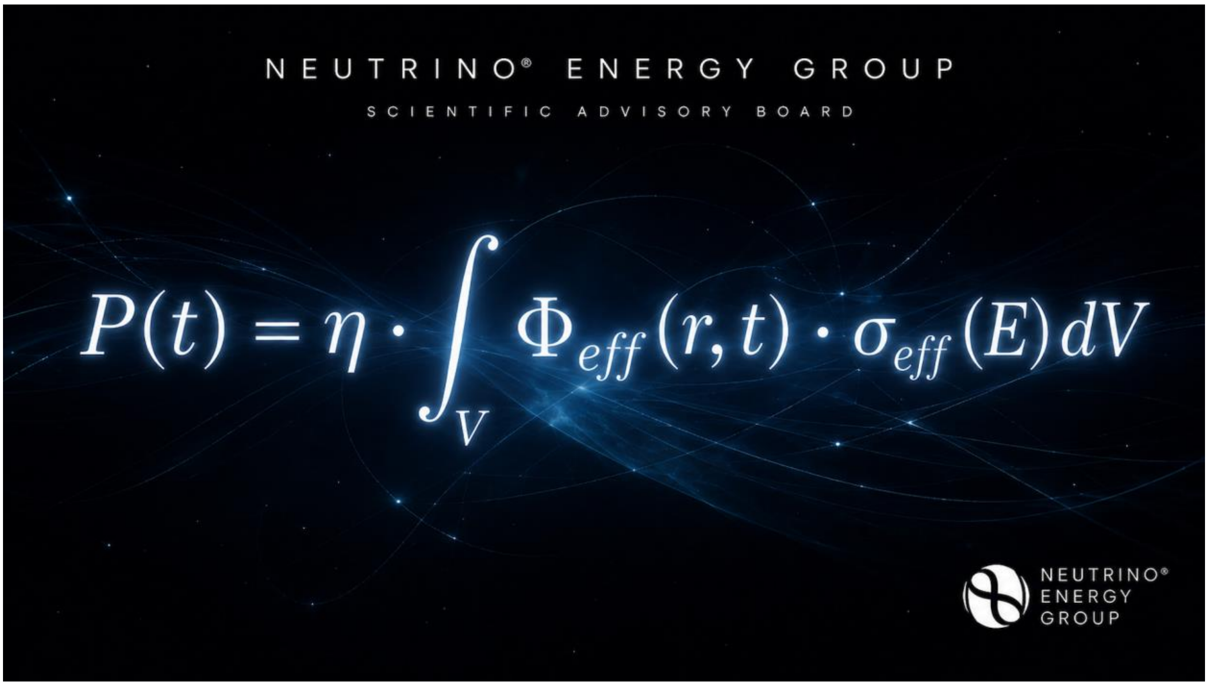
Review of Neutrino Astronomy and Neutrino Physics



Author: Daniel Lee, Member of the Neutrino Energy Group Committee

Abstract

Neutrinos are the only fermions in the Standard Model that solely participate in weak interactions. They act as dual information carriers integrating particle physics and astrophysics, serving as core messengers linking microscopic fundamental interactions and the macroscopic evolution of the universe. This paper systematically reviews the research progress and frontier issues in neutrino astronomy and neutrino physics. From the theoretical framework perspective, it elaborates on the PMNS flavor mixing mechanism, MSW matter effect and the seesaw theory for neutrino mass generation, and summarizes the global fitting precision of the three mixing angles and two mass squared differences. From the experimental detection perspective, it covers a complete experimental spectrum including precise solar neutrino measurements, calibration of reactor and accelerator neutrino oscillation parameters, and high-energy neutrino detection by IceCube, and analyzes the technical routes and performance complementarity of the global detection network. From the perspective of astrophysical sources, it analyzes neutrino generation mechanisms of active galactic nuclei, supernova explosions, neutron star mergers, tidal disruption events and other celestial bodies, and reviews cutting-edge observational achievements such as Galactic plane neutrino imaging. From the interdisciplinary frontier perspective, it illustrates the observational paradigm of multi-messenger astronomy and the scientific value of neutrinos as probes for new physics. Based on a comprehensive perspective of fundamental physics, this paper divides fundamental physics into ten research branches and constructs an interdisciplinary correlation system between neutrino physics and various disciplines, clarifying the pivotal role of neutrinos in the fundamental science system. Finally, this paper assesses core unsolved scientific problems in this field and prospects the development of neutrino mass ordering determination, CP violation measurement and next-generation neutrino telescopes.

Keywords: neutrino astronomy; neutrino oscillation; high-energy neutrino; multi-messenger astronomy; interdisciplinary correlation analysis

1 Introduction

Neutrinos rank among the most distinctive fundamental particles in the Standard Model of particle physics. As neutral members of the lepton family, neutrinos only engage in weak and gravitational interactions, and their reaction cross-sections with ordinary matter are extremely low, hence the nickname "ghost particles". In the original theoretical system of the Standard Model, neutrinos were hypothesized to be massless Weyl fermions. In 1998, the Super-Kamiokande experiment in Japan observed atmospheric neutrino oscillation, providing the first definitive proof that neutrinos possess non-zero mass. This discovery broke the theoretical predictions of the Standard Model and opened a core experimental window for new physics beyond the Standard Model[1].

The birth of neutrino astronomy is marked by the detection of neutrinos from Supernova SN1987A in the Large Magellanic Cloud. In that year, three underground detectors, namely Kamiokande-II (Japan), IMB (USA) and Baksan (Soviet Union), recorded approximately 25 neutrino events originating from the supernova explosion. This observation verified for the first time that astrophysical processes can produce detectable neutrino signals and laid the observational foundation for neutrinos as cosmic messengers[2-3]. For nearly thirty years afterwards, neutrino astronomy remained in a stage of source accumulation and technological iteration. It was not until 2013 that the IceCube Collaboration at the South Pole first detected diffuse astrophysical neutrinos at the PeV scale, officially inaugurating a new era of high-energy neutrino astronomy[4].

Entering the third decade of the 21st century, neutrino research has entered a phase of rapid development featuring parallel progress in precision measurement and source identification. In particle physics, the Daya Bay Experiment accurately measured the smallest mixing angle θ_{13}, and the Borexino Experiment completed full-spectrum measurements of solar neutrinos, continuously improving the precision of neutrino oscillation parameters. In astrophysics, IceCube has successively completed the identification of NGC 1068 as a neutrino source and high-energy neutrino imaging of the Galactic plane, while detectors including KM3NeT and Baikal-GVD have formed a globally complementary observational network. In interdisciplinary research, the collaborative observational paradigm combining gravitational waves, neutrinos and electromagnetic waves has gradually matured, and neutrinos have become critical probes for frontier topics such as dark matter and quantum gravity.

This paper systematically sorts out the existing research status of neutrino astronomy and neutrino physics. Chapter 2 elaborates core theoretical frameworks of neutrino oscillation and mass generation as well as extensions to new physics. Chapter 3 reviews experimental detection advances and technical systems from low to high energy bands. Chapter 4 analyzes the radiation mechanisms and observational evidence of various astrophysical neutrino sources. Chapter 5 discusses the paradigm of multi-messenger astronomy and interdisciplinary frontiers. Chapter 6 divides fundamental physics into ten research branches and establishes the correlation system between neutrino physics and each branch. Chapter 7 summarizes research consensus, evaluates outstanding scientific puzzles and forecasts future research directions.

2 Theoretical Foundations of Neutrino Physics

2.1 Neutrinos within the Standard Model

In the Standard Model of particle physics, neutrinos form SU(2) weak isospin doublets together with the three generations of charged leptons (electron, muon, tau). Neutrinos only participate in weak interactions mediated by W^+, W^- and Z^0 bosons. Charged-current interactions are accompanied by lepton flavor transformation, serving as the core physical basis for neutrino detection and flavor oscillation; neutral-current interactions do not change lepton flavor and only transmit momentum and energy.

Weak interactions feature short ranges and low coupling strengths, leading to ultra-small neutrino-matter reaction cross-sections. Under high-energy approximation, the scaling relation holds:

$$\sigma_{\nu N} \approx \frac{G_F^2 E_\nu^2}{\pi}$$

where G_F denotes the Fermi constant and E_ν stands for neutrino energy[5]. This property allows high-energy neutrinos to penetrate the Earth with negligible interactions, which creates technical challenges for neutrino detection while endowing neutrinos with unique advantages as cosmic messengers. Unlike high-energy photons, which are absorbed by cosmic background radiation or source media, neutrinos can traverse dense celestial bodies and intergalactic space without attenuation, directly delivering physical information from stellar cores.

2.2 Neutrino Oscillation and the PMNS Mixing Matrix

The physical essence of neutrino oscillation lies in the mismatch between flavor eigenstates (ν_e, ν_μ, ν_τ) and mass eigenstates (ν_1, ν_2, ν_3). The two sets of eigenstates are linked via unitary transformation described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix[6]:

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} \quad (2)$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$; $\theta_{12}, \theta_{23}, \theta_{13}$ represent the three mixing angles and δ_{CP} is the Dirac CP-violating phase. If neutrinos are Majorana particles, two additional Majorana phases need to be introduced.

Under the simplified two-flavor approximation, the vacuum neutrino oscillation probability reads:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(1.27 \cdot \frac{\Delta m^2 L}{E_\nu}\right) \qquad (3)$$

$\Delta m^2 = m_i^2 - m_j^2$ refers to mass squared difference (unit: eV^2), L the propagation baseline length (km), E_ν neutrino energy (GeV). Oscillation phenomena directly prove the existence of non-zero neutrino mass differences, providing experimental evidence for neutrino mass.

According to the 2024 global fitting results (v6.0) released by the Nu-Fit Collaboration, the optimal fitting values of three-flavor oscillation parameters are listed in Table 1[7]. At present, the three mixing angles and two independent mass squared differences have reached percent or even sub-percent precision. Nevertheless, neutrino mass ordering (normal ordering NO / inverted ordering IO), the octant of θ_{23} and the exact value of δ_CP remain core unresolved issues in this field.

Table 1 Global Fitting Results of Three-Flavor Neutrino Oscillation Parameters (Normal Mass Ordering, Nu-Fit v6.0, 2024)

Parameter Symbol	Physical Meaning	Best-Fit Value	1σ Uncertainty
$\sin^2\theta_{12}$	Solar mixing angle	0.307	±0.012
$\sin^2\theta_{23}$	Atmospheric mixing angle	0.545	+0.016 / −0.021
$\sin^2\theta_{13}$	Reactor mixing angle	0.0220	±0.0007
δ_{CP}/π	CP-violating phase	1.03	+0.16 / −0.13
Δm_{21}^2	Solar mass squared difference ($10^{-5}eV^2$)	7.42	±0.20
Δm_{31}^2	Atmospheric mass squared difference	2.514	±0.027

	(10^{-3}eV^2)		

2.3 Matter Effect and MSW Mechanism

When neutrinos propagate through matter, electron neutrinos undergo coherent scattering with medium electrons via charged-current interactions, acquiring an extra effective potential that modifies effective mass eigenstates and mixing angles. This phenomenon is known as the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect[8-9].

When the electron density of the medium meets specific resonance conditions, the mixing angle is drastically amplified, enabling nearly complete flavor conversion even if the vacuum mixing angle is small. The MSW effect constitutes the core mechanism of solar neutrino flavor transformation, and also serves as the key physical basis for distinguishing mass ordering in long-baseline accelerator and reactor experiments.

2.4 Neutrino Mass Origin and the Seesaw Mechanism

The Standard Model cannot naturally generate tiny neutrino masses via the Higgs mechanism. The seesaw mechanism is the most widely recognized mass generation theory. It introduces heavy right-handed Majorana neutrinos and derives the effective mass matrix of light left-handed neutrinos after electroweak symmetry breaking:

$$m_\nu \approx -m_D^T M_R^{-1} m_D \qquad (4)$$

where m_D denotes the Dirac mass matrix generated by lepton Yukawa couplings and M_R the mass matrix of heavy right-handed neutrinos. If M_R lies at the Grand Unified Theory (GUT) scale ($\sim 10^{14}$GeV), light neutrinos naturally obtain masses at the eV scale, explaining why neutrinos are far lighter than other fermions[10].

Apart from the canonical Type-I seesaw mechanism, Type-II and Type-III mechanisms realize mass suppression by introducing SU(2) triplet Higgs scalars and triplet fermions respectively, offering multiple theoretical paths for neutrino mass generation.

Whether neutrinos are Dirac or Majorana particles is a fundamental problem in particle physics. Neutrinoless double-beta decay (0νββ) is the sole experimental probe for the Majorana nature, and its decay rate is proportional to the square of the effective Majorana mass $|m_{\beta\beta}|$. Confirmation of this process would prove lepton number non-conservation and supply critical evidence for cosmic leptogenesis[11].

2.5 New Physics Beyond the Standard Model

The three-flavor oscillation framework has been validated by diverse experiments, yet several experimental anomalies and theoretical motivations drive research on new physics:

1. **Non-Standard Interactions (NSI)**: Hypothesized new couplings between neutrinos and matter fermions beyond weak interactions would alter matter effects and oscillation behaviors. Current experiments impose strict constraints on NSI parameters, though degeneracies with standard oscillation parameters persist.

2. **Sterile Neutrinos**: New neutrino states that do not participate in standard weak interactions and only mix with active neutrinos. eV-scale sterile neutrinos were once proposed to explain short-baseline anomalies, yet IceCube atmospheric neutrino analysis places strong limits on this parameter space, requiring further experimental verification of their existence.

3. **Neutrino Magnetic Moment and Decay**: In the Standard Model, Dirac neutrinos have a magnetic moment of merely $\sim 10^{-19}\mu_B$. Measurement of a larger magnetic moment would signal new physics. Neutrino decay modifies the flavor composition and energy spectra of astrophysical neutrinos, representing a key search target for high-energy experiments.

3 Advances in Neutrino Experimental Detection and Technical Systems

3.1 Solar and Atmospheric Neutrino Experiments

Solar and atmospheric neutrinos pioneered the discovery of neutrino oscillation and fostered the development of the whole discipline.

- **Solar Neutrino Experiments**: In 1968, the Homestake Chlorine Detector in the US observed a solar neutrino flux far below Standard Solar Model predictions, launching over thirty years of research on the solar neutrino problem. In 2002, the Sudbury Neutrino Observatory (SNO) in Canada measured charged-current and neutral-current reactions simultaneously with heavy water, directly proving solar neutrino flavor conversion and reconciling total flux with theoretical predictions, thereby resolving the solar neutrino puzzle experimentally.

- **Atmospheric Neutrino Experiments**: In 1998, the Super-Kamiokande Experiment precisely measured the zenith angle distribution of atmospheric neutrinos and discovered periodic variations of muon neutrino flux with propagation distance, delivering definitive experimental proof of oscillation and constraining parameters of atmospheric mass squared difference and θ_{23} [1].

- **Borexino Experiment**: Located at the Gran Sasso Underground Laboratory in Italy, it employs 278 tons of ultra-pure liquid scintillator with radioactive background down to 10^{-17}g/g. During its 14-year operation, it made the first precise measurement of pp neutrinos, improved the precision of ^{7} Be neutrino flux to 2.7%, and achieved a 7σ detection of CNO cycle neutrinos in 2020. It fully covers the entire energy spectrum of neutrinos from the solar pp chain and CNO cycle for the first time, providing key constraints on the solar metallicity problem[12-13].

3.2 Reactor and Accelerator Neutrino Oscillation Experiments

Benefiting from controllable beam conditions, reactor and accelerator experiments undertake precision measurements of oscillation parameters.

- **Reactor Neutrinos and θ_{13} Measurement**: In 2012, China's Daya Bay Experiment measured a non-zero θ_{13} with a confidence level above 5σ, precisely yielding $\sin^2 2\theta_{13} \approx 0.092$. This result indicates the third mixing angle is larger than theoretical expectations and opens experimental windows for CP violation and mass ordering measurements. The RENO (South Korea) and Double Chooz (France) experiments independently confirmed this finding.

- **Long-Baseline Accelerator Experiments**: T2K (Japan, 295 km baseline) and NOvA (USA, 810 km baseline) utilize accelerator muon neutrino beams to constrain the δ_CP phase and mass ordering by measuring electron neutrino appearance at far detectors. The latest T2 data favor maximal CP violation and normal mass ordering; joint analysis of the two experiments continuously narrows parameter space and lays foundations for next-generation facilities.

- **KamLAND Experiment**: Using reactor antineutrino measurements over a 180 km baseline, it accurately determined solar oscillation parameters Δm^2_{21} and θ_{12}, consistent with solar neutrino results and cross-verifying the MSW effect.

3.3 Global Detection Network for High-Energy Astrophysical Neutrinos

High-energy neutrino astronomy centers on kilometer-scale Cherenkov detectors. A global network covering the South Pole, Mediterranean Sea and Lake Baikal has been established.

- **IceCube Neutrino Observatory**: Installed under the Amundsen-Scott South Pole Station, it has an effective volume of ~1 km^3 with 5,160 digital optical modules mounted on 86 strings to capture Cherenkov light from charged particles. It discovered astrophysical neutrinos in 2013[4], made the first multi-messenger association with blazar TXS 0506+056 in 2018, detected a 6.3 PeV Glashow resonance event in 2021, confirmed neutrino emission from NGC 1068 in 2022, and realized Galactic plane neutrino imaging in 2023.

- **Baikal-GVD & KM3NeT**: By 2024, Russia's Baikal-GVD deployed 4,104 optical modules and independently verified the cosmic diffuse neutrino flux. The Mediterranean KM3NeT consists of ARCA (astrophysics array) and ORCA (oscillation array; it reported PeV-scale neutrino events in 2025, achieving northern-sky complementarity with IceCube.

- **LHAASO (China)**: The Large High Altitude Air Shower Observatory features ultra-high sensitivity to PeV gamma rays and has discovered over one hundred ultra-high-energy Galactic gamma sources, supplying critical electromagnetic counterparts for Galactic neutrino accelerators and advancing Galactic multi-messenger astrophysics.

3.4 Measurements of Absolute Neutrino Mass and Fundamental Properties

The absolute mass scale and Majorana nature of neutrinos constitute core unsolved puzzles in particle physics.

- **Direct Tritium Beta-Decay Measurement**: Germany's KATRIN Experiment constrained the upper limit of effective electron neutrino mass to $m_\nu < 0.8$eV (90% C.L.) in 2024 via endpoint spectrum distortion measurements of tritium decay, representing the strictest laboratory constraint to date. The future Project 8 using cyclotron radiation spectroscopy is expected to reach 40 meV sensitivity.

- **Neutrinoless Double-Beta Decay Experiments**: GERDA, CUORE, EXO-200 and other experiments have pushed the upper limit of effective Majorana mass to the hundred-meV range. Ton-scale next-generation detectors LEGEND-1000, nEXO and CUPID will operate from 2027 to 2030 with a target sensitivity of 10 meV, covering the full Majorana parameter space under inverted ordering[11].

- **Cosmological Indirect Constraints**: Joint analysis of Planck CMB data and large-scale structure surveys restricts the sum of three neutrino masses to $\Sigma m_\nu < 0.12$eV (CMB only) or $\Sigma m_\nu < 0.60$eV (including BAO and supernovae), offering complementary limits to laboratory measurements.

3.5 Next-Generation Experimental Facilities and Scientific Goals

Multiple next-generation experiments are under construction, adopting distinct technical routes to address core physical problems. Their key parameters and objectives are summarized in Table 2.

Table 2 Core Parameters and Scientific Goals of Next-Generation Neutrino Experiments

Facility	Technical Route	Effective Mass/Volume	Core Scientific Goals	Scheduled Operation
JUNO (Jiangmen, China)	Liquid scintillator	20 kt	Mass ordering, precision oscillation parameters	2025 onwards
DUNE (USA)	Liquid argon TPC	40 kt	Precision CP measurement, mass ordering, new physics	2029 onwards
Hyper-Kamiokande (Japan)	Water Cherenkov	260 kt	CP violation, proton decay, supernova neutrinos	2027 onwards
IceCube-Gen2 (South Pole)	Ice Cherenkov	~8 km^3	High-energy source survey, new physics tests	2030 onwards
KM3NeT-ARCA (Mediterranean)	Seawater Cherenkov	~1 km^3	Northern sky high-energy neutrino observation	Phased expansion
TRIDENT (China Hai-Ling Project)	Deep-sea Cherenkov	Multi-cubic km	Northern sky ultra-high-energy neutrino detection	Around 2030

Distinct technical routes feature complementary strengths: water/ice Cherenkov detectors suit large-volume high-energy observation with excellent angular resolution; liquid scintillators deliver superior energy resolution for low-energy precision measurements; liquid argon TPCs excel at particle identification and fine track reconstruction.

4 Astrophysical Neutrino Sources and Radiation Mechanisms

4.1 Extragalactic AGNs and Gamma-Ray Bursts

Active Galactic Nuclei (AGNs) and Gamma-Ray Bursts (GRBs) are primary candidates for extragalactic high-energy neutrino emission.

- **Active Galactic Nuclei**: Protons are accelerated to ultra-high energies by shocks in AGN relativistic jets or accretion disk coronae, generating charged pions via pγ or pp collisions. Charged pions decay into muon and electron neutrinos. Two source classes are observationally identified:

a. Blazars (e.g., TXS 0506+056): Jets point toward Earth with strong relativistic beaming; neutrino emission accompanies gamma flares.

b. Radio-quiet Seyfert galaxies (e.g., NGC 1068): Neutrinos are produced in dense gas around accretion disks; high-energy gamma rays are absorbed by the medium, leading to a "neutrino-bright, gamma-dim" signature.

- **Gamma-Ray Bursts**: The canonical fireball model predicts internal shocks accelerate protons to produce high-energy neutrinos. However, IceCube searches across hundreds of GRBs yield no significant signals, with flux upper limits far below model predictions, driving revisions of GRB neutrino models and research on low-luminosity GRB contributions.

4.2 Transient Burst Sources: Supernovae and Compact Binary Mergers

Transient sources are core targets for multi-messenger observation, simultaneously emitting gravitational waves, electromagnetic radiation and neutrinos.

- **Core-Collapse Supernovae**: During the core collapse of massive stars, ~99% of gravitational binding energy (\$10^{53} \text{erg}$) is released as neutrinos with average energies of 10–20 MeV. The 25 SN1987 neutrino events revealed the second-scale timeline of core collapse. Hyper-Kamiokande will detect \ 10^5 events from a Galactic supernova, while DUNE offers unique sensitivity to the neutronization burst at collapse onset.

- **Binary Neutron Star Mergers**: The 2017 gravitational wave event GW170817 established mergers as multi-messenger sources, yet IceCube detected no associated high-energy neutrinos, indicating lower-than-expected flux. Future high-sensitivity detectors will continue testing hadronic acceleration mechanisms during mergers.

- **Tidal Disruption Events (TDEs)**: Stars tidally disrupted by supermassive black holes form accretion flows that accelerate protons into neutrinos. In 2020, IceCube reported a ~3.5σ spatial correlation between a high-energy neutrino and TDE AT2019dsg, incorporating TDEs into neutrino source candidates for the first time.

4.3 Diffuse Galactic Neutrinos and Discrete Accelerators

In 2023, IceCube produced the first high-energy neutrino map of the Galactic plane, confirming significant diffuse Galactic neutrino emission. Its spatial distribution correlates strongly with interstellar molecular gas, pointing to hadronic interactions between cosmic rays and interstellar medium as the origin.

Candidate discrete Galactic sources include supernova remnants, pulsar wind nebulae and starburst regions. Supernova remnants are regarded as primary PeV cosmic-ray accelerators in the Milky Way: Fermi acceleration boosts protons above PeV energies, which collide with ambient gas to produce pions decaying into neutrinos. Ultra-high-energy gamma sources discovered by LHAASO supply key electromagnetic counterparts for locating such accelerators.

4.4 Cosmic Neutrino Background and Ultra-High-Energy Neutrinos

- **Cosmic Neutrino Background (CνB)**: Relic neutrinos decoupled ~1 second after the Big Bang, with a current temperature of 1.95 K and number density of 336 cm^{-3}, the oldest cosmic messengers. Direct detection poses extreme technical challenges; experiments such as PTOLEMY aim to achieve the first observation.
- **GZK Neutrinos**: Ultra-high-energy neutrinos with energies of 10^{18} – 10^{20}eV generated via photopion (GZK) interactions between ultra-high-energy cosmic rays and CMB photons, acting as critical probes of ultra-high-energy cosmic ray origins. Future experiments GRAND and POEM will employ thousand-cubic-kilometer effective volumes to search for them.
- **Cosmological Probe Function**: Neutrinos modify CMB anisotropies and large-scale structure formation. Combined galaxy and CMB surveys constrain the total neutrino mass, forming a core interdisciplinary bridge between cosmology and particle physics.

5 Multi-Messenger Astronomy and Interdisciplinary Frontiers

5.1 Multi-Messenger Coordinated Observation and Global Network

Multi-messenger astronomy utilizes gravitational waves, neutrinos, electromagnetic radiation and cosmic rays to jointly study extreme astrophysical phenomena. Thanks to their strong penetration, neutrinos occupy an irreplaceable position in global networks. High-energy photons above TeV are absorbed by cosmic background photons, while neutrinos traverse dense stellar cores and intergalactic space unattenuated, carrying core information of emission sources.

A systematic global multi-messenger network has been built, enabling real-time alerts and follow-up triggers via platforms GCN and AMON. Facilities including IceCube, LIGO/Virgo/KAGRA, Fermi and Swift are integrated. Upon detection of high-energy neutrinos or gravitational wave transients, dozens of telescopes worldwide are immediately triggered for multi-band follow-up. Two milestone events TXS 0506+056 and GW170817 represent the neutrino-triggered and gravitational wave-triggered observation modes respectively.

5.2 Neutrinos as Cosmic Testbeds for Fundamental Physics

The ultra-long cosmic propagation baselines of neutrinos create natural laboratories for testing fundamental physical laws.

1. **Lorentz Invariance Tests**: Time delay and flavor measurements of cosmic neutrinos impose tight limits on Lorentz violation, pushing the violation scale close to the Planck energy.

2. **Quantum Decoherence Tests**: Quantum gravitational effects may induce oscillation decoherence; IceCube’s atmospheric and astrophysical neutrino data show no decoherence signals, validating quantum mechanics at cosmic scales.

3. **Dark Matter Probes**: If dark matter annihilates or decays into neutrinos, excess flux will appear in dense regions such as the Galactic center and the Sun. IceCube and Super-Kamiokande place strict upper limits on annihilation cross-sections for multiple dark matter models, complementary to direct detection experiments.

5.3 Cross Applications of Computing and Artificial Intelligence

With expanding detector scales and explosive data growth, artificial intelligence has become a core tool for neutrino physics. Convolutional and graph neural networks greatly improve angular reconstruction and particle identification efficiency, suppressing atmospheric neutrino backgrounds. AI is widely deployed in background rejection, real transient alerts and full detector Monte Carlo simulation, cutting computational costs drastically. Future quantum computing will further boost event reconstruction and large-scale parameter fitting efficiency.

6 Cross-Correlation Analysis of Ten Fundamental Physics Branches

This paper divides all fundamental physics into ten non-overlapping, comprehensive research branches and systematically sorts the internal links between neutrino physics and each branch, unified into correlation types, shared concepts and representative research topics, as shown in Table 3.

Table 3 Cross Correlations Between Neutrino Physics and Ten Fundamental Physics Branches

Branch Module	Correlation Type	Shared Core Concepts	Typical Interdisciplinary Topics
Branch 01 High-Energy Physics Fundamentals	Theoretical Homology	PMNS matrix, seesaw mechanism, GUT	Neutrino mass origin, physics beyond Standard Model, lepton flavor symmetry
Branch 02 Particle Astrophysics	Observational Synergy	Cosmic ray acceleration, source modeling	Joint origin of ultra-high-energy cosmic rays and diffuse neutrino background
Branch 03 Gravity & Cosmology	Cosmological Probe	CMB, large-scale structure evolution	CMB constraints on total neutrino mass, neutrino decoupling & Big Bang Nucleosynthesis
Branch 04 Quantum Gravity Frontiers	Test Platform	Lorentz symmetry, quantum decoherence	Tests of quantum gravity via long-baseline neutrino oscillation
Branch 05 Nuclear & Dense Matter Physics	Dense Astrophysics	Nuclear EoS, neutron star matter	Constraints on nuclear equation of state from supernova neutrinos
Branch 06 Computational	Shared Methodology	Detector simulation, event	Machine learning for neutrino

Physics & AI		reconstruction	classification and angular reconstruction
Branch 07 Gravitational Wave Astronomy	Multi-Messenger Synergy	Binary mergers, extreme transients	Joint neutrino-gravitational wave-electromagnetic events like GW170817
Branch 08 Dark Matter Physics	Detection Probe	Sterile neutrinos, dark matter scattering	Neutrinos as probes of dark matter interactions
Branch 09 Early Universe Cosmology	Historical Traceability	Relic neutrino background, cosmic energy density	Prospects for direct detection of Big Bang neutrinos
Branch 10 Stellar Physics & Evolution	Stellar Interior Probe	Standard Solar Model, nuclear fusion	Solar metallicity problem diagnosed by Borexino solar neutrinos

6.1 Methodological Value of Interdisciplinary Research

Interdisciplinary analysis across the ten branches essentially transfers theoretical and experimental methodologies of neutrino physics to other subfields. For instance, ultra-low-background technologies developed for neutrino experiments can be directly applied to dark matter direct detection; source modeling of astrophysical neutrinos supports cosmic ray acceleration theory; multi-messenger coordination itself represents an innovative cross-disciplinary paradigm. Large facilities including IceCube, JUNO and DUNE act as cross-branch observatories, delivering results for both particle physics and high-energy astrophysics.

7 Conclusions and Prospects

7.1 Core Research Consensus

After over half a century of development, neutrino astronomy and physics have established a set of high-confidence conclusions:

1. Neutrinos possess non-zero mass; the three-flavor oscillation framework is consistently verified by solar, atmospheric, reactor and accelerator experiments.

2. The three mixing angles and two independent mass squared differences reach percent to sub-percent precision, forming a complete oscillation parameter system.

3. IceCube and other experiments definitively confirm diffuse astrophysical neutrino flux following an approximate $E^{-2.5}$ power-law spectrum.

4. NGC 1068 and the Galactic plane are identified as high-energy neutrino sources, forming an initial observational picture of Galactic and extragalactic neutrino emission.

5. Borexino completes full-spectrum measurements of pp and CNO solar neutrinos, supplying critical constraints for stellar physics.

6. The SN1987A neutrino detection marked the birth of neutrino astronomy; total energy and temporal profiles of supernova neutrinos are preliminarily validated by observations.

7.2 Core Unsolved Scientific Problems

Multiple critical puzzles remain unresolved in the field:

1. Unsettled particle properties: mass ordering, θ_{23} octant, precise δ_CP, absolute mass scale, Dirac/Majorana nature are all undetermined.

2. Ambiguous astrophysical source mechanisms: the fraction and acceleration channels of diffuse high-energy neutrinos are unclear; most candidate sources lack definitive neutrino signals.

3. Unconfirmed new physics signatures: sterile neutrinos, NSI, large neutrino magnetic moments have no conclusive experimental evidence.

4. Undetected cosmic relic neutrinos: CvB direct observation remains unachieved; GZK neutrinos are still in blind search.

7.3 Future Development Outlook

Over the next decade, three major breakthrough opportunities await the neutrino field:
First, definitive determination of neutrino mass ordering. JUNO, DUNE and Hyper-Kamiokande will adopt three independent methods (reactor spectral distortion, long-baseline matter oscillation, atmospheric oscillation) to reach a unified consensus around 2030.

Second, precision measurement of lepton CP violation. Joint DUNE and Hyper-Kamiokande analysis will narrow δ_CP uncertainty to 5°–15°, testing whether lepton

CP violation mirrors the quark sector and providing experimental evidence for cosmic leptogenesis and matter-antimatter asymmetry.

Third, completion of the global neutrino telescope network. IceCube-Gen2, full-scale KM3NeT and TRIDENT will form a hemispheric network, boosting sensitivity to transients and diffuse backgrounds by an order of magnitude, likely discovering numerous new sources and revealing the origin of ultra-high-energy cosmic rays.

In the longer term, direct detection of cosmic relic neutrinos, real-time alerts for Galactic supernova neutrinos, and final confirmation of the Majorana nature of neutrinos will push the field toward deeper fundamental questions. As the lightest elementary particles in the Standard Model, neutrinos will continue to uncover the deepest mysteries of the universe via their unique physical properties.

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