US CLIVAR Workshop on Quantum Computing and Sensing for Weather and Climate Applications

From Near-Term to Fault-Tolerance:

When Axis-Aligned QML Can Outperform Classical Counterparts in Earth Observation

Authors: Xin Jin, Yuqing Li, Xiaowei Jia, Junyu Liu

Presenter: Yuqing Li · University of Pittsburgh

Quantum Computing for Earth System Models session · August 3, 2026 · Boulder, CO

CLAIM UNIT

QML family → Preserved EO axis → Matched classical peer → Hardware horizon

Not "does QML work?" When, where, and under which resource model?

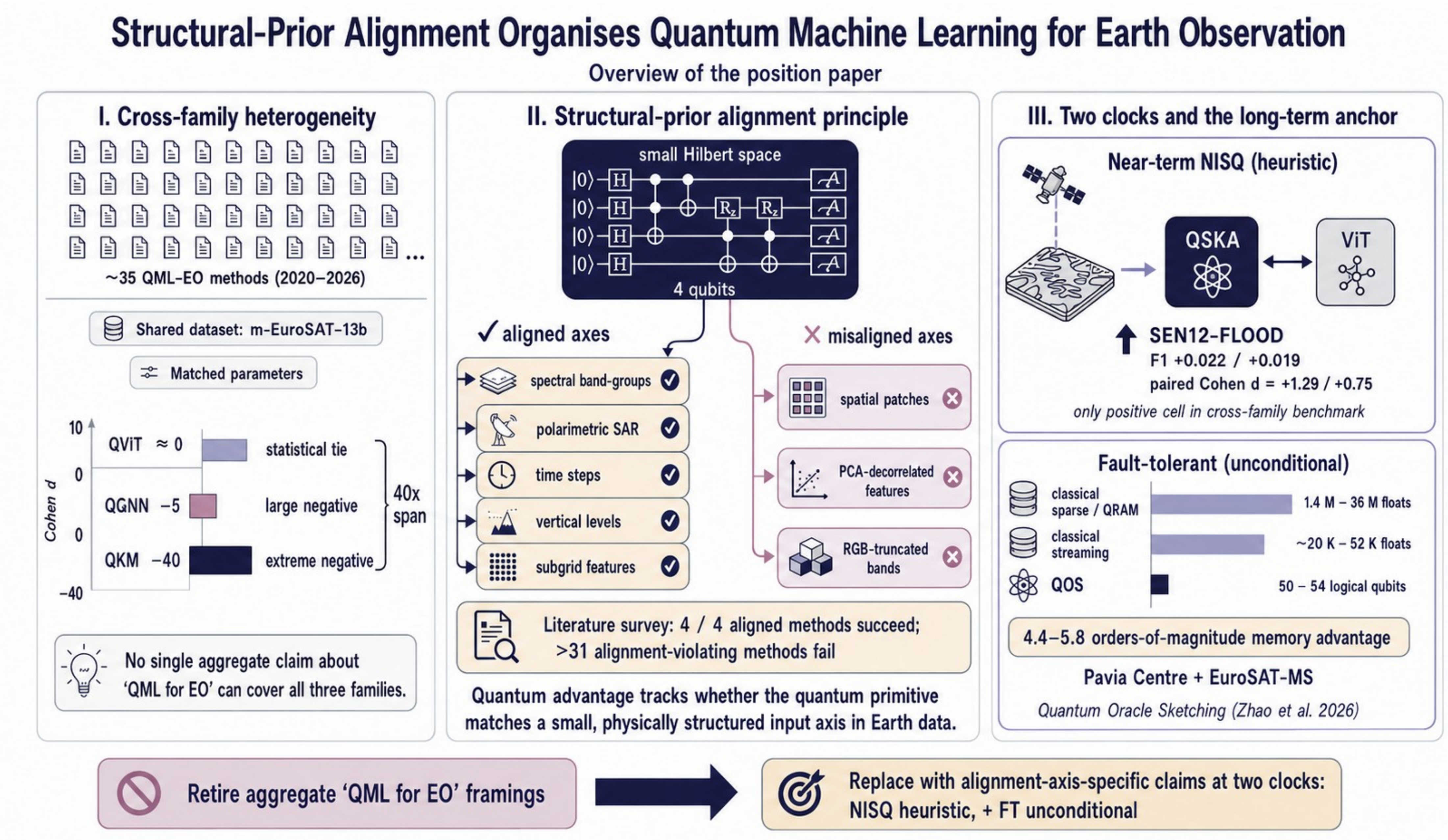
The useful question is narrower than “does QML work?”

Earth observation is a hard classical learning domain; the task itself has three defining characteristics.

EARTH OBSERVATION TASK FEATURES	Large	Physically structured spectra	Label scarcity

instead of one field-level claim → state the competitive cell

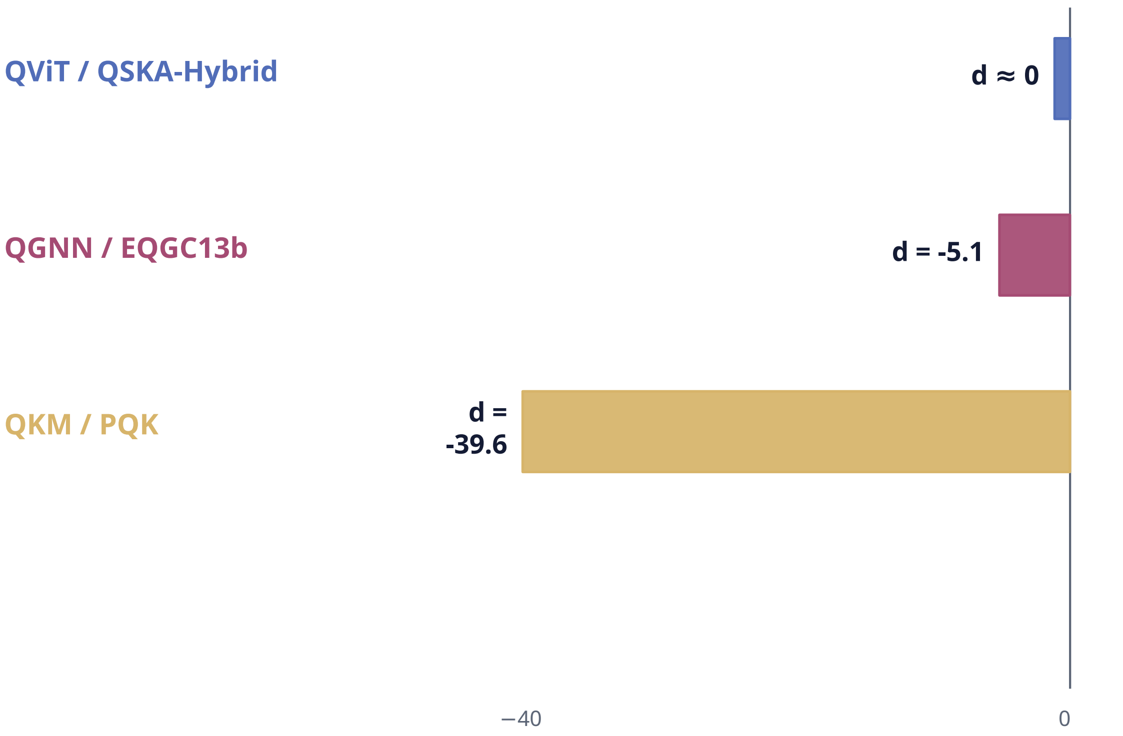
model family + preserved axis + matched baseline + hardware/data-access horizon


Structural-Prior Alignment Organises Quantum Machine Learning for Earth Observation
Overview of the position paper
I. Cross-family heterogeneity
~35 QML-EO methods (2020–2026)
Shared dataset: m-EuroSAT-13b
Matched parameters
10
0
0
−40
Cohen d
QViT ≈ 0
statistical tie
QGNN −5
large negative
QKM −40
extreme negative
40x span
No single aggregate claim about 'QML for EO' can cover all three families.
II. Structural-prior alignment principle
small Hilbert space
|0⟩
H
Rz
4 qubits
✓ aligned axes
spectral band-groups
polarimetric SAR
time steps
vertical levels
subgrid features
✕ misaligned axes
spatial patches
PCA-decorrelated features
RGB-truncated bands
Literature survey: 4 / 4 aligned methods succeed; >31 alignment-violating methods fail
Quantum advantage tracks whether the quantum primitive matches a small, physically structured input axis in Earth data.
III. Two clocks and the long-term anchor
Near-term NISQ (heuristic)
QSKA
ViT
SEN12-FLOOD
F1 +0.022 / +0.019
paired Cohen d = +1.29 / +0.75
only positive cell in cross-family benchmark
Fault-tolerant (unconditional)
classical sparse / QRAM
1.4 M – 36 M floats
classical streaming
~20 K – 52 K floats
QOS
50 – 54 logical qubits
4.4–5.8 orders-of-magnitude memory advantage
Pavia Centre + EuroSAT-MS
Quantum Oracle Sketching (Zhao et al. 2026)
Retire aggregate 'QML for EO' framings
Replace with alignment-axis-specific claims at two clocks: NISQ heuristic, + FT unconditional

Matched-resource family results split immediately

The three representative families use the same EO benchmark but act on different axes through different access representations.

Cohen d: quantum cell vs matched classical peer



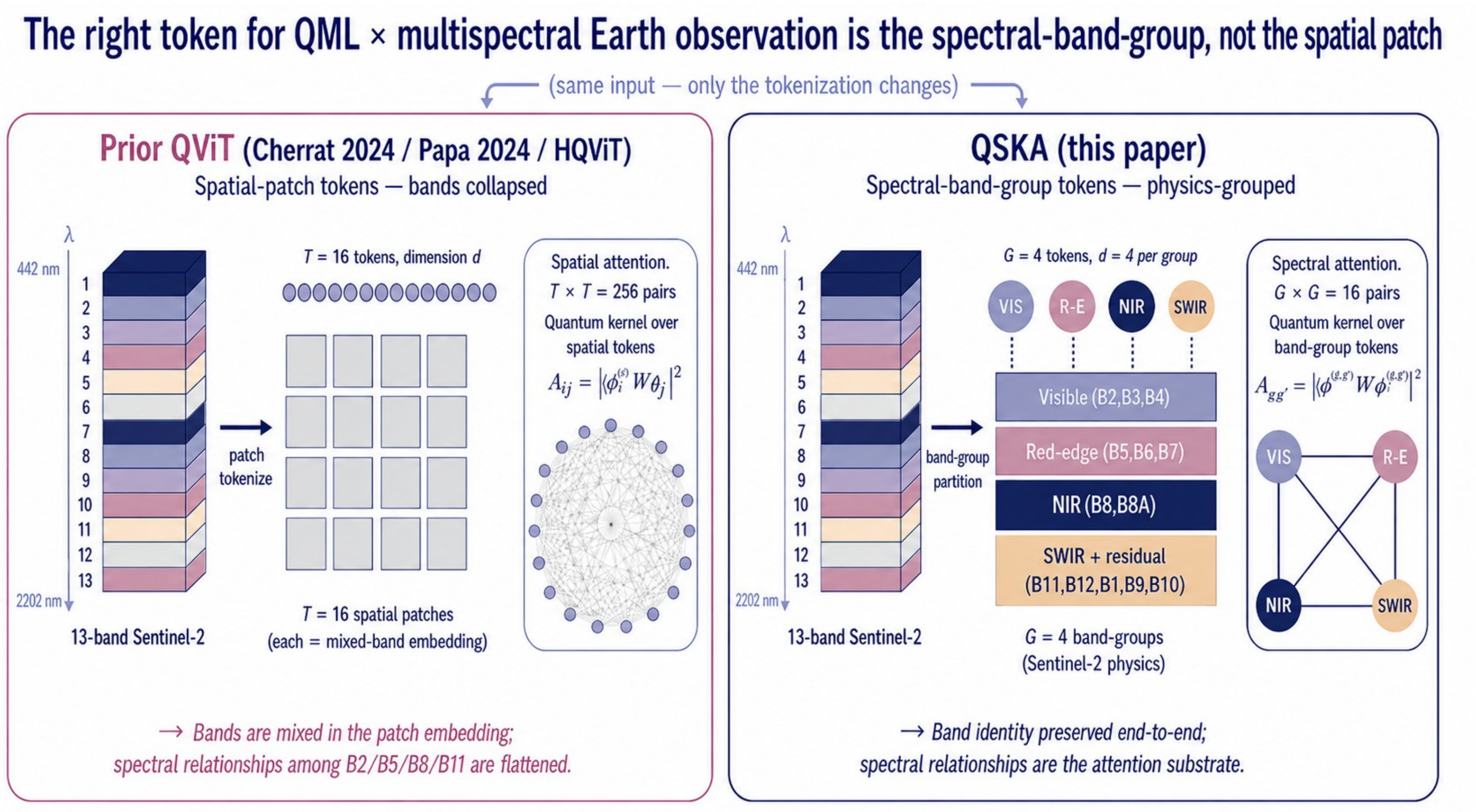
Axis by model family

MODEL	EARTH-DATA AXIS
QViT / QSKA-Hybrid	spectral channel axis
QGNN / EQGC13b	spatial graph axis
QKM / PQK	PCA feature axis

Takeaway: no single aggregate statement about “QML for EO” can cover all three families.

Quantum Spectral Kernel Attention Hybrid

Move the quantum attention block onto physically meaningful spectral band-group tokens.



Prior Quantum Vision Transformer: bands collapse inside patch embeddings.

Quantum Spectral Kernel Attention: band identity is preserved end-to-end.

Structural-Prior Alignment Principle

Structure alignment asks whether the quantum primitive is placed on a preserved, physically meaningful Earth-data axis.

Three diagnostic questions

1. Does the quantum primitive operate on a small physical axis?
2. Is that axis preserved through preprocessing?
3. Does it perform the main axis-interaction step?

Feature examples

Recommended aligned features

- spectral band groups
- SAR polarizations
- time steps

Not aligned features

- RGB truncation
- PCA-decorrelated features
- generic CNN features

CONTROLLED EXPERIMENT

How the SEN12-FLOOD control experiment is designed

Each pair changes one design factor while the dataset, split, sample size, training protocol, and parameter scale stay fixed.

1 Synthetic aperture radar modality

without synthetic aperture radar

vs.

with synthetic aperture radar

2 Quantum versus classical attention

classical linear value / mixing map

vs.

quantum butterfly quantum orthogonal layer

3 Spectral-attention path

without spectral path

vs.

with spectral path

4 Effect of token shape

spectral bands grouped as physical tokens

vs.

separate optical + radar modality tokens

Fixed protocol: SEN12-FLOOD dataset; event-group split; 50 / 100 / 200 samples per class; 3 seeds; matched parameter scale

Quantum versus classical attention under the same controls

This table isolates the “quantum versus classical attention” feature group: all other SEN12-FLOOD settings are held fixed.

Feature group being compared

Classical attention
linear value / mixing map

vs.

Quantum attention
butterfly quantum orthogonal layer

Compared at n = 50, 100, 200 samples per class; values are mean F1 over three seeds.

n / class	Classical attention F1	Quantum attention F1	ΔF1
50	0.746	0.756	**+0.010**
100	0.758	0.787	**+0.029**
200	0.776	0.797	**+0.021**

Result for this feature group: quantum attention is sign-consistently higher at all three sample sizes.

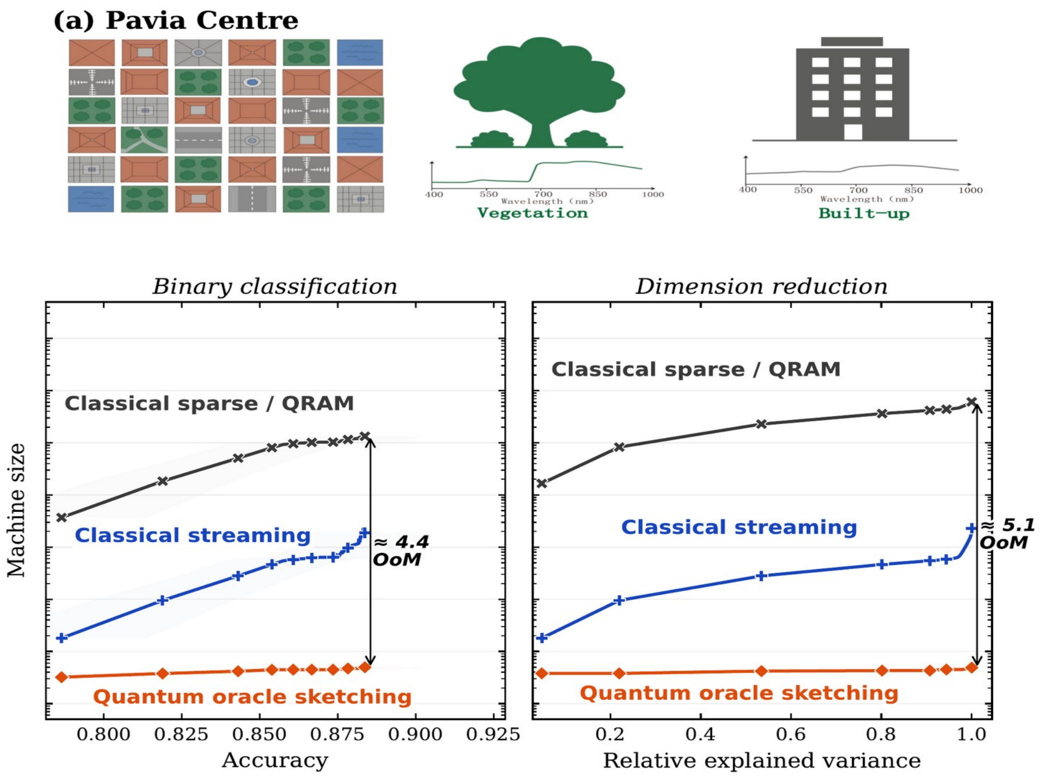
Interpretation: the pilot edge is more consistent with the quantum value/mixing parameterization than with token shape alone.

Controlled comparison: same dataset, event-group split, sample sizes, training protocol, spectral path, synthetic aperture radar modality, and matched parameter scale.

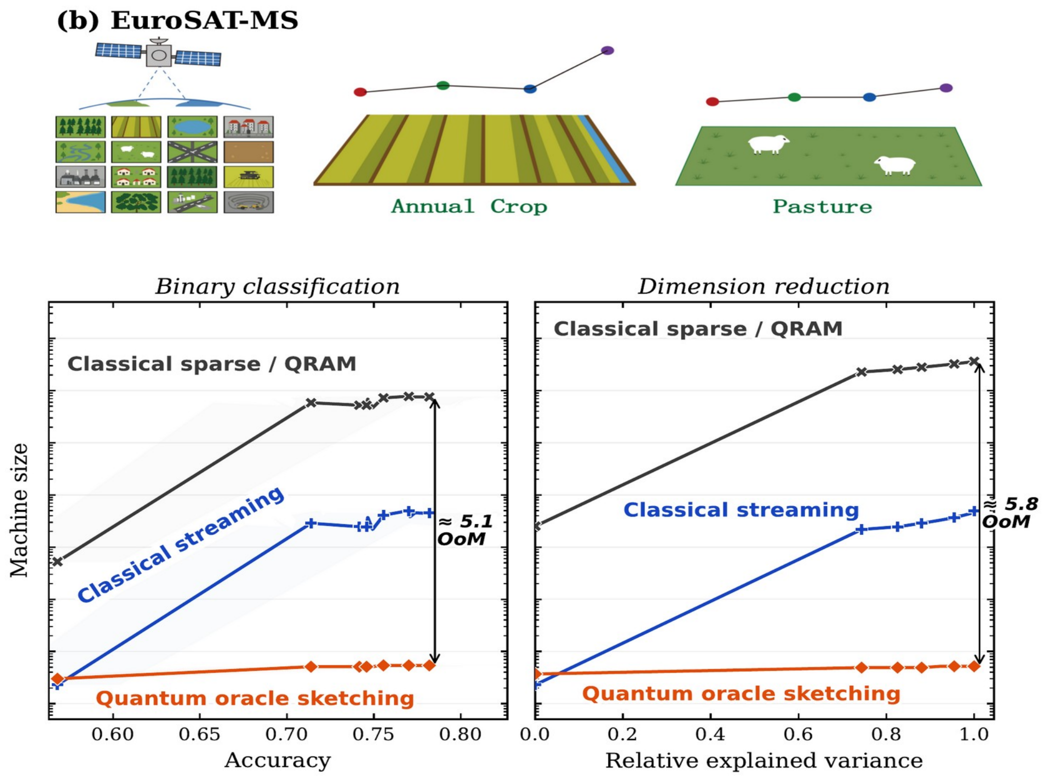
Quantum Oracle Sketching on Earth-observation data

A fault-tolerant machine-size comparison under explicit data-access assumptions.

Pavia Centre



EuroSAT-MS



Reported memory gap: 4.4–5.8 orders of magnitude; quantum machine size ≈ 50–54 logical qubits.

Three claims of the paper

Replace broad “QML for Earth observation” promises with axis-specific claims at two hardware clocks.

1

Evaluation unit

Report a concrete quantum family, architecture, preserved Earth-data axis, matched classical peer, and resource setting.

2

Near-term cell

Quantum Spectral Kernel Attention Hybrid is a bounded parameter-efficient positive cell on SEN12-FLOOD, not a universal Quantum Vision Transformer claim.

3

Fault-tolerant path

Quantum Oracle Sketching gives a separate memory-scaling anchor when streaming, sparse, high-dimensional access assumptions hold.

Final message: when, where, and under which resource model?