Quantum Simulation of Integrable Models

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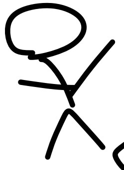
QuantHEP @ Queen Mary University of London

Introduction



We are now in the "Utility Era"

with $\mathcal{O}(100)$ qubits

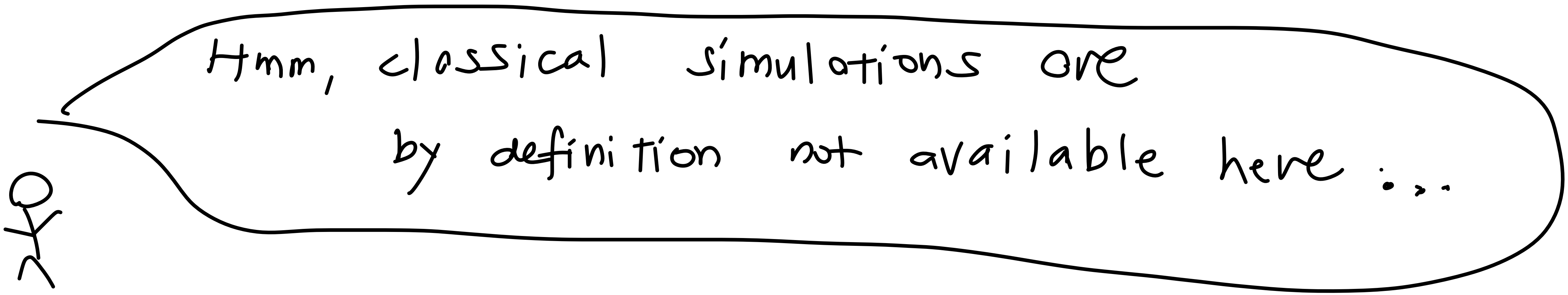
Quantum computations

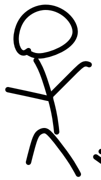
hard to be simulated classically

We are now in the "Utility Era" with $O(100)$ qubits

Quantum computations hard to be simulated classically

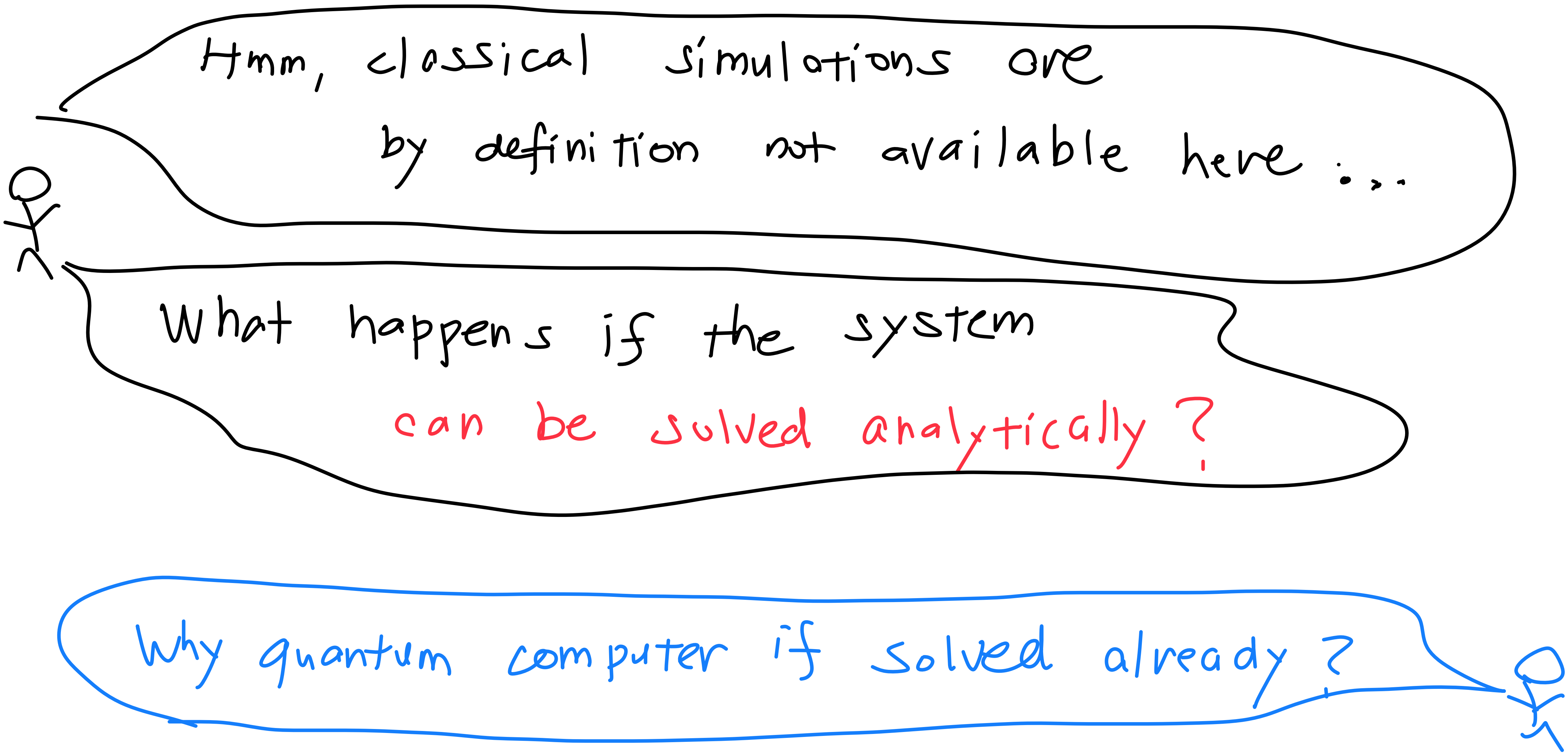
How do you make sure quantum computation is correct?


Hmm, classical simulations are by definition not available here...



Hmm, classical simulations are by definition not available here...

What happens if the system can be solved analytically?


Hmm, classical simulations are by definition not available here...
What happens if the system can be solved analytically?
Why quantum computer if solved already?

integrable models as stepping stones

Integrable Models: "exactly solvable"

- some observables can be computed exactly
- many conserved charges $\{Q_n\}$; $\frac{dQ_n}{dt} = 0$

Idea: Measure Q_n on quantum hardware

Idea: Measure Q_n on quantum hardware

benchmark quantum devices

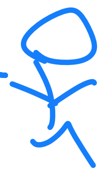
- noise
- error mitigation /correction

study the physics of integrability (breaking)

- ~~integrability~~ perturbation
- thermalization

non-equilibrium dynamics

Why quantum computer if 'solved already?



We can

* verify results
* benchmark devices
* study unsolved observables
* break solvability by perturbation
* study thermalization (ETH breaking)
* compare with chaotic systems

Quantum Simulation of Integrable Modes

I started working on this in 2021 :

arXiv > quant-ph > arXiv:2208.00576

Search...

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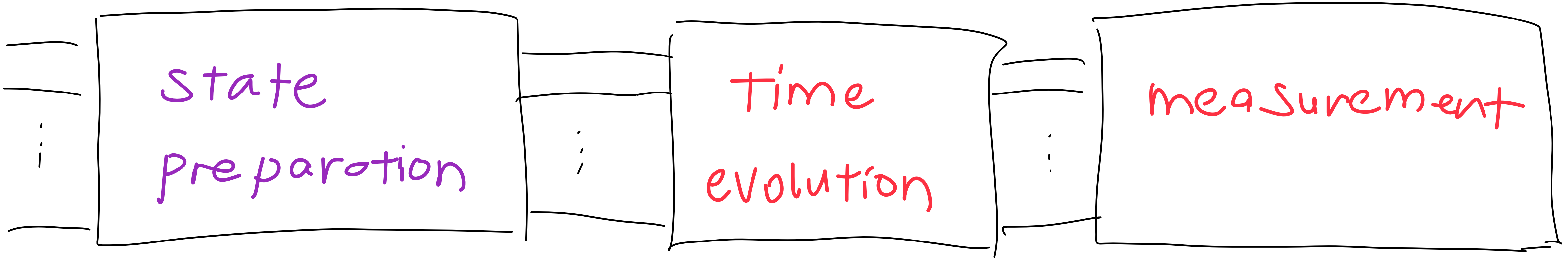
Quantum Physics

[Submitted on 1 Aug 2022 (v1), last revised 3 Apr 2023 (this version, v2)]

Conserved charges in the quantum simulation of integrable spin chains

Kazunobu Maruyoshi, Takuya Okuda, Juan William Pedersen, Ryo Suzuki, Masahito Yamazaki, Yutaka Yoshida

When simulating the time evolution of quantum many-body systems on a digital quantum computer, one faces the challenges of quantum noise and of the Trotter error due to time discretization. The Trotter error in integrable spin chains can be under control if the discrete time evolution preserves integrability. In this work we implement, on a real quantum computer and on classical simulators, the integrable Trotterization of the spin-1/2 Heisenberg XXX spin chain. We study how quantum noise affects the time evolution of several conserved charges, and observe the decay of the expectation values. We in addition study the early time behaviors of the time evolution, which can potentially be used to benchmark quantum devices and algorithms in the future. We also provide an efficient method to generate the conserved charges at higher orders.


state preparation
time evolution
measurement

Time Evolution

e.g. XXX spin-$\frac{1}{2}$ spin chain

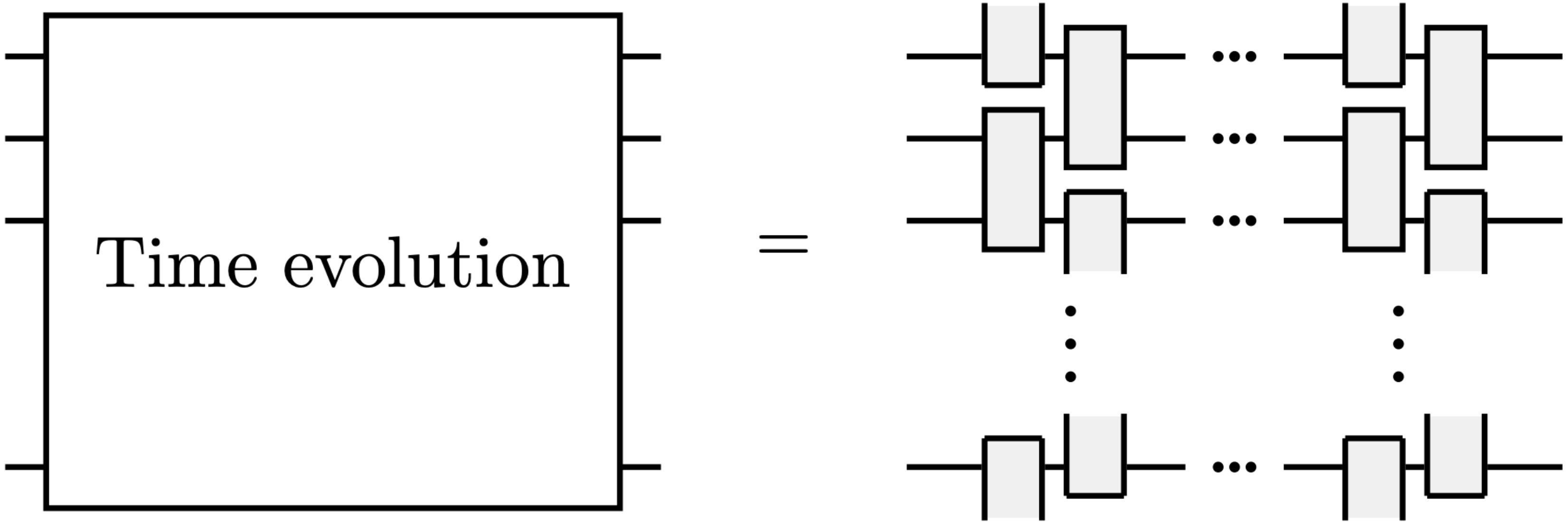
$$H = \sum_{i=1}^{N} \left(X_i X_{i+1} + Y_i Y_{i+1} + Z_i Z_{i+1} \right)$$

$$= \sum_{i=1}^{N} \left(2 \underbrace{P_{i,i+1}}_{\text{permutation}} - I_i I_{i+1} \right)$$

$$= \underbrace{\sum_{i:\text{ even}} \left(2P_{i,i+1} - I_i I_{i+1} \right)}_{H_{\text{even}}} + \underbrace{\sum_{i=\text{odd}} \left(2P_{i,i+1} - I_i I_{i+1} \right)}_{H_{\text{odd}}}$$

Standard Trotterization

$$e^{iHt} \sim \left(e^{i\frac{H_{even}}{N}t} \; e^{i\frac{H_{odd}}{N}t} \right)^N$$



brick-wall circuit

This, however, breaks integrability

Integrable Trotterization

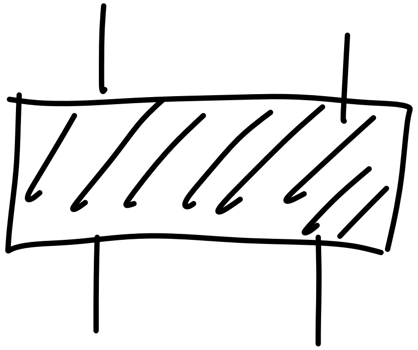
[Destri – de Vega ('88, '89)
Vanicat – Zadnik – Prosen ('17)]

spectral parameter

R-matrix

permutation

$$\check{R}_{ij}(\lambda) = (1 + i\lambda P_{i,j})/(1+i\lambda)$$



$\check{R}$

$$= \frac{1}{1+i\lambda} \begin{array}{c} \\ |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{array} \begin{array}{c} \begin{array}{cccc} |00\rangle & |01\rangle & |10\rangle & |11\rangle \end{array} \\ \begin{pmatrix} 1 & & & \\ & 1 & i\lambda & \\ & i\lambda & 1 & \\ & & & 1 \end{pmatrix} \end{array}$$

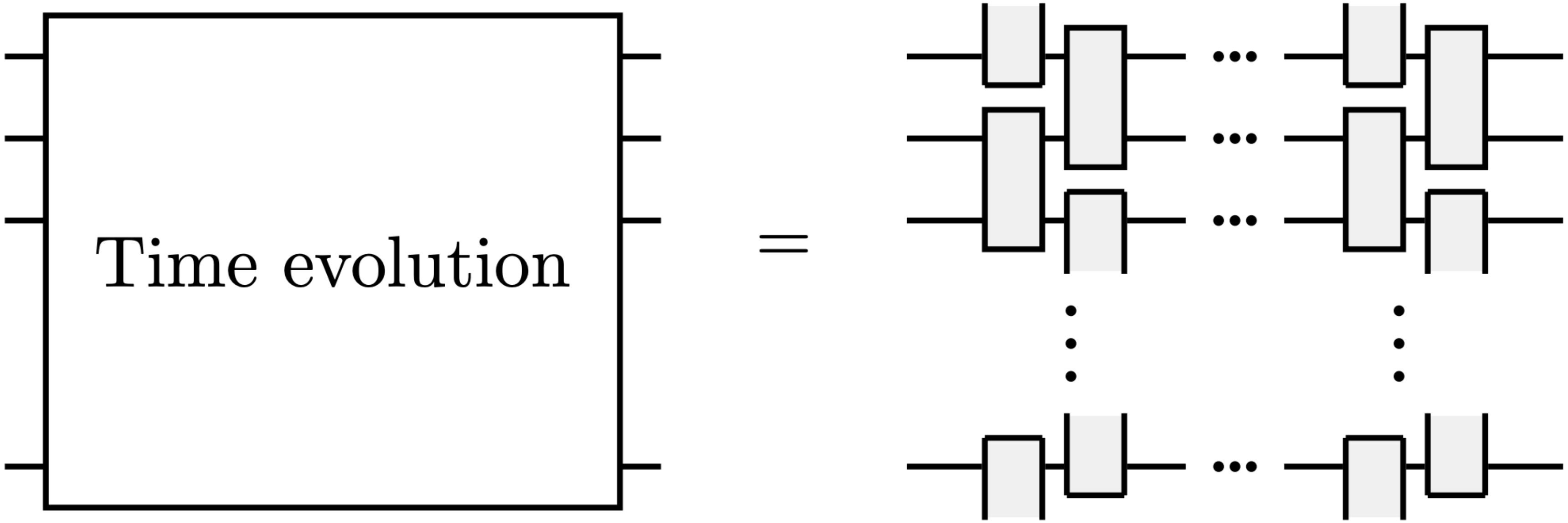
Integrable Trotterization

[Destri – de Vega ('88, '89)
Vanicat – Zadnik – Prosen ('17)]

$$\mathcal{U}(\delta) = \left(\prod_{j=1}^{N/2} \check{R}_{2j-1,2j}(\delta) \right) \left(\prod_{j=1}^{N/2} \check{R}_{2j,2j+1}(\delta) \right)$$

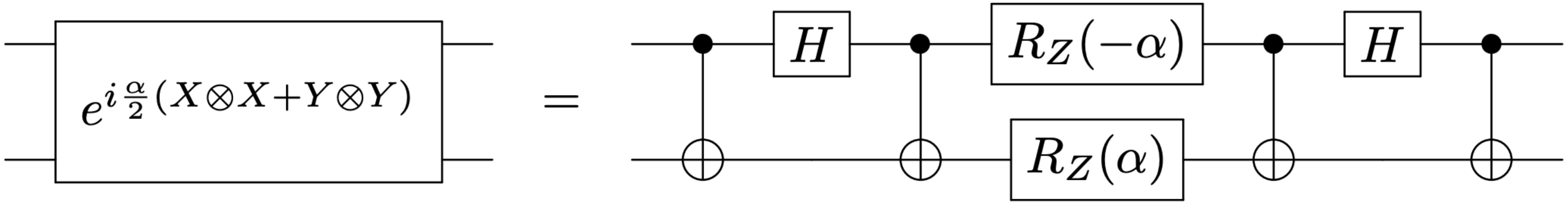
deformation parameter

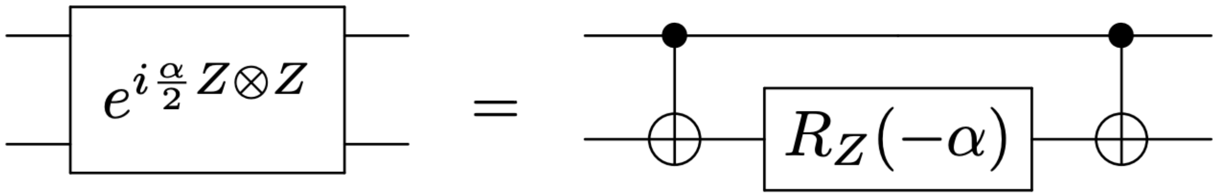
R-matrix



$$\check{R}_{j,j+1}(\delta) = e^{-i\frac{\alpha}{2}} e^{i\frac{\alpha}{2}(X_j X_{j+1} + Y_j Y_{j+1})} e^{i\frac{\alpha}{2} Z_j Z_{j+1}}$$

$(\delta = \tan\alpha)$





Measurement of Conserved Changes

- $\underbrace{T(\lambda)}_{\text{transfer matrix}} := \mathrm{tr}_0 \left[\prod_{1 \leq j \leq N} R_{0j}\left(\lambda - \underbrace{(-1)^j \frac{\delta}{2}}\right) \right]$

$\times \times \times \rightarrow \times \times \times_{\delta}$

- Conserved charges

$$Q_n^{\pm} = \frac{d^n}{d\lambda^n} \log T(\lambda) \Big|_{\lambda = \pm\delta/2}$$

- recursion by boost operator B

$$Q_{n+1}^{\pm} = [B, Q_n^{\pm}]$$

known from R-matrix

$$Q_n^+(\delta) = \sum_{j=1}^{N/2} q^{[n,+]}_{2j-2,2j-1,\ldots,2j+2n-2}(\delta),$$

$$Q_n^-(\delta) = \sum_{j=1}^{N/2} q^{[n,-]}_{2j-1,2j,\ldots,2j+2n-1}(\delta),$$

$$q^{[1,\pm]}_{1,2,3}(\delta) = \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \boldsymbol{\sigma}_2 \cdot \boldsymbol{\sigma}_3 \mp \delta \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_2 \times \boldsymbol{\sigma}_3) + \delta^2 \boldsymbol{\sigma}_2 \cdot \boldsymbol{\sigma}_3 \, ,$$

$$\begin{aligned} q^{[2,\pm]}_{1,2,3,4,5}(\delta) = {} & \mp 2\delta(\boldsymbol{\sigma}_3 \cdot \boldsymbol{\sigma}_4 + \boldsymbol{\sigma}_4 \cdot \boldsymbol{\sigma}_5 - \boldsymbol{\sigma}_3 \cdot \boldsymbol{\sigma}_5) - (1-\delta^2)\boldsymbol{\sigma}_3 \cdot (\boldsymbol{\sigma}_4 \times \boldsymbol{\sigma}_5) - \boldsymbol{\sigma}_2 \cdot (\boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_4) - \delta^2 \boldsymbol{\sigma}_2 \cdot (\boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_5) \\ & - \delta^2 \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_4) - \delta^4 \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_5) \pm \delta \boldsymbol{\sigma}_2 \cdot (\boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_4 \times \boldsymbol{\sigma}_5) \pm \delta \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_2 \times \boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_4) \\ & \pm \delta^3 \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_4 \times \boldsymbol{\sigma}_5) \pm \delta^3 \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_2 \times \boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_5) - \delta^2 \boldsymbol{\sigma}_1 \cdot (\boldsymbol{\sigma}_2 \times \boldsymbol{\sigma}_3 \times \boldsymbol{\sigma}_4 \times \boldsymbol{\sigma}_5). \end{aligned}$$

$$
\begin{aligned}
q^{[3,+]}_{1,2,3,4,5,6,7} = &-4\boldsymbol{\sigma}_6\cdot\boldsymbol{\sigma}_7 + 2\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_7 - 4\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_6 + 2\boldsymbol{\sigma}_4\cdot\boldsymbol{\sigma}_6 + 2\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\\
&+\delta\Big(10\boldsymbol{\sigma}_5\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 4\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7) + 8\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6) - 4\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\\
&-2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_6) - 4\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_2\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\Big)\\
&+\delta^2\Big(2\boldsymbol{\sigma}_6\cdot\boldsymbol{\sigma}_7 - 10\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_7 + 2\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_6 + 2\boldsymbol{\sigma}_4\cdot\boldsymbol{\sigma}_7 + 2\boldsymbol{\sigma}_4\cdot\boldsymbol{\sigma}_6 + 2\boldsymbol{\sigma}_3\cdot\boldsymbol{\sigma}_6\\
&-6\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 6\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 6\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7)\\
&-6\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6) + 2\boldsymbol{\sigma}_2\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\\
&+2\boldsymbol{\sigma}_2\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_2\times\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\Big)\\
&+\delta^3\Big(6\boldsymbol{\sigma}_5\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 4\boldsymbol{\sigma}_4\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 8\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7)\\
&-2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_6) + 4\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6) - 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_7) + 4\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7)\\
&-2\boldsymbol{\sigma}_2\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_2\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\\
&-2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_2\times\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6) - 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_2\times\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7)\Big)\\
&+\delta^4\Big(-2\boldsymbol{\sigma}_6\cdot\boldsymbol{\sigma}_7 - 8\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_7 - 2\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_6 + 2\boldsymbol{\sigma}_4\cdot\boldsymbol{\sigma}_7 + 2\boldsymbol{\sigma}_3\cdot\boldsymbol{\sigma}_6 + 2\boldsymbol{\sigma}_3\cdot\boldsymbol{\sigma}_7 - 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7)\\
&+2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_2\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6)\\
&+2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_2\times\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) + 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_2\times\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7)\Big)\\
&+\delta^5\Big(4\boldsymbol{\sigma}_5\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_3\cdot(\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_6\times\boldsymbol{\sigma}_7)\\
&-2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_4\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7) - 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_2\times\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7)\Big)\\
&+\delta^6\Big(-4\boldsymbol{\sigma}_5\cdot\boldsymbol{\sigma}_7 + 2\boldsymbol{\sigma}_3\cdot\boldsymbol{\sigma}_7 + 2\boldsymbol{\sigma}_1\cdot(\boldsymbol{\sigma}_3\times\boldsymbol{\sigma}_5\times\boldsymbol{\sigma}_7)\Big).
\end{aligned}
$$

$$Q = \sum_{P \in \{I, X, Y, Z\}^{\otimes n}} \overbrace{c_{Q,P}}^{\mathbb{C}} \; \overbrace{P}^{\text{Pauli word}}$$

measure in

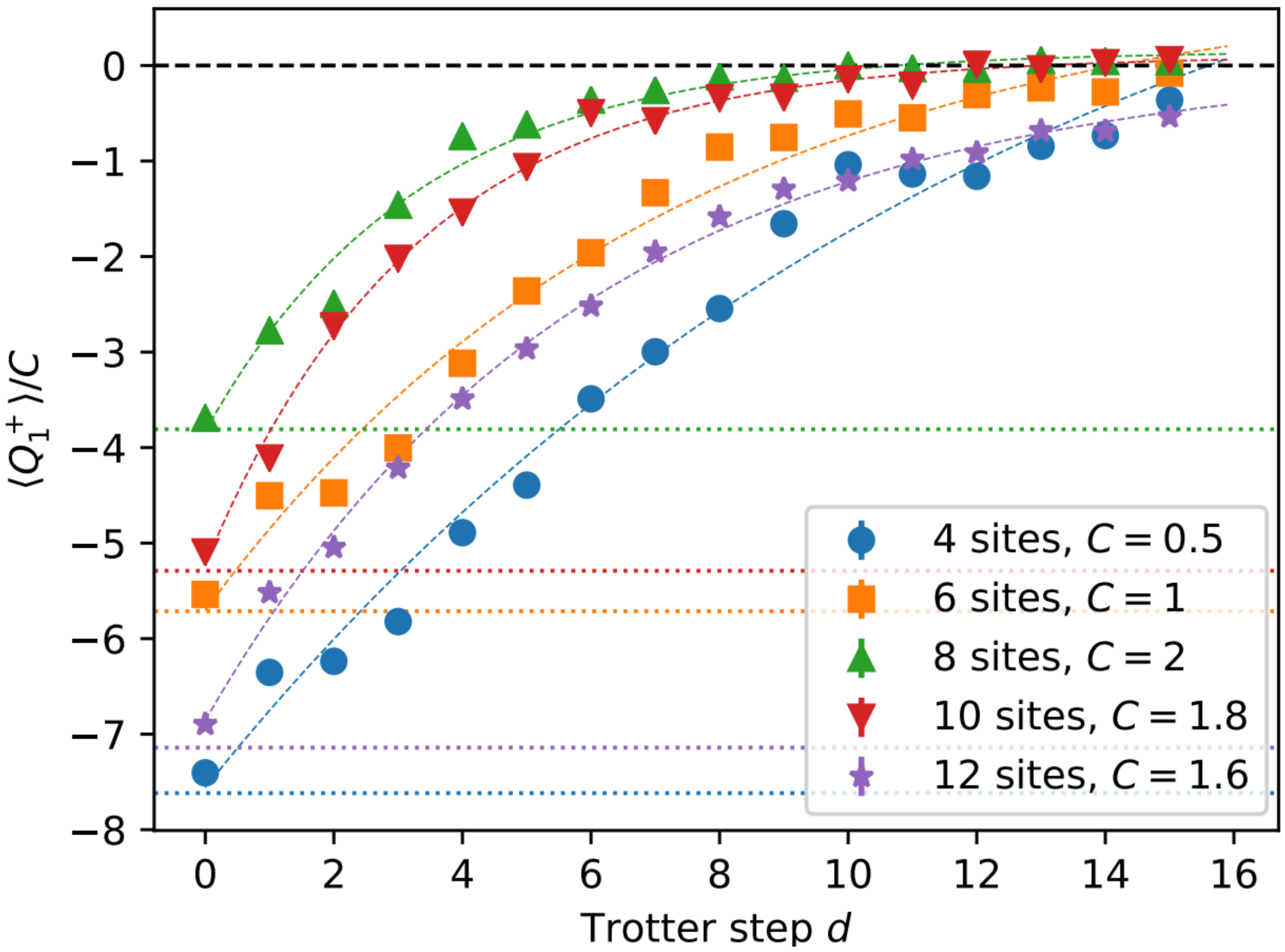
$$\left(\begin{array}{l} Z: |0\rangle, |1\rangle \\ X: H|0\rangle, H|1\rangle \\ Y: SH|0\rangle, SH|1\rangle \end{array} \right)$$

Results

[Maruyoshi-Okuda-Pedersen-Suzuki-Yamazaki-Okuda ('22)]

[MY + Alberton-Lindner-Scheider (to appear)]

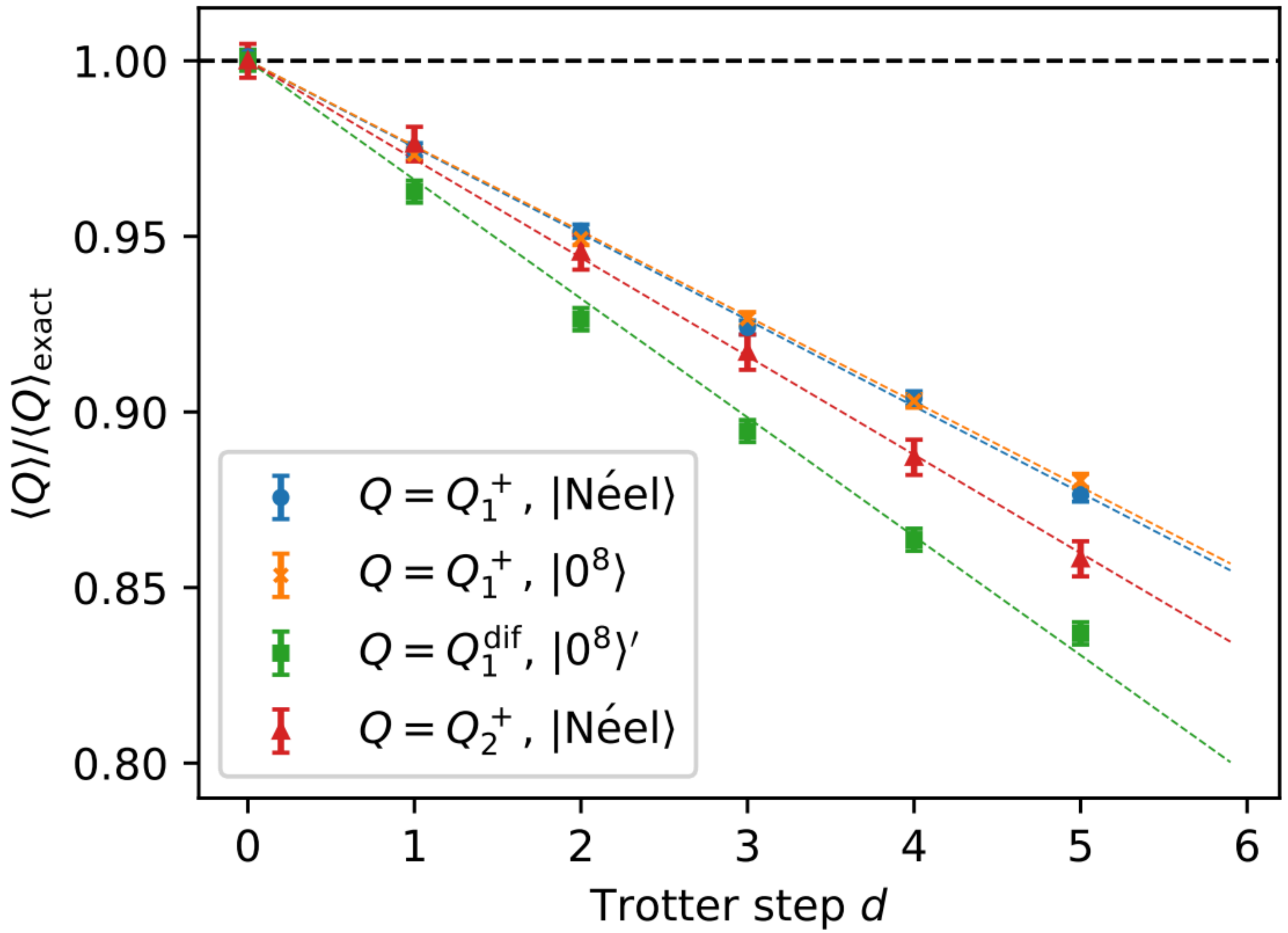
[Maruyoshi - Okuda - Pedersen - Suzuki - Yamazaki - Okuda]
('22)



superconducting qubits

(ibm kawasaki
10^5 shots)

also ion traps



classical sim..

$$\begin{pmatrix} \text{2Q error} & p = 0.0013 \\ \text{1Q error} & p = 0.00013 \end{pmatrix}$$

benchmark quantum devices?

After ~ 5 years,

things are "better than expected"!

Game - Changers

* upgrade of IBM machines

Falcone → Eagle → Heron

* Advancement of error mitigation

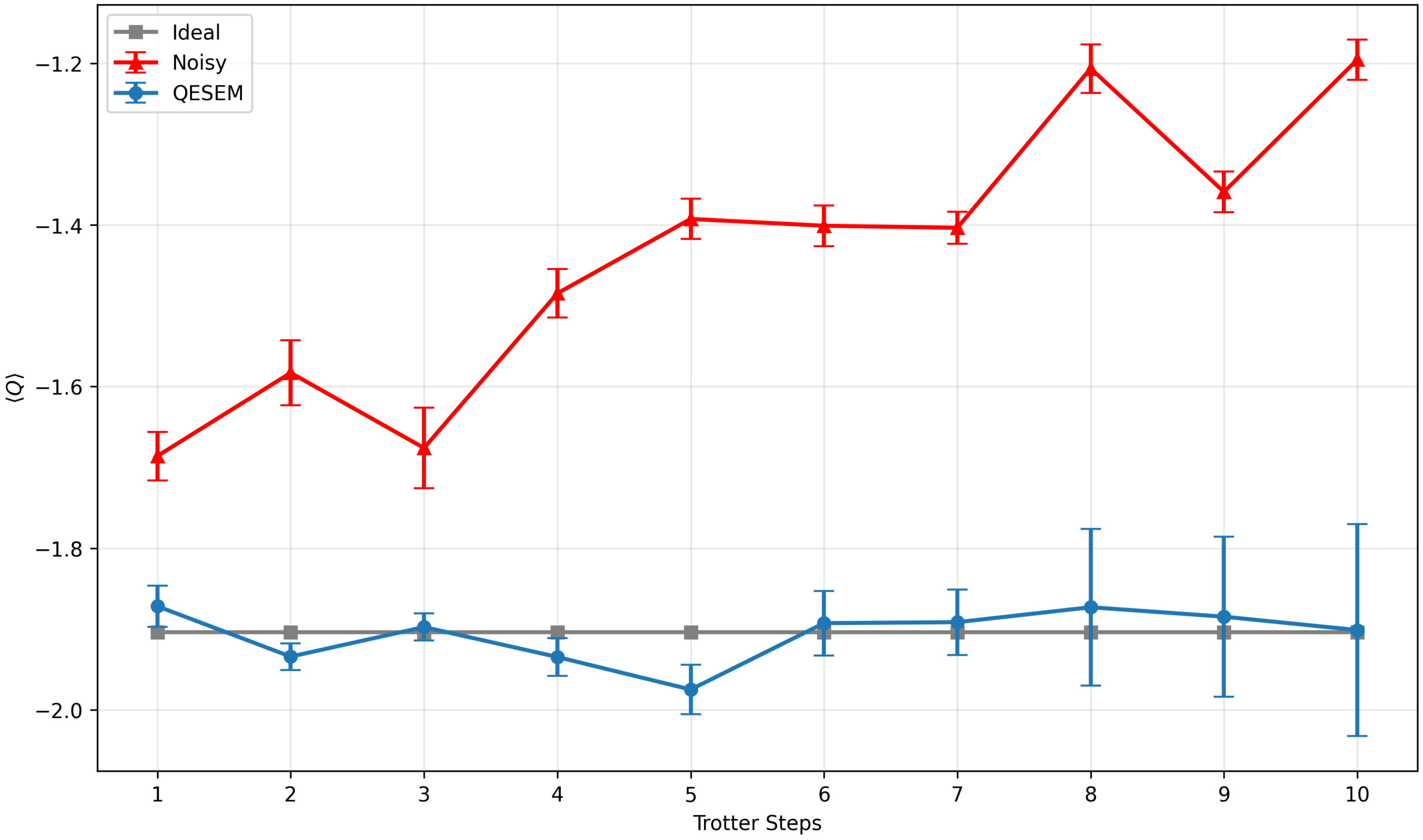
Qiskit-function QESEM

arXiv: 2508.10997

QEDMA

collaboration w/ T. Schneider, O. Alberton, N. Lidner

Preliminary Results



QPU: ibm_kingston
Number of qubits: 12
Trotter steps: 10
Number of 2 qubit gates: 480

almost constant after error mitigation

Quantum Simulation of

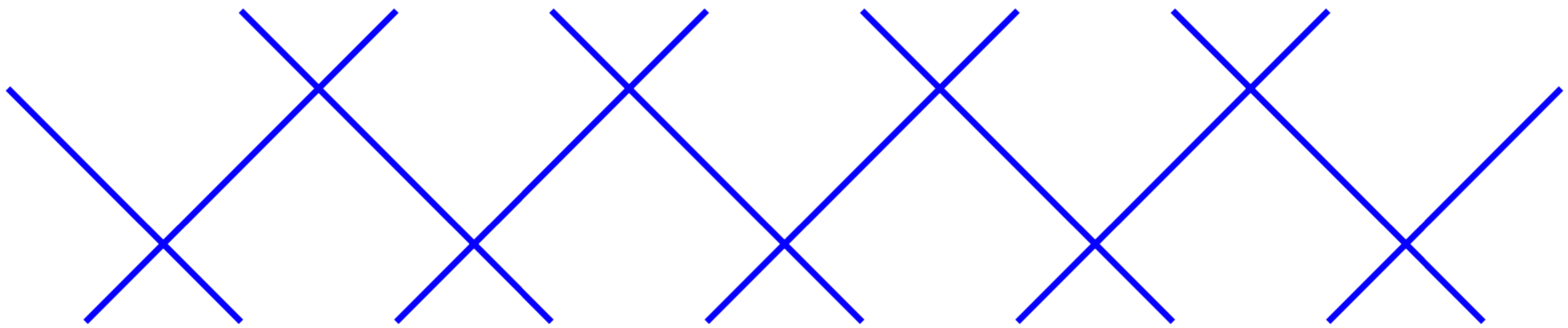
Integrable Quantum Field Theories

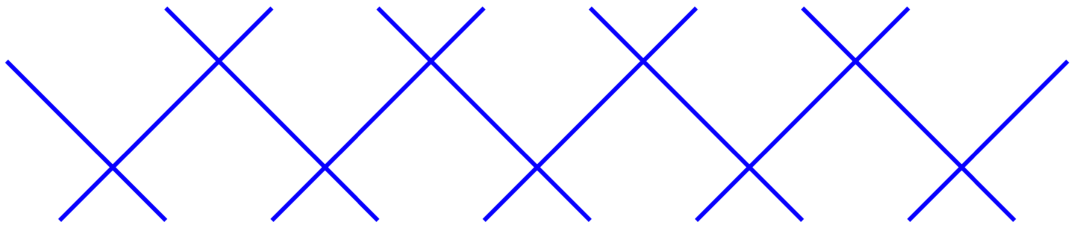
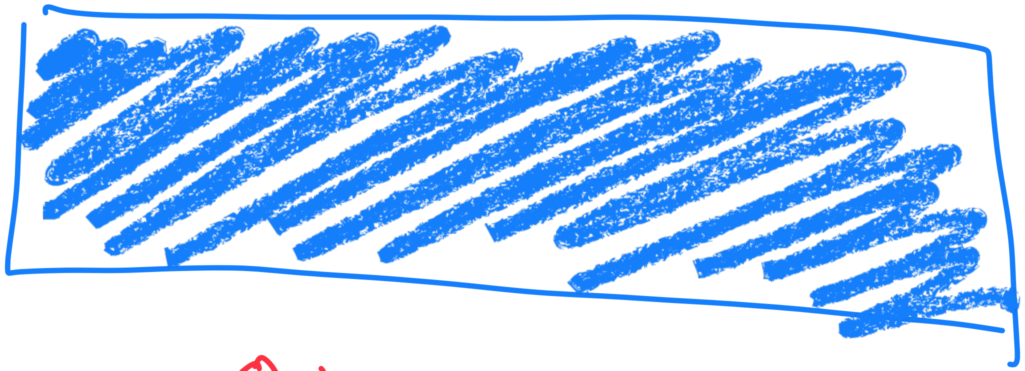
Historically, one of the motivations of

integrable models is to solve QFT

[Faddeev-Reshetikhin ('86), Faddeev-Volkov ('92, '93)]

brick-wall circuit = light-cone discretization of spacetime



 ⟺ 

quantum circuit ⟺ QFT

bosonization

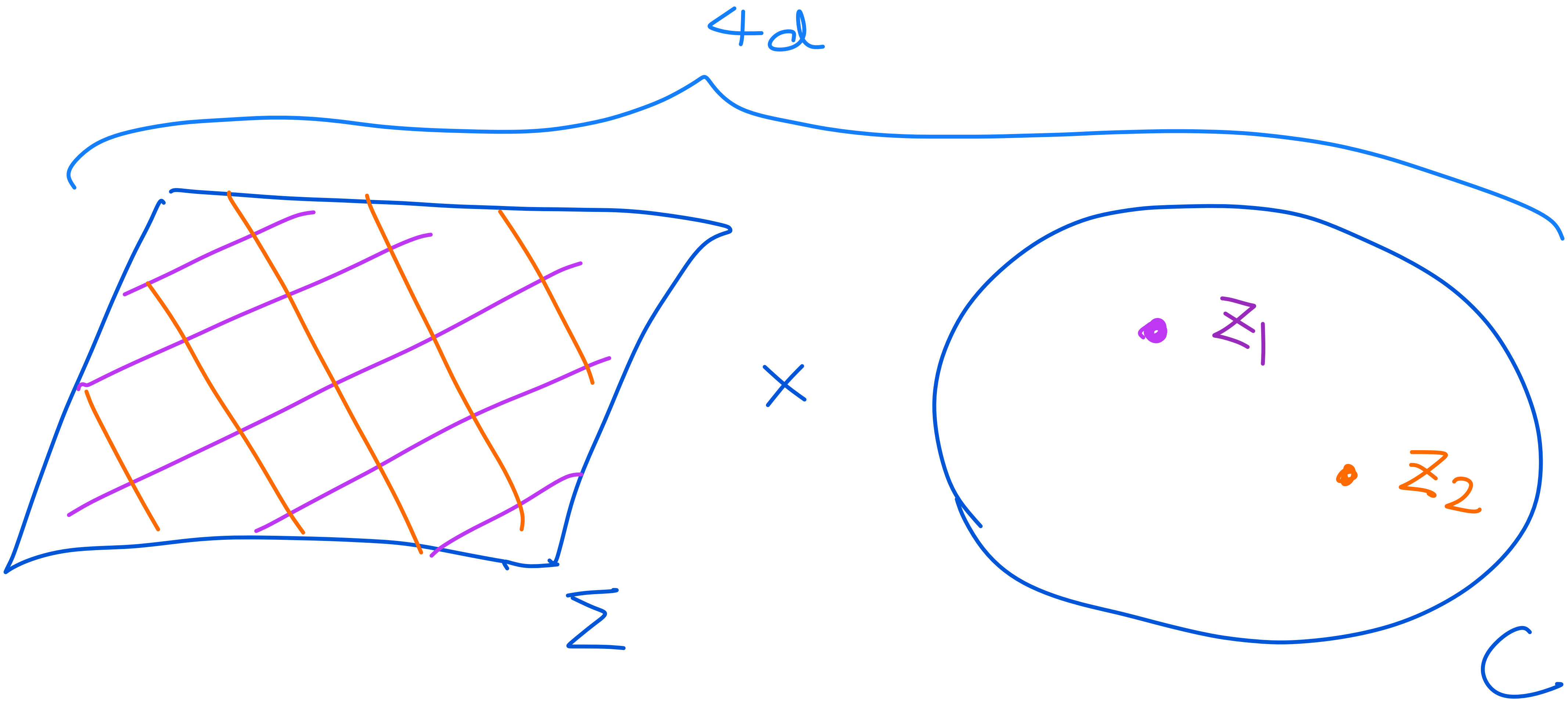
XXZ ⟺ Sine-Gordon / massive-Thirring

[Luther-Peshel ('75)
Destri-de Vega ('90s)]

Surprisingly, no general prescription existed for (lattice / circuit) ⟺ QFT until 2023!

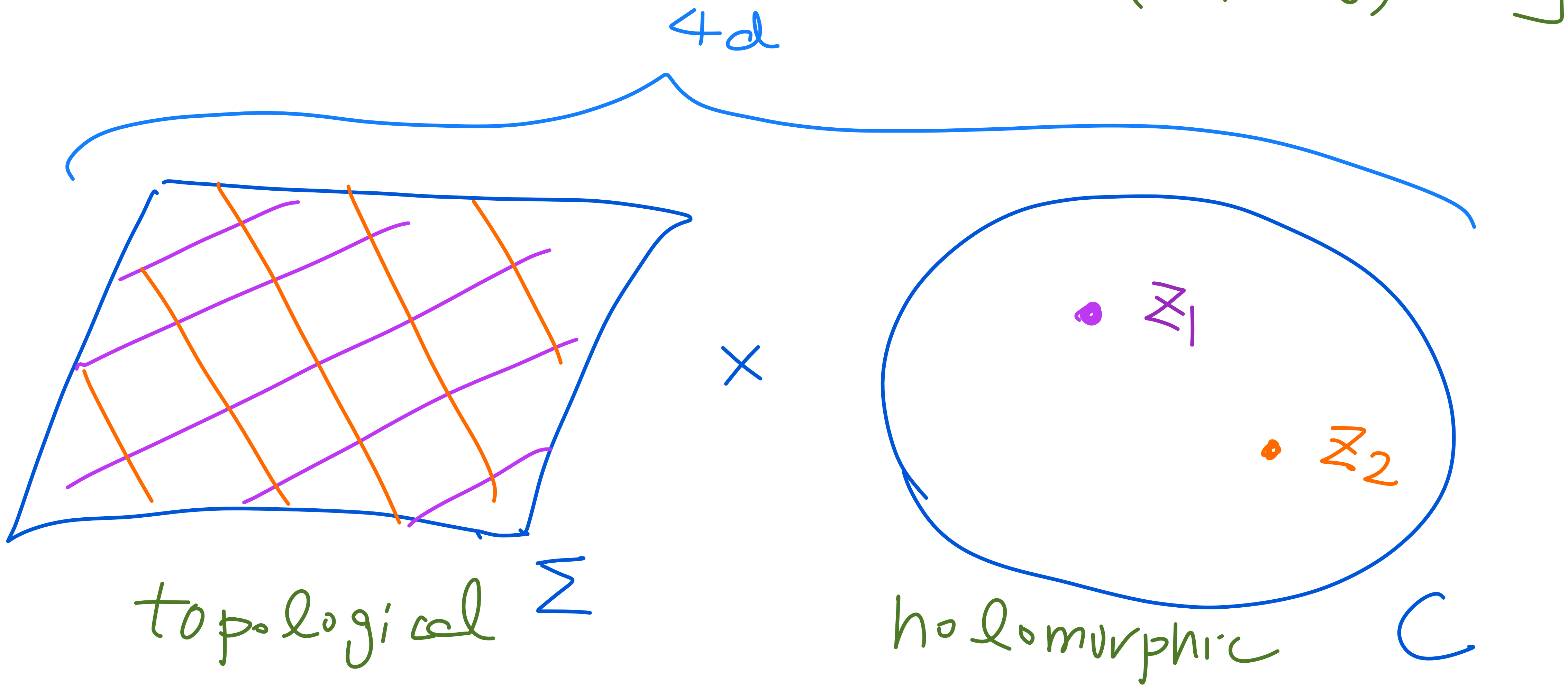
The problem simplifies dramatically

when we go to four dimensions

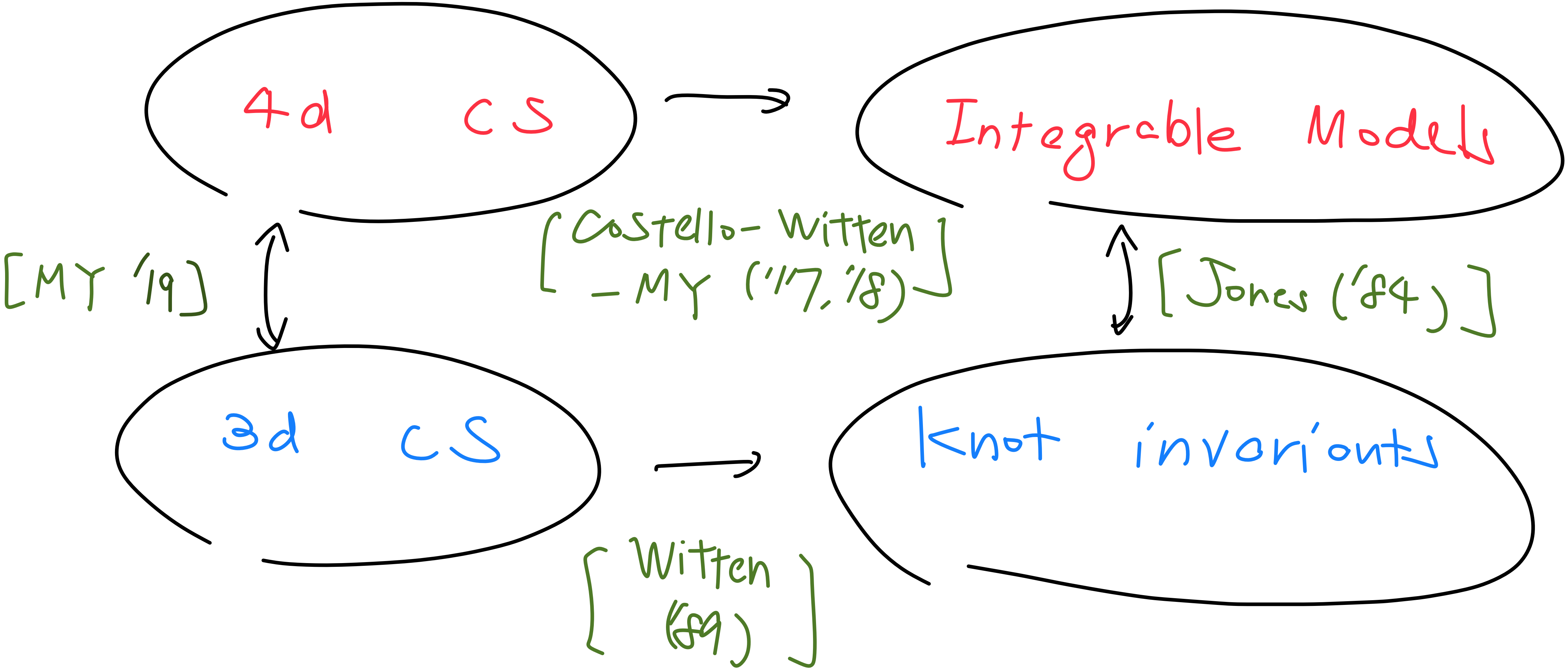


The relevant theory is the

4d Chern-Simons theory [Costello-Witten-MY ('17, '18)]



This gives conceptual explanation of integrable models

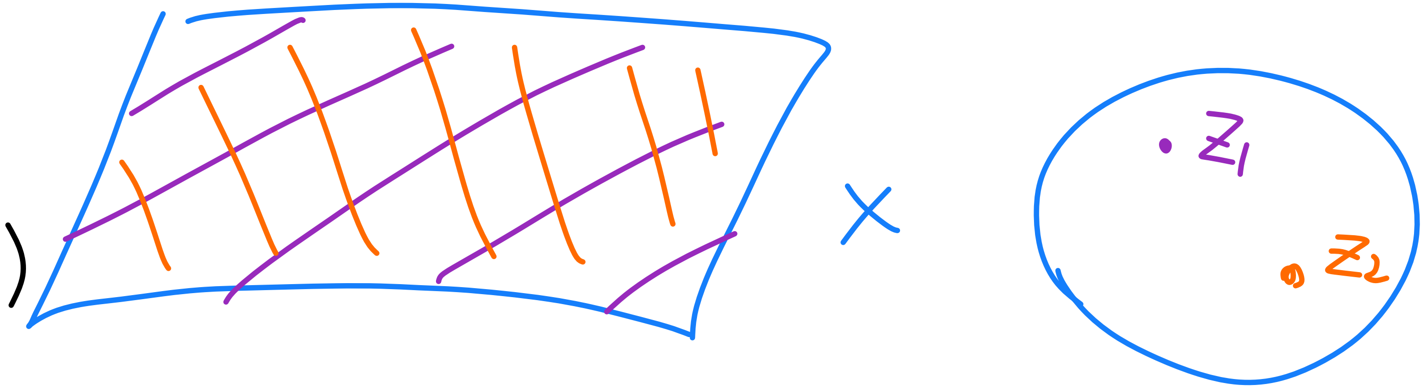


We can take the limit "defect-wise"

[Costello-Witten-MY ('17, '18)]

quantum circuit

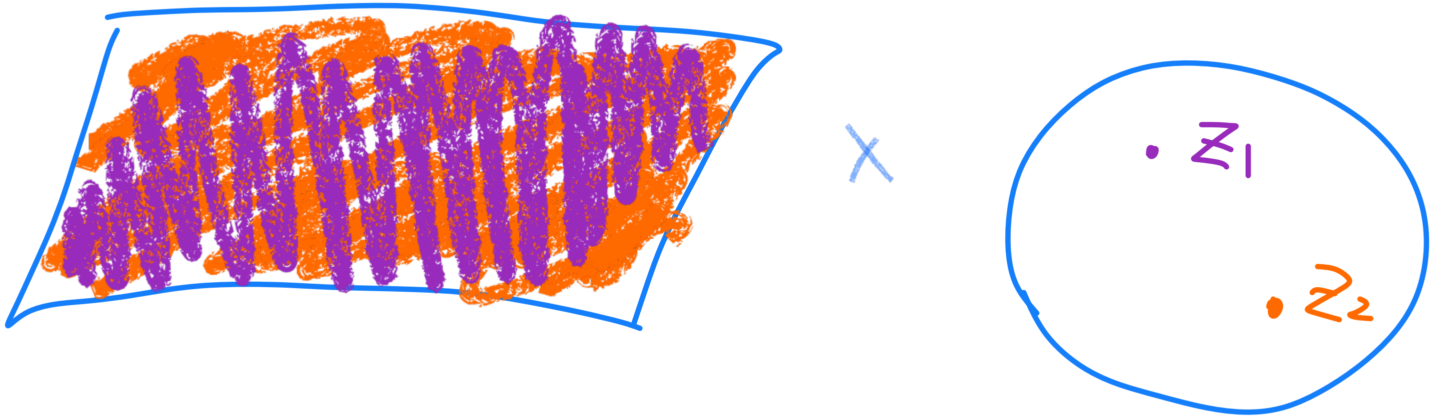
(4d + 1d defect)



[Ashwinkumar-Sakamoto-MY ('23)]

QFT

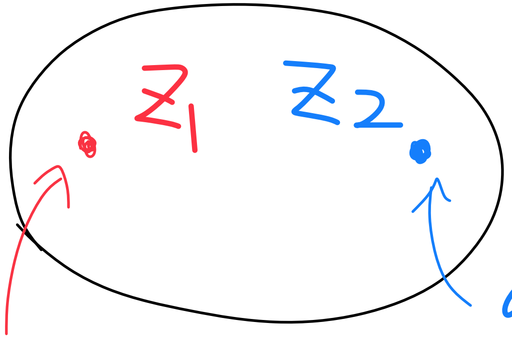
(4d + 2d defect)



[Costello-MY ('19)]

e.g.)

[Costello–MY('19)]

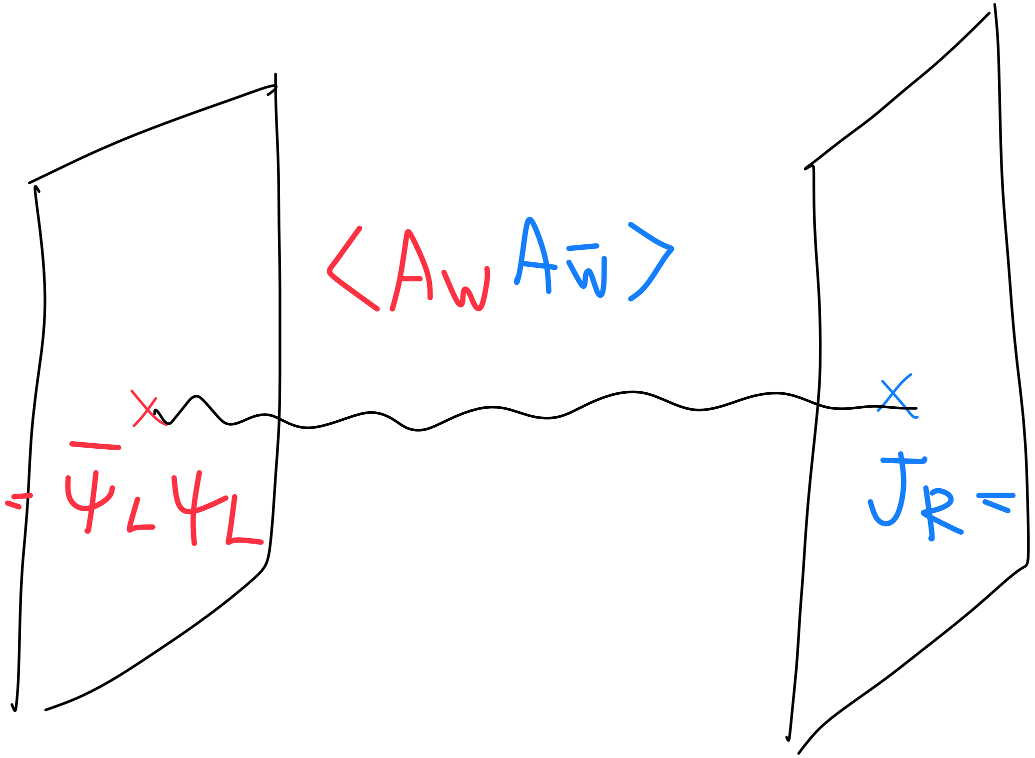


chiral fermion

$$\mathcal{L}_1 = \bar{\psi}_L (\not{\partial} + \not{A}_w) \psi_L$$

anti-chiral fermion

$$\mathcal{L}_2 = \bar{\psi}_R (\not{\partial} + \not{A}_{\bar{w}}) \psi_R$$



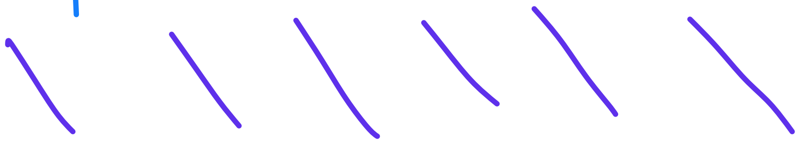
$$\mathcal{L}_1 + \mathcal{L}_2 + \frac{1}{z_1 - z_2} \underbrace{(\bar{\psi}_L \psi_L)(\bar{\psi}_R \psi_R)}_{\text{4-Fermi}}$$

chiral defect

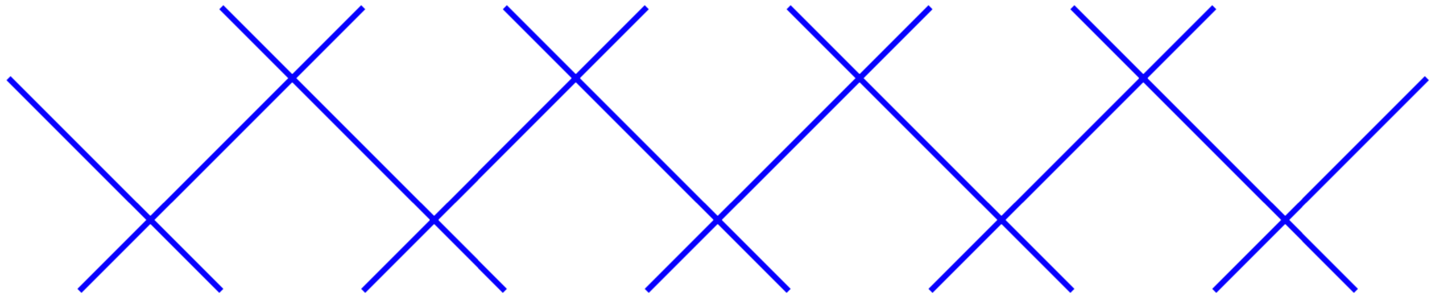
$$S=\int d^2\sigma\, \bar{\Psi}\,(\not{\partial}_w+\not{A}_w)\,\Psi \rightsquigarrow S=\sum_i \int d\sigma^-\, \bar{\Psi}_i\,(\not{\partial}_w+\not{A}_w)\,\Psi_i$$

anti-chiral defect

$$S=\int d^2\sigma\, \bar{\Psi}\,(\not{\partial}_{\bar{w}}+A_{\bar{w}})\,\Psi \rightsquigarrow S=\sum_i \int d\sigma^+\, \bar{\Psi}_i\,(\not{\partial}_{\bar{w}}+\not{A}_{\bar{w}})\,\Psi_i$$



when combined, light-cone lattice of 1d defects



$\downarrow$ [Borel-Weil-Bott]

quantum circuit

This construction gives

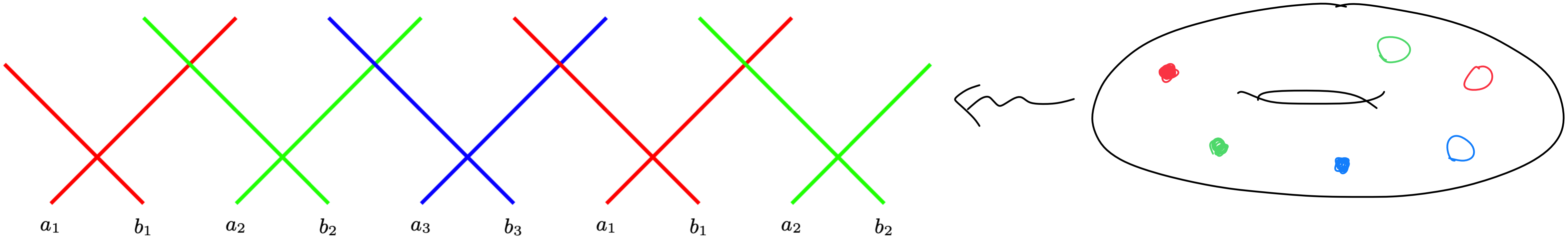
a zoo of new integrable QFTs

[Costello – MY ('19)]

& their quantum-circuit realizations

[Ashwinkumar – Sakamoto – MY ('23)]

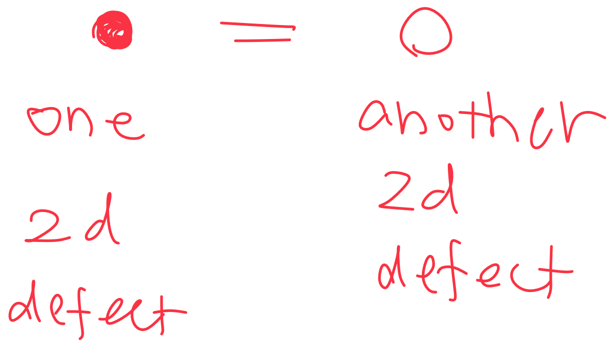
We can discuss many defects of different types

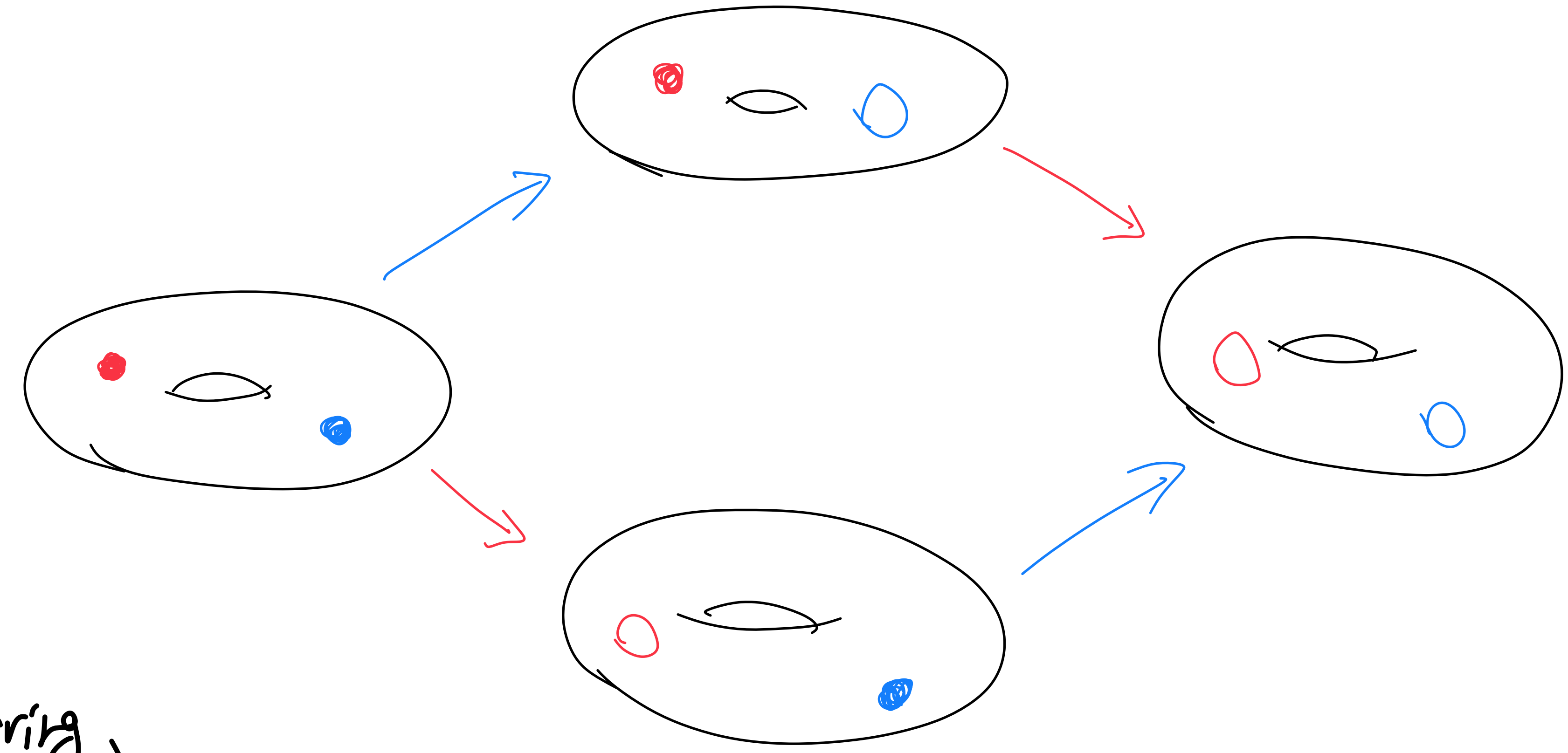


giving rise to coupling between QFTs

$$\mathcal{L} = \underbrace{\sum \mathcal{L}_i}_{\text{separately integrable}} + \underbrace{\sum \mathcal{L}_{ij}}_{\text{coupling}}$$

We can disuss dualities among defects (e.g. bosonization)





"duality web"

(e.g. massless Thirring

$\updownarrow$

coupled WZW)

The 4d CS framework

has recently been extended to

time-dependent integrability

[Komatsu - Sakamoto - Wallberg - MY
I: ('26), II: (to appear)]

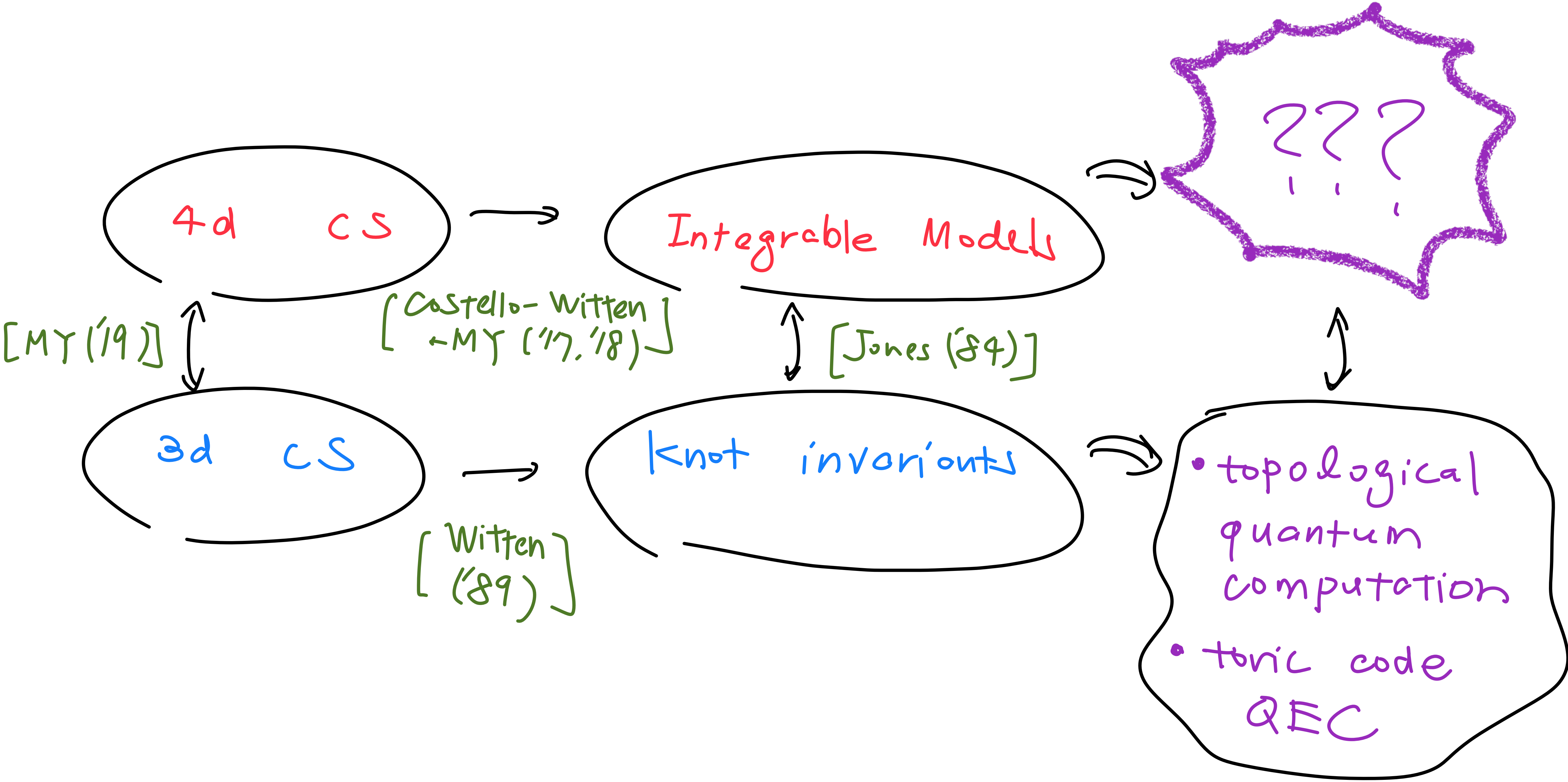
Solvable circuits for non-equilibrium dynamics!?

Summary

- Integrable Models: ideal playground in quantum simulations

- Quantum Circuits for Quantum Field Theories

  systematic construction via 4d CS



4d CS
Integrable Models
???!!!
[MY ('19)]
[Costello-Witten +MY ('17, '18)]
[Jones ('84)]
3d CS
Knot invariants
[Witten ('89)]
• topological quantum computation
• toric code QEC