Supernova Neutrinos, LSND and MiniBooNE

- Constraints on neutrino oscillations from supernovae
- MiniBooNE as a supernova neutrino detector
- MiniBooNE status

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Moriond EW 2002
Three good reasons to look for supernova (SN) neutrinos

1. High-energy astrophysicists can learn much about core-collapse SN explosion mechanism from neutrinos ⇒ 99% of SN energy is released in neutrinos

2. Particle physicists can learn much about neutrino masses and mixings

3. Astronomers want to have advanced warning so they can see early stages of a SN ⇒ Neutrinos arrive before photons
Neutrinos in supernova explosions

- Neutrinos and antineutrinos of all flavors are produced via: $NN \rightarrow NN\nu\bar{\nu}$, $e^+e^- \rightarrow \nu\bar{\nu}$, . . .

- Neutrinos get trapped for some time and reach thermal equilibrium

- Neutrinos eventually escape, each flavor taking away same fraction of energy

- Different neutrino temperatures due to different allowed neutrino interactions:
  - More interactions $\Leftrightarrow$ larger trapping radius $\Leftrightarrow$ lower temperature
  - Duration of neutrino burst: 1-10s

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SN neutrino energy spectra as a probe for neutrino oscillations

- At last scattering surface, $\bar{\nu}_e$’s are on average less energetic than $\bar{\nu}_\mu$’s and $\bar{\nu}_\tau$’s:

  Flux at neutrinosphere

  Flux times cross-section

- At a $\bar{\nu}_e$ detector on Earth, the observed average neutrino energy is higher than that predicted by the primary $\bar{\nu}_e$ spectrum, if $\bar{\nu}_{\mu,\tau} \rightarrow \bar{\nu}_e$ oscillations occur.

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There are three experimental hints pointing toward neutrino oscillations:

- \( \vartheta_{\text{eff}} \): effective mixing angle
- \( \Delta m^2_{\text{eff}} \): leading \( \Delta m^2 \) responsible for oscillations
- For two-flavor \((\alpha, \beta)\) oscillations:

\[
\begin{align*}
\vartheta_{\text{eff}} &= \vartheta \\
\Delta m^2_{\text{eff}} &= m_2^2 - m_1^2
\end{align*}
\]

\[
\begin{pmatrix}
\bar{\nu}_{\alpha} \\
\bar{\nu}_{\beta}
\end{pmatrix}
= \begin{pmatrix}
\cos \vartheta & \sin \vartheta \\
-\sin \vartheta & \cos \vartheta
\end{pmatrix}
\begin{pmatrix}
\bar{\nu}_1 \\
\bar{\nu}_2
\end{pmatrix}
\]

- To explain all of the data with oscillations, (at least) four neutrinos are needed
Popular 4-neutrino models

- In these models, a **sterile** neutrino with no standard weak coupling is added.

- Popular models:
  
  **2+2 Models**
  - Normal hierarchy
  - "LSND-inverted" hierarchy

  **1+3 Models**
  - Normal hierarchy
  - "LSND-inverted" hierarchy

- Flavor content: \( \bar{\nu}_e \) \( \bar{\nu}_\mu \) \( \bar{\nu}_\tau \) \( \bar{\nu}_s \)
Constraints on LSND-oscillations (not from supernovæ)

2+2 Models

1+3 Models

- LSND allowed region (99% CL)
- Regions to the right of lines are excluded at 99% CL by: Karmen (2000), Bugey, Bugey+CDHS+SuperK
- MiniBooNE projected sensitivity at 90% CL
Matter effects on neutrino propagation

- In matter:
  - $\bar{\nu}_e$’s undergo CC forward-scattering from electrons
  - All active flavor $\bar{\nu}$’s undergo NC forward-scattering from electrons, protons, neutrons

- Hamiltonian in the flavor basis:

$$(H)_{\alpha\beta} = (H_0 + V)_{\alpha\beta} = U_{\alpha i}^* U_{\beta i} m_i^2 + A_{\alpha} \frac{G_F \rho}{m_N} \delta_{\alpha\beta}$$

- $H_0$: Neutrino mass
- $V$: Mixing matrix
- $A_{\alpha}$: Density
- $G_F$: Flavor-dependent numerical coefficient
- $m_i$: Mass index
- $\delta_{\alpha\beta}$: Flavor index
Adiabatic approximation

- Matter density varies slowly enough so that transitions between local Hamiltonian eigenstates are suppressed
- Oscillations occur because the eigenstates’ flavor content changes with density
- Simple two-neutrino example (\(\bar{\nu}_e\), \(\bar{\nu}_\mu\)):
  
  Normal hierarchy
  
  Inverted hierarchy

- Inverted hierarchy \(\Leftrightarrow\) large \(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e\) conversion
SN1987A

- On Feb 23rd, 1987, a supernova exploded in the Large Magellanic Cloud
- Its neutrino emission was detected by Kamiokande (Japan) and IMB (US)
SN1987A neutrino signal

- Overall, twenty neutrinos detected
- All neutrinos interpreted as $\bar{\nu}_e$'s
- From the measured energy spectrum, a low-energy flux $F_{\bar{\nu}_e}$ was inferred, consistent with no oscillations
- Smirnov et al., PRD 49 (1994) 1389:

\[ p \leq 0.35 \text{ @ 99\% CL} \]

where the permutation factor $p$ is defined as:

\[ F_{\bar{\nu}_e}(E) \propto pF_{\bar{\nu}_\mu}^0(E) + (1 - p)F_{\bar{\nu}_e}^0(E) \]

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Time (UT) on Feb 23</th>
<th>$E_{det}$ (MeV)</th>
<th>$\vartheta_{LMC}$ (deg)</th>
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<tbody>
<tr>
<td>Kam-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-1</td>
<td>7:35:35.00</td>
<td>20.0 ± 2.9</td>
<td>18 ± 18</td>
</tr>
<tr>
<td>K-2</td>
<td>35.11</td>
<td>13.5 ± 3.2</td>
<td>40 ± 27</td>
</tr>
<tr>
<td>K-3</td>
<td>35.30</td>
<td>7.5 ± 2.0</td>
<td>108 ± 32</td>
</tr>
<tr>
<td>K-4</td>
<td>35.32</td>
<td>9.2 ± 2.7</td>
<td>70 ± 30</td>
</tr>
<tr>
<td>K-5</td>
<td>35.51</td>
<td>12.8 ± 2.9</td>
<td>135 ± 23</td>
</tr>
<tr>
<td>K-6</td>
<td>35.69</td>
<td>6.3 ± 1.7</td>
<td>68 ± 77</td>
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<tr>
<td>K-7</td>
<td>36.54</td>
<td>35.4 ± 8.0</td>
<td>32 ± 16</td>
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<tr>
<td>K-8</td>
<td>36.73</td>
<td>21.0 ± 4.2</td>
<td>30 ± 18</td>
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<tr>
<td>K-9</td>
<td>36.92</td>
<td>19.8 ± 3.2</td>
<td>38 ± 22</td>
</tr>
<tr>
<td>K-10</td>
<td>44.22</td>
<td>8.6 ± 2.7</td>
<td>122 ± 30</td>
</tr>
<tr>
<td>K-11</td>
<td>45.43</td>
<td>13.0 ± 2.6</td>
<td>49 ± 26</td>
</tr>
<tr>
<td>K-12</td>
<td>47.44</td>
<td>8.9 ± 1.9</td>
<td>91 ± 39</td>
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<td>IMB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-1</td>
<td>7:35:41.37</td>
<td>38 ± 7</td>
<td>80 ± 10</td>
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<td>41.79</td>
<td>37 ± 7</td>
<td>44 ± 15</td>
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<tr>
<td>I-3</td>
<td>42.02</td>
<td>28 ± 6</td>
<td>56 ± 20</td>
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<tr>
<td>I-4</td>
<td>42.52</td>
<td>39 ± 7</td>
<td>65 ± 20</td>
</tr>
<tr>
<td>I-5</td>
<td>42.92</td>
<td>36 ± 9</td>
<td>33 ± 15</td>
</tr>
<tr>
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<td>44.06</td>
<td>36 ± 6</td>
<td>52 ± 10</td>
</tr>
<tr>
<td>I-7</td>
<td>46.38</td>
<td>19 ± 5</td>
<td>42 ± 20</td>
</tr>
<tr>
<td>I-8</td>
<td>46.96</td>
<td>22 ± 5</td>
<td>104 ± 20</td>
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Constraints on neutrino oscillations from SN1987A

• LSND-inverted hierarchies are excluded (\(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau, \bar{\nu}_s\)):

2+2 Models

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<tr>
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<tr>
<td>(\Delta m^2_{\text{atm}})</td>
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<tr>
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1+3 Models

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• For the normal mass hierarchy schemes, SN1987A data do not provide competitive constraints

• A future SN neutrino detection will help in further constraining neutrino mass & mixing models
• $\nu_\mu \rightarrow \nu_e$ oscillation experiment at Fermilab

• 12m in diameter spherical Cherenkov detector filled with 800t of mineral oil

• 1280 PMTs (10% coverage)

• 99% efficient veto shield

• Beam duty factor: $8 \cdot 10^{-6}$

• 3m dirt overburden
BooNE collaboration & SN team

- I. Stancu, University of Alabama
- S. Koutsoliotas, Bucknell University
- E. Church, G. J. VanDalen, University of California, Riverside
- E. Hawker, R. A. Johnson, J. L. Raaf, N. Suwonjandee, University of Cincinnati
- T. Hart, E. D. Zimmerman, University of Colorado
- D. Smith, Embry Riddle Aeronautical University
- P. J. Nienaber, College of the Holy Cross
- D. C. Cox, A. Green, H.-O. Meyer, R. Tayloe, Indiana University
- R. Imlay, W. Metcalf, M. Sung, M. O. Wascko, Louisiana State University
- J. Cao, Y. Liu, B. P. Roe, University of Michigan

MiniBooNE SN team:
- John Beacom
- Matthew Sharp
- Joe Formaggio
- Richard Schirato
- Janet Conrad
- Michel Sorel
SN signal in MiniBooNE

- For a SN explosion in the center of our Galaxy, we expect $\sim 200$ neutrino interactions in MiniBooNE, mostly from the CC reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$

- Half of the detected positrons have an energy in the range $10\text{MeV} < E < 35\text{MeV}$

- The NC reaction: $^{12}\text{C} + \nu \rightarrow^{12}\text{C}^* + \nu$ \hspace{1cm} $\rightarrow^{12}\text{C} + \gamma(15.1\text{MeV})$

is expected to give 20-30 interactions
Backgrounds to SN events

- Background due to 10kHz rate of cosmic ray muons entering the detector, 2kHz of which stop inside. Muons typically tagged by veto shield.

1. Muons decaying
   - **Signature:** “high-energy”, Michel electrons

2. Muons capturing on C atoms
   - $^{12}B$ atoms created, which $\beta$-decay (long half-life)
   - **Signature:** low-energy, $\beta$-decay electrons
Background reduction

- Excluding events within 10$\mu$s of a 99\% efficient veto tag, left with:
  - 90\% of SN signal
  - 40Hz of background Michel electrons, 15Hz of background $^{12}B$ $\beta$-decay electrons

- Integrating over the 10s of a typical SN neutrino burst:

- We will measure the energy spectrum of the backgrounds very accurately
Triggering on a SN

- Selecting only events in the $10\text{MeV} < E < 35\text{MeV}$ energy range:
  - 45% of SN signal
  - 20Hz of background Michel electrons, 1-2Hz of background $^{12}\text{B} \beta$-decay electrons

- Easy to catch a real SN trigger, while keeping false trigger rate reasonably low

- For a typical, galactic SN signal (sharp rise with $\tau=3\text{s}$ exponential decay):

\[\text{Events (Hz)}\]

\[\text{SN Signal}\]

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SNEWS
SuperNova Early Warning System

- Many $\nu$ detectors watching for SN
- If the network sees a SN, an alert is sent to astronomers
- More nodes reduce drastically false alarm rates
MiniBooNE detector
General status of MiniBooNE

The detector:

– PMT’s and calibration systems installed
– 1/2 filled with oil
– DAQ works
– Starting to look at cosmic ray events!

The beamline (for main $\nu_\mu \rightarrow \nu_\epsilon$ search):

– Magnets are being installed in tunnel
– Magnetic focusing horn tested to $>10$ million pulses
– First bit of beam in April!

We have much to learn!

– “Learning Curve” in late spring/early summer
– Last fixes during “July shutdown”
– and then...we run!
MiniBooNE’s first Cherenkov ring!