Supernova neutrinos as a probe of CP violation

Vedran Brdar, [1] **Leonardo J. Ferreira Leite**, [2] George Parker [3], Xunjie Xu [4]

[1]Oklahoma State University [2]Instituto de Física Gleb Wataghin, UNICAMP [3]Johannes Gutenberg-Universität Mainz (JGU) [4]Institute of High Energy Physics (IHEP)

Abstract

Supernova neutrinos have never been considered, to this date, as a possible probe of δ_{CP} due to their small energy, high uncertainty, and, most of all, lack of information about the full flavor components of the flux. This work is intended to address some of these issues and offer a complementary probe of such parameter. We show how it is possible to extract some information about the PMNS matrix complex phase, δ_{CP}, using supernova neutrinos. First, we use the next-to-leading order (NLO) calculation for the cross-section of neutrino-electron elastic scattering to distinguish between muon neutrinos and tau neutrinos at the detection. Consequently, one can use this flavor information to probe the CP-violating phase. We also explore the possibility of detecting high energy (100-200 MeV) neutrinos from shock acceleration which can also produce muons in the detector and provide a clear signal of flavor conversion that can also be used as a probe of δ_{CP}.

Introduction

There have been considerable efforts to measure the parameters of the neutrino mixing matrix PMNS (Pontecorvo-Maki-Nakagawa-Sakata). Considering the usual 4 mixing parameters of a Dirac neutrino, the least known is the complex CP-violating phase, δ_{CP}. Accelerator experiments, such as DUNE for example, are the leading candidates to measure it with high significance. Nonetheless, we propose here a new complementary avenue to probe δ_{CP} using Supernova neutrinos.

Neutrino Conversion Scenario

Considering the usual framework of neutrino conversion in Supernovae and neglecting non-adiabatic transitions or collective oscillation effects, we have,

$$\phi_\alpha = |U_{\alpha 3}|^2 \phi_e^0 + |U_{\alpha 1}|^2 \phi_\mu^0 + |U_{\alpha 2}|^2 \phi_\tau^0, \quad (1)$$

For neutrinos following normal ordering, and,

$$\phi_\alpha = |U_{\alpha 2}|^2 \phi_e^0 + |U_{\alpha 3}|^2 \phi_\mu^0 + |U_{\alpha 1}|^2 \phi_\tau^0, \quad (2)$$

For inverted ordering. For antineutrinos, we have trivially in the normal ordering,

$$\phi_{\bar\alpha} = |U_{\alpha 1}|^2 \phi_{\bar e}^0 + |U_{\alpha 3}|^2 \phi_{\bar\mu}^0 + |U_{\alpha 2}|^2 \phi_{\bar\tau}^0, \quad (3)$$

And,

$$\phi_{\bar\alpha} = |U_{\alpha 3}|^2 \phi_{\bar e}^0 + |U_{\alpha 2}|^2 \phi_{\bar\mu}^0 + |U_{\alpha 1}|^2 \phi_{\bar\tau}^0, \quad (4)$$

For inverted ordering.

The conditions to see an effect of δ_{CP} are:

1. Detecting either ν_μ or ν_τ directly.
2. Inbalance of number of ν_μ and ν_τ in detection, i.e. break the degeneracy of counting ν_x,

Neutral Current Next-To-Leading Order (NC-NLO)

Using the same formalism developed in Ref. [1],

$$\frac{dN}{dT}(\delta_{\text{CP}}) = N_{\text{target}} \sum_{e,\mu,\tau,\bar e,\bar\mu,\bar\tau} \int dE_\nu, \phi_\alpha(E_\nu, \delta_{\text{CP}}) \frac{d\sigma_\alpha}{dT}(T, E_\nu), \quad (5)$$

The difference in cross-section for muon and tau flavors makes the total number of events to depend on the CP-violating phase.

We perform a χ^2 test against the $\delta_{\text{CP}} = 0$ hypothesis using the total number of elastic electron scattering.

Results

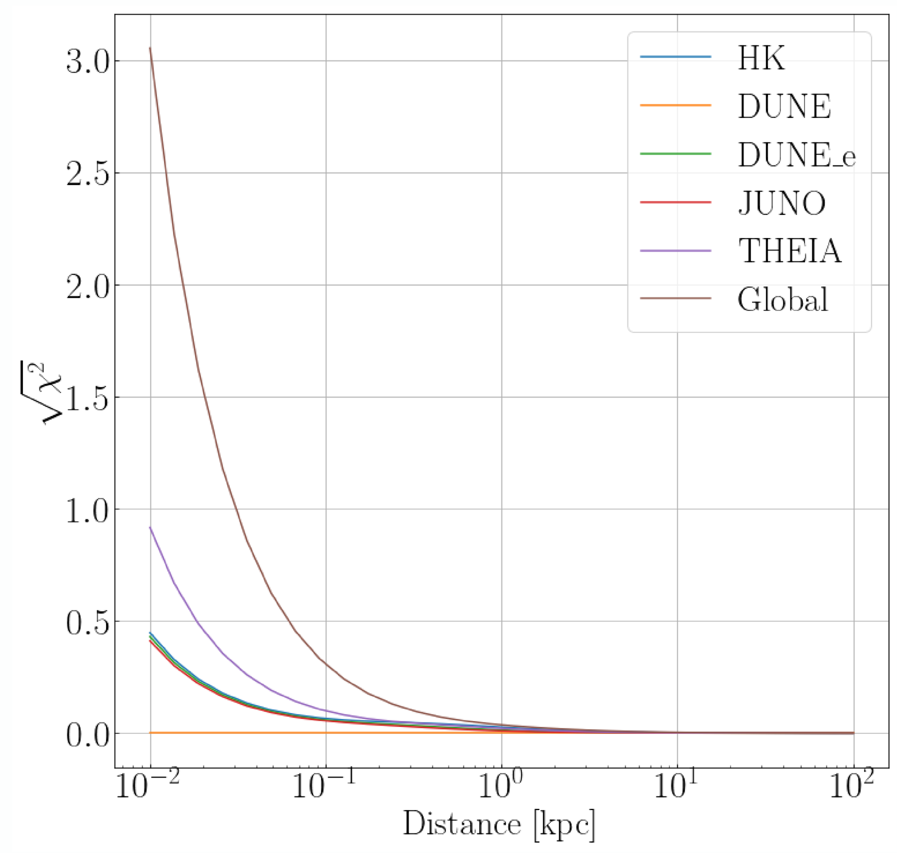

Figure 1. Expected maximum χ^2 (when $\delta_{\text{CP}} = \pi$) considering a supernova as function of the distance for different experiments and the global χ^2.

Charged Current Muon Production (CCμ)

Shock acceleration

Following the discussion from Ref. [2], it is possible to have non-thermal neutrinos up to energy ($E \approx 200$ MeV) coming out of a CCSN or a failed-CCSN by the mechanism of shock acceleration.

Neutrinos are kept at equilibrium by the interactions,

$$\nu_\alpha + n \rightleftharpoons p + \ell_\alpha^- \quad (6)$$

$$\bar\nu_\alpha + p \rightleftharpoons n + \ell_\alpha^+ \quad (7)$$

With the energy threshold given by the charged lepton masses. This means that the spectrum consists of

$$\nu_e, \nu_\mu, \nu_\tau \qquad (E \lesssim 50 \text{ MeV}) \quad (8)$$

$$\nu_\mu, \nu_\tau \qquad (50 \text{ MeV} \lesssim E \lesssim 106 \text{ MeV}) \quad (9)$$

$$\boldsymbol{\nu_\tau} \qquad \mathbf{(106 \text{ MeV} \lesssim \boldsymbol{E} \lesssim 200 \text{ MeV})} \quad (10)$$

Detection

Two detection strategies can be used.

- Usual Cherenkov detection of the muon ($E_\mu > 160$ MeV);
- Double bang for "invisible muon" detection (105 MeV$< E_\mu < 160$ MeV).

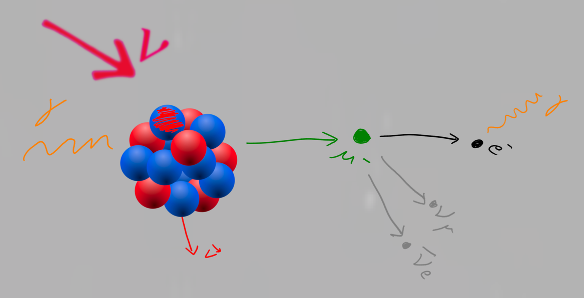

Figure 2. Double bang detection signal.

We perform a χ^2 test against the $\delta_{\text{CP}} = 0$ hypothesis using the total number of muon production events.

Results

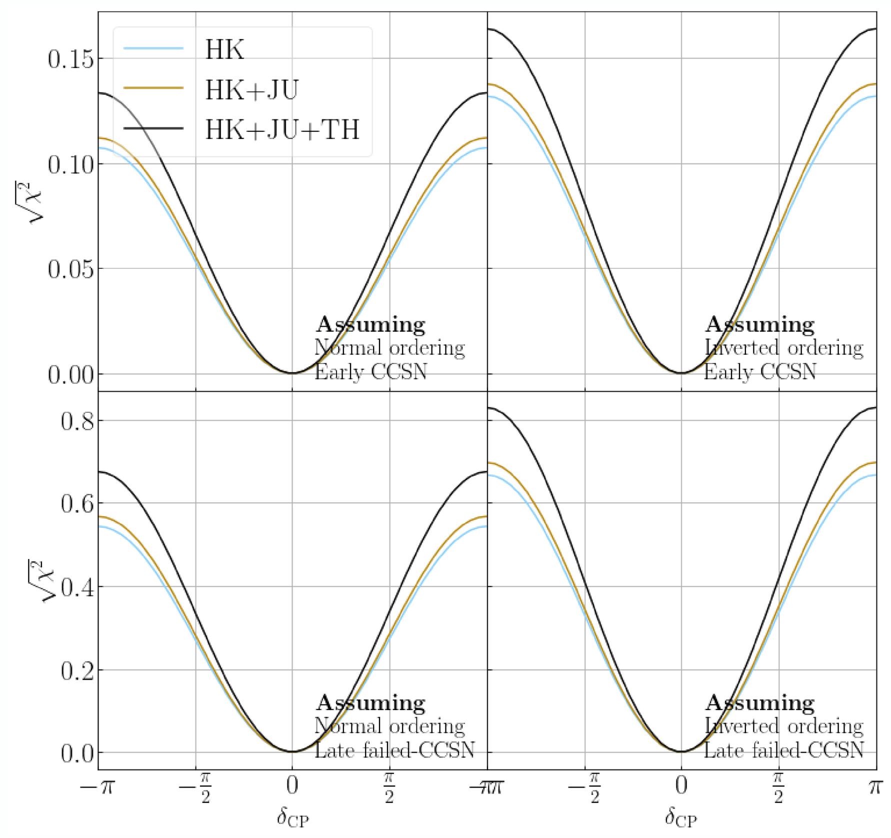

Figure 3. Expected sensitivity considering events that produce a muon as a final state with any energy. The distance to the supernova was taken to be 10 kpc.

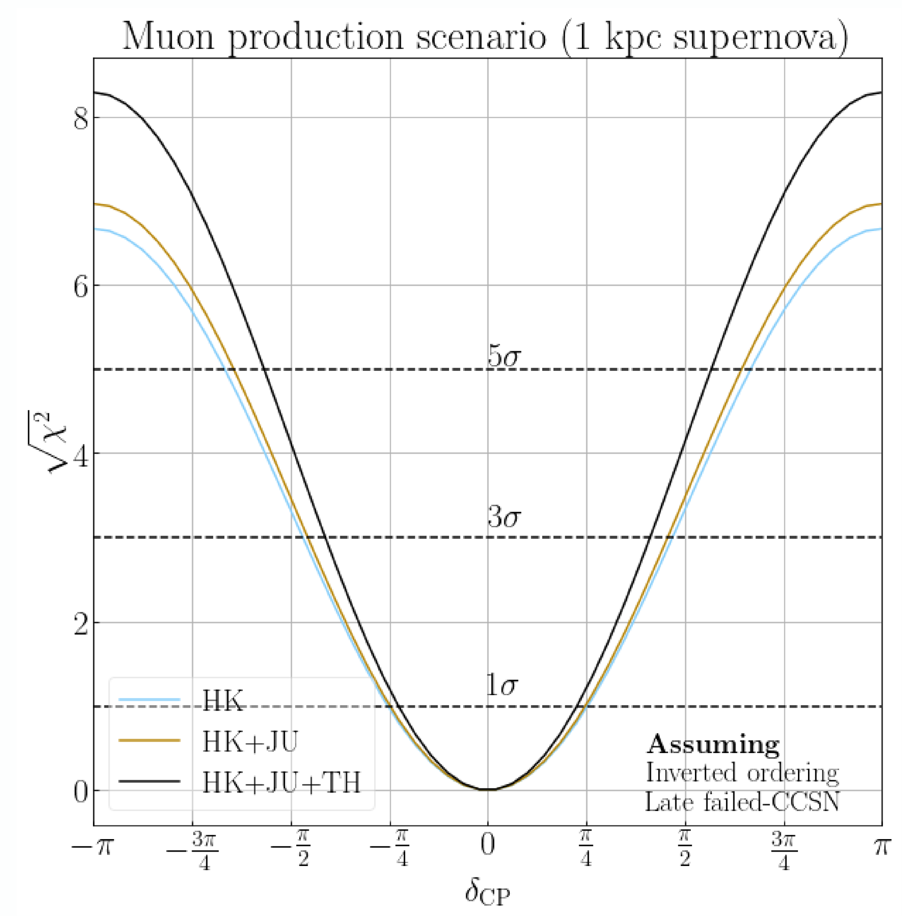

Figure 4. Expected sensitivity considering events that produce a muon as a final state with any energy. The distance to the supernova was taken to be 1 kpc.

Conclusions

We show it is possible to probe the δ_{CP} parameter in Supernova explosions. As a proof of concept, it is possible to probe such parameter in the neutral current elastic scattering of neutrinos on electrons, but the sensitivity is too small to be considered as a viable way to measure it. For charged current, we find that, in general, for the usual distance considered (10 kpc), for a 1% flux uncertainty and neglecting collective and non-adiabatic effects, it is possible to obtain a small sensitivity that can be used as a complementary probe of δ_{CP}. Improvements in the theoretical knowledge of Supernova conversion and production mechanisms are crucial to make this result more robust.

Acknowledgements: We are thankful to the Theory Department of CERN for its welcoming stay, in which this work was partially developed. LJFL is also thankful to CAPES funding that made this work possible under grants 88887.716533/2022-00 and 88887.613742/2021-00.

References

[1] V. Brdar and X.-J. Xu, *Beyond tree level with solar neutrinos: Towards measuring the flavor composition and CP violation*, *Phys. Lett. B* **846** (2023) 138255, [2306.03160].

[2] H. Nagakura and K. Hotokezaka, *Non-thermal neutrinos created by shock acceleration in successful and failed core-collapse supernova*, *Mon. Not. Roy. Astron. Soc.* **502** (2021), no. 1 89–107, [2010.15136].