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Calibration of Neutrino Detectors: Bridging Engineering Challenges to Cosmic Discoveries

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Overview & Challenges

- **Energy range**: From MeV (reactor/solar) up to TeV–PeV (astrophysical) neutrinos.
- **Calibration goals**: Accurately determine energy scale, timing, and position; target ~1% or better accuracy.
- **Impact**: Calibration precision directly affects event reconstruction and physics sensitivity (e.g. directional resolution of TeV–PeV events).
- **Next-gen demands**: Experiments like Hyper-K and JUNO require simultaneous optimization of detector and reconstruction parameters.

Calibration Methodologies

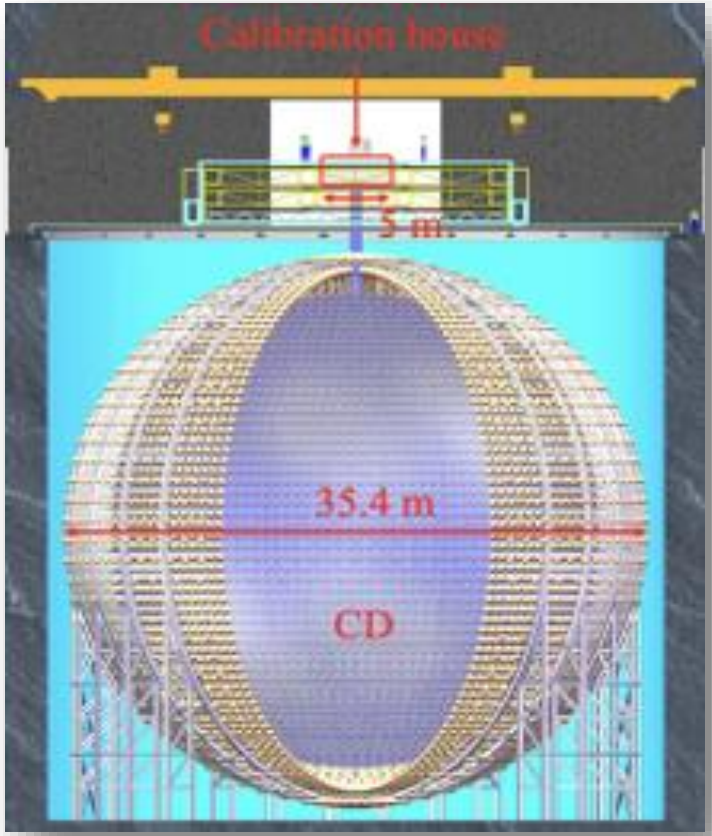
- **Radioactive sources**: Deploy known gamma/neutron sources inside detector (or on moveable arms) to map energy response.
- **Optical systems**: Use lasers/LEDs and fiber-optic diffusers for light injection (timing & light-yield calibration)
- **Cosmic rays**: Exploit cosmic muons/tracks for alignment and uniformity checks (e.g. IceCube DOM geometry).
- **Simulation & ML**: Fit calibration parameters jointly with event reconstruction using differentiable/AI-enhanced simulations.

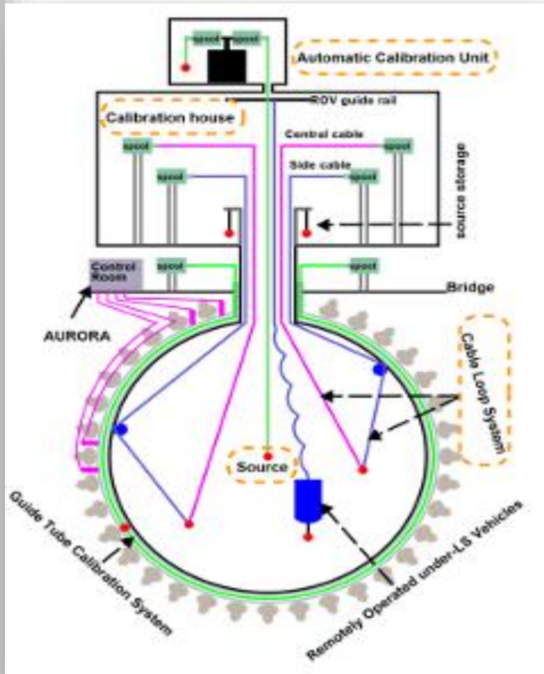
➜ Calibration has become a design driver

Reactor Neutrino Experiments (MeV)

- **STEREO (ILL reactor):** Segmented liquid scintillator; used γ sources (0.5–4.4 MeV) in each cell to constrain scintillator nonlinearity and achieve ≤1 %scale precision.

- **JUNO :** 20 kt LS – uses a custom laser diffuser (isotropic timing to ±0.25 ns) and an array of sealed radioactive sources (e.g. ^{18}F, ^{40}K, ^{226}Ra et ^{241}Am, covering energies from ≈10 keV to ≈1 MeV, designed to keep energy-scale uncertainty < 1 %.





Calibration system design (ACU, CLS, ROV, ACU tower)

Calibration house installed (2025 commissioning)

https://arxiv.org/pdf/2507.09208v1

Accelerator Neutrino Experiments (GeV)

- **T2K (ND280 Upgrade – SuperFGD):** 3D finely-segmented scintillator with WLS fibers; LED calibration system yields ~1 ns ns timing resolution for fiber readout and corrects light attenuation.
- **DUNE (LArTPCs):** Calibration with cosmic muons for alignment, UV laser tracks for electric field mapping, and internal sources (e.g. ^{39}Ar, ^{83m}Kr) for uniform energy scale.
- **ICARUS (SBN, LAr):** 360 VUV-sensitive PMTs were time-calibrated to <1 ns via multi-stage corrections using pulsed LED/laser signals.

https://doi.org/10.1016/j.nima.2025.170616.

Water Cherenkov Detectors

- **Super-Kamiokande:** Extensive calibration campaign (LINAC electron beams, laser/LED, deployed radioactive sources) to map water transparency and PMT response; achieves %–level energy accuracy.
- **Hyper-Kamiokande (data taking planned ~2027):** Will similarly use LINAC, diffuse laser, radioactive sources. Recent R&D proposes a differentiable simulation approach: ML-based calibration that optimizes detector and reconstruction parameters simultaneously.
- **IceCube (deep-ice Cherenkov):** (See next slide – telescopes).

Liquid Scintillator Detectors

- **Borexino** (solar ν): Achieved world-leading radiopurity; calibrations used internal α/β sources and external beams to verify uniform response.
- **JUNO** (reactor, see Slide 4): Its LS calibration also serves geoneutrino/astro channels; demands uniformity across 20 kt volume.
- **SNO+ (0νββ):** Will calibrate with deployed sources (e.g. ^{16}N , ^{8}Li) and light sources in its LAB scintillator.

A. Takenaka *et al* 2024 *JINST* 19 P12019

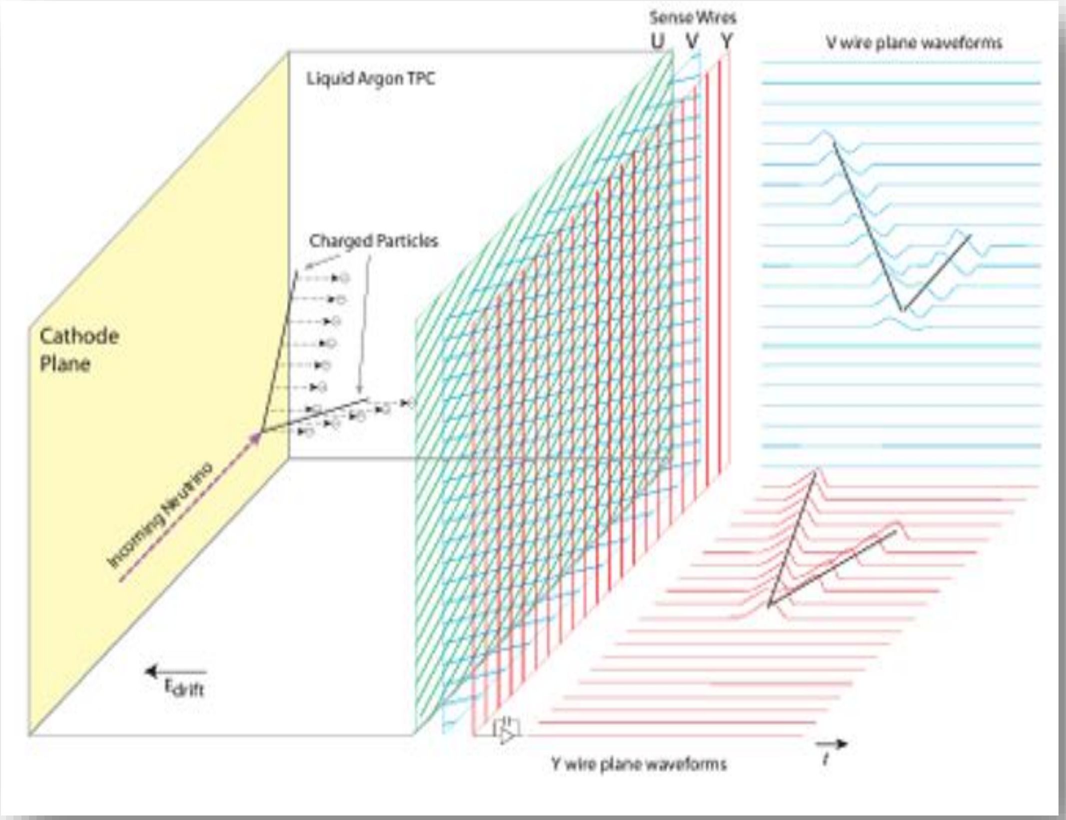
https://doi.org/10.1016/S0168-9002(01)02062-9

Liquid Argon TPCs

- **ICARUS-T600 (87 K LAr):** Extensive calibration of scintillation light system (360 PMTs); achieved sub-ns timing precision, enabling precise drift time determination.

- **MicroBooNE, ProtoDUNE**: Use UV laser systems to ionize tracks for mapping drift field distortions; also deploy ^{83m}Kr sources for uniform light and charge yield.

- **DUNE Far Detector**: Plans µBooNE calibrations plus large-volume ^{39}Ar, activity monitoring; future addition of photon detectors (SiPMs, ARAPUCAs) will need precise VUV response calibration (wavelength shifter uniformity).



The diagram illustrates the signal formation in a Liquid Argon Time Projection Chamber (LArTPC) with three wire planes

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Neutrino Telescopes (Ice/WATER)

- **IceCube (Antarctic ice):** Each DOM has 12 LED “flashers”; flasher data are fit against simulations to infer ice scattering/absorption and correct anisotropies.
- **Geometry calibration:** IceCube used >10^6 muon tracks to refine DOM positions (horizontal shifts); LED-flasher fits confirm these improvements.
- **IceCube Upgrade:** New dense strings include calibration devices (wide-angle LEDs, “pencil-beam” light sources) to better characterize both bulk ice and hole ice.
- **KM3NeT (Mediterranean):** Uses White Rabbit network for sub-ns timing among optical modules and calibrates orientation via known light sources – similar principles.

Optical Calibration & Photon Detection

- **Laser Systems**: Tunable lasers with isotropic diffusers calibrate PMT timing offsets and light yield. For example, JUNO's laser can adjust intensity over 4+ orders of magnitude, enabling gain linearity studies.
- **LED Pulsers**: Fast LEDs (often 400–450 nm) via optical fibers are used to define single-photoelectron (SPE) spectra for PMTs/SiPMs. In cryogenic tests, a 410 nm LED fiber-illumination calibrates SiPM gain.
- **PMT/SiPM Gain Calibration**: Each photodetector's gain vs bias and transit-time spread is measured. ICARUS tuned PMT delays (voltage-dependent) to sub-ns precision. SiPMs in cryo require repeated dark-count and LED pulsing calibrations (bias current→ gain).

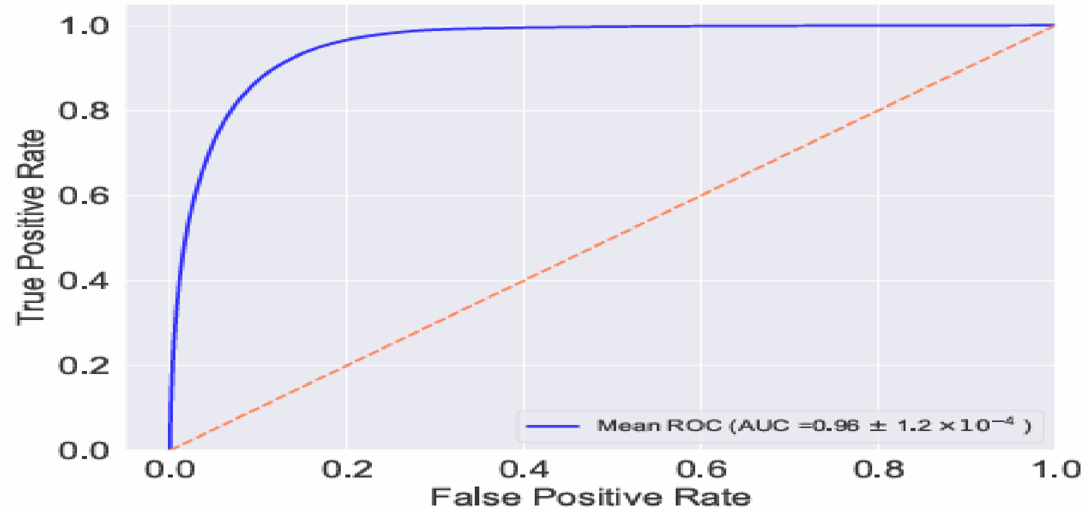
Cryogenic Detectors Calibration

- **LAr/LXe Photon Systems**: VUV photons (128 nm for Ar, 178 nm for Xe) detected via wavelength shifters. Calibrations involve flooding the detector with light pulses (laser or LED through fibers) and measuring uniformity. (***mapping via LED 405-410 nm/fiber-injected laser for SPE and uniformity)***
- **Fiber-based Light Injection**: Calibration LEDs are mounted outside the cryostat and feed light via quartz fibers to the cryogenic volume. For example, deploying an optical fiber with LED to a SiPM yields a narrow time-spread pulse for SPE calibration.
- **Purity Monitors**: In LAr, purity (O_2,H_2O content) affects light/charge yield. Dedicated purity monitors (drift TPCs) are calibrated with known ionization to track transparency over time

Simulation & Machine Learning

- **Differentiable Simulations**
  New frameworks represent detector response in differentiable form, enabling gradient-based joint tuning of calibration and reconstruction parameters.

- **Event Reconstruction ML** *https://doi.org/10.22323/1.476.0214*
  Deep learning models (e.g. XGBoost) trained on Geant4 toy simulations can separate Cherenkov vs. scintillation light in hybrid WbLS detectors**, achieving ≳ 96 % ROC AUC** in demonstrator studies.



The Receiver Operating Characteristic (ROC) curve plots the True Positive Rate (TPR) against the False Positive Rate (FPR) **JINST 19 P04027 (2024)**

- **Fast Simulations**
  GPU-accelerated photon propagation and parameterized optical tables drastically reduce calibration fit time. These are increasingly coupled with ML surrogates to minimize systematics.

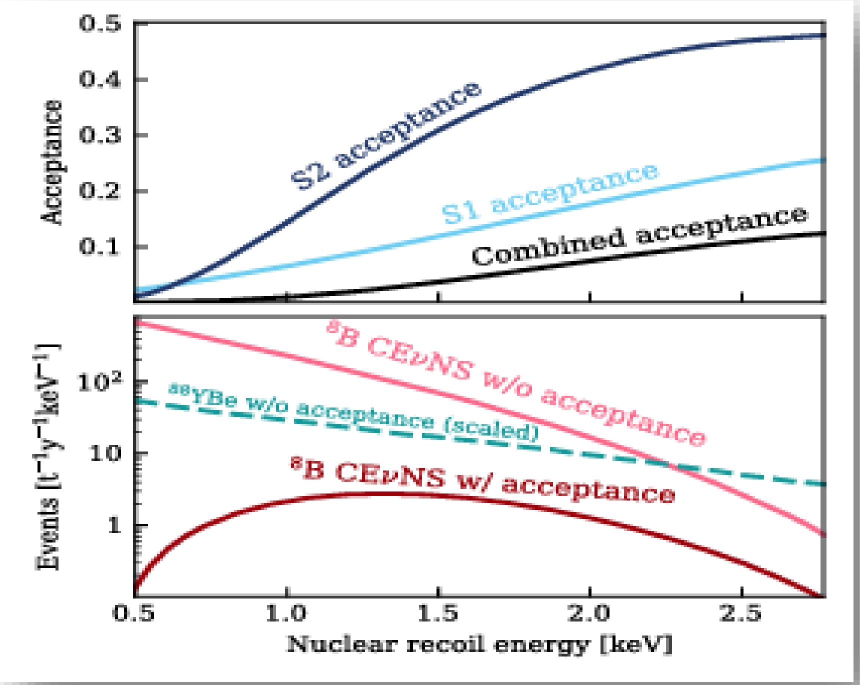
- **ML / SBI Calibration Interface**
  Simulation-Based Inference (SBI) methods are adopted in **DUNE, JUNO and others to build full event likelihoods.** *Yankelevich, A. (2025).*

➢ These methods are **prior-sensitive**: uncalibrated detector response can bias inference
➢ Best practice: integrate calibration uncertainties as nuisance parameters, perform closure tests and coverage validation.
➢ Example: a **JUNO** toy study shows a **2 % energy-scale drift can lead to a 10 % underestimation of CP-violation sensitivity.**

Dark Matter & Neutrino Synergies

The Neutrino Floor: A Calibration Frontier JHEP 06 (2022) 147

Detector Technology	Energy Target (Threshold)	Calibration Sources (ER)	Calibration Sources (NR)	Techniques / Notes
Cryogenic Bolometers (NUCLEUS, CRESST; SuperCDMS)	**10 - 100 eV** (Recoils)	^{55}Fe (XRF)	D-D Neutron Generator	Absolute energy scale calibration.
Dual-Phase TPCs (XENONnT, LZ, PandaX-4T)	**keV - tens of keV**	^{83}mKr, CH_3T, ^{220}Rn	AmBe, D-D Neutron Generator	Energy scale control at **<1%** precision.
CEvNS Detectors (COHERENT)	**~10 keV** (Recoils)	–	Spallation Neutron Source (SNS)	Nuclear recoil calibration in CsI/LAr.
LArTPCs (DUNE, DarkSide)	**MeV** (ν) / **keV** (DM)	^{83}mKr, ^{39}Ar	Neutron Beams	Synergy on **light/charge yield** model



First Evidence of CEvNS from Solar ^{8}B Neutrinos by XENONnT – PHYSICAL REVIEW LETTERS 133, 191002 (2024)

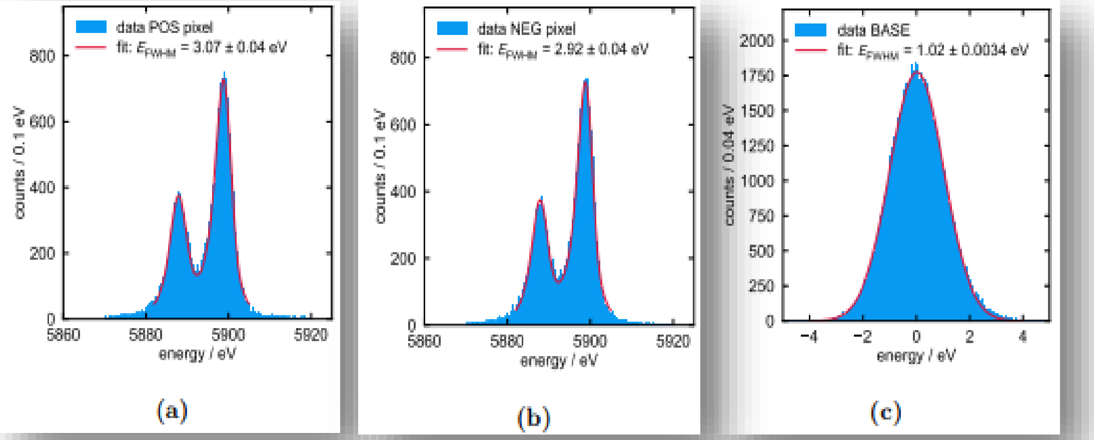
- **CEvNS from solar ν (^{8}B) (by the XENONnT)** is now a measured background in LXe TPCs defining the ultimate sensitivity limit for WIMP DM.
- **Shared Techniques:** A common calibration toolbox (sources, neutron generators, simulation with e.g., **FIFRELIN**) is used across DM and ν experiments.
- **Precision Challenge:** Discriminating spectra requires unprecedented **sub-keV nuclear recoil calibration** and control of systematic uncertainties.
- **Cross-Discipline Transfer:** Advanced calibration developed for DM directly enables next-generation neutrino physics (e.g., solar ν, supernova ν).

Quantum Sensors & Advanced Techniques

•Metallic Magnetic Calorimeters (MMCs):

Quantum cryogenic calorimeters (ECHo, HOLMES) for Ho-163 spectroscopy.
Achieved ~5–6 eV FWHM energy resolution (goal <5 eV), with SQUID readout.

https://arxiv.org/pdf/2301.06455



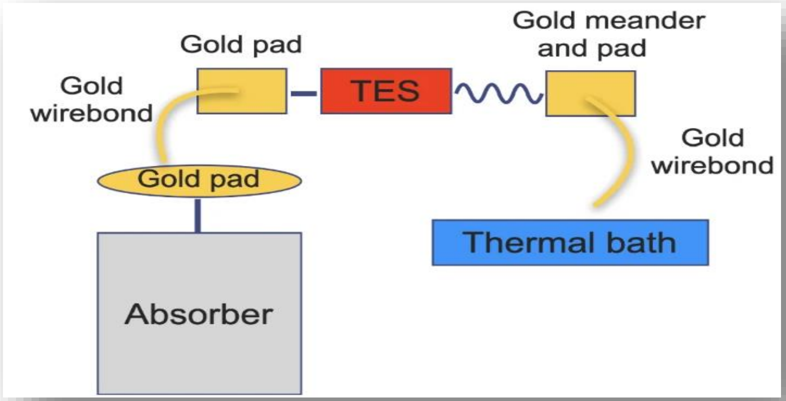
^{55}Fe Kα doublet calibration with MMC: (a) POS and (b) NEG signal polarities; (c) baseline histogram with Gaussian fit.

✓ **^{55}Fe Kα doublet measured with MMCs (ECHo/HOLMES). Calibration demonstrates ~5–6 eV FWHM resolution, benchmark for Ho-163 spectroscopy**

•Superconducting Detectors:

TES and MKIDs provide ultra-sensitive photon/electron detection.
Applications: eV-threshold calibration, UV photon counting, potential novel neutrino sensors.

10.1140/EPJC/S10052-025-13844-4



Simplified TES thermal scheme: particle energy creates phonons in the absorber, transferred via gold coupling to the TES, which converts them into measurable signals while maintaining thermal equilibrium.

Additional Frontiers:

- TES, SNSPDs, SQUIDs → demonstrated eV thresholds.
- Laser frequency combs → ps-level timing metrology.
- Cold-atom interferometers → mapping magnetic/vibrational noise in cryogenic detectors.
- Early integration underway in cryogenic neutrino and dark-matter experiments.

Quantum Computation (R&D): Exploratory research into quantum optimization algorithms (e.g. quantum gradient descent) for multi-parameter calibration fitting

Emerging Techniques

- **Acoustic Calibration**: SPATS (IceCube): acoustic characterization of ice and pinger (timing/properties). - ANTARES/AMADEUS, KM3NeT: acoustics at sea (positioning/hydrophones)
- **Radio Calibration**: Radio neutrino detectors (ANITA, RNO, IceCube-Gen2 Radio) use buried pulsers to map ice radio transparency, analogous to optical calibration.
- **High-Purity Materials**: Ongoing R&D on ultra-pure scintillator cocktails and cryogenics (e.g. low-radio Xenon, argon purified to ppt) reduces background and improves calibration stability.
- **Self-Monitoring Sources**: Devices like the "self-monitoring light source" (POCAM) automatically track their own output for long-term stability.

Calibration Archetype Table – Part 1

Detector (site)	Tech / scale	Calibration systems	Achieved / targeted performance	Distinctive / transferable
Borexino (LNGS)	Liquid scintillator, 0.3 kt	Deployed γ sources, position scans, optical mapping	Position res. ~10 cm @ 1 MeV; $\sigma/E \approx 5\%/\sqrt{E}$	Ultra-low backgrounds; pioneering uniformity campaigns
KamLAND (Kamioka)	Liquid scintillator, 1 kt	Off-axis source deployment; minical	Fiducial vol. syst. 1.6%; energy-scale syst. 1.9%	First large-scale off-axis calibration
SNO+ (SNOLAB)	LS, 0.78 kt	Laserball, sealed γ sources	Optical timing model, low-threshold validation	Modernized isotropic light injection
JUNO (China)	LS, 20 kt	ACU, cable loop, guide-tube, CLS, ROV	Goal: 3% @ 1 MeV; <1% nonlinearity	3D scans-ROV ; dual calorimetry (LPMT/SPMT)
Super-K (Japan)	Water Cherenkov, 50 kt	LINAC e^-, 16N γ, LED/laser injection	Sub-% timing; energy scale ~few %	Long-baseline LINAC anchors absolute e^- response
Hyper-K (Japan)	Water Cherenkov, 190 kt	Multi-λ LI, LINAC planned	Target: <1% systematics	Next-gen electronics; ns-level timing

Calibration Archetype Table – Part 2

Detector (site)	Tech / scale	Calibration systems	Achieved / targeted performance	Distinctive / transferable
IceCube (South Pole)	Cherenkov in ice, 1 km^3	LED flashers, RAPCal, in-ice pulsers	Timing ~1.2 ns; optical anisotropy constrained	RAPCal: km-scale ns sync
KM3NeT (Med.)	Cherenkov in sea water	White Rabbit sync, nanobeacons, acoustics	~1 ns sync; ~10 cm positioning	Industrialized WR timing at sea
ICARUS T600 (FNAL)	LArTPC, 760 t	Fiber laser fan-out, CRT, SCE mapping	~100 ps PMT timing	Optical timing distribution blueprint
MicroBooNE (FNAL)	LArTPC, 85 t	Michel e^-, π^0, UV-laser SCE, cosmic μ	Michel e^- scale ~5%	Data-driven MeV–100 MeV anchors
ProtoDUNE-SP (CERN)	LArTPC, 770 t test beam	Beam e, π, p; cosmics; laser SCE	Low-E e^- calib O(10%)	Absolute hadron/e response anchors
XENONnT (LNGS)	Dual-phase Xe TPC, 8.6 t	Internal: 83mKr, tritiated methane; neutron gens (D-D, AmBe)	Sub-% ER scale (keV); NR calibration up to ~50 keV	Calibration frontier at ν–DM interface; transferable to sub-MeV ν detectors

Design Patterns Across Technologies

Timing

Timing cross-check *(to verify synchronization)*:

$$\Delta t_{ij} = (t_i - t_j) - \frac{d_{ij}}{v}$$

- ✓ **Goal:** ns-level (or better) synchronization.
- ✓ **Examples:** RAPCal (IceCube); White Rabbit (KM3NeT); PMT timing fan-out (ICARUS);
  LINAC/laser timing references (SK/SNO+).
- ✓ **Principle:** independent timing backbone + in-situ cross-checks (optical beacons, early photons).

Position / Uniformity/ Geometry

- ✓ **Goal:** cm–10 cm vertex & uniform response.
- ✓ **Examples:** off-axis source scans (KamLAND); laserball maps (SNO+);
  acoustic positioning (KM3NeT); flasher-based ice model fits (IceCube).
- ✓ **Principle:** independent geometry monitors reduce timing–optics degeneracy.

Energy Scale

Energy non-linearity parametrization:

$$E_{\text{rec}} = \alpha\, E_{\text{true}} \left(1 + \beta\, e^{-\gamma E_{\text{true}}}\right)$$

- ✓ **Goal:** sub-% to few-% absolute scale & linearity across regimes.
- ✓ **Examples:** LINAC & ^{16}N (water); deployed γ/β sources (LS); Michel e^-, π^0 (LAr); test-beam (ProtoDUNE).
- ✓ **Principle:** multiple anchors spanning MeV–GeV mitigate model degeneracies.

Nonlinearity / Medium

Birks' Law (quenching):

$$\frac{dL}{dx} = \frac{S\,(dE/dx)}{1 + k_B\,(dE/dx)}$$

- ✓ **Goal:** control **of quenching/Birks** , optical scattering/ absorption, SCE (LAr).
- ✓ **Examples:** JUNO multi-axis campaigns; UV laser for space-charge (LAr);
  D'n'R methods (radio arrays).
- ✓ **Principle:** dedicated campaigns per medium + periodic stability checks.

Strategic R&D Roadmap

- **Near-term (1–3 years)**:
  - Standardize RAPCal-like timing systems for surface-to-underground installations
  - Share calibration data libraries and software frameworks across experiments.
- **Mid-term (3–5 years):**
  - Develop cross-collaboration portable laserball systems
  - Joint development of low-energy calibration sources (D–D neutron generators, X-ray fluorescence.
- **Long-term (5–10 years)**:
  - Integrate **quantum sensors** (TES, SNSPDs, MKIDs, MMCs) into calibration toolkits
  - Embed calibration uncertainties directly into Simulation-Based Inference (SBI) pipelines

Future Directions

- **Integrated Calibration**: Cross-calibration between different experiments (e.g. using an astrophysical neutrino burst observed in multiple detectors) could provide a common scale.
- **Automated Calibration**: Expand use of robotics/automation to position.
- **Artificial Intelligence**: Further use of AI to predict calibration drifts (aging PMTs, cryo-sensors) and auto-correct in real time.
- **Quantum Metrology**: As quantum sensors mature, they may enable wholly new calibration regimes (e.g. single-photon truth detectors).

Conclusions

Comprehensive calibration is essential across all neutrino detector technologies (scintillator, Cherenkov, TPCs, radio/acoustic) to reach physics goals.

- **Innovations**: New methods – from ML/differentiable simulations to quantum sensors – are being actively developed to improve accuracy and efficiency.
- **Case Studies**: Diverse experiments (STEREO, JUNO, IceCube, DUNE, XENONnT, etc.)
- **Outlook**: Ongoing R&D and shared techniques between neutrino and dark matter fields promise ever more precise calibrations in the next decade

Thank you for your attention

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