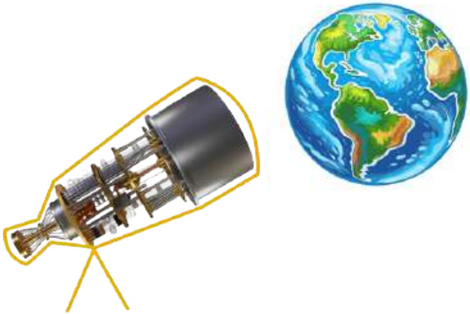
Exploring Quantum Machine Learning through Earth Observation Case Studies.

Artur Miroszewski

Artificial Intelligence in Research and Applications Seminar
26.06.2025



JAGIELLONIAN UNIVERSITY IN KRAKÓW

Quantum Cosmos Lab

- Quantum machine learning for analyzing multi- and hyperspectral satellite images

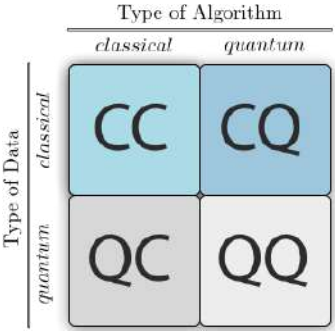
JAGIELLONIAN UNIVERSITY IN KRAKÓW — KP LABS Mission Complete — esa European Space Agency

- QA4EO: Quantum Advantage for Earth Observation

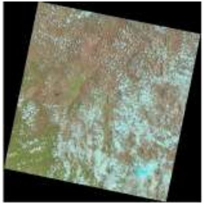
DLR — VTT — CSC — SYDERAL POLSKA — CENTRUM ETOS projekty • eZdrowie — JAGIELLONIAN UNIVERSITY IN KRAKÓW

- GBS4EO: Gaussian Boson Sampling for Earth Observation

KP LABS Mission Complete — JAGIELLONIAN UNIVERSITY IN KRAKÓW — VŠB TECHNICKÁ UNIVERZITA OSTRAVA | IT4INNOVATIONS NÁRODNÍ SUPERPOČÍTAČOVÉ CENTRUM



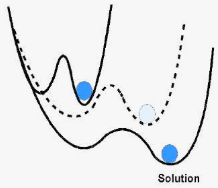
- Earth observation data
  - Multispectral
  - Hyperspectral
  - Synthetic Aperture Radar
  - Lidar



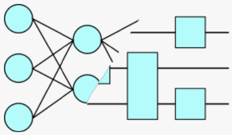
- Algorithms
  - Classical ML — baseline
  - Fully quantum — not in the near future
  - Hybrid

Most researched approaches

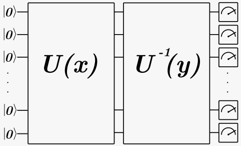
Quantum Annealing



Quantum Neural Networks



Quantum Kernel Methods



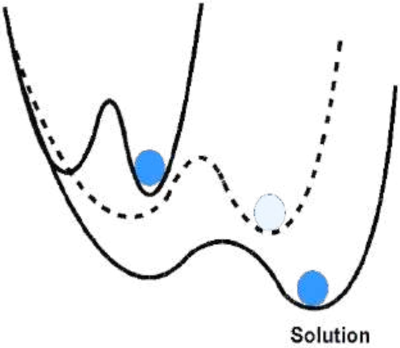
Adiabatic theorem

A physical system remains in its instantaneous eigenstate if a given perturbation is acting on it slowly enough and if there is a gap between the eigenvalue and the rest of the Hamiltonian's spectrum.

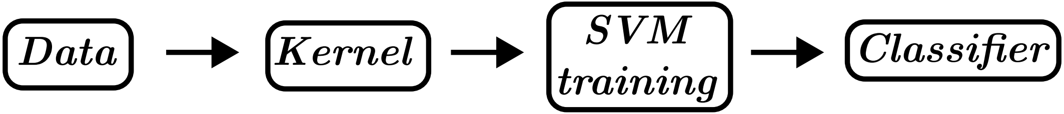
$$H(t) = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_1,\; T = \mathcal{O}\left(\frac{1}{\Delta_{min}^2}\right)$$

$$H(t) = -\sum_{i,j} J_{ij}\sigma_i\sigma_j - \mu\sum_i h_i\sigma_i,\; \sigma_i = \{-1, 1\}$$

Easy implementation for Quadratic unconstrained binary optimization (QUBO) problems.



Adiabatic evolution


Data
Kernel
SVM training
Classifier

- Classification supervised learning algorithm
- Maximization of margins

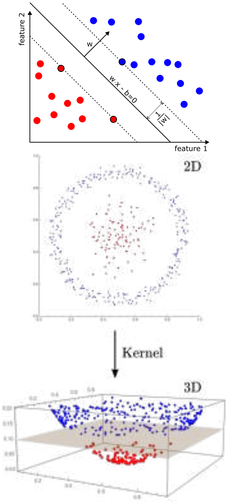
$$\min_{w,b} \frac{1}{2}|w|^2,$$

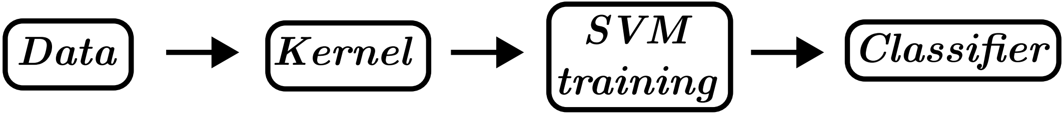
$$\textit{such that}: \; y^{(i)}(w \cdot w^{(i)} + b) \geq 1, i = 1, \ldots, m$$

- Kernel trick: exchange inner product for some ‘arbitrary‘ similarity measure

$$\langle x^{(i)}, x^{(j)} \rangle \mapsto K_{ij} = \langle \phi\left(x^{(i)}\right), \phi\left(x^{(j)}\right) \rangle$$

- The transformation ϕ:
  - leads to higher dimensional space - improved separability
  - allows for nonlinear class boundaries

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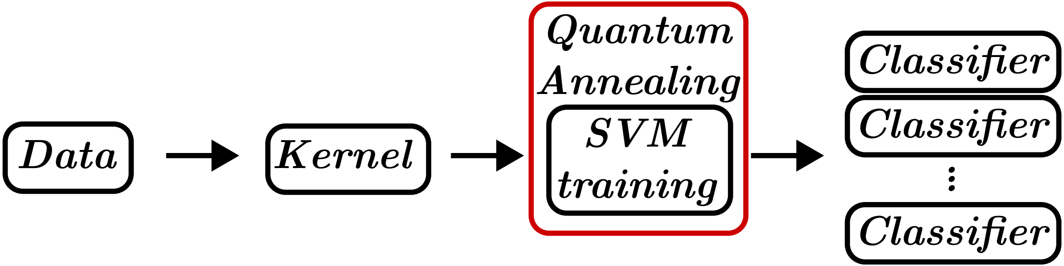
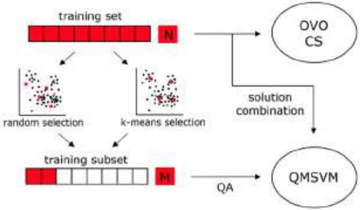
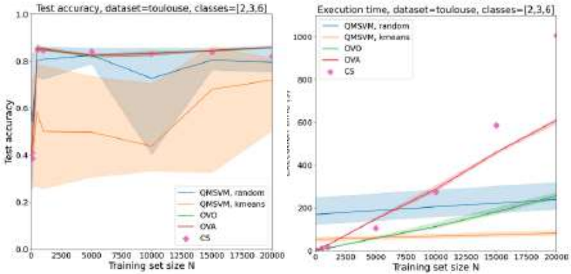
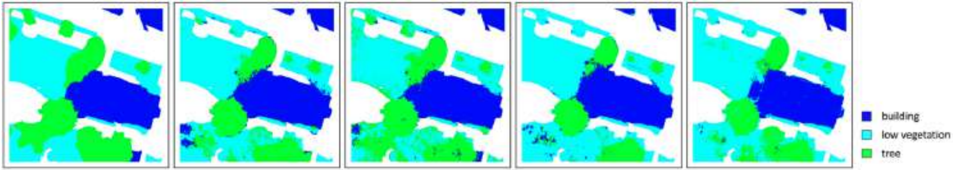

Data
Kernel
Quantum Annealing
SVM training
Classifier
Classifier
Classifier







GT *OVO* *OVA* *CS* *QMSVM*

Delilbasic, Amer, et al. *A single-step multiclass SVM based on quantum annealing for remote sensing data classification.* IEEE JSTARS (2023)

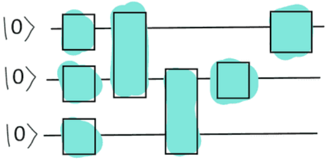
Study / Ref.	Task / Dataset	ML Problem	QML Method	QML Acc.	Class. Acc.	SOTA	Mode	Notes
Otgonbaatar, et al. (2021) [47]	Indian Pines / Land Cover	Binary classification	QA	**92%**	90%	—	⚛	Multiple binary comparisons, on par
Otgonbaatar, et al. (2021) [47]	PolSAR / Land Cover	Binary classification	QA	**99%**	**99%**	—	⚛	—
Delilbasic, et al. (2021) [19]	SemCity Toulouse / Land Cover	Binary classification	QA	87.4%	**87.6%**	—	⚛	—
Delilbasic, et al. (2024) [45]	SemCity Toulouse / Land Cover	Multiclass classification	QA	**86.6%**	86.0%	—	⚛	Advantage in computational time scaling claim
Delilbasic, et al. (2024) [45]	ISPRS Postdam / Land Cover	Multiclass classification	QA	81.2%	**85.2%**	—	⚛	Advantage in computational time scaling claim
Pasetto, et al. (2022) [46]	SeaBAM / Chlorophyll concentration	Regression	QA	MSE 10.88	**MSE 8.40**	—	⚛	On par

Gate model of computation

- Capable of universal computation

$$QC \overset{\text{Simulation}}{\leftrightarrows} CC$$

- Quantum circuits consist of:
  - qubit registers
  - quantum gates
- Gates can be parameterized with continuous parameters

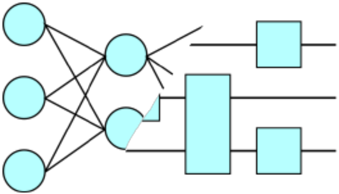


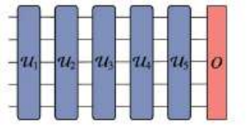
Parameterized Quantum Circuits

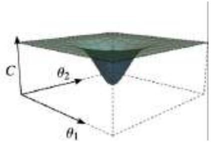
- Some gates can be parameterized with parameters
  - Datum as a parameter
  - Tunable parameter
- Gates gathered into repeating layers
- Tunable parameter landscape - training of QNN

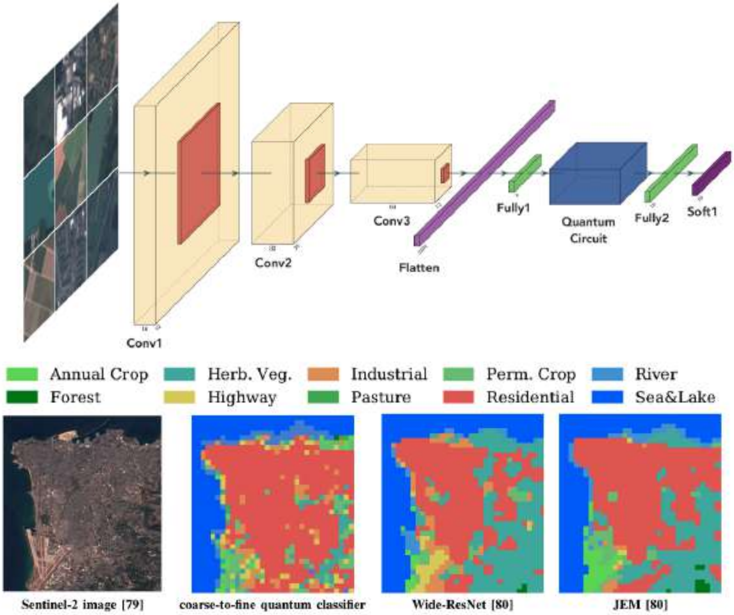
$$\mathcal{L}_{\mathrm{MSE}} = (\hat{y} - y)^2, \ \hat{y} = \langle \psi(\Theta) | \hat{O} | \psi(\Theta) \rangle$$

- Unitarity?



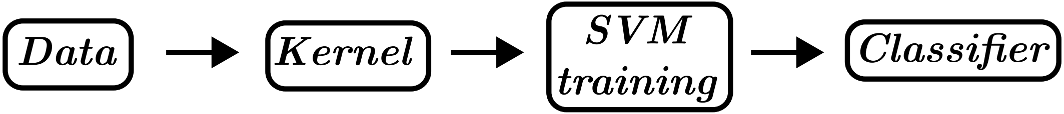


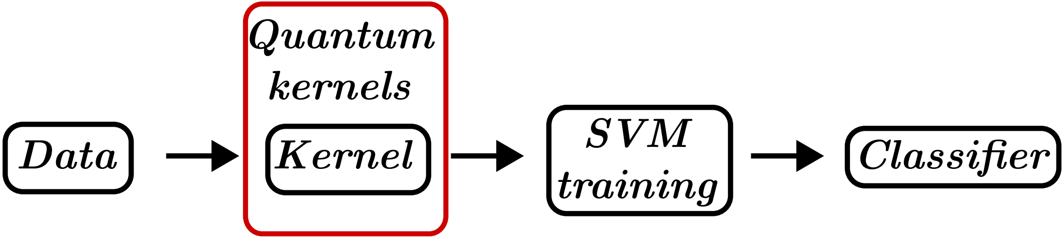




Sebastianelli, Alessandro, et al. *On circuit-based hybrid quantum neural networks for remote sensing imagery classification.* IEEE JSTARS (2021)

Study / Ref.	Task / Dataset	ML Problem	QML Method	QML Acc.	Class. Acc.	SOTA	Mode	Notes
Chang, et al. (2022) [88]	EuroSAT, SAT4 / Land cover	Binary classification	QCNN	98%	—	**98.5%** [89]		On par
Sebastianelli, et al. (2021) [72]	EuroSAT / Land cover	Multiclass classification	QCNN	92%	83%	**98.5%** [89]		—
Sebastianelli, et al. (2023) [90]	Volcanic Eruption Prediction	Binary classification	QCNN	**96%**	88%	85%		—
Mauro, et al. (2025) [91]	ΦSat-2 / Water Quality Monitoring	Regression	QCNN	RMSE 0.198	RMSE 0.214	—		Advantage in decrease of model parameters claim

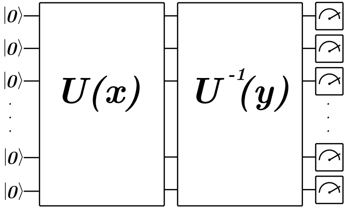

Data
Kernel
SVM training
Classifier

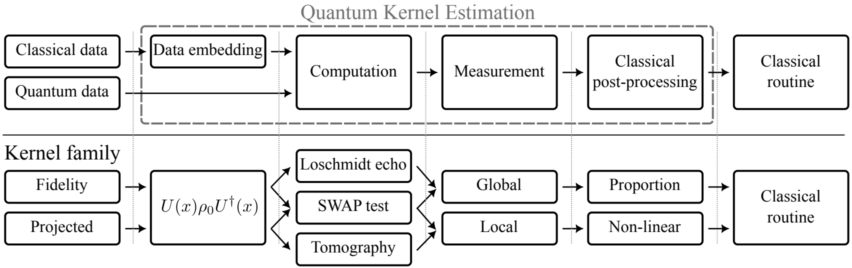

Data
Quantum kernels
Kernel
SVM training
Classifier

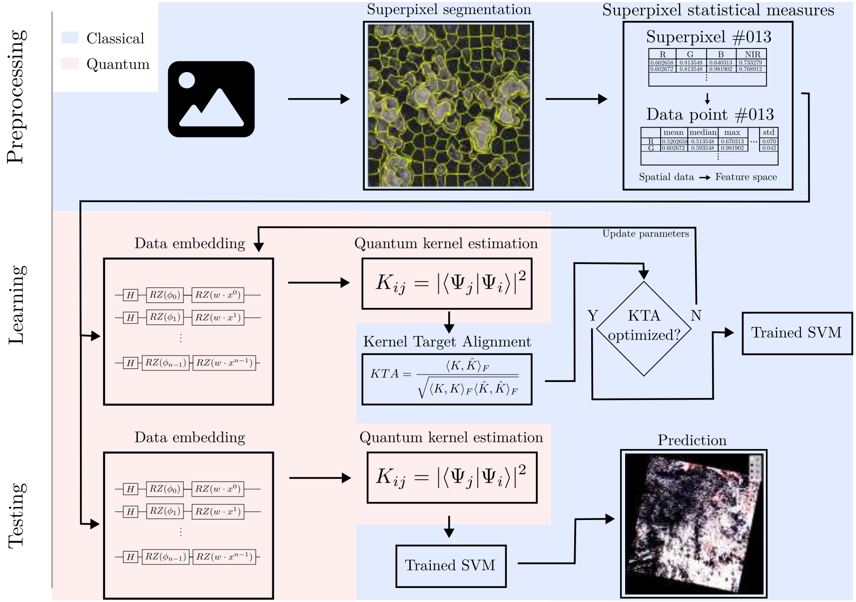
Quantum kernel methods

Quantum Kernel Estimation

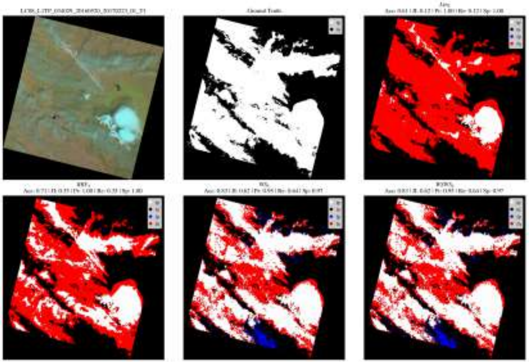
- Parameterized Quantum Circuits $\mapsto$ encode data
- Measure specific properties of the encoded state
- Infer similarity between quantum states

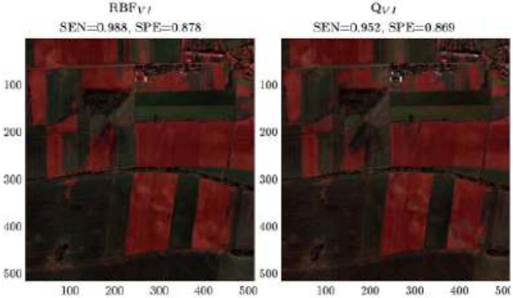






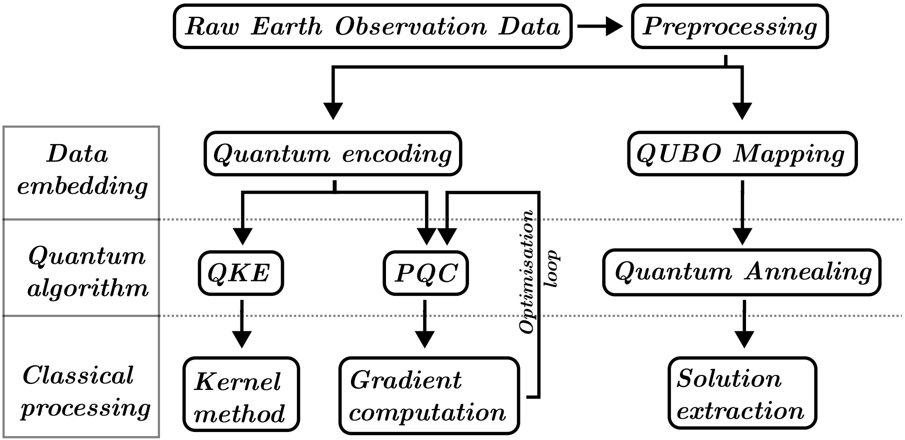
Miroszewski, Artur, et al. *Detecting clouds in multispectral satellite images using quantum-kernel support vector machines.* IEEE JSTARS (2023)





Miroszewski, Artur, et al. *Detecting clouds...* IEEE JSTARS (2023);
Wijata, Agata M., et al. *Detection of bare soil...* IEEE IGARSS (2024)

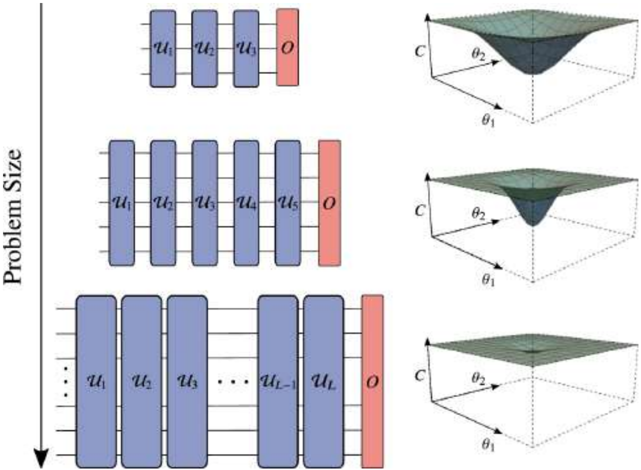
Study / Ref.	**Task / Dataset**	**ML Problem**	**QML Method**	**QML Acc.**	**Class. Acc.**	**SOTA**	**Mode**	**Notes**
Rodriguez-Grasa, et al. (2024) [92]	Photovoltaic Array [93]	Binary classification	QK	$86.5(2.5)\%$	$\mathbf{89.4}(\mathbf{2.5})\%$	—		—
Wijata, et al. (2024) [92]	Hyperview / Bare soil detection	Binary classification	QK	$88.2(3.5)\%$	$\mathbf{90.4}(\mathbf{3.4})\%$	—		—
Gupta, et al. (2022) [94]	Artificial / Land cover	Binary classification	QK	$\sim \mathbf{80}\%$	$\sim 50\%$	—		Advantage for QK aligned dataset
Miroszewski, et al. (2023) [20]	38-Clouds / Cloud detection	Binary classification	QK	$91.1(3.1)\%$	$91.9(1.0)\%$	$\mathbf{96}\%$ [95]		—


Raw Earth Observation Data
Preprocessing
Data embedding
Quantum encoding
QUBO Mapping
Quantum algorithm
QKE
PQC
Optimisation loop
Quantum Annealing
Classical processing
Kernel method
Gradient computation
Solution extraction

Problems: Quantum Computation speed

Parameters	SC	T.ions	Photonic	N.atoms	S.spin	NV	CPUs
Clock cycle	1MHz	1KHz	10Hz	1MHz	0.76MHz	1MHz	3GHz
Measurement	660ns	300μs	x	200ms	1.3μs	x	x
2-qubit gate	34ns	200μs	x	$<$ 100μs	x	700ns	x
1-qubit gate	25ns	15μs	x	x	x	9ns	x
Readout fidelity	99.4%	97.3%	50.0%	99.1%	99%	98%	x
1Q fidelity	99.99%	99.99%	99.84%	99.83%	99.99%	99.99%	x
2Q fidelity	99.97%	99.9%	99.69%	99.4%	99.5%	99.2%	x

Problems: Curse of dimensionality



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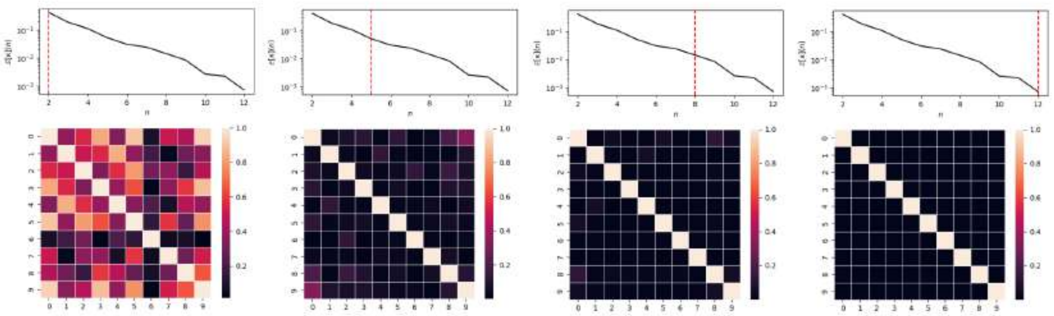
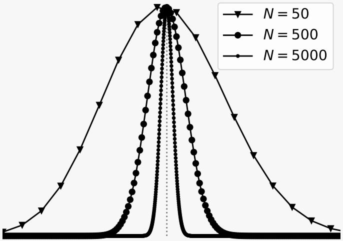


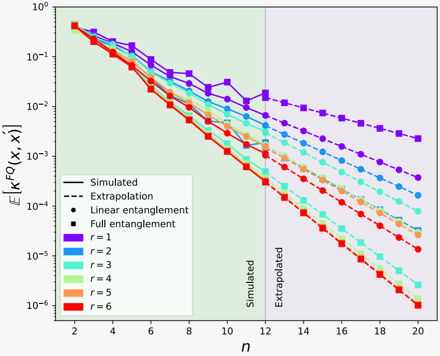
Measurement in the QKE

QKE inextricably linked with the proportion estimation in the Bernoulli process

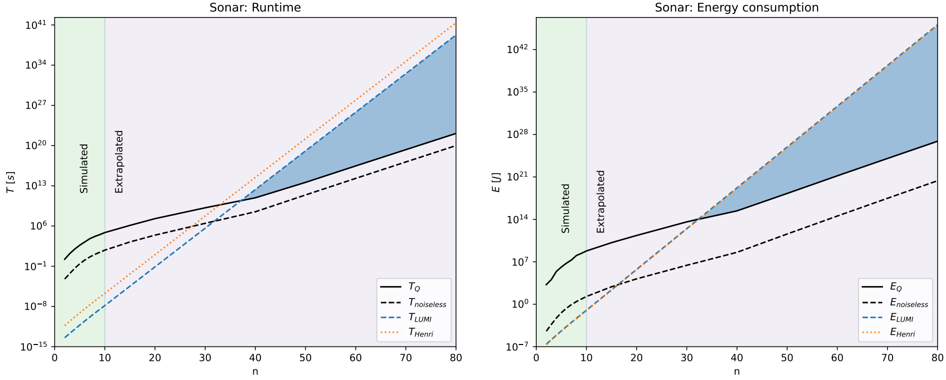


Exponential value concentration

The kernel values statistically concentrate around the constant value



measurement uncertainty + exponential value concentration ⇒ exponential number of measurements



Miroszewski, Artur, et al. *In search of quantum advantage:...* arXiv:2407.15776 (2024).

Problems: Noise

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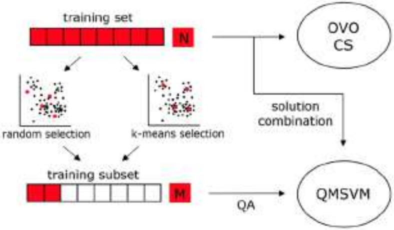
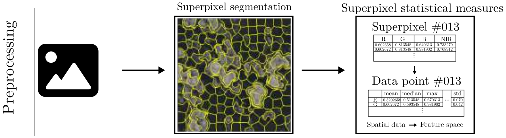
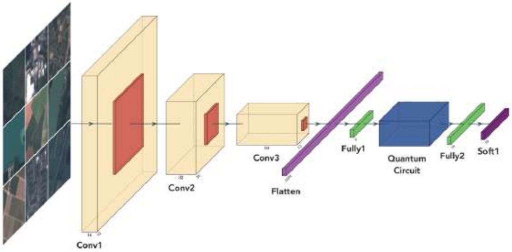
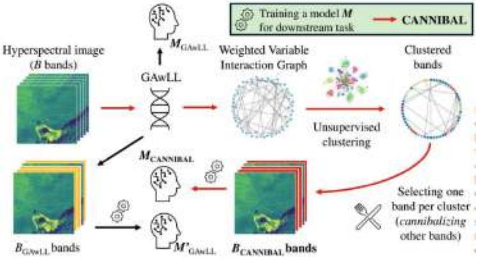
Problems: Large data

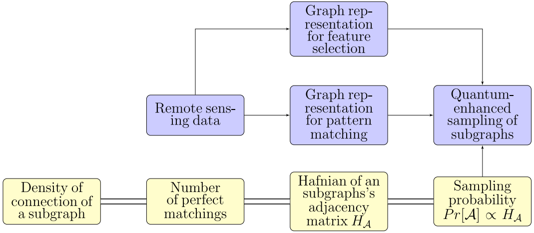


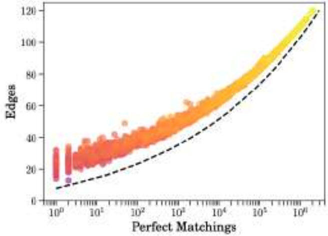




Future directions







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