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Neutrinos & Dark Matter: Detector Technologies and Geometric Insights in Cosmic Exploration

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Outline

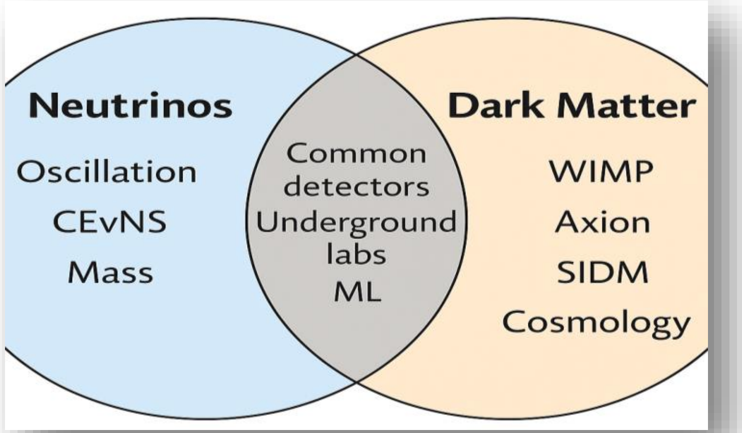
- Scientific Context and Motivation
- Detector Technologies for Neutrinos
- Detector Technologies for Dark Matter
- Geometric and Theoretical Frameworks
- Multimessenger Astrophysics
- Future Perspectives & Conclusions

Scientific Motivation: Connecting the Invisible

Why Neutrinos and Dark Matter? — Connecting the Invisible Sectors

Key Questions:

- Why do neutrinos and dark matter share common detection challenges ?
- Can they probe complementary or overlapping aspects of the cosmic dark sector ?
- Is there a unified theoretical or experimental approach that justifies studying them together ?



Feature	Neutrinos	Dark Matter Candidates
Weakly interacting	✓	✓
Requires shielding/underground	✓	✓
Detected via nuclear/electron recoils	✓ (CEvNS, IBD, ES)	✓ (WIMP, SIDM, etc.)
Sensitive to cosmological relics	✓ (**Σm_ν , N_{eff}**)	✓ (Ω_DM, σ_8, structure)
Accessible through astrophysical sources	✓ (SN, AGN, solar)	✓ (Halo, galaxies, CMB)

Shared Technologies

Key Detection Technologies Used in Both Neutrino and Dark Matter Experiments

✓ The convergence of detection technologies in neutrino and dark matter physics is now a strategic advantage for both communities.

Technology	Neutrino Experiments	Dark Matter Experiments	Purpose / Advantage
Ultra-low background shielding	JUNO, SNO+, Hyper-Kamiokande	XENONnT, LZ, DarkSide-20k	Suppress cosmogenic/ambient radiation
Cryogenic operation	DUNE (LAr TPC), LEGEND-200	SuperCDMS, CRESST-III, EDELWEISS-III	Phonon/electron discrimination, enhanced sensitivity
Deep underground labs	Borexino, KamLAND, SNO+, DUNE	XENONnT, PandaX-4T, DarkSide-20k	Muon flux reduction by 5–6 orders of magnitude
High-purity materials	LEGEND-1000 (Ge), SNO+ (scintillator)	DarkSide-20k (Ar), LZ (Xe)	Reduce intrinsic backgrounds (Rn, Kr, 40K, 85Kr)
Precision timing & topology	DUNE, JUNO	DarkSide-50/20k, XENONnT	Signal/background separation via S1/S2, event reconstruction
Hybrid signal readout	DUNE (charge + light), ICARUS	XENONnT (S1+S2), ARGO/DARWIN (dual-phase)	Multiple channels improve particle ID and noise rejection

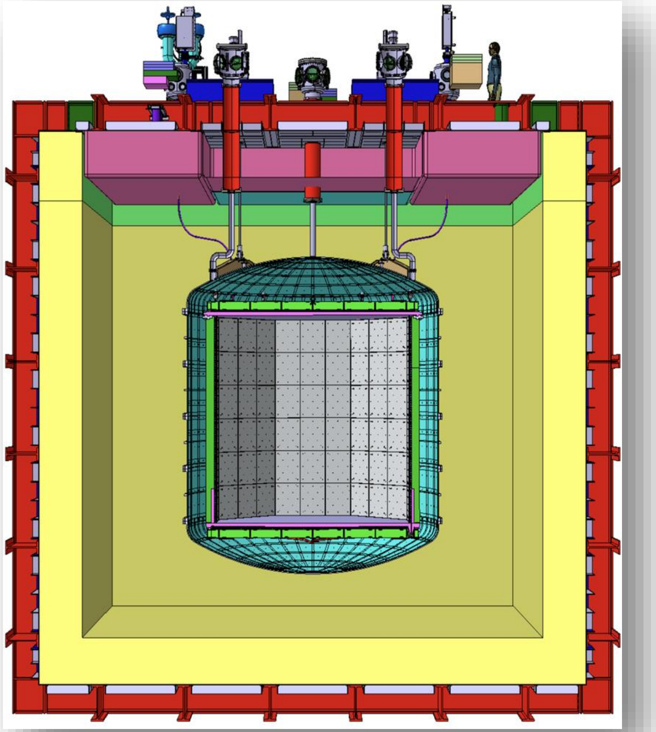
- Shared challenges: rare signals, low rates → shared innovations
- Cryogenic technologies increasingly hybrid: charge, light, phonons
- Deep sites, ultra-pure materials = common baseline for DM and v
- Data analysis protocols (blind, ML-based) are being exchanged
- Radiopurity R&D: coordinated across SNOLAB, LNGS, SUR

From Photons to Phonons: Shared Architectures in Rare Event Detection

Converging Technologies in Neutrino and Dark Matter Experiments

Table: Signal Modalities Across Neutrino & Dark Matter Detectors

Signal Modality	ν Detectors	Dark Matter Detectors	Technological Notes
Scintillation (Light)	JUNO, Hyper-K, SNO+	XENONnT, DarkSide-20k, LZ	Dual-phase operation; SiPM/PMT readout
Ionization (Charge)	DUNE, ProtoDUNE, ICARUS	SuperCDMS, EDELWEISS,	Drift fields in LAr or Ge; low-noise readout
Phonons (Heat)	R&D (e.g., ν detection in crystals)	CRESST-III, EDELWEISS-III, SPHERES	Ultra-low temperature bolometry (<50 mK)
Hybrid (Light + Charge)	DUNE-DP, ARGONCUBE	XENONnT, PandaX-4T, DarkSide-20k	S1/S2 signal analysis; position reconstruction
Hybrid (Phonon + Charge)	—	SuperCDMS SNOLAB, EDELWEISS	Discrimination via timing & energy partition
3D Event Topology	DUNE, MicroBooNE	CYGNUS, NEWS-G (gas TPCs)	Directional signatures in TPCs, sub-GeV DM & CEvNS



Schematic of the DarkSide-20k dual-phase liquid argon TPC. Similar designs are used in ProtoDUNE-DP and DUNE for neutrino detection

10.22323/1.449.0113

Design Challenges & Background Mitigation in Ultra-Low Signal Regimes

Engineering at the Frontier : Suppressing Noise in Rare Event Detectors

Table: Dominant Backgrounds & Mitigation Strategies (ν & DM)

Background Type	Source	Impact	Mitigation Strategy
Radiogenic (γ, β)	Detector materials, radon daughters	ER backgrounds in DM & ν detectors	Material screening, radon traps, passive shields
Cosmogenic (μ, neutrons)	Atmospheric cosmic rays	Neutron spallation, muon-induced noise	Deep underground siting, active muon vetoes, neutron moderators
Neutrino Coherent Scattering (CEνNS)	Solar, reactor, geo-ν	Irreducible background for DM	Signal modeling, timing cuts, directional detection (R&D)
Electronic Noise	Readout, preamplifiers	Threshold limitation, fake signals	Cryogenic ASICs, shielding, pulse shape discrimination (PSD)
Surface Events	Beta decays near surface (e.g. 210Pb)	Background in phonon/charge detectors	Fiducial volume cuts, dead layer design, phonon timing
Internal Radioactivity	39Ar (LAr), 85Kr (Xe), 222Rn	High event rate, pileup	Isotope separation (Ar), cryogenic distillation (Kr, Rn)

Some “backgrounds” for dark matter are actually the **signal** for neutrino physics (CEνNS). Designing to reject these requires extreme care in modeling and engineering.

Real-World Engineering – Dual Approach

- ✓ **DarkSide-20k**: Cryogenic distillation to reach ppt-level Kr/Rn suppression
- ✓ **DUNE-DP**: HV noise control using cold electronics and grounding topology
- ✓ **SuperCDMS SNOLAB**: Phonon pattern discrimination for surface event veto

Neutrino Probes: Current and Emerging Insights

- **Solar & Atmospheric ν**
  – Precision θ_{12}, Δm^2_{21} (JUNO), flavor composition (IceCube, KM3NeT)
  – Test of MSW effect, Earth matter profile, flavor anomalies
- **Long-Baseline ν** (DUNE, T2HK, NOvA)
  – CP violation (δ_{CP}), mass hierarchy (MH), unitarity tests
- **Reactor ν** (JUNO, PROSPECT-II)
  – Sub-percent precision on Δm^2_{21}, spectral anomalies
- **Supernova ν**
  – Time-resolved ν burst signals, ν–ν interactions, early warning (SNEWS 2.0)
- **Cosmological ν**
  – Σmν from Planck+BAO+DESI+Euclid (→ < 0.06 eV?)
  – Neff constraints (ΔNeff < 0.3 at 2σ), sterile ν exclusion
- **Coherent ν–N Scattering (CEνNS)**
  – Precision low-Eν cross-section (CONUS, COHERENT), BSM probes (NSI, light Z′)

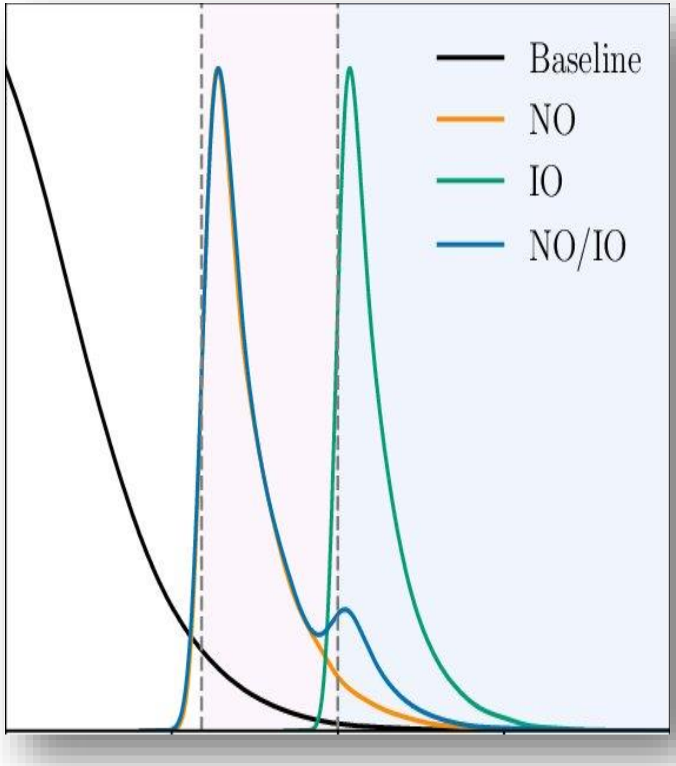
Highlights

- **JUNO**: Construction 98% complete (2025), energy resolution 3% @ 1 MeV → Δm^2_{21} to 0.5%
- **DUNE**: Far detector module installation started, near detector design finalized (2024 TDR)
- **Hyper-K:** Gd-doped water, 187 kton fiducial, CP reach ~75% at 5σ in 10 years
- **KM3NeT**: ORCA shows ν mass ordering sensitivity > 3σ with 6 years of data
- **CMB-S4 & Euclid**: joint forecasts push Σmν limit below 0.05 eV
- **CEνNS**: Machine Learning used for CEνNS-background separation at COHERENT, novel nuclear form factor constraints (2023)

Absolute Neutrino Mass Scale

Table: Absolute Neutrino Mass Scale: Experimental & Cosmological Bounds

Method	Observable	Upper Limit	Experiment / Survey	Status (2025)
Beta decay (kinematic)	$m_\beta = \sqrt{\sum_i \|U_{ei}\|^2 m_i^2}$	< 0.45 eV (90 % C.L.)	Katrin (Science	Phase II complete, 259 days of data analysed
Cyclotron radiation	Tritium spectrum endpoint	~ 0.35 eV (projected)	Project 8 (R&D Phase III)	R&D continues; design for Phase IV
Cosmology (Σ m_{nu})	Sum of neutrino masses	≤ 0.053–0.064 eV **(95 % C.L.)**	Planck + DESI DR2 + ACT	Strongest to date; approaching normal ordering
Neutrinoless double β-decay	Effective Majorana mass mββ	~ 0.04–0.15 eV (NME−dependent)	LEGEND, CUPID, KamLAND-Zen	Model-dependent; assumes neutrinos Majorana

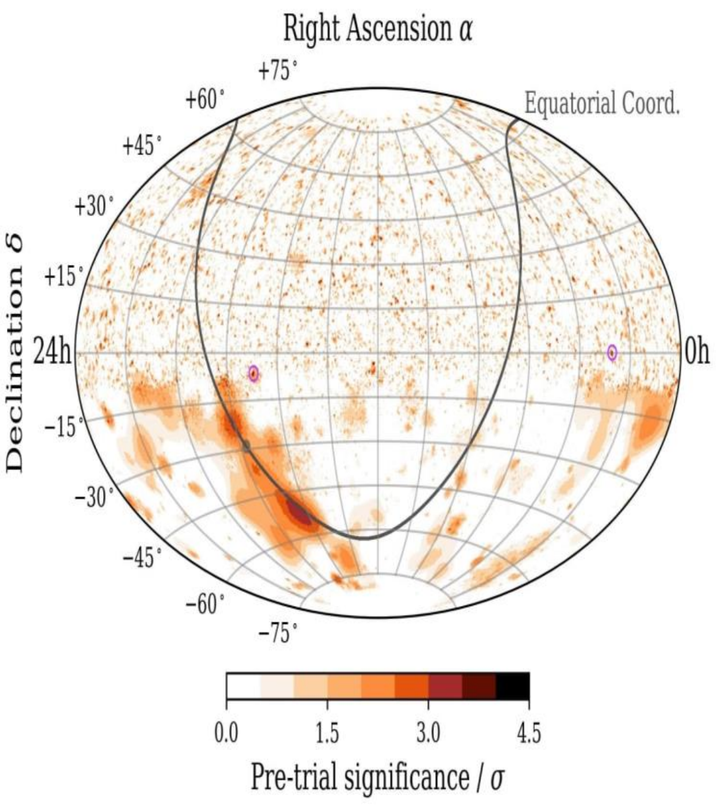


Constraints on Σ m_{nu} from Planck + DESI DR2 + ACT, by mass ordering [10.48550/arXiv.2503.14744](https://doi.org/10.48550/arXiv.2503.14744)

Neutrino Astrophysics with IceCube & KM3NeT

- ✓ IceCube and KM3NeT represent **cubic-kilometre scale detectors** embedded in ice or seawater, exploiting geometric detection volume for astrophysical ν.
- ✓ IceCube has pioneered **combined track + cascade searches**, revealing the strongest signal near **NGC 1068** (~ 4σ)
- ✓ KM3NeT deployments accelerate: **ARCA** targets TeV–PeV astrophysical ν; **ORCA** focuses on few-GeV to ~100 GeV range for oscillations & mass hierarchy

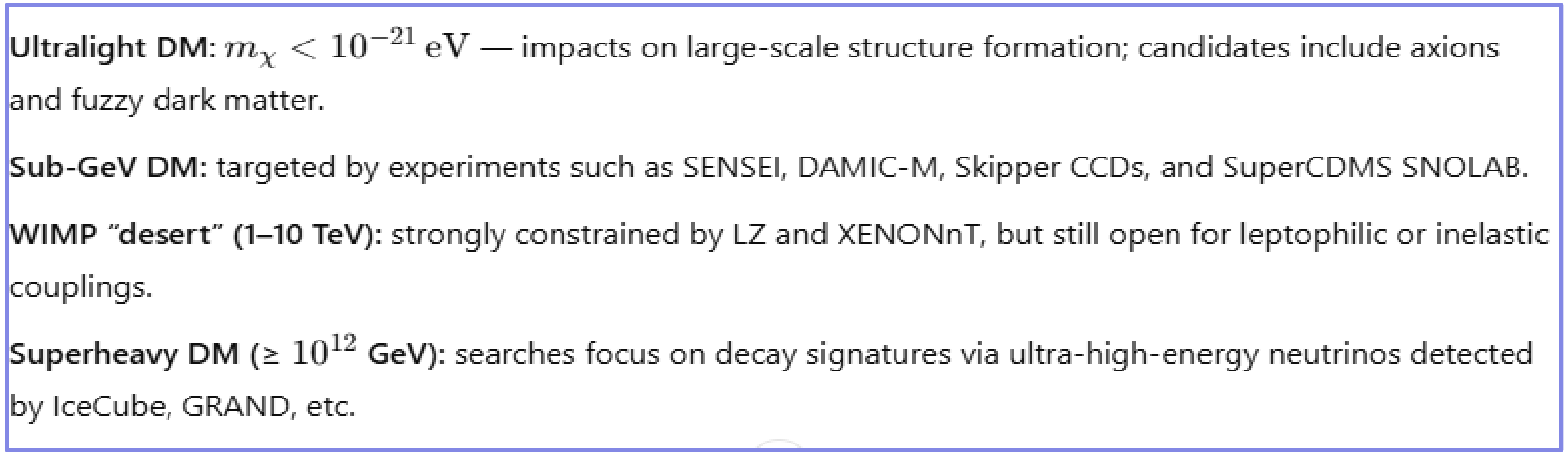
Detector	Medium	Instrumented Volume	Primary Channel	Energy Threshold	Energy Range	Roles
IceCube	Antarctic ice	~1 km³	Upward μ tracks	~100 GeV	100 GeV–10 PeV	Diffuse flux, point-source identification
IceCube-Gen2	Antarctic ice	~8 km³ (planned)	Extended sensor array	~10 GeV (DeepCore)	up to ~100 PeV	Cosmogenic ν, next-gen multimessenger
KM3NeT/ARCA	Deep-sea (Sicily)	~1 km³	Up-going μ events	~100 GeV	~100 GeV–few PeV	Galactic & extragalactic sources
KM3NeT/ORCA	Deep-sea (France)	~0.005 km³	νe/νμ atmospheric flux	~3 GeV	1–100 GeV	Mass ordering & oscillation precision



IceCube collaboration: *Figure based on combined track and cascade data (2025), showing a sky map in J2000 equatorial coordinates. The hot spots indicate regions with the highest local significance of astrophysical neutrinos (notably NGC 1068).*

Dark Matter Frontiers: Detection Landscapes & Theory

Mass ranges and experimental landscape



Ultralight DM: $m_\chi < 10^{-21}\,\mathrm{eV}$ — impacts on large-scale structure formation; candidates include axions and fuzzy dark matter.

Sub-GeV DM: targeted by experiments such as SENSEI, DAMIC-M, Skipper CCDs, and SuperCDMS SNOLAB.

WIMP "desert" (1–10 TeV): strongly constrained by LZ and XENONnT, but still open for leptophilic or inelastic couplings.

Superheavy DM (≥ 10^{12} **GeV):** searches focus on decay signatures via ultra-high-energy neutrinos detected by IceCube, GRAND, etc.

Direct dark matter detection rate

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi} \cdot \frac{C_T}{m_T} \cdot \int_{v_{\min}}^{v_{\max}} v\, f(\vec{v})\, \frac{d\sigma_T}{dE_R}(v, E_R)\, dv$$

✓ Event rate per unit recoil energy, depending on the local dark matter density ρχ, the cross section σ, and the galactic velocity distribution $f(\vec{v})$

Table: Strategic directions in dark matter research

Frontier	Approach	Mass Range	Tech/Experiments	Goal
Direct Detection	Nuclear/electron recoils	~1 GeV – few TeV	LXe (XENONnT, LZ), Ge (SuperCDMS)	Test weak couplings (SI/SD)
Indirect Detection	Neutrinos, gamma rays, cosmic rays from DM	10 GeV – 10 TeV (to PeV)	IceCube, KM3NeT, Fermi-LAT	Detect DM annihilation/decay products
Collider Searches	Direct DM production; Signature: Missing Transverse Energy	>10 GeV – ~1 TeV	LHC (ATLAS/CMS: monojet, monoZ)	Search for DM mediators, direct DM production
Astrophysics/Cosmology	Signatures on CMB, LSS, 21 cm	10^{-24} GeV – 10^{4} GeV	Planck, JWST, SKA	Constrain DM density, distribution, interactions

Dark Matter Direct Detection: Experimental Sensitivities

- Spin-independent WIMP–nucleon cross-section limits (2023–2025), with mass reach and detector specs

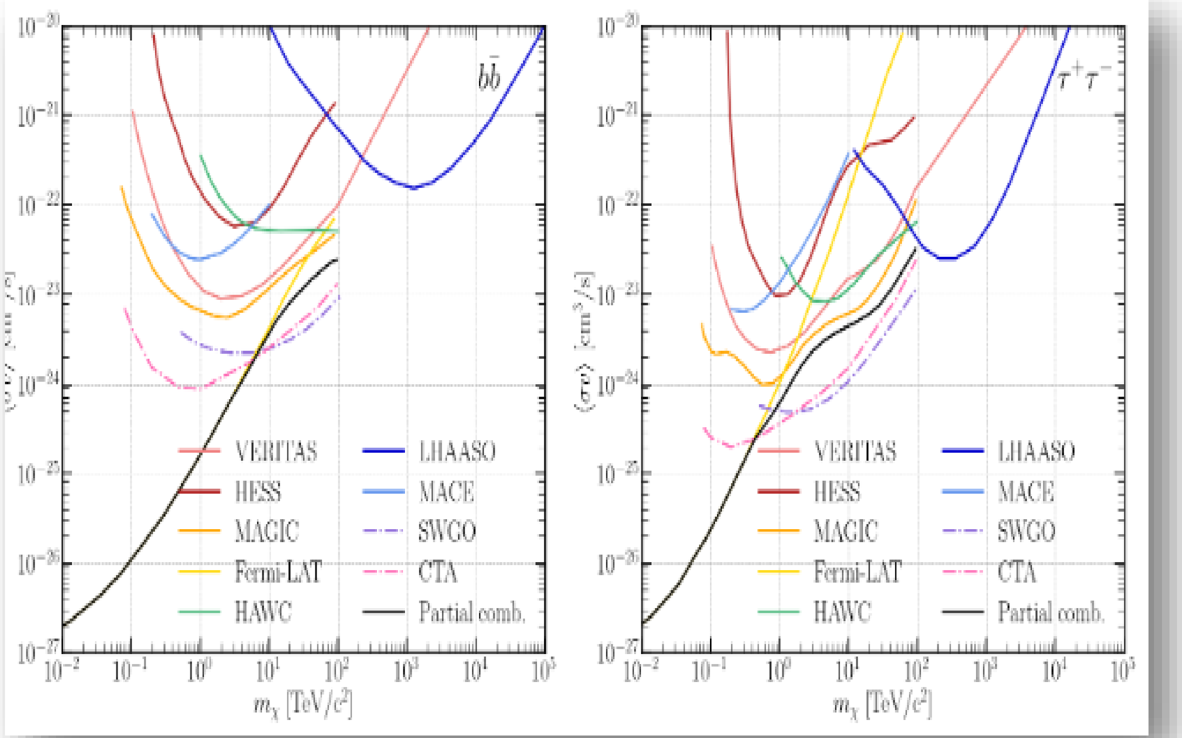
Table –Direct Detection Experiments

Experiment	Target Material	Mass [kg]	Threshold [keV]	σSI Limit [cm^2]	WIMP Mass Range [GeV]
LZ	Xe (dual-phase TPC)	7000	~1.5	5.9×10^{-48} @ 30 GeV	5 – 1000
XENONnT	Xe (dual-phase TPC)	5900	~1.6	1.06×10^{-47} @ 28 GeV	6 – 1000
PandaX-4T	Xe (dual-phase TPC)	4000	~1.5	1.4×10^{-47} @ 30 GeV	5 – 1000
DarkSide-20k	Ar (depleted LAr TPC)	20,000	~5.0	Goal: 1×10^{-47} @ 100 GeV	10 – 1000
SuperCDMS SNOLAB	Ge, Si (cryogenic)	~30	< 0.04 (Ge HV)	Goal: $<10^{-43}$ @ 1 GeV	0.3 – 10
CRESST-III	$CaWO_4$ (phonon/scint.)	~24	< 0.03	2.2×10^{-38} @ 1 GeV	0.16 – 5
DARWIN (proto–ARGO)	Xe (TPC, ultra-large)	~50,000	1.0	Goal: 1×10^{-49} @ 40 GeV	5 – 5000

Indirect and Non-Standard Dark Matter Probes

- ✓ Indirect methods (**gamma rays, antiprotons, neutrinos**) complement direct research by exploring the annihilation or decay of DM partials in astrophysical environments.

Probe	Channel / Technique	Mass Range [GeV]	Result / Limit
Fermi-LAT (dSphs)	γ-ray stacking on 54 dSphs	2–1000	$\langle\sigma v\rangle \lesssim$ few $\times 10^{-26}$ cm^3/s; local excesses~2σ en ττ & μμ
AMS-02 p̄/p	Cosmic-ray antiprotons	10–200	No detection DM; thermal WIMP exclu < ~200 GeV ; excess ≤1.8σ
VERITAS dSphs	VHE γ-rays (ττ channel)	200 – 30 000	Combined limit close to thermal threshold for ττ, high coverage
DM + LLL Mediators	Capture in dSph → decay outside	~100	σ constrained ~10^{-36} cm² via LLLM model



Limits on DM annihilation cross section from dwarf spheroidal searches assuming DM decay into $\bar{b}\,b$ (left) and $\tau+\tau-$ (right).

From : Zurowski et al., Dark Matter Signatures, Conf. ICRC 2023

Neutrino–Dark Matter Couplings & BSM Frameworks

Models of Neutrino–Dark Matter Couplings and Constraints

Model / Interactions	**Observable effects**	**Control**
ν-portal (fermion χ) via Yukawa HDL	ΔN_{eff} ν-invisible decays	$y \lesssim 10^{-7}$, $m\chi \gtrsim 10$ MeV (CMB + BBN)
Neutrinophilic scalar ϕ	ν–DM scattering, supernova attenuation	Couplings exclues sauf couplings ultra- faibles
Lμ – Lτ vector mediator DM	Oscillations modulées, ν self-interact	$g \lesssim 10^{-6}$–10^{-7} (SK, DUNE projections)
LED portal + Majoron	ΔN_{eff}, ν decay, stériles KK warm DM	Consistent avec CMB-S4 ; param. restreints

Geometric Insights in Dark Sector Models

(Gauge Structure, Modified Geometry, and Effective Mediation in Neutrino–Dark Matter Coupling)

•Dark sectors may not only introduce **new mediators** (e.g., **Z′,** scalar portals) but also alter **the effective geometry** experienced by standard model fields.

•**Neutrino–dark matter interactions** can imprint signatures of these geometric deformations — both in **field space** (gauge structure) and in **spacetime** (metric, torsion, anisotropy).

•Such effects are detectable via time delays, energy spectra distortions, and halo profile asymmetries.

Theoretical Framework

1. Extended Gauge Symmetry (**U(1)′, Z′** portal):

$$\mathcal{L}_{\text{int}} \supset g_{Z'}\, \bar{\nu}\gamma^{\mu}\nu Z'_{\mu} + g_{\chi}\, \bar{\chi}\gamma^{\mu}\chi Z'_{\mu}$$

→ A **Z′** mediator couples neutrinos and dark matter in a field-theoretic portal.

2. Effective Geometry Modifications:

Torsion from dark fields → modified affine connection:

$$\Gamma^{\lambda}_{\mu\nu} \to \Gamma^{\lambda}_{\mu\nu} + K^{\lambda}_{\mu\nu}$$

with $K^{\lambda}_{\mu\nu}$: contorsion tensor.

Impacts neutrino **phase**, potentially altering oscillation paths or propagation delay.

3. Halo Geometry and Neutrino Propagation:

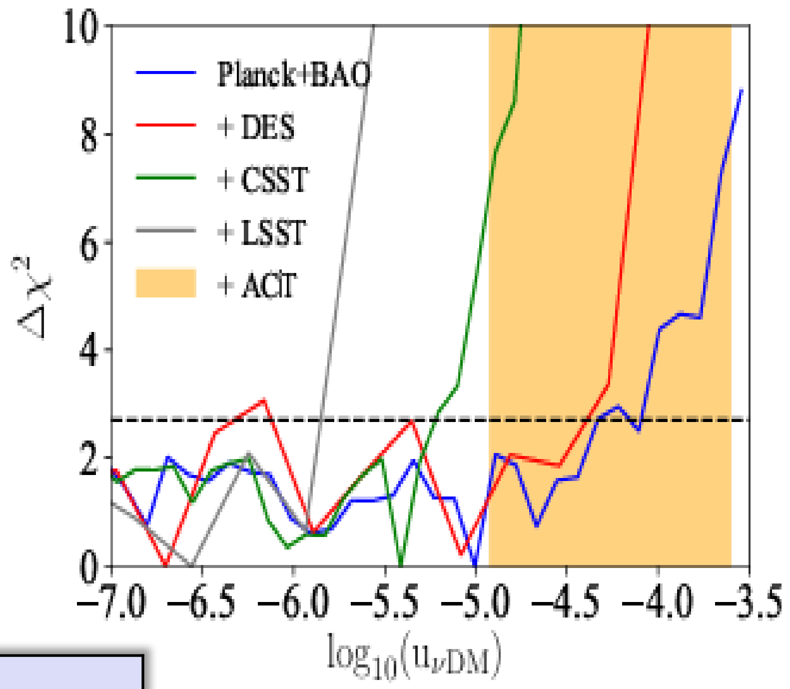
- DM halos with **non-spherical** or **rotating** structure distort neutrino trajectories.
- Predictive effects on **diffuse neutrino flux anisotropies**, and local time-of-flight distortions.

DM–ν coupling may encode more than just interaction terms — it may reflect a **geometrical structure of the dark sector**, manifesting through torsion, effective metrics, or anisotropic propagation.

Cosmological & Multimessenger Probes of Neutrinos and Dark Matter

- **Neutrino–DM interactions alter structure growth** by damping small-scale matter fluctuations.

- These couplings are now probed via:
  - ✓ **Weak lensing (S_8 tension)**: DM–ν scattering reduces structure growth.
  - ✓ **CMB + LSS**: affects phase shifts and diffusion damping (Planck, DESI).
  - ✓ **Supernovae**: cooling via dark sector channels constrains low-mass DM–ν couplings.
  - ✓ **Local gravitational tracers**: orbits of asteroids and planetary data offer limits on local DM/neutrino clustering.



Δχ2 profile vs. . $u_{\nu DM}$. Blue: Planck+BAO; red/green/gray: with DES Y3, CSST, LSST. Dashed line: 2σ limit. Orange band: 68% CL from Planck+BAO+ACT

Observable / Probe	Insight	Reference
S_8 (structure growth)	Detection of DMν coupling $u \sim 10^{-4}$ reduces tension	Zu et al. (2025) [arXiv:2501.13785]
Supernova cooling (SN1987A)	$\times 10^4$ stronger constraints for sub-100 MeV DM–ν interactions	Cappiello & Dev (2025) [arXiv:2503.09691]
∑mν (CMB + DESI DR2)	Refined to ~0.07 eV (95% CL)	
Solar System dynamics (Bennu, LAGEOS)	Gravitational limits on local DM–ν clustering	Tsai et al. (2024) [JCAP]

Neutrino Echo Time Delays from BSM Scattering

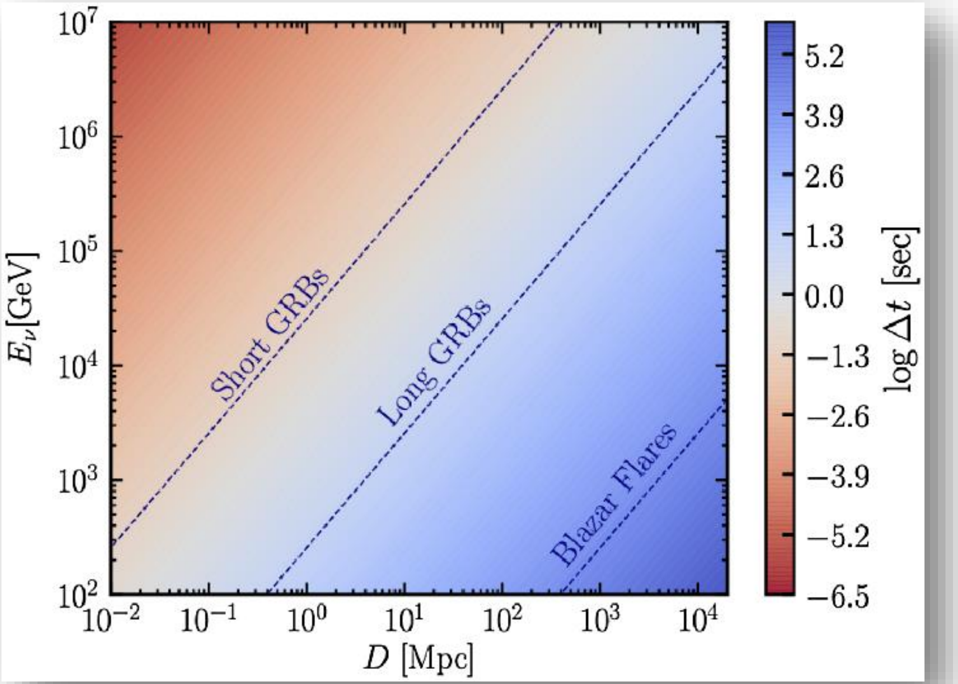
Neutrino Echoes from BSM ν–ν / ν–DM Interactions (Optically-Thin Limit)

✓ High-energy neutrinos traveling through the cosmic neutrino background or dark matter may experience **single scattering**, producing characteristic **delayed 'echo' light-curves**. These time-delay profiles are observationally accessible via multimessenger triggers

$$P(t) \approx \int d\phi \, \frac{1}{\sigma_\nu} \frac{d\sigma_\nu}{d\theta}\Big|_{\theta\approx\phi+2t/(D\phi)} \qquad \text{with} \quad \tau_\nu \approx n_\nu \sigma_\nu D \ll 1$$

- $P(t)$: time-delay probability distribution
- D: source distance
- τ_ν: optical depth
- Derived analytically in Eskenasy et al. 2023

Scenario	Parameter Range	Observable Effects	Experimental Reach
ν–ν scattering	$g\nu \gtrsim 10^{-2}$,$m\varphi \sim$MeV	Delayed ν echo tail (Δt up to ~10^4 s)	IceCube-Gen2, KM3NeT, Hyper-K
ν–DM scattering	Similar range + DM density factor	Tail broadened, energy spectrum modified	Detection possible for extragalactic GRBs



Neutrino echo time-delay distributions in the optically-thin regime, varying with neutrino energy and source distance. The dashed horizontal lines mark typical transient durations: short-GRBs (~0.1 s), long-GRBs (~10^2 s), and blazar flares (~10^5 s).
"Light curves of BSM-induced neutrino echoes in the optically thin limit »
From: Phys. Rev. D 107, 103038 (2023)

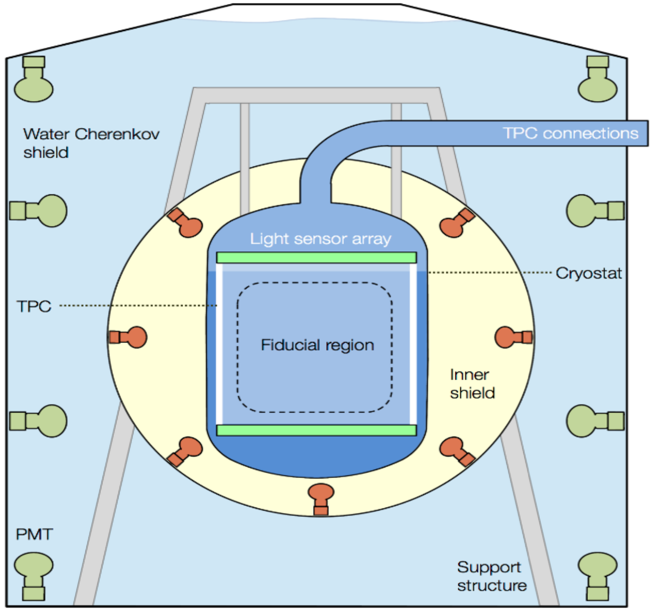
Advanced Detector Architectures for Ultra-Rare Signal Detection

Next-Generation Architectures: DARWIN, ARIA, GridPix & Paleo-Detectors

Emerging detection platforms—including **DARWIN's multi-ton xenon TPC**, **ARIA's argon isotope distillation**, **GridPix-based micro-TPCs**, and **paleo-detectors in ancient minerals**—are pushing sensitivities to the **zeptobarn scale**, vital for probing neutrino echoes and dark matter beyond the **neutrino floor**.

Table: Architecture Highlights

Platform	Target Material	Innovation & Status	Sensitivity Goal	Dual ν/DM Reach
DARWIN	Liquid Xenon (~40–50 t)	Large-scale multi-TPC; ultra-pure LXe; neutron veto, sub-keV threshold	~10^{-49} cm²	Solar ν, SNB, DM WIMPs
ARIA (Seruci-0 proto)	Underground Argon (UAr)	26 m column prototype; isotopic separation of ^{39}Ar from ^{40}Ar; full 350 m installation underway	~10^{-48}–10^{-49} cm²	DM direct, CEνNS neutrino background
GridPix	Pixelated micro-TPC	Ultra-fine readout (Timepix/Medipix family) for sub-keV recoil detection; recent application for axion and DM searches at CAST	~10^{-48}–10^{-50} cm² possible	Low-energy DM, solar & axion-like particles
Paleo-detectors	Ancient minerals	Geological exposure over gigayears; fossil nuclear recoils captured in mica/olivine; projections include DM sub-halo tracking and cosmic wall imprints	$\lesssim 10^{-48}$ cm² over Gyr exposure	Paleo-ν, historic DM interactions



Pictorial view of the DARWIN base-line detector design
Aalbers et al., JCAP 1611 (2016) no.11, 017

Sensitivity Scaling:

σ_min ∝ 1 / (M · T · B)

Neutrino Floor Breakthrough:

– CEνNS mimics WIMP recoils at sub-10^{-48} cm²

– Requires ML, directionality, recoil topology

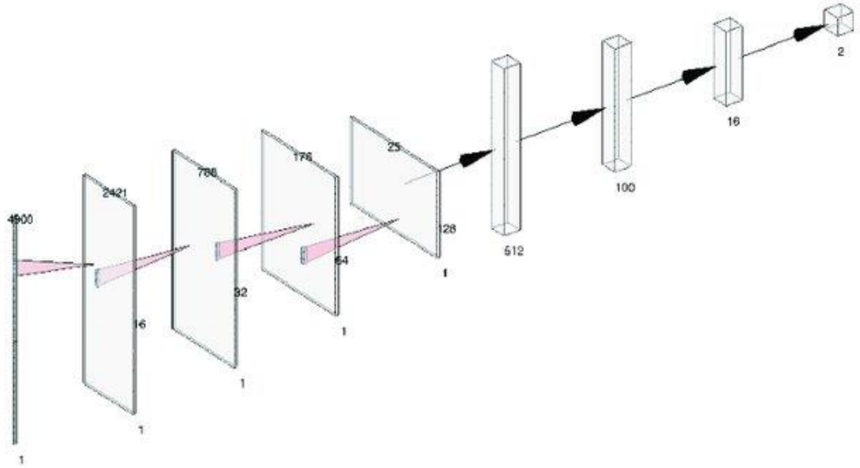
ML-based Data Strategy for Signal Discrimination in ν and DM Detectors

Machine Learning-powered Signal/Background Discrimination: Shared Innovations

- Both **neutrino** and **dark matter** detectors face extreme signal rarity and complex backgrounds.
- Machine learning models—**CNNs**, **GNNs**, **autoencoders**—are essential for accurate classification, energy estimation, topology reconstruction, and anomaly detection.
- Real-time inference on **edge devices** (FPGA/ASIC) is now feasible, improving trigger strategies and reducing false positives.
- Yet systematic robustness and explainability remain active research frontiers.

Experiment	ML Model	Application Area	Performance / Benefit
DarkSide-20k	CNN (1D-S2 pattern)	xy position & energy reconstruction	~1 cm spatial resolution; improved PSD
DUNE / ProtoDUNE	GNN (e.g., NuGraph2)	Hit clustering, track-shower separation, tau-neutrino ID	~98 % interaction labeling efficiency; improved event topology classification
Neutrino telescopes	GraphNeT framework	Real-time event reconstruction across multiple detectors	Real-time inference for IceCube extensions, scalable across platforms

Architecture of a 1D CNN for position reconstruction in the DarkSide-20k TPC



DarkSide-20k position-reconstruction CNN using top-array SiPM data, as presented in EPJ Web Conf., 251 (2021) 03029

Synthetic Table: Detector Technologies & Sensitivities for Neutrino and Dark Matter Searches (2023–2025)

Comprehensive Comparison of Detection Technologies & Sensitivities

Technology	Detector / Experiment(s)	Target Material(s)	Energy Sensitivity Range	Signal Types	Sensitivity / Limits (Cross-section or Equivalent)
Liquid Xenon TPC	XENONnT, LZ, DARWIN	Liquid Xenon (Xe)	keV to 100 keV	WIMPs (NR), Solar & DSNB ν	~1.4×10^{-47} cm² (WIMP-nucleon SI) (XENONnT)
Liquid Argon TPC	DarkSide-20k, ARIA	Underground Argon (UAr)	keV to 100 keV	WIMPs, CEvNS, Solar neutrinos	~10^{-48} cm² projected (DarkSide-20k)
Cryogenic Solid-State	SuperCDMS SNOLAB, EDELWEISS	Ge, Si Crystals	~40 eV to few keV	Light WIMPs, low-energy neutrinos	~10^{-48}–10^{-49} cm² (SuperCDMS)
Neutrino Liquid Argon	DUNE, ProtoDUNE	Liquid Argon	MeV to GeV	Accelerator, supernova, atmospheric ν	Few % energy resolution, excellent timing
Water Cherenkov	Hyper-Kamiokande, Super-K	Water	MeV to multi-GeV	Solar, atmospheric neutrinos	Large volume, ms timing resolution
Neutrino Telescopes	IceCube Gen2, KM3NeT	Ice, Sea Water	TeV to PeV	Astrophysical neutrinos	Effective area ~10 km², angular resolution ~0.2°
Direct Light DM Detectors	CRESST-III, DAMIC-M	$CaWO_4$, Si CCDs	~30 eV to keV	Sub-GeV dark matter candidates	Threshold ~30 eV; limits ~10^{-41}–10^{-43} cm²
Indirect DM Detection	Fermi-LAT, AMS-02, JWST	Space-based telescopes	keV to TeV (γ-rays, cosmic rays)	DM annihilation/decay products	Annihilation cross-section limits ~10^{-26} cm³/s
Advanced Gas TPCs	GridPix, CYGNUS	Gaseous Ar, CF_4 mixtures	sub-keV to tens of keV	Directional DM, low-energy recoils	Target ~10^{-49}–10^{-50} cm² sensitivity
Paleo-detectors	Ancient Minerals (mica, olivine)	Solid-state minerals	Integrate recoils over Gyr	Long-term DM, neutrino archaeology	Projected ~10^{-48} cm² over geological exposure

Conclusion & Key Questions

Synthesis and Fundamental Challenges Ahead

- **Unified progress:** Recent advances in neutrino and dark matter detection technologies are converging to provide complementary insights into the invisible universe.

- **Parameter space narrowing:** Precision measurements from JUNO, DUNE, IceCube, XENONnT, and LZ are increasingly constraining beyond-Standard Model scenarios.

- **BSM and coupling frontiers:** Novel probes such as neutrino echo time delays and ν–DM interactions in astrophysical environments open promising pathways for dark sector physics.

- **Multimessenger synergy:** Combined data from neutrino observatories, gravitational wave detectors, electromagnetic surveys, and cosmology enhance discovery potential and model discrimination.

- **Outstanding challenges:** Fundamental questions remain regarding the absolute neutrino mass scale, the particle nature of dark matter, and possible neutrino–dark matter coupling mechanisms.

- **Technological innovation essential:** Next-generation detectors, machine learning approaches, and interdisciplinary efforts will be critical for advancing sensitivities and interpretation frameworks

Outlook & Interdisciplinary Pathways

Future Directions: Synergies and Transformative Approaches

- **Next-generation facilities:** DARWIN, IceCube Gen2, Hyper-K, and ARIA poised to dramatically improve sensitivity to neutrinos and dark matter at unprecedented scales.

- **Machine learning and AI:** Integration of advanced ML algorithms for enhanced signal discrimination, background rejection, and real-time event classification.

- **Geometric and theoretical innovations:** Emerging models invoking modified spacetime geometry, torsion effects, and novel symmetry groups (U(1)’, dark sectors) to explain astrophysical anomalies and particle couplings.

- **Multimessenger astrophysics growth:** Increasing synergy across neutrino, gravitational wave, electromagnetic, and cosmic surveys enabling deeper insights into cosmic phenomena and dark sector physics.

- **Interdisciplinary collaborations:** Strengthening bridges between particle physics, astrophysics, cosmology, and data science to tackle complex challenges.

- **Long-term visions:** Paleo-detectors and mineral-based neutrino archaeology to probe gigayear timescales; scalable, modular detector designs for future large-volume observatories

Thank you for your attention

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