

Discovering Quantum Phenomena with Interpretable Machine Learning

from raw measurements to order parameters

By Paulin de
Schoulepnikoff,
Hendrik P. Nautrup,
Hans J. Briegel and
Gorka Muñoz-Gil

Challenge

Modern quantum experiments produce large, **complex datasets** in which the physically relevant structures are often hidden and difficult to access directly.

In addition, quantum measurements are intrinsically **stochastic**, making the analysis of raw experimental data challenging.

Approach

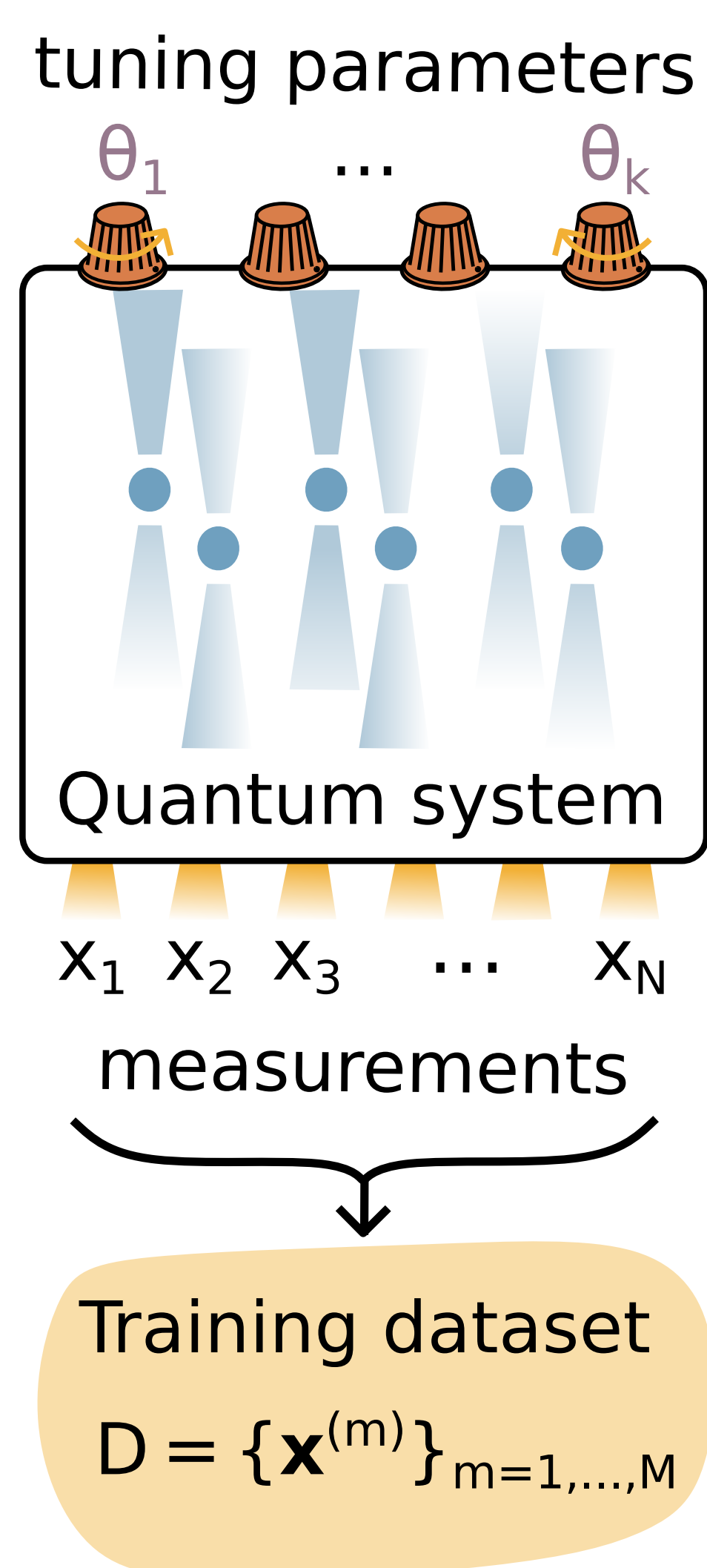
Interpretable Machine Learning provides powerful tools to uncover patterns and emergent structures within high-dimensional data.

This motivates the development of interpretable ML approaches capable of **learning directly from raw, single-shot quantum measurements**.

Pipeline

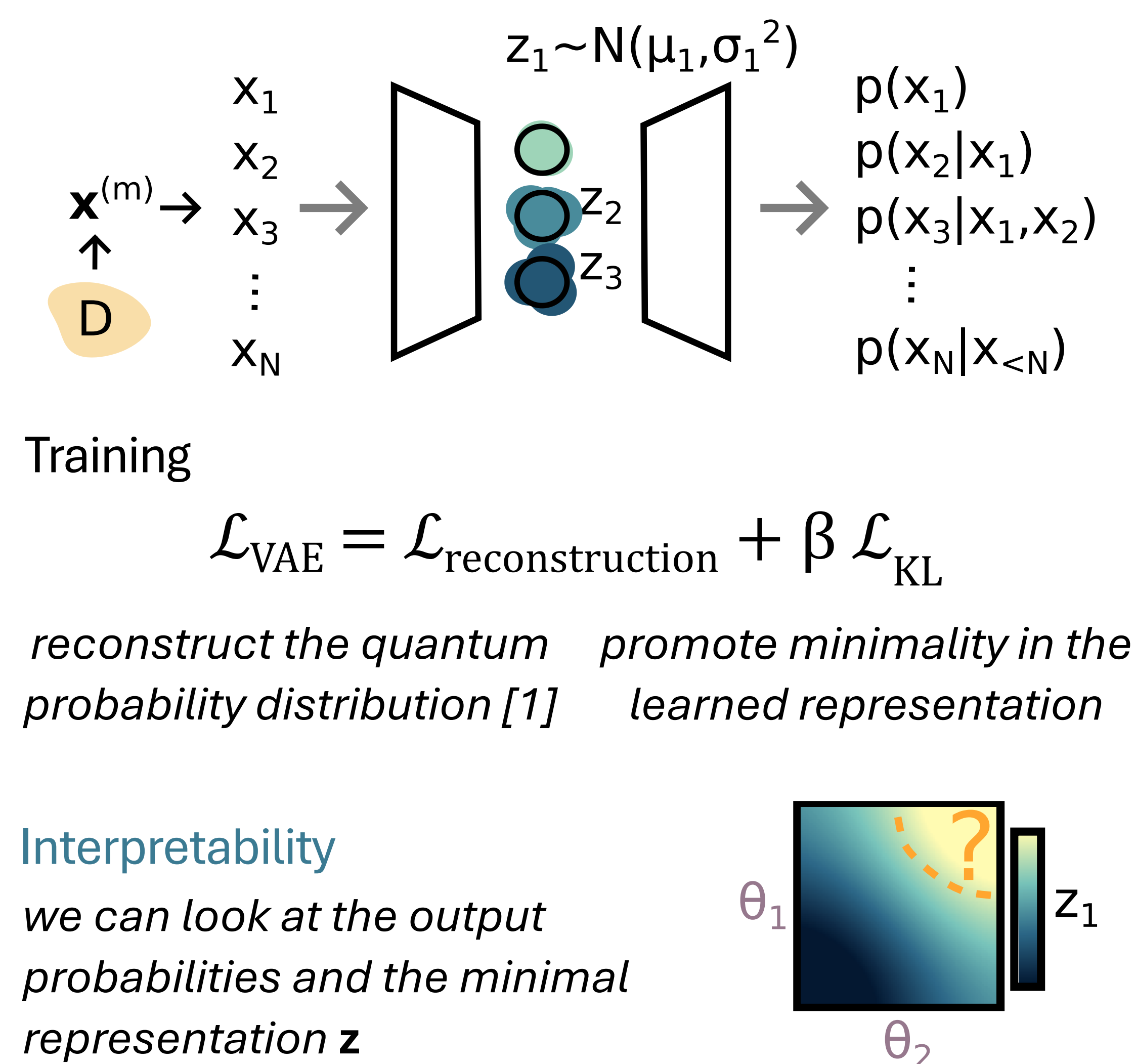
1. Train a variational autoencoder (VAE), adapted to handle quantum stochasticity, to **learn a representation of the parameter space** from raw single-shot data. This will reveal phases and unknown regimes.
2. Apply symbolic regression (SR) techniques to produce compact **analytical descriptors** that will help us to understand unknown phenomena.

0. Data Acquisition



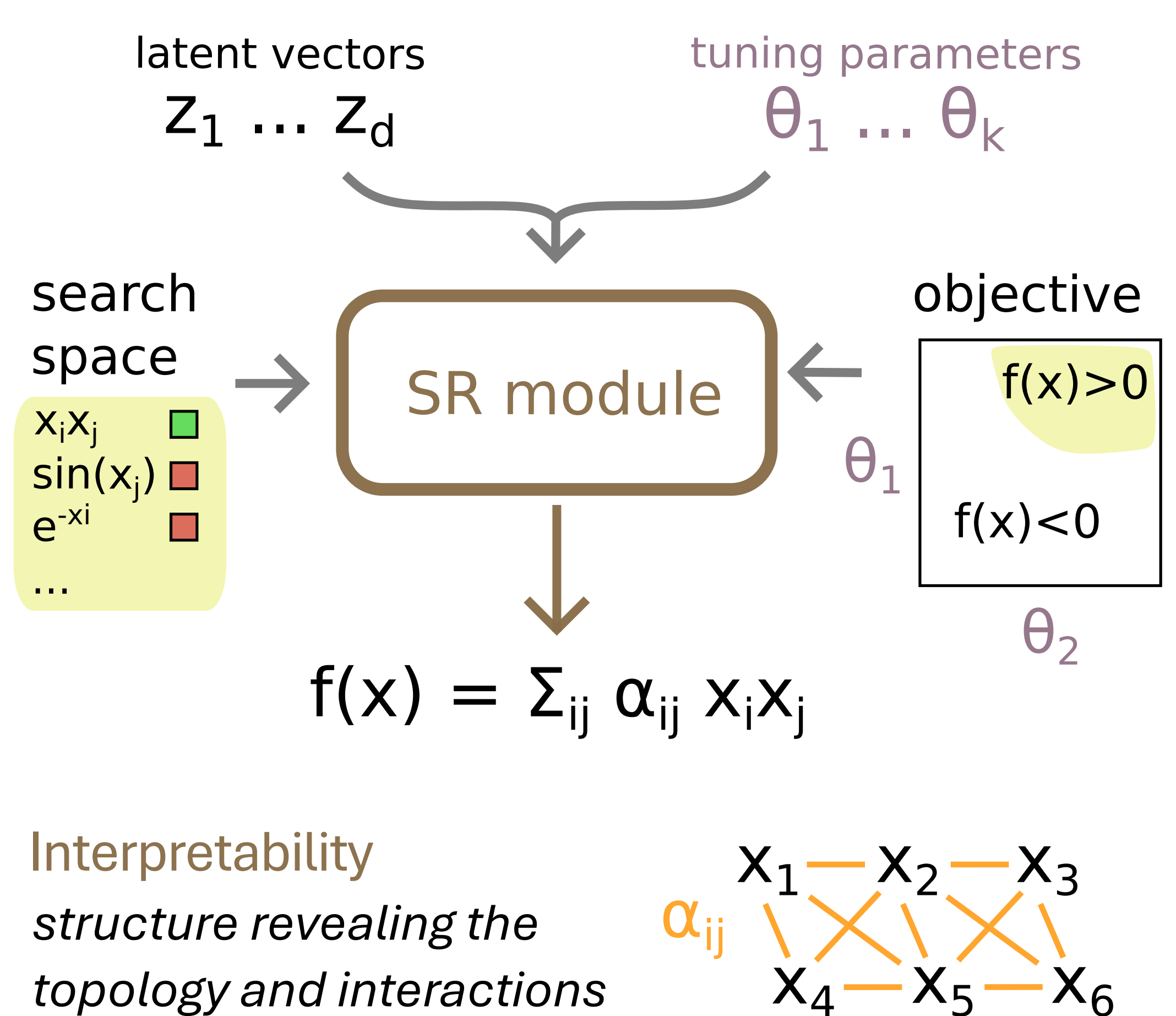
1. Parameter Space Representation

VAE architecture



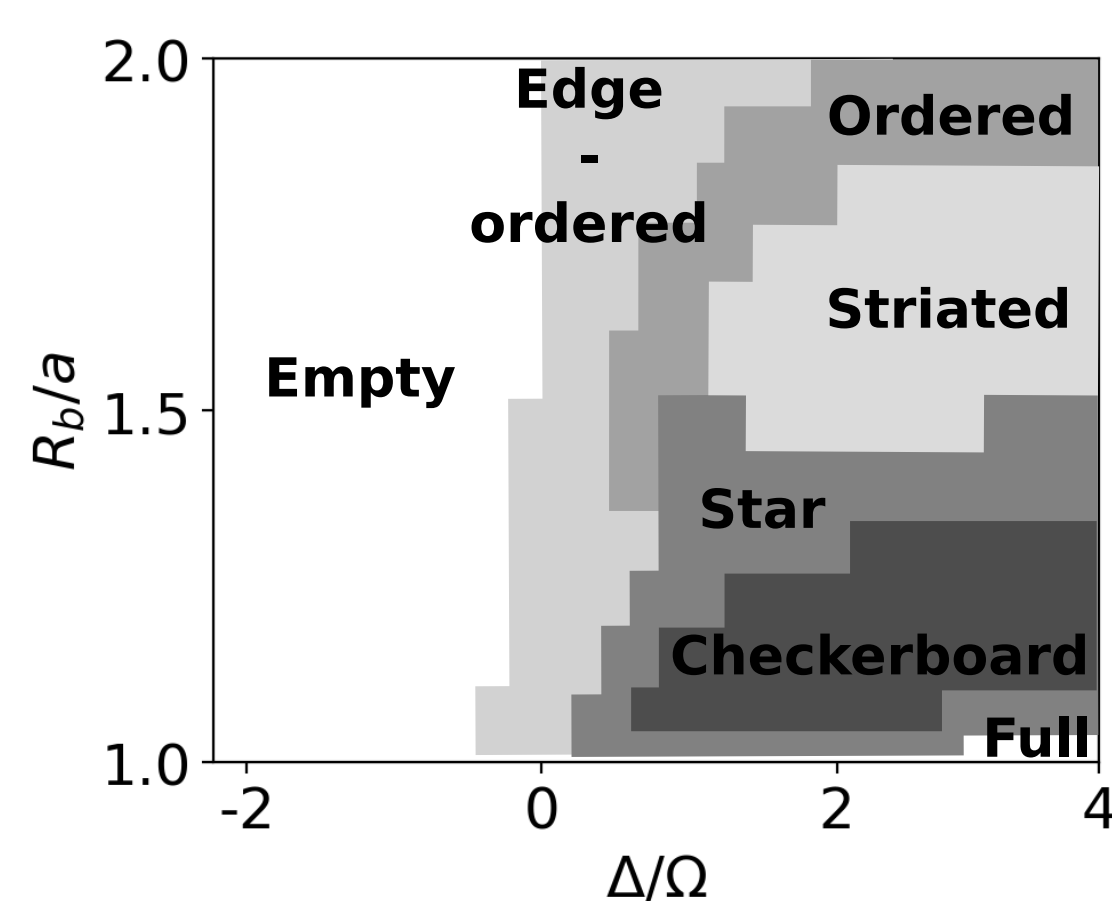
2. Symbolic Regression (SR)

Find a symbolic function that explains the cluster. It can act as a candidate order parameter.

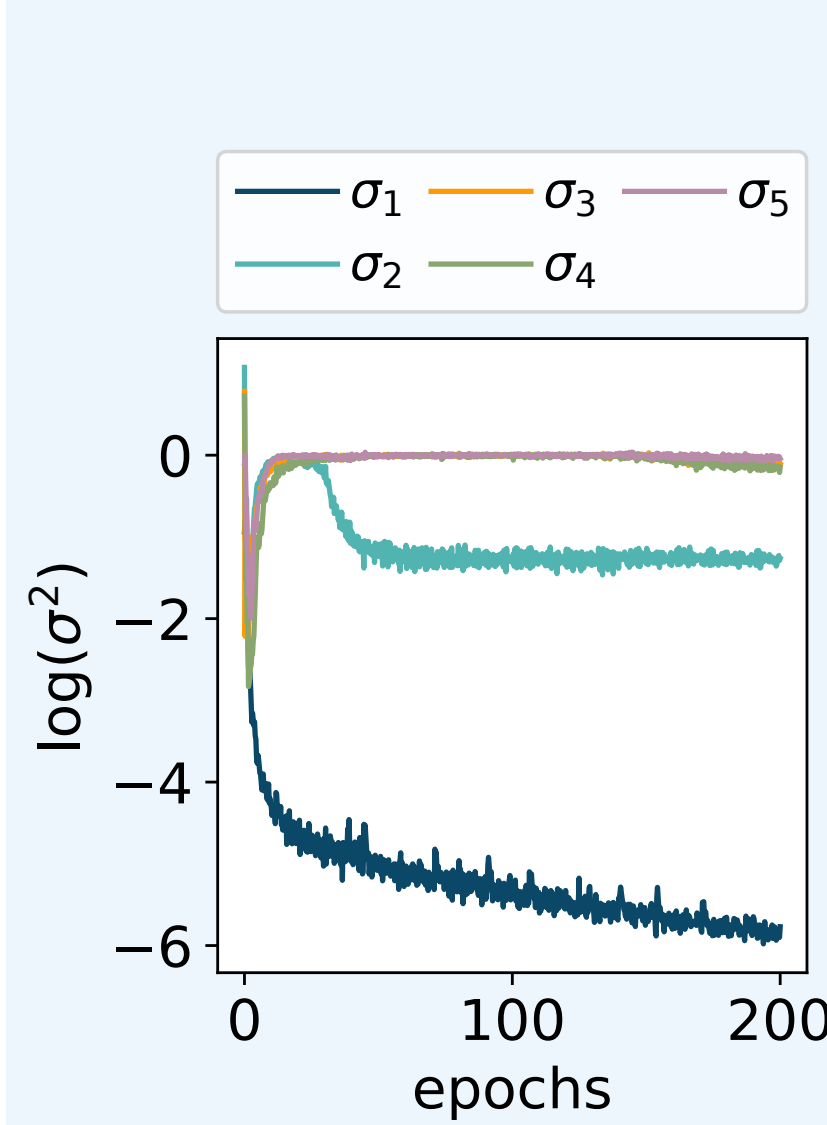


Rydberg atoms

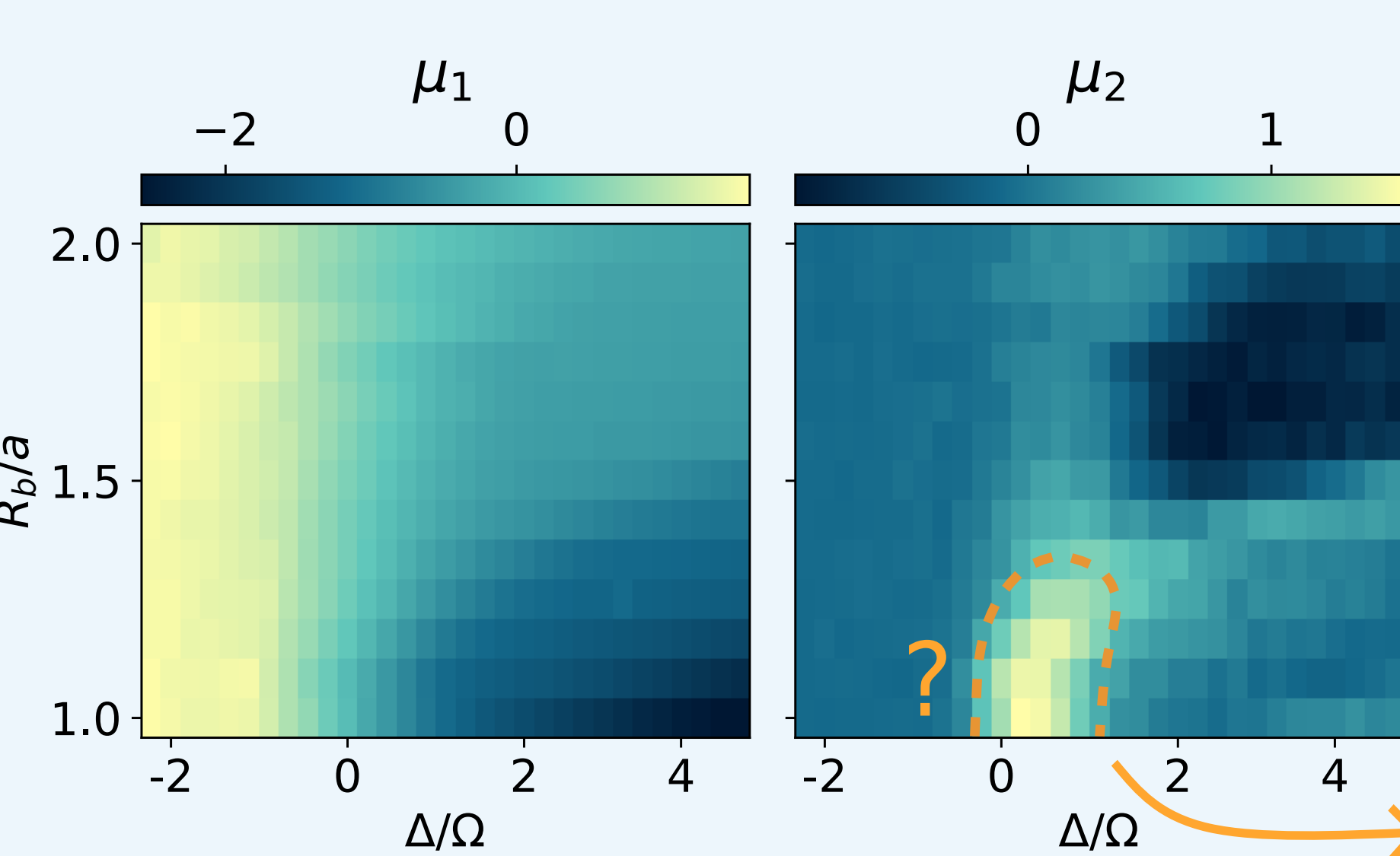
Phase diagram [2]



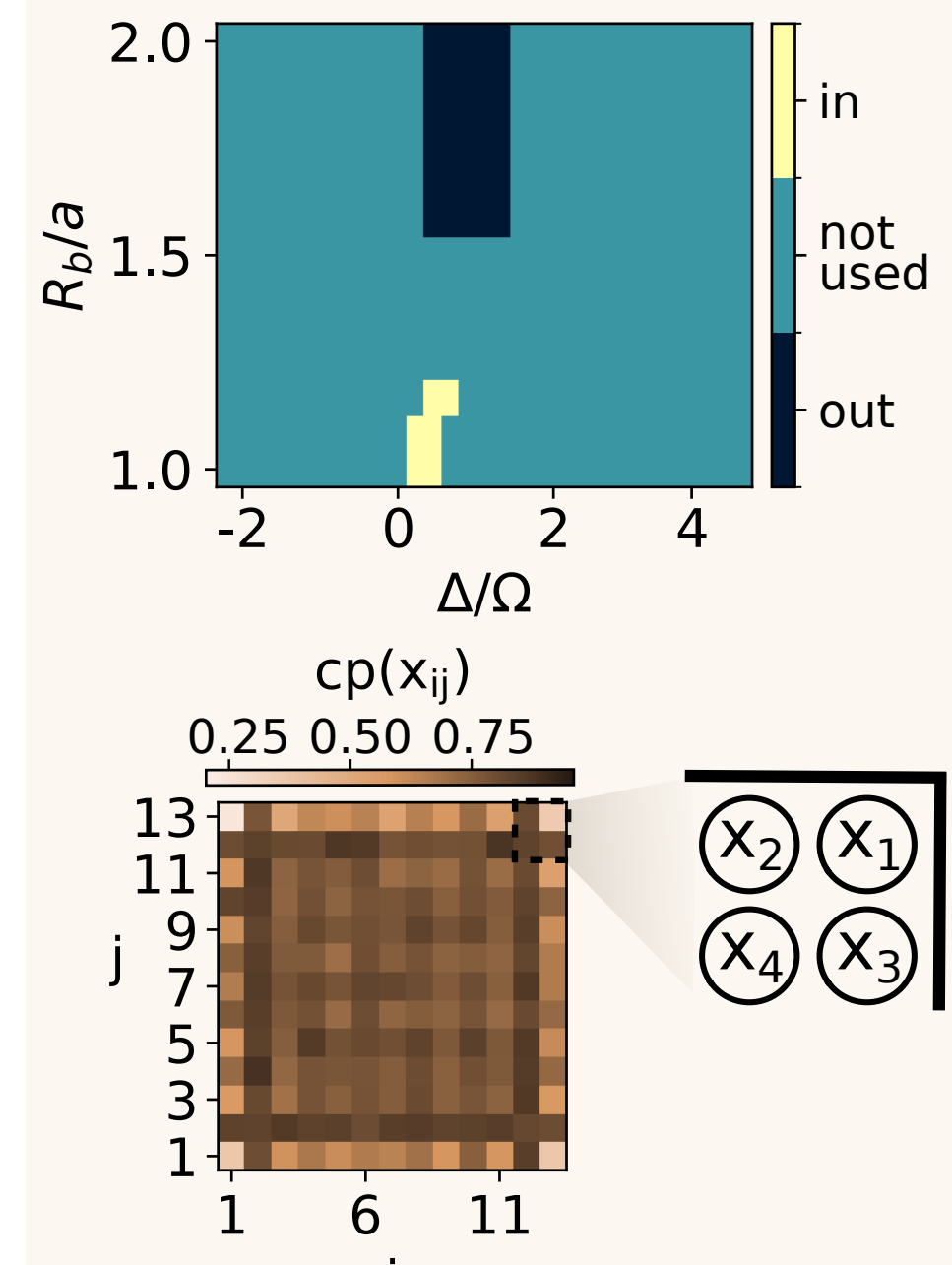
Training



Representation

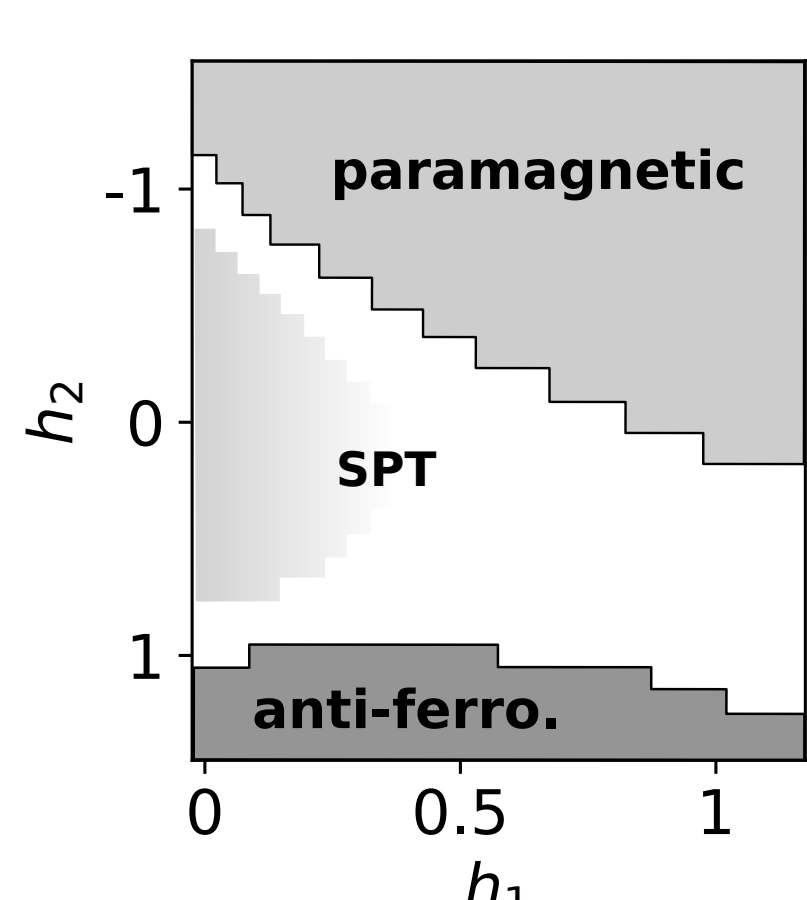


Symbolic Regression

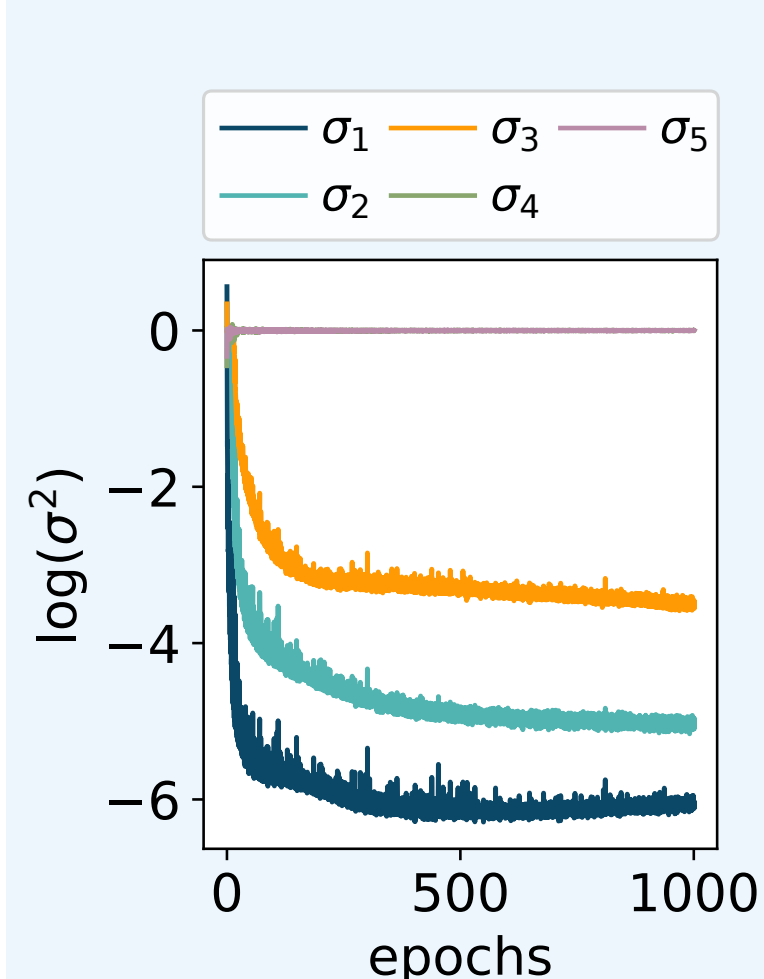


Cluster Ising

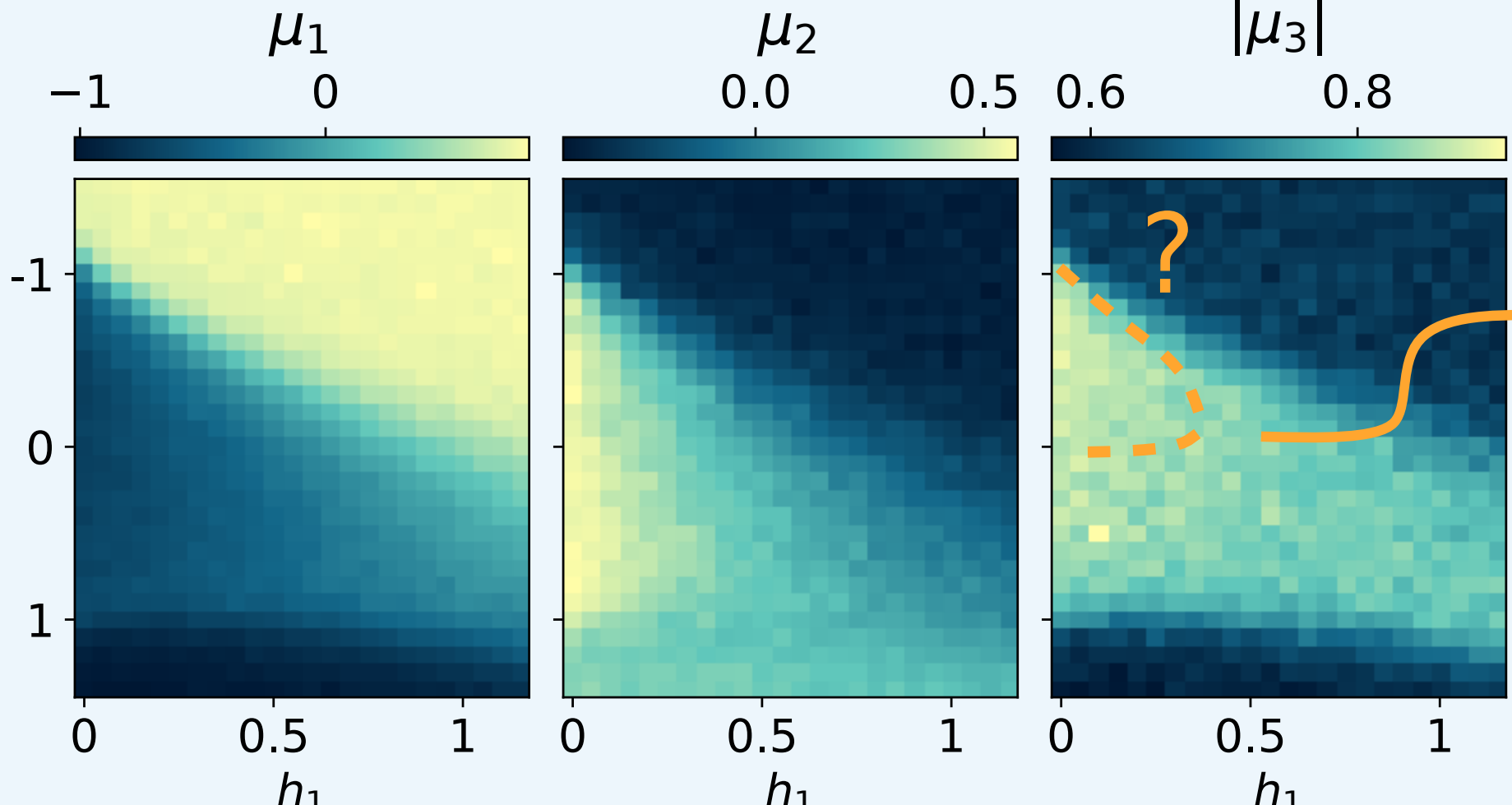
Phase diagram



Training



Representation

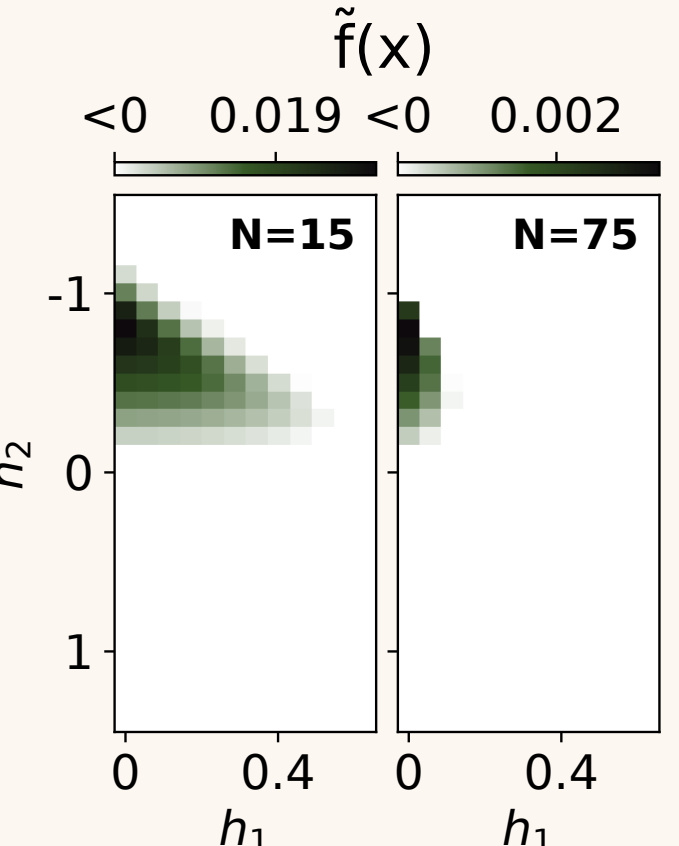


Symbolic Regression

Search space
 $f(x) = \sum_{ij} \alpha_{ij} x_i x_j$ (x-basis only)

Result
 $f(x) = \sum_{i,j>1} [-0.20 + \frac{0.07}{r_{ij}-0.95}] x_i x_j$
revealing short-range alignment and long-range anti-alignment.

Scaling analysis



Takeaway

Probabilistic VAEs + symbolic methods = an interpretable, efficient, broadly applicable framework for exploring and discovering new phases from diverse quantum datasets.

Outlook

- Explore more exotic regimes.
- Artificial agent performing **adaptive measurements**.
- Data coming from **quantum evolutions**:
 - Interpretable modeling of the dynamics
 - Dynamical phase space representation

Preprint

arXiv:2604.16015



Library



[1] P. de Schoulepnikoff, et al., PRA 112, 062423 (2025).
 [2] C. Miles et al., PRR 5, 013026 (2023).
 [3] Ebadi et al., Nature 595, 227 (2021).