Diffuse Supernova Neutrino Background (DSNB): status and updates

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May 15, 2013

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- modeling the DSNB: updates
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- Discussion and summary
  implications for next generation detectors
from cosmological SNe: peak at $\sim 5 - 7$ MeV, due to SNe at $z \gtrsim 1$

energy window: $\sim 18 - 40$ MeV
Physics potential

- continuous flux: from rare event to constant data-taking
  - Test physics of core collapse and of neutrinos similarly to SN1987A (or better) without the wait!

- Complementary to individual SN:
  - image of \textit{entire SN population of the universe}
  - diversity of progenitors, rare types (ONeMg, failed SNe, PopIII)
  - independent, complementary probe of star formation history
  - neutrino propagation on \textit{cosmological} scale
Theory and experiment status

- SuperK limit, 
  \[ E_\nu > 17.3 \text{ MeV (90\% C.L.)} \]
  \[ \phi_{\bar{\nu}_e} \leq 2.8 - 3.1 \text{ cm}^{-2}\text{s}^{-1} \]
  - lower threshold
  - background-limited

- theory: 
  \[ \sim \mathcal{O}(10^{-1}) \text{ cm}^{-2}\text{s}^{-1} \]
  factor of several uncertainty

Bays et al. [SuperKamiokande coll.] PRD 85, (2012)
Future prospects: a *conservative* revision

- detectable at a future *realistic* detector?
  1. Mt-scale may be unrealistic
  2. depth may be unrealistic
  3. ...... may be unrealistic

- can any *physics* be extracted, from multitude of effects at play?
  1. SN rates
  2. progenitor dependence
  3. neutrino spectra
  4. oscillations
  5. SN demographics
Recession-style approach: improve the theory

- Theory-based
  - reduce theoretical uncertainties
  - evaluate theoretical errors
  - evaluate the size of all participating effects and estimate detectability

  C. L. and I. Tamborra, JCAP 1207, 012 (2012)

- Phenomenological (data-based)
  - establish a model-independent, conservative range of flux using current observations

  C. L. and L. Yang, in preparation
Calculating the DSNB

\[ \Phi_{\nu_\beta}(E) = \frac{c}{H_0} \int_{M_0}^{M_{\text{max}}} dM \int_0^{z_{\text{max}}} dz \frac{\dot{\rho}_{\text{SN}}(z, M) F_{\nu_\beta}(E', M)}{\sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}}, \]

\( F_{\nu_\beta}(E', M) \) oscillated \( \nu_\beta \) flux,
\( M \) progenitor mass, \( M_0 = 8 \, M_\odot, \, M_{\text{max}} \approx 125 \, M_\odot \)
\( \dot{\rho}_{\text{SN}} \) cosmological SN rate (SNR)
Supernova rate and star formation rate

\[ \dot{\rho}_{SN}(z, M) = \frac{\eta(M)}{\int_{0.5M_\odot}^{M_{\text{max}}} dM \, M \eta(M)} \dot{\rho}_\star(z). \]

\( \dot{\rho}_\star \) Star Formation Rate (SFR) \( \eta(M) \propto M^{-2.35} \), mass distribution of stars at birth

\[ \dot{\rho}_\star \propto \begin{cases} (1 + z)^\delta & \text{if } z < 1 \\ (1 + z)^\alpha & \text{if } 1 < z < 4.5 \\ (1 + z)^\gamma & \text{if } 4.5 < z \end{cases}. \]

from SFR data: \( \delta = 3.28, \alpha = -0.26, \gamma = -7.8 \)

\[ \int_{M_0}^{M_{\text{max}}} dM \, \dot{\rho}_{SN}(0, M) = 1.5 \times 10^{-4} \text{ Mpc}^{-3} \text{yr}^{-1}. \]

Neutrino emission

- quasi-thermal, $\alpha$-spectrum:

$$\varphi_{\nu\beta}(E) \propto L_{\nu\beta} \left( \frac{E}{\langle E_{\nu\beta} \rangle} \right)^{\alpha_{\beta}} e^{-(\alpha_{\beta}+1)E/\langle E_{\nu\beta} \rangle}.$$ 

$\alpha_{\beta}(t)$ “shape” parameter, $L_{\nu\beta}(t)$ luminosity

$$\langle E_{\nu_{\mu,\tau}}(t) \rangle > \langle E_{\bar{\nu}_e}(t) \rangle > \langle E_{\nu_e}(t) \rangle$$ in cooling phase.

$\nu_X = \nu_\mu, \nu_\tau$

Contributors


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Theory-based: including recent advancements

- more realistic SN simulations
  1. $\sim 10$ s long cooling phase
  2. dependence on progenitor mass
  3. constantly improving microphysics

- more advanced oscillation studies
  1. collective oscillations + MSW resonances
  2. measured $\theta_{13}$

- goal: evaluate quantitative effect of each

C. L. and I. Tamborra, JCAP 1207, 012 (2012)
Long-term, progenitor dependent simulations (from Fischer et al.)

- three mass bins, neglect failed SNe
- cooling phase: colder spectra, smaller differences between flavors

Collective oscillations + MSW resonances

- vacuum + matter + neutrino-neutrino interaction:

\[
\begin{align*}
H_E &= H_E^{\text{vac}} + H_E^m + H_E^{\nu\nu} \\
H_E^{\text{vac}} &= U \text{ diag} \left( -\frac{\omega_L}{2}, +\frac{\omega_L}{2}, \omega_H \right) U^\dagger, \\
H_m &= \sqrt{2} G_F \text{ diag}(N_e, 0, 0) \\
H_E^{\nu\nu} &= \int dE' (\rho_{E'} - \bar{\rho}_{E'}) (1 - \cos \theta_{EE'})
\end{align*}
\]

\[ \omega_L = \delta m^2_{\text{sol}} / 2E, \quad \omega_H = \delta m^2_{\text{atm}} / 2E, \]

\[ \theta_{EE'} \text{ angle between incident momenta} \]

- normal hierarchy (NH): \( \delta m^2_{\text{atm}} > 0 \)
- inverted hierarchy (IH): \( \delta m^2_{\text{atm}} < 0 \)
collective oscillations (multi-angle): [see Balantekin’s talk]

- step-like $\nu_e, \bar{\nu}_e$ survival probabilities (“splits”, “swaps”)
  $P_c(F^c_{\nu_e}, F^c_{\bar{\nu}_e}, E)$, $\bar{P}_c(F^c_{\nu_e}, F^c_{\bar{\nu}_e}, E)$
- suppressed in accretion phase

$P_c$ (blue, solid) and $\bar{P}_c$ (red, dashed) as functions of energy, for $M = 8.8 \, M_\odot$ and $t = 3 \, s$ pb. Left: NH. Right: IH
factorization of collective and MSW resonances (spatial separation)

\[ \sin^2 \theta_{13} \approx 0.02: \text{adiabatic MSW resonance, } P_H = 0 \]
\[ \nu_e \rightarrow \nu_3 \text{ for normal hierarchy (NH, } \delta m^2_{\text{atm}} > 0) \]
\[ \bar{\nu}_e \rightarrow \bar{\nu}_3 \text{ for inverted hierarchy (IH, } \delta m^2_{\text{atm}} < 0) \]

\[ \nu_3 \approx \nu_x \rightarrow \text{total flavor permutation} \]
spectra at exit of the star

\[
F_{\nu_e}^{\text{NH}} = \sin^2 \theta_{12} [1 - P_c(F_{\nu_e}^c, F_{\bar{\nu}_e}^c, E)](F_{\nu_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0, \\
F_{\bar{\nu}_e}^{\text{NH}} = \cos^2 \theta_{12} P_c(F_{\nu_e}^c, F_{\bar{\nu}_e}^c, E)(F_{\bar{\nu}_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0,
\]

\[
F_{\nu_e}^{\text{IH}} = \sin^2 \theta_{12} P_c(F_{\nu_e}^c, F_{\bar{\nu}_e}^c, E)(F_{\nu_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0, \\
F_{\bar{\nu}_e}^{\text{IH}} = \cos^2 \theta_{12} [1 - P_c(F_{\nu_e}^c, F_{\bar{\nu}_e}^c, E)](F_{\bar{\nu}_e}^0 - F_{\nu_y}^0) + F_{\nu_y}^0.
\]

- collective effects decrease (increase) flavor permutation for resonant (non resonant) channels
Single star, time-integrated, with cooling

- oscillations suppressed by similarity of cooling spectra
- splits are smeared by t-integration suppressed by accretion contribution
Thick: with progenitor mass dependence
Thin: 10.8 $M_\odot$ as representative of all

Black: $\nu_e$, Red: $\bar{\nu}_e$
DSNB: comparing different effects

**DSNB above the SuperKamiokande threshold,** $E_{\nu} > 17.3\text{MeV}$

(a) with $t_{pb} = 0.5\text{s}$ as representative of all post-bounce times and the $10.8\,M_{\odot}$ progenitor as representative of the whole stellar population, no oscillations;
(b) with time-dependent fluxes for the $10.8\,M_{\odot}$ model, no flavor oscillations;
(c) with time-dependent fluxes for the $10.8\,M_{\odot}$ model, MSW flavor conversions;
(d) with time-dependent fluxes for the $10.8\,M_{\odot}$ model, MSW + $\nu-\bar{\nu}$ interactions;
(e) with progenitor mass dependence, time-dependent fluxes, MSW + $\nu-\bar{\nu}$ interactions;
(f) same as (e) for SN rate favored by direct SN observations

Error bars: normalization uncertainty of supernova rate
<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle E_{\nu e} \rangle_{\text{NH}}$ (MeV)</td>
<td>9.53</td>
<td>8.96</td>
<td>12.24</td>
<td>11.90</td>
<td>11.96</td>
</tr>
<tr>
<td>$\langle E_{\nu e}^2 \rangle_{\text{NH}}$ (MeV$^2$)</td>
<td>113.85</td>
<td>100.18</td>
<td>209.53</td>
<td>198.13</td>
<td>199.66</td>
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<tr>
<td>$\langle E_{\nu e} \rangle_{\text{NH}}$ (MeV)</td>
<td>11.82</td>
<td>10.84</td>
<td>11.23</td>
<td>11.50</td>
<td>11.62</td>
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<tr>
<td>$\langle E_{\nu e}^2 \rangle_{\text{NH}}$ (MeV$^2$)</td>
<td>174.20</td>
<td>149.17</td>
<td>165.88</td>
<td>176.72</td>
<td>179.62</td>
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<tr>
<td>$\langle E_{\nu e} \rangle_{\text{IH}}$ (MeV)</td>
<td>9.53</td>
<td>8.96</td>
<td>10.83</td>
<td>11.08</td>
<td>11.23</td>
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<td>$\langle E_{\nu e}^2 \rangle_{\text{IH}}$ (MeV$^2$)</td>
<td>113.85</td>
<td>100.18</td>
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<td>170.62</td>
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<tr>
<td>$\langle E_{\bar{\nu} e} \rangle_{\text{IH}}$ (MeV)</td>
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<td>10.83</td>
<td>12.24</td>
<td>12.17</td>
<td>12.18</td>
</tr>
<tr>
<td>$\langle E_{\bar{\nu} e}^2 \rangle_{\text{IH}}$ (MeV$^2$)</td>
<td>174.20</td>
<td>149.17</td>
<td>209.53</td>
<td>206.77</td>
<td>206.06</td>
</tr>
</tbody>
</table>
Good news: hierarchy of effects

- MSW resonance dominates
  - All other effects are $\mathcal{O}(10\%)$, less than SN rate uncertainty

- Data well reproduced with effective permutation $P \simeq P_{MSW}$
  - extract original spectra?
Phenomenological: use direct observations

- SN1987A: $\bar{\nu}_e$ oscillated spectra
  - applicable, if progenitor mass dependence is negligible
- Direct measurement of SN rate
  - from SN observations, up to $z \sim 1$
- Idea:
  1. Find statistically allowed region of parameters: $\chi^2 = \chi^2_{87} + \chi^2_{SNR}$
  2. Marginalize to find allowed interval of the DSNB
    - pro: robust, (quasi) model-independent
    - con: large (but meaningful) interval of flux allowed

C. L. and L. Yang, in preparation
SN1987A: $\bar{\nu}_e$ data

![Graph showing $N$ vs. $E/\text{MeV}$ for K2 and IMB datasets.](image-url)
Fit: NH (composite spectrum) favored

- free parameters (time-integrated/averaged): $L_{\bar{\nu}_e}, L_{\bar{\nu}_x}, \langle E_{\bar{\nu}_e} \rangle, \langle E_{\bar{\nu}_x} \rangle$, mass hierarchy
- collective effects neglected

Fit of direct SNR measurement

\[ \text{SNR} \propto \sim (1 + z)^3, \]
\[ \text{SNR} \propto \sim (1 + z)^4 \]

- factor of 2 difference in local rate \((z = 0)\)
- physics? systematics?

- SFR \(\propto (1 + z)^3\),
- SNR \(\propto (1 + z)^4\)

Black: SNR inferred from star formation data. Blue: SNR from SN counting. Only statistical errors shown here.
Fit of direct SNR measurement

\[ \text{SNR}(0) h_7^3 \times 10^{-4} \text{yr}^{-1} \text{Mpc}^{-3} \]


- Including systematic errors lessens tension
  C. L. and L. Yang, in preparation
Results: allowed $\bar{\nu}_e$ flux and event rate

$\bar{\nu}_e$ normal mass hierarchy (composite spectrum)
$E > 19.3$ MeV (older SuperK threshold), at 99% C.L.

<table>
<thead>
<tr>
<th>flux, stat. only $\bar{\nu}_e$ cm$^{-2}$s$^{-1}$</th>
<th>flux, stat. + sys cm$^{-2}$s$^{-1}$</th>
<th>event rate in 1 Mt water yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07-0.37</td>
<td>0.06-0.38</td>
<td>5.0-32.6</td>
</tr>
</tbody>
</table>

- factor of several below SuperK limit
- uncertainty dominated by SN1987A
- valid only if SN1987A is *typical*
For equal flavor spectra: $\nu_e$ flux and event rate

$\bar{\nu}_e$, inverted hierarchy (single $\alpha$-spectrum)
or any flavor for equal spectra
$E > 19.3$ MeV, at 99% C.L.

<p>| flux, stat. only $\nu_e$ event rate | flux, stat. + sys $\nu_e$ event rate |</p>
<table>
<thead>
<tr>
<th>cm$^{-2}$s$^{-1}$</th>
<th>cm$^{-2}$s$^{-1}$</th>
<th>yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05-0.29</td>
<td>0.05-0.3</td>
<td>0.18-1.19</td>
</tr>
</tbody>
</table>
unique potential:
- cosmological neutrinos
- image the SN population

experiments are becoming more (financially) conservative

theory is becoming more conservative: \( \phi \sim \mathcal{O}(0.1) \, \text{cm}^{-2}\text{s}^{-1} \)
- theory-based predictions: softer spectra, cooling
- phenomenology-based predictions: lower *direct* SN rate

Can we learn anything?
- hierarchy of effects: there is hope
- a deep, 100 kt liquid argon detector is the *bare minimum*