} = \int D\tilde{\psi}\, D\tilde{\varphi}\, e^{-S_k[\tilde{\psi},\tilde{\varphi}]+\eta\tilde{\psi}+j\tilde{\varphi}}$$

with

$$\begin{aligned} S_k[\tilde{\psi},\tilde{\varphi}] &= S_\psi[\tilde{\psi}] + \frac{1}{2}\tilde{\psi}(R_k^\psi)\tilde{\psi} + \frac{1}{2}\tilde{\varphi}(Q + R_k^\varphi)\tilde{\varphi} \\ &\quad + \frac{1}{2}(\tilde{\psi}\tilde{\psi}H)Q^{-1}(H\tilde{\psi}\tilde{\psi}) - \tilde{\varphi}(H\tilde{\psi}\tilde{\psi}). \end{aligned}$$

Scale-dependent bosonization

- Hubbard-Stratonovich transformation with k-dependent Q ("boson propagator") and H ("Yukawa interaction").
- Scale-dependent Schwinger functional

$$e^{W_k[\eta,j]} = \int D\tilde{\psi}\, D\tilde{\varphi}\, e^{-S_k[\tilde{\psi},\tilde{\varphi}]+\eta\tilde{\psi}+j\tilde{\varphi}}$$

with

$$\begin{aligned} S_k[\tilde{\psi},\tilde{\varphi}] &= S_\psi[\tilde{\psi}] + \frac{1}{2}\tilde{\psi}(R_k^\psi)\tilde{\psi} + \frac{1}{2}\tilde{\varphi}(Q + R_k^\varphi)\tilde{\varphi} \\ &\quad + \frac{1}{2}(\tilde{\psi}\tilde{\psi}H)Q^{-1}(H\tilde{\psi}\tilde{\psi}) - \tilde{\varphi}(H\tilde{\psi}\tilde{\psi}). \end{aligned}$$

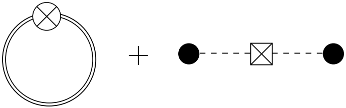
- k-dependent are: R_k, H and Q.

Exact flow equation

$$\begin{aligned}\partial_k \Gamma_k \;&=\; \frac{1}{2}\mathsf{STr}\left\{\left(\Gamma_k^{(2)} + R_k\right)^{-1}\left(\partial_k R_k - R_k(\partial_k Q^{-1})R_k\right)\right\} \\ &\quad -\frac{1}{2}\Gamma_k^{(1)}\left(\partial_k Q^{-1}\right)\Gamma_k^{(1)} + \gamma_k\end{aligned}$$

- One-loop term is supplemented by “tree” term.

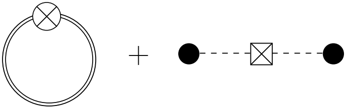
$\partial_k \Gamma_k \;=$



Exact flow equation

$$\begin{aligned}\partial_k \Gamma_k \;=\;& \frac{1}{2}\mathsf{STr}\left\{\left(\Gamma_k^{(2)} + R_k\right)^{-1}\left(\partial_k R_k - R_k(\partial_k Q^{-1})R_k\right)\right\} \\ & -\frac{1}{2}\Gamma_k^{(1)}\left(\partial_k Q^{-1}\right)\Gamma_k^{(1)} + \gamma_k\end{aligned}$$

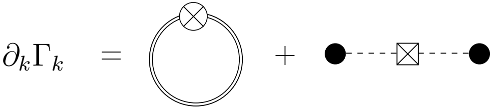
- One-loop term is supplemented by "tree" term.
- Q^{-1} has entries in φ, φ-block, only.

$\partial_k \Gamma_k \quad =$ 

Exact flow equation

$$
\begin{aligned}
\partial_k \Gamma_k \;=\;& \frac{1}{2}\mathsf{STr}\left\{\left(\Gamma_k^{(2)} + R_k\right)^{-1}\left(\partial_k R_k - R_k(\partial_k Q^{-1})R_k\right)\right\} \\
& -\frac{1}{2}\Gamma_k^{(1)}\left(\partial_k Q^{-1}\right)\Gamma_k^{(1)} + \gamma_k
\end{aligned}
$$

- One-loop term is supplemented by "tree" term.
- Q^{-1} has entries in φ, φ-block, only.
- Field-independent term γ_k can often be dropped.



Properties of exaxt flow equation

- Scale dependence of H was choosen such that

$$\partial_k H_{\epsilon\alpha\beta} = (\partial_k \ln Q)_{\epsilon\rho} H_{\rho\alpha\beta}.$$

Properties of exaxt flow equation

- Scale dependence of H was choosen such that

$$\partial_k H_{\epsilon\alpha\beta} = (\partial_k \ln Q)_{\epsilon\rho} H_{\rho\alpha\beta}.$$

- Indepently choosen $\partial_k Q$ and $\partial_k H = (\partial_k F) H$ are equivalent to linear change in φ.

Properties of exaxt flow equation

- Scale dependence of H was choosen such that

$$\partial_k H_{\epsilon\alpha\beta} = (\partial_k \ln Q)_{\epsilon\rho} H_{\rho\alpha\beta}.$$

- Indepently choosen $\partial_k Q$ and $\partial_k H = (\partial_k F) H$ are equivalent to linear change in φ.
- Generalization to other composite operators are possible.

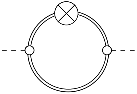
Properties of exaxt flow equation

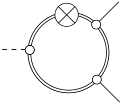
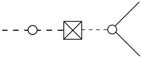
- Scale dependence of H was choosen such that

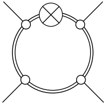
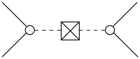
$$\partial_k H_{\epsilon\alpha\beta} = (\partial_k \ln Q)_{\epsilon\rho} H_{\rho\alpha\beta}.$$

- Indepently choosen $\partial_k Q$ and $\partial_k H = (\partial_k F) H$ are equivalent to linear change in φ.
- Generalization to other composite operators are possible.
- For $R_k^\varphi = 0$ formalism is close to purely fermionic flow.

Flowing bosonization

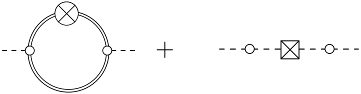
$\partial_k \mathcal{P}_\varphi =$  $+$ 

$\partial_k h =$  $+$ 

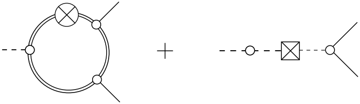
$\partial_k \lambda =$  $+$ 

Flowing bosonization

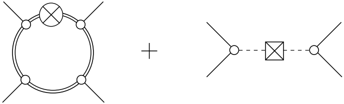
$\partial_k \mathcal{P}_\varphi =$



$\partial_k h =$

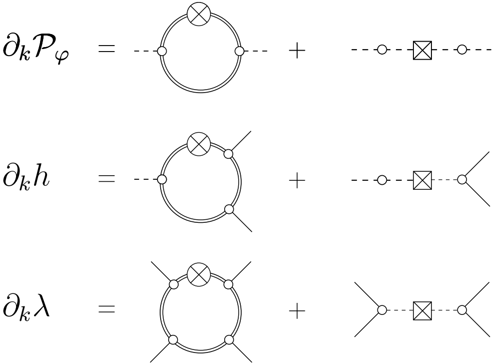


$\partial_k \lambda =$



- $\partial_k Q^{-1}$ can be choosen such that $\partial_k \lambda = 0$.

Flowing bosonization



- $\partial_k Q^{-1}$ can be choosen such that $\partial_k \lambda = 0$.
- This gives corrections to $\partial_k h$ and $\partial_k \mathcal{P}_\varphi$.

Proof of flow equation

Schwinger functional

$$e^{W_k[\eta,j]} = \int D\tilde{\psi}\, D\tilde{\varphi}\, e^{-S_k[\tilde{\psi},\tilde{\varphi}]+\eta\tilde{\psi}+j\tilde{\varphi}} \tag{1}$$

with

$$\begin{aligned} S_k[\tilde{\psi},\tilde{\varphi}] &= S_\psi[\tilde{\psi}] + \frac{1}{2}\tilde{\psi}R_k^\psi\tilde{\psi} + \frac{1}{2}\tilde{\varphi}(Q+R_k^\varphi)\tilde{\varphi} \\ &\quad +\frac{1}{2}\chi Q^{-1}\chi - \tilde{\varphi}\chi. \end{aligned} \tag{2}$$

Shift in field $\tilde{\varphi}$

$$\begin{aligned} e^{W_k[\eta,j]} &= \int D\tilde{\psi}\, e^{-S_\psi[\tilde{\psi}]-\frac{1}{2}\tilde{\psi}R_k^\psi\tilde{\psi}+\eta\tilde{\psi}} \\ &\quad \times e^{\frac{1}{2}(j+\chi)(Q+R_k^\varphi)^{-1}(j+\chi)-\frac{1}{2}\chi Q^{-1}\chi} \\ &\quad \times \int D\tilde{\varphi}\, e^{-\frac{1}{2}\tilde{\varphi}(Q+R_k^\varphi)\tilde{\varphi}}. \end{aligned} \tag{3}$$

Equivalence of both equations yields

$$\langle \chi_\epsilon \rangle = Q_{\epsilon\rho}\varphi_\rho - l_\epsilon \tag{4}$$

with the modified source $l_\epsilon = j_\epsilon - (R_k^\varphi)_{\epsilon\sigma}\varphi_\sigma$. Similarly

$$\begin{aligned} \langle \chi_\epsilon \chi_\sigma \rangle &= [(Q + R_k^\varphi)(\delta_j \delta_j W_k)(Q + R_k^\varphi)]_{\epsilon\sigma} \\ &\quad + (Q\varphi - l)_\epsilon (Q\varphi - l)_\sigma - (Q + R_k^\varphi)_{\epsilon\sigma}, \end{aligned} \tag{5}$$

and

$$\begin{aligned} &\langle \tilde{\varphi}_\epsilon \chi_\sigma \rangle = \langle \tilde{\varphi}_\epsilon \tilde{\varphi}_\tau \rangle (Q + R_k^\varphi)_{\tau\sigma} - \varphi_\epsilon j_\sigma - \delta_{\epsilon\sigma} \\ &= \varphi_\epsilon (Q\varphi)_\sigma + [(\delta_j \delta_j W_k)(Q + R_k^\varphi)]_{\epsilon\sigma} - \varphi_\epsilon l_\sigma - \delta_{\epsilon\sigma}. \end{aligned} \tag{6}$$

We now turn to the scale-dependence of $W_k[\eta, j]$

$$\begin{aligned} \partial_k W_k &= -\frac{1}{2}\langle\tilde{\psi}(\partial_k R_k^\psi)\tilde{\psi}\rangle - \frac{1}{2}\langle\tilde{\varphi}(\partial_k R_k^\varphi + \partial_k Q)\tilde{\varphi}\rangle \\ &+\frac{1}{2}\langle\chi\left(\partial_k Q^{-1}\right)\chi\rangle \\ &-\langle\tilde{\varphi}Q(\partial_k Q^{-1})\chi\rangle. \end{aligned} \tag{7}$$

Use now (2), (3), (4)

$$\begin{aligned} \partial_k W_k &= -\frac{1}{2}\psi(\partial_k R_k^\psi)\psi - \frac{1}{2}\varphi(\partial_k R_k^\varphi)\varphi \\ &-\frac{1}{2}\mathsf{STr}\{(\partial_k R_k^\psi)(\delta_\eta\delta_\eta W_k)\} \\ &-\frac{1}{2}\mathsf{Tr}\{\left[\partial_k R_k^\varphi - R_k^\varphi(\partial_k Q^{-1})R_k^\varphi\right](\delta_j\delta_j W_k)\} \\ &+\frac{1}{2}l(\partial_k Q^{-1})l + \frac{1}{2}\mathsf{Tr}\{\partial_k Q^{-1}(Q - R_k^\varphi)\}. \end{aligned} \tag{8}$$

The average action is defined as the modified Legendre transform

$$\Gamma_k[\psi,\varphi] = \eta\psi + j\varphi - W_k[\eta, j] - \frac{1}{2}\psi R_k^\psi \psi - \frac{1}{2}\varphi R_k^\varphi \varphi. \quad (9)$$

As usual, one has

$$\frac{\delta}{\delta\psi_\alpha}\Gamma_k = \pm\eta_\alpha - (R_k^\psi)_{\alpha\beta}\psi_\beta, \quad (10)$$

and

$$\frac{\delta}{\delta\varphi_\epsilon}\Gamma_k = j_\epsilon - (R_k^\varphi)_{\epsilon\sigma}\varphi_\sigma = l_\epsilon. \quad (11)$$

This yields our central result

$$\begin{aligned}\partial_k \Gamma_k &= \frac{1}{2}\mathsf{STr}\left\{(\Gamma_k^{(2)} + R_k)^{-1}\left(\partial_k R_k - R_k(\partial_k Q^{-1})R_k\right)\right\} \\ &\quad -\frac{1}{2}\Gamma_k^{(1)}\left(\partial_k Q^{-1}\right)\Gamma_k^{(1)} + \gamma_k \end{aligned} \tag{12}$$

with

$$\gamma_k = -\frac{1}{2}\mathsf{Tr}\left\{(\partial_k Q^{-1})(Q - R_k)\right\}. \tag{13}$$

Conclusions

- Simple but exact flow equation was derived.

Conclusions

- Simple but exact flow equation was derived.
- This allows an implementation of “flowing bosonization”.

Conclusions

- Simple but exact flow equation was derived.
- This allows an implementation of “flowing bosonization”.
- Details can be found in arXiv:0905.0915.

Conclusions

- Simple but exact flow equation was derived.
- This allows an implementation of “flowing bosonization”.
- Details can be found in arXiv:0905.0915.
- Thank you for your attention!