CNO: Collective Neutrino Oscillation
Signature of CNO in 8.8M_s star

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Expectation of a Next Supernova

sn1987A:
Only about 20 neutrinos were detected.
However that opened field of neutrino astronomy.
We confirmed the standard scenario of CC-SNe.

Next Galactic or nearby supernova:
Now the volume of the detectors become 100 times larger.
More than 1000 of events are expected.

Q: What is the task for the theorists?

(1) Make a good model of Core-collapse supernovae
(2) Predict neutrino spectra taking neutrino oscillations into account
Kinds of Neutrino Oscillations

Among them, Collective Neutrino Oscillation (CNO) is the most complicated and not understood well.

Collective Effect, Neutrino Self interaction

MSW Effect, Neutrino-Matter interaction

Vacuum Oscillation

Earth Effect

Exploding Star

Neutron Star
A demonstration of CNO

Original Spectrum

\[
\langle E_e \rangle = 10 \text{ MeV}, \quad \langle E_e \rangle = 15 \text{ MeV}, \quad \langle E_\tau \rangle = 24 \text{ MeV},
\]

\[
L(t) = \frac{E_B}{6} \frac{e^{-t/\tau}}{\tau}
\]

After CNO

Inverted mass hierarchy, small \(\theta_{13}\)

Spectral split at 3MeV?
Can KamLAND detect it?
Problem of the studies on CNO

Caveat: The results strongly depends on
(1) numerical method
(2) neutrino luminosities,
(3) energies,
(4) angular distributions and
(5) matter density profiles.

The situation is not clear for non-expert.
In this study, we want to present rough sketch of the effect with standard numerical method and discuss its detectability.
Summary of Numerical Methods

- Hydro Simulation
  3DnSNe
  Spherical coordinate 1D, 2\textsuperscript{nd} order PLM (Mignone 2014)
  HLLC (Toro 2003), van Lear Limiter
  Phenomenological General Relativity (Marek+ 2006)

- Neutrino Radiation Simulation
  3flavor IDSA
  Updated Reaction Set (next page)

- Neutrino oscillation (post process)
  Multi angle approximation (Sasaki et al. 2017)
  The 3D simulation of r(or t), E, θ.
New Reaction Sets

Horowitz +2017, Many body effects (RPA&Virial)

$\nu_e n \rightarrow e^- p$
$\bar{\nu}_e p \rightarrow e^+ n$
$\nu_e A' \rightarrow e^- A$
$\nu N \rightarrow \nu N$
$\nu A \rightarrow \nu A$
$\nu e^\pm \rightarrow \nu e^\pm$
$e^- e^+ \rightarrow \nu \bar{\nu}$

$NN \rightarrow \nu \bar{\nu} NN$
$\nu_e + \bar{\nu}_e \rightarrow \nu_x + \bar{\nu}_x$
$\nu_x + \nu_e(\bar{\nu}_e) \rightarrow \nu'_x + \nu'_e(\bar{\nu}'_e)$

Horowitz et al. (2017)

Juodagalvis et al. (2010)
Bruenn (1985), Horowitz (1997)
Bruenn (1985)
Bruenn (1985)
Fischer (2016)
Hannestad & Raffelt (1998)
Buras et al. (2003); Fischer et al. (2009)
Buras et al. (2003); Fischer et al. (2009)

$\Rightarrow$ Decrease the cross section of nucleon scattering.
More neutrino can escape from the neutron star.
Neutrino Luminosities.

The hierarchy of the flux is similar to the previous work of accretion phase before 200ms. \( \nu_e > \bar{\nu}_e > \nu_X \)

After that, my model shows more typical feature of cooling phase. \( \nu_e \sim \bar{\nu}_e \sim \nu_X \)

Note that hierarchy of mean energy is standard one. \( \nu_e < \bar{\nu}_e < \nu_X \)
The envelop of the progenitor is really dilute. That is preferable condition to see the effect of CNO. In other progenitors, the effect of CNO is not prominent due to matter suppression (in early phase).
Matter Suppression – preparation –

Suppose Schrödinger equation

\[ i\hbar \frac{d\psi_\nu}{dt} = \mathcal{H}\psi_\nu, \quad \nu = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \]

Hamiltonian can be decomposed in three terms

\[ \mathcal{H} = \mathcal{H}_{\text{vac}} + \mathcal{H}_e + \mathcal{H}_\nu \]

MSW resonance

CNO OSC.

Transition from a state to the other state causes a large flavor conversion.

Matter Suppression: \[ \mathcal{H}_e \geq \mathcal{H}_\nu \]

Effect of CNO is suppressed compared to \[ \mathcal{H}_e = 0 \]
Matter Suppression
Matter suppression = Matter induced decoherence

\[ \mathcal{H}_e = 0 \]
\[ \mathcal{H}_\nu \text{ can be large} \]

Phase of the \( \nu \) wave function is coherent.

\[ \mathcal{H}_e \geq \mathcal{H}_\nu \]
\[ \mathcal{H}_\nu \text{ becomes small} \]

\[ \lambda \propto \frac{1}{n_e} \]

Phase of the \( \nu \) wave function is decoherent.
To investigate the effect of CNO, light progenitors with dilute envelope are preferable. 8.8M$_s$ progenitor is the best. In other progenitors, CNO will occur later. Or CNO will be completely suppressed.
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Entropy per baryon $= T^3 / \rho$ is a good probe to show the exploding region.
This progenitor explodes even in 1D since the envelope is light. After 200ms, CNO starts to emerge since the density becomes significantly low at about 400km.
Time evolution of Spectrum

181ms: No CNO

231ms: CNO occurs at high energy side

331ms: CNO occurs in all energy.
The partial swap is seen at 231 ms, 100 ms later, neutrino swapped in all energy.
Detectability?

Can we see the impact of CNO by observations?
Neutrino spectrum at Earth

Inverted mass hierarchy.  \( \text{w/o CNO} \)

\[ \bar{\nu}_x = \frac{\bar{\nu}_\mu}{\bar{\nu}_\tau} \]

\[ \bar{\nu}_e = \bar{\nu}_e \]

\[ \bar{\nu}_y = \frac{\bar{\nu}_\mu}{\bar{\nu}_\tau} \]

\[ P_{suv} = 0 \quad P_{suv} = 0 \quad P_{suv} = 1 \]

\( \text{w/o CNO} \quad P_{suv} = 0 \)
Inverted mass hierarchy. \textit{w/ CNO}

\begin{align*}
\tilde{\nu}_x &= \frac{\tilde{\nu}_\mu}{\tilde{\nu}_\tau} \\
\tilde{\nu}_e &= \tilde{\nu}_e \\
\tilde{\nu}_y &= \frac{\tilde{\nu}_\mu}{\tilde{\nu}_\tau}
\end{align*}

\begin{align*}
P_{\text{su}v} &= 1 - \epsilon \\
P_{\text{su}v} &= 0.7 (1 - \epsilon) \quad \text{w/ CNO} \\
P_{\text{su}v} &= \epsilon \\
P_{\text{su}v} &= 1
\end{align*}

Significant fraction of anti-electron neutrino survives in the spectrum at earth.
Observation with HK

In HK, 1000 of anti-\(e^\nu\) is detected in every 50ms. CNO make spectrum soft. Eventually, the event number decreases.
Observation with HK

Hardness ratio:

\[ R_{H/L} = \frac{N_{20<E}}{N_{E<20}} \]

Is not affected by uncertainty of flux.

- w/o CNO, \( P_{\text{suv}} = 0 \)
  - Original \( \bar{\nu} X \)
  - Hard
- w/ CNO, \( P = 0.7(1-\epsilon) \)
  - Original \( \bar{\nu} e \)
  - Soft
Observation with KamLAND

R depends on the detector due to $E_{\text{th}}$.

<table>
<thead>
<tr>
<th></th>
<th>HK</th>
<th>KamLAND</th>
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</thead>
<tbody>
<tr>
<td>$E_{\text{th}}$[MeV]</td>
<td>7</td>
<td>1.5</td>
</tr>
<tr>
<td>w/ CNO</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>w/o CNO</td>
<td>3.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>

To distinguish the effect of CNO, the source distance should be less than 1kpc.
Observation with DUNE (40kton)

By CNO $P_{\text{suv}} \downarrow$, the spectrum becomes hard.

If the source is within 2kpc, the Poisson error is smaller than the model difference. However, the hardness ratio also rises as time goes. It is difficult to distinguish the effect.
In normal mass hierarchy, the tendency is inverse of that of the inverted mass hierarchy.
In HK, CNO increases the hardness ratio.
In DUNE, CNO decease the hardness ratio.
### Summary of the scenario

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Inverted</th>
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<tr>
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<td>On</td>
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<td>On</td>
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<tr>
<td>$\bar{\nu}_e$ (HK)</td>
<td>Hard MSW−H(0)</td>
<td>Soft CNO,MSW−H MSW−L (0.7(1−$\varepsilon$))</td>
<td>Soft MSW−L(0.7)</td>
<td>Hard CNO, MSW−L (0.3+0.4$\varepsilon$)</td>
</tr>
<tr>
<td>$\nu_e$ (DUNE)</td>
<td>Soft MSW−L(0.3)</td>
<td>Hard CNO($\varepsilon$) MSW−L(0.3$\varepsilon$)</td>
<td>Hard MSW−H(0)</td>
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$\varepsilon$: $P_{\text{suv}}$ after CNO, $\varepsilon=1$ for w/o CNO
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**$\bar{\nu}_e$**
- Hard: MSW–H(0)
- Soft: CNO, MSW–H
  - MSW–L(0.7(1–\(\varepsilon\)))

**$\nu_e$**
- Soft: MSW–L(0.3)
- Hard: CNO(\(\varepsilon\))
  - MSW–L(0.3\(\varepsilon\))

In this phase, spectrum naturally becomes hard. So the softening of the spectra is easy to distinguish.
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<td>DUNE</td>
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When Anti-\(e\) sector becomes soft, e-sector becomes hard. The collaboration of HK and DUNE make the detection robust.
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Summary

We performed multi-angle CNO simulation with 8.8M_s model both case of inverted (IH) and normal (NH) hierarchy.

- After 200ms post bounce, we found a signature of CNO.
- We defined the hardness ratio, R, of spectrum and the evolution of that depends on flavor and mass hierarchy.
- In HK, $\bar{\nu}_e$, CNO decreases R in IH and in DUNE, $\nu_e$, CNO increases R in IH.
  - In HK, $\bar{\nu}_e$, CNO increases R in NH and in DUNE, $\nu_e$, CNO decreases R in NH.
- In this phase, R is naturally increases w/o CNO, so the decreasing trend would be easy to detect.
- A synergetic observation of HK and DUNE will draw a robust conclusion.
backup
Inverted mass hierarchy.

\[ \bar{\nu}_x = \bar{\nu}_\mu / \bar{\nu}_\tau \]
\[ \bar{\nu}_e = \bar{\nu}_e \]
\[ \bar{\nu}_y = \bar{\nu}_\mu / \bar{\nu}_\tau \]

\[ \nu_x = \nu_\mu / \nu_\tau \]
\[ \nu_e = \nu_e \]
\[ \nu_y = \nu_\mu / \nu_\tau \]
Normal mass hierarchy.

\[
\begin{align*}
\bar{\nu}_x &= \frac{\nu_\mu}{\nu_\tau} \\
\bar{\nu}_e &= \bar{\nu}_e \\
\bar{\nu}_y &= \frac{\nu_\mu}{\nu_\tau}
\end{align*}
\]