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Absolute Neutrino Mass Determination: Machine-Learning-Driven Signal Processing and Event Reconstruction for QTNM

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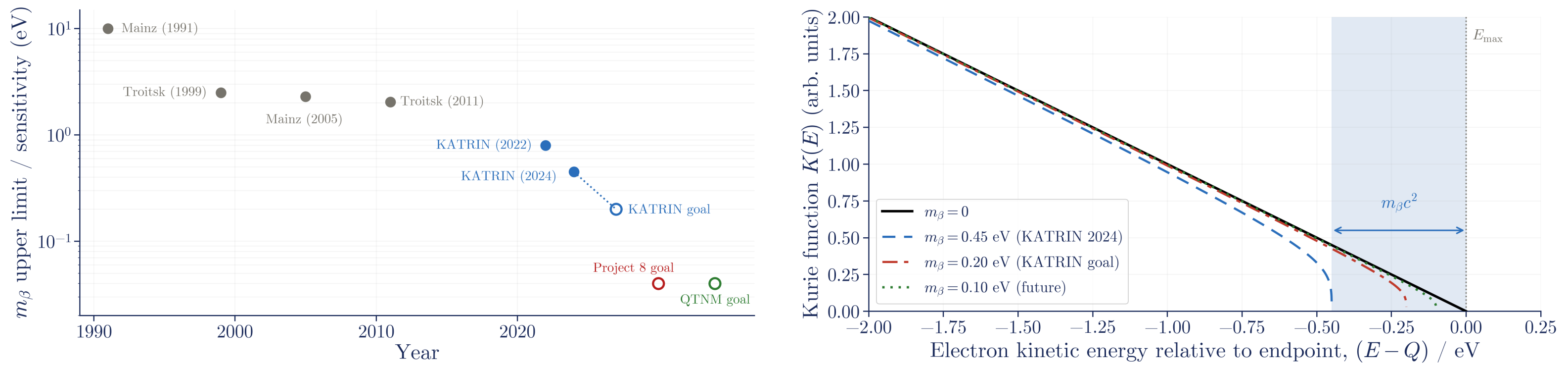
Direct measurements of m_β

- Neutrinos oscillate, so they have mass - but only mass-squared splittings are known.
- The β-decay mass is the only model-independent lab handle.
- KATRIN bound 0.45 eV/c², QTNM aims to surpass this.



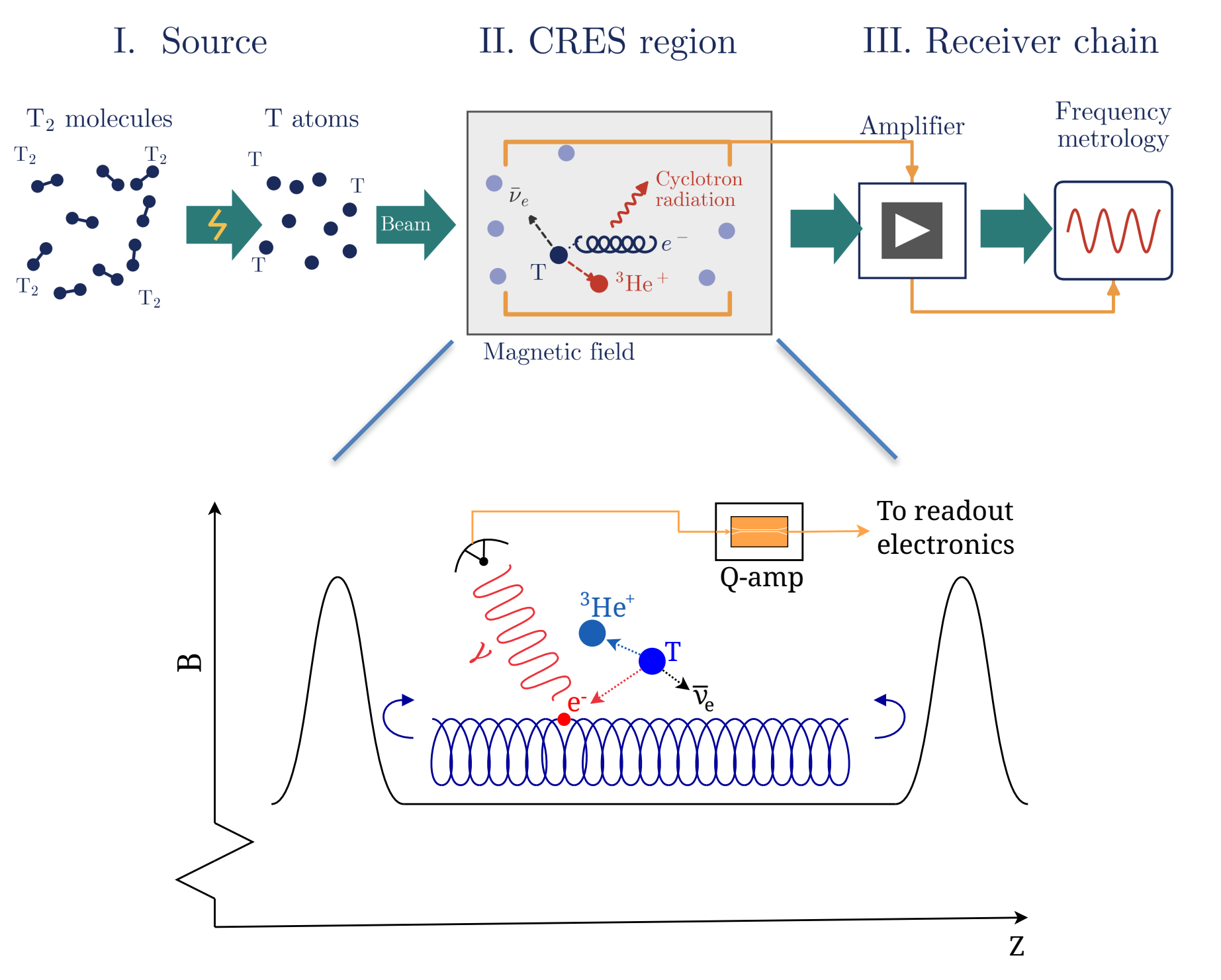
Left: bounds on the effective beta-decay mass since 1991. Right: Kurie plot - a non-zero mass affects the spectrum endpoint.

QTNM's aim

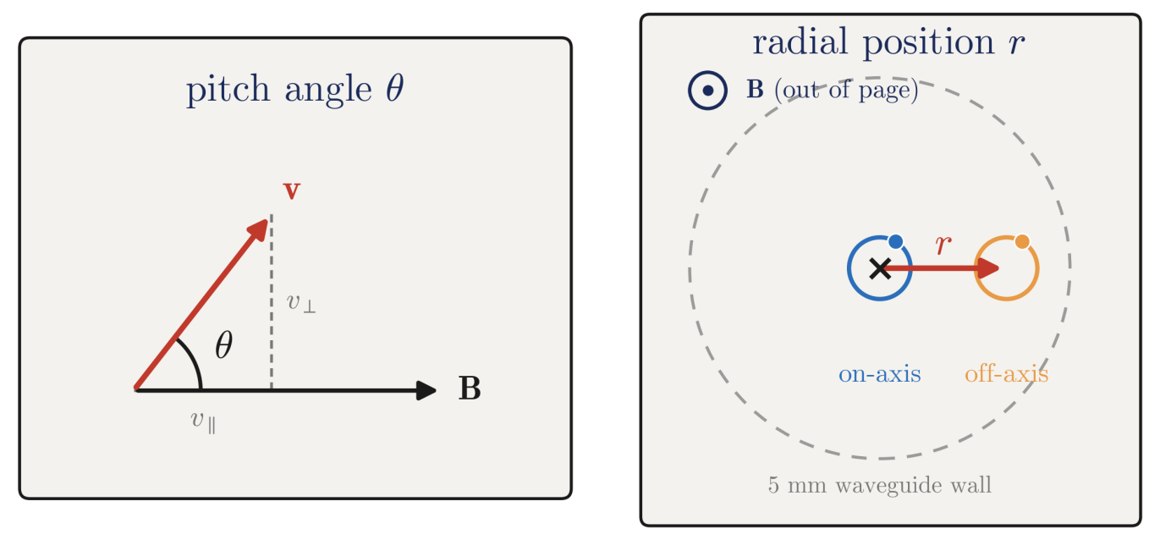
Push bound on absolute neutrino mass from **0.45 eV/c²** (KATRIN) to <100 meV/c²

Quantum Technologies (for) Neutrino Mass + CRES *Cyclotron Radiation Emission Spectroscopy*

- A magnetically trapped β-electron radiates at its relativistic cyclotron frequency.
- Signal is a femtowatt-scale chirp, deep in thermal noise.



QTNM apparatus: (I) atomic-T source, (II) magnetic trap where β-electrons radiate, expanded below (III) quantum-limited receiver chain.



QTNM and PROJECT 8 : Parallel CRES efforts

Both groups use CRES as the backbone of their experiment. Project 8 demonstrated single-electron CRES from molecular T_2 and set today's best lab bound. QTNM runs in parallel with the shared goal.

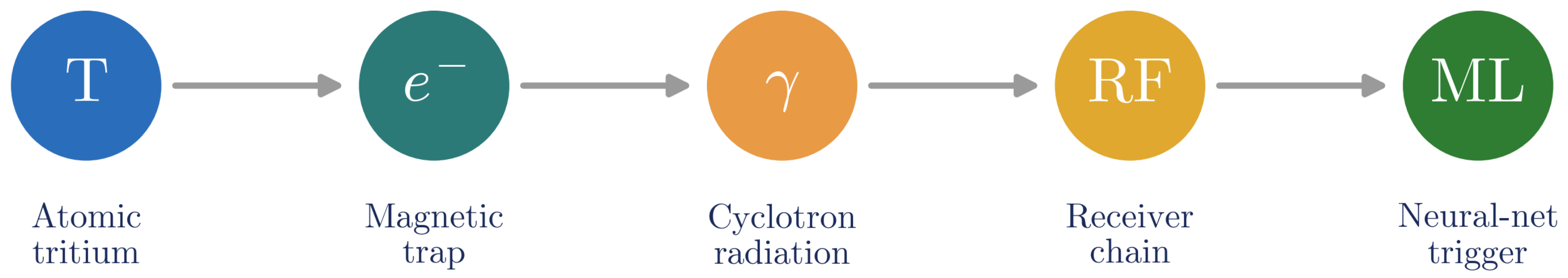
	QTNM (this work)	Project 8 [2]
Source	Novel atomic Tritium	Molecular T_2 (Currently)
Trigger	ML ensemble	Power threshold (Physics runs)
Status	Technical demonstrations	Best CRES m_β bound today

Simulation pipeline

QTNMSim: Geant4 simulation of the QTNM CRESDA geometry; novel inelastic tritium-scattering model (Goffrey et al., in prep.).

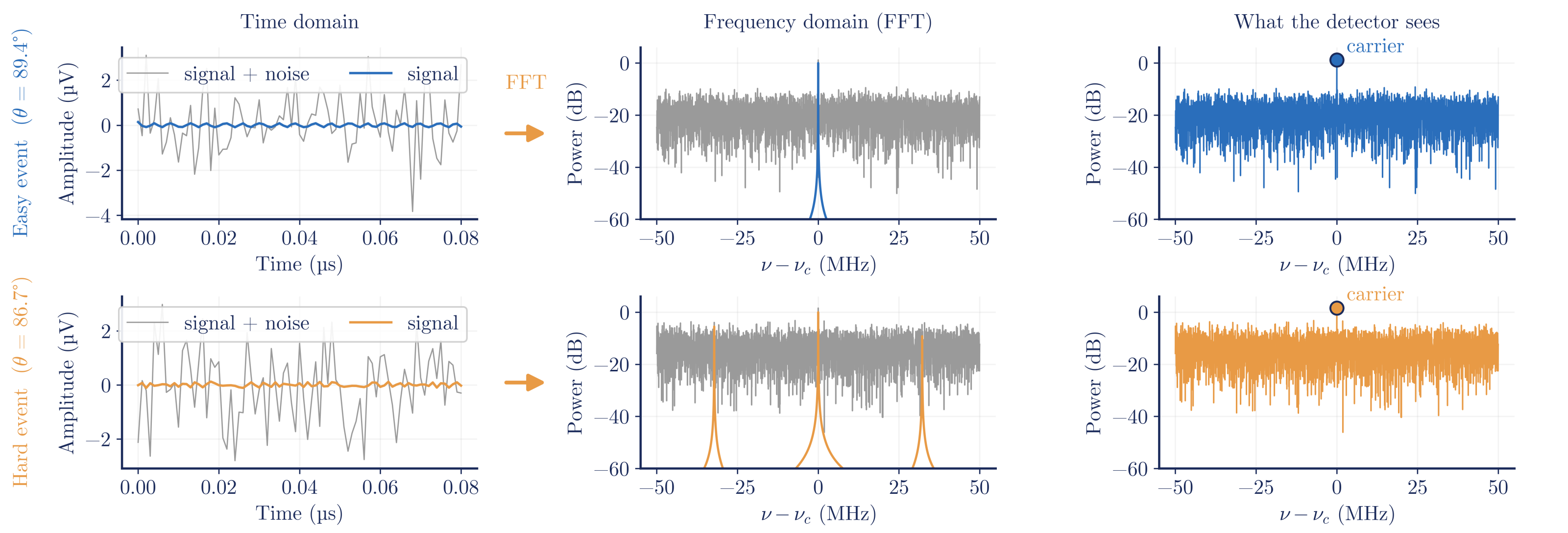
CRESSignalStructure (CSS) + RadiatedPowerPackages (RPP): UCL analytical (CSS) and full trajectory (RPP) signal generator with scattering capabilities (S. Jones). Carrier + Bessel-comb model, receiver chain, downmixing to ~200 MHz IQ.

From β-decay electron to machine-learned trigger



Signal & noise model

A CRES electron from β-decay radiates a chirping cyclotron carrier until it scatters out of the trap. Both real and imaginary parts of its FFT act as the two model input channels, then add thermal noise to reproduce what the detector sees.



CRES events + thermal noise (T_{sys}=10K)

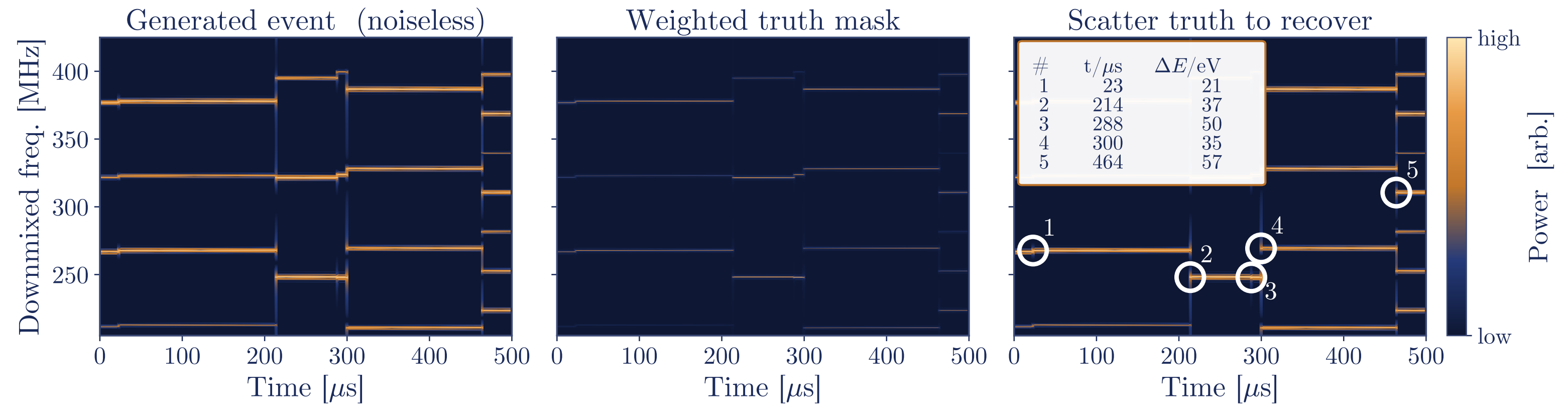
Event reconstruction & parameter estimation

A trapped electron scatters off residual gas, changing its energy and cyclotron frequency. We reconstruct these events to determine the electron kinematics.

SIMULATE
CRES events at a chosen residual-gas density
$\tau^{-1} = n\sigma v$

RECONSTRUCT
Denoising U-Net + parameter estimation
energy + f_c per event

INFER
Population scatter rate → residual gas density
in-situ trap diagnostic



TARGET
Reconstruct every electron precisely enough to turn gas scattering from a systematic into a measurement of the trap itself.

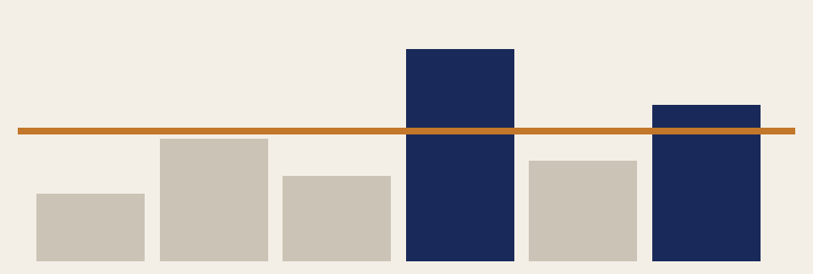
3 ways to trigger CRES

Matched filter

Dot product CRES templates across data; pick the best match. Optimal only when the signal shape is perfectly known.

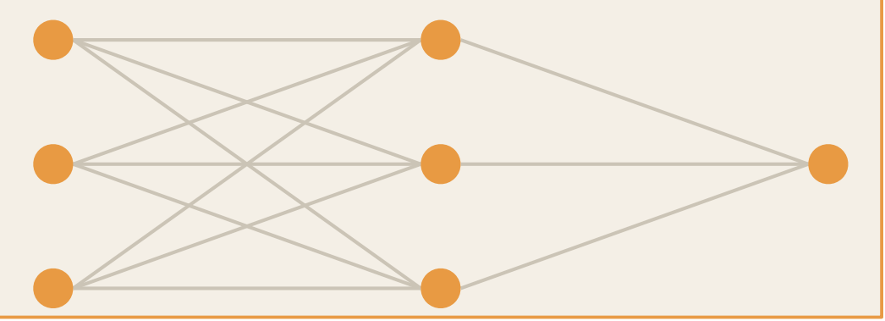
Rician likelihood-ratio test (LRT)

Threshold on FFT's top-K spectral magnitudes. Optimal test for a signal of unknown phase: the classical ceiling



Machine learning

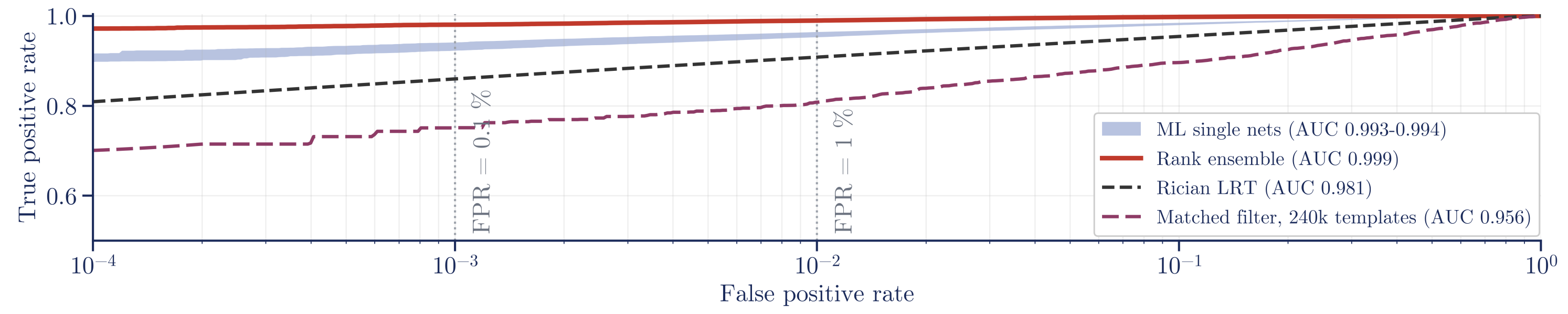
A neural net learns the signal structure from labelled signal events. Near-optimal at a fraction of the cost of classical approaches.



Machine learning trigger study

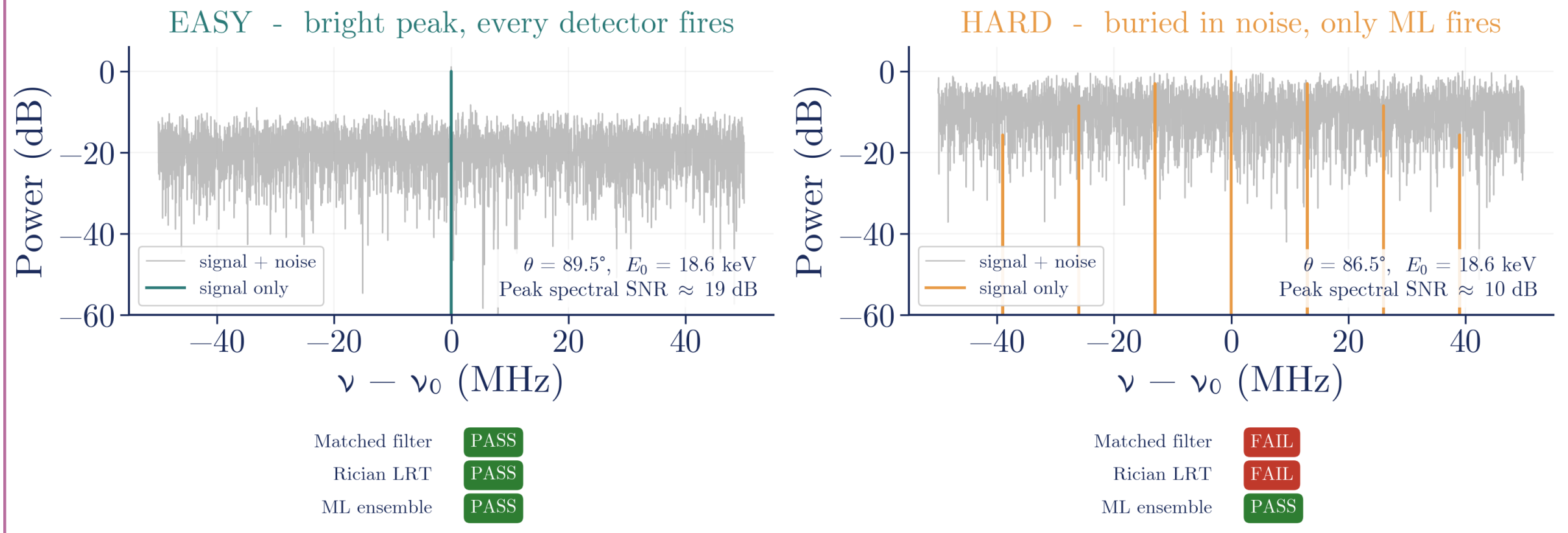
Recovers 99.0 % of CRES electrons

(rank-mean ensemble TPR at 1-in-100 false-alarm rate, 200K events 50/50 split signal and noise with 40μs slices, further parameters below)



TPR at 1-in-100 false-alarm rate	
Rician LRT bound (optimal magnitude-only ceiling)	90.8 %
Matched filter (240K Templates; ~$10^{6\text{-}7}$ templates to approach ML)	80.8 %
Single SE-ResNet (best of 4 archs)	96.2 %
Rank-mean ensemble	99.0 %

The case for machine learning



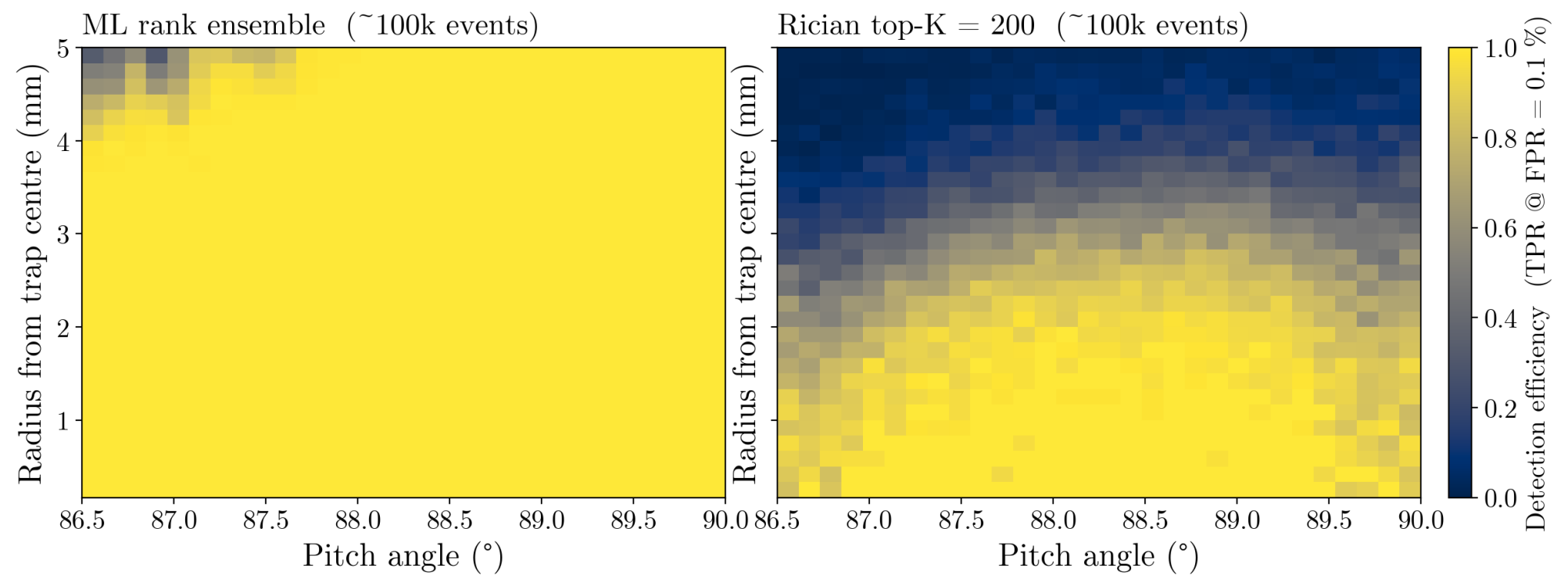
Two test events; same noise and FPR=1% threshold. High ϑ: every detector fires. Low ϑ: classical fails.

Experimental Parameters:

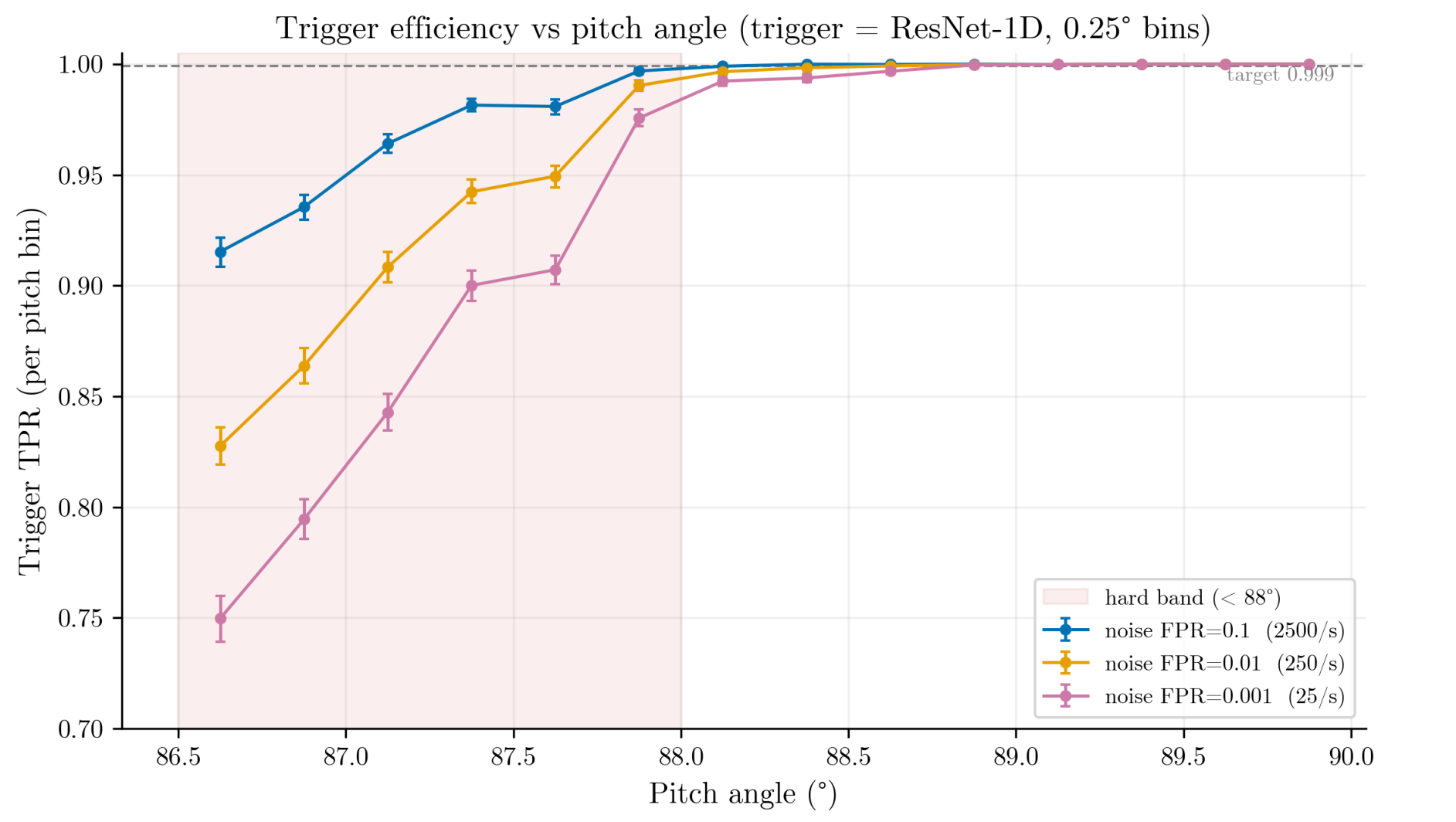
1.0 T Background Field (harmonic trap, 4 mT depth) · 18.5 to 18.6 keV Electrons
Cyclotron frequency ~26.9 GHz, downmixed ~200 MHz · ϑ/r range 86.5-90°/5mm
1 GHz sampling, 40k IQ samples · 5 mm circular waveguide, TE_{11} mode
T_{sys}=10K (Thermal, 50Ω) · Signal Events (train/val/test) 80K/10K/100K

Detection performance and feasibility

Detection efficiency (TPR at FPR = 0.1%) per (ϑ, r) bin. ML ensemble (left) saturates everywhere; Rician LRT (right) fails at low pitch and large radius.



Trigger efficiency vs pitch angle at three false-alarm working points, modelling a cascaded trigger: a tight online FPGA stage feeding a looser offline analysis.



What's next

- Online CRES triggering on FPGA via hls4ml [5].
- Robustness across the full QTNM operating range.
- Expansion of Reconstruction and Parameter Estimation capabilities.

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[1] QTNM Collab. (A. A. S. Amad et al.), New J. Phys. 27, 105006 (2025). [2] Esfahani et al. (Project 8), PRC 109, 035503 (2024) [3] Aker et al. (KATRIN), Nat. Phys. 18, 160 (2022) [4] Hu et al., CVPR 2018 (Squeeze-and-Excitation) [5] Duarte et al. (hls4ml), JINST 13 P07027 (2018)

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