Boundary limits for the six-vertex model

Vadim Gorin

UC Berkeley

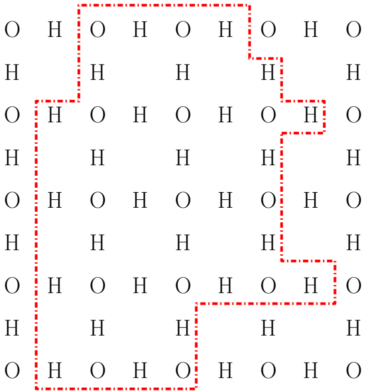
May, 2023

Six–vertex model

O	H	O	H	O	H	O	H	O
H		H		H		H		H
O	H	O	H	O	H	O	H	O
H		H		H		H		H
O	H	O	H	O	H	O	H	O
H		H		H		H		H
O	H	O	H	O	H	O	H	O
H		H		H		H		H
O	H	O	H	O	H	O	H	O

Square grid with O in the vertices and H on the edges.

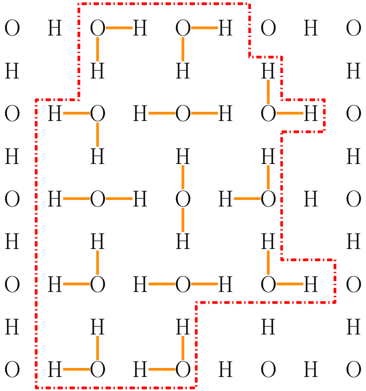
Six–vertex model



Square grid with O in the vertices and H on the edges.

Take a finite/infinite domain.

Six–vertex model



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Take a finite/infinite domain.

Configurations: possible matchings of *all* atoms inside domain into H_2O molecules.

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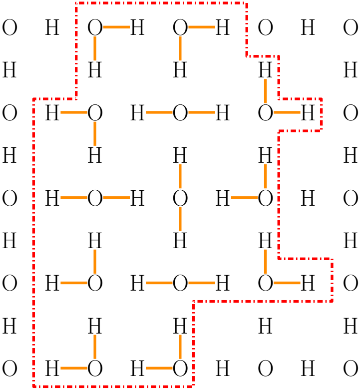

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Take a finite/infinite domain.

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This is **square ice model**. Real-world ice has somewhat similar (although 3d) structure.

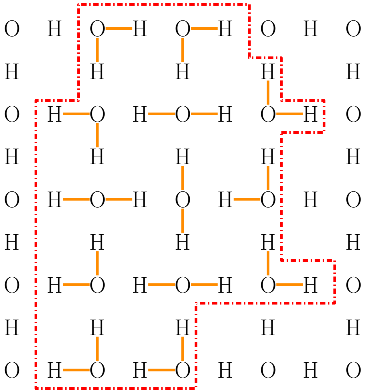
PHYSICAL REVIEW VOLUME 162, NUMBER 1 5 OCTOBER 1967

Residual Entropy of Square Ice

Elliott H. Lieb*
Department of Physics, Northeastern University, Boston, Massachusetts
(Received 22 May 1967)

At low temperatures, ice has a residual entropy, presumably caused by an indeterminacy in the positions of the hydrogen atoms. While the oxygen atoms are in a regular lattice, each O–H–O bond permits two possible positions for the hydrogen atom, subject to certain constraints called the "ice condition." The statement of the problem in two dimensions is to find the number of ways of drawing arrows on the bonds of a square planar net so that precisely two arrows point into each vertex. If N is the number of molecules and (for large N) W^N is the number of arrangements, then $S = Nk \ln W$. Our exact result is $W = (\frac{4}{3})^{3/2}$.

Six–vertex model



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Published: 25 March 2015

Square ice in graphene nanocapillaries

G. Algara-Siller, O. Lehtinen, F. C. Wang, R. R. Nair, U. Kaiser, H. A. Wu, A. K. Geim & I. V. Grigorieva

Nature **519**, 443–445 (2015) | Cite this article

43k Accesses | **543** Citations | **277** Altmetric | Metrics

Published: 23 December 2015

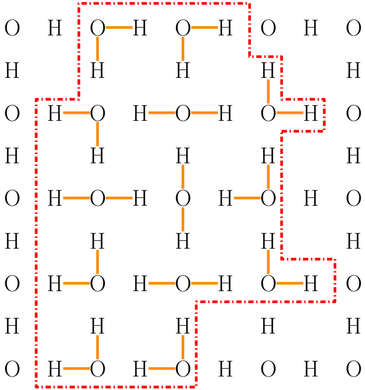
The observation of square ice in graphene questioned

Wu Zhou, Kuibo Yin, Cunhui Wang, Yuyang Zhang, Tao Xu, Albina Borisevich, Litao Sun, Juan Carlos Idrobo, Matthew F. Chisholm, Sokrates T. Pantelides, Robert F. Klie & Andrew R. Lupini

Nature **528**, E1–E2 (2015) | Cite this article

12k Accesses | **85** Citations | **25** Altmetric | Metrics

Six–vertex model



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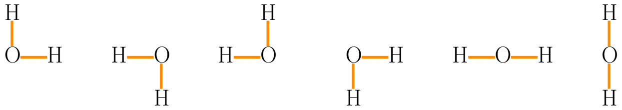
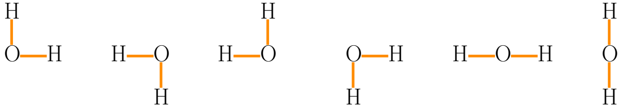
Also known as the **six vertex model**.



Gibbs measures

Six positive weights corresponding to types of vertices.



a_1 a_2 b_1 b_2 c_1 c_2

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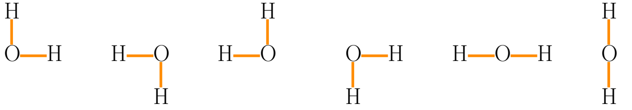

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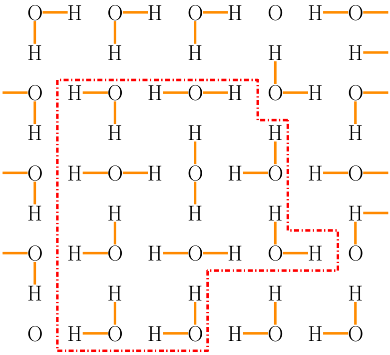

Gibbs probability measure on configurations:

$$\frac{a_1^{\#(a_1)} a_2^{\#(a_2)} b_1^{\#(b_1)} b_2^{\#(b_2)} c_1^{\#(c_1)} c_2^{\#(c_2)}}{Z(\Omega; a_1, a_2, b_1, b_2, c_1, c_2)}$$

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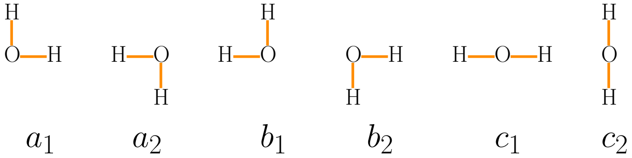
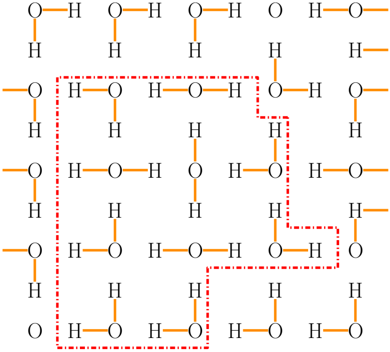


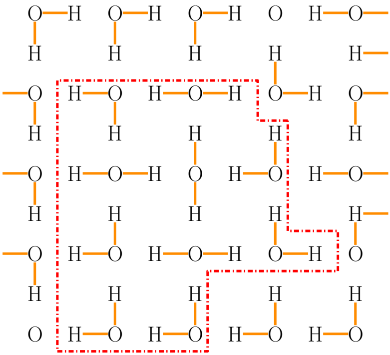


Gibbs probability measure on configurations:

$$\frac{a_1^{\#(a_1)}\, a_2^{\#(a_2)}\, b_1^{\#(b_1)}\, b_2^{\#(b_2)}\, c_1^{\#(c_1)}\, c_2^{\#(c_2)}}{Z(\Omega; a_1, a_2, b_1, b_2, c_1, c_2)}$$

Remark. Distribution depends only on $\frac{b_1 b_2}{a_1 a_2}$ and $\frac{c_1 c_2}{a_1 a_2}$.

Gibbs measures



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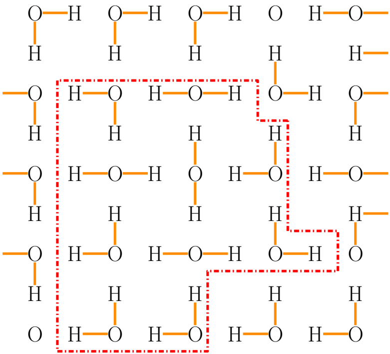
Example. *Uniform* measure on configurations in a fixed domain is Gibbs with $a_1 = a_2 = b_1 = b_2 = c_1 = c_2 = 1$.

Gibbs measures



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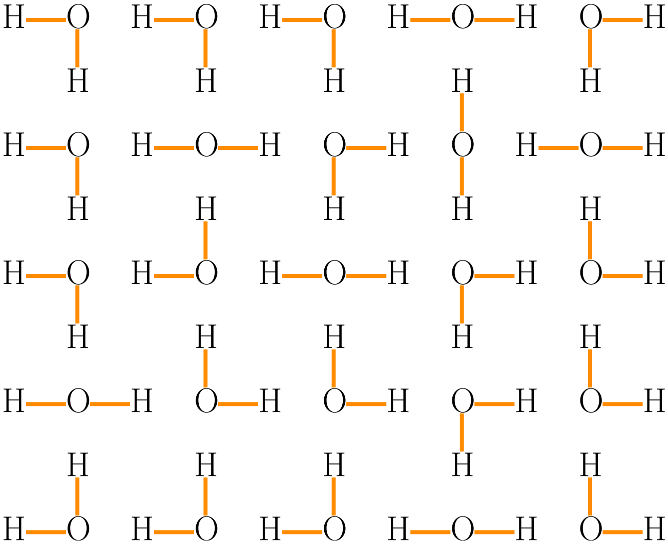
Example. *Uniform* measure on configurations in a fixed domain is Gibbs with $a_1 = a_2 = b_1 = b_2 = c_1 = c_2 = 1$.

We aim to study asymptotic properties of Gibbs measures.

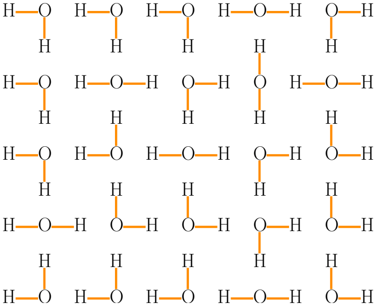
Domain wall boundary conditions (DWBC)



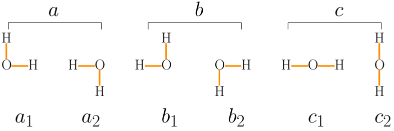
Simplest possible domain: $N \times N$ square.

Our setup: (a, b, c)–measure with DWBC.

$N \times N$ square



Symmetric weights:

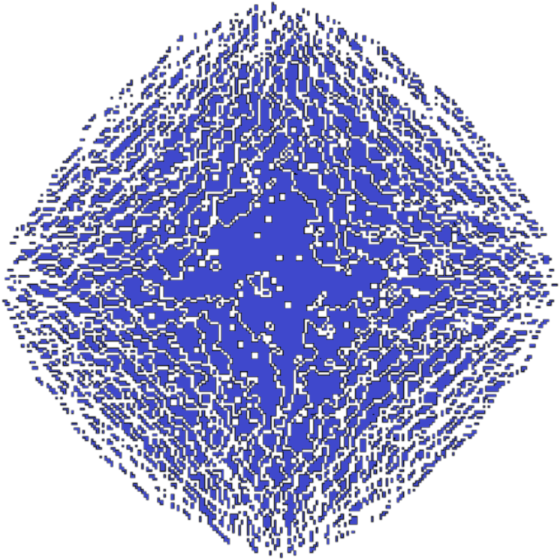


No loss of generality, because of dependence on $\frac{b_1 b_2}{a_1 a_2}$ and $\frac{c_1 c_2}{a_1 a_2}$.

How does a **random** configuration look like as $N \to \infty$?

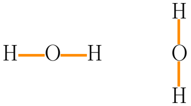
$\Delta = \frac{a^2+b^2-c^2}{2ab}$ will play a role.

$N = 200$ simulation by David Keating



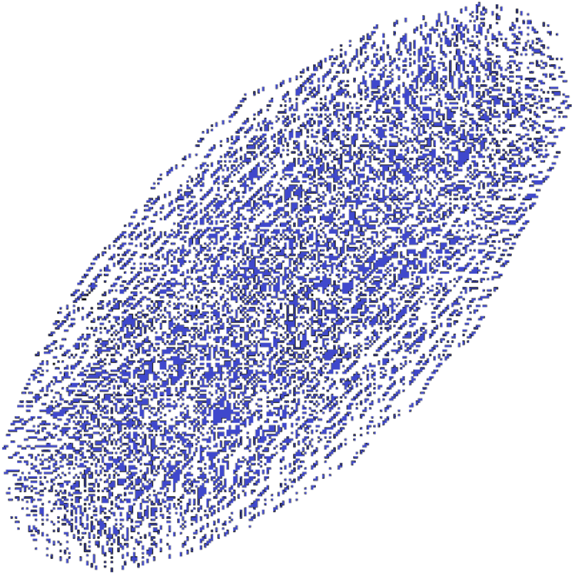
$a = 1$
$b = 1$
$c = \sqrt{8}$
$\Delta = -3$

only c-vertices shown



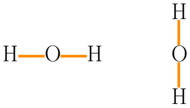
Almost **nothing** in this picture was explained rigorously.

$N = 256$ simulation by David Keating

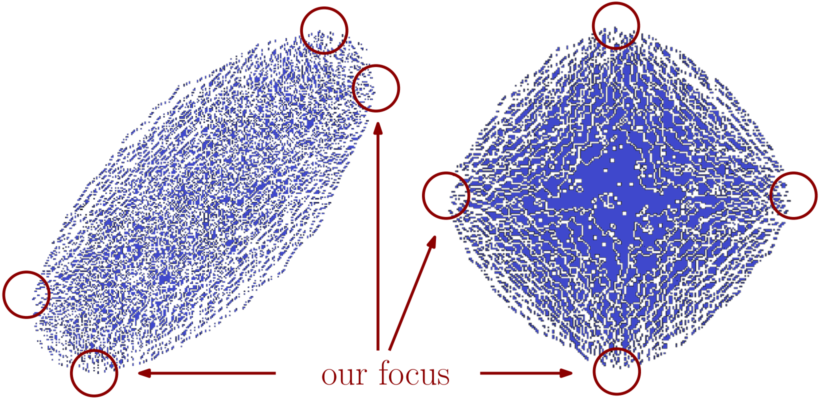


$a = 2$
$b = 1$
$c = 2$
$\Delta = \frac{1}{4}$

only c-vertices shown



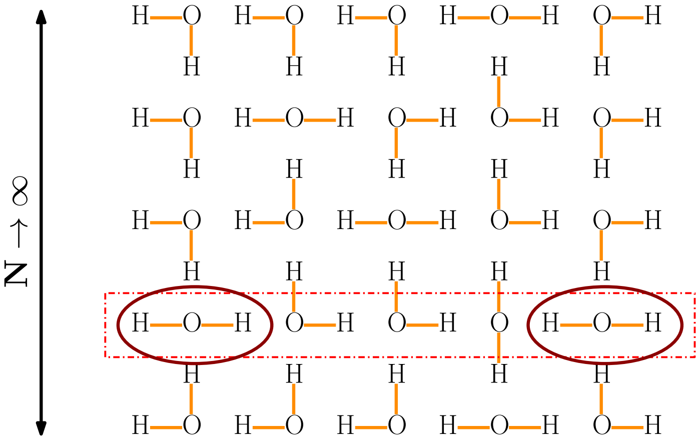
Boundary limits?



- What happens near boundaries as $N \to \infty$?
- Boundary conditions are seen **only** through these points.
- By symmetries, it is sufficient to deal with lower boundary.

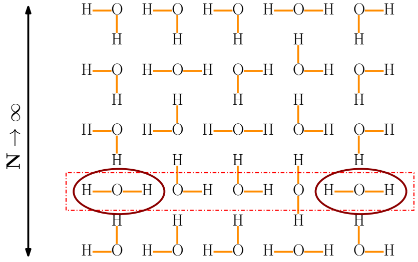
GUE for all $\Delta < 1$

Theorem. (Gorin–Liechty-23) For $\Delta < 1$ the probability that there are precisely k horizontal molecules in line k tends to 1 as $N \to \infty$.



GUE for all $\Delta < 1$

Theorem. (Gorin–Liechty-23) For $\Delta < 1$, the positions of horizontal molecules in line k, after subtracting $\mathfrak{m}(a,b,c)N$ and dividing by $\mathfrak{s}(a,b,c)\sqrt{N}$, converge in distribution to the eigenvalues of $k \times k$ matrix of **Gaussian Unitary Ensemble**.



$\longrightarrow$ Eigenvalues of $\frac{X+X^*}{2}$.

$X = k \times k$ matrix with i.i.d. $\mathcal{N}(0,1) + \mathbf{i}\mathcal{N}(0,1)$ elements.

- Horizontal molecules uniquely fix all others.
- **Corollary:** The first k rows $\to$ **GUE–corners process.**

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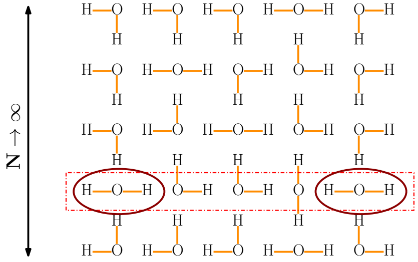

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- Previous results:
  1. $\Delta = 0$: [Johansson-Nordenstam-06] through **domino tilings**.
  2. $a = b = c = 1$: [Gorin-Panova-15] through **Schur functions**.

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$|\Delta| < 1$: $a = \sin(\gamma - t)$, $b = \sin(\gamma + t)$, $c = \sin(2\gamma)$, $|t| < \gamma < \pi/2$

$$\mathfrak{m}(a,b,c) = \frac{\cot(\gamma+t) + \frac{\pi}{2\gamma}\tan\left(\frac{\pi t}{2\gamma}\right)}{\cot(\gamma-t)+\cot(\gamma+t)}, \qquad \mathfrak{s}(a,b,c) = \frac{\sin(\gamma-t)\sin(\gamma+t)}{\sin(2\gamma)} \times$$

$$\times \sqrt{\frac{2}{3}\left(\frac{\pi^2}{4\gamma^2}-1\right) - \left(\cot(\gamma-t) - \frac{\pi}{2\gamma}\tan\left(\frac{\pi t}{2\gamma}\right)\right)\left(\cot(\gamma+t)+\frac{\pi}{2\gamma}\tan\left(\frac{\pi t}{2\gamma}\right)\right)}.$$

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$\Delta < -1$: $a = \sinh(\gamma - t)$, $b = \sinh(\gamma + t)$, $c = \sinh(2\gamma)$, $|t| < \gamma$

$$\mathfrak{m}(a,b,c) = \frac{\coth(\gamma+t) - \frac{\pi}{2\gamma}\frac{\vartheta_2'\left(\frac{\pi t}{2\gamma}\right)}{\vartheta_2\left(\frac{\pi t}{2\gamma}\right)}}{\coth(\gamma-t)+\coth(\gamma+t)}, \qquad \mathfrak{s}(a,b,c) = \frac{\sinh(\gamma-t)\sinh(\gamma+t)}{\sinh(2\gamma)} \times$$

$$\times \sqrt{\frac{2}{3} - \frac{\pi^2}{12\gamma^2}\left(\frac{\vartheta_2'\left(\frac{\pi t}{2\gamma}\right)}{\vartheta_2\left(\frac{\pi t}{2\gamma}\right)}\right)^2 + \frac{\pi^2}{12\gamma^2}\sum_{j=1}^{4}\left(\frac{\vartheta_j'(\omega)}{\vartheta_j(\omega)}\right)^2 - \frac{\pi(\coth(\gamma+t)-\coth(\gamma-t))}{2\gamma}\frac{\vartheta_2'\left(\frac{\pi t}{2\gamma}\right)}{\vartheta_2\left(\frac{\pi t}{2\gamma}\right)} - \coth(\gamma+t)\coth(\gamma-t)}$$

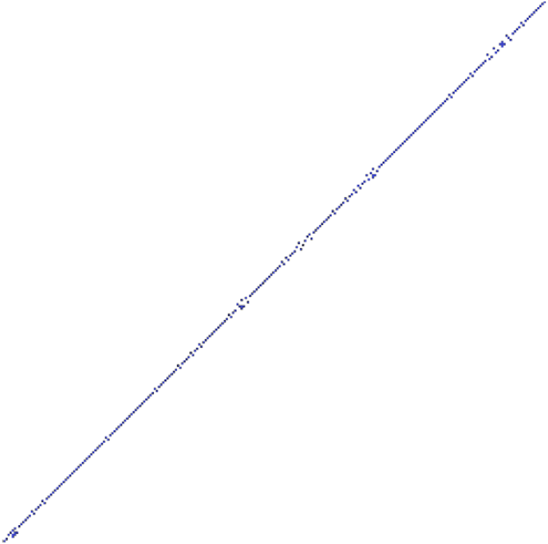
$\omega = \frac{\pi(1+t/\gamma)}{4}$, $\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4$ = Jacobi elliptic theta functions with nome $q = e^{-\pi^2/(2\gamma)}$.

$\Delta > 1$: $N = 256$ simulation by David Keating

Is $\Delta < 1$ just a technical restriction?

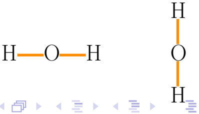
$\Delta > 1$: $N = 256$ simulation by David Keating

Is $\Delta < 1$ just a technical restriction? **No!**



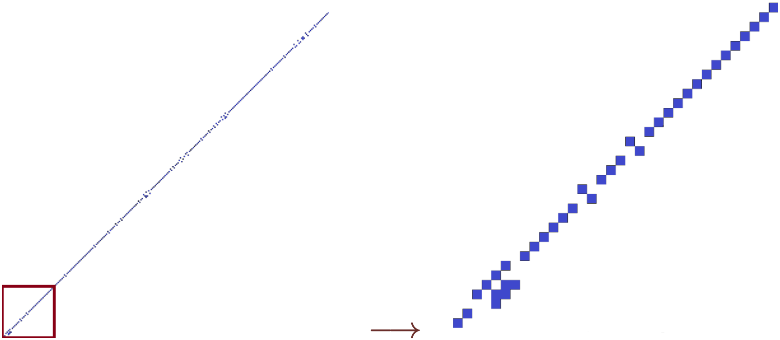
$a = 3$
$b = 1$
$c = 1$
$\Delta = \frac{3}{2}$

only c-vertices shown



$\Delta > 1$: stochastic six-vertex model.

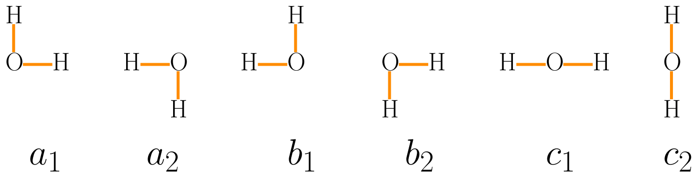
Theorem. (Gorin–Liechty-23) For $\Delta > 1$ and $a > b$, as $N \to \infty$ the configuration converges near the bottom–left corner to the **stochastic six-vertex model** *without any rescaling.*



(Complementary $a < b$ case is obtained by a vertical flip.)

Stochastic six–vertex model.

$$a_1 = a_2 = 1, \quad b_1 + c_1 = 1, \quad b_2 + c_2 = 1.$$



Remark. This implies $\Delta = \frac{a_1 a_2 + b_1 b_2 - c_1 c_2}{2\sqrt{a_1 a_2 b_1 b_2}} \geq 1.$

The model in quadrant defined by **local sampling algorithm**.

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⋮											
4	H	O	H	O	H	O	H	O	H	O	
		H		H		H		H		H	
3	H	O	H	O	H	O	H	O	H	O	
		H		H		H		H		H	
2	H	O	H	O	H	O	H	O	H	O	
		H		H		H		H		H	
1	H	O	H	O	H	O	H	O	H	O	
		1		2		3		4		5	. . .

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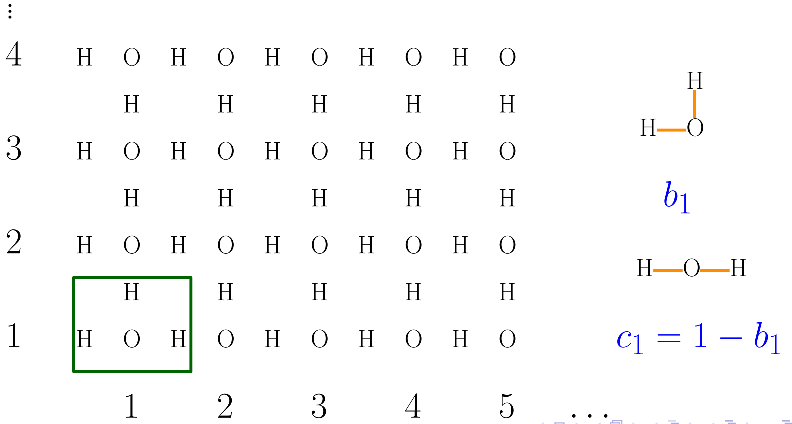

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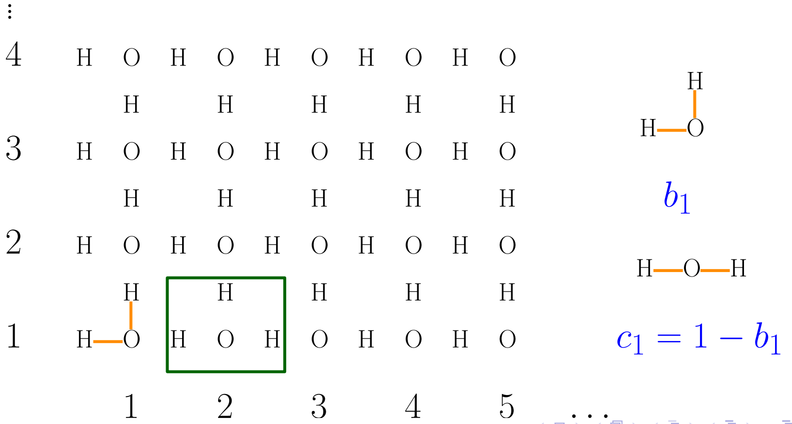

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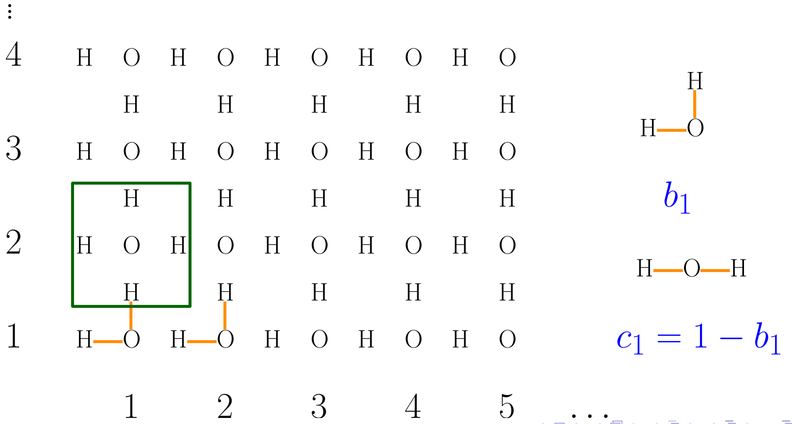

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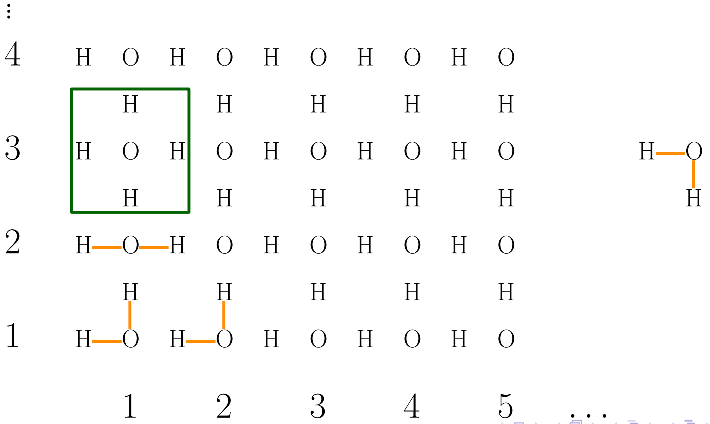

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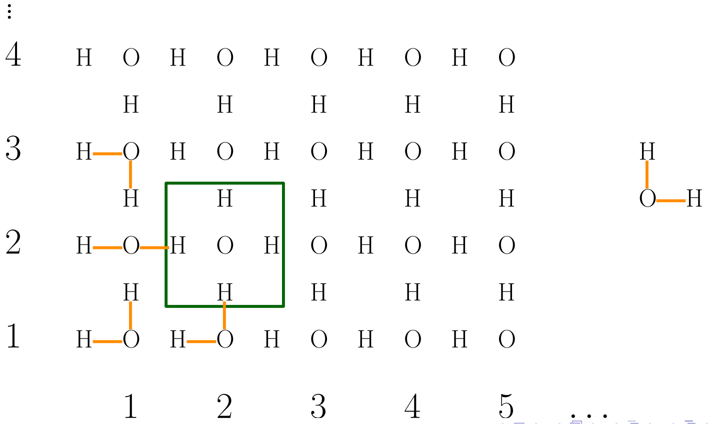

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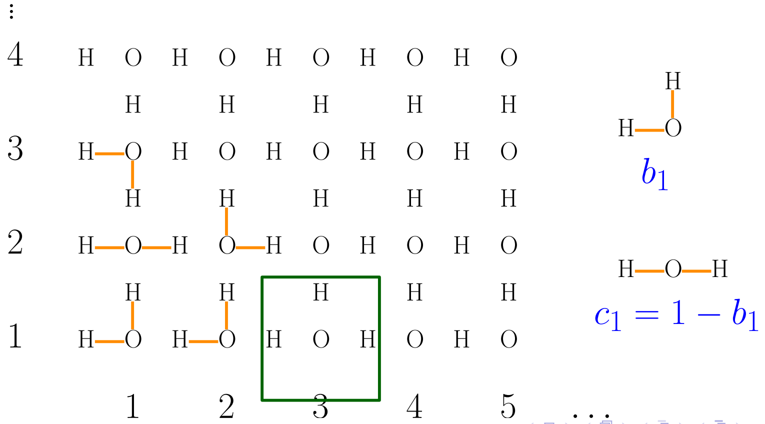

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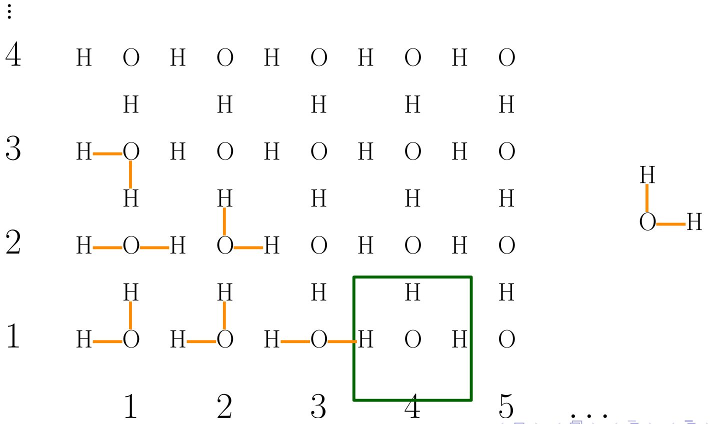

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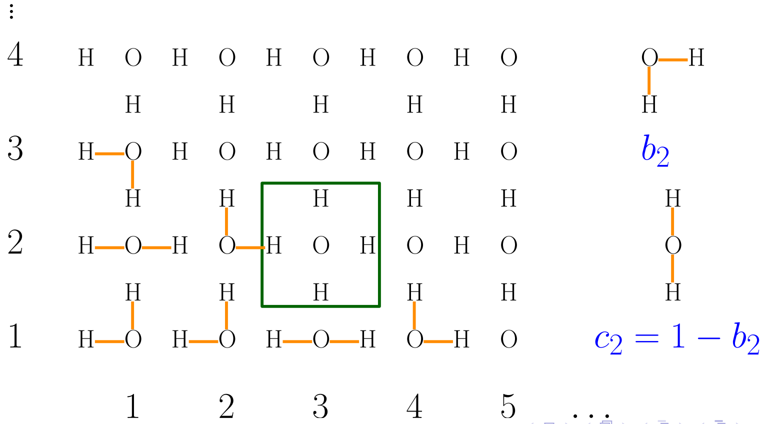

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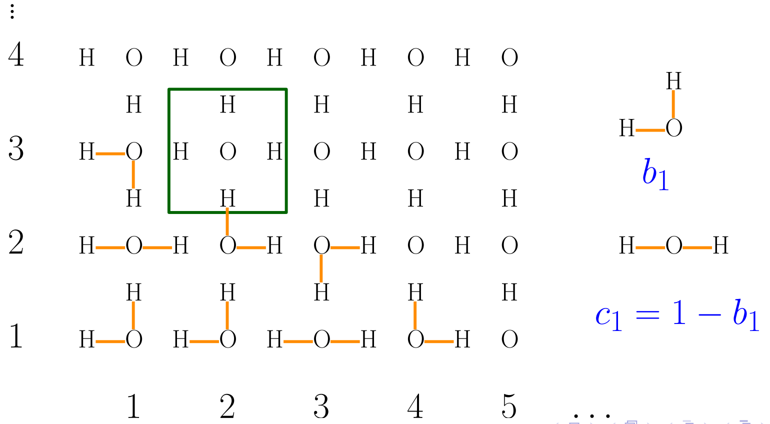

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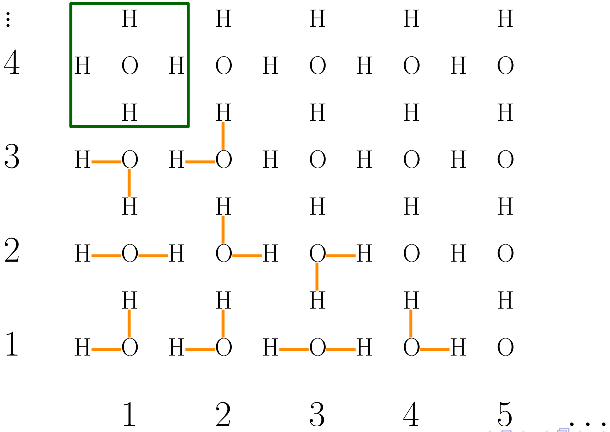

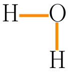

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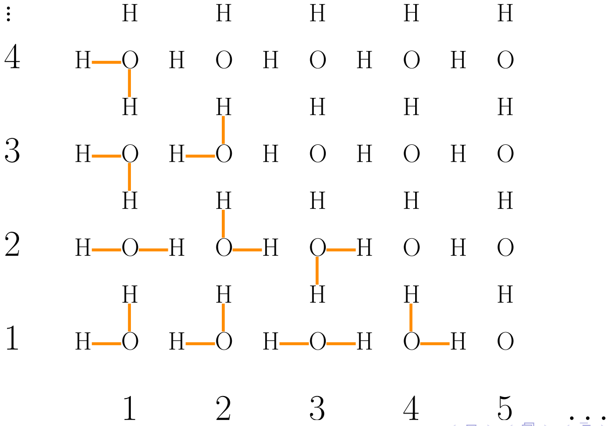

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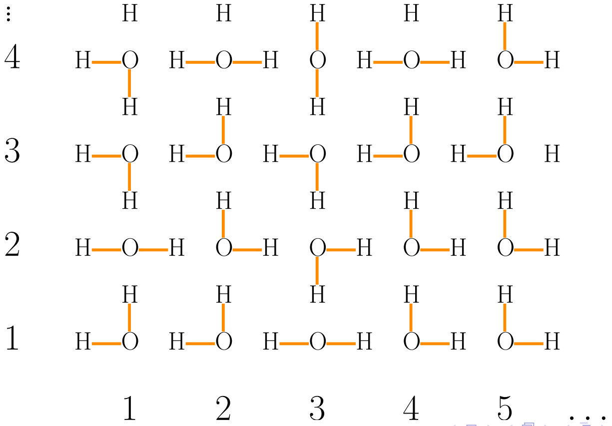

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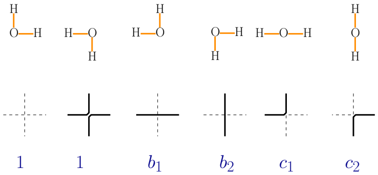

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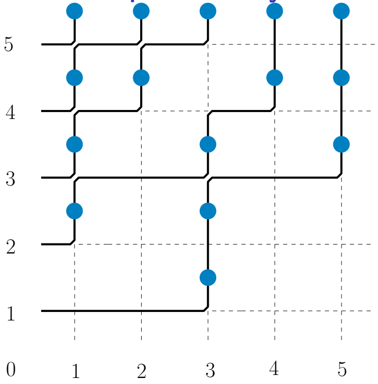

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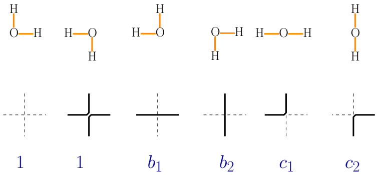

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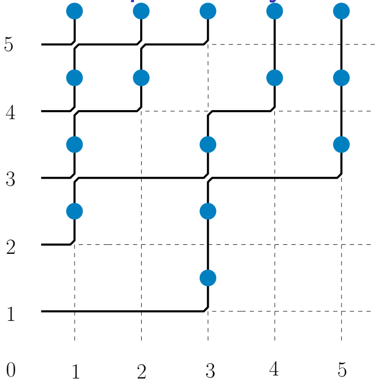

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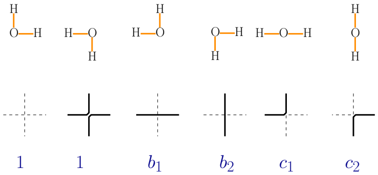

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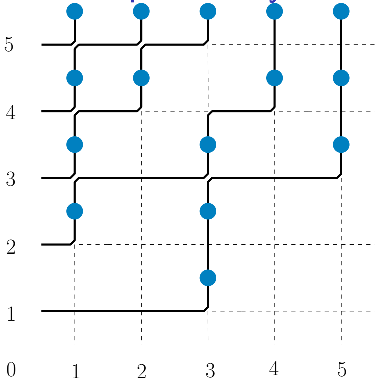

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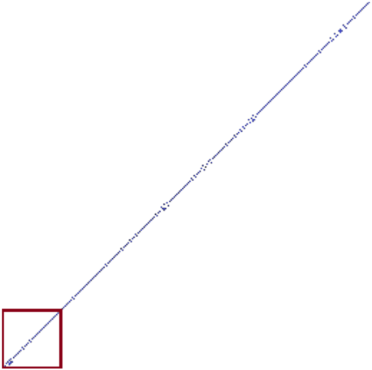
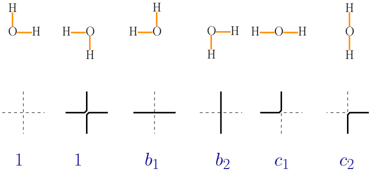
- Stationary regime $b_1 < b_2$ is relevant for DWBC.

$\Delta > 1$: stochastic six-vertex model.

Theorem. (Gorin–Liechty-23) For $\Delta > 1$ and $a > b$, as $N \to \infty$ the configuration converges near the bottom–left corner to the **stochastic six-vertex model** with $0 < b_1 < b_2 < 1$:

$$b_1 = \frac{a^2 + b^2 - c^2 - \sqrt{(a^2+b^2-c^2)^2 - 4a^2b^2}}{2a^2}, \quad b_2 = \frac{a^2 + b^2 - c^2 + \sqrt{(a^2+b^2-c^2)^2 - 4a^2b^2}}{2a^2}.$$





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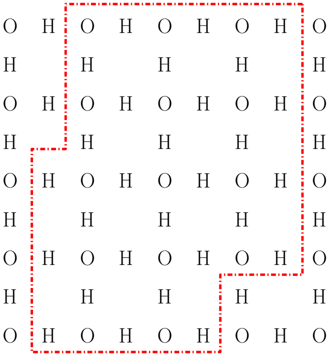
General domains

Conjecture. For any $\Delta < 1$ and any large polygonal domain near boundaries we always see $\sqrt{N}$ fluctuations and GUE–eigenvalues.



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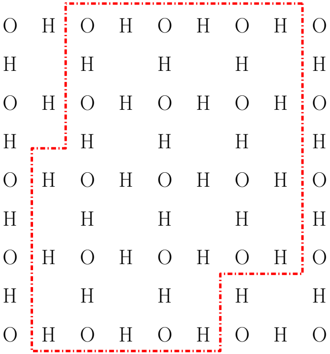

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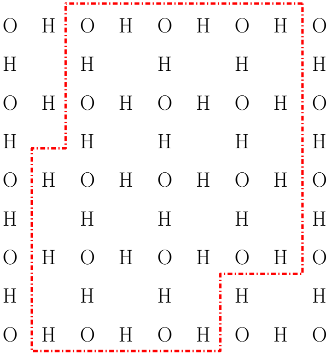

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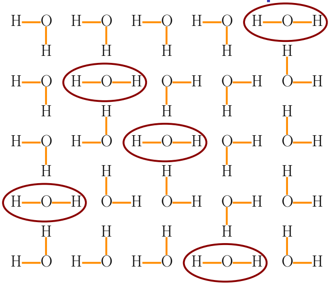
And what about $\Delta \approx 1$?

The simplest case to probe $\Delta \approx 1$.



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For fixed N send $c \to 0$ to get the **Mallows measure on permutations**.

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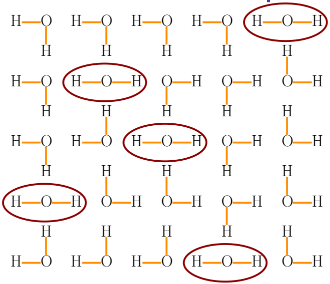

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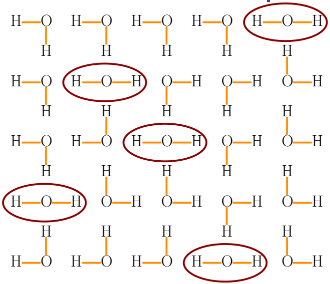

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Conclusion. We expect a rich world of boundary limits for $\Delta \approx 1$.

A glimpse into proofs

Step 1. Introduce **row and column dependent** vertex weights.

$$\omega(x,y;\sigma) = \begin{cases} a(\psi_y - \chi_x, \gamma), \\ b(\psi_y - \chi_x, \gamma), \\ c(\psi_y - \chi_x, \gamma). \end{cases}$$

$$\mathcal{Z}_n(\chi_1,\dots,\chi_N;\psi_1,\dots,\psi_N;\gamma) = \sum_{\sigma} \prod_{x=1}^{N} \prod_{y=1}^{N} \omega(x,y;\sigma).$$

[Izergin, Korepin — 1982, 1987] Partition function evaluates:

$$\frac{\prod_{i,j=1}^{N} \big(a(\psi_j-\chi_i,\gamma) b(\psi_j-\chi_i,\gamma)\big)}{\prod_{i<j} \big(b(\chi_i-\chi_j,0) b(\psi_i-\psi_j,0)\big)} \det\left[\frac{c(\psi_j-\chi_i,\gamma)}{a(\psi_j-\chi_i,\gamma) b(\psi_j-\chi_i,\gamma)}\right]_{i,j=1}^{N}.$$

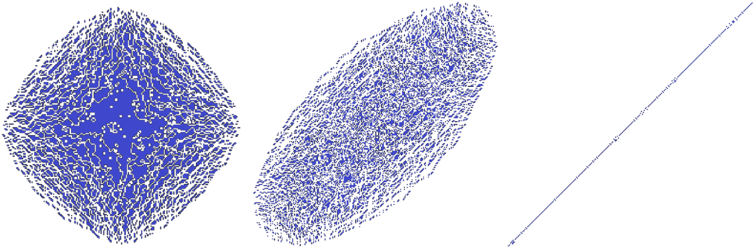
Step 2. Delicate $N \to \infty$ asymptotic analysis of IK-determinant when $\psi_1 = \cdots = \psi_N = \psi$ and all but finitely many χ_i are set to 0.

Step 3. Use the Gibbs property for probabilistic consequences.

Summary

Boundary limits for the 6v–model in $N \times N$ square with DWBC:

- **GUE** asymptotics after $\sqrt{N}$–rescaling for $\Delta < 1$.
- **Stationary stochastic six-vertex model** for $\Delta > 1$.
- Rich, but only partially understood limits for $\Delta \approx 1$.



- Asymptotic analysis based on the Izergin-Korepin determinant.