3.B Additional neutrino cosmology

- Kenny CY Ng
- kcyng@cuhk.edu.hk
- Sci Cen North Black 345
- CUHK

- Course webpage: https://blackboard.cuhk.edu.hk

Neutrinos in cosmology

- We covered that from standard model (of particle physics) temperature evolution, we expect that there should be an Cosmic Neutrino background, that decoupled from the Universe.

- There are other interesting things one can do with neutrinos in cosmology
  - The smallest/lightest particles play a surprisingly important role.

N_eff: Number of effective relativistic degrees of freedom
Theory expectation

$$N_{\rm eff}^{\rm SM} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_\nu}{\rho_\gamma}\right),$$

CIELO, ESCUDERO, MANGANO, and PISANTI

TABLE I. Various contributions to $N_{\rm eff}$ in the Standard Model. We highlight each effect to the first digit. When all are taken together, we find $N_{\rm eff}^{\rm SM} = 3.043$.

Physical scenario	$N_{\rm eff}^{\rm SM} - 3$
Instantaneous neutrino decoupling	0
Neutrino interactions: residual $e^+e^- \to \bar{\nu}\nu$	0.03
QED corrections to $\rho_{e^+e^-}$ and ρ_γ	0.01
Neutrino oscillations	0.0007
QED corrections to $e^+e^- \leftrightarrow \bar{\nu}\nu$ rates (this work)	−0.0007

$N_{\rm eff}$ in the Standard Model at NLO is 3.043

Mattia Cielo,[1,*] Miguel Escudero,[2,†] Gianpiero Mangano,[1,‡] and Ofelia Pisanti[1,§]
[1]Dipartimento di Fisica E. Pancini, Naples, and INFN, Sezione di Napoli, Monte S. Angelo I-80126 Naples, Italy
[2]Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland

(Received 20 June 2023; accepted 9 November 2023; published 13 December 2023)

The effective number of relativistic neutrino species is a fundamental probe of the early Universe, and its measurement represents a key constraint on many scenarios beyond the Standard Model of Particle Physics. In light of this, an accurate prediction of $N_{\rm eff}$ in the Standard Model is of pivotal importance. In this work, we consider the last ingredient needed to accurately calculate $N_{\rm eff}^{\rm SM}$: standard zero and finite-temperature QED corrections to $e^+e^- \leftrightarrow \nu\bar{\nu}$ interaction rates during neutrino decoupling at temperatures around $T \sim$ MeV. We find that this effect leads to a reduction of −0.0007 in $N_{\rm eff}^{\rm SM}$. This next-to-leading-order QED correction to the interaction rates, together with finite-temperature QED corrections to the electromagnetic density of the plasma, and the effect of neutrino oscillations, implies that $N_{\rm eff}^{\rm SM} = 3.043$ with a theoretical uncertainty that is much smaller than any projected observational sensitivity.

DOI: 10.1103/PhysRevD.108.L121301

N_eff, observations

Neutrinos in Cosmology

Eleonora Di Valentino*
School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom

Stefano Gariazzo†
Instituto de Fisica Teorica, CSIC-UAM C/ Nicolás Cabrera 13-15, Campus de Cantoblanco UAM, 28049 Madrid, Spain

Olga Mena‡
Instituto de Física Corpuscular (CSIC-Universitat de València), E-46980 Paterna, Spain

(Dated: May 1, 2024)

All in all, our current knowledge confirms that $N_{\rm eff}$ is close to 3 as measured by CMB observations ($N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ at 95% confidence level (CL) [52]) or BBN abundances (e.g., $N_{\rm eff} = 2.87^{+0.24}_{-0.21}$ at 68% CL [41]) independently. Furthermore, the above constraints have been

- N_{eff} contributes to the radiation energy density (during radiation dominated era)
  - It directly affects the Hubble rate, and thus all the physical processes
    - Big bang nucleosynthesis, formation of light nuclei (relativistic neutrinos)
    - Recombination, when photons decouple from the universe and form CMB (relativistic?)

Sum of neutrino masses, observations

Neutrinos in Cosmology

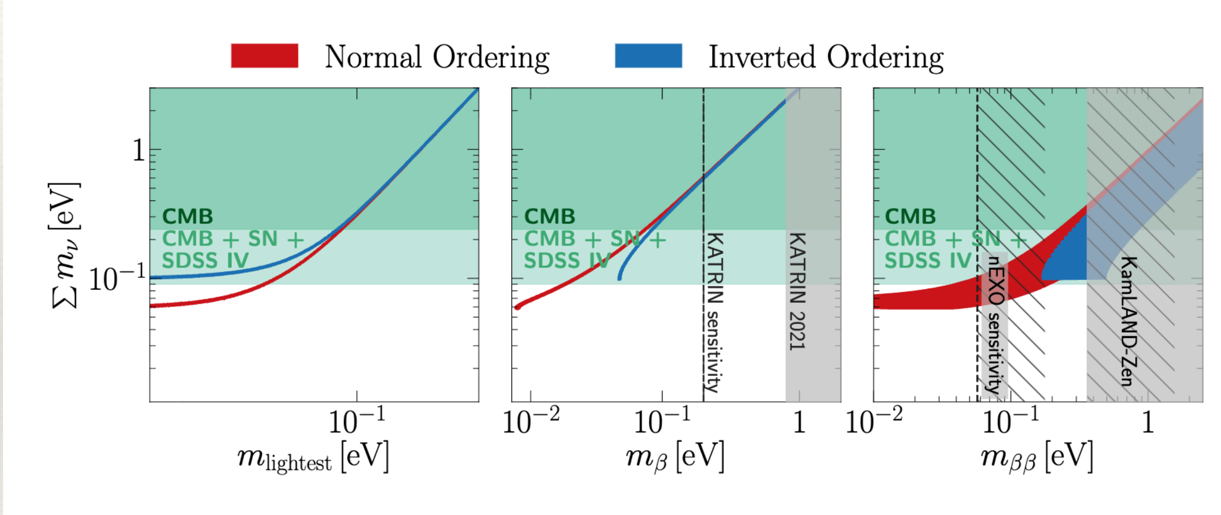
Eleonora Di Valentino*
School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom

Stefano Gariazzo†
Instituto de Fisica Teorica, CSIC-UAM C/ Nicolás Cabrera 13-15, Campus de Cantoblanco UAM, 28049 Madrid, Spain

Olga Mena‡
Instituto de Física Corpuscular (CSIC-Universitat de València), E-46980 Paterna, Spain
(Dated: May 1, 2024)

- Neutrinos could contribute to non-negligible of total mass density of the universe.
- It is special as it changes from radiation to matter and the Universe evolve.
- Neutrino mass constraint from cosmological structures

ordering scenario, one might claim the rejection of the former at a given significance level. Plenty of debate and various studies in the literature have been devoted to settling this issue, see e.g. [58, 77–81]. Recently, in [81], the authors quantified the current preference for the normal mass ordering versus the inverted one using the Bayes factor. None of the cases explored by the authors (i.e., using terrestrial data alone or current cosmology without terrestrial data) show a particularly significant preference for the normal mass ordering. The same reference indicates that future cosmological experiments, expected to achieve a 1σ precision on $\sum m_\nu$ at the level of 0.02 eV, will not provide a strong preference in favor of the normal ordering (if nature has chosen this scenario), reaching a $2-3\sigma$ significance at most.



Normal ordering: m1 < m2 < m3
Inverted ordering: m3< m1 < m2

How many “active” neutrinos are there?

- Particle physics -> Z boson properties
- Neutrinos contributes to the Z decay width
- This shows that there are only 3 “active” neutrinos that are coupled to Z boson
- ** they must be lighter than Z boson.