Summary of the Working Group on Neutrino Astrophysics

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Nuclear Astrophysics Town Meeting
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Working Group on Neutrino Astrophysics
Organizers: George Fuller & YZQ

Joint Session with the Working Group on Core-Collapse Supernovae (CCSNe), Neutron Star Mergers (NSMs), & Gamma-Ray Bursts (GRBs)
Organizers: Raph Hix & Christian Ott

31 Participants
Some of the Biggest Questions Connecting Quarks and the Cosmos

Board on Physics and Astronomy
US National Academy of Sciences

- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
- How were the elements from iron to uranium made?
central theme: where there is hot & dense matter, there is interesting neutrino astrophysics

neutrino physics is the bridge between
particle physics (ν masses & mixings)
cosmology (galaxy formation & evolution)
and
astrophysics of CCSNe, NSMs, GRBs
(disturbing the universe, origin of the elements)

neutrino/nuclear theory & experiments,
astrophysical theory & observations,
all essential input in this enterprise
roles of neutrinos in big bang nucleosynthesis

set expansion rate & n/p

\[ \nu_e + n \rightleftharpoons p + e^- , \quad \bar{\nu}_e + p \rightleftharpoons n + e^+ \]

sensitive to mixing between active & sterile neutrinos

future CMB measurements, abundance observations, laboratory experiments on neutrino masses & mixings

a nearly over-determined situation where new Beyond Standard Model neutrino physics likely must show itself!
Interplay between CCSN and Neutrino Physics

Exact quantum transport of neutrinos is a hard problem, but approximate treatments are manageable, & the payoff is potentially huge!
roles of weak interactions in CCSNe

pre-SN evolution: set n excess & core mass

core collapse: affect launch & initial propagation of shock

post core bounce: neutrino heating

nucleosynthesis: set conditions in neutrino-driven winds, induce $\nu$, $\nu p$, & r processes

differences in luminosities & spectra among different neutrino species

importance of neutrino mixing
Big Bang:
76% H + 24% He
(by mass)

Sun:
70.7% H + 27.4% He
+ 1.9% “Metals”

“p” → “n” + e^+ + \nu_e
Neutrino Mass: what we know and don’t know

We know the mass-squared differences:

\[ \delta m_{21}^2 \equiv m_2^2 - m_1^2 \]

\[ \begin{align*}
\delta m_{\odot}^2 &\approx 7.6 \times 10^{-5} \text{ eV}^2 \\
\delta m_{\text{atm}}^2 &\approx 2.4 \times 10^{-3} \text{ eV}^2
\end{align*} \]

We do not know the absolute masses or the mass hierarchy:

**normal mass hierarchy**

\[ m_1 \rightarrow m_2 \rightarrow m_3 \]

**inverted mass hierarchy**

\[ m_1 \rightarrow m_3 \rightarrow m_2 \]
\[
\left( \begin{array}{c}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{array} \right) = U_m \left( \begin{array}{c}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{array} \right)
\]

P-Maki-Nakagawa-Sakata matrix:

\[
U_m = U_{23} U_{13} U_{12} M
\]

\[
U_{23} \equiv \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\]

\[
U_{13} \equiv \begin{pmatrix}
\cos \theta_{13} & 0 & e^{i\delta} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{-i\delta} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\]

4 parameters:

\[
\theta_{12}, \theta_{23}, \theta_{13}, \delta
\]

\[
\theta_{12} \approx 0.59^{+0.02}_{-0.015}
\]

\[
\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}
\]

\[
\theta_{13} \approx 0.154^{+0.065}_{-0.065}
\]

\[
\delta = CP \text{ violating phase} = ?
\]