

Noise-aware reconstruction for ultra-low-threshold superfluid-helium detectors

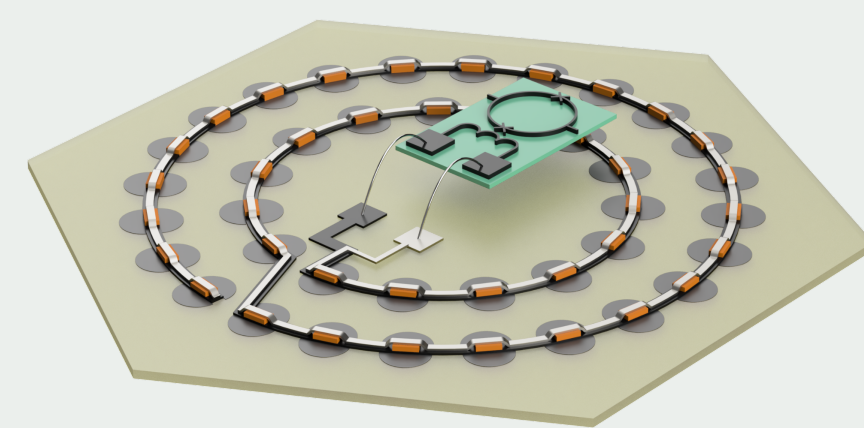
Likelihood → noise geometry → learned manifold → geometry-aware architecture

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1. Noise covariance defines the reconstruction metric

Detector likelihood → Mahalanobis geometry

DELIGHT uses superfluid ^4He and **56 MMC calorimeters** (37 top, 19 bottom) for sub-GeV dark matter and $\text{CE}\nu\text{NS}$. Near threshold, pulse shape, timing and channel sharing carry the information.

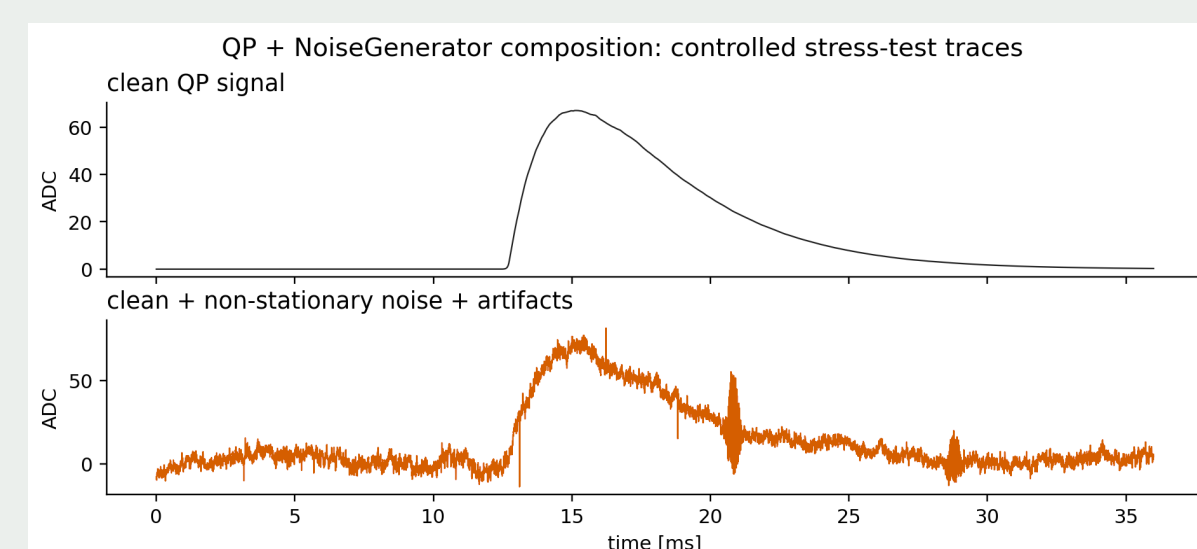


MMC-based LAMCAL array: 37 top + 19 bottom channels.

Under a Gaussian-noise approximation,

$$x = s(z) + n, \quad n \sim \mathcal{N}(0, \Sigma), \quad \|x - s\|_{\Sigma^{-1}}^2 = (x - s)^T \Sigma^{-1} (x - s).$$

Σ^{-1} is the **precision metric**: it weights colored, cross-channel noise when present; a fixed template reduces it to the Optimal Filter.



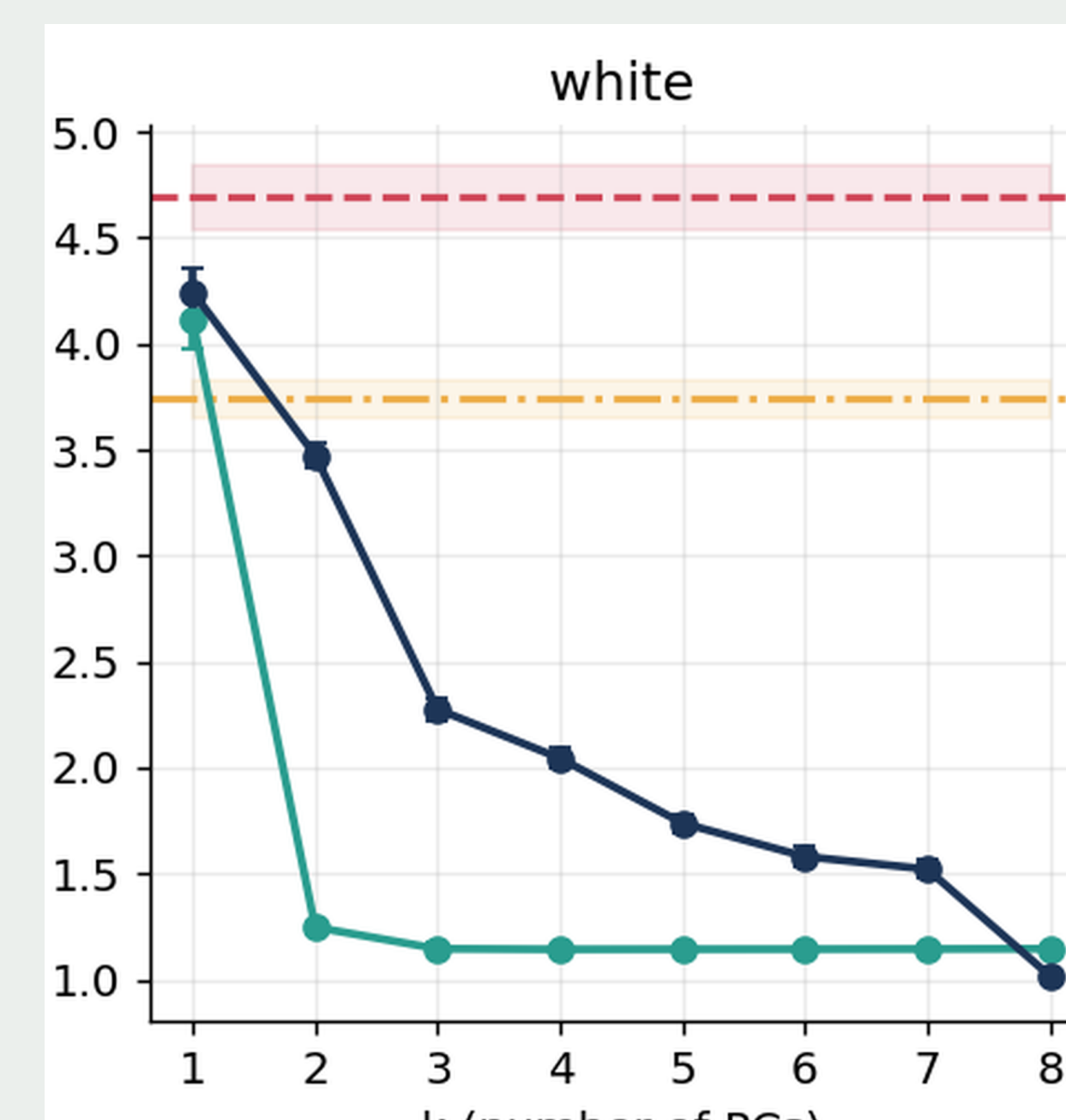
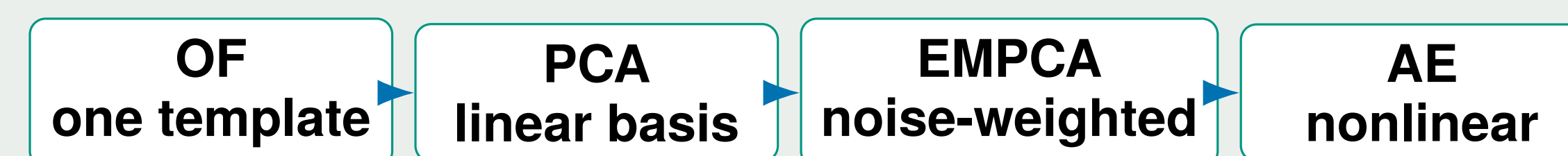
Noise model: clean pulse vs. the same pulse under non-stationary, artifact-laden noise (NPML 2026).

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2. Learned manifolds outperform a mismatched fixed template

Optimal Filter → PCA → EMPCA → autoencoder

The Optimal Filter is optimal only within a **single-template model**. Real pulses vary with event position, channel and timing, forming a low-dimensional manifold.



Amplitude width σ vs. learned PCs (DPG 2026, 500 eV NR, white-noise stress test, mismatched template); dashed = OF baselines.

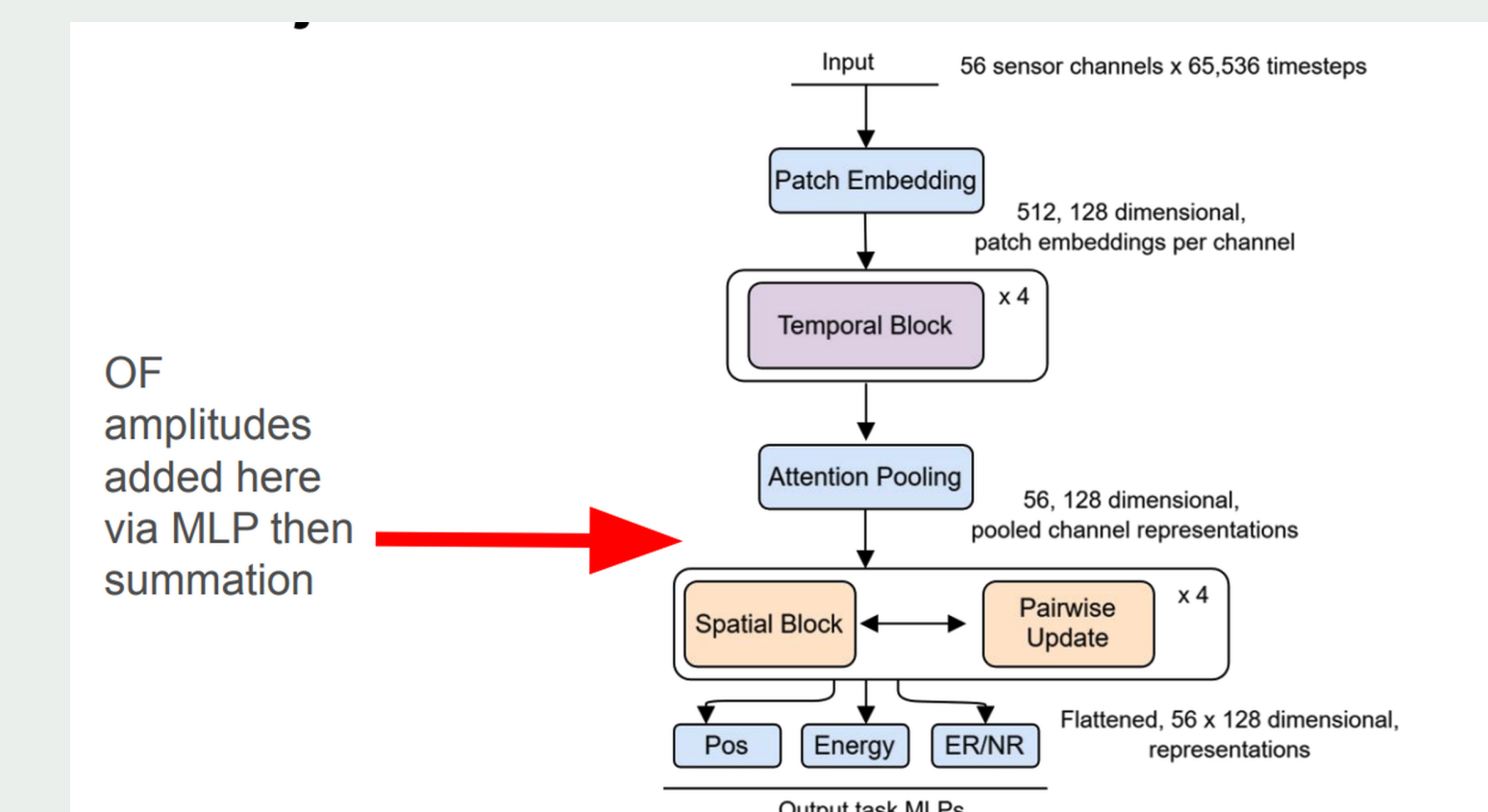
$\sigma : 4.7 \rightarrow 1.0$ **a.u. (8-PC basis)** — richer basis → narrower σ

Refs: [1] von Krosigk *et al.*, SciPost Phys. Proc. **12**, 016 (2023); [2] DELIGHT, arXiv:2512.15278; [3] Gatti & Manfredi, RNC **9**, 1 (1986).

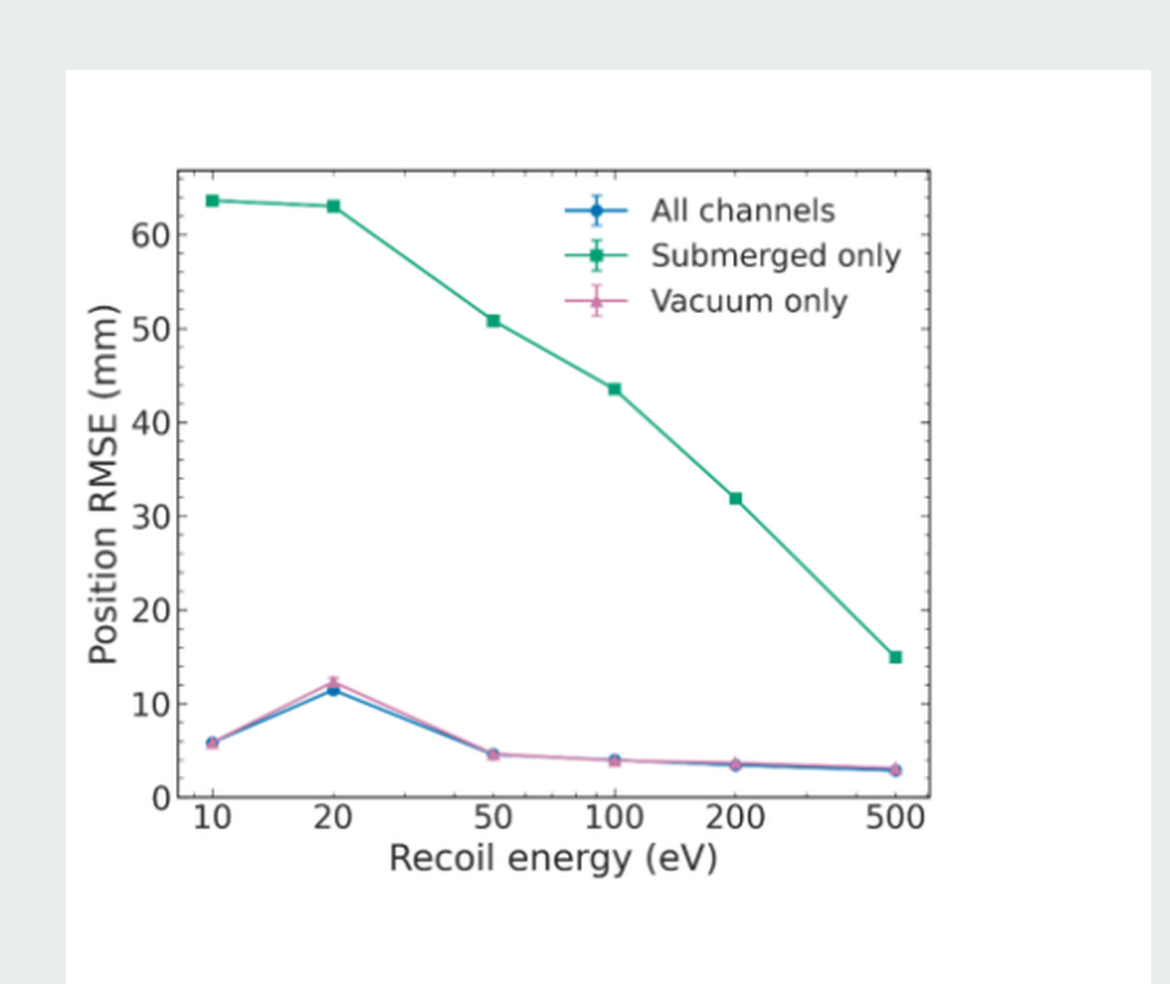
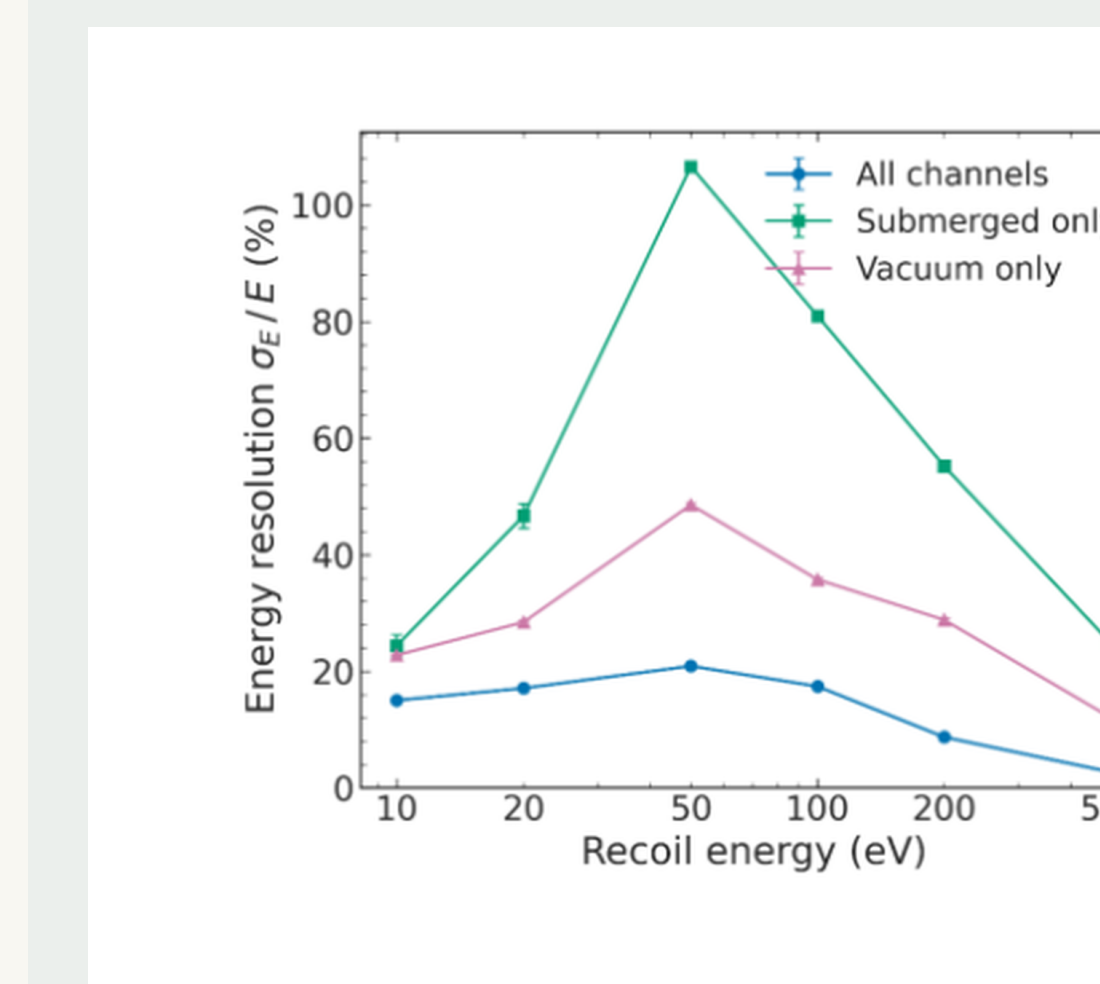
3. Structured sensor dependence motivates geometry-aware attention

Proposed transformer + sensor-group ablations

Likelihood sets the metric; coverage and **architecture** decide what is recovered.



Proposed geometry-aware transformer; OF amplitudes injected via an MLP (NPML 2026).



Sensor-group ablation: resolution and position RMSE both track the channel group (signal partitioning).

DELIGHT Collaboration
<https://delight.kit.edu>