QAMP 2025

Local and Multi-Scale Strategies to Mitigate Exponential Concentration in Quantum Kernels

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Speaker name:
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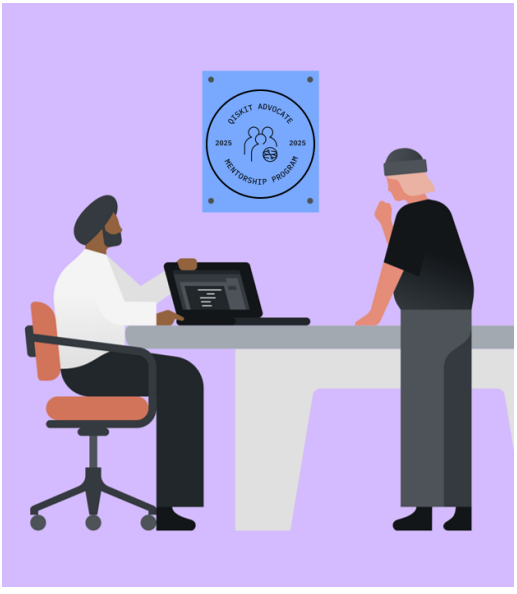
Team members:

- Claudia Zendejas-Morales
- Debashis Saikia
- Sarvagya Kaushik

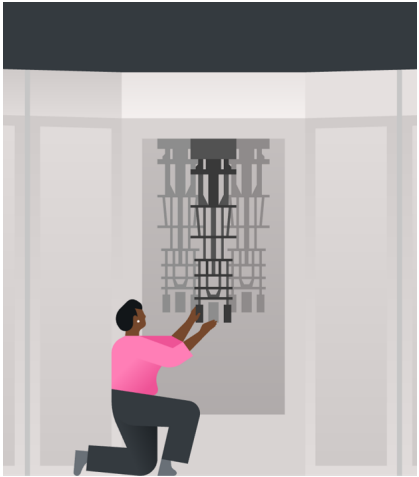
Mentor: Utkarsh Singh



Team Introduction

- **Claudia Zendejas-Morales**
  (MSc QIS, University of Copenhagen)
  Multi-Scale Kernels: combines kernels across scales and performs ablation tests.
- **Debashis Saikia**
  (BS-MS Physics, IISER, Thiruvananthapuram)
  Local Kernels: builds patch-wise kernels using subcircuits/RDMs and aggregates them.
- **Sarvagya Kaushik**
  (B.Tech. Engineering Physics IIT, Dhanbad)
  Global Baseline: implements fidelity kernel and prepares baseline diagnostics.

Mentor: **Utkarsh Singh**



Project Overview

- **Problem Overview**
  - Quantum Kernel method is a powerful tool that uses quantum states to embed classical data into high-dimensional Hilbert space and use their overlaps as a similarity score, enabling powerful non-linear learning.
  - Global Quantum Kernels especially Fidelity Quantum Kernel collapse as system grows due to expressivity, entanglement and layer-wise noise.[1]
  - The off diagonal entries shrink → kernel matrices become almost identity → the model becomes non-informative, and fails to learn.
  - This **exponential concentration** makes standard quantum kernels unusable beyond tiny circuits.
- **Project Goal**
  - Design and evaluate Local and Multi-Scale quantum kernels that preserve useful variance, stay robust on realistic qubit counts, and outperform or match global kernels on small datasets.

[1] Thanasilp, Wang, Cerezo, Holmes, *Exponential concentration in quantum kernel methods*, Nature Communications, 2024.

Deliverables

- **MVP**
  - A working Qiskit notebook that demonstrates exponential concentration in the kernel.
  - One dataset where Local or Multi-Scale wins clearly (or shows stronger robustness).
- **Expected Deliverables**
  - Qiskit implementations of Local and Multi-Scale quantum kernels.
  - Visualization of kernel matrices, off-diagonal histograms, and eigenvalue spectra showing differences between fidelity, local, and multi-scale kernels.
  - A preprint (arXiv ready draft) summarizing the problem, methods, results and open questions with reproducible appendix (settings, seeds, versions).
  - GitHub repository containing all code and experiments.

Progress Update

- Multi-Scale kernel (v1): RDM + HS mix, unit-diag norm, optional centering & rank report
- Local kernel (v1): first version ready (under review)
- Diagnostics: heatmap, off-diagonal histogram, eigen-spectrum
- SVM eval (precomputed): C sweep, CSV metrics
- Scripts & recipes
- PRs merged: code, tests, figures

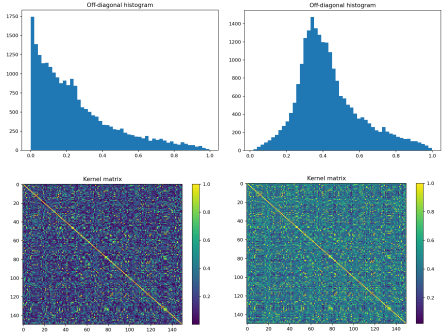


Figure: Baseline (left) vs Multi-Scale (right) on **`make_circles`**: off-diagonal similarities shift away from 0 and the kernel matrix shows richer structure, less concentration, more informative variance.

Approach and Methodology

- Feature maps: ZZ (Qiskit & manual-canonical), depth=1, linear/ring
- Local: per-patch RDMs → Hilbert-Schmidt inner product → aggregate
- Multi-Scale: non-negative mix of *local (1q)* + *global (all)* scales
- Datasets: `make_circles` (d=2), `iris` (d=4)
- Metrics/diagnostics: SVM accuracy, off-diagonal histogram (concentration), eigen-spectrum (effective rank); optional centering (HKH)
- Collaborative work: async workstreams (Baseline / Local / Multi-Scale) with shared APIs & tests

Next Steps

- Finalize Baseline + Local & Multi-scale implementations
- Ablations: only-local vs only-global vs multi-scale (fixed splits & seeds)
- Stability: optional centering, effective rank reporting, small noise robustness
- Datasets: verify exponential concentration, use 20-30 features
- Benchmarks: complete Iris & one extra small tabular (if time)
- Writing: mid-report with figures & methods, prep MVP figures

GO: team aligned, scope clear, initial pipeline working

Qiskit Advocate Mentorship Program 2025