Managing Singular Kernels and Logarithmic Corrections in the Staggered Six-Vertex Model

On the alternating spin chain with continuous spectrum of scaling dimensions

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Contents

Outline

- The NN interaction spin-1/2 Heisenberg chain
- The alternating spin-1/2 Heisenberg chain
- continuously varying scaling dimensions

  Bethe ansatz, TQ-equation

  analytical reformulation in terms of NLIE with 4 functions

  singular kernel, regular kernel
- numerical results by use of the regular kernel, $L = 2, 10, ..., 10^{24}$
- derivation of asymptotical behaviour of energies by use of the singular kernel
- The $3\bar{3}$-network model, $sl(2|1)$ supersymmetric

Work in collaboration with Mouhcine Azhari [arxiv 2406.09889]
within DFG research group 2316 “Correlations in Integrable Quantum Many-Body Systems”

Heisenberg Model

Partially anisotropic Heisenberg model

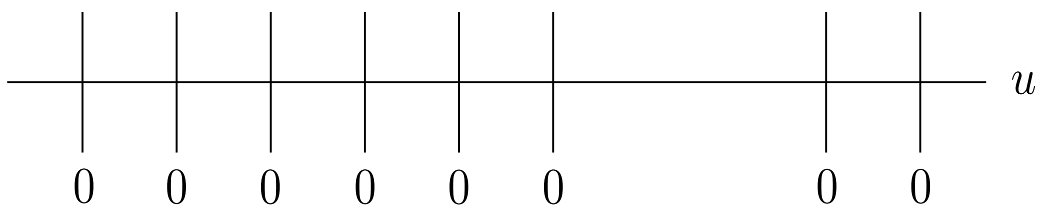
$$H = \sum_{j=1}^{L} [S_j^x S_{j+1}^x + S_j^y S_{j+1}^y + \Delta S_j^z S_{j+1}^z], \quad \Delta = \cos\gamma$$

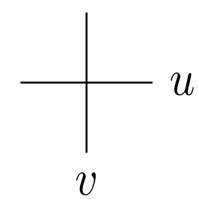
three phases for ground state:

$\Delta < -1$ (ferromagnetic), $-1 < \Delta < +1$ (critical), $+1 < \Delta$ (antiferromagnetic).

It is integrable/exactly solvable:

infinitely many conserved currents, Yang-Baxter equation for R-matrix of the 6-vertex model

$T(u) =$ 

$R(u,v) =$ 

Transfer matrix $T(u)$ is family of commuting operators $[T(u_1), T(u_2)] = 0$

$$H = \frac{d}{du} \log T(u)|_{u=0}$$

Properties

• Conformal spectrum (free massless compact boson)

$$E(L) = Le_0 + \frac{2\pi}{L} v_F \left(-\frac{1}{12} + \frac{1-\gamma/\pi}{2} m^2 + \frac{1}{2(1-\gamma/\pi)} (w - \phi/\pi)^2 \ + N \right), \qquad v_F = \pi \frac{\sin(\gamma)}{\gamma}$$

with integers m (magnetization), w (momentum), and angle ϕ (in case of twisted boundary conditions).

• The lattice model satisfies the Temperley-Lieb Algebra

The spin-1/2 XXZ chain (alias 6-vertex model) is a faithful representation. The same eigenvalues are found in other representations of the TL-algebra

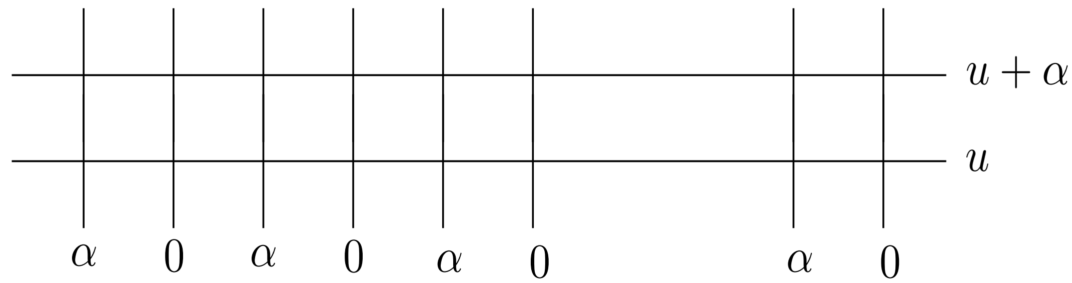
- self-dual Potts model
- loop models, $O(n)$ models, critical bond percolation (2d)
- restricted solid-on-solid models
- higher spin quantum chains, $sl(2|1)$ supersymmetric spin chain...

Mapping can be used to solve these models. Attention:
“new TL-model” with periodic b.c. $\Leftrightarrow$ spin-1/2 XXZ chain with twist

The (alternating) Heisenberg Chain with NN and NNN interactions

We use the construction

$T(u) =$



Transfer matrix $T(u)$ is family of commuting operators $[T(u_1), T(u_2)] = 0$

$$H = \frac{d}{du} \log T(u)|_{u=0}$$

With broken translational invariance, except for $\alpha = \pi/2$ for which

$$H = \sum_{j=1}^{2L} \left[-\frac{1}{2} \vec{\sigma}_j \vec{\sigma}_{j+2} + \sin^2\gamma \sigma^z_j \sigma^z_{j+1} - \frac{\mathrm{i}}{2} \sin\gamma \left(\sigma^z_{j-1} - \sigma^z_{j+2} \right) \left(\sigma^x_j \sigma^x_{j+1} + \sigma^y_j \sigma^y_{j+1} \right) \right]$$

Jacobsen, Saleur 2006, Ikhlef, Jacobsen, Saleur 2008+12 (non-compact continuum limit, log-corrections)

Frahm, Martins 2011+12 (density functions, numerical solns.)

Candu, Ikhlef 2013, Frahm, Seel 2013 (non-linear integral eqs.)

The problem

Conformal spectrum

$$E(L) = Le_0 + \frac{2\pi}{L} v_F \left(-\frac{1}{6} + \frac{\gamma}{2\pi} m^2 + \frac{\pi}{2\gamma} w^2 + \frac{2\gamma}{\pi - 2\gamma} s^2 + N \right), \qquad v_F = \sin(2\gamma) \frac{\pi}{\pi - 2\gamma}$$

with "usual" integers m (magnetization), w (momentum) and
"continuous" s, growing with reallocating n BA-roots from one line to the other (see later).

$$s \simeq \frac{\pi n}{2 \log L}, \quad \text{large } L,\ n = 0, 1, 2, \ldots \qquad \text{(Wiener-Hopf technique by IJS 12)}$$

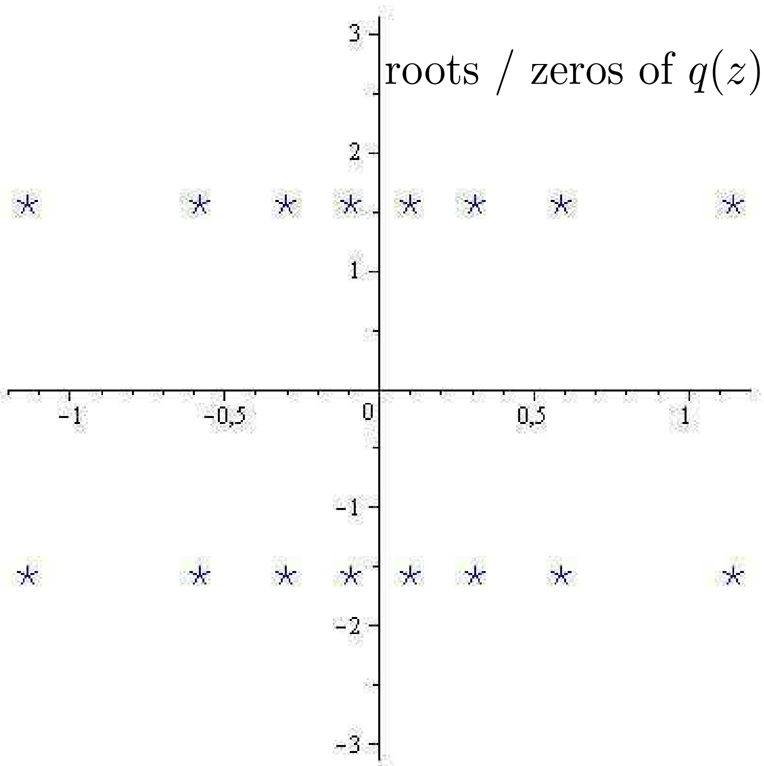
- "non-compact continuum limit", continuous component in the spectrum of conformal dimensions
- Ikhlef, Jacobsen, Saleur 12: Euclidean black hole NLSM (Maldacena, Ooguri (2001), Maldacena, Ooguri, Son (2001), Hanany, Prezas, Troost (2002)) is the CFT governing the scaling limit
- Fantastically accurate quantization condition for s valid even for quite finite systems by Bazhanov, Kotousov, Koval, Lukyanov 2019, 20, 21, $\Rightarrow SL(2,\mathbb{R})/U(1)$ NLSM on Euclidean $\rightarrow$ Lorentzian black hole.
  They use, among other things, the ODE/IQFT correspondence in the scaling limit.

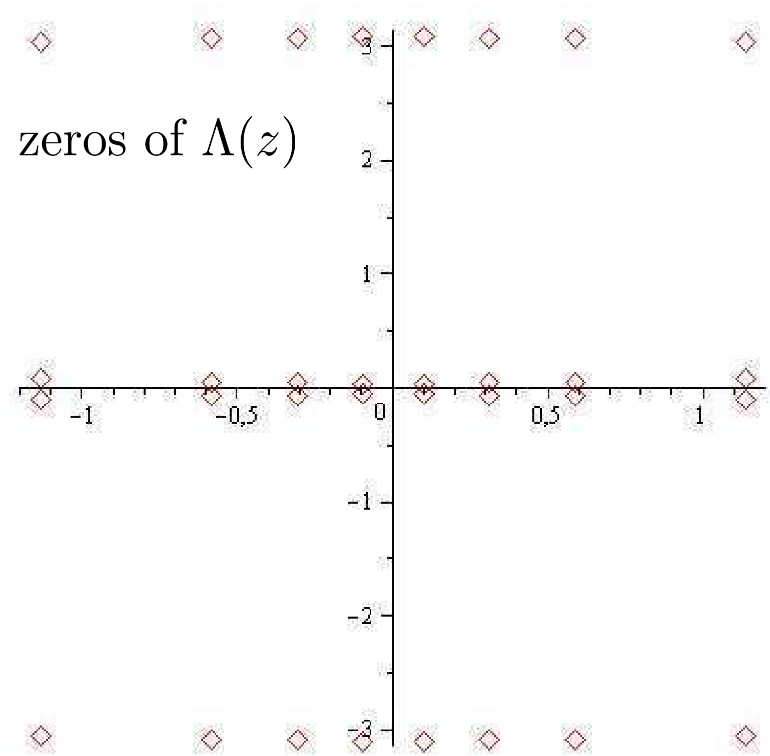
Bethe ansatz equations / TQ relations

$$\Lambda(z) = \Phi(z - \mathrm{i}\gamma)\,\frac{q(z+2\mathrm{i}\gamma)}{q(z)} + \Phi(z+\mathrm{i}\gamma)\,\frac{q(z-2\mathrm{i}\gamma)}{q(z)}\,, \qquad (Tq = \Phi q + \Phi q)$$

$$\Phi(z) = \sinh^L z, \qquad q(z) = \prod_j \sinh \tfrac{1}{2}(z - z_j)$$

Parameterization with 2πi-periodicity, 2 independent analyticity regions. For ground state





The usual procedure... and beyond

The Bethe ansatz equations (e.g. from analyticity condition for $\Lambda(z)$)

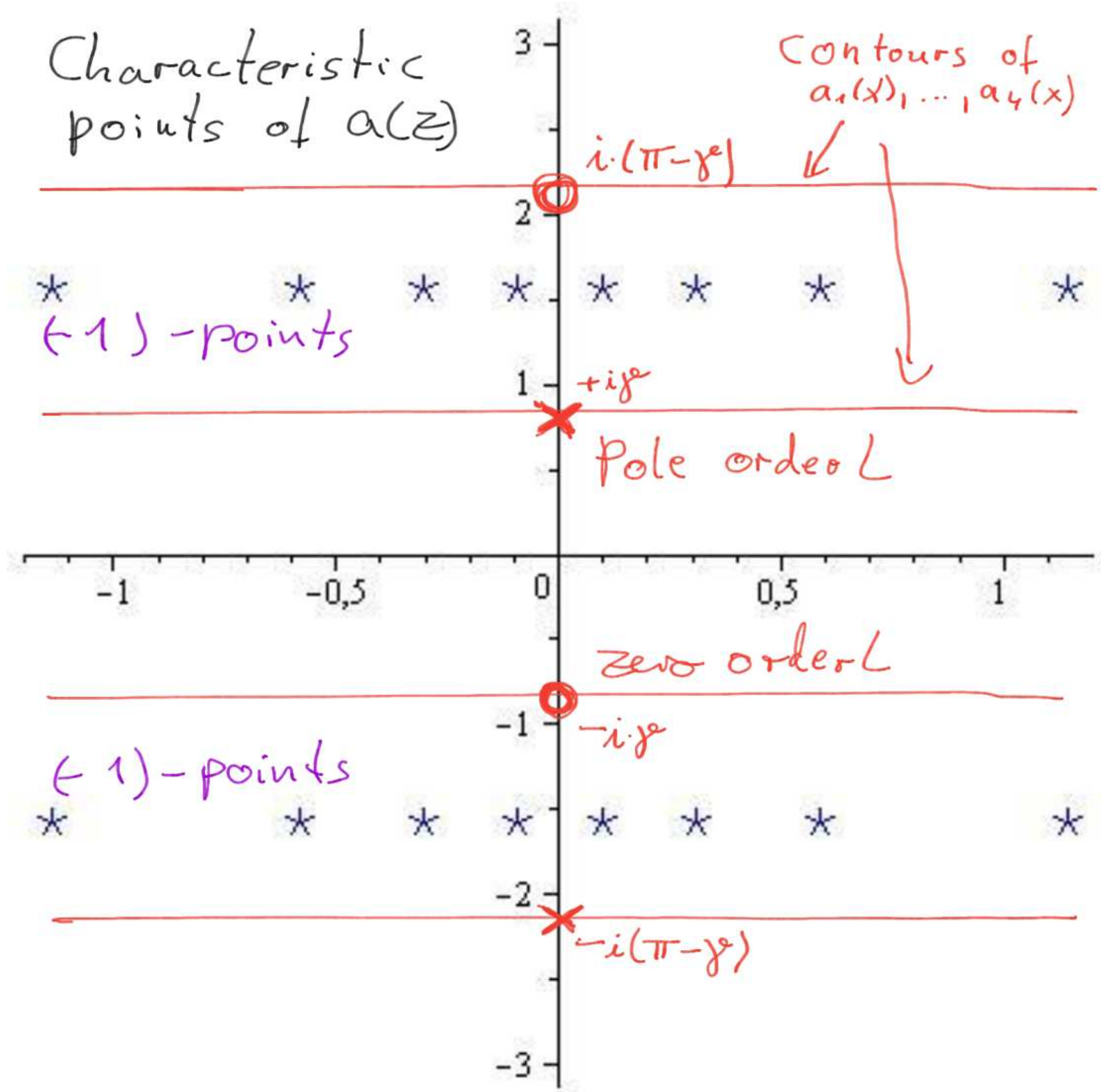
$$\frac{\Phi(z_i+\mathrm{i}\gamma)}{\Phi(z_i-\mathrm{i}\gamma)} = -\frac{q(z_i+2\mathrm{i}\gamma)}{q(z_i-2\mathrm{i}\gamma)} \quad \text{explicitly} \quad \left(\frac{\sinh(z_i+\mathrm{i}\gamma)}{\sinh(z_i-\mathrm{i}\gamma)}\right)^L = -\prod_j \frac{\sinh\frac{1}{2}(z_i-z_j+2\mathrm{i}\gamma)}{\sinh\frac{1}{2}(z_i-z_j-2\mathrm{i}\gamma)}$$

Or more compactly

$$a(z) := \frac{\Phi(z+\mathrm{i}\gamma)q(z-2\mathrm{i}\gamma)}{\Phi(z-\mathrm{i}\gamma)q(z+2\mathrm{i}\gamma)}, \qquad \text{BA eqns} \quad a(z_i) = -1$$

We use this function **off** the distribution lines like in AK, Batchelor 90; AK, Batchelor, Pearce 91; AK 92; Destri, de Vega 92, 95; J. Suzuki 98.

The four specializations of $a(z)$



The "auxiliary functions" ... destined to satisfy integral equations

"It is convenient to consider" ($A_k = 1 + a_k$ factorize thanks to the TQ relation)

$$a_1(x) := \frac{1}{a(x+\mathrm{i}\gamma)} = \frac{\Phi(x)}{\Phi(x+2\mathrm{i}\gamma)} \frac{q(x+3\mathrm{i}\gamma)}{q(x-\mathrm{i}\gamma)}$$

$$a_2(x) := a(x+\mathrm{i}\pi-\mathrm{i}\gamma) = \frac{\Phi(x)}{\Phi(x-2\mathrm{i}\gamma)} \frac{q(x+\mathrm{i}\pi-3\mathrm{i}\gamma)}{q(x+\mathrm{i}\pi+\mathrm{i}\gamma)}$$

$$a_3(x) := a(x-\mathrm{i}\gamma) = \frac{\Phi(x)}{\Phi(x-2\mathrm{i}\gamma)} \frac{q(x-3\mathrm{i}\gamma)}{q(x+\mathrm{i}\gamma)}$$

$$a_4(x) := \frac{1}{a(x+\mathrm{i}\pi+\mathrm{i}\gamma)} = \frac{\Phi(x)}{\Phi(x+2\mathrm{i}\gamma)} \frac{q(x+\mathrm{i}\pi+3\mathrm{i}\gamma)}{q(x+\mathrm{i}\pi-\mathrm{i}\gamma)}$$

$$A_1(x) := 1 + a_1(x) = \frac{1}{\Phi(x+2\mathrm{i}\gamma)} \frac{q(x+\mathrm{i}\gamma)}{q(x-\mathrm{i}\gamma)} \Lambda(x+\mathrm{i}\gamma)$$

$$A_2(x) := 1 + a_2(x) = \frac{1}{\Phi(x-2\mathrm{i}\gamma)} \frac{q(x+\mathrm{i}\pi-\mathrm{i}\gamma)}{q(x+\mathrm{i}\pi+\mathrm{i}\gamma)} \Lambda(x+\mathrm{i}\pi-\mathrm{i}\gamma)$$

$$A_3(x) := 1 + a_3(x) = \frac{1}{\Phi(x-2\mathrm{i}\gamma)} \frac{q(x-\mathrm{i}\gamma)}{q(x+\mathrm{i}\gamma)} \Lambda(x-\mathrm{i}\gamma)$$

$$A_4(x) := 1 + a_4(x) = \frac{1}{\Phi(x+2\mathrm{i}\gamma)} \frac{q(x+\mathrm{i}\pi+\mathrm{i}\gamma)}{q(x+\mathrm{i}\pi-\mathrm{i}\gamma)} \Lambda(x+\mathrm{i}\pi+\mathrm{i}\gamma)$$

Analyzing multiplicative functional equations by Fourier transform

- We have 2 analytic functions $q(z), \Lambda(z)$ each with 2 horizontal strips with convergent Fourier representation for its logarithm: makes 4 "independent functions"
- We defined additional 8 functions: $a_1(x), \ldots, a_4(x), A_1(x), \ldots, A_4(x)$.
- We set up 8 multiplicative functional equations, like (indices of q, Λ refer to analyticity strips)

$$a_1(x) = \frac{\Phi(x)}{\Phi(x+2i\gamma)} \frac{q_{II}(x+3i\gamma)}{q_I(x-i\gamma)}, \quad A_2(x) = \frac{1}{\Phi(x-2i\gamma)} \frac{q_{II}(x+i\pi-i\gamma)}{q_{II}(x+i\pi+i\gamma)} \Lambda_{II}(x+i\pi-i\gamma)$$

- Solve $a_1, \ldots, a_4, q_I, q_2, \Lambda_I, \Lambda_{II}$ in terms of $A_1, \ldots, A_4$.

How do we do with this? Equations like

$$f(x) = g(x+i\alpha)/h(x+i\beta)$$

after log-derivative and Fourier transform turn into

$$\mathrm{FT}\left[(\log f)'\right]_k = e^{-\alpha k}\,\mathrm{FT}\left[(\log g)'\right]_k - e^{-\beta k}\,\mathrm{FT}\left[(\log h)'\right]_k$$

The 8 multiplicative functional equations turn into 8 linear equations for the Fourier transforms...

The non-linear integral equations, version I – singular kernel

$$\begin{pmatrix} \log a_1 \\ \log a_2 \\ \log a_3 \\ \log a_4 \end{pmatrix} = d + K * \begin{pmatrix} \log A_1 \\ \log A_2 \\ \log A_3 \\ \log A_4 \end{pmatrix}, \qquad d(x) = L \log \mathrm{th}(\tfrac{1}{2} g x) \cdot \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}, \quad g := \frac{\pi}{\pi - 2\gamma}$$

The kernel in Fourier transform notation

$$K = \begin{pmatrix} \sigma_1 & \sigma_2 \\ \sigma_2^{\dagger} & \sigma_1^{T} \end{pmatrix} \qquad (\dagger \text{ interchanges diagonal elements})$$

$$\sigma_1 = \frac{\cosh((\pi - 3\gamma)k)}{2 \sinh(\gamma k) \sinh((\pi - 2\gamma)k)} \begin{pmatrix} -1 & e^{(\pi - 2\gamma)k} \\ e^{(2\gamma - \pi)k} & -1 \end{pmatrix}$$

$$\sigma_2 = \frac{\cosh(\gamma k)}{2 \sinh(\gamma k) \sinh((\pi - 2\gamma)k)} \begin{pmatrix} -e^{(\pi - 2\gamma)k} & 1 \\ 1 & -e^{(2\gamma - \pi)k} \end{pmatrix}$$

which is highly singular: in real space with asymptotics $K_{i,j}(x) \simeq |x|$.

The eigenvalue

For x (slightly below the real axis) the eigenvalue splits into pure bulk and finite size part

$$\log[\Lambda(x-i\gamma)\Lambda(x+i(\pi-\gamma))] = L\cdot\lambda(x) + \kappa * [\log A_1 + \log A_2 + \log A_3 + \log A_4]$$

$$\kappa(x) = -i\frac{g}{\sinh(gx)}, \quad g = \frac{\pi}{\pi-2\gamma}$$

Energy expression from derivative at $x=0$

$$\begin{aligned} E &= \sin(2\gamma)\frac{d}{dx}\log[\Lambda(x-i\gamma)\Lambda(x+i(\pi-\gamma))] \\ &= Le_0 - \sin(2\gamma)\int_{-\infty}^{\infty} dx\, \frac{g^2\cosh gx}{(\sinh gx)^2}[\log A_1(x) + \log A_2(x) + \log A_3(x) + \log A_4(x)] \end{aligned}$$

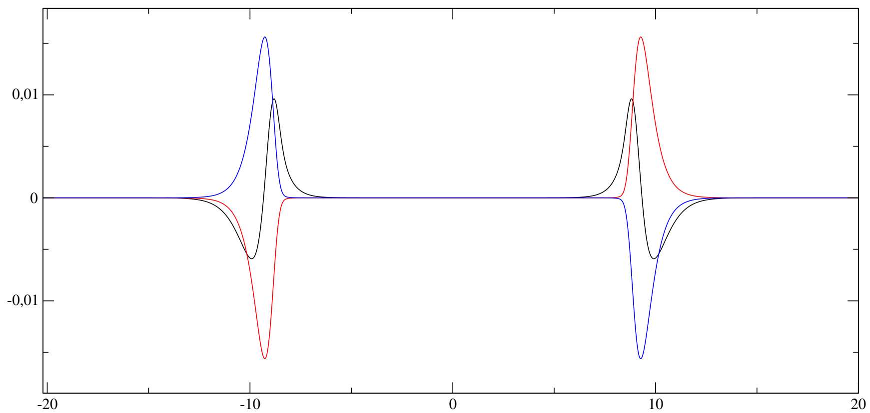
where $g = \frac{\pi}{\pi-2\gamma}$.

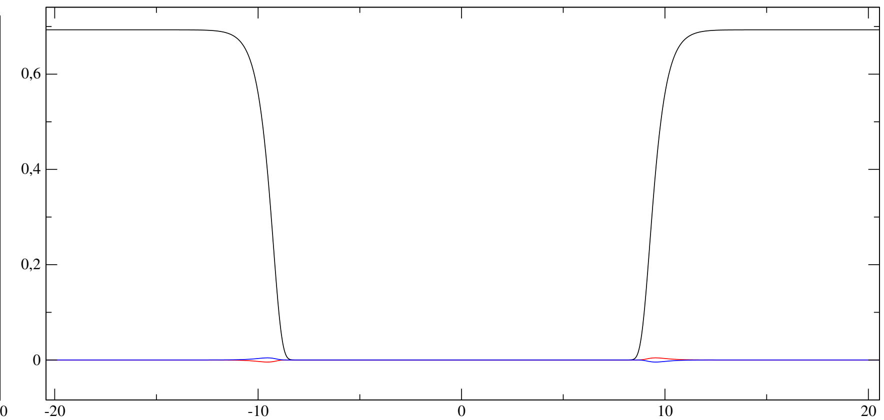
Quasi-momentum

$$Q = ig\int_{-\infty}^{\infty} dx \coth gx\, [\log A_1(x) - \log A_2(x) + \log A_3(x) - \log A_4(x)]$$

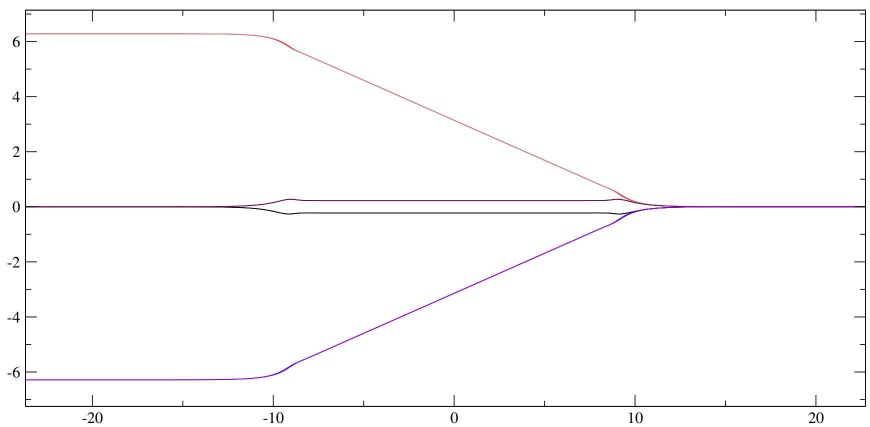
The ground-state solution and 1st excited state

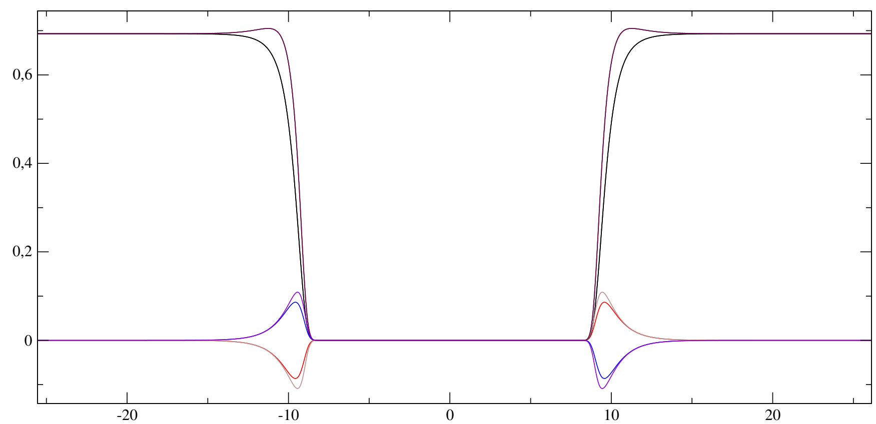
True ground state solution: $\log a_i - d$ and $\log A_i = \log(1+a_i)$ for $L = 10^9$





Reallocating 1 BA root from one line to the other ($n = \pm 1$) has solution



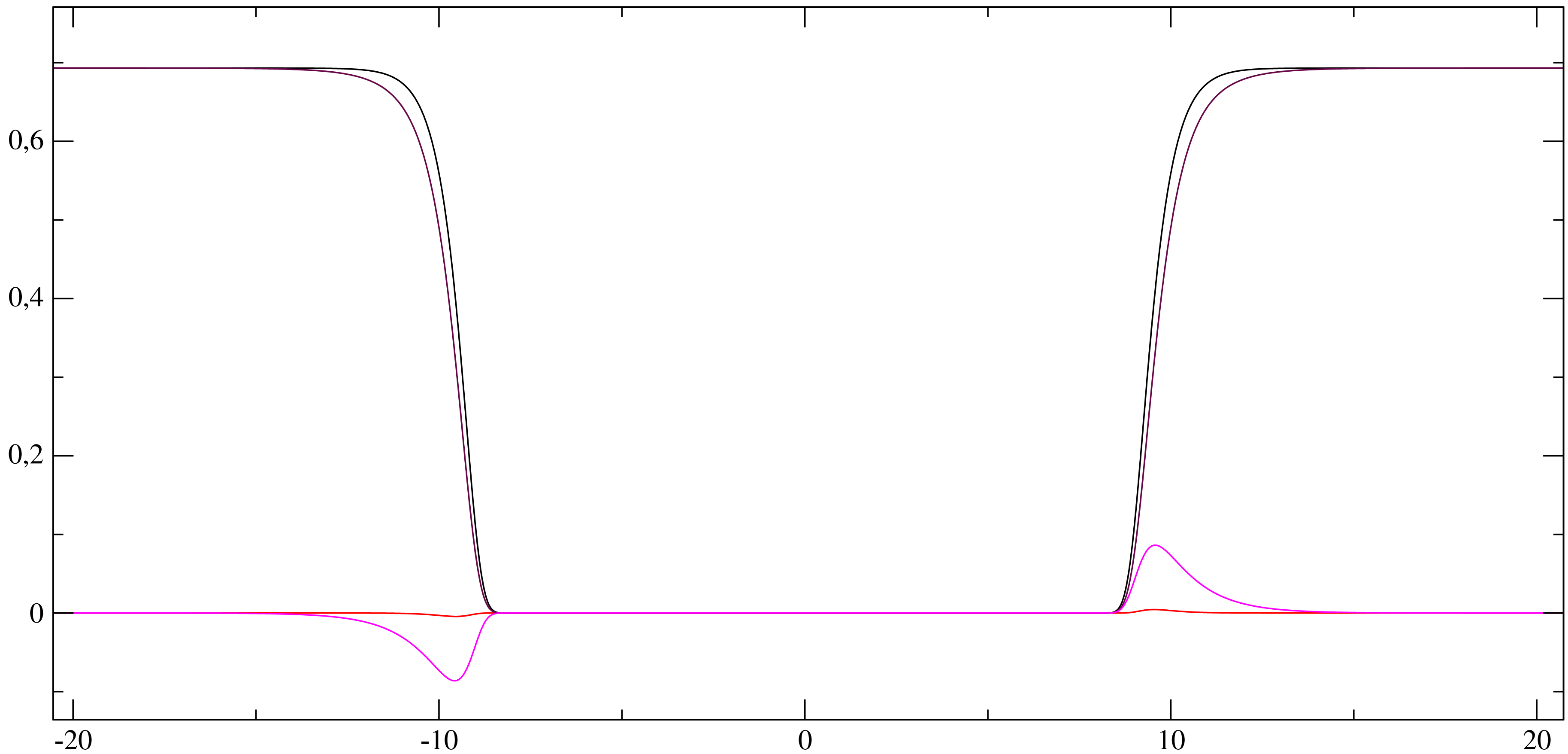


with huge changes in the $\log a_i$ functions, but only little in the $\log A_i$.

Why has the kernel to be singular and what are the alternatives I

...with huge changes in the $\log a_i$ functions, but only little in the $\log A_i$.

$\log A_1$ for ground state and excited state



The optimal arrangement of the NLIE, version II – regular kernel

Super-great manipulation $\qquad a = (\log a_i), A = (\log(1 + a_i)$

$$a = d + K * A$$

$$2(a - d) = K * 2A = K * (2A - (a - d)) + K * (a - d)$$

$$(2 - K) * (a - d) = K * (2A - (a - d))$$

$$a = d + K_r * (a - d - 2A) \qquad \text{with} \quad K_r := \frac{K}{K - 2}$$

This kernel is regular! In Fourier transform notation

$$K_r = \begin{pmatrix} \kappa_1 & \kappa_2 \\ \kappa_2^\dagger & \kappa_1^T \end{pmatrix} \qquad \text{($\dagger$ interchanges diagonal elements)}$$

$$\kappa_1 = \frac{\sinh((\pi - 2\gamma)k)}{2\sinh(\pi k)} \begin{pmatrix} 1 & -e^{(\pi-2\gamma)k} \\ -e^{(2\gamma-\pi)k} & 1 \end{pmatrix}, \quad \kappa_2 = \frac{\sinh(2\gamma k)}{2\sinh(\pi k)} \begin{pmatrix} e^{(\pi-2\gamma)k} & -1 \\ -1 & e^{(2\gamma-\pi)k} \end{pmatrix}$$

Regular kernel K_r has one eigenvalue $+1$ for “momentum” $k = 0$ with eigenstate $(1, -1, 1, -1)$, and two eigenvalues 0 and one eigenvalue close to 0.

How to select the states?

Shifting n BA roots from one line to the other yields a winding of the $\log a_i(x)$ functions:
$\log a_i(\infty) - \log a_i(-\infty) = \pm n 2\pi \mathrm{i}$ $\quad\rightarrow$ quantization condition for the quasi-momentum

Modifications necessary for numerical evaluation of convolutions by Fourier transform

$$a = d + K_r * (a - d - 2A) = d + n w + K_r * (a - d - n\tilde{w} - 2A)$$

where $n = 0, 1, 2\ldots$ is the winding number and

$$w(x) = \begin{pmatrix} w_1(x) \\ w_2(x) \\ w_3(x) \\ w_4(x) \end{pmatrix}, \quad \tilde{w}(x) = 2 \log \mathrm{th}\left(\frac{g}{2}x + \mathrm{i}\frac{\pi}{4}\right) \cdot \begin{pmatrix} +1 \\ -1 \\ +1 \\ -1 \end{pmatrix}$$

$$w_1(x) = -w_4(x) := \log \mathrm{th}\tfrac{1}{2}\left(x + \mathrm{i}\left(\frac{\pi}{2} - \gamma\right)\right) + \log \mathrm{th}\tfrac{1}{2}\left(x + \mathrm{i}\left(3\gamma - \frac{\pi}{2}\right)\right)$$
$$w_2(x) = -w_3(x) := \log \mathrm{th}\tfrac{1}{2}\left(x - \mathrm{i}\left(\frac{\pi}{2} - \gamma\right)\right) + \log \mathrm{th}\tfrac{1}{2}\left(x - \mathrm{i}\left(3\gamma - \frac{\pi}{2}\right)\right)$$

Numerical Results I

Energy expression from derivative at $x = 0$

$$E - Le_0 = -\sin(2\gamma) \int_{-\infty}^{\infty} dx \, \frac{g^2 \cosh gx}{(\sinh gx)^2} \left[\log A_1(x) + \log A_2(x) + \log A_3(x) + \log A_4(x)\right]$$

$$= \frac{2\pi}{L} v_F \left[-\frac{1}{6} + \frac{2\gamma}{\pi - 2\gamma} s^2 \right], \qquad \text{where } g = \frac{\pi}{\pi - 2\gamma}.$$

Results for $L = 2, 10, 10^2, 10^3, 10^6, \ldots, 10^{24}$ and $N = 2^{14} = 16384$ ($N = 2^{15} = 32768$) grid points.

Computation time 40 s (80 s) for 1000 iterations (Intel i7 2.4 GHz), 16 decimals.

Next page: Plot of s from E by NLIE and above equation

Next after next page:

Comparison of energy E by NLIE with results by Bazhanov, Kotousov, Koval, Lukyanov 2019 (ODE/IQFT correspondence)

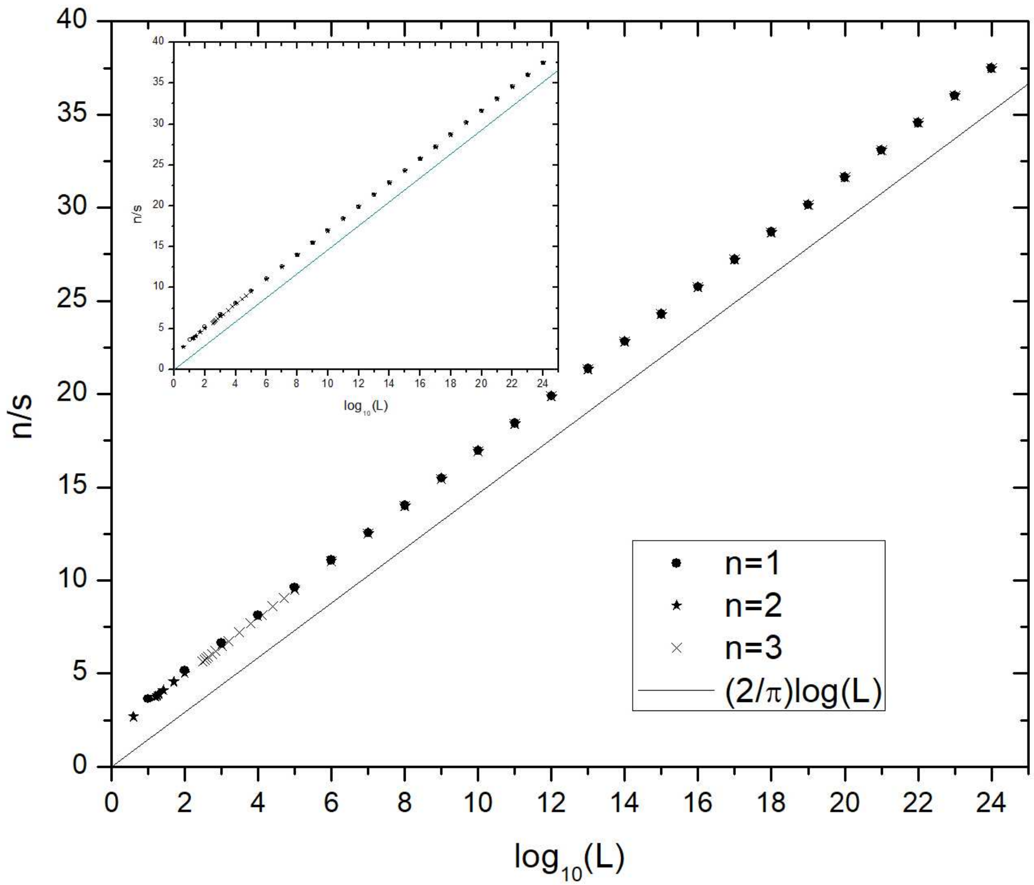
$$4\, s \log \left(\frac{L\Gamma\left(3/2 + \frac{\gamma}{\pi - 2\gamma}\right)}{\sqrt{\pi}\Gamma\left(1 + \frac{\gamma}{\pi - 2\gamma}\right)} \right) + 8\, s \frac{\pi - \gamma}{\gamma} \log(2) - 2\,\mathrm{i} \log \left(\frac{\Gamma(1/2 - \mathrm{i}s)}{\Gamma(1/2 + \mathrm{i}s)} \right) = n\, 2\pi$$

Numerical Results II

Plot of ratio n/s against system size L for parameters $\gamma = 0.8$ and $n = 1,2,3$.

quasi-momentum parameter s obtained from energies (main panel) and quasi-momenta (inset)

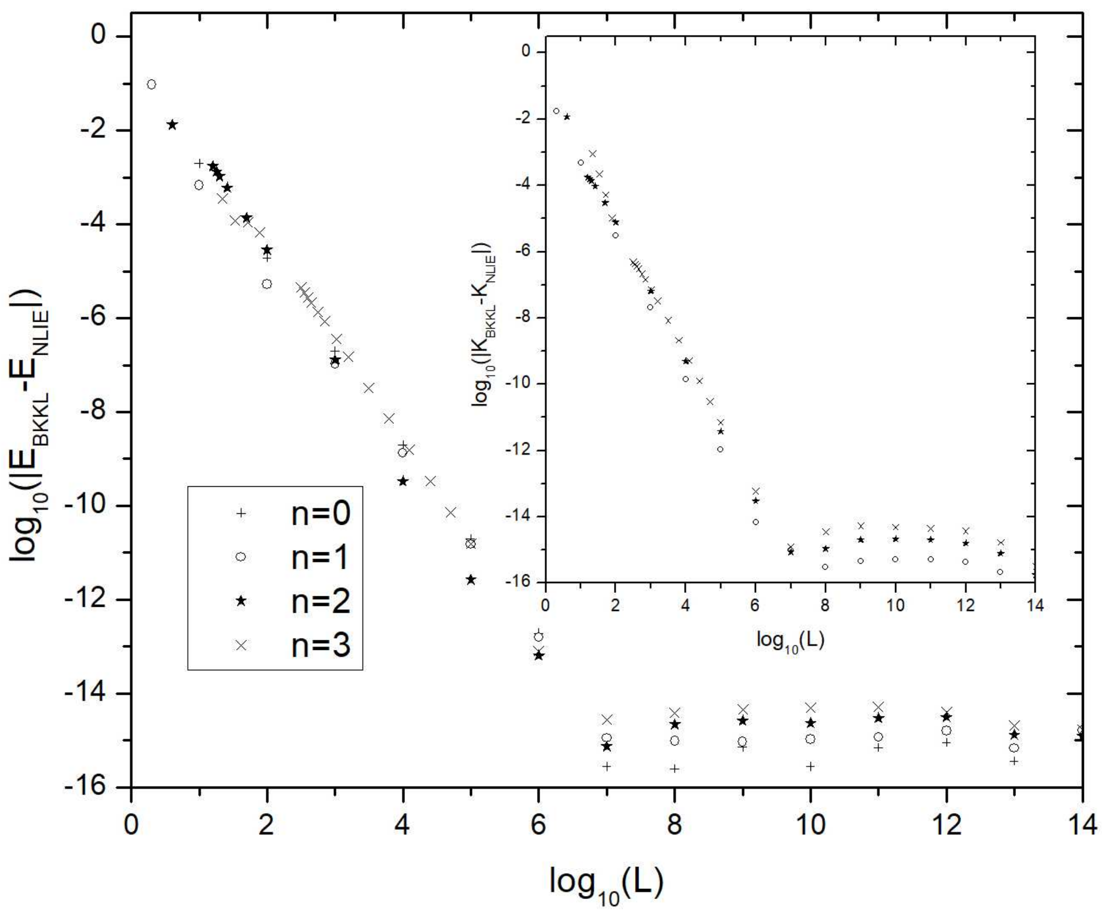
Continuous line corresponds to the asymptotic behavior $s \simeq \pi n/2\log L$



Deviations between NLIE results and ODE/IQFT of order $O\left(L^{-2}\right)$.

Numerical Results III

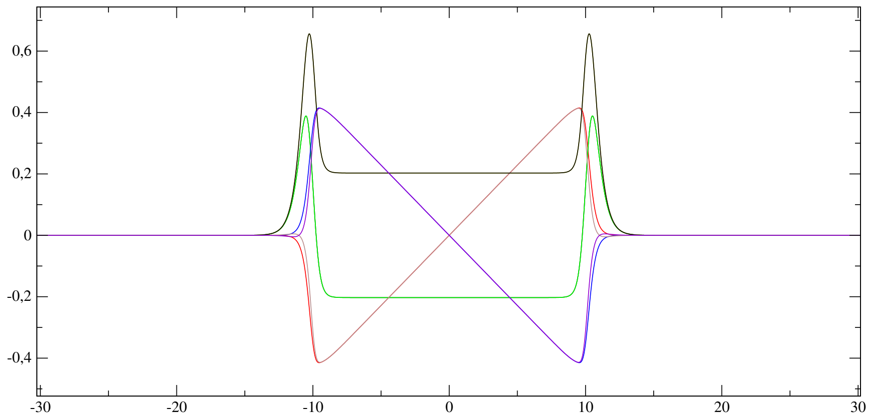
Comparison of energies and quasi-momenta to ODE/IQFT results $E = (2g\gamma/\pi)\, s^2$ and $K = 4g\gamma s$ (inset) with s computed from Bazhanov, Kotousov, Koval, Lukyanov 2019 ($\gamma = 0.8$, $n = 0, 1, 2, 3$).

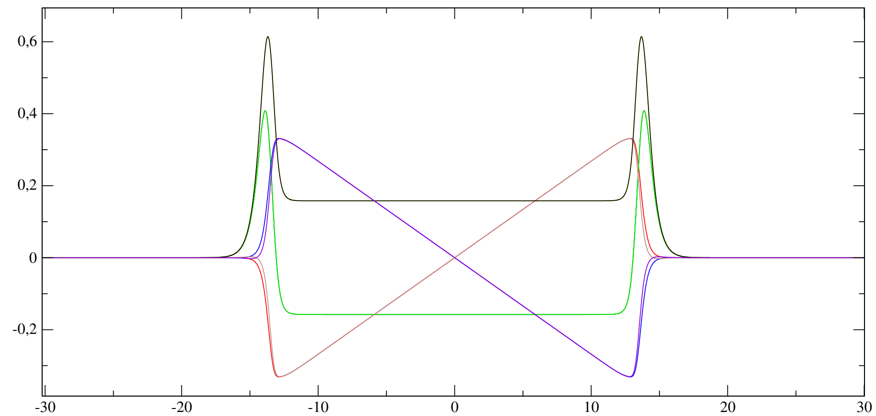


difference vanishes algebraically like $O(L^{-2})$, but not below values of the order 10^{-15} to 10^{-14}

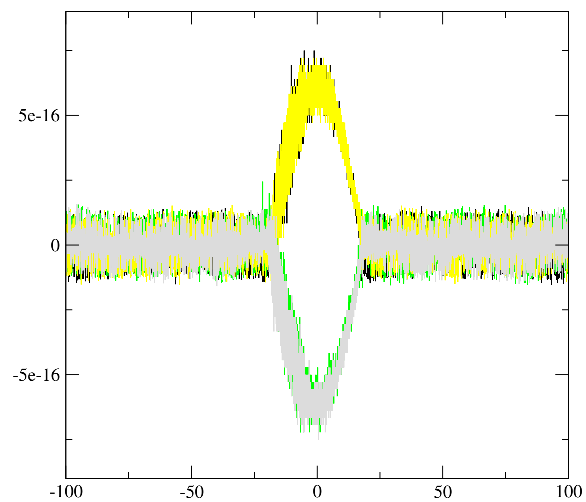
What limits the accuracy?

To solve $a = d + nw + K_r * (a - d - n\tilde{w} - 2A)$ where terms in brackets for $L = 10^9, 10^{12}$ look like





Equations are solved, LHS-RHS=0



Why has the kernel to be singular and what are the alternatives II

Claim / Theorem: All of us use the “same” functions and equivalent equations!

Candu, Ikhlef 2013: solve NLIE in the scaling limit

use same functions on possibly slightly shifted contours, work with the singular kernel.

Frahm, Seel 2013: solve up to $L = 10^9$

use “practically” same functions, two replaced in the way $\tilde{a}_i = 1/a_j$, then

$$\log a_i = -\log \tilde{a}_i, \qquad \log A_i = \log(1 + a_i) = \log(1 + 1/\tilde{a}_i) = \log \tilde{A}_i - \log \tilde{a}_i$$

Difference in way of organizing of what is on the left and what is on the right hand side.

Analytical derivation of correction terms from NLIE version I

"Calculation of some result without solving integral equations"

(i) We use the NLIE with singular (!) kernel and differentiate it once

$$(\log a_i)' = d' + \sum_{j=1}^{4} K'_{ij} * \log(1+a_j)$$

then we multiply from left with...

$$\int_0^\infty dx \sum_{i=1}^{4} \log(1+a_i(x))(\log a_i(x))' =$$

$$\int_0^\infty dx \sum_{i=1}^{4} \log(1+a_i(x)) d'(x) + \frac{1}{2\pi} \int_0^\infty dx \int_{-\infty}^{\infty} dy \sum_{i,j=1}^{4} \log(1+a_i(x)) K'_{ij}(x-y) \log(1+a_j(y))$$

LHS: change of variable gives dilogarithmic integral, only data $a_i(0)$, $a_i(\infty)$ enter $\rightarrow \pi^2/3$.

RHS: 1st term is the wanted object, 2nd term – double integral – can be massaged

$$\int_0^\infty dx \int_{-\infty}^{\infty} dy \ldots = \underbrace{\int_0^\infty dx \int_0^\infty dy \ldots}_{=0} + \int_0^\infty dx \int_{-\infty}^{0} dy \ldots$$

the first term is zero by antisymmetry of the kernel, $K'_{ij}(x-y) = -K'_{ji}(y-x)$.

Analytical derivation of correction terms from NLIE version I

In the second term the kernel K is linear and K'_{ij} can be replaced by constants

$$\ldots = -\frac{\pi}{2\gamma(\pi-2\gamma)}\int_0^\infty dx\int_{-\infty}^0 dy\sum_{i,j=1}^4(-1)^{i+j}\log(1+a_i(x))\log(1+a_j(y)) = \frac{\pi}{2\gamma(\pi-2\gamma)}|I|^2$$

where

$$I := \int_0^\infty dx \log\frac{(1+a_1(x))(1+a_3(x))}{(1+a_2(x))(1+a_4(x))}$$

such an integral from $-\infty$ to 0 gives $-I$ (and is purely imaginary).

(ii) What is I? From the NLIE we derive

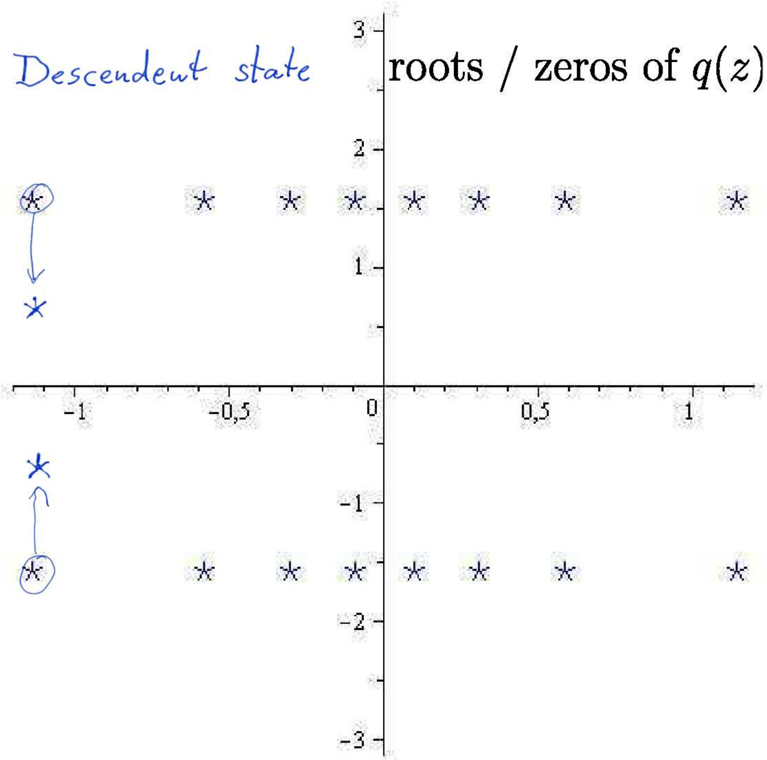
$$n\,2\pi\mathrm{i} = \log a_1(+\infty) - \log a_1(-\infty) = \ldots = 2\frac{1}{4\gamma(\pi-2\gamma)}\frac{2\log L}{g}\cdot I$$

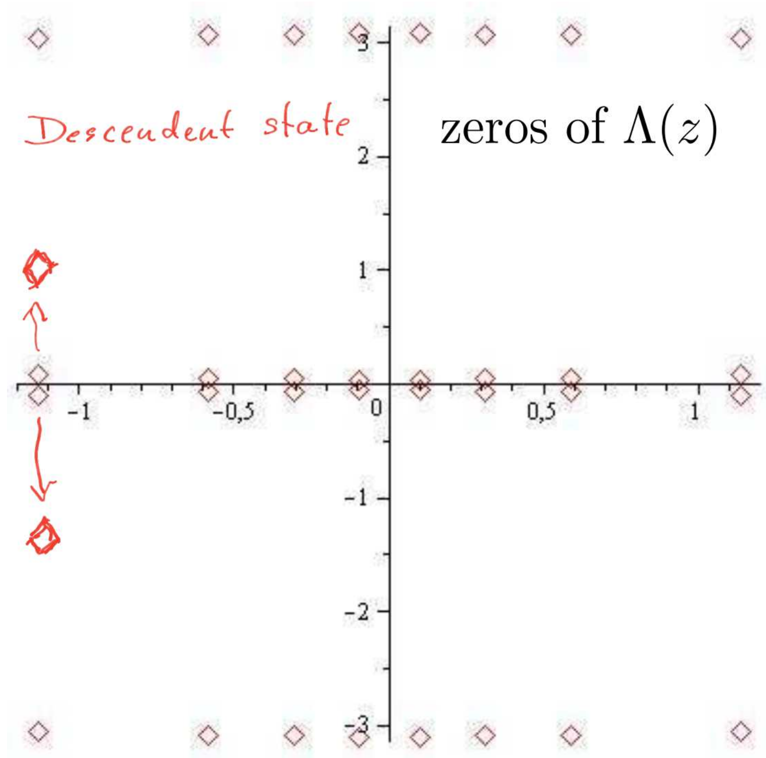
Now we have for the double integral

$$\ldots = 2\pi\frac{\gamma}{\pi-2\gamma}\left(\frac{\pi^2 n}{\log L}\right)^2$$

without having solved the NLIE or having applied Wiener-Hopf techniques.

Descendent states: Bethe pattern for tower level $N = 1$

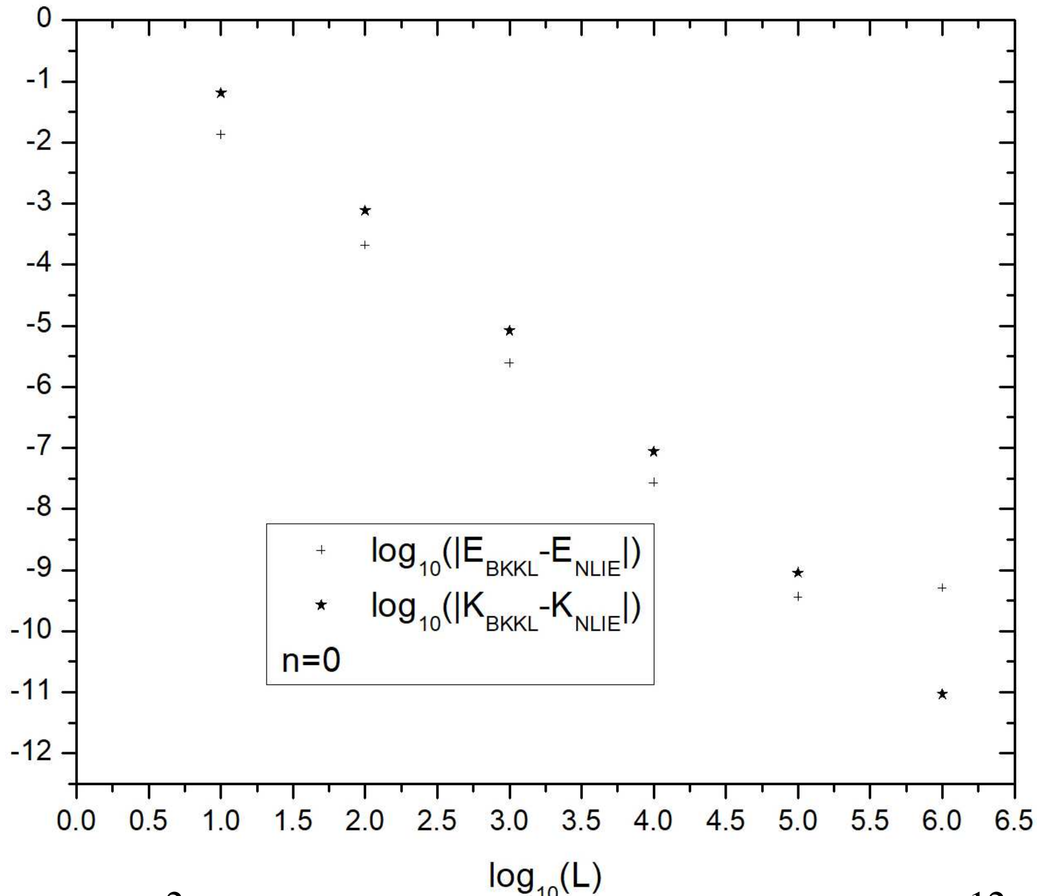




Leads to NLIE with additional source terms.

Descendent states: ground-state and 1st excited state for $N = 1$

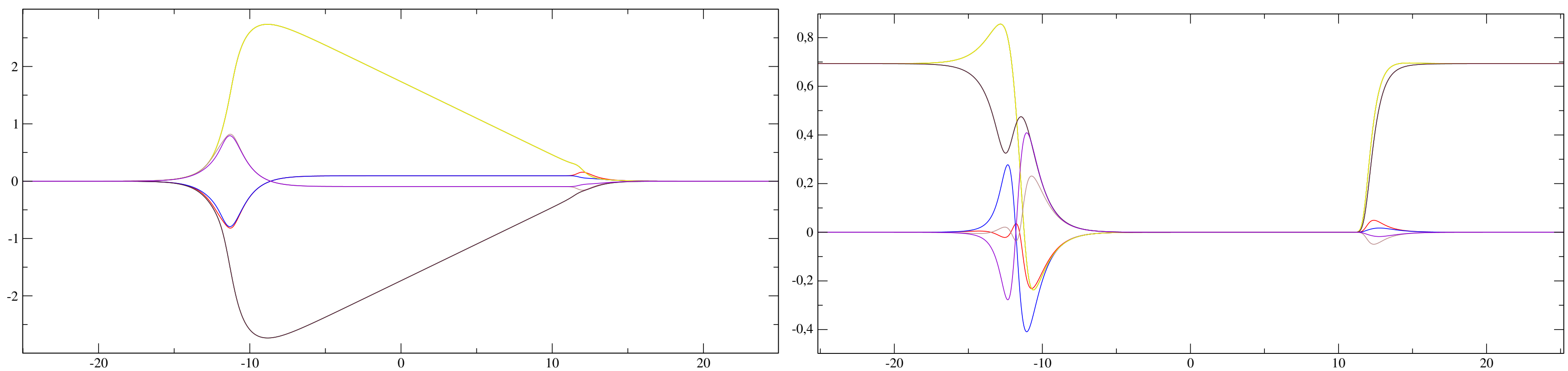
Comparison of energies and quasi-momenta for the descendant states $E = (2g\gamma/\pi)\, s^2$ and $K = 4g\gamma s$ with s computed from the quantization condition in BKKL 2019 ($\gamma = 0.9$, $n = 0$).



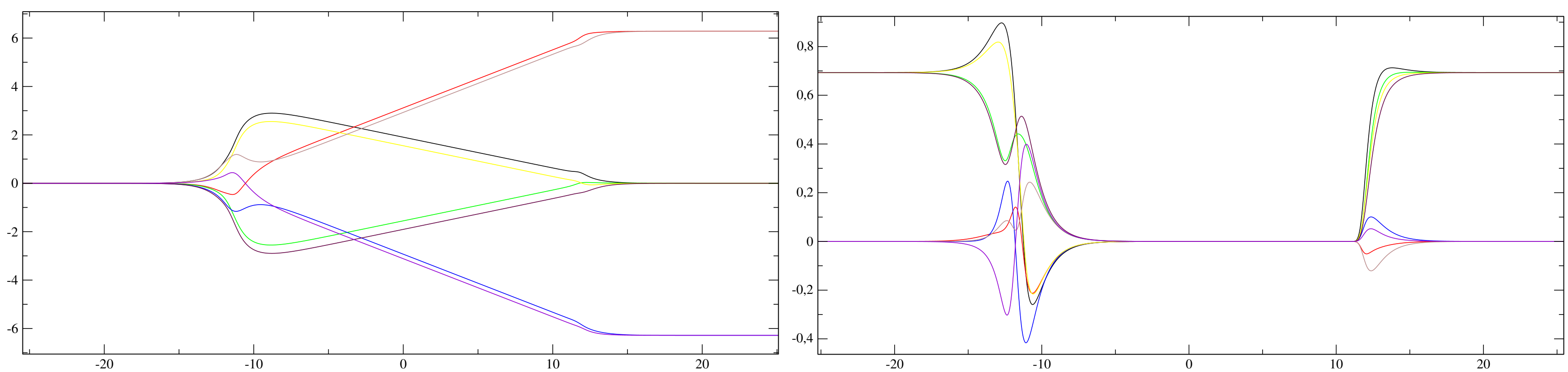
Difference vanishes like $O(L^{-2})$, but not below values of the order 10^{-12} set by the accuracy of our numerical calculations.

Descendent states: ground-state and 1st excited state for $N = 1$

Solutions to NLIE for $n = 0$: $\log a_i - d$ and $\log A_i = \log(1 + a_i)$ for $L = 10^{11}$



Reallocating 1 BA root from one line to the other ($n = \pm 1$)



with huge differences to functions for primary states.

The supersymmetric $sl(2|1)$ supersymmetric $3\bar{3}$ model

Derivation of staggered vertex model and proof of integrability by R. Gade (1998)
extensive investigations of spectrum by Essler, Frahm, Saleur (2005)

Bethe ansatz equations as for the QTM of the supersymmetric tJ model

$$\frac{\Phi_-(u_j+\mathrm{i})}{\Phi_-(u_j-\mathrm{i})} = -e^{\mathrm{i}\varphi}\frac{q_\gamma(u_j+\mathrm{i})}{q_\gamma(u_j-\mathrm{i})}, \qquad j=1,\dots,N$$

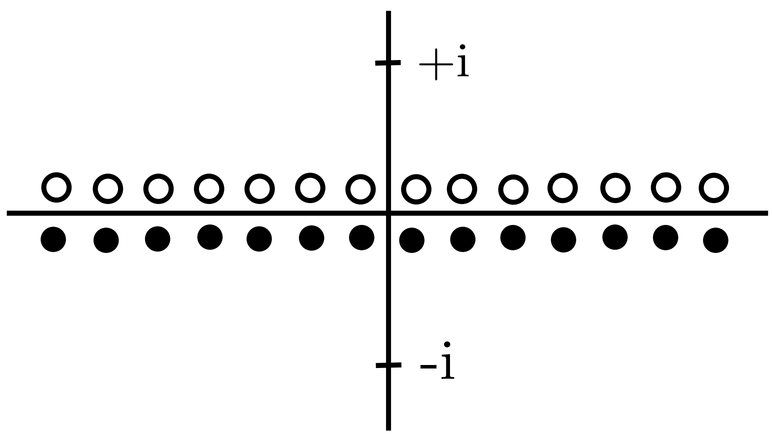
$$\frac{\Phi_+(\gamma_\alpha+\mathrm{i})}{\Phi_+(\gamma_\alpha-\mathrm{i})} = -e^{\mathrm{i}\varphi}\frac{q_u(\gamma_\alpha+\mathrm{i})}{q_u(\gamma_\alpha-\mathrm{i})}, \qquad \alpha=1,\dots,M$$

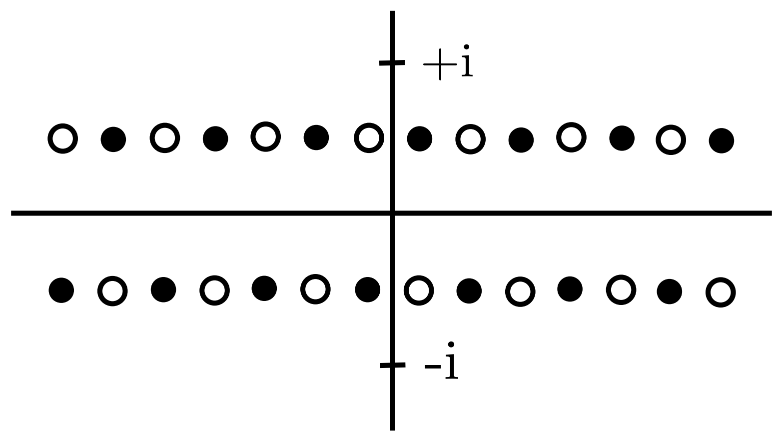
These equations are the same for the QTM of the tJ model and for the supersymmetric network model.

Characterization of largest eigenvalue differs:

tJ: maximum value of Λ

network model: maximum value(s) of $\Lambda\cdot\bar{\Lambda}$





"strange strings" (Essler, Frahm, Saleur 2005)

Compact notation for NLIEs: network model (version I)

Supersymmetric network model: 6 non-linear integral equations, version I

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} d \\ d \end{pmatrix} + \begin{pmatrix} K - K_s & K_s \\ K_s & K - K_s \end{pmatrix} * \begin{pmatrix} A_1 \\ A_2 \end{pmatrix}$$

where a_1 and a_2 are two copies of the 3d vector a, and A_1 and A_2 are two copies of the 3d vector A.
Driving terms

$$d := \begin{pmatrix} L \log \operatorname{th} \frac{\pi}{2} x - i\varphi/2 \\ L \log \operatorname{th} \frac{\pi}{2} x + i\varphi/2 \\ 0 \end{pmatrix},$$

and kernel matrices (in Fourier representation)

$$K(k) = \frac{1}{2\cosh k/2} \begin{pmatrix} e^{-|k|/2} & -e^{-|k|/2-k} & 1 \\ -e^{-|k|/2+k} & e^{-|k|/2} & 1 \\ 1 & 1 & 0 \end{pmatrix}, \quad K_s(k) = \begin{pmatrix} \frac{1}{2\sinh|k|} & -\frac{e^{-k}}{2\sinh|k|} & -\frac{e^{-k/2}}{2\sinh(k)} \\ -\frac{e^{k}}{2\sinh|k|} & \frac{1}{2\sinh|k|} & \frac{e^{k/2}}{2\sinh(k)} \\ \frac{e^{k/2}}{2\sinh(k)} & -\frac{e^{-k/2}}{2\sinh(k)} & 0 \end{pmatrix}$$

Good properties: symmetry $K(-k)^T = K(k)$, $K_s(-k)^T = K_s(k)$ may allow for analytic calculations of CFT
bad properties: K_s is very singular! Kernel of integral equations not integrable!

NLIEs version II: regular kernels

Most compact notation of NLIE as two weakly coupled 3×3 systems

$$a_i = d \pm \tilde{d} + K * A_i, \qquad i = 1,2 \quad \text{for which } +,- \text{ applies}$$

and additional driving term

$$\tilde{d} := \frac{1}{2}(\tilde{K} - K) * (A_1 - A_2) - \frac{1}{2}\tilde{K} * (a_1 - a_2)$$

Regular kernels

$$K(k) = \frac{1}{2\cosh k/2}\begin{pmatrix} e^{-|k|/2} & -e^{-|k|/2-k} & 1 \\ -e^{-|k|/2+k} & e^{-|k|/2} & 1 \\ 1 & 1 & 0 \end{pmatrix}, \qquad K(k) = K^T(-k)$$

$$\tilde{K}(k>0) = \begin{pmatrix} -\frac{1}{e^k+1} & e^{-k} - e^{-2k} + \frac{e^{-k}}{e^k+1} & e^{-k/2} - e^{-3k/2} \\ \frac{e^k}{e^k+1} & -\frac{1}{e^k+1} & 0 \\ 0 & e^{-k/2} - e^{-3k/2} & -e^{-k} \end{pmatrix}, \quad \tilde{K}(k<0) := \tilde{K}^T(-k)$$

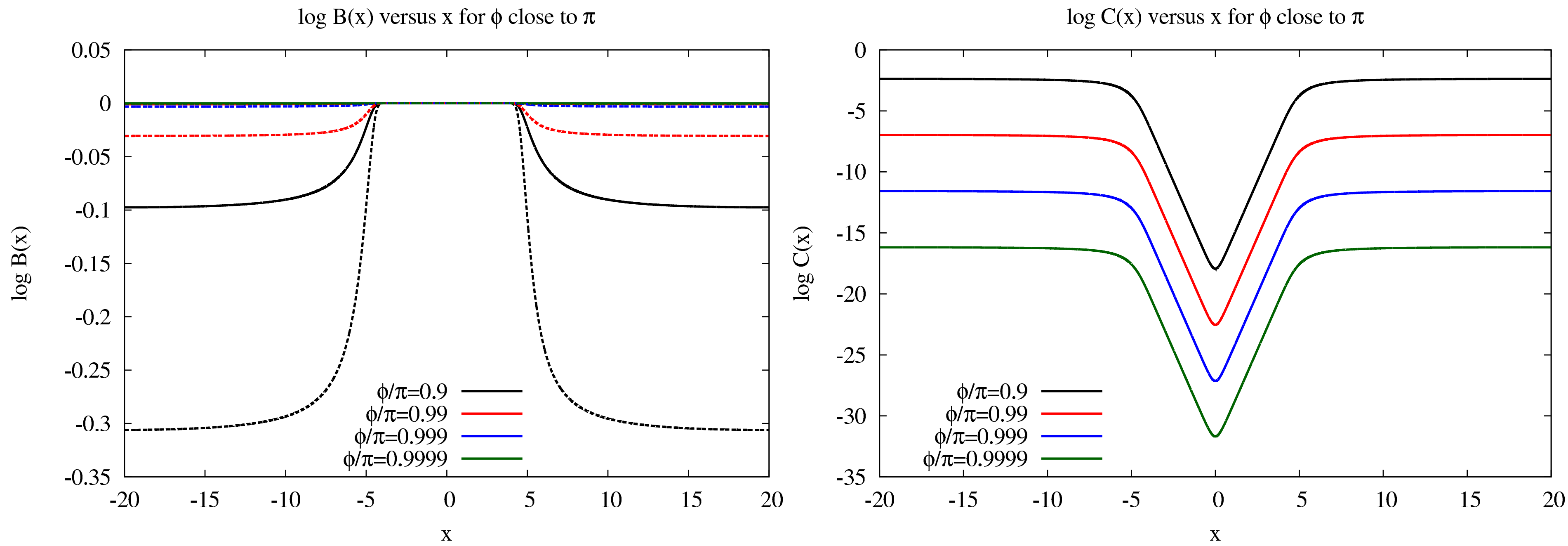
Numerical solution to NLIE: ground-state

Ground state of model with $\varphi = \pi$ completely degenerate, but not for $\varphi \neq \pi$.

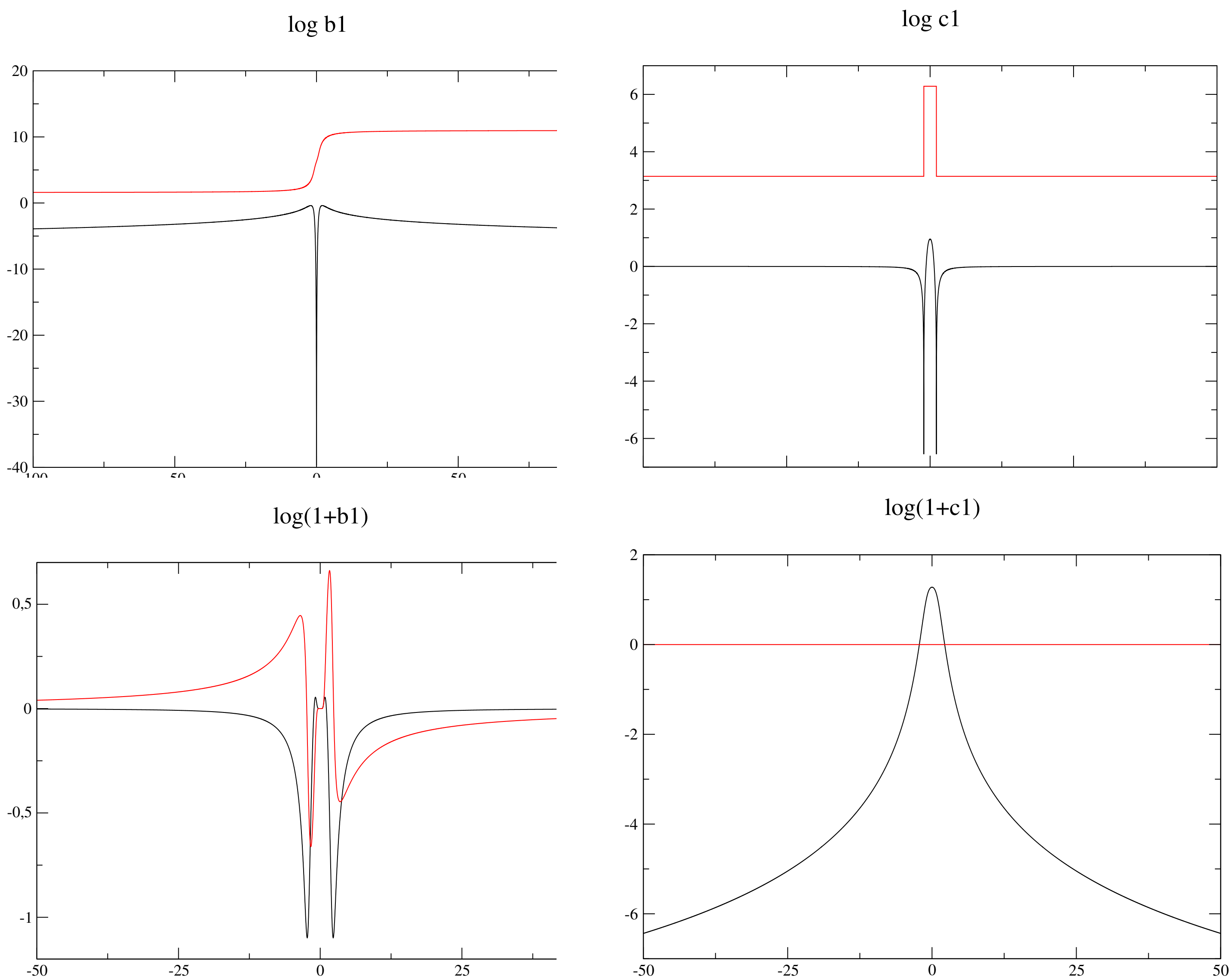
$$a_j := \begin{pmatrix} \log b_j \\ \log \bar{b}_j \\ \log c_j \end{pmatrix}, \qquad A_j := \begin{pmatrix} \log B_j \\ \log \bar{B}_j \\ \log C_j \end{pmatrix}$$

For $\varphi = \pi$ we know $\quad b_j = \bar{b}_j = 0,\ B_j = \bar{B}_j = 1, \quad c_j = -1, C_j = 0.$

For $\varphi \neq \pi$ with $\tilde{d} = 0$ we find numerically ($L = 10^6$)



Numerical solution to NLIE: excited states, $\varphi = \pi$



Summary

Results:

- Quick derivation of NLIEs
- Understanding of all published NLIE equations from one “master set” of NLIE
- Transformation from the singular form into a regular version
- Numerics by use of regular NLIE up to $L = 10^{24}$
- Asymptotics analytically derived from singular version of NLIE
- Derivation and solution of NLIEs for non-primary states
- Some results for the $3\bar{3}$ model with $sl(2|1)$ symmetry: finite size correction $O(1/\log L)$

To do:

- What is the relation of the NLIE to ODE/IQFT?
- spectrum of the complex sinh-Gordon model
- treat the $3\bar{3}$ model to same level of understanding