Supernova Neutrinos
Neutrinos Beyond the Solar System

The Physics of Neutrinos: Progress and Puzzles
The 87th Compton Lecture Series
Enrico Fermi Institute, University of Chicago

Andrew T. Mastbaum

April 14, 2018
# Agenda

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Supernovae & Neutrinos

Supernova
Supernova

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\[ \times 1,000,000,000,000,000,000,000,000,000 \] (a billion billion billion)
Supernova

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\times 1,000,000,000,000,000,000,000,000,000
(a billion billion billion)

The death of a large star

When stars eventually run out of their nuclear fuel
Supernova

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\[ \times 1,000,000,000,000,000,000,000,000,000 \] (a billion billion billion)

The death of a large star

When stars eventually run out of their nuclear fuel

Produce heavy elements

A source of heavy elements essential to form planets, galaxies, people, etc.
Supernova

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\[ \times 1,000,000,000,000,000,000,000,000,000 \] (a billion billion billion)

The death of a large star

When stars eventually run out of their nuclear fuel

Produce heavy elements

A source of heavy elements essential to form planets, galaxies, people, etc.

Plus: Oodles of neutrinos!
NGC 4526
A galaxy, far away
(50 million light years)
NGC 4526
A galaxy, far away
(50 million light years)

Supernova 1994D
Type Ia Supernova

Credit: NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team
Supernova Taxonomy
Supernova Taxonomy

Light Curves

Intensity vs. Time
Supernova Taxonomy

Based on Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics, Fig 15.1
Supernova Taxonomy

Supernova

H

H

no H

SN I

SN II

Based on Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics, Fig 15.1
Supernova Taxonomy

Based on Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics, Fig 15.1
Supernova Taxonomy

Supernova

H

Core Collapse

H

no H

Thermonuclear

Si

no Si

He

rich

poor

SN I

SN II

SN Ia

SN Ib

SN Ic

SN IIb

SN IIL

SN IIF

SN IIpec

SN IIn

Based on Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics, Fig 15.1
Supernova Taxonomy

Based on Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics, Fig 15.1
Supernova Taxonomy

fun for astronomers!
Thermonuclear

Based on Giunti & Kim, Fundamentals of Neutrino Physics and Astrophysics, Fig 15.1
Core-Collapse Supernovae

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\[ \times 1,000,000,000,000,000,000,000,000,000 \]  
(a billion billion billion)
Core-Collapse Supernovae

Extremely powerful explosion

Most powerful nuclear bomb ever tested

$\times 1,000,000,000,000,000,000,000,000,000$ (a billion billion billion)

Credit: David Malin, Anglo-Australian Observatory
Core-Collapse Supernovae

Extremely powerful explosion

Most powerful nuclear bomb ever tested
$\times 1,000,000,000,000,000,000,000,000,000,000,000,000$ (a billion billion billion)

Supernova Energy Loss
Core-Collapse Supernovae

Extremely powerful explosion

Most powerful nuclear bomb ever tested
× \(1,000,000,000,000,000,000,000,000,000\) (a billion billion billion)

0.01%: Electromagnetic radiation

Supernova Energy Loss
Core-Collapse Supernovae

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\[ \times 1,000,000,000,000,000,000,000,000,000,000 \] (a billion billion billion)

Supernova Energy Loss

0.01%: Electromagnetic radiation
1%: Ejecta Kinetic Energy
Core-Collapse Supernovae

Extremely powerful explosion

Most powerful nuclear bomb ever tested
\times 1,000,000,000,000,000,000,000,000,000,000 (a billion billion billion)

Supernova Energy Loss

- 98.99%: Neutrinos!
- 1%: Ejecta Kinetic Energy
- 0.01%: Electromagnetic radiation
A Giant Star
A Giant Star

Our Sun
A Giant Star

Our Sun

Fe, Si, O, He, H
A Giant Star in Trouble
A Giant Star in Trouble
A Giant Star in Trouble

About 1 solar mass
(the mass of our Sun)
The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

(c) UChicago
The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

Fe
Fe

The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

Chandrasekhar's former office

My office

(c) UChicago

UChicago faculty 1937 - 1995
The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

(c) UChicago

UChicago faculty
1937 - 1995

Chandrasekhar's former office

My office
The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

Fe

Pressure

Gravity

Hydrogen

electron

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My office

Fe

Gravity

Pressure

Hydrogen
Helium

electron
Gravity

Pressure

Fe

The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

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Chandrasekhar's former office
My office

Hydrogen
Helium

Pauli Exclusion Principle
The Chandrasekhar Limit

UChicago faculty
1937 - 1995

Subrahmanyan Chandrasekhar

Fe

Gravity

Pressure

Hydrogen

Helium

Carbon

electron

Pauli Exclusion Principle

l = 0

l = 1

l = 0

l = 1

Chandrasekhar's former office

My office

(c) UChicago
The Chandrasekhar Limit

Subrahmanyan Chandrasekhar

Pauli Exclusion Principle
Gravity
Pressure

$e^- + p \rightarrow n + \nu_e$

**Electron Capture**

Further energy loss through **neutrinos**

$\gamma + ^{56}\text{Fe} \rightarrow 13\alpha + 4n$

**Photodissociation**

This **endothermic** reaction absorbs 124 MeV of energy
Gravity crushes the core into a proto-neutron star

The object reaches the density of a nucleus, stops, and bounces

A shock wave moves outward, leading to an explosion
**Neutrino Production**

1. *Capture Phase*

\[ e^- + p \rightarrow n + \nu_e \]

Early on, these come right out

2. *Neutronization Burst*

Neutrinos are trapped behind the very dense shock wave, until it grows and the density is reduced

3. *The Proto-Neutron Star*

This is extremely hot and produces many neutrino/antineutrino pairs

\[ \gamma \rightarrow \nu + \bar{\nu} \]
\[ e^+ + e^- \rightarrow \nu + \bar{\nu} \]
Models make a definite prediction for the timing and energy of neutrinos expected on Earth.
Models make a definite prediction for the **timing** and **energy** of neutrinos expected on Earth

We expect about **3 per century** close enough to detect a burst

*Phys. Rev. D 89, 013011 (2014)*
SN1987A
February 23, 1987
Large Magellanic Cloud
(170,000 light years away)
Type II Supernova
SN1987A

February 23, 1987

Large Magellanic Cloud
(170,000 light years away)

Type II Supernova

1987 NEUTRINO

Kamiokande-II
Japan

(c) Kamioka Observatory, ICRR
University of Tokyo

IMB
USA

J. Vander Velde,
http://www-personal.umich.edu/~jcv

Baksan
Russia

(c) Institute for Nuclear Research
of Russian Academy of Sciences
Kamiokande-II Experiment
Kamioka, Hida, Japan
February 23, 1987, 07:53 UTC
The world's collection of supernova neutrino data...
SN1987A Neutrinos

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The world's collection of supernova neutrino data...
SN1987A

What can neutrinos teach us about supernovae?
SN1987A

What can **neutrinos** teach us about **supernovae**?

The Sun
SN1987A
What can neutrinos teach us about supernovae?
SN1987A

What can **neutrinos** teach us about **supernovae**?

A validation of the basic supernova dynamics model, based on neutrino **energy** and **timing** measurements.
What can **neutrinos** teach us about **supernovae**?

A validation of the basic supernova dynamics model, based on neutrino **energy** and **timing** measurements.
SN1987A

What can supernovae teach us about neutrinos?
SN1987A

What can supernovae teach us about neutrinos?

1. How heavy are neutrinos?

\[ m_\nu \lesssim 14 \text{ eV} \left( \frac{E}{10 \text{ MeV}} \right) \sqrt{\frac{E}{\Delta E} \times \frac{\Delta T_{\text{obs}}}{10 \text{ s}} \times \frac{50 \text{ kpc}}{D}} \]

Compare the observed time spread to the intrinsic time spread of the burst

\[ m_{\nu_e} \lesssim 30 \text{ eV} \quad \text{(smaller than 0.006\% the electron's mass)} \]
SN1987A

What can **supernovae** teach us about **neutrinos**?

1. **How heavy are neutrinos?**

\[
m_\nu \lesssim 14 \text{ eV} \left( \frac{E}{10 \text{ MeV}} \right) \sqrt{\frac{E}{\Delta E} \times \frac{\Delta T_{\text{obs}}}{10 \text{ s}} \times \frac{50 \text{ kpc}}{D}}
\]

Compare the observed time spread to the intrinsic time spread of the burst

\[
m_{\nu_e} \lesssim 30 \text{ eV} \quad \text{(smaller than 0.006% the electron's mass)}
\]

2. **Do neutrinos decay?**

Well, some of them made it to Earth from 50 kpc away, so

\[
\text{Lifetime} \quad \tau_{\bar{\nu}_e} \gtrsim 1.5 \times 10^5 \left( \frac{m_{\nu_e}}{E_{\bar{\nu}_e}} \right) \text{ years}
\]
SN1987A

What can **supernovae** teach us about **neutrinos**?
What can **supernovae** teach us about **neutrinos**?

3. Neutrino Oscillations

Matter-enhanced (MSW) oscillations in the supernova material affect the ratios of $\nu_e/\nu_\mu/\nu_\tau$ as a function of energy.
SN1987A

What can supernovae teach us about neutrinos?

3. Neutrino Oscillations

Matter-enhanced (MSW) oscillations in the supernova material affect the ratios of $\nu_e/\nu_\mu/\nu_\tau$ as a function of energy.

4. Neutrino-neutrino interactions

The environment in the collapse is so dense that neutrino interactions with other neutrinos are believed to be important.

We can test the Standard Model by measuring the neutrino energy spectrum.
SN1987A

What can supernovae teach us about neutrinos?

3. Neutrino Oscillations

Matter-enhanced (MSW) oscillations in the supernova material affect the ratios of $\nu_e/\nu_\mu/\nu_\tau$ as a function of energy

![Diagram showing neutrino oscillations between $\nu_e$, $\nu_\mu$, and $\nu_\tau$]

4. Neutrino-neutrino interactions

The environment in the collapse is so dense that neutrino interactions with other neutrinos are believed to be important.

We can test the Standard Model by measuring the neutrino energy spectrum.

![Graph showing neutrino energy spectrum after interactions](arxiv:1006:2459 via K. Scholberg)
The Next One

To study supernova models in detail, we need **more data**
To study supernova models in detail, we need more data

more experiments  more supernovae
The Next One

To study supernova models in detail, we need more data

- more experiments
- more supernovae

Models predict \( \sim 3 \) supernovae in our galaxy per century

1987 was 31 years ago

Maybe time for another? Are we ready?
The Next One

To study supernova models in detail, we need more data

more experiments  more supernovae

Models predict ~3 supernovae in our galaxy per century

1987 was 31 years ago

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SuperNova Early Warning System

A network of 7 neutrino detectors

Super-Kamiokande  KamLAND  Daya Bay
   Japan      Japan      China

Borexino  LVD  HALO  IceCube
   Italy   Italy  Canada  South Pole

Alerts to the astronomical community
The Next One

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Canada

IceCube
South Pole

Alerts to the astronomical community

snews.bnl.gov

"No nearby core collapses have occurred since SNEWS started running, but we are ready for the next one."
To study supernova models in detail, we need **more data**

- **more experiments**
- **more supernovae**

Models predict \( \sim 3 \) supernovae in our galaxy per century

1987 was 31 years ago

Maybe time for another?
Are we ready?

SuperNova Early Warning System

A network of 7 neutrino detectors

- **Super-Kamiokande**
  - Japan

- **KamLAND**
  - Japan

- **Daya Bay**
  - China

- **Borexino**
  - Italy

- **LVD**
  - Italy

- **HALO**
  - Canada

- **IceCube**
  - South Pole

**snews.bnl.gov**

"No nearby core collapses have occurred since SNEWS started running, but we are ready for the next one."

**Be there! Join the mailing list!**
Supernova Neutrino Detectors
Supernova Neutrino Detectors

Everyone is looking for supernova neutrinos!
Supernova Neutrinos in SNO+
Supernova Neutrinos in SNO+

6800 feet underground!
Supernova Neutrinos in SNO+

6800 feet underground!

1,000 tonnes heavy water ($^2\text{H}_2\text{O}$) inside a 12 meter diameter acrylic sphere
Supernova Neutrinos in SNO+

6800 feet underground!

1,000 tonnes heavy water ($^2\text{H}_2\text{O}$) inside a 12 meter diameter acrylic sphere

7,000 tonnes water (shielding)
Supernova Neutrinos in SNO+

6800 feet underground!

1,000 tonnes heavy water ($^{2}$H$_{2}$O) inside a 12 meter diameter acrylic sphere

7,000 tonnes water (shielding)

10,000 Photomultiplier Tubes
Supernova Neutrinos in SNO+

6800 feet underground!

Electronics & Instrumentation

1,000 tonnes heavy water ($^{2}$H$_{2}$O)
inside a 12 meter diameter acrylic sphere

7,000 tonnes water (shielding)

10,000 Photomultiplier Tubes
Supernova Neutrinos in SNO+

6800 feet underground!

Electronics & Instrumentation

1,000 tonnes heavy water (\(^{2}\text{H}_2\text{O}\)) inside a 12 meter diameter acrylic sphere

7,000 tonnes water (shielding)

10,000 Photomultiplier Tubes
Supernova Neutrinos in SNO+

- 6800 feet underground!
- Electronics & Instrumentation
- 1,000 tonnes heavy water ($^{2}$H$_2$O) inside a 12 meter diameter acrylic sphere
- 7,000 tonnes water (shielding)
- 10,000 Photomultiplier Tubes

(upgraded)
Supernova Neutrinos in SNO+

6800 feet underground!

(upgraded)
Electronics & Instrumentation

780 tonnes scintillator (LAB)

1,000 tonnes heavy water ($^2\text{H}_2\text{O}$)
inside a 12 meter diameter acrylic sphere

7,000 tonnes water (shielding)

10,000 Photomultiplier Tubes
Supernova Neutrinos in SNO+

- 6800 feet underground!
- (upgraded) Electronics & Instrumentation
- 780 tonnes scintillator (LAB)
- 1,000 tonnes heavy water ($^2\text{H}_2\text{O}$) inside a 12 meter diameter acrylic sphere
- 7,000 tonnes water (shielding)
- 10,000 Photomultiplier Tubes
- New hold-down rope net
Supernova Neutrinos in SNO+
Supernova Neutrinos in SNO+
Supernova Neutrinos in SNO+
Supernova Neutrinos in SNO+

Main Course: Inverse Beta Decay
Supernova Neutrinos in SNO+

**Main Course:** Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)
**Main Course:** Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)
Supernova Neutrinos in SNO+

Main Course: Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

\( (\text{Cowan} \ & \ \text{Reines}, \ 1956) \)

Dessert: Proton Elastic Scattering
**Main Course:** Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

\[ \bullet + \bigcirc \rightarrow \bullet + \bigcirc \]

(Cowan & Reines, 1956)

**Dessert:** Proton Elastic Scattering

Any type \((\nu_x)\) of neutrino gives a proton a kick

\[ \nu_x + p \rightarrow \nu_x + p \]

\[ \bullet + \bigcirc \rightarrow \bullet + \bigcirc \]
Supernova Neutrinos in SNO+

Main Course: Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

Dessert: Proton Elastic Scattering

Any type \((\nu_x)\) of neutrino gives a proton a kick

\[ \nu_x + p \rightarrow \nu_x + p \]


200 events

Counts / (100 keV, 1 kt)

Counts / (100 keV, 1 kt)
Supernova Neutrinos in SNO+

Main Course: Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Dessert: Proton Elastic Scattering

Any type (\(\nu_x\)) of neutrino gives a proton a kick

\[ \nu_x + p \rightarrow \nu_x + p \]

200 events
**Main Course:** Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

**Dessert:** Proton Elastic Scattering

Any type (\(\nu_x\)) of neutrino gives a proton a kick

\[ \nu_x + p \rightarrow \nu_x + p \]

\[ \bullet + \bullet \rightarrow \bullet + \bullet \]
Main Course: Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

\( \bullet + \bigcirc \rightarrow \bullet + \circ \)  

(Cowan & Reines, 1956)

Dessert: Proton Elastic Scattering

Any type \( (\nu_x) \) of neutrino gives a proton a kick

\[ \nu_x + p \rightarrow \nu_x + p \]

\( \bullet + \bigcirc \rightarrow \bullet + \bigcirc \)

200 events

\[ e^+ \text{ events per 0.5 MeV} \]

\[ \text{Observed Energy [MeV]} \]

\[ \text{Counts / (100keV x 1keV)} \]

\[ E_{\text{vis}} \text{ [MeV]} \]
Supernova Neutrinos in SNO+

Main Course: Inverse Beta Decay

![Oscilloscope Pictures](Cowan & Reines, 1956)

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Dessert: Proton Elastic Scattering

Any type (\(\nu_x\)) of neutrino gives a proton a kick

\[ \nu_x + p \rightarrow \nu_x + p \]

Menu:

- NC: \(\nu_x + p \rightarrow \nu_x + p\)  
  429 events?
- CC: \(\bar{\nu}_e + p \rightarrow n + e^+\)  
  195 events
- CC: \(\bar{\nu}_e + ^{12}C \rightarrow ^{12}B + e^+\)  
  7 events
- CC: \(\nu_e + ^{12}C \rightarrow ^{12}N + e^-\)  
  3 events
- NC: \(\nu_x + ^{12}C \rightarrow ^{12}C^* + \nu'\)  
  44 events
- CC/NC: \(\nu_x + ^{12}C \rightarrow ^{11}C/^{11}B + X\)  
  2 events
- CC/NC: \(\nu_x + e^- \rightarrow \nu_x + e^-\)  
  13 events

Hundreds of events for a supernova at 10 kpc

(33,000 light years)

Thousands across all detectors

Patience...?
Diffuse Supernova Neutrino Background (DSNB)
Diffuse Supernova Neutrino Background (DSNB)
Diffuse Supernova Neutrino Background (DSNB)
Diffuse Supernova Neutrino Background (DSNB)

Earth

SN1987A

Milky Way

50 kpc
(163,000 light years)

100 kpc
(325,000 light years)

Milky Way: CC-BY-SA 3.0, A. Colvin and F. Michel, Wikimedia Commons
Diffuse Supernova Neutrino Background (DSNB)
Diffuse Supernova Neutrino Background (DSNB)

Production of neutrino-antineutrino pairs

\[ \gamma \rightarrow \nu + \bar{\nu} \]

\[ e^+ + e^- \rightarrow \nu + \bar{\nu} \]

\[ e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu} \]
Diffuse Supernova Neutrino Background (DSNB)

Proto-Neutron Star

Production of neutrino-antineutrino pairs

\[ \gamma \rightarrow \nu + \bar{\nu} \]
\[ e^+ + e^- \rightarrow \nu + \bar{\nu} \]
\[ e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu} \]
Diffuse Supernova Neutrino Background (DSNB)

Proto-Neutron Star

Production of neutrino-antineutrino pairs

\[ \gamma \rightarrow \nu + \bar{\nu} \]
\[ e^+ + e^- \rightarrow \nu + \bar{\nu} \]
\[ e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu} \]

The Sun

Diagram showing the shock wave and production of neutrino-antineutrino pairs.
Diffuse Supernova Neutrino Background (DSNB)

Proto-Neutron Star

Production of neutrino-antineutrino pairs

\[ \gamma \rightarrow \nu + \bar{\nu} \]
\[ e^+ + e^- \rightarrow \nu + \bar{\nu} \]
\[ e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu} \]

Emerge with an averaged energy distribution given by the temperature, \( T \)

\[ \frac{dN(E)}{dE} = \frac{E_{\nu}^{\text{tot}}}{6} \frac{120}{7\pi^4} \frac{E^2}{T^4} \left[ \exp \left( \frac{E}{T} \right) + 1 \right]^{-1} \]
Diffuse Supernova Neutrino Background (DSNB)

Proto-Neutron Star

Production of neutrino-antineutrino pairs

The Sun

ε
ν
T=3.2 MeV
ε≥ 12 MeV
T=4.2 MeV
ε≥16 MeV
T=5.3 MeV
ε≥20 MeV
T=6.3 MeV
ε≥24 MeV

FIG. 1. Neutrino energy spectra. The upper panels show different power-law parametrizations for supernova neutrinos. (Left) Fixed-width Fermi-Dirac distributions. The width is expressed in units of (MeV).

FIG. 2. Michel spectra, showing the production of neutrino-antineutrino pairs stemming from pion decay at rest.

FIG. 3. Normalized neutrino energy distributions (FDνPLν) for different boost factors. The left panel shows production of neutrino-antineutrino pairs. The right panel shows the energy distribution for different boost factors. The Sun is shown with a straight side length of more than 90 m.
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect

Lower Frequency

Higher Frequency
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect

Lower Frequency

Higher Frequency

redshift
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect

Lower Frequency  Higher Frequency

redshift

Intensity

Neutrino Energy
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect

Lower Frequency

Higher Frequency

redshift

more distant

Intensity

Neutrino Energy
Diffuse Supernova Neutrino Background (DSNB)
Diffuse Supernova Neutrino Background (DSNB)

Earth

Milky Way

50 kpc
(163,000 light years)

100 kpc
(325,000 light years)

$\sum N_{SN} \times E_{SN}$

Milky way: CC-BY-SA 3.0, A. Colvin and F. Michel, Wikimedia Commons
Diffuse Supernova Neutrino Background (DSNB)

$$d\phi(E) = \int R_{SN}(z) \frac{dN[E(1+z)]}{dE} (1+z) \left| \frac{dt}{dz} \right| dz$$

Earth

50 kpc
(163,000 light years)

Milky Way

$$\sum N_{SN} \times E_{SN}$$

Neutrino Energy

Intensity

Total

Milky way: CC-BY-SA 3.0, A. Colvin and F. Michel, Wikimedia Commons
**Diffuse Supernova Neutrino Background (DSNB)**

This provides an average measurement of the **total number** and the **energy** of core-collapse supernova neutrinos.

\[
\frac{d\phi(E)}{dE} = \int R_{SN}(z) \frac{dN[E(1+z)]}{dE} (1+z) \left| \frac{dt}{dz} \right| dz
\]

---

50 kpc
(163,000 light years)

---

Milky Way

---

Earth

---

\[ \sum N_{SN} \times E_{SN} \]

---

Intensity

---

Neutrino Energy

---

Total

---

Milky way: CC-BY-SA 3.0, A. Colvin and F. Michel, Wikimedia Commons
Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth
i.e., how many neutrinos per unit area, per second

Figure 3.2: Solar neutrino spectrum. This figure shows the energy spectrum of neutrinos predicted by the standard solar model (Bahcall and Pinsonneault 2004). The neutrino fluxes from continuum sources (like $^{7}$Be and $^8$B) are given in the units of number per cm$^2$ per second per MeV at one AU. The line fluxes ($^{7}$Be and $^7$Be) are given in number per cm$^2$ per second. The spectra from the $^{7}$Be chain are drawn with solid lines; the neutrino energy spectra from reactions with carbon, nitrogen, and oxygen (CNO) isotopes are drawn with dotted lines. Figure from Reference [33].

Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth
i.e., how many neutrinos per unit area, per second

So rare we haven't seen it yet
Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth

i.e., how many neutrinos per unit area, per second

So rare we haven't seen it yet

Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth
i.e., how many neutrinos per unit area, per second

Solar Neutrino Spectrum

\[ \frac{d\phi}{dE_{\nu}} (\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}) \]

Flux (cm\(^{-2}\) s\(^{-1}\))

Neutrino Energy in MeV

Solar hep \( \nu \)

So rare we haven't seen it yet


DNSB \( \nu_e \) Flux, on Earth

So rare we haven't seen it yet

DSNB, \( T = 4 \text{ MeV} \)
DSNB, \( T = 6 \text{ MeV} \)
DSNB, \( T = 8 \text{ MeV} \)
Solar hep \( \nu \)
Solar \( ^7\text{B} \nu \)

DSNB \( \nu_e \) (about 1000 times smaller)
Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth
i.e., how many neutrinos per unit area, per second

![Solar Neutrino Spectrum](image)

Solar Neutrino Flux, on Earth

So rare we haven't seen it yet

DSNB $\nu_e$ Flux, on Earth

So rare we haven't seen it yet

It's really faint!
But sort of like solar neutrinos
Diffuse Supernova Neutrino Background (DSNB)

**DNSB $\nu_e$ Flux, on Earth**

- DSNB, $T = 4$ MeV
- DSNB, $T = 6$ MeV
- DSNB, $T = 8$ MeV
- Solar hep $\nu$
- Solar $^8$B $\nu$

**Figure 4.2:** Expected flux of DSNB neutrinos on Earth, assuming a thermal spectrum. The unoscillated solar $^8$B band fluxes are shown for scale. Compare to Figure 1 in [63].

So rare we haven't seen it yet

DSNB $\nu_e$ (about 1000 times smaller)
Diffuse Supernova Neutrino Background (DSNB)

CONSTRAINING THE HEP SOLAR NEUTRINO AND DIFFUSE SUPERNova NEUTRINO BACKGROUND FLUXES WITH THE SUDbury NEUTRINO OBSERVATORY

Andrew T. Mastbaum

A DISSERTATION
in
Physics and Astronomy
Presented to the Faculties of the University of Pennsylvania in
Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy
2016


DNSB $\nu_e$ Flux, on Earth

So rare we haven't seen it yet

- DSNB, $T = 4$ MeV
- DSNB, $T = 6$ MeV
- DSNB, $T = 8$ MeV
- Solar hep $\nu$
- Solar $^8$B $\nu$

DSNB $\nu_e$ (about 1000 times smaller)
Diffuse Supernova Neutrino Background (DSNB)
Searching with the SNO Experiment
Diffuse Supernova Neutrino Background (DSNB)

Searching with the SNO Experiment

Sudbury Neutrino Observatory
Sudbury, Ontario, Canada
1000 tonnes Heavy Water
Diffuse Supernova Neutrino Background (DSNB)

Searching with the SNO Experiment

Sudbury Neutrino Observatory

Sudbury, Ontario, Canada

1000 tonnes Heavy Water

Figure 8.16: Energy spectra around the hep and DSNB regions of interest, after corrections and all cuts except on energy, with all parameters fixed to their mean values.
Diffuse Supernova Neutrino Background (DSNB)

Searching with the SNO Experiment

Sudbury Neutrino Observatory
Sudbury, Ontario, Canada
1000 tonnes Heavy Water

Too small to see, but we can rule out some funny business
Diffuse Supernova Neutrino Background (DSNB)

Searching with the SNO Experiment

Sudbury Neutrino Observatory
Sudbury, Ontario, Canada
1000 tonnes Heavy Water

Too small to see, but we can rule out some funny business
Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd

Super-Kamiokande
Kamioka, Hida, Japan

50,000 tons of water

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd

Looking for DSNB electron antineutrinos via inverse beta decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$

(Cowan & Reines, 1956)

50,000 tons of water

Super-Kamiokande

Kamioka, Hida, Japan

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd

Looking for DSNB electron antineutrinos via inverse beta decay

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Kamioka, Hida, Japan

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Super-Kamiokande + Gd

Looking for DSNB electron antineutrinos via inverse beta decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

50,000 tons of water

Super-Kamiokande

Kamioka, Hida, Japan

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd

50,000 tons of water

Super-Kamiokande
Kamioka, Hida, Japan

Looking for DSNB electron antineutrinos via inverse beta decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

\[ \text{Excluded by SK (2003)} \]

Different DSNB models

SuperK upper limit

Diffuse Supernova Neutrino Background (DSNB)

Looking for DSNB electron antineutrinos via inverse beta decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

50,000 tons of water

Super-Kamiokande + Gd

Super-Kamiokande
Kamioka, Hida, Japan
50,000 tons of water + Gadolinium

Super-Kamiokande
Kamioka, Hida, Japan

Looking for DSNB electron antineutrinos via inverse beta decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)
Di 50,000 tons of water + Gd

Looking for DSNB electron antineutrinos via inverse beta decay

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Cowan & Reines, 1956)

By adding gadolinium, the ability to detect neutrons (and therefore inverse beta decay) is greatly improved.

There's hope that Super-Kamiokande will detect the DSNB soon!

(this work starts in June!)
Supernova Neutrinos

Supernova Neutrinos
Supernova Neutrinos

Enormously powerful events crucial to the existence of the universe as we know it.

Supernova Neutrinos

Enormously powerful events crucial to the existence of the universe as we know it

Like with the Sun, neutrinos can teach us about SNe, and SNe about neutrinos
Supernova Neutrinos

Enormously powerful events crucial to the existence of the universe as we know it

Like with the Sun, neutrinos can teach us about SNe, and SNe about neutrinos

While we wait for a SNe neutrino burst, we can study the DSNB, and learn about the average behavior of supernovae

Supernova Neutrinos

xkcd

"How close would you have to be to a supernova to get a lethal dose of neutrino radiation?"

https://what-if.xkcd.com/73/
Next Week
Saturday, April 21, 2018

"study of the origin, evolution, and eventual fate of the universe"

Neutrino Cosmology
with
Dr. Marco Raveri
KICP, UChicago

What can the structure of the universe teach us about neutrinos, and vice versa?
Thank You!