Quantum many-body states

A novel neuromorphic application

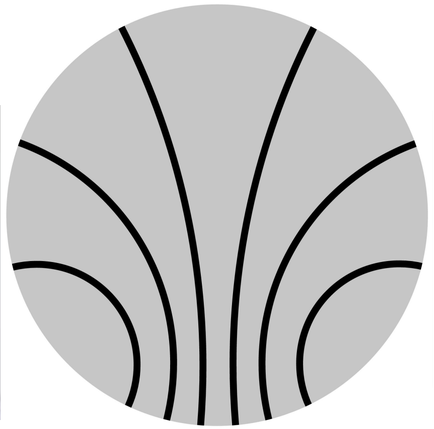
Andreas Baumbach - 29th March 2022 - NICE Workshop

Overview

- How this came to be?
  - People, Working Groups, Theory and Hardware
- What are Qbit Systems?
- Neuromorphic Sampling
- Results
  - Bell States and Stoquastic Ground States
- An Argument for taking Chances

Ingredients

Thomas Gasenzer



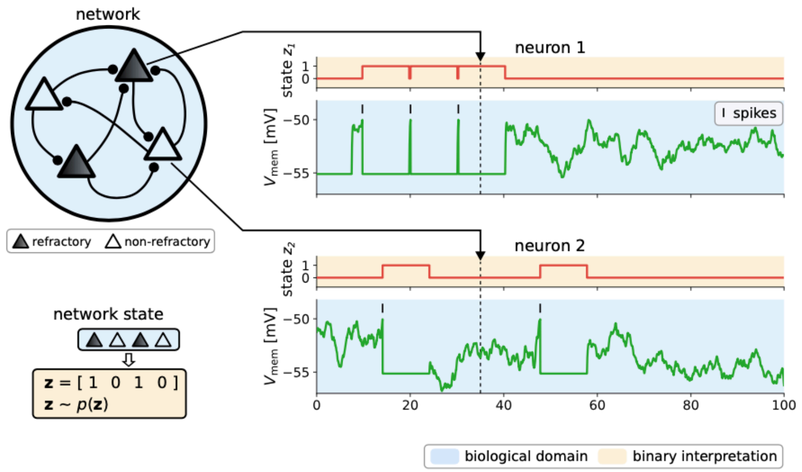
Kirchhoff Institute for Physics

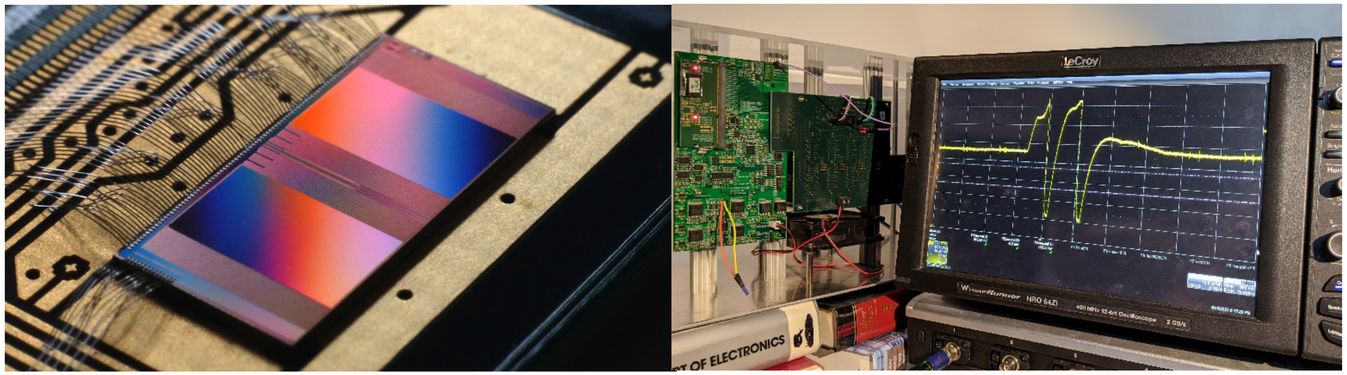
Karlheinz Meier
† 2018

Stefanie Czischek

Robert Klassert

Martin Gärttner





Plus: Lots of support from the Electron Vision(s) group

[Czischek et al., 2022;
Klassert et al., 2021]

What are Qbit Systems?

A very abbreviated description

- Simplest system: Two basis states of each component

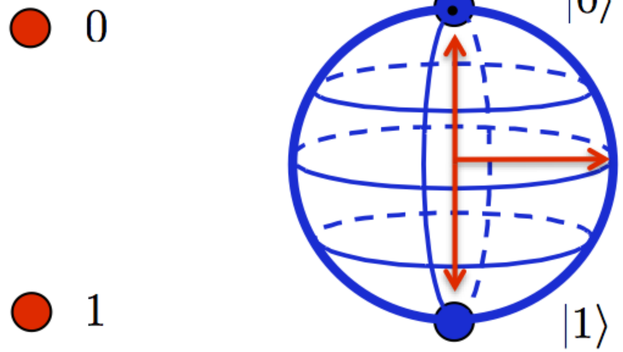
$$|\uparrow\rangle, |\downarrow\rangle$$

- General state: Complex superposition of basis states

$$|\psi\rangle = c_{\uparrow}|\uparrow\rangle + c_{\downarrow}|\downarrow\rangle$$

- Many body states: Need exponentially many $c_{\uparrow\downarrow\uparrow\ldots}$

- Task: (Efficient) description for general quantum many-body states



Classical Bit

Qubit

What are Qbit Systems? (continued)

- General state: Complex superposition of basis states

$$|\psi\rangle = \sum_{\phi \in \{\uparrow\downarrow\ldots\}} c_\phi |\phi\rangle$$

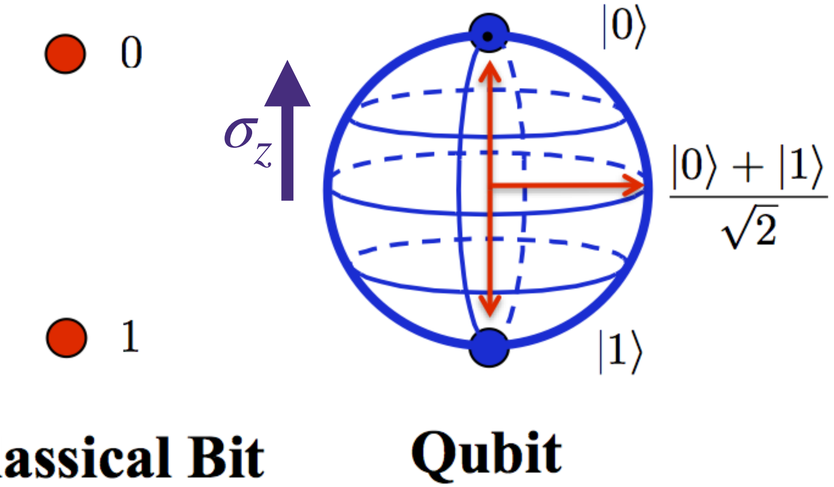
- Interested in: Measurement outcomes
  - Example: z-magnetisation

This looks like an expectation value

$$m_z = \langle\psi|\sigma_z|\psi\rangle \propto \sum_{\phi,\phi' \in \{\uparrow\downarrow\ldots\}} \boxed{c^*_{\phi'} c_\phi \langle\phi'|\sigma_z|\phi\rangle} = \sum_x p(x)\, f_m(x)$$

- For certain types of quantum states this can be expressed as probabilistic expectation values:

$$m_z = \langle f_m(x) \rangle_{p(x)}$$

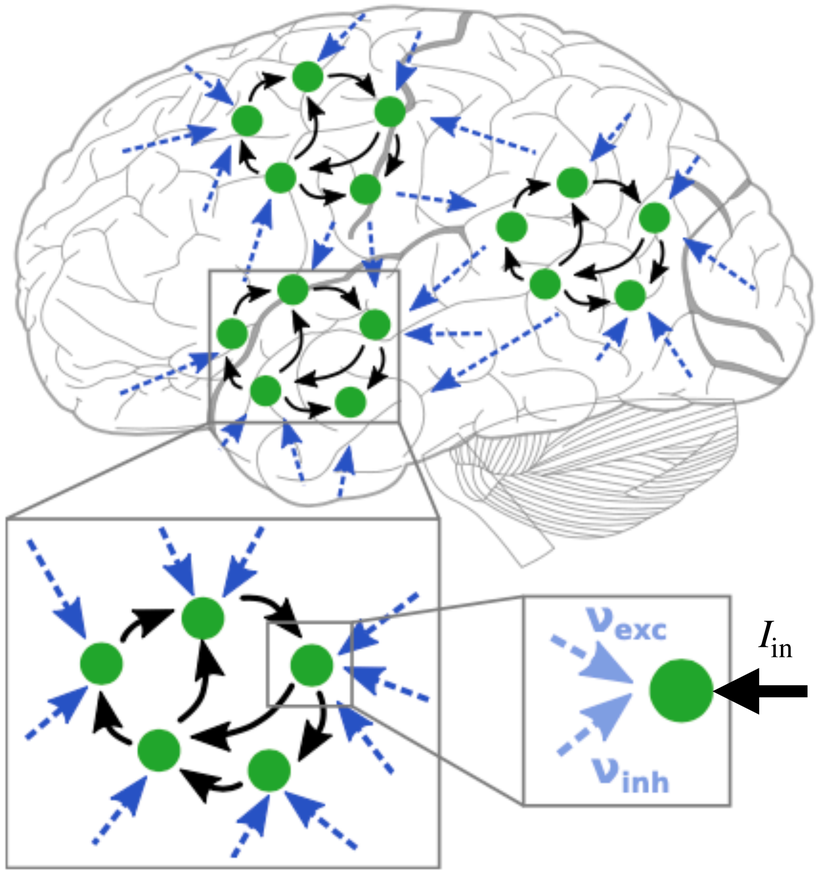


So far we learned:

- Quantum many-body states require exponentially many complex numbers
- Some can be translated into a probability distribution $p(x)$
- Expectation values can be calculated from $p(x)$
- Assuming $\{c_{\uparrow\downarrow\ldots}\} \leftrightarrow p(x)$ and $\sigma_z \leftrightarrow f(x)$ translations are given: Need to sample $p(x)$

Neuromorphic Sampling

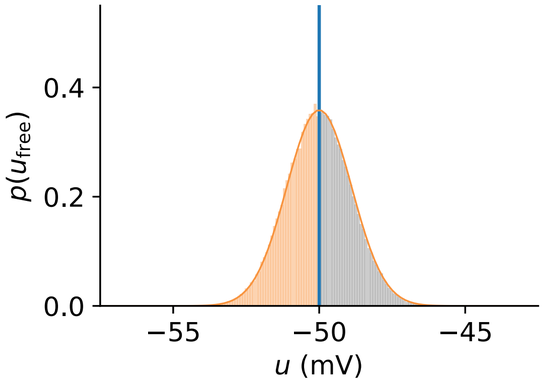
Stochastic spiking neurons

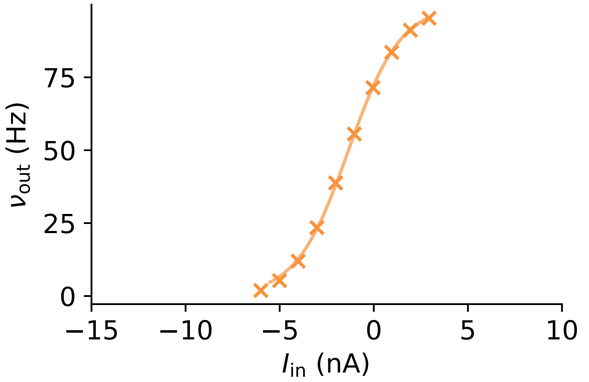


Boltzmann distribution:

$$p(z) \propto \exp\left(-\frac{b^T z + \frac{1}{2} z^T W z}{T}\right)$$

$$p(z=1) \propto \nu_{out}\left(I_{in}\right) \propto \frac{1}{1+\exp[\beta\left(I_{in}-I_0\right)]}$$

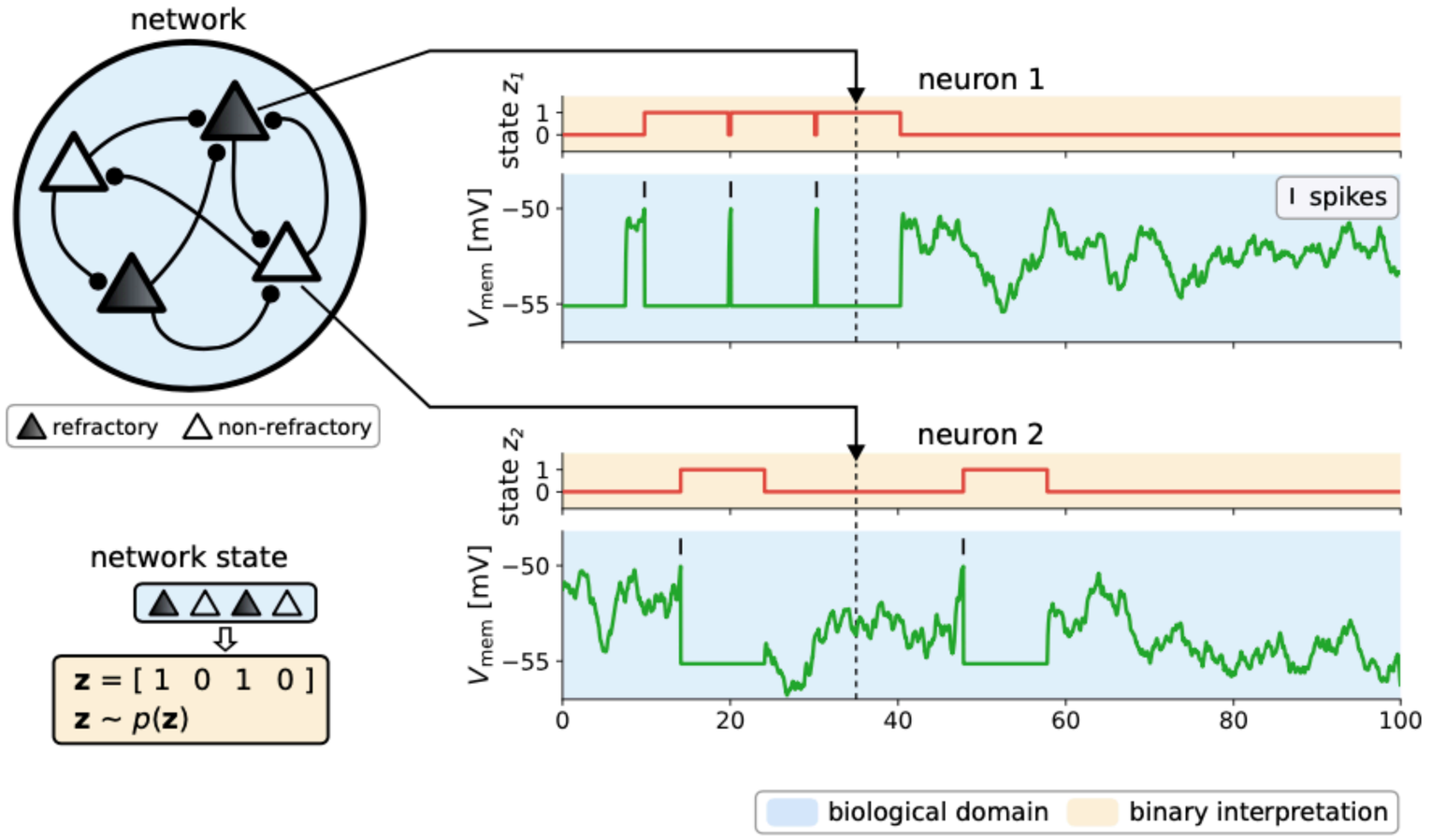




[Petrovici et al., 2016;
Korcsak-Gorzo et al., 2022]

Neuromorphic Sampling

Stochastic spiking neurons



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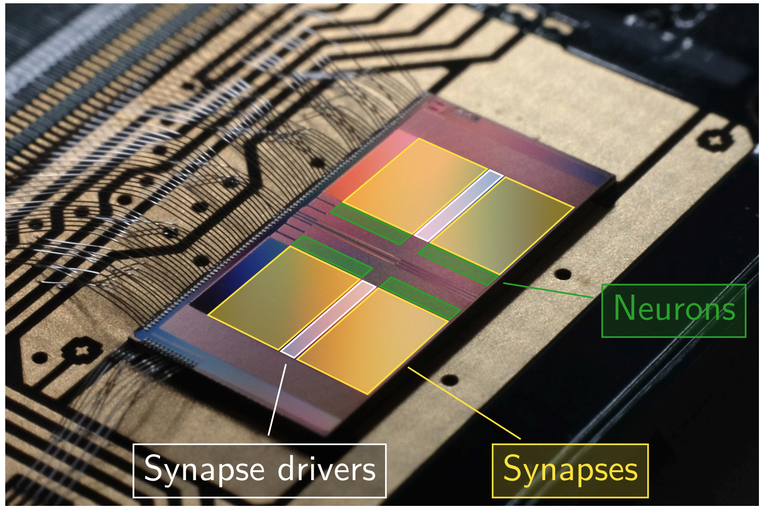
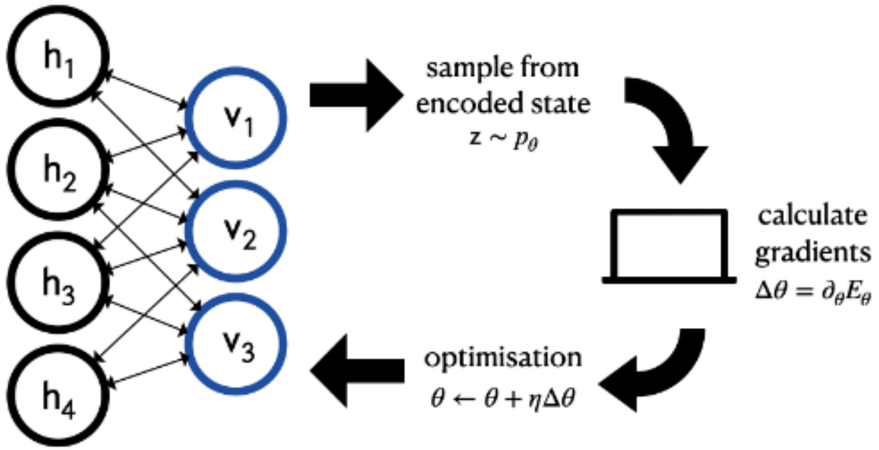
Neuromorphic Sampling



BrainScaleS-2 ASIC



- Layered network
  - visible layer represents $p(x)$
  - hidden layer forms $p(x)$
- Iterative host-based training
  - calculate gradients based on sampled $p(x)$
  - 30 Hz experiment rate

[Czischek et al., 2022; Klassert et al., 2021]

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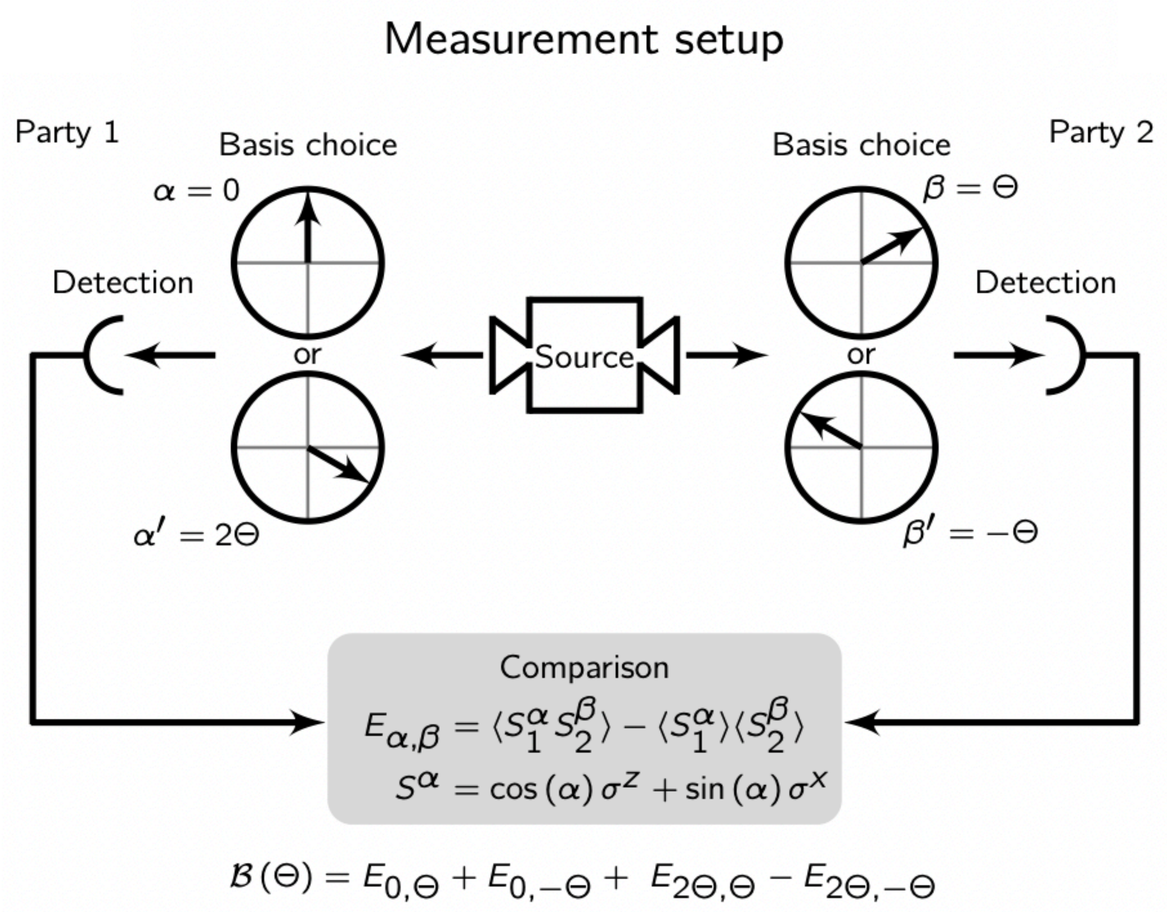
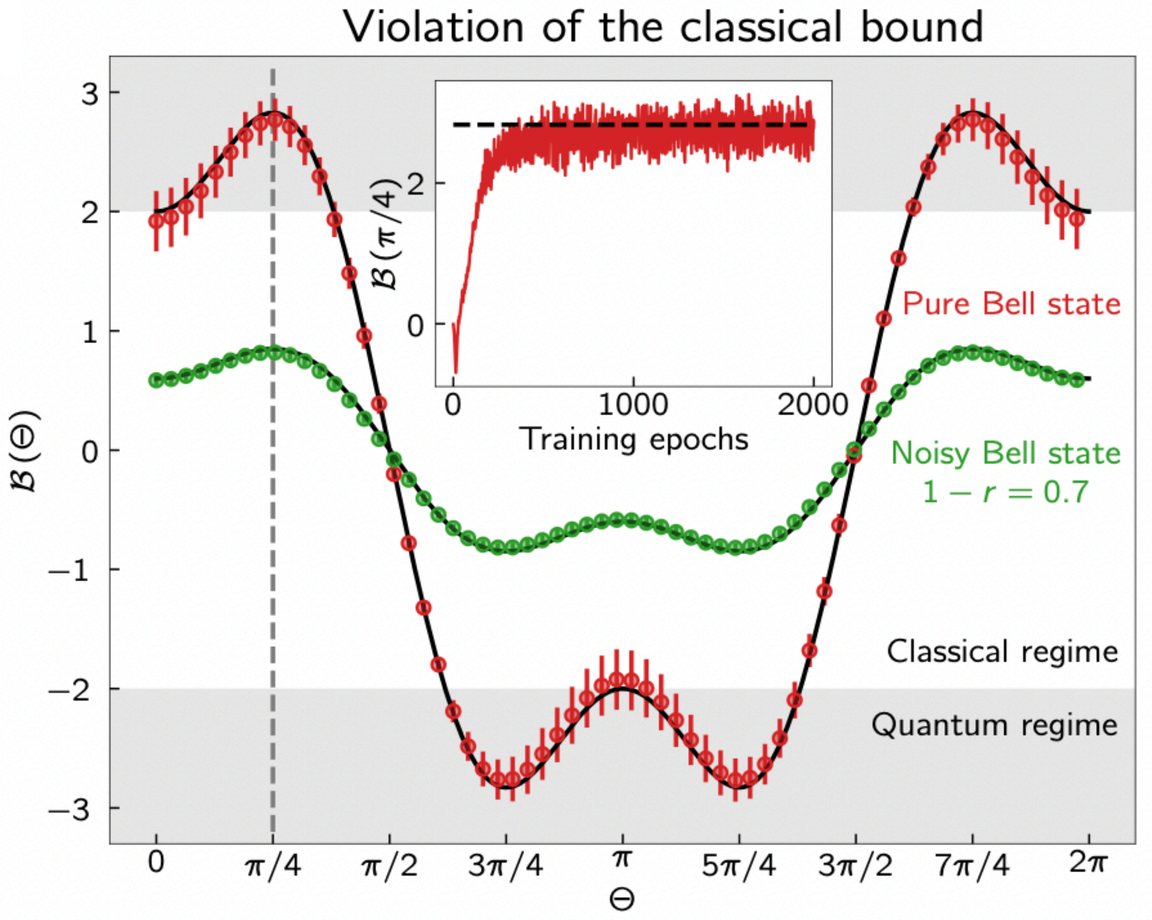
Bell States



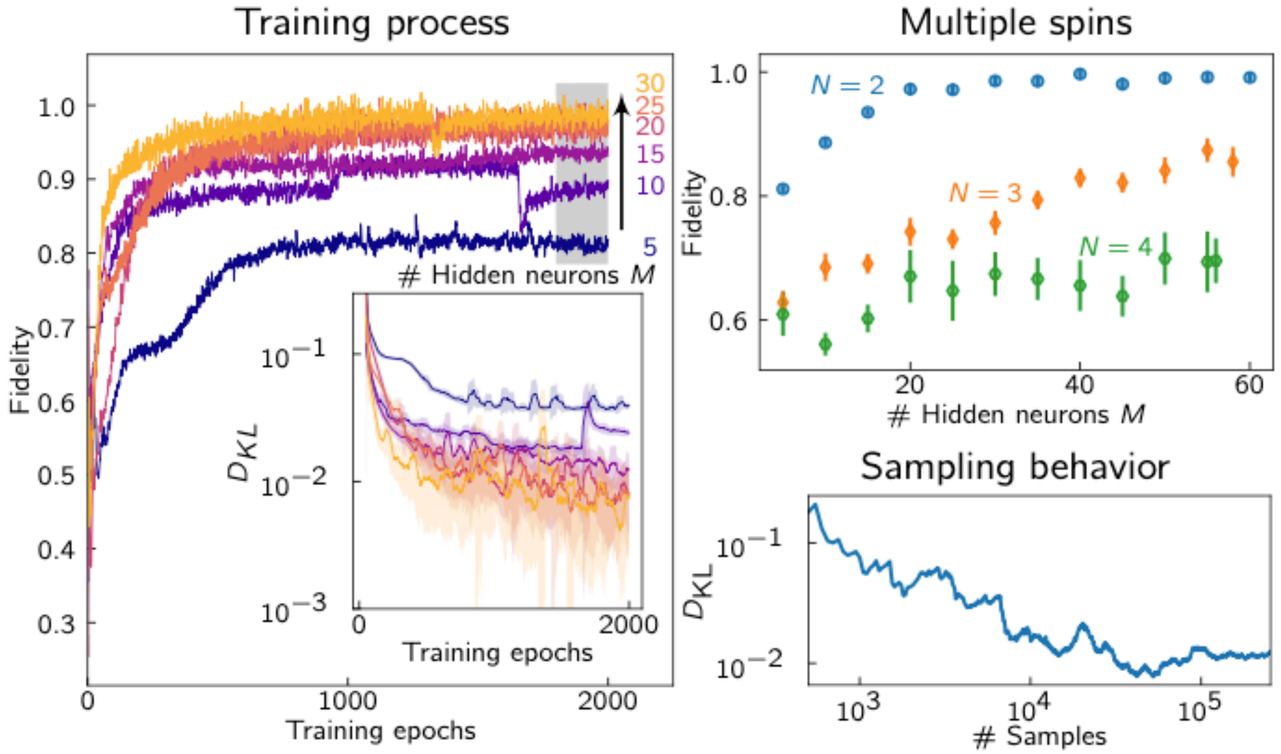


$$|\psi_+\rangle = \frac{1}{\sqrt{2}}|\uparrow\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\downarrow\rangle$$

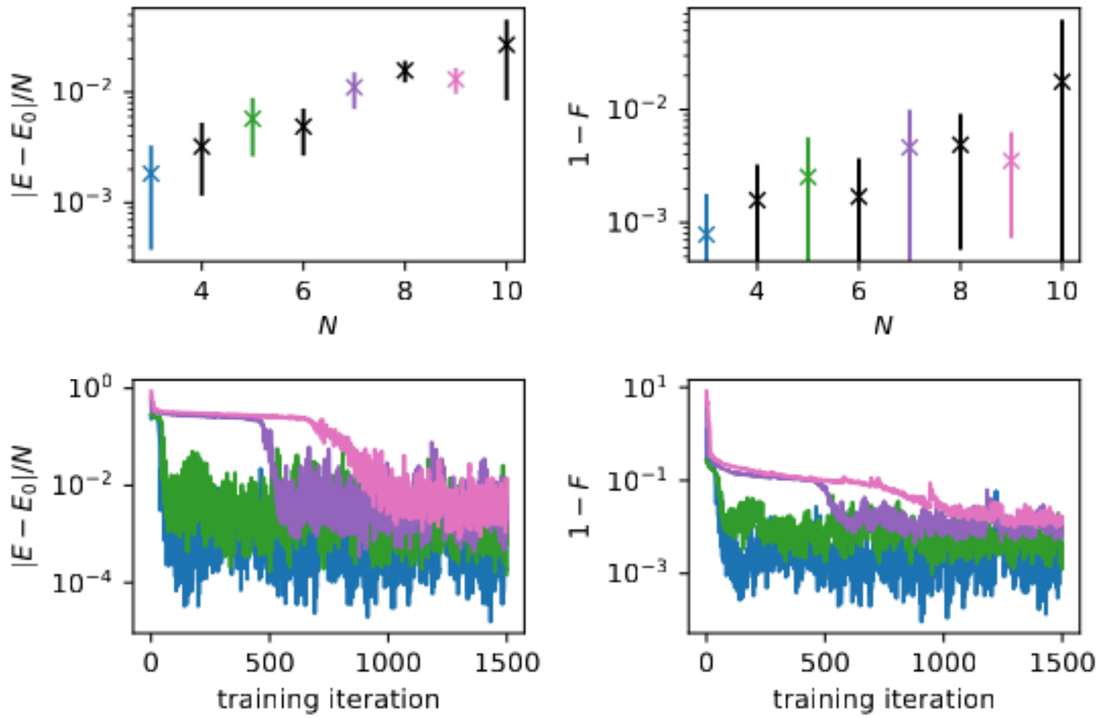
[Czischek et al., 2022]

More General Quantum States

Generalised Bell-states



Stoquastic Quantum States

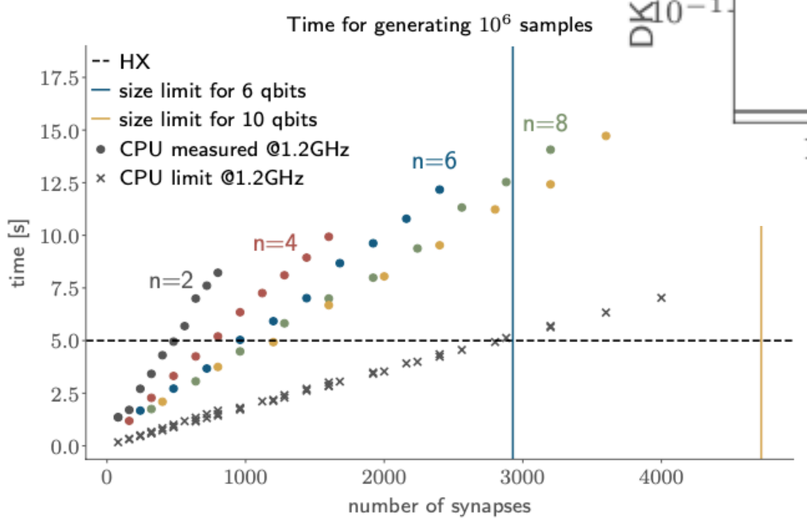


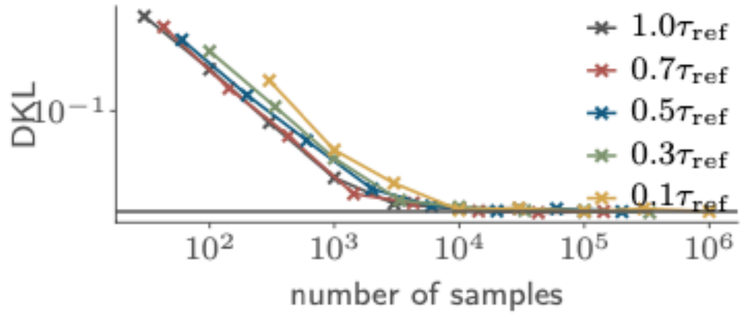
[Czischek et al., 2022; Klassert et al., 2021]

Why even bother?

It’s fun!

- Different fields: Different way of thinking ⇒ opportunity to learn
- Stress-test for BrainScaleS ⇒ opportunity to improve
- Physical computing: Flat scaling





Acknowledgements

Karlheinz Meier
† 2018

Czischek et al., 2022

Klassert et al., 2021

Electronic Vision(s)

Stefanie Czischek

Martin Gärttner

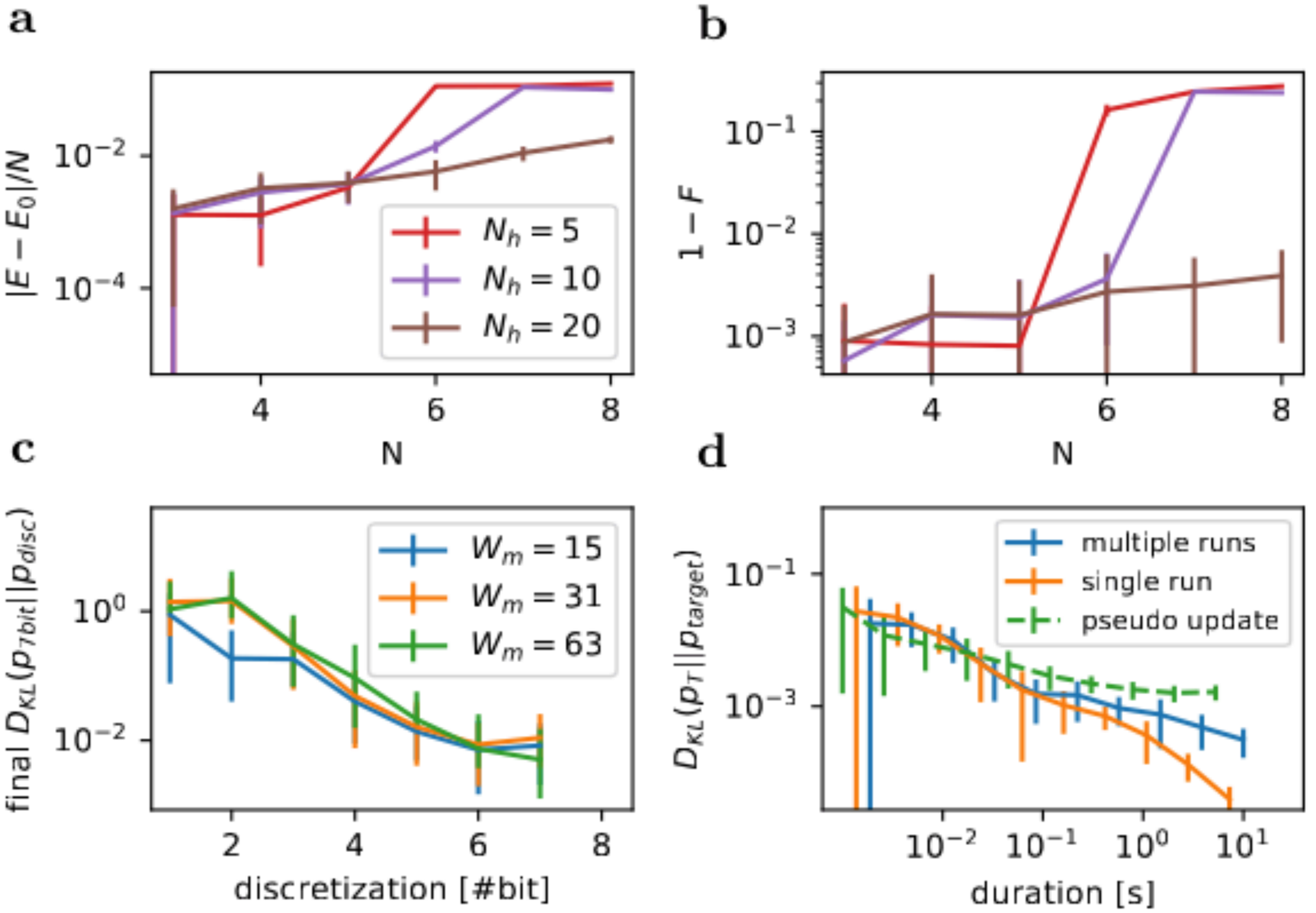
Johannes Schemmel

Sebastian Billaudelle

Mihai A. Petrovici

Manfred Stärk Foundation

NeuroTMA @UniBE


a
b
c
d
$|E - E_0|/N$
10^{-2}
10^{-4}
$N_h = 5$
$N_h = 10$
$N_h = 20$
4
6
8
N
$1 - F$
10^{-1}
10^{-2}
10^{-3}
final $D_{KL}(p_{7bit}||p_{disc})$
10^{0}
$W_m = 15$
$W_m = 31$
$W_m = 63$
2
discretization [#bit]
$D_{KL}(p_T||p_{target})$
multiple runs
single run
pseudo update
10^{-2}
10^{-1}
10^{0}
10^{1}
duration [s]