The Puzzle of Neutrinos on Cosmic Scales

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History

1. Wolfgang Pauli's prediction of the neutrino was made in a famous letter dated December 4, 1930, addressed to "Dear Radioactive Ladies and Gentlemen." This letter outlined his hypothesis of a neutral, lightweight particle that could explain the apparent loss of energy in beta decay processes.

2. The experimental detection of the neutrino was achieved by Clyde Cowan and Frederick Reines in 1956. They used a nuclear reactor as a neutrino source and detected the antineutrinos produced during uranium fission. Their groundbreaking experiment provided the first direct evidence of neutrinos.

History

3. In the 1960s and 1970s, Raymond Davis Jr. conducted experiments to detect solar neutrinos using a chlorine-based detector. His work revealed a deficit in the number of detected solar neutrinos compared to theoretical predictions, a problem known as the solar neutrino problem.

4. The Super-Kamiokande experiment in Japan, which began operations in 1996, provided crucial evidence of neutrino oscillations. This phenomenon, where neutrinos change from one flavor to another as they travel, confirmed that neutrinos have mass.

History

5. Starting operations in 1999, the SNO experiment, located in Canada, used heavy water to detect solar neutrinos and confirmed neutrino oscillations as the solution to the solar neutrino problem. SNO could distinguish between different neutrino flavors and provided precise measurements of neutrino properties.

6. Operating since 2002, KamLAND is designed to detect antineutrinos from nuclear reactors and geoneutrinos from the Earth's interior. It provides further evidence of neutrino oscillations.

History

7. The Borexino detector began operating in May 2007. It is a deep underground particle physics experiment designed to study low-energy solar neutrinos. The detector is known for its extreme radiopurity and sensitivity, making it capable of detecting neutrinos with very low energies.
8. Operating in December 2010, IceCube, located at the South Pole, is designed to detect high-energy neutrinos from astrophysical sources. It has made significant contributions to neutrino astronomy, including the detection of neutrinos from a distant blazar.
9. KATRIN (KArlsruhe TRitium Neutrino experiment) began operating in 2016. It is designed to measure the mass of the electron antineutrino with high precision by examining the beta decay of tritium. The experiment aims to improve the sensitivity of neutrino mass measurements or discover the actual mass if it is within the detectable range.
10. Observations of the CMB (e.g., WMAP, ACT, SPT and Planck) and large-scale structure (e.g., SDSS, DESI and DES) provide constraints on the sum of neutrino masses and their contribution to the universe's energy density.

Known neutrino properties (particle physics)

1. Electrically Neutral: Neutrinos have no electric charge, which allows them to pass through matter almost undetected.
2. Low Mass: Neutrinos have a very small but non-zero mass. The exact values of their masses are still a subject of ongoing research.
3. Three Flavors: There are three types, or "flavors," of neutrinos: electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ).
4. Weak Interaction: Neutrinos interact with other particles only through the weak nuclear force and gravity, making them extremely difficult to detect.
5. Neutrino Oscillations: Neutrinos can change their flavor as they travel, a phenomenon known as neutrino oscillations. This behavior implies that neutrinos have mass and mix with each other.
6. Possible mass hierachies: NH, where the two lightest mass eigenstates have a small mass difference, of the order of 10 meV, and IH, where the two heaviest mass eigenstates have a small mass difference, of the order of 10 meV.

Known neutrino properties (cosmology)

1. Relic Neutrinos: The Big Bang theory predicts the existence of a cosmic neutrino background, similar to the cosmic microwave background (CMB) for photons. These relic neutrinos are believed to permeate the universe but have not yet been directly detected.
2. Dark Matter Candidate: Due to their low mass and weak interactions, neutrinos were once considered candidates for dark matter. However, their low mass makes them too "hot" to explain the structure of the universe, so they are not the primary component of dark matter.
3. Structure Formation: Neutrinos affect the formation of large-scale structures in the universe. Their free-streaming nature can suppress the growth of structures on small scales.
4. Background expansion: Neutrinos contribute to the total energy density of the universe, influencing its expansion rate and the formation of cosmic structures.

Neutrino cosmology

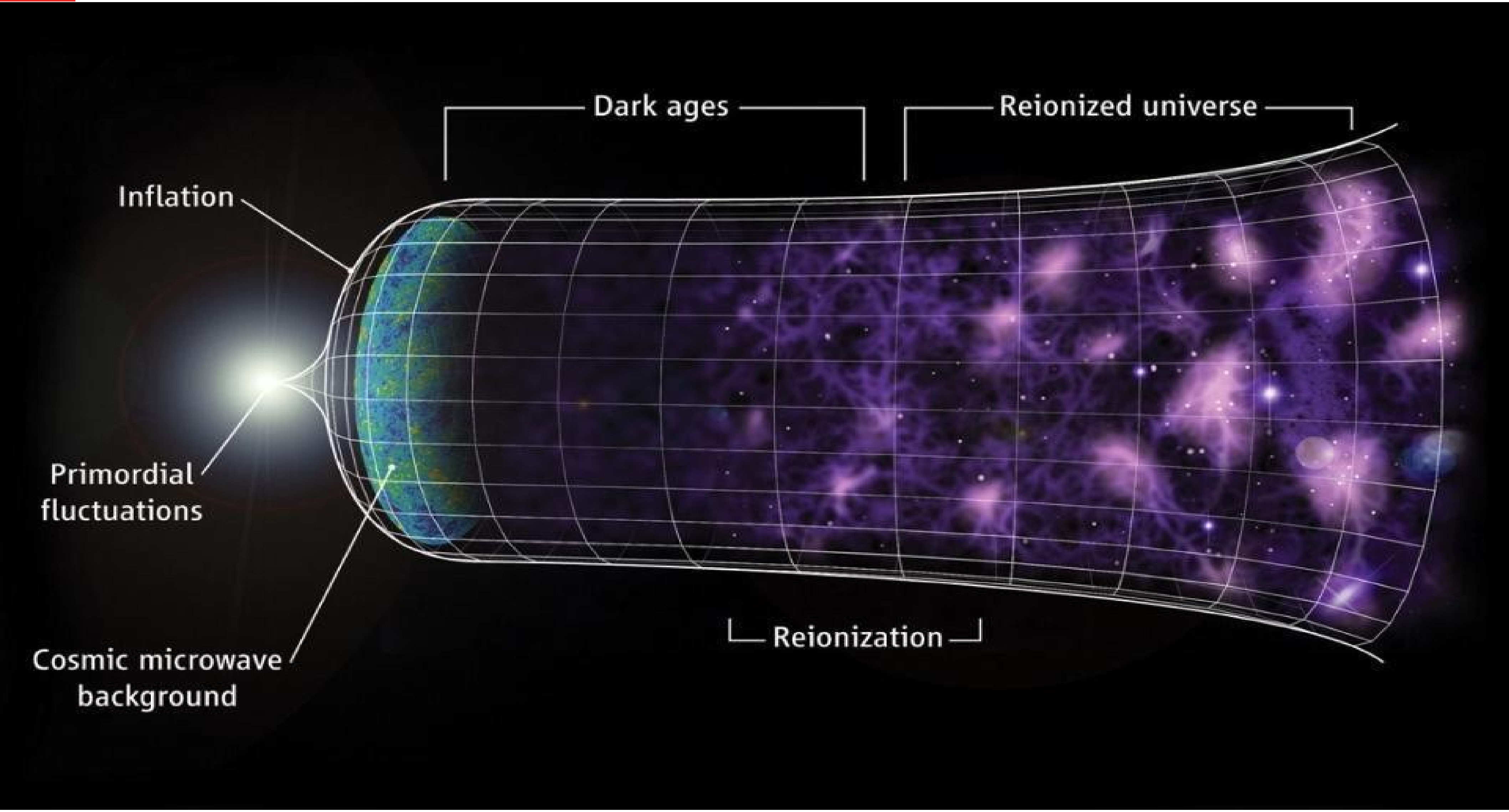
Two key parameters

1. Σm_ν
2. N_{eff}

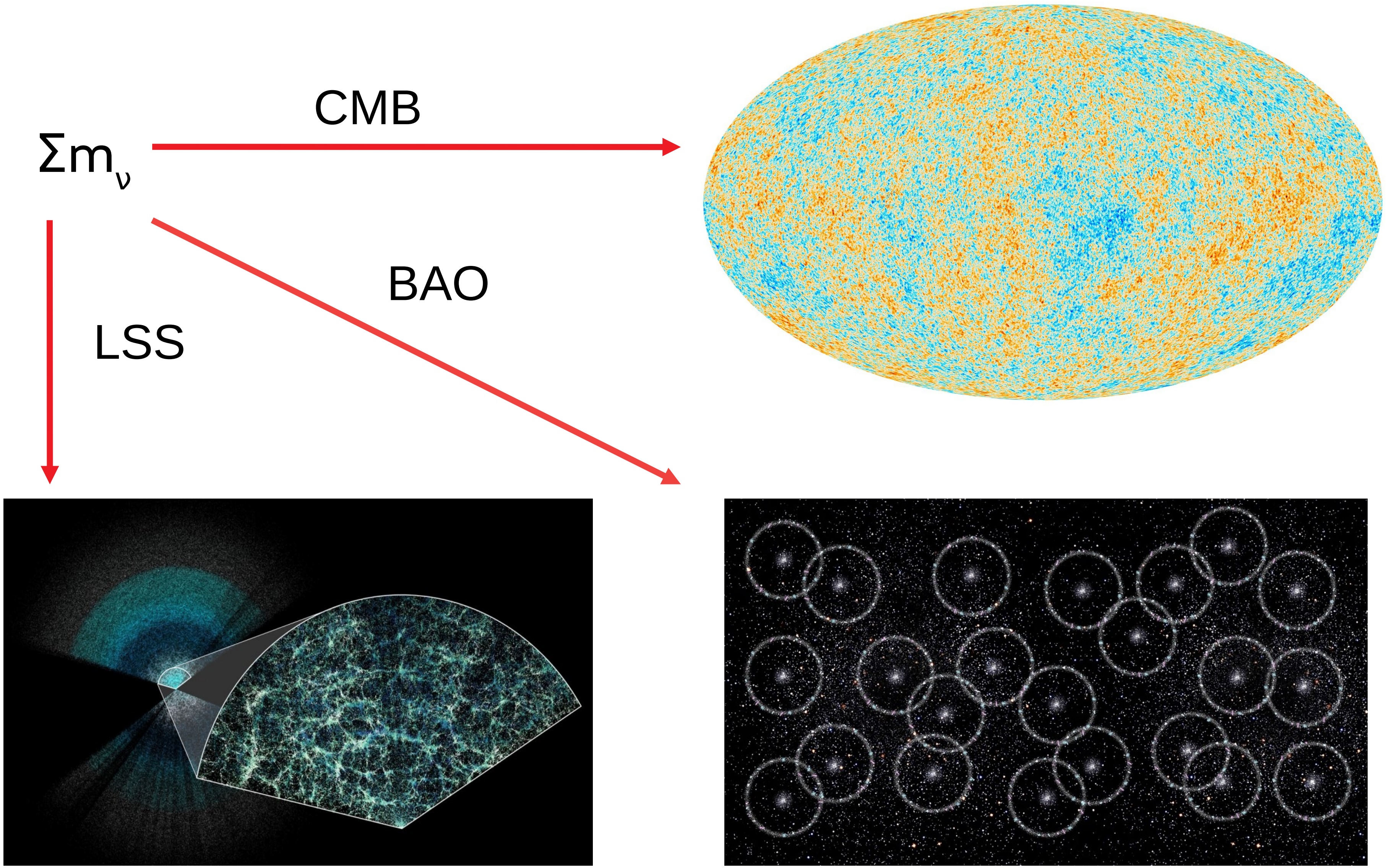
$$\text{Theory} \longrightarrow \begin{cases} \Sigma m_\nu > 0 \text{ eV} \\ N_{eff} = 3.044 \end{cases}$$

$$\Sigma m_\nu$$

Standard cosmology



Observational probes



Previous constraints

Use a degenerate hierarchy with $\Sigma m_\nu > 0$ eV:

1. Planck: $\Sigma m_\nu < 0.12$ eV, 2018 — Aghanim et al., 1807.06209

(95 %, Planck TTTEEE+lowE+lensing+BAO)

2. DESI DR1: $\Sigma m_\nu <$ 0.072 eV, 2024 — Adame et al., 2404.03002

(95 %, Planck TTTEEE+lowE+lensing+ACT DR6 lensing+DESI DR1 BAO)

3. Ours: $\Sigma m_\nu <$ 0.043 eV, 2024 — Wang et al., 2405.03368

(95 %, Planck TTTEEE+lowE+lensing+DESI DR1 BAO+ADD+GRBs)

2025

1. DESI DR2: Σm_ν < 0.064 eV, 2025

(95 %, Planck TTTEEE+lowE+lensing+ACT DR6 lensing+DESI DR2 BAO)

Karim et al., 2503.14738

2. Actually, current data prefer phenomenologically an effective negative neutrino mass.

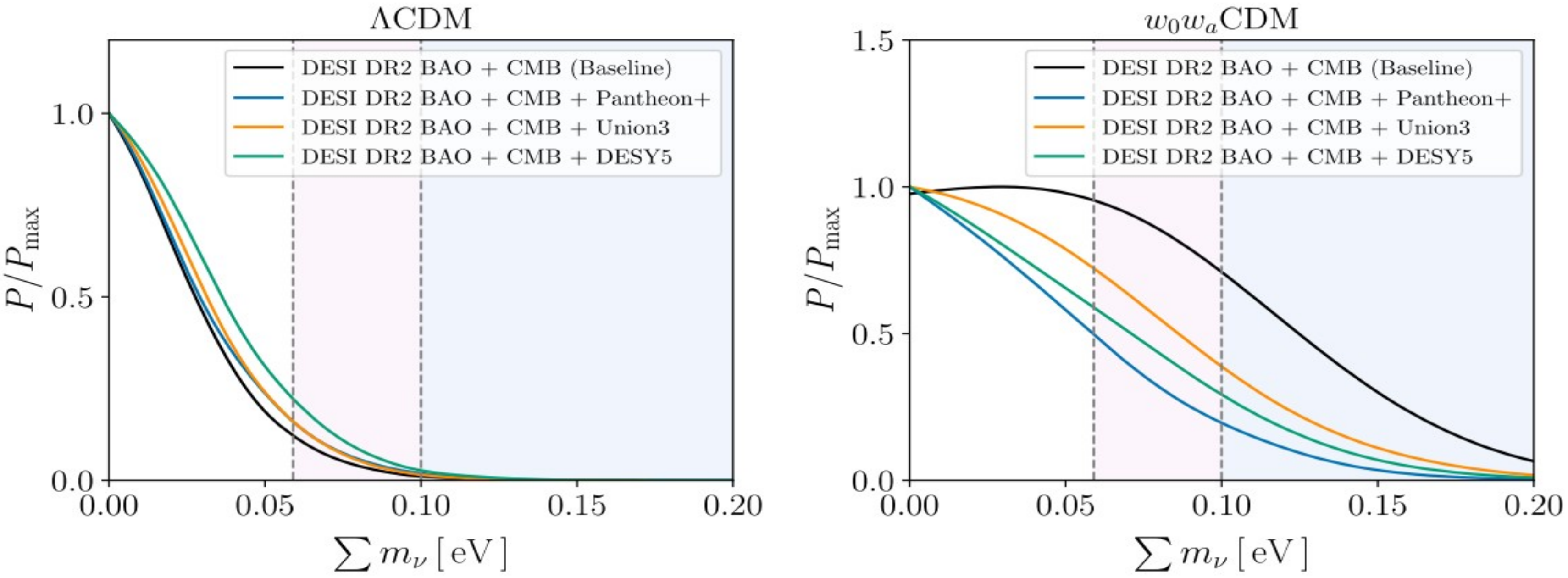
Craig et al., 2503.14738

Q: Is there cosmic massive neutrinos with postive masses in light of current observations at all?

A possible solution

Dynamical dark energy can relax the neutrino mass bound to a safe region of $\Sigma m_\nu > 0$ eV.

Karim et al., 2503.14738



How about LCDM?

Within LCDM, traditional method assumes a constant neutrino mass over full redshifts and scales. Ignore the possible evolution details on cosmic scales.

Solution: We assume a redshift-dependent, a scale-dependent, and a redshift- and scale-dependent neutrino mass over full redshifts or/and scales, i.e., $\Sigma m_\nu(z)$, $\Sigma m_\nu(k)$ and $\Sigma m_\nu(z, k)$.

Goal: Make a neutrino mass search framework when future CMB, LSS, BAO data are precise enough (e.g., 2050-2100).

Note: $\Sigma m_\nu(z)$ is firstly studied in Lorenz et al., 2102.13618, but the more important scale dependence is not considered.

Simple Modelling

1. $\Sigma m_\nu(z)$ 6 redshift bins: [0, 1], [1, 3], [3, 10], [10, 100], [100, 1100] and [1100, +∞).

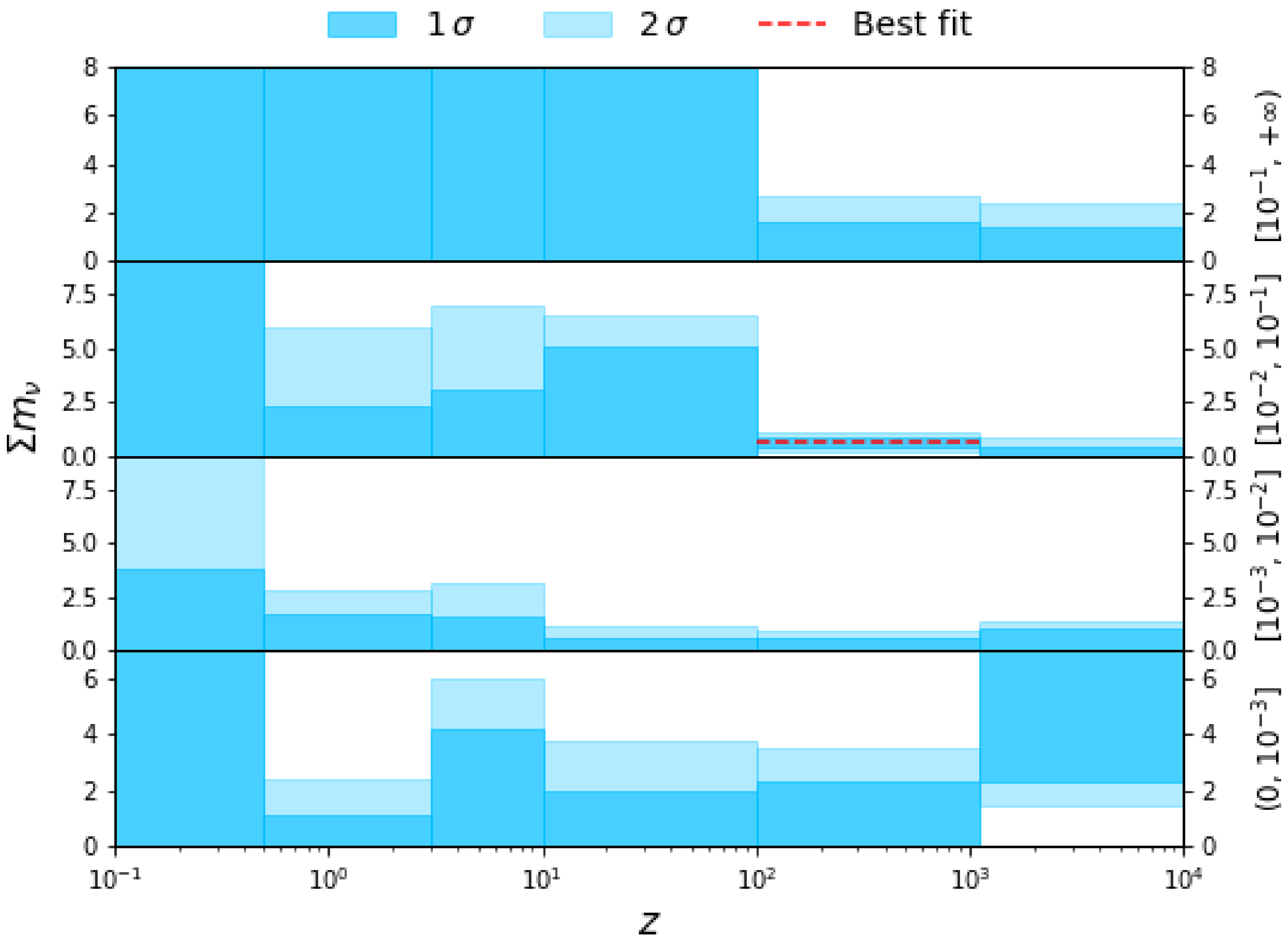
2. $\Sigma m_\nu(k)$ 4 scale bins: $[10^{-1}, +\infty)$,$[10^{-2}, 10^{-1}]$, $[10^{-3}, 10^{-2}]$ and $(0, 10^{-3}]$ h Mpc^{-1}.

3. $\Sigma m_\nu(z, k)$ 24 (z, k) bins: z: [0, 0.5], [1, 3], [3, 10], [10, 100], [100, 1100] and [1100, +∞), k: $[10^{-1}, +\infty)$,$[10^{-2}, 10^{-1}]$, $[10^{-3}, 10^{-2}]$ and $(0, 10^{-3}]$ h Mpc^{-1}.

Results

DW 2503.21026, Wang et al., 2503.18745

CMB



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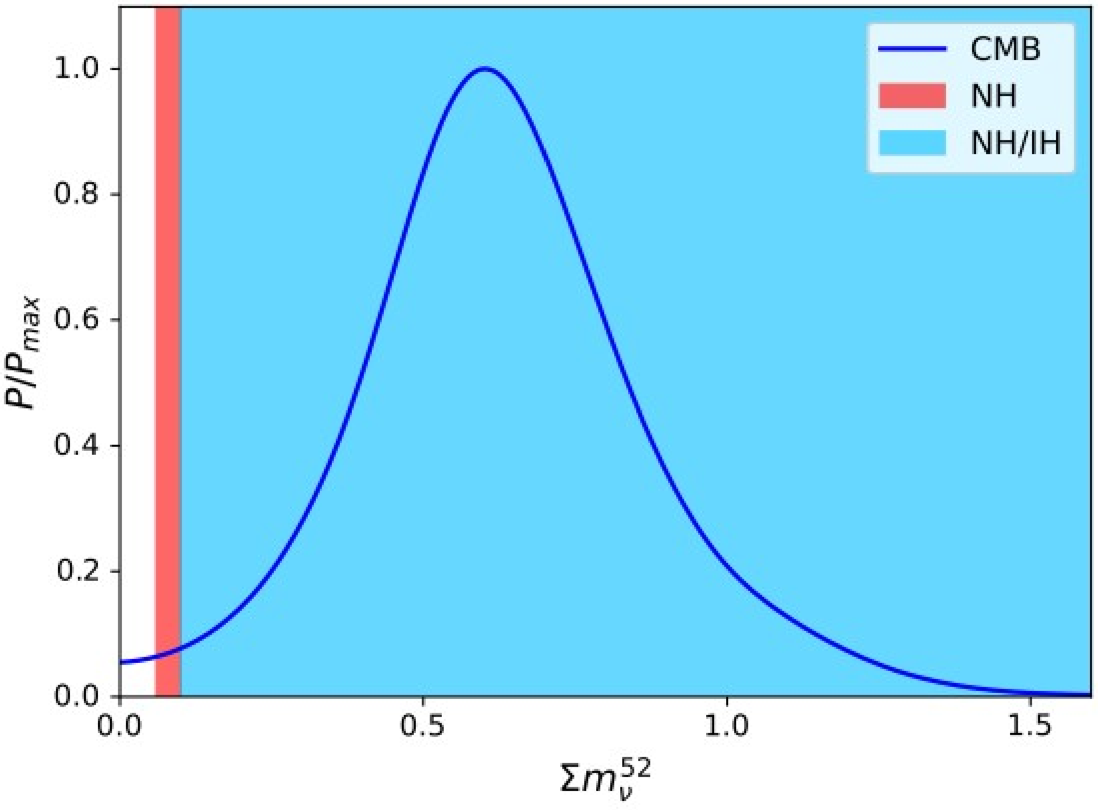
CMB



Results

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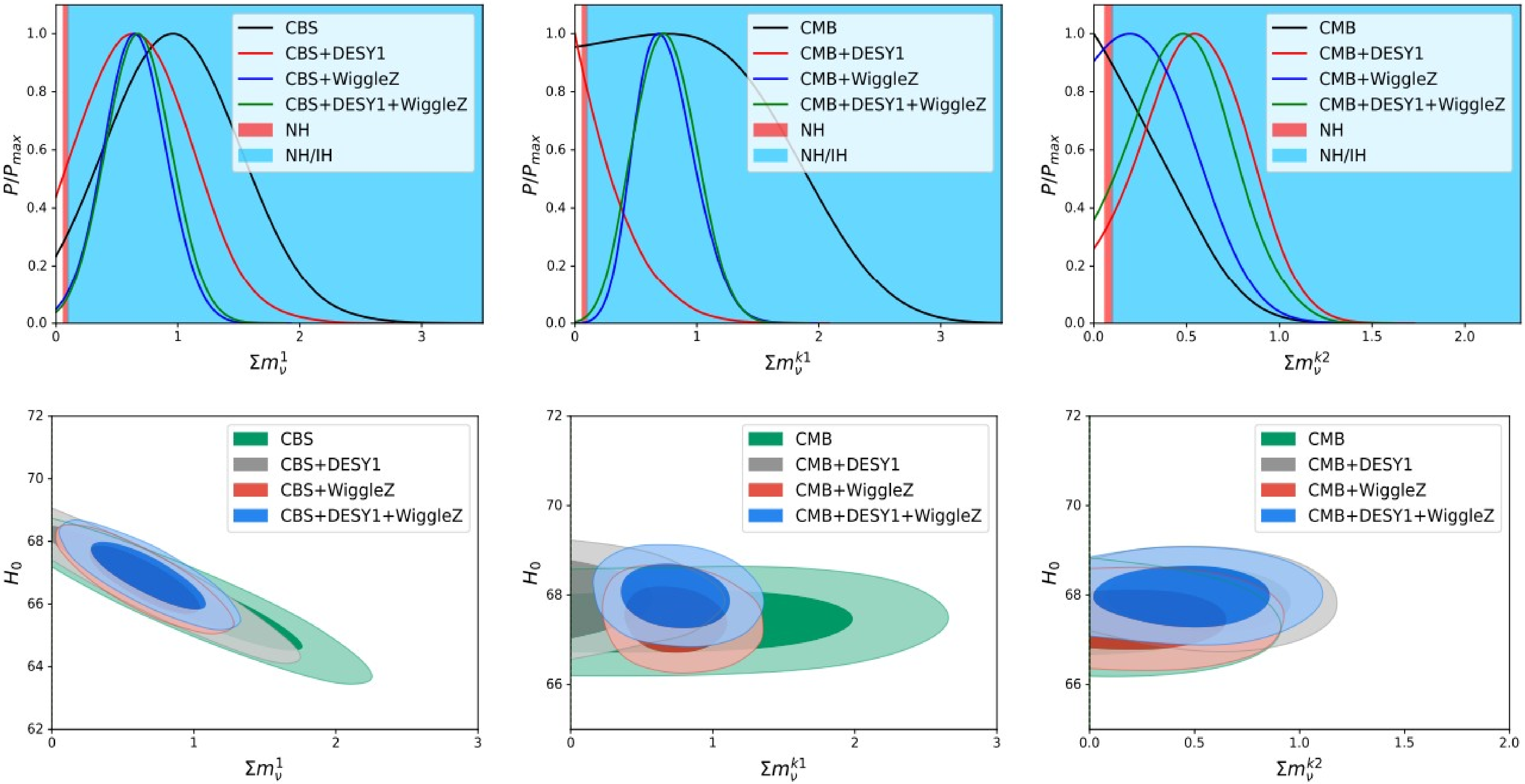

Results

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TABLE I: The 1σ (68%) errors and mean values of the parameters Σm_ν^{52}, Σm_ν^{1}, Σm_ν^{k1} and Σm_ν^{k2} from different datasets in $\sum m_\nu(z,\,k)$, $\sum m_\nu(z)$ and $\sum m_\nu(k)$ models, respectively.

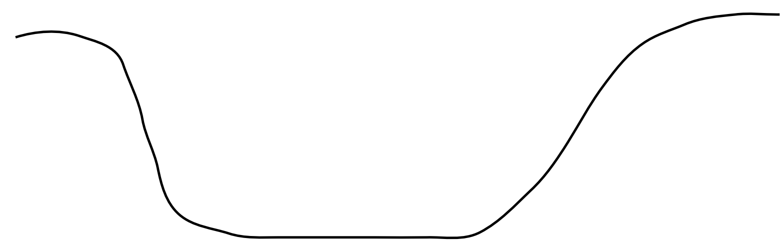
Model	$\sum m_\nu(z,\,k)$	$\sum m_\nu(z)$		$\sum m_\nu(k)$	
Data	C	CBS	CBSW	CW	CD
Parameter	$\Sigma m_\nu^{52} = 0.63^{+0.20}_{-0.24}$	$\Sigma m_\nu^{1} = 1.01^{+0.47}_{-0.58}$	$\Sigma m_\nu^{1} = 0.65 \pm 0.25$	$\Sigma m_\nu^{k1} = 0.75^{+0.20}_{-0.27}$	$\Sigma m_\nu^{k2} = 0.55 \pm 0.27$

We find one beyond 5 σ, two 3 σ and two 2 σ evidences of massive neutrinos, spanning both high and low redshifts, as well as both small and intermediate scales. Interestingly, these five neutrino masses are well consistent within 1 σ confidence level, indicating a possible suppression of neutrino mass during the evolution of the universe.

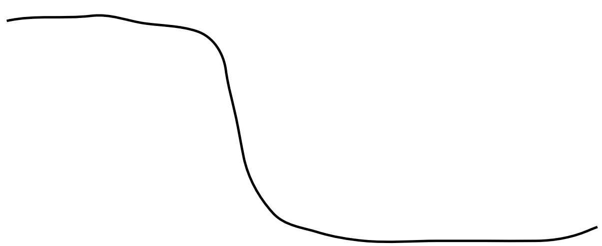
Results

DW 2503.21026, Wang et al., 2503.18745

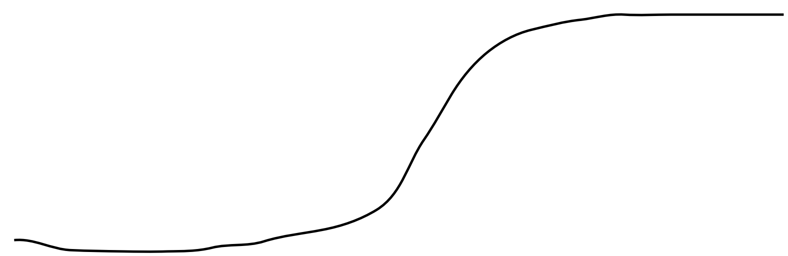
(a) constant



(b) freedom-suppression-freedom



(c) freedom-suppression



(d) suppression-freedom

Shortcomings

1. Look-elsewhere effect;
2. Complexity introduced by many bins;
3. Limited CMB data quality.

Discussions

1. Our goal is searching for massive neutrinos with a positive mass in the framework of LCDM. If considering alternative models such as dynamical dark energy (DDE), more complexities will be introduced. Considering DDE is inconsistent with our initial motivation, i.e., curing the unphysical neutrino mass bounds in LCDM.
2. Future high-precision CMB observations such as CMB-S4 and Simons Observatory will provide more clues of non-zero masses, i.e., $\Sigma m_\nu > 0$ eV.

Takeways

1. Using CMB observations to constrain a redshift- and scale-dependent neutrino mass, we make the first neutrino mass map through the cosmic history and full scales for future high precision search.

2. Suffering from several internal shortcomings in the methods, we find one beyond 5 σ, two 3 σ and two 2 σ evidences of massive neutrinos, spanning both high and low redshifts, as well as both small and intermediate scales. These five neutrino masses are well consistent within 1 σ level, suggesting a possible suppression of neutrino mass in the early universe.

Thanks!