GPU implementation of tensor network states

CERN openlab Summer Student Programme Lightning talks

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Introduction

Tensor Networks and the project

Tensor networks are a framework for efficiently simulating highly-entangled quantum systems by representing them as chains of tensors.

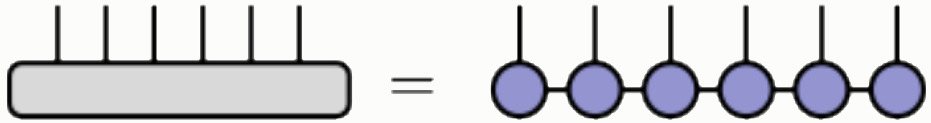


Fig. 1. The full Ising Model Hamiltonian for a 6-site system represented as a matrix product operator

Aim of the project:

- Utilise GPUs to efficiently implement parallel tensor contractions, enabling scalable simulations with large bond dimensions χ.

The Ising Model

The physics being simulated for verification

The simplest 1+1D system with a phase transition (at $g_z = 1$) we simulate to verify our solver with Hamiltonian:

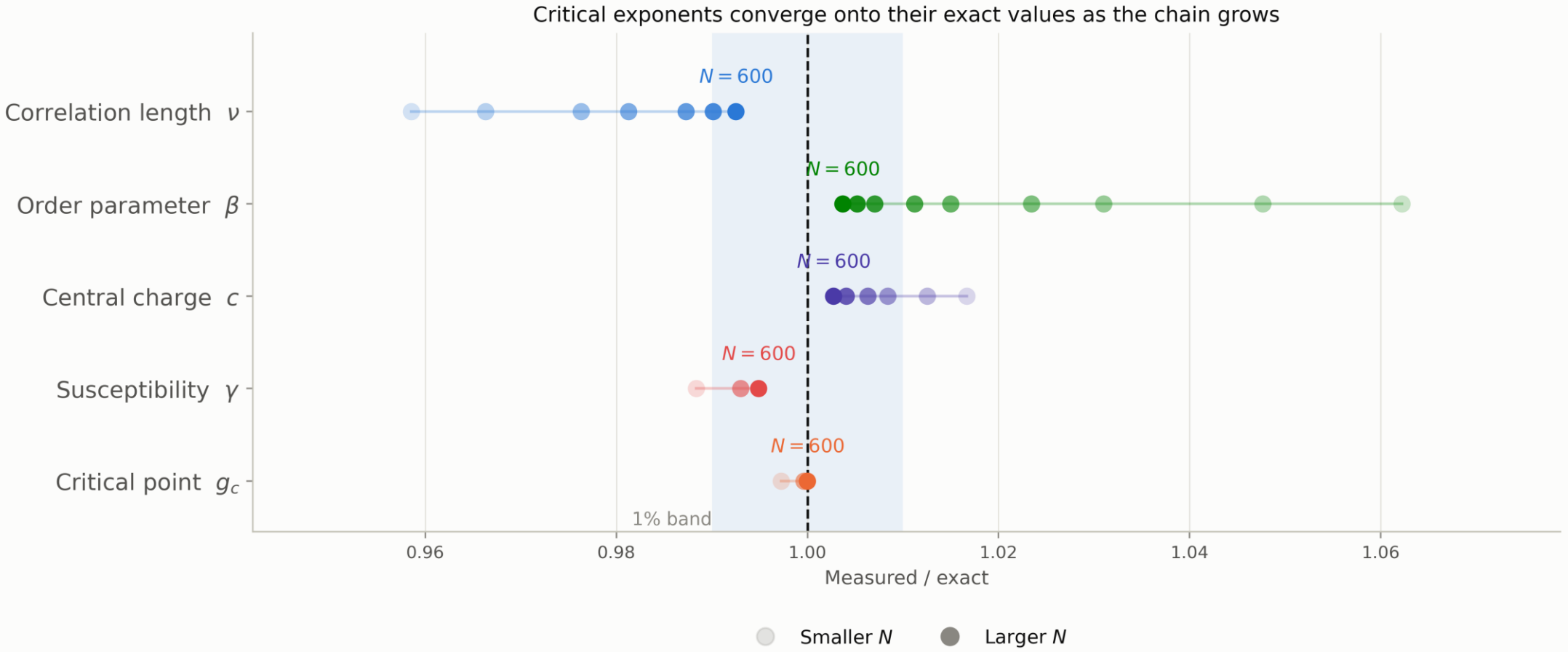
$$H = -\sum_i \sigma_i^x \sigma_{i+1}^x - g_z \sum_i \sigma_i^z$$

It represents atoms on a lattice with spins coupling along the x axis and a magnetic field in the transverse z direction.

- For an infinitely long chain, it exhibits analytically calculable scaling exponents which we recover by finite-size scaling of the chain.

The Ising Model

The critical exponents



Benchmarking

Previous Masters' thesis and external libraries

Building a GPU-native library in Python which was benchmarked against previously built solvers and existing libraries.

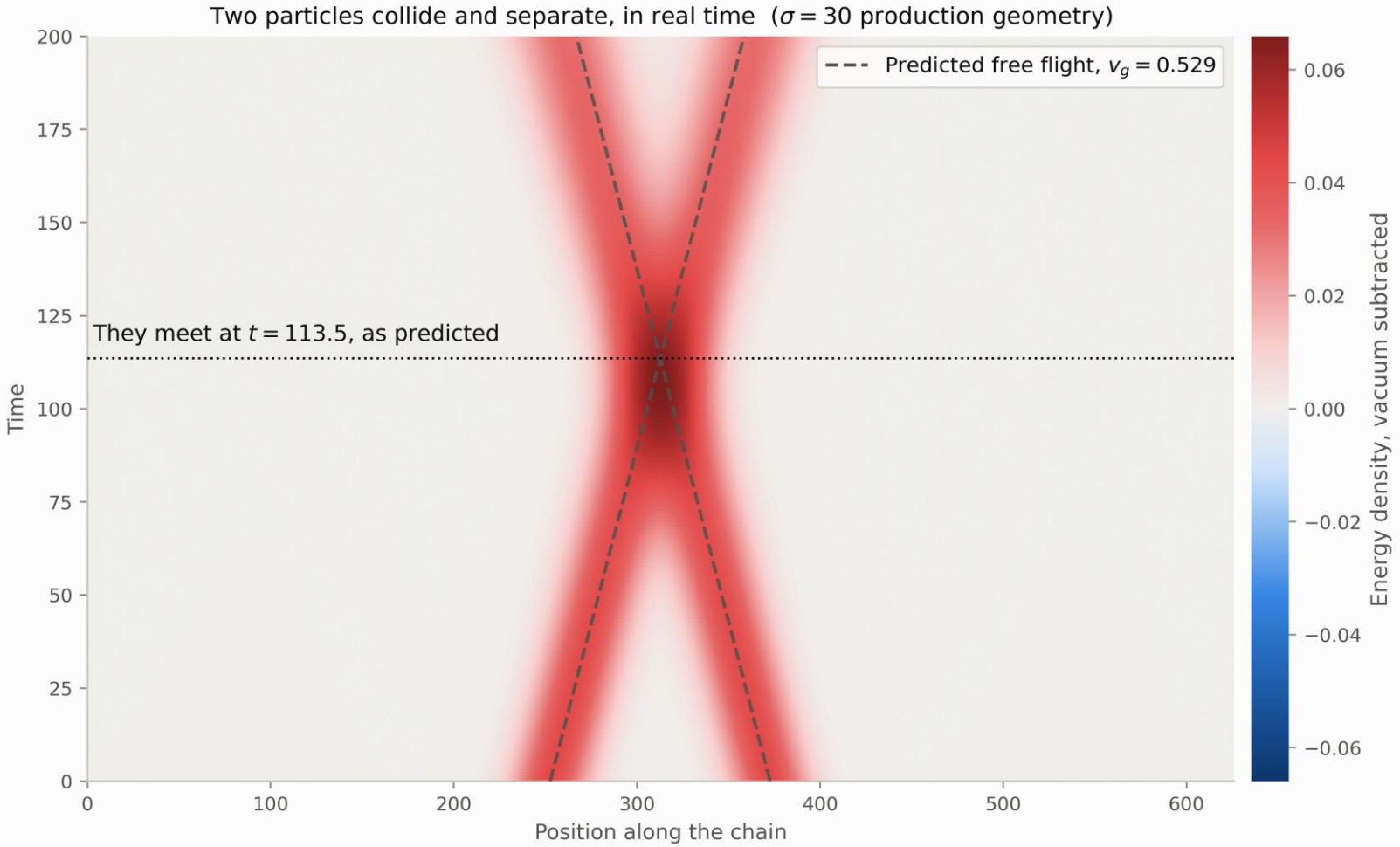
- Upto $7.20\times$ faster than the predecessor thesis code at matched accuracy at bond dimension $\chi = 512$.
- Speedup achieved by eliminating CPU-GPU transfers via an on-GPU Lanczos solver.
- $\geq 6.4\times$ faster than Cytnx (on CPU), an independent published library; both codes unmodified on an identical Hamiltonian.

Ising Field Theory

Critical Limit of the Ising model, with a longitudinal field h_x (Jha et al., 2025)

At criticality ($g = 1$), an arbitrarily small h_x makes the theory massive: it contains 8 stable particles whose mass ratios are fixed by the E_8 Lie algebra.

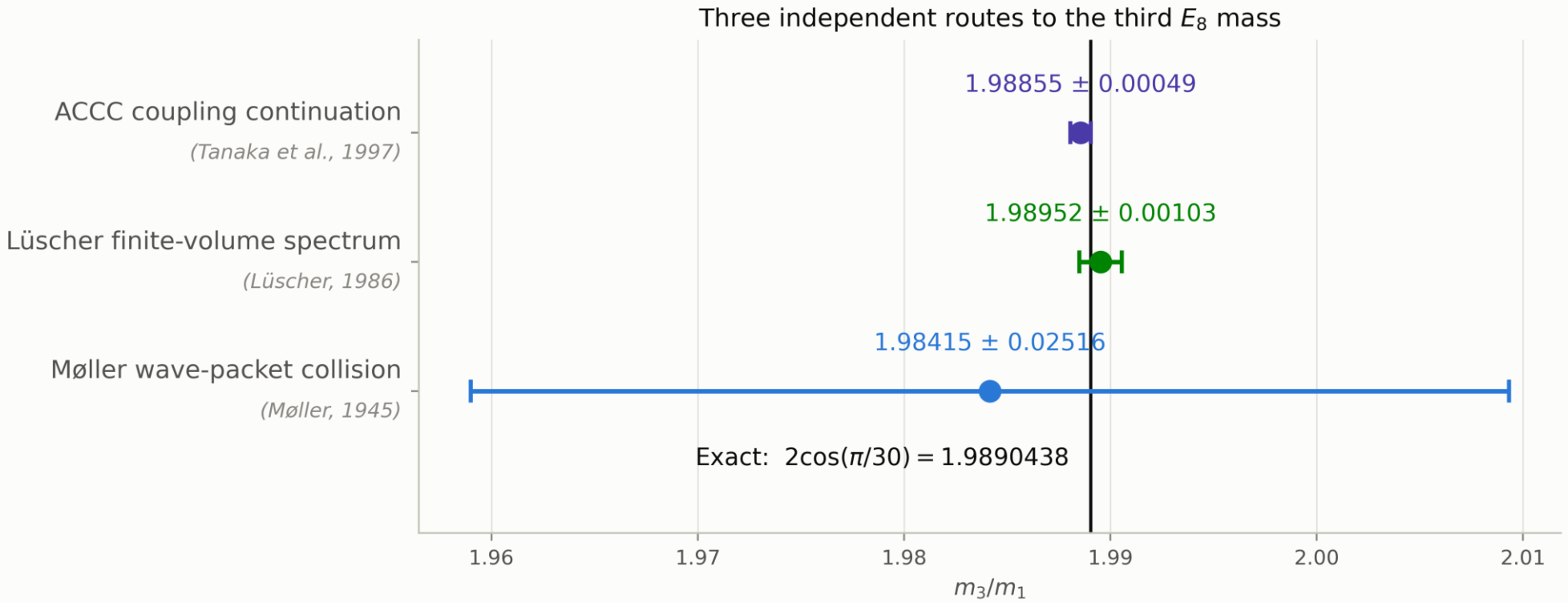
These states can undergo collisions which we simulate (shown here).



Ising Field Theory

Going beyond the paper: estimating m_3/m_1 from data

Borrowed methods from nuclear physics and lattice QCD to estimate m_3 from simulations – something the paper reports as unresolvable with their construction.



Lüscher and Møller routes invert the E_8 S-matrix of Delfino (2004); exact spectrum from Zamolodchikov (1989)

Outlook

Work to be done

To push the research frontier, there are several directions that we need to work towards:

- Doing simulations of high-energy mesons – all current simulations target low-energy scatterings.
- Extending the simulation suite to also be capable of efficiently simulating planar entangled systems, moving away from single dimension chains.

Thank you!

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