

Integrating Neural Networks and Quantum Simulators

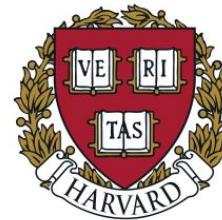
Evert van Nieuwenburg

Institute for Quantum Information and Matter

California Institute of Technology

arXiv:1904.08441

The Team



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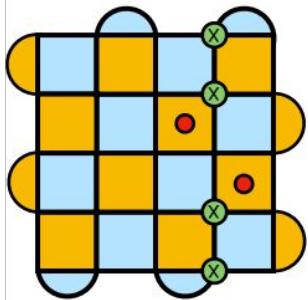


Vladan Vuletic

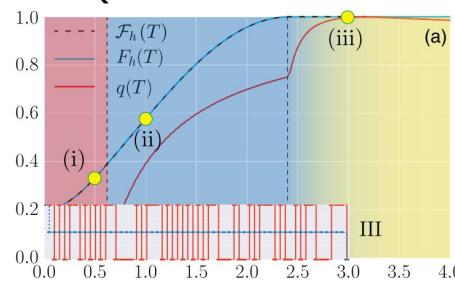
Context

Integrating machine learning & physics experiments

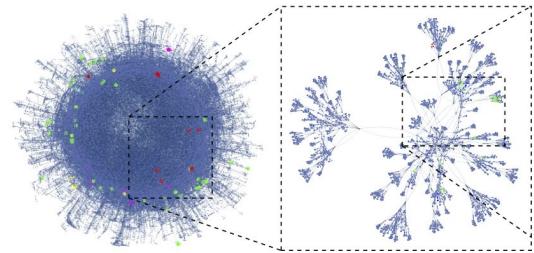
Quantum Error Correction



Quantum Control



Experimental Design
and Optimization

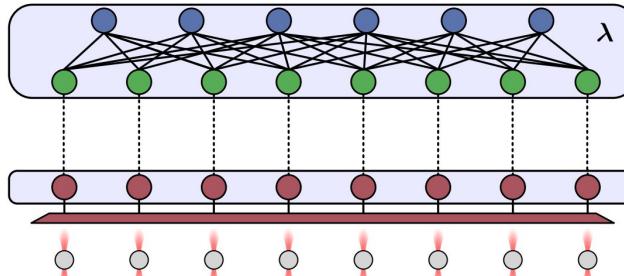


Phase Transitions



$\lambda_{\text{critical}}$

State Reconstruction



The setup

Experiment

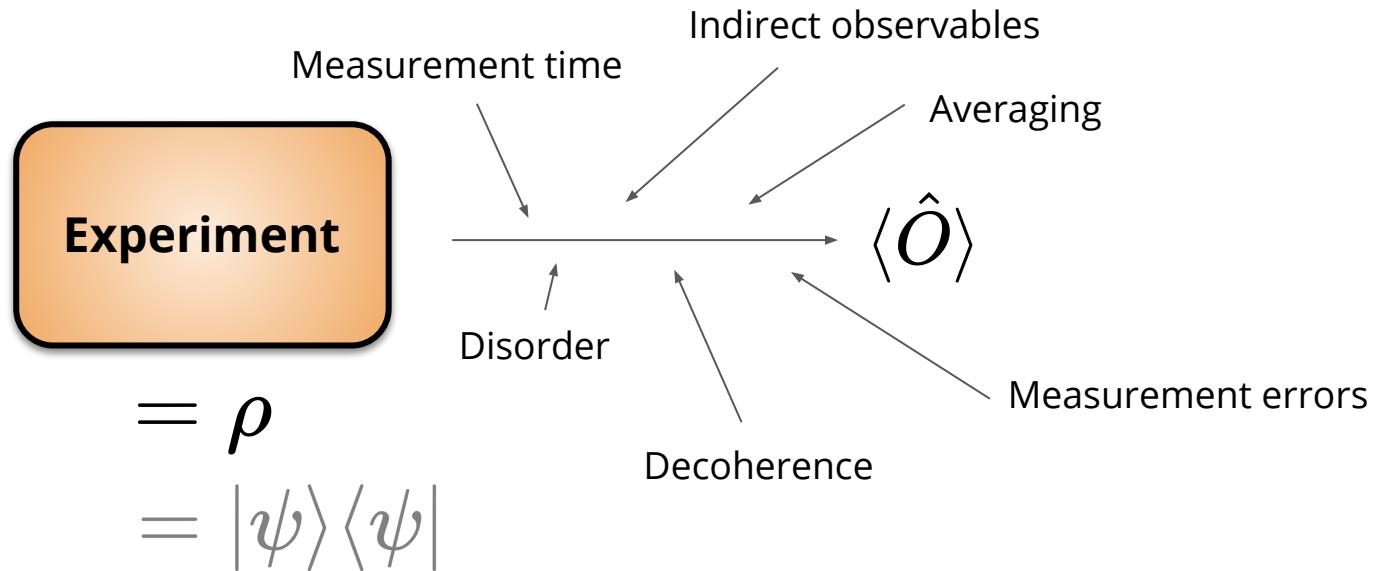
$$\longrightarrow \langle \hat{O} \rangle$$

$$= \rho$$

$$= \text{Tr} (\rho \hat{O})$$

$$= |\psi\rangle\langle\psi|$$

The setup



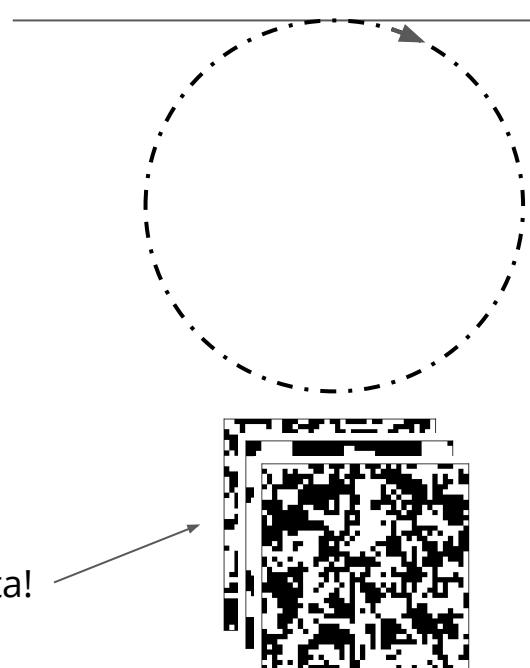
The setup

Experiment

$$= \rho$$

$$= |\psi\rangle\langle\psi|$$

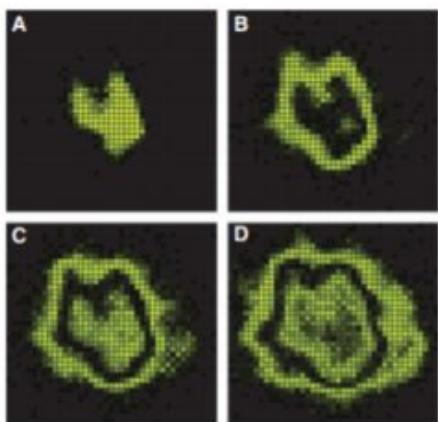
“Raw” data!



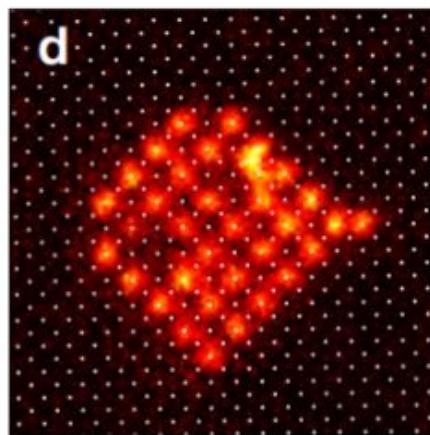
$\langle \hat{\sigma}_z \rangle$ snapshots

Projective measurements!

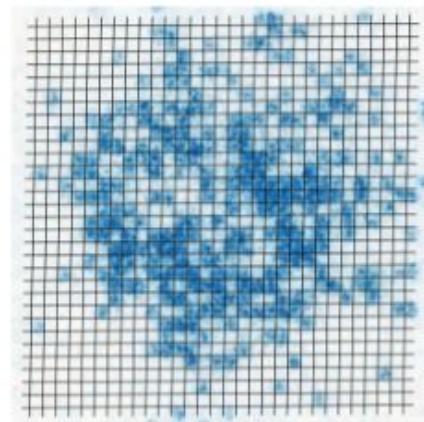
Snapshots



Bakr *et al*, Science (2010)

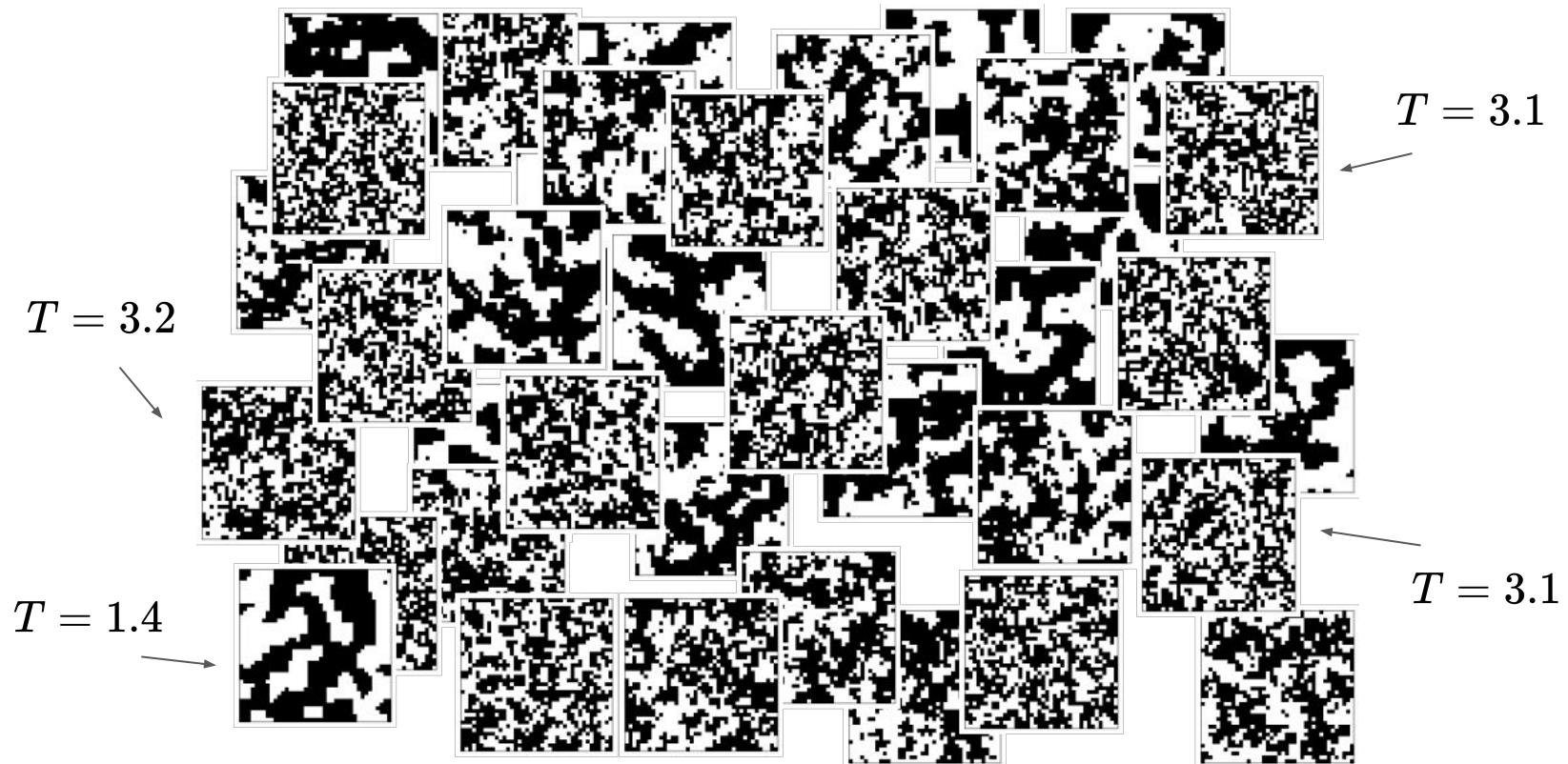


Weitenberg *et al*, Nature (2011)



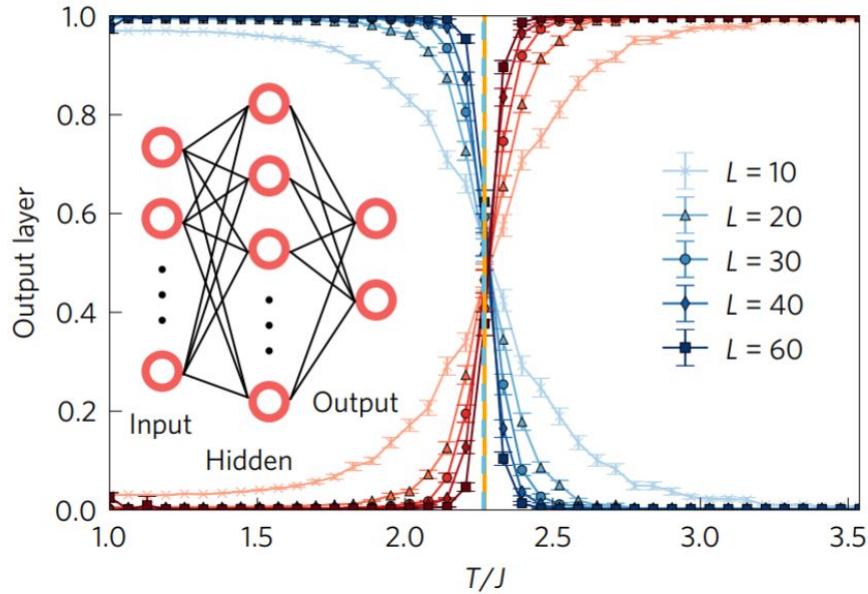
Grief *et al*, Science (2016)

Snapshots



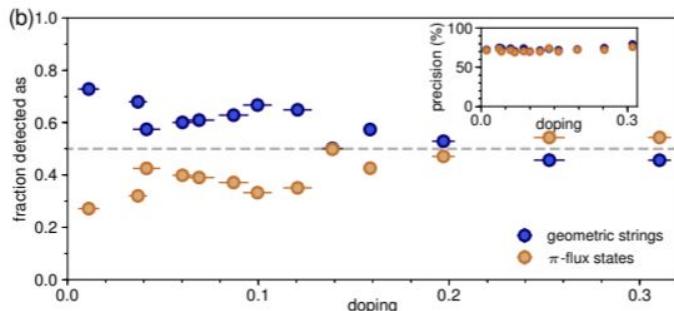
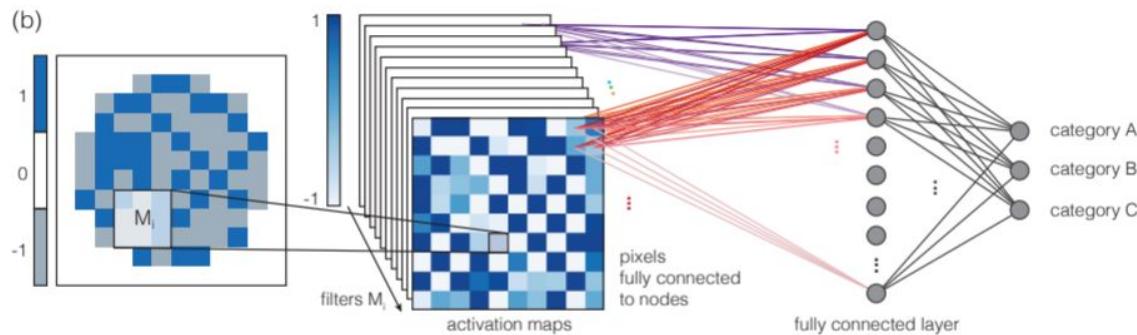
Learning phases

Supervised learning!

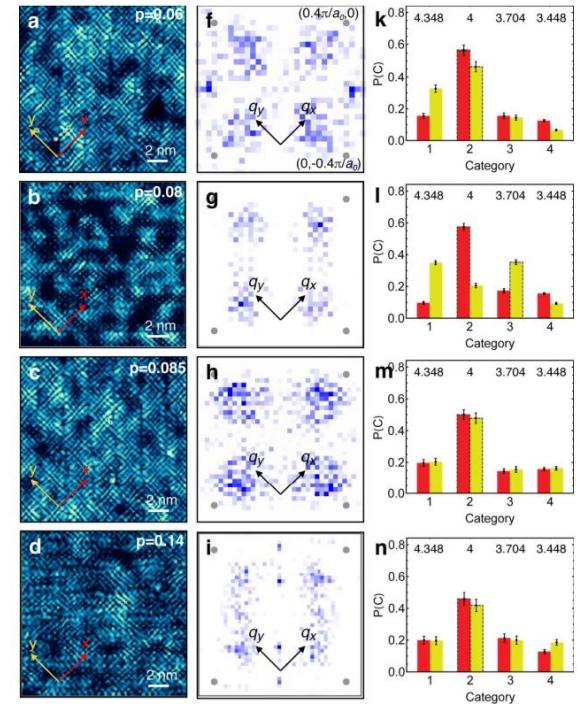


Carrasquilla and Melko - Nature Physics (2017)

Experiments



A. Bohrdt *et al*, arXiv:1811.12425

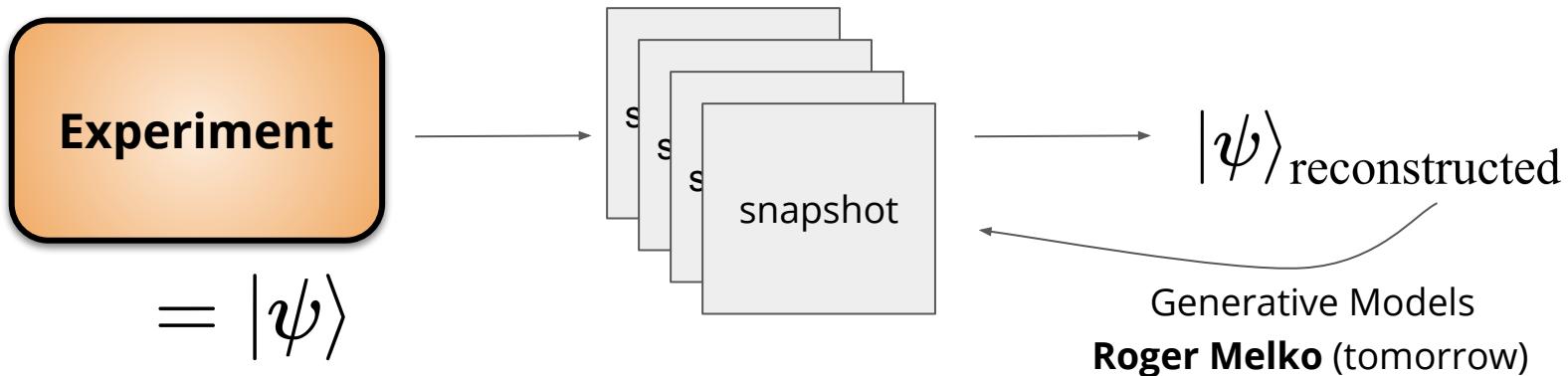


Yi Zhang *et al*, arXiv:1808.00479

Learning phases states



Learning states



Example

$$|\psi\rangle = \sum_{\sigma} \psi(\sigma) |\sigma\rangle \longrightarrow P(\sigma) = |\psi(\sigma)|^2$$

Experiment



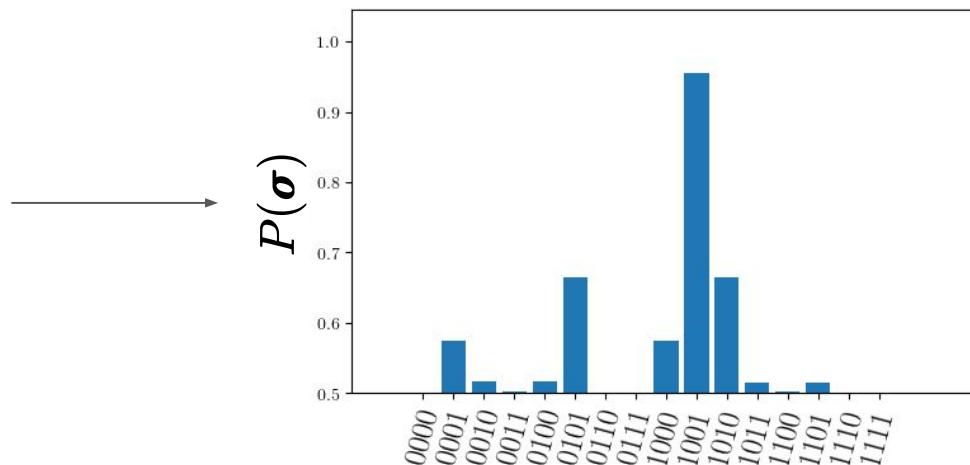
$$= |\psi\rangle$$

Example

$$|\psi\rangle = \sum_{\sigma} \psi(\sigma) |\sigma\rangle \longrightarrow P(\sigma) = |\psi(\sigma)|^2$$

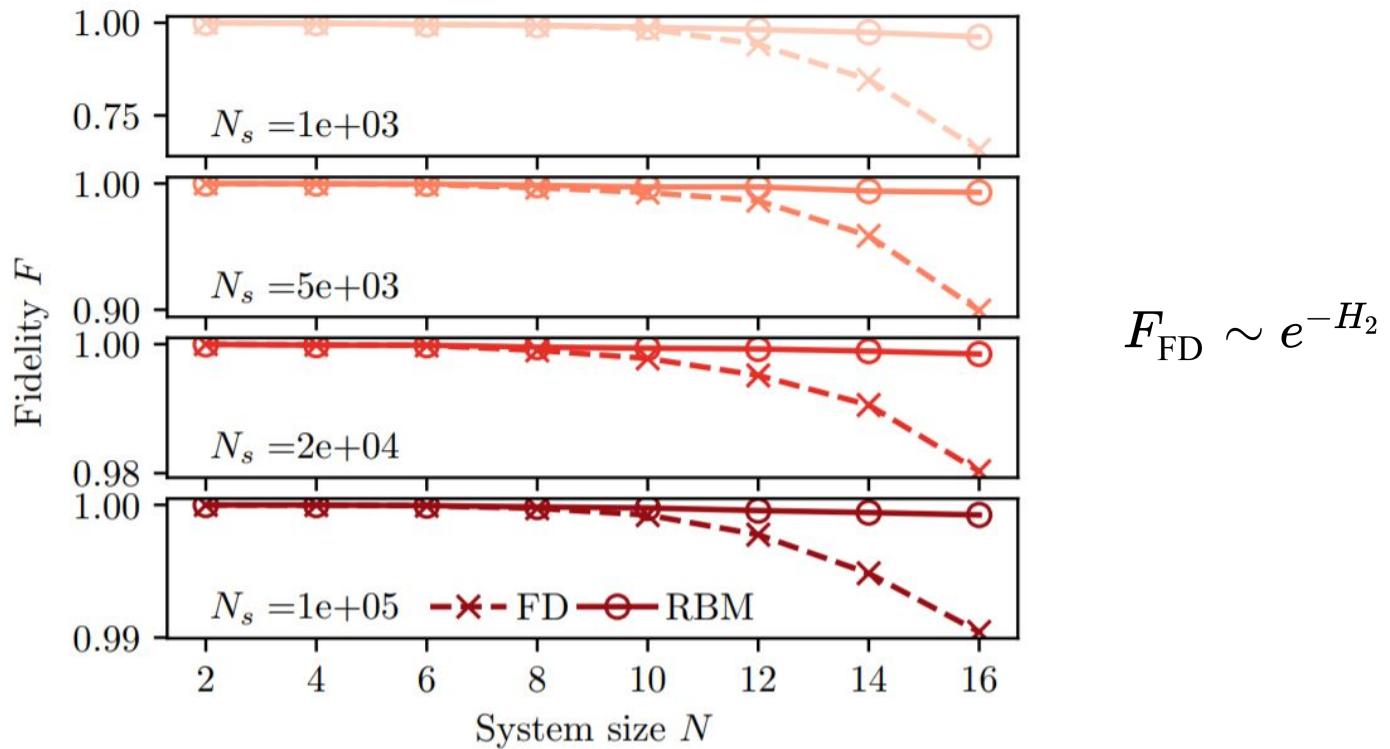
Experiment

$$= |\psi\rangle$$



$$|\psi\rangle = \sum_{\sigma} \sqrt{P(\sigma)} |\sigma\rangle$$

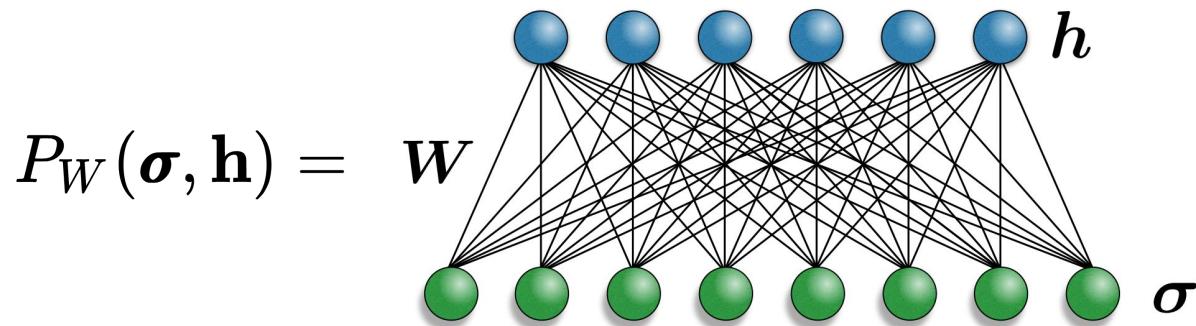
Why not use the histogram?



A better representation

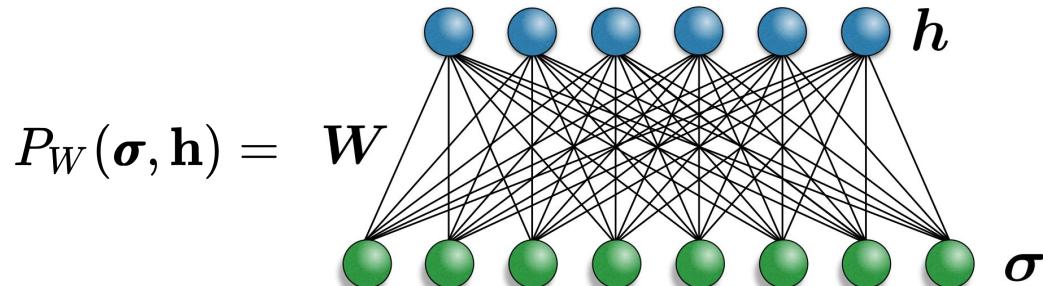
$$|\psi\rangle = \sum_{\sigma} \psi(\sigma) |\sigma\rangle \longrightarrow P(\sigma) = |\psi(\sigma)|^2$$

↳ Exponentially many



$$P_W(\sigma, h) = \frac{1}{Z} \exp(-E_W(\sigma, h))$$

Restricted Boltzmann Machine



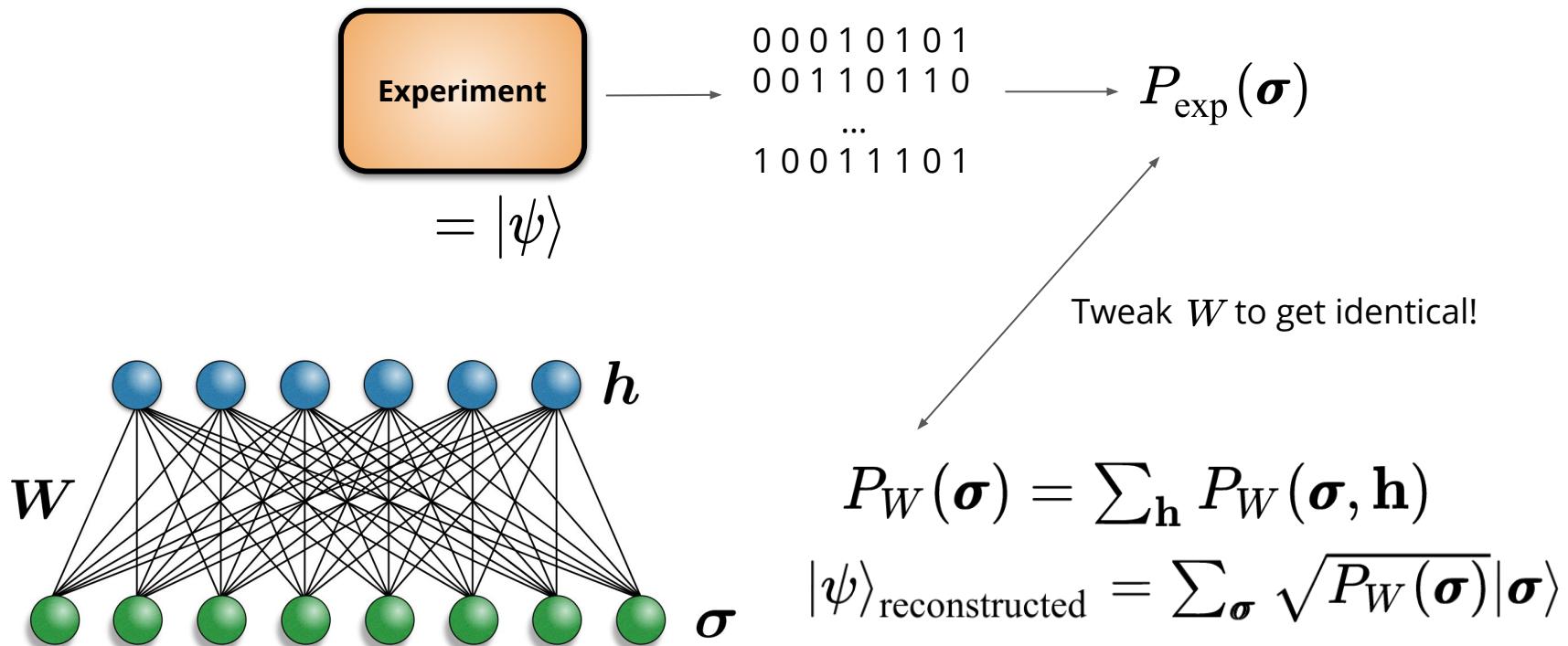
$$P_W(\boldsymbol{\sigma}, \mathbf{h}) = \frac{1}{Z} \exp(-E_W(\boldsymbol{\sigma}, \mathbf{h}))$$

$$E_W(\boldsymbol{\sigma}, \mathbf{h}) = \boldsymbol{\sigma} \cdot W_{\sigma, h} \cdot \mathbf{h} + W_\sigma \cdot \boldsymbol{\sigma} + W_h \cdot \mathbf{h}$$



$$P_W(\boldsymbol{\sigma}) = \sum_{\mathbf{h}} P_W(\boldsymbol{\sigma}, \mathbf{h})$$

Method Summary



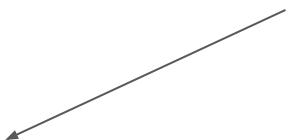
Training

Kullback Leibler Divergence

$$\text{KL}(P_{\text{exp}} || P_W) = \sum_{\sigma} P_{\text{exp}}(\sigma) \log \frac{P_{\text{exp}}(\sigma)}{P_W(\sigma)}$$

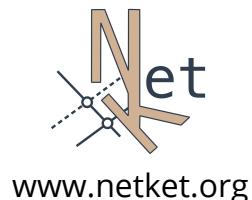
$$\simeq - \sum_{\sigma \in \text{exp}} \log P_W(\sigma)$$

Log-Likelihood



$$W \rightarrow W - \eta \nabla_W \text{KL}(P_{\text{exp}} || P_W)$$

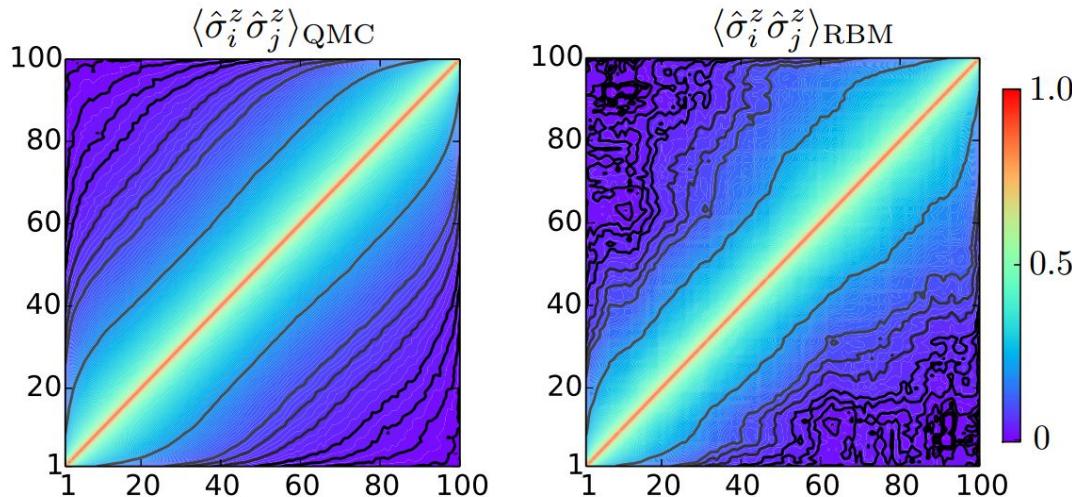
Contrastive Divergence
Block Gibbs sampling



github.com/PIQuIL/QuCumber

Works really well empirically

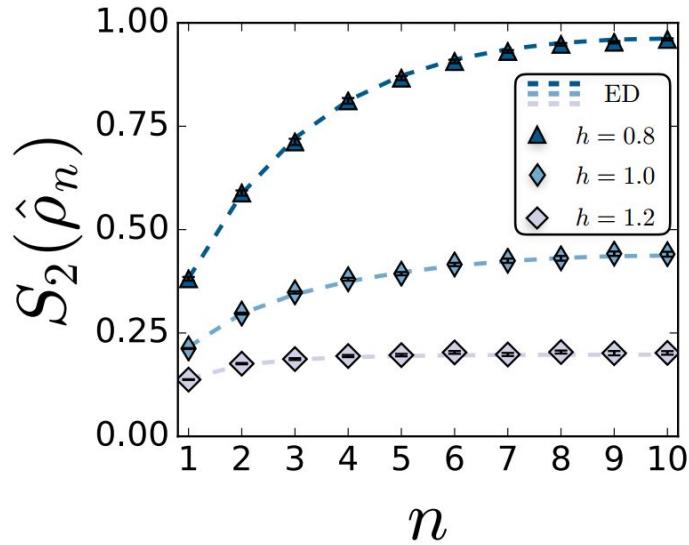
$$H = - \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z - \sum_i \sigma_i^x$$



Synthetic data (no noise) and observables in z-basis

Works really well empirically

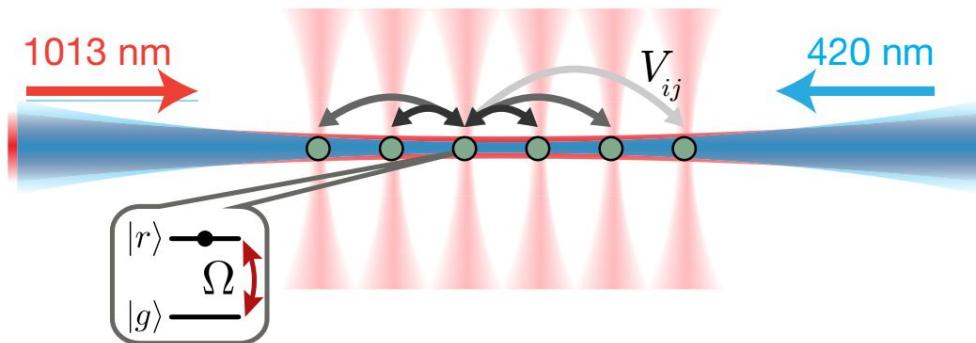
$$H = - \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z - \sum_i \sigma_i^x$$



Synthetic data (no noise) and observables in z-basis

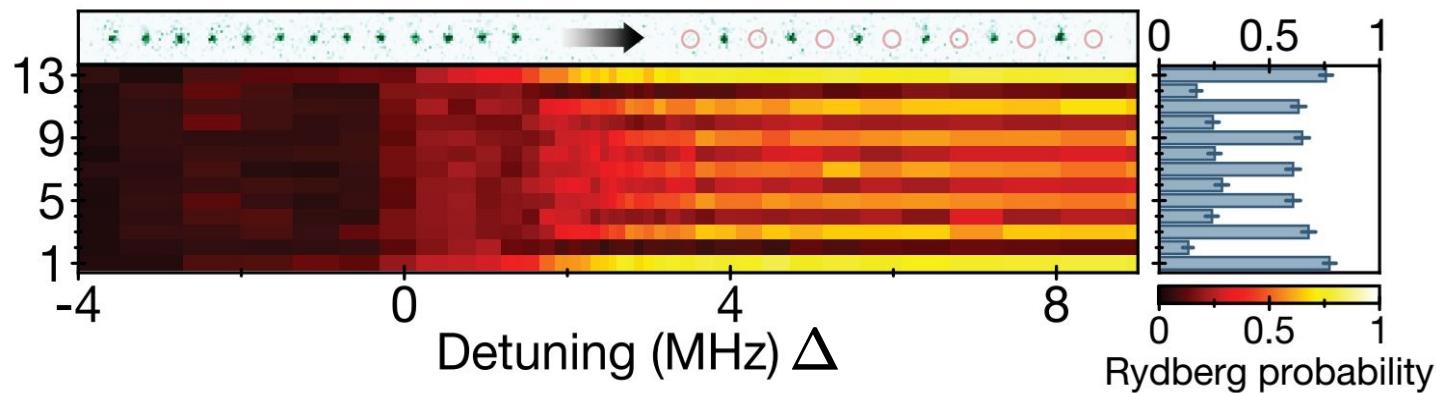
Quantum Simulator

$$H = -\Delta \sum_i n_i - \frac{\Omega}{2} \sum_i \sigma_i^x + \sum_{i < j} \frac{V}{|i-j|^6} n_i n_j$$



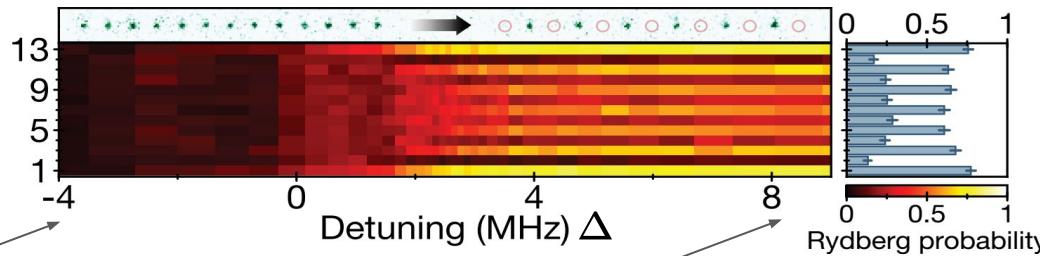
Quantum Simulator

$$H = -\Delta \sum_i n_i - \frac{\Omega}{2} \sum_i \sigma_i^x + \sum_{i < j} \frac{V}{|i-j|^6} n_i n_j$$



The Experiment

$$H = -\Delta \sum_i n_i - \frac{\Omega}{2} \sum_i \sigma_i^x + \sum_{i < j} \frac{V}{|i-j|^6} n_i n_j$$



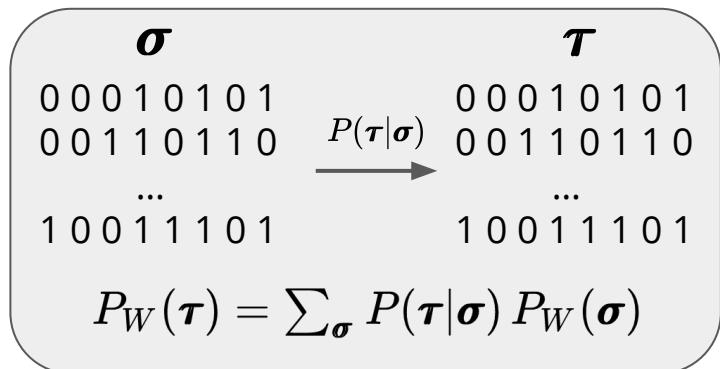
$$|\psi(t=0)\rangle = |0000000\rangle$$

$$|\psi(T)\rangle \approx \frac{1}{\sqrt{2}}|10100101\rangle + \frac{1}{2}|10101001\rangle + \frac{1}{2}|10010101\rangle$$

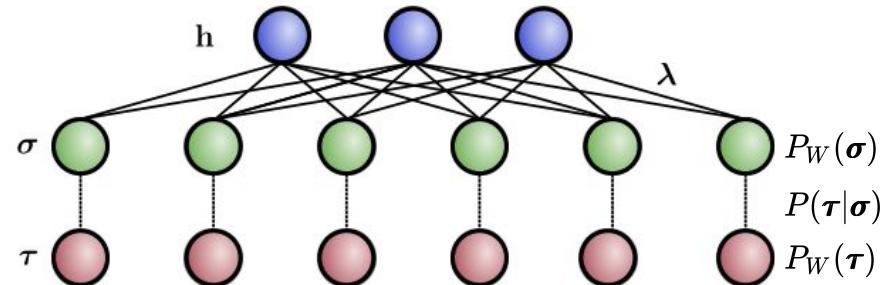
3000 snapshots at 15 different detunings
With decoherence and measurement errors!

Measurement errors

$$\text{Loss} = - \sum_{\sigma \in \text{data}} \log P_W(\sigma)$$



$$P(\tau|\sigma)$$



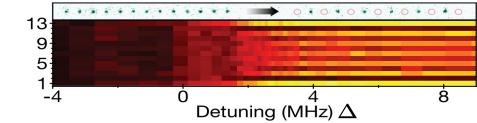
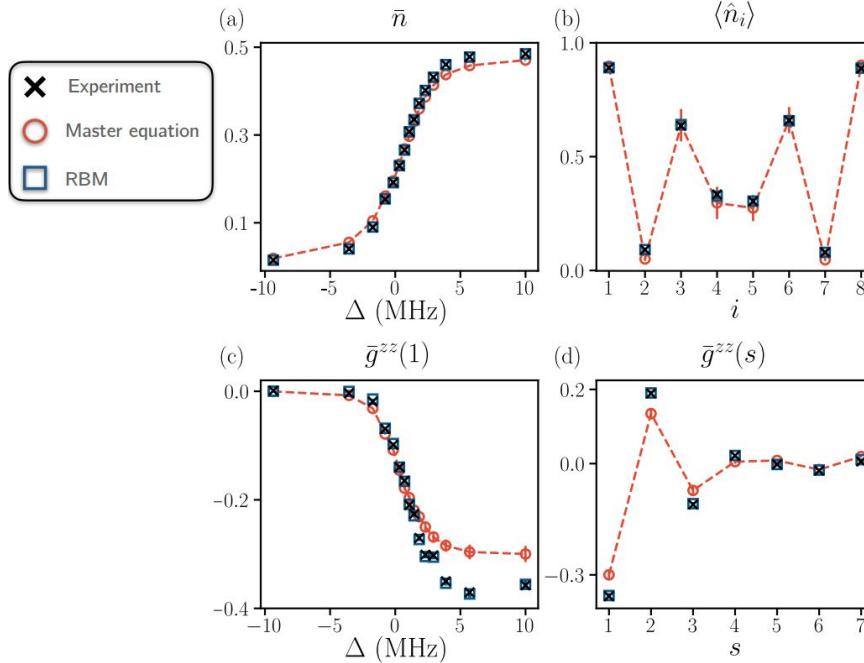
$$\text{Loss} = - \sum_{\tau \in \text{data}} \log P_W(\tau)$$

From the experiment:

$$P(0|1) = 0.04$$

$$P(1|0) = 0.01$$

Diagonal Observables

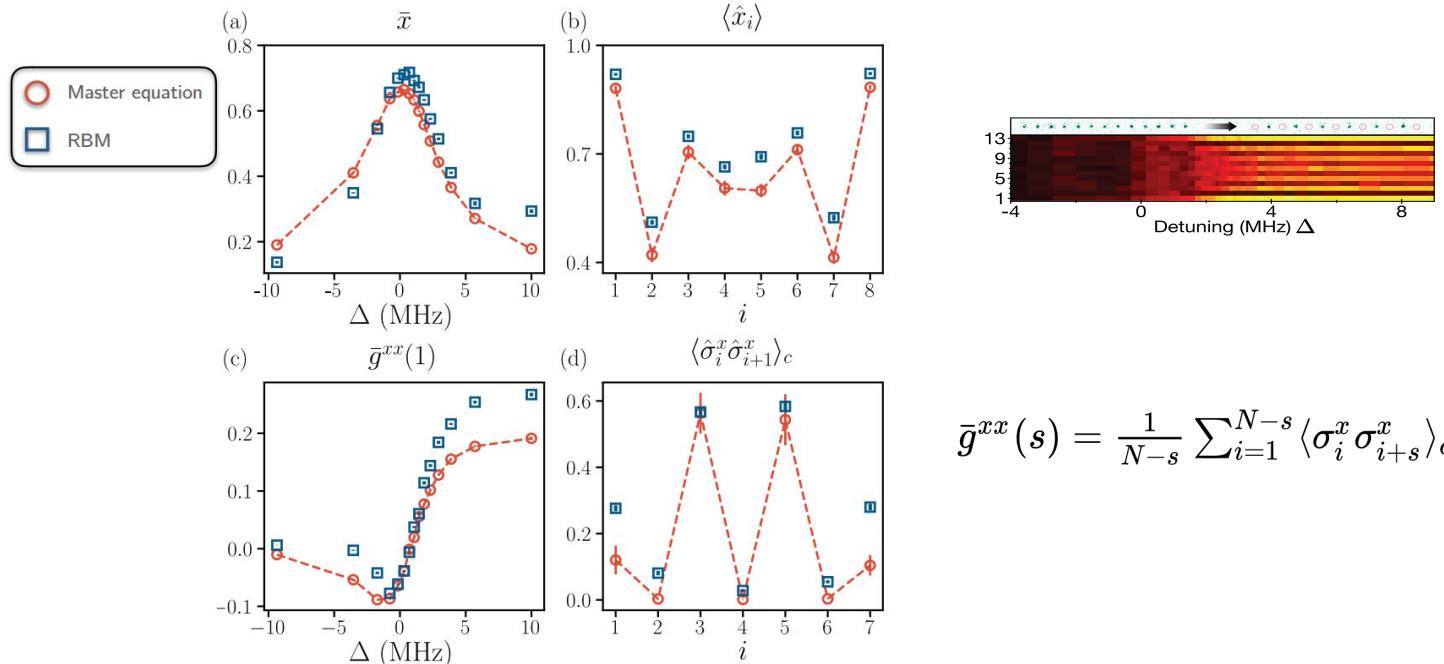


$$\bar{g}^{zz}(s) = \frac{1}{N-s} \sum_{i=1}^{N-s} \langle \sigma_i^z \sigma_{i+s}^z \rangle_c$$

$$|\psi(T)\rangle \approx \frac{1}{\sqrt{2}}|10100101\rangle + \frac{1}{2}|10101001\rangle + \frac{1}{2}|10010101\rangle$$



Off-Diagonal Observables



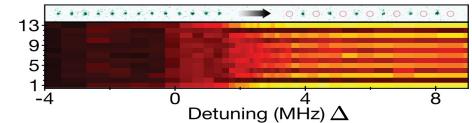
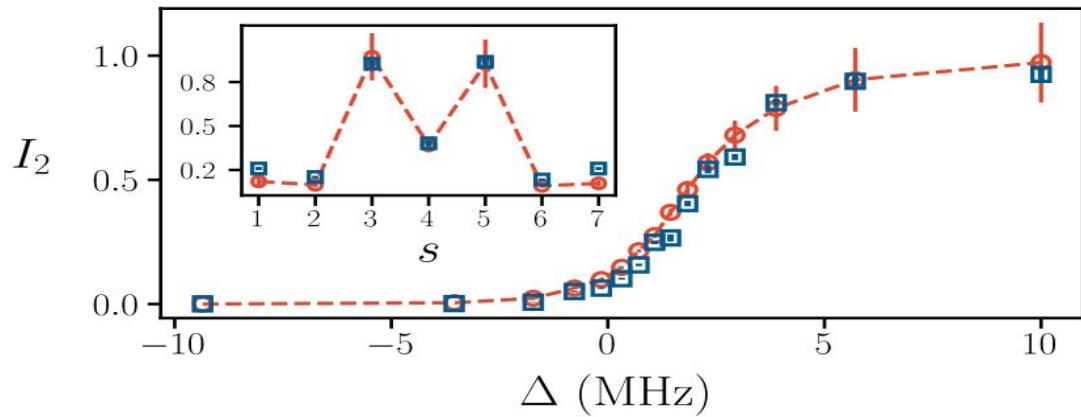
$$|\psi(T)\rangle \approx \frac{1}{\sqrt{2}}|10100101\rangle + \frac{1}{2}|10101001\rangle + \frac{1}{2}|10010101\rangle$$



Entanglement

$$S_2(\rho) = -\log \text{Tr} \rho^2$$

$$I_2(\rho) = S_2(\rho_A) + S_2(\rho_B) - S_2(\rho)$$



$$|\psi(T)\rangle \approx \frac{1}{\sqrt{2}}|10100101\rangle + \frac{1}{2}|10101001\rangle + \frac{1}{2}|10010101\rangle$$



Summary

$$|\psi\rangle_{\text{reconstructed}} = \sum_{\sigma} \sqrt{P_W(\sigma)} |\sigma\rangle$$

Generative model
Restricted Boltzmann Machine

Trained on samples drawn from the **experiment**

Good empirical results for reconstructed properties, *despite*

- Non-pure
- Measurement errors

Extensions

1

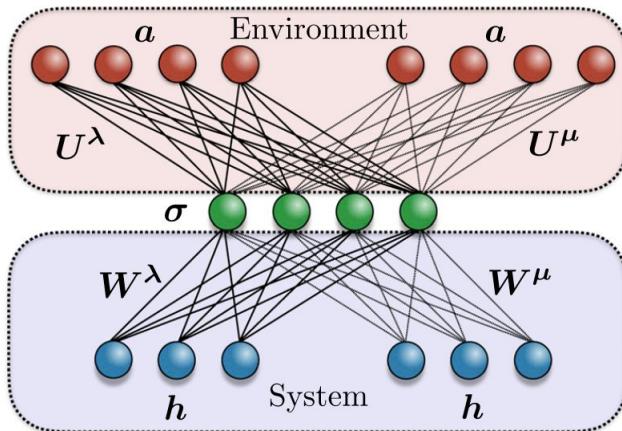
Adding back in the sign-structure

$$\psi_{W,W'} = \sqrt{P_W(\sigma)} e^{i\theta_{W'}(\sigma)}$$

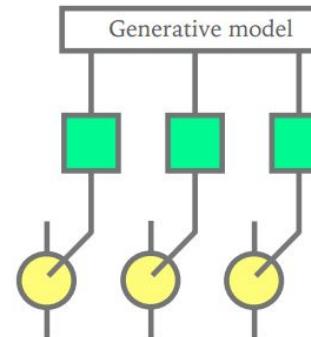
Torlai *et al*, Nat. Phys (2018)

Mixed states

2

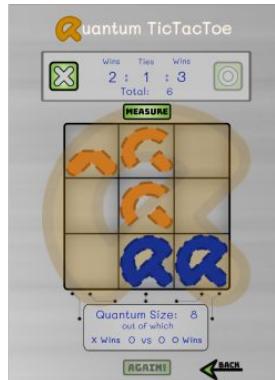
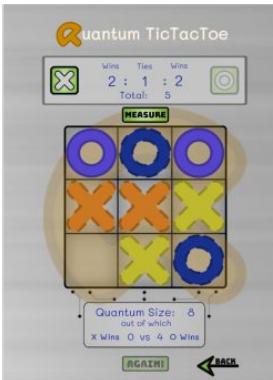
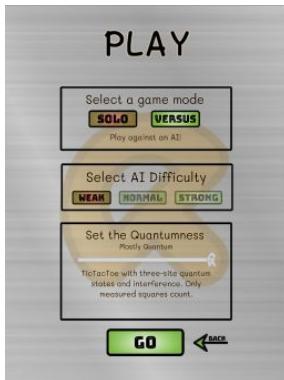


Torlai and Melko, PRL(2018)



Carrasquilla *et al*, Nat. Machine Intel (2019)

Quantum Games



Want to play-test the app?
Please send me an e-mail!
evert@caltech.edu

Noise Layer

