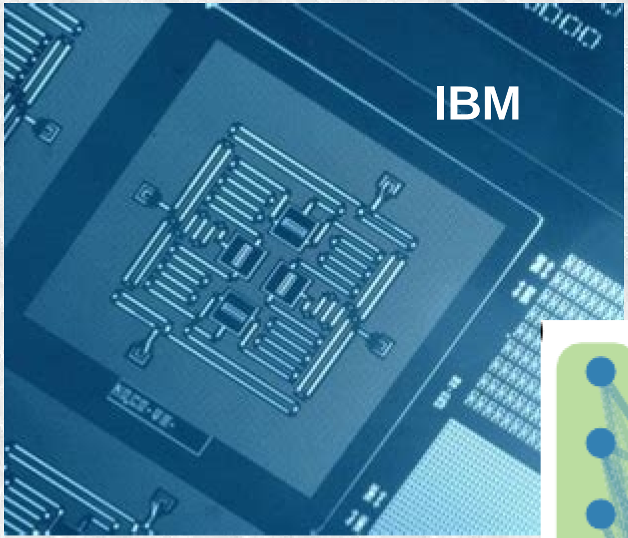
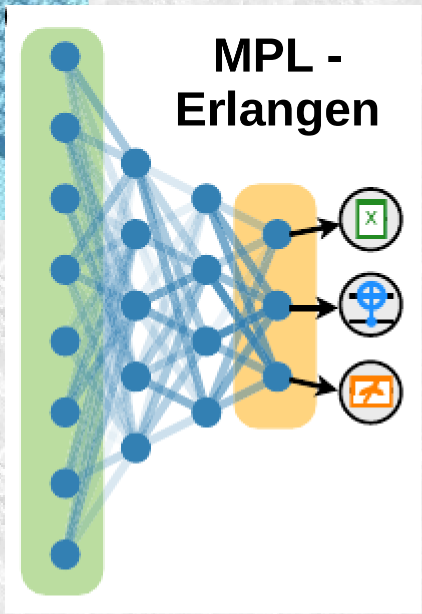
Machine Learning and Quantum Technology

German Sinuco
Department of Physics and Astronomy
University of Sussex

Sussex Data Science MeetUp
Brighton, 27th June 2019

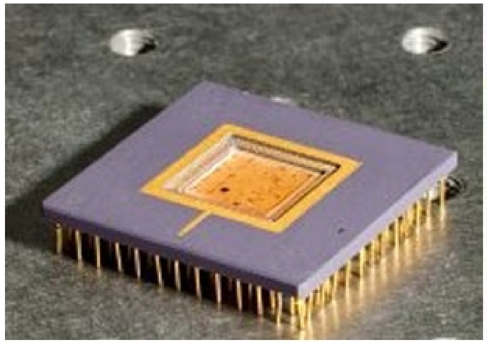


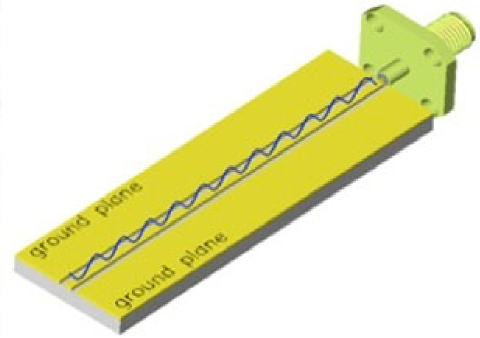


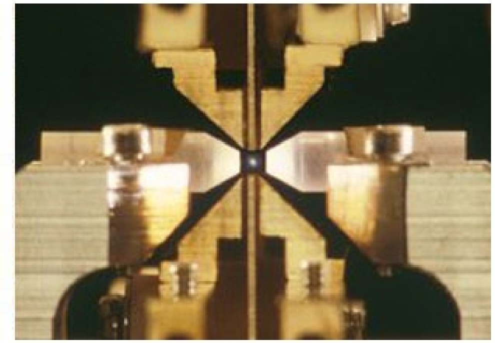
UNIVERSITY OF SUSSEX

Atomic, Molecular and Optical Physics at Sussex

UNIVERSITY OF SUSSEX







Atomic, Molecular, and Optical (AMO) research at Sussex University is devoted to the study of fundamental physics and quantum effects using the techniques of atomic and laser physics.

- 10 academic staff, (Lecturers +)
- ~10+ Postdocts
- ~30 PhD students
- ? Master students

Experimental research in:

- Trapped ions
- Cold atomic gases
- Trapped electrons
- Non-linear Photonics
- Terahertz technology

Theoretical studies:

- Quantum optics
- Quantum metrology

www.sussex.ac.uk/amo/

Plan

- What is Quantum technology?
- Machine Learning interlude
- How is ML helping us to develop QS/QT?

What is quantum technology?

“Quantum technology is an emerging field of physics and engineering, which is about creating practical applications … based on properties of quantum mechanics ...” Wikipedia

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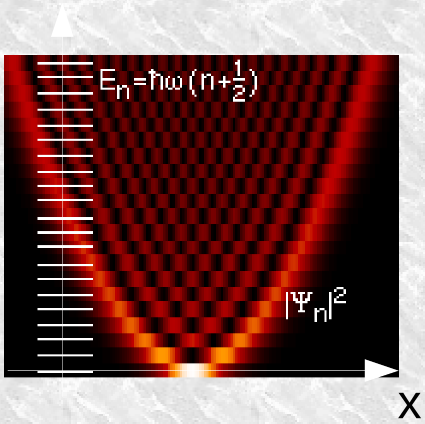
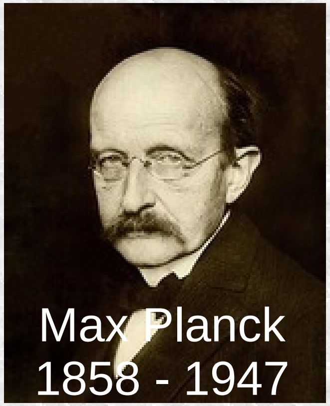
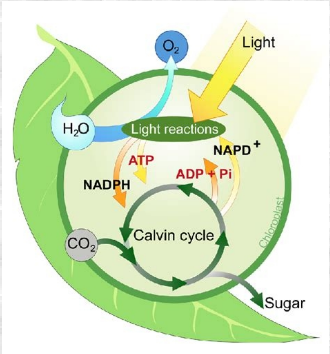
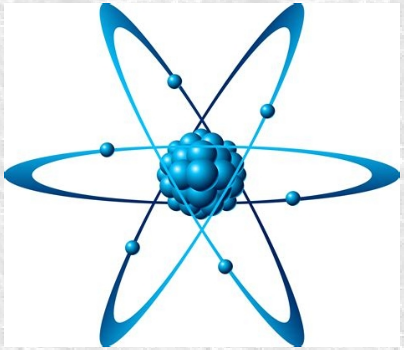


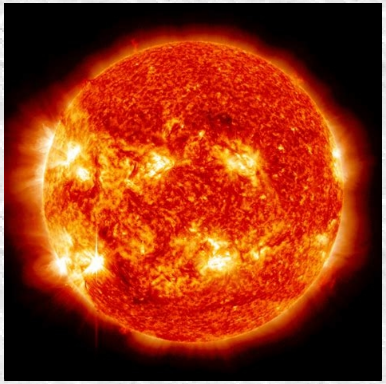
$$i\hbar\partial_t\Psi = H\Psi$$

Spatio-temporal evolution of the wave-function ~ ***probability distribution***



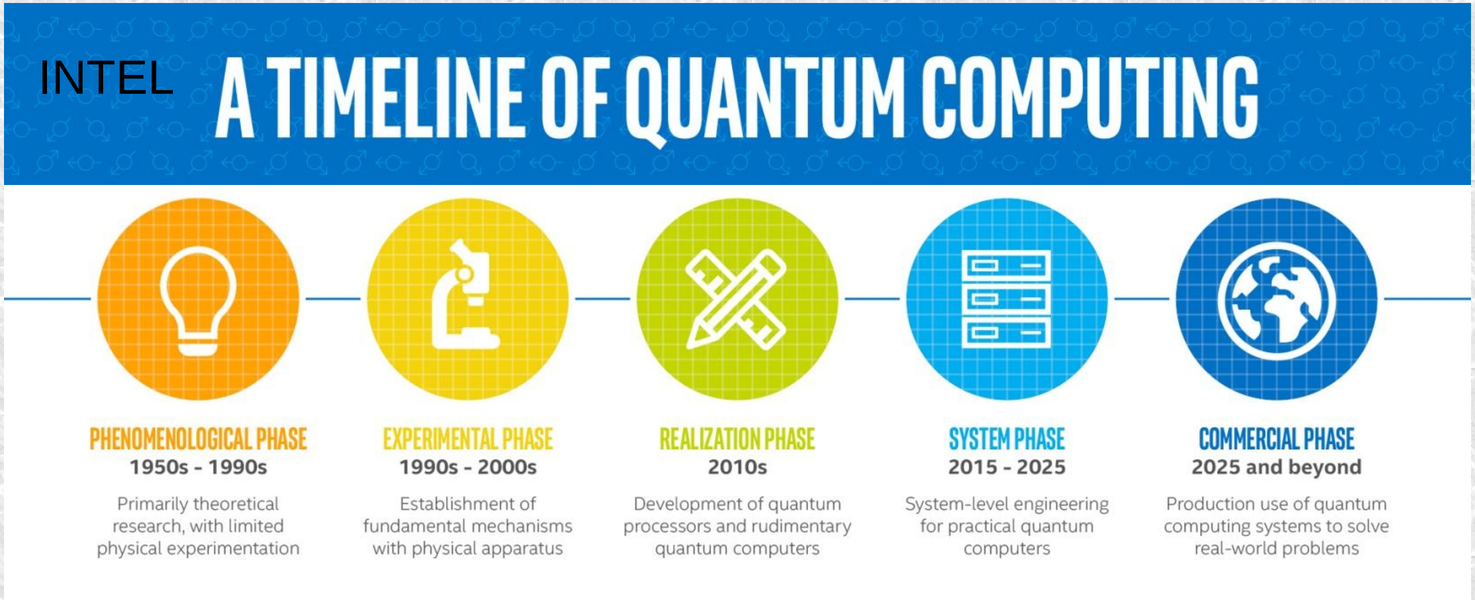






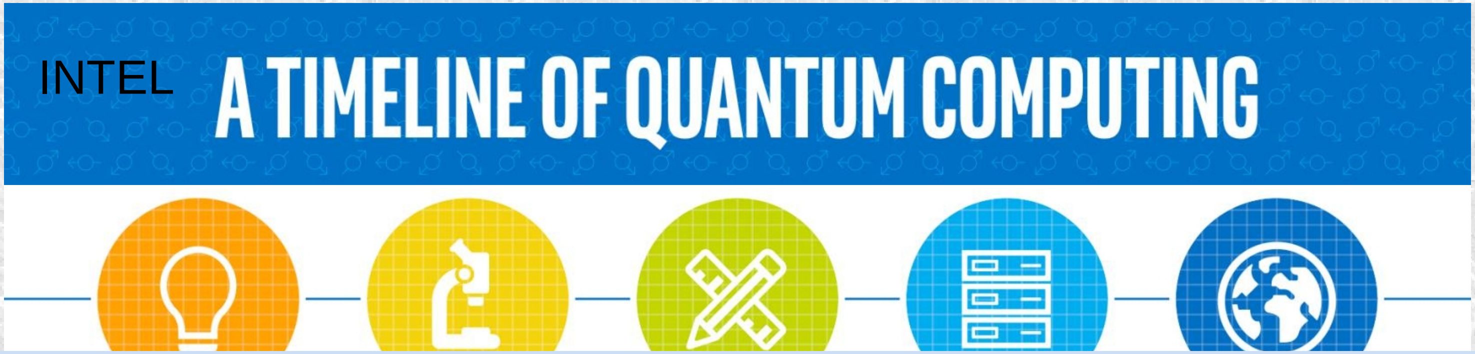
Quantum technology

INTEL



- UK national program in QT: £270 millions 2014-2019
- Europe's Quantum Flagship initiative: 1billion for the next 10 years (July 2017)
- Quantum information science and tech. in Japan: 1billion in the last 15 years
- Quantum Canada: 1billion, last decade alone.
- Quantum Computing: Google, Microsoft, IBM, Intel, D-Wave, Riggetti, QuTech, …
- Bosh, Total, AirBus, Facebook, ...

Quantum technology



Quantum Science and Technology

Focus on Quantum Science and Technology Initiatives Around the World

Rob Thew, *University of Geneva, Switzerland*
Thomas Jennewein, *University of Waterloo, Canada*
Masahide Sasaki, *National Institute of Information and Communications Technology, Japan*

The 20th century had two significant scientific revolutions—quantum physics and information science. Quantum physics has been a fascinating field of research for over a century and one that, for the most part, has been seen as a complex and difficult to understand concept. Information science was the reserve of complex and often abstract mathematics, despite changing the tide of a world war. Nonetheless, their combination has given rise to much of the information technology around us. These technologies emerged in what is often referred to as the first quantum revolution, from our improved understanding of quantum physics.

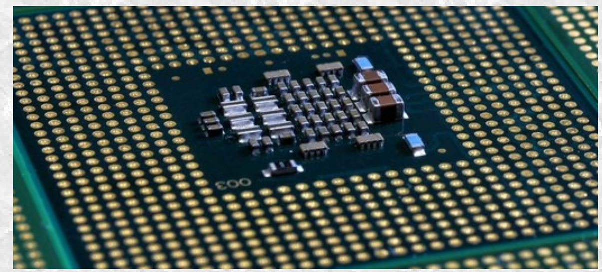
Photo credit: Shutterstock/Vijay Kumar.

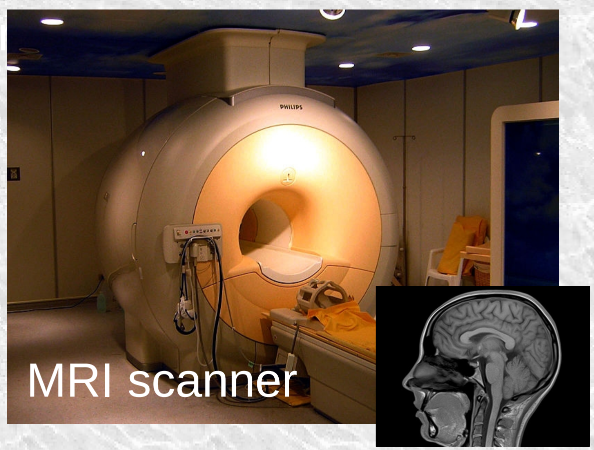
- UK na
- Europ … 2017)
- Quant … years
- Quant
- Quantum Computing: Google, Microsoft, IBM, Intel, D-Wave, Riggetti, QuTech, …
- Bosh, Total, AirBus, Facebook, ...

What is quantum technology?

Devices that rely in our understanding of quantum mechanics:
Quantum 1.0

Information technology

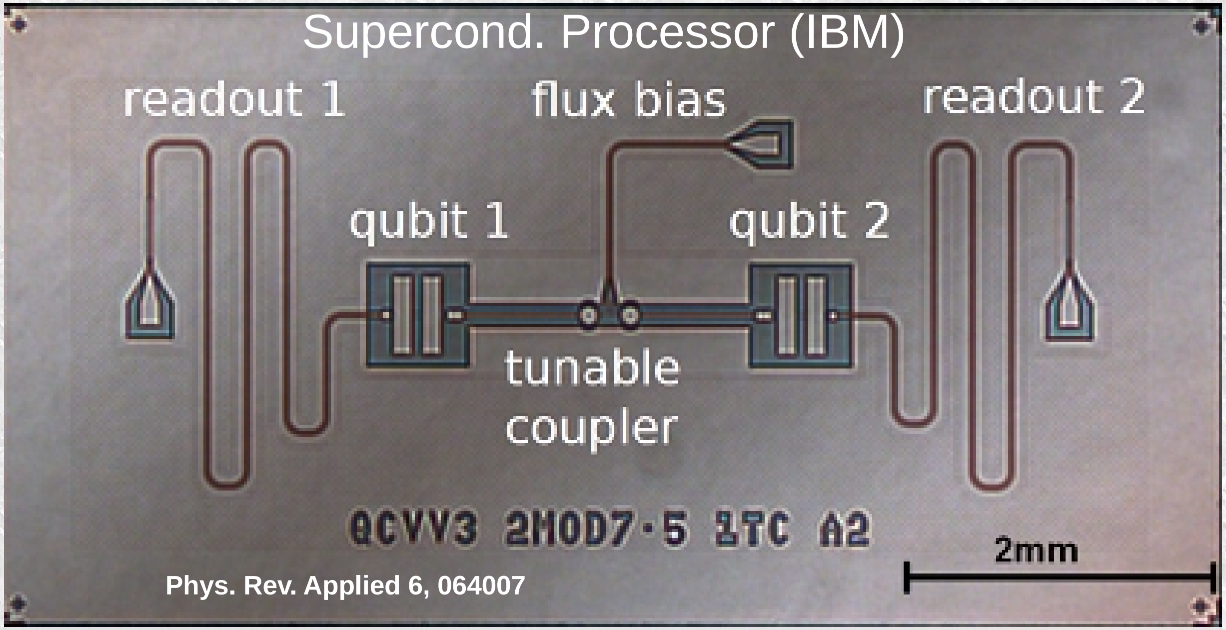




Devices/technology exploits the quantum behaviour of very large ensembles of subsystems (~ 10^{23})

What is quantum technology?

Quantum 2.0 . Generation of devices that exploit controlling individual systems and their interactions.



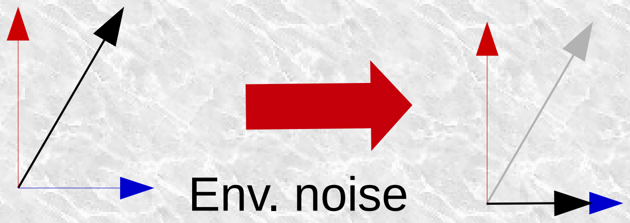
Qubit: $|0\rangle, |1\rangle, D=2$

Challenges to develop quantum technology

- Many technical challenges:
  - low-noise generators
  - improve the yield of fabrication processes
  - Slow process to characterise/tuning devices

- Quantum devices have very large number of configurations, and full numerical studies are impossible.

- Quantum devices are highly sensitive to environmental noise.



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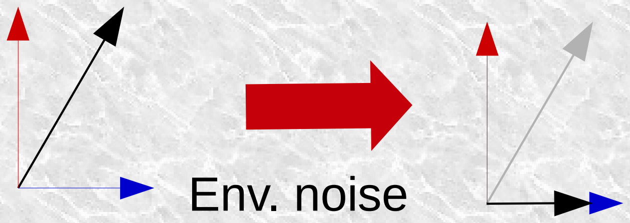


To be continued ...

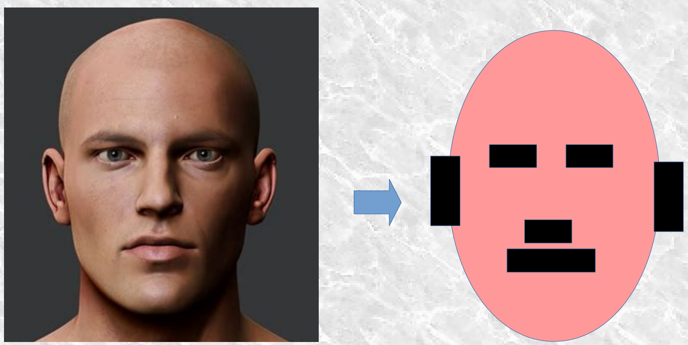
Plan

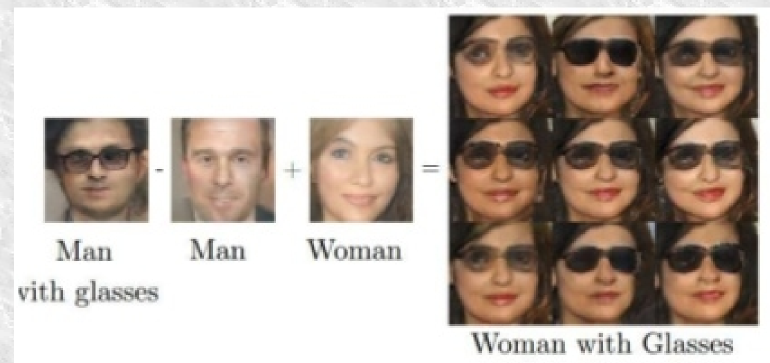
- What is Quantum technology?
- Machine Learning interlude
- How is ML helping us to develop QT?

Machine Learning

Machine learning: refers to a set of statistical tools for analysis of large data sets

- It can extract features of large data set.
- Generate new data.



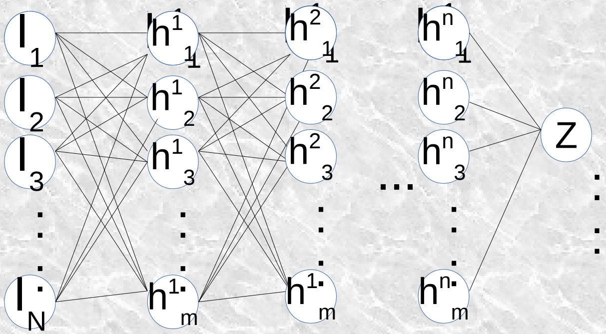


Machine Learning craze motivated by:

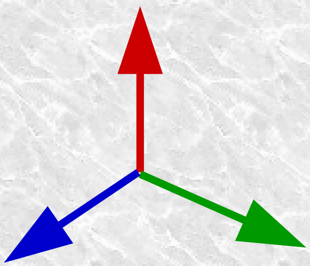
- Big data sets from the internet flow
- Massiv`e computing resources
- Good algorithms
- Success of AlphaGo

Machine Learning
3 Flavours

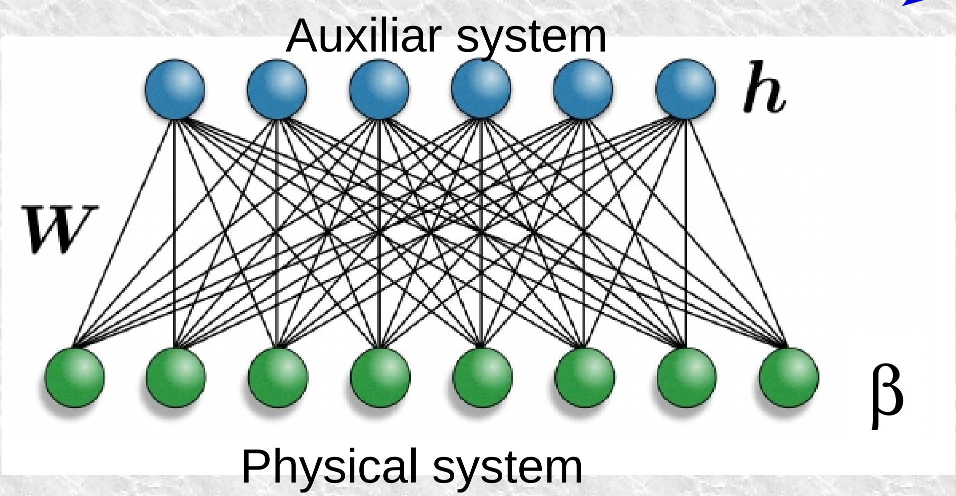
Supervised training



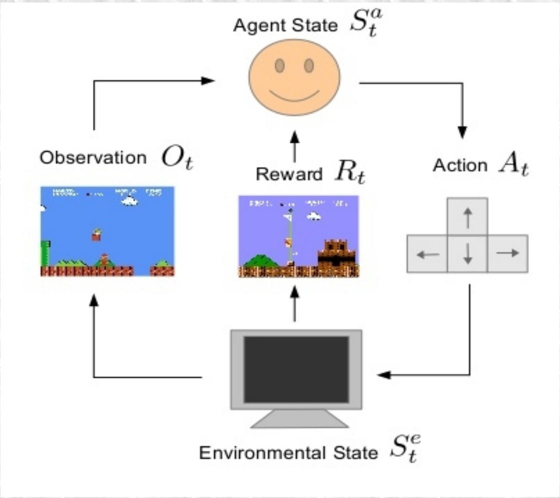
$$CNN(\Omega): N^N \Rightarrow N$$



Unsupervised training



Reinforced learning



Machine Learning
3 Flavours

Supervised training

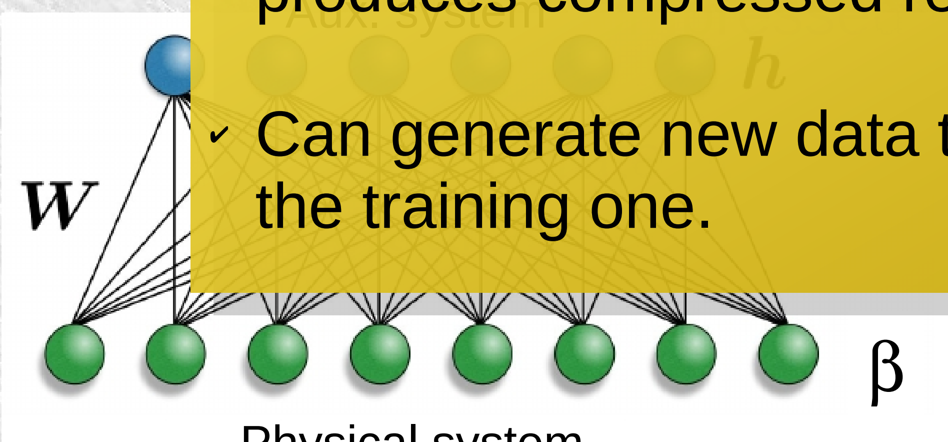
The ML system (network, Agent) defines a non-linear function that depends on the data and on a large set of parameters Ω

Training: the process of adjusting the parameters Ω to obtain optimal representation of the data.

This results in an algorithm that:

- ✓ produces compressed representation of the data.
- ✓ Can generate new data that reflect the properties of the training one.

Unsupervised training



Physical system

Reinforced learning

Plan

- What is Quantum technology?
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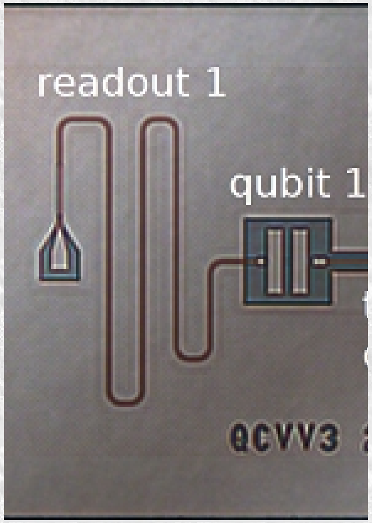
- How is ML helping us to develop QT?

Compact representation of quantum states

Wave-function of the system:

$$|\Psi\rangle = \sum_{\beta=1}^{2^N} C_{\beta,\Psi} |\beta\rangle \equiv \begin{pmatrix} C_{1,\Psi} \\ C_{2,\Psi} \\ C_{3,\Psi} \\ \dots \\ C_{2^N,\Psi} \end{pmatrix}$$



$$|0\rangle, |1\rangle, D=2$$

Compact representation of quantum states

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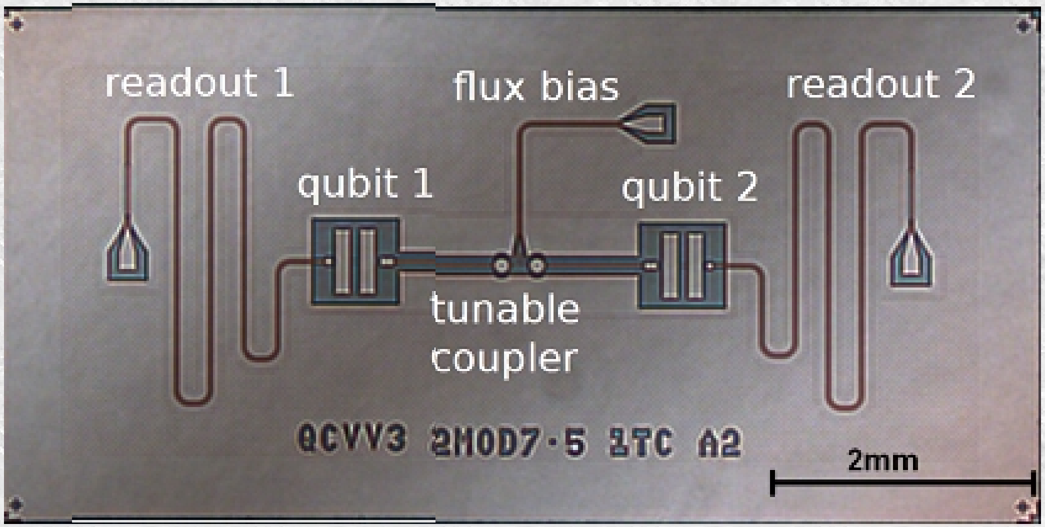

$$|00\rangle, |10\rangle, |01\rangle, |11\rangle, D = 2^2$$

Compact representation of quantum states

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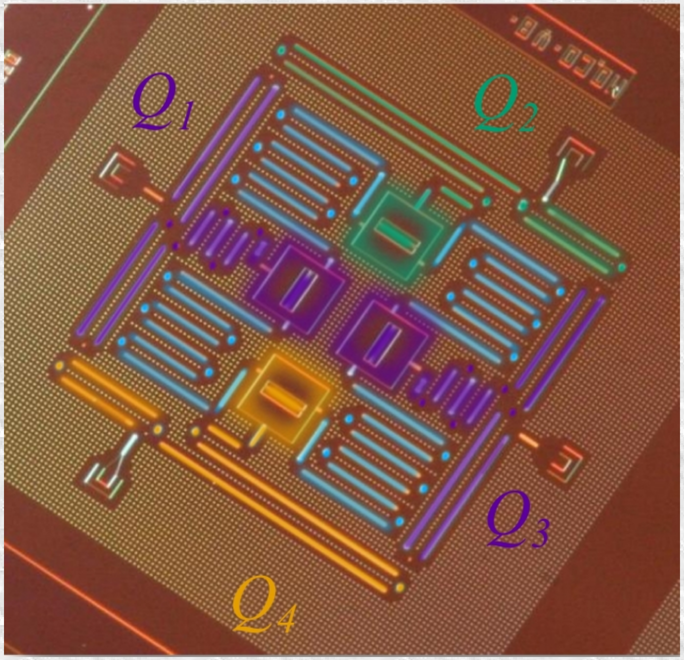
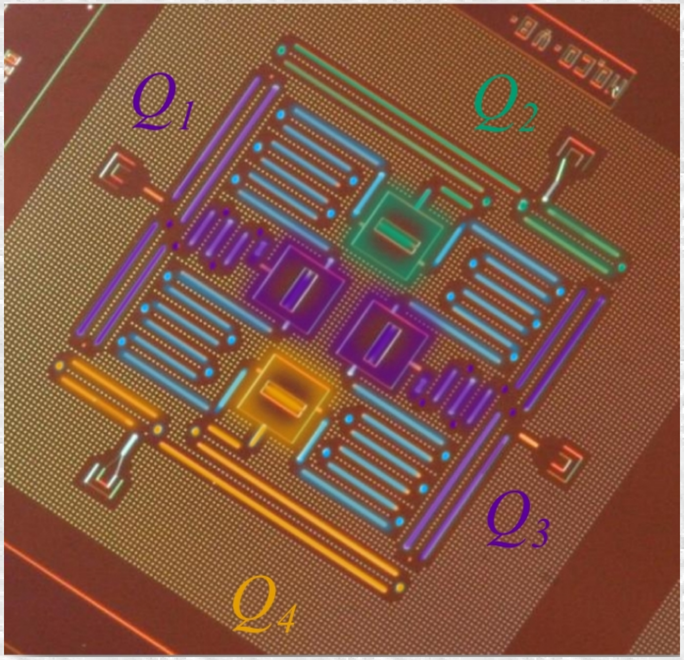


$$|0000\rangle, |1000\rangle, \ldots |1111\rangle \; D = 2^4$$

Compact representation of quantum states



$$|\Psi\rangle = \sum_{\beta=1}^{2^N} C_{\beta,\Psi} |\beta\rangle$$

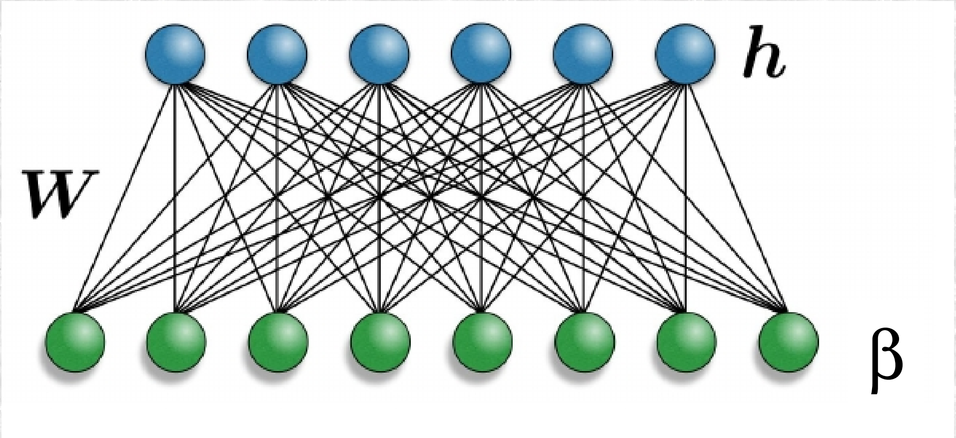
Variational parametrisation

$$C_{\beta,\Psi} = \Phi(\beta,\Omega)$$

$$\Phi(\beta,\Omega) = \sum_{[h_k]} e^{\sum_k a_k \sigma_k^z + \sum_{k'} b_{k'} h_{k'} + \sum_{kk'} W_{kk'} h_k' \sigma_k^z}$$

$$|0000\rangle, |1000\rangle, \ldots |1111\rangle \; D = 2^4$$

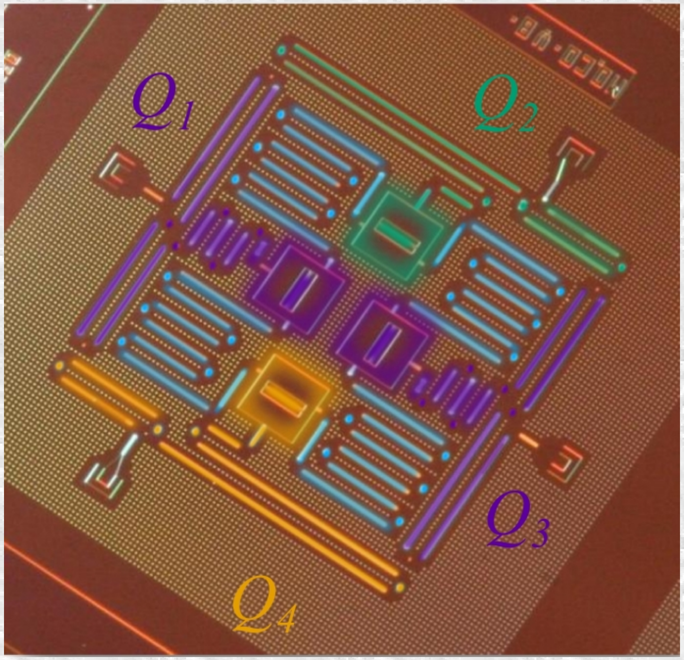
$$\Omega = (a_k, h_{k'}, W_{kk'})$$



Training
==
tweak Ω to minimise the energy

Carleo and Troyer, Science **355**, 602 (2017)

Compact representation of quantum states



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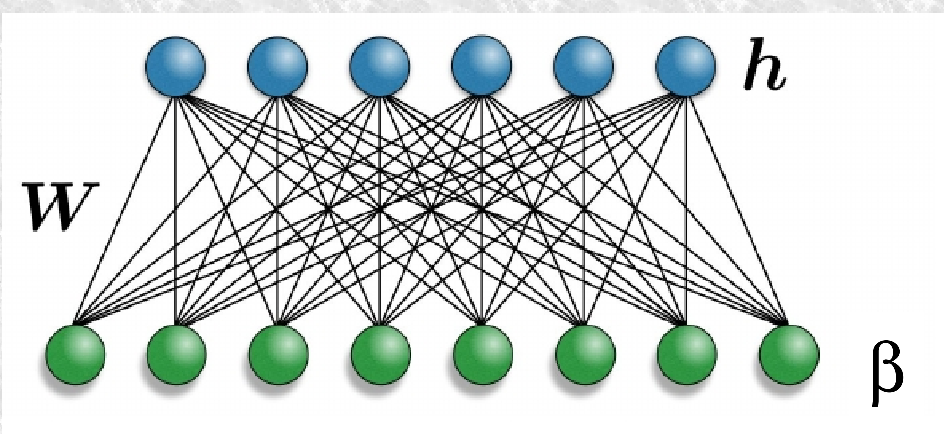
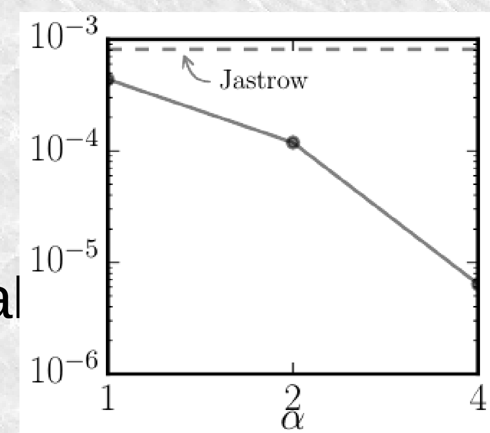


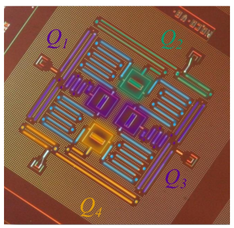
Carleo and Troyer, Science **355**, 602 (2017)

tweal … e energy



Accuracy of the ground state energy

Compact representation of quantum states
Reconstruction/Certification

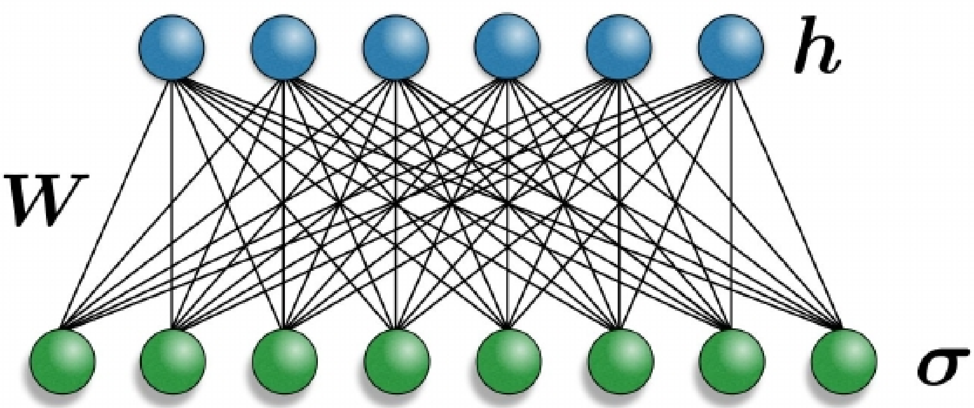


Experiment $= |\psi\rangle$

0 0 0 1 0 1 0 1
0 0 1 1 0 1 1 0
...
1 0 0 1 1 1 0 1

$P_{\mathrm{exp}}(\beta)$

Tweak W to get identical!



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

$$|\psi\rangle_{\mathrm{reconstructed}} = \sum_{\beta} \sqrt{P_W(\beta)}\,|\beta\rangle$$

QuCUMBER

github.com/PIQuIL/QuCumber

Nieuwenburg, *et al* arXiv 1904.08441 (2019)

Reduction of effect of noise
Error correction

$$|\Psi\rangle = \sum_{\beta=1}^{2^N} C_{\beta,\Psi} |\beta\rangle$$

$$|\Psi(0)\rangle = \begin{pmatrix} \alpha \\ \beta \\ 0 \\ \cdots \\ 0 \end{pmatrix}$$

Noise modifies the qubit state.

$$|\Psi(t)\rangle = \begin{pmatrix} \tilde{\alpha} \\ \tilde{\beta} \\ \tilde{\eta} \\ \cdots \\ \tilde{\theta} \end{pmatrix}$$

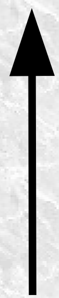
$$|\langle \Psi(0) | \Psi(T) \rangle|^2 = e^{-\Gamma T}$$

Goal: To protect arbitrary quantum states against deleterious effects of environmental noise during a period of time T

Reduction of effect of noise
Error correction

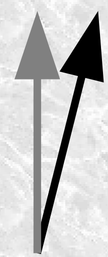
$$|\Psi\rangle = \sum_{\beta=1}^{2^N} C_{\beta,\Psi}|\beta\rangle$$

$$|\Psi(0)\rangle = \begin{pmatrix} \alpha \\ \beta \\ 0 \\ \dots \\ 0 \end{pmatrix}$$



Noise + **actions**

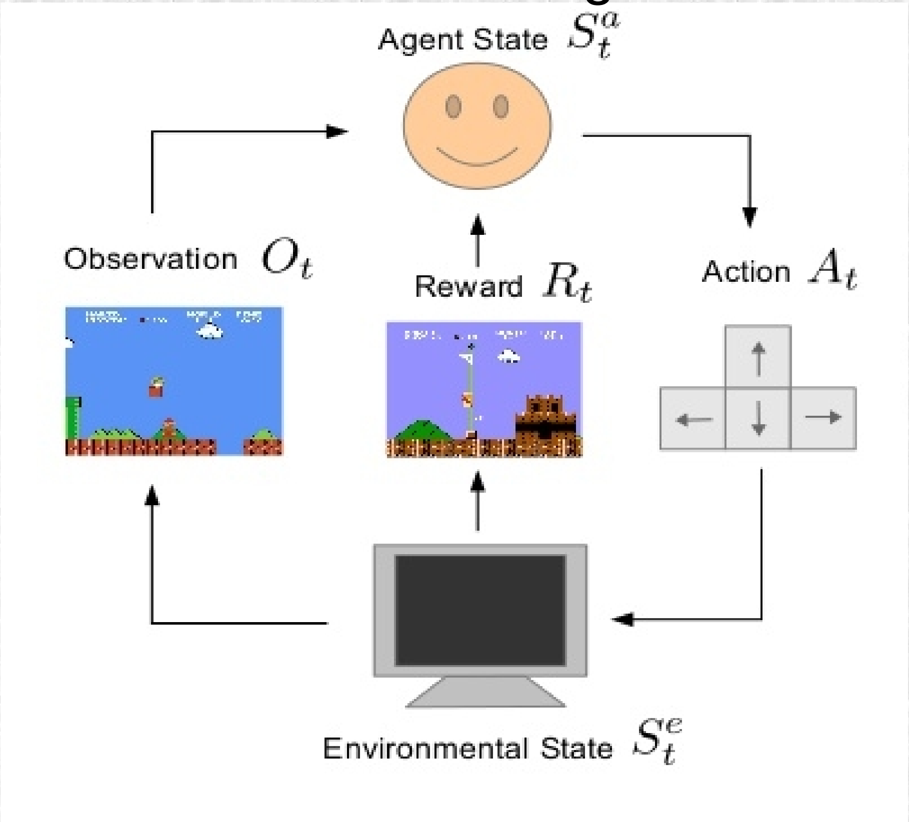
$$|\Psi(t)\rangle = \begin{pmatrix} \tilde{\alpha} \\ \tilde{\beta} \\ \tilde{\eta} \\ \dots \\ \tilde{\theta} \end{pmatrix}$$



$|\Psi(0)\rangle, |\Psi(T)\rangle$ Contain the same information

Reduction of effect of noise
Error correction with RL

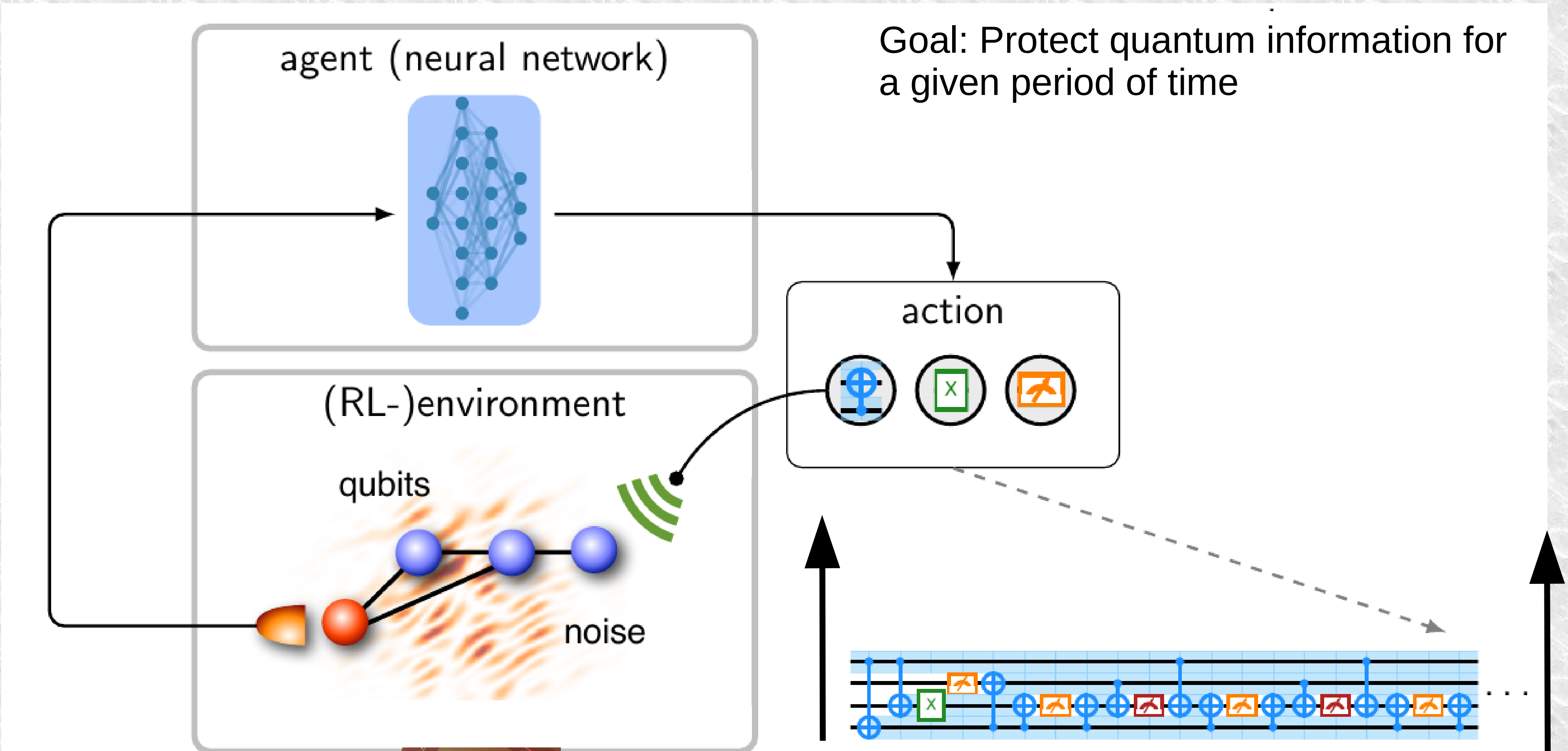
Reinforced learning

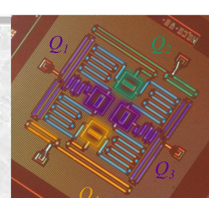


MPI – Earlangen, Fosel, *et al* PRX **8**, 031084 (2018)

Reduction of effect of noise
Error correction

Goal: Protect quantum information for a given period of time

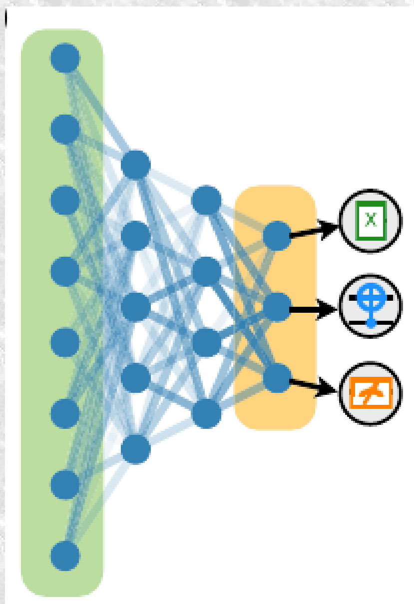


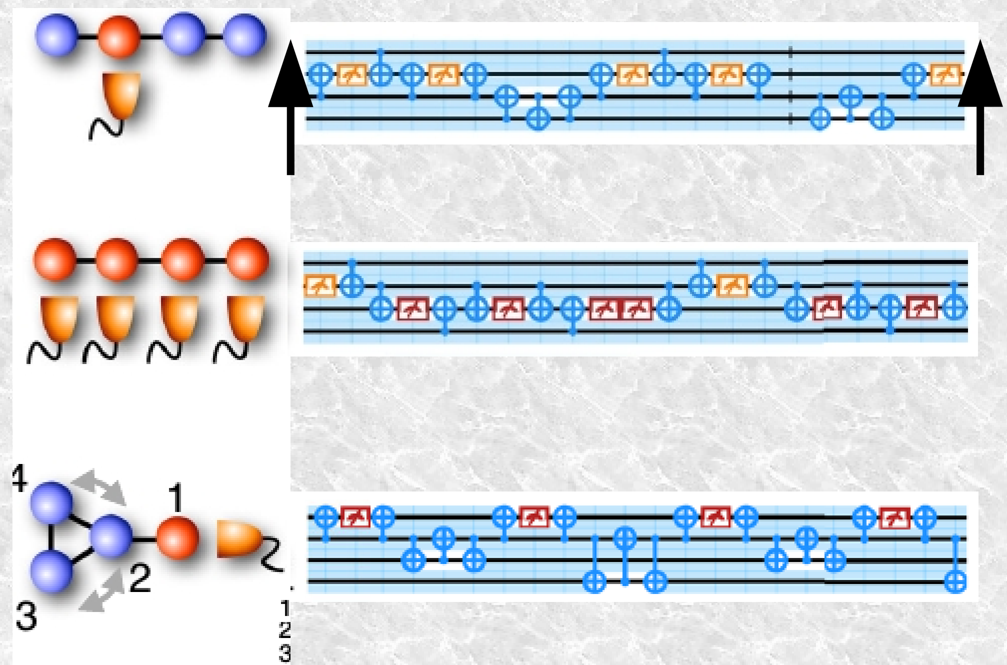


MPI – Earlangen, Fosel, *et al* PRX **8**, 031084 (2018)

Reduction of effect of noise
Error correction

State aware network:
We know the multiqubit state





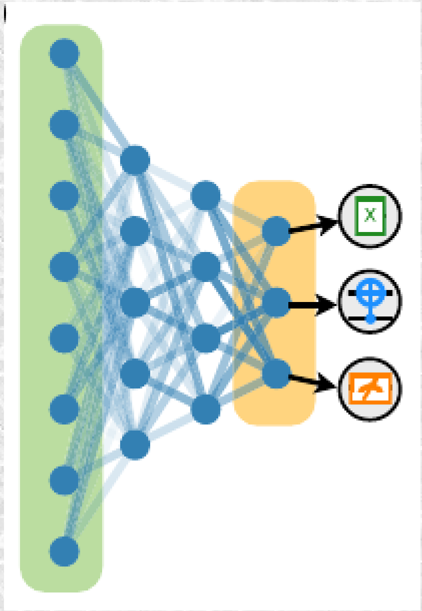
$$|\Psi\rangle = \sum_{\beta=1}^{2^N} C_{\beta,\Psi} |\beta\rangle$$

This procedure can be applied to any model

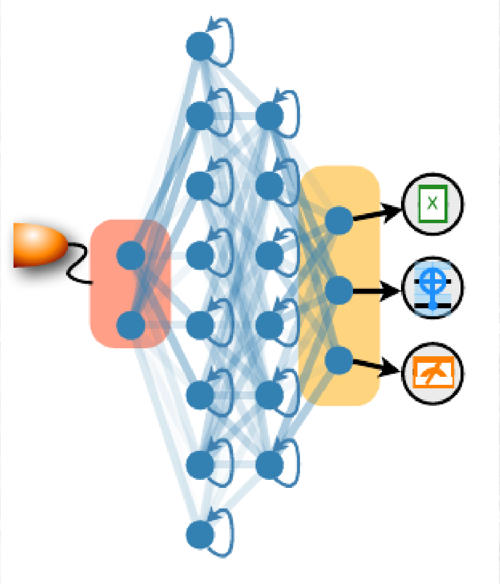
MPI – Earlangen, Fosel, *et al* PRX **8**, 031084 (2018)

Reduction of effect of noise
Error correction

State aware network



Event aware network



Produce training examples
To train a second NN

The event aware network becomes a controller that decides on gate sequences depending on measurements

MPI – Earlangen, Fosel, *et al* PRX **8**, 031084 (2018)

ML is a hot-topic in quantum science:

- ML achieve better performances than established numerical tools to study/design Quantum Devices
- Studying how the learning process can give insights about quantum physics.
- Speeding the process of tuning QD
- Estimation model parameters
- Error correction schemes
- …..

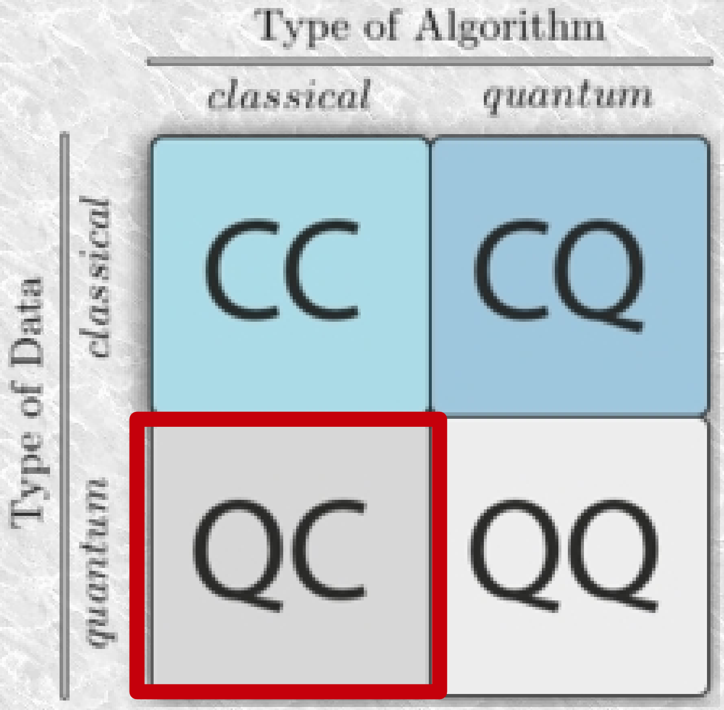
Review

- Dunjko and Breigel, *Machine Learning & AI in the quantum domain*, Rep. Prog. Phys **81**, 074001 (2018)

Learning material

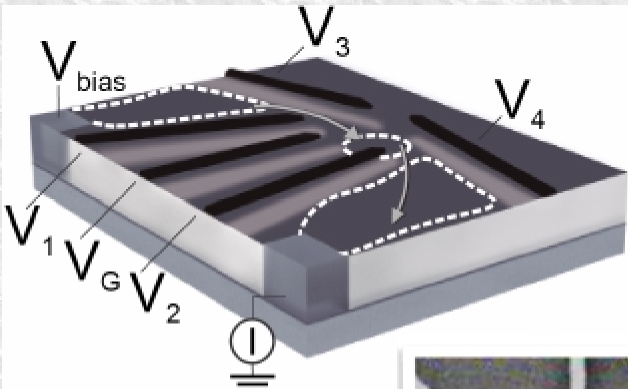
- Florian Maquart website, https://machine-learning-for-physicists.org/

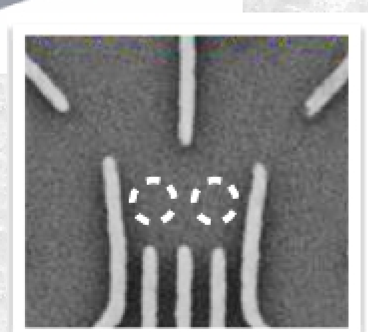
ML plus Quantum Science



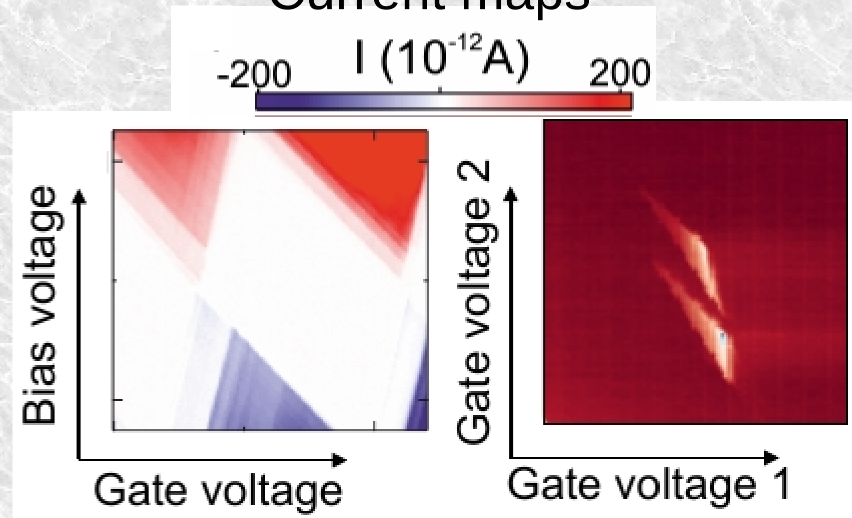
Thanks for listening!

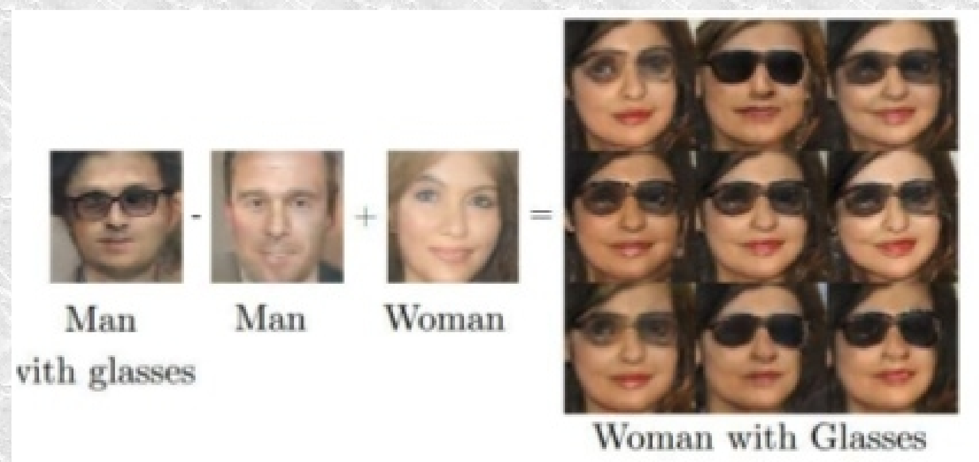
Characterisation of quantum devices





Current maps

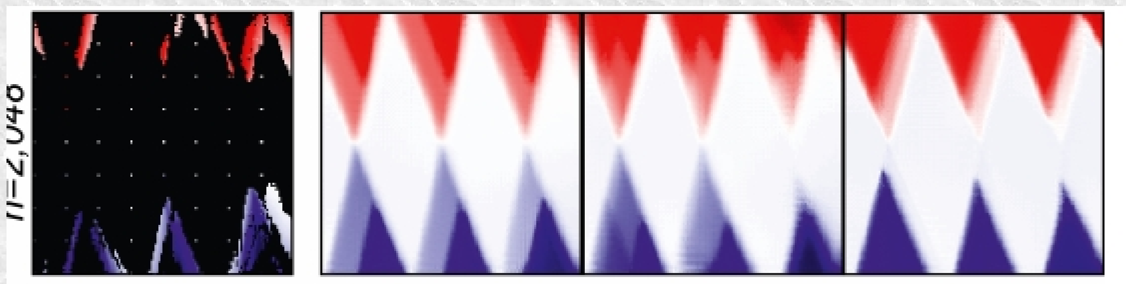




Ares' group (Oxford) arXiv 1810.10042 (2018)

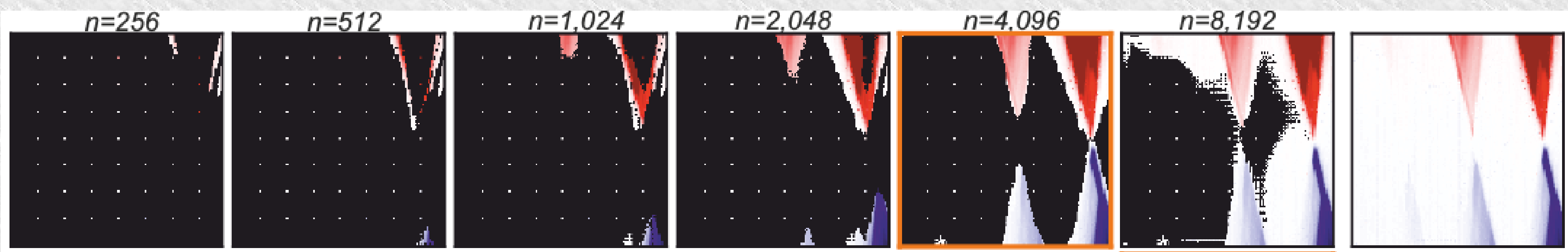
Characterisation of quantum devices

Use experimental data to reconstruct full resolution current maps and select next combination of parameters to measure.



Data Reconstructed current maps

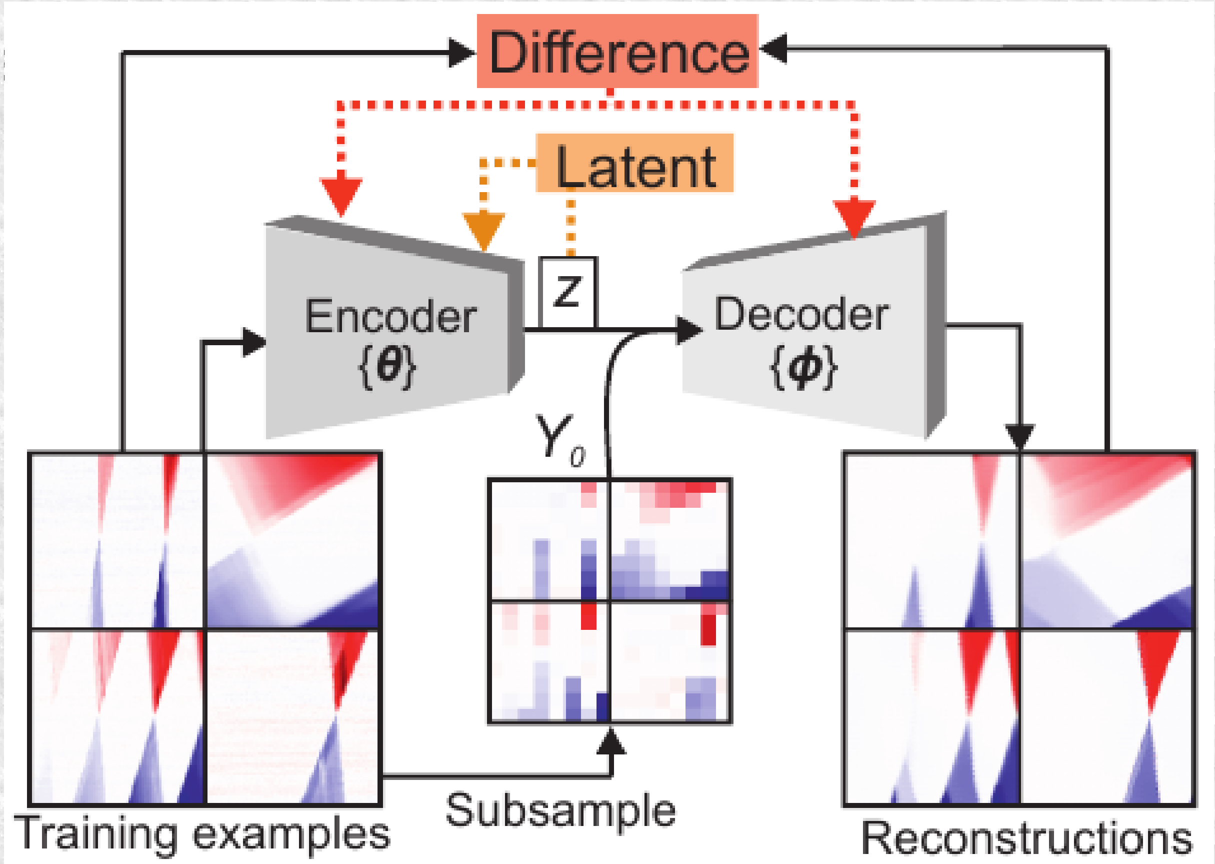
Next set of measurements is selected identifying the regions with the largest average current gradient



Ares' group (Oxford) arXiv 1810.10042 (2018)

Characterisation of quantum devices

Training an autoencoder



1. Encoder: CNN to build a compact representation of the training examples (Latent set Z).
2. Decoder: Feed with the latent set Z + low resolution sample. Trained to reduced the difference between the training current map and one reconstruction.

Ares' group (Oxford) arXiv 1810.10042 (2018)