Pathways to Discovering Supernova Neutrinos

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Direct observation of a SN event in our Galaxy
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Observing the Diffuse background from SN throughout the Universe
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Direct observation of a SN event in our Galaxy

Observing the collective emission of SN from within the galaxy

Observing the Diffuse background from SN throughout the Universe
Typical Recoil Energies for SN Neutrinos

- Recoil energy of a collision is $O(1) \text{ KeV}$ - very small energy deposit to detect

- Although neutrinos have a small mass, there increased velocities lead to $O(1-10) \text{ KeV}$ recoils

\[
E_R \leq 2 \frac{m^2 \chi M_T}{(m \chi M_T)^2} \nu^2
\]

![Graph showing typical recoil energies for SN Neutrinos](image)
Small Damage Track Features can be Observed in Minerals

- Paleo-detectors are minerals from far below the Earth's surface (5-10 km). Importantly they are 1 billion years old.

- Permanent damage track features in the structure of the mineral.
Basics of Building a Detector: Mass vs Exposure

Recoil Rate $\propto$ Target Mass $\times$ Observation Time
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Huge Targets

Smallish Exposure
Basics of Building a Detector: Mass vs Exposure

Recoil Rate \propto \text{Target Mass} \times \text{Observation Time}
Basics of Building a Detector: Mass vs Exposure

\[ \text{Recoil Rate} \propto \text{Target Mass} \times \text{Observation Time} \]
Reading the Tracks: X-ray Tomography

Holler et al. 14
Cosmic Rays Induce Large Backgrounds

<table>
<thead>
<tr>
<th>Depth [km]</th>
<th>2</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Flux [1/cm²/Gpc]</td>
<td>$10^3$</td>
<td>$10^1$</td>
<td>$10^{-4}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

[Image of a rusty, damaged surface with debris and rusted metal objects.]

Natural Radioactivity: Single alphas

- **Natural radioactivity**, most importantly *Uranium-238* causes multiple backgrounds

\[
\begin{align*}
^{238}\text{U} & \rightarrow ^{234}\text{Th} \rightarrow ^{234m}\text{Pa} \rightarrow ^{234}\text{U} \rightarrow ^{230}\text{Th} \\
& \rightarrow ^{226}\text{Ra} \rightarrow ^{222}\text{Rn} \rightarrow \ldots \rightarrow ^{206}\text{Pb}
\end{align*}
\]
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\[
\begin{align*}
238\text{U} & \rightarrow^{\alpha} 234\text{Th} & \rightarrow^{\beta^-} 234\text{mPa} & \rightarrow^{\beta^-} 234\text{U} & \rightarrow^{\alpha} 230\text{Th} \\
& \rightarrow^{\alpha} 226\text{Ra} & \rightarrow^{\alpha} 222\text{Rn} & \rightarrow \ldots & \rightarrow 206\text{Pb}
\end{align*}
\]

- Half life of the second alpha in the decay chain is \(10^5\) yr

- Alpha does not leave a track, but the daughter nucleus does
Natural Radioactivity: Spontaneous Fission

- Sometimes uranium spontaneously splits into two lighter nuclei, whilst emitting fast neutrons.

- These neutrons cause many well separated tracks - **huge background**.
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- These neutrons cause many well separated tracks - **huge background**.

![Graph showing the concentration of Epsomite; $C_{238} = 0.01$ ppb across different $x$ values.](null)

**Uranium-238 Concentration $\sim 0.01$ ppb**
Background Neutrinos: Solar and Atmospheric

\[ p + p \rightarrow d + e^+ + \nu_e \]

Epsomite; \( C_{238} = 0.01 \text{ ppb} \)

\[
\frac{dR}{dx} \quad [\text{mm}^{-1} \cdot \text{kg}^{-1} \cdot \text{Myr}^{-1}] 
\]

Graph showing the change in \( R \) as a function of distance \( x \) in nanometers.
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\[
\frac{dR}{dx} \quad [\text{nm}^{-1} \text{kg}^{-1} \text{Myr}^{-1}]
\]

\[
x \quad [\text{nm}]
\]
Galactic Signal much Larger than the Diffuse Background

The signal from galactic supernovae is much larger than the Diffuse Neutrino Background (DSNB) at different energies due to redshift. Galactic SN spectrum peaks at different energy due to redshift.
Paleo-detectors can Observe Galactic Supernovae

- **3-sigma detection** if we achieve low enough concentrations of Uranium-238

- Here we assume a constant rate of SNe throughout the history of the galaxy

![Graph showing minimum detectable rate vs. Uranium-238 concentration](image-url)

- **M = 100 g, t_{age} = 1 Gyr**

- Epsomite - C&C
- Epsomite
- Halite
- Nchwaningite
- Olivine
Star Formation Rates

- **Look-back Time [Gyr]**
  - 0.0
  - 0.25
  - 0.50
  - 0.75
  - 1.0

- **Uranium-238 Concentration [ppb]**
  - 10^(-3)
  - 10^(-2)
  - 10^(-1)
  - 10^0

- **SFR, \( \psi(t_*)/\psi(0) \)**
  - 1.00
  - 1.25
  - 1.50
  - 1.75
  - 2.00
  - 2.25
  - 2.50
  - 2.75

**Discrimination Significance [\( \sigma \)]**

- **Mor et al. SFR (1901.07564)**
- **Cosmological SFR (1403.0007)**
Star Formation Rates

Estimate of the Milky Way SFR from Gaia

Uranium-238 Concentration [ppb]

Discrimination Significance $[\sigma]$
Star Formation Rates

Estimate of the Milky Way SFR from Gaia

Baseline case can rule out constant rate at 2 \( \sigma \) depending on model
Conclusions

1. Paleo-Detectors represent a new way to probe keV scale interactions

2. Paleo-Detectors can detect neutrinos from supernovae within our galaxy

3. With enough clean samples, we can learn about the galactic star formation history
We use swordfish to Analyse the Spectra Easily

Counting Experiment
\( S(\theta) \): Signal  
\( B \): Background  
\( K \): Bkg. Covariance  
\( E \): Exposure

Fisher Information Matrix
\[ I_{ij}(\theta) = -\left\langle \frac{\partial^2 \ln L(D(\theta))}{\partial \theta_i \partial \theta_j} \right\rangle_{D(\theta)} \]

Information Flux
\[ F(\Omega|\theta)_{ij} = \frac{\delta I(\theta)_{ij}}{\delta E(\Omega)} \]

Information Geometry
\[ g_{ij}(\theta) = I_{ij}(\theta) \]

Euclideanized Signal
\( (S(\theta), B) \rightarrow x(\theta) \)

Model Discrimination
\[ TS \approx \|x(\theta_1) - x(\theta_2)\|^2 \]

Tensor field visualization

Confidence Contours

1704.05458, 1712.05401
https://github.com/cweniger/swordfish
We can Constrain Burst Like Events

Number of normal SN at a distance of 10 kpc

Burst look-back time $t_\star$ [Gyr]

$F \propto \frac{L}{d^2}$

Minimum Detectable $N_\star$

Epsomite, $M = 100$ g

10 samples, $\Delta t_{\text{age}} = 0.1$ Gyr

$10^{7}$ $10^{8}$ $10^{9}$

$1$ ppb

$0.1$ ppb

$0.01$ ppb

$0.001$ ppb
Constraining Burst Like Events

Bursts that happened recently can be detected more easily

Bursts a long time ago must be brighter
Star Burst Scenario

Number of burst CC SN, $N_x$

Distance to burst region, $D_*$ [kpc]

Number of CC SN at 10 kpc, $N_{x,10\text{kpc}}$

Star Formation Rate: 
$[0.1, 1000] \, M_\odot \text{yr}^{-1}$

$\Delta t_{\text{starburst}} = 10 \text{ Myr}$

LMC
GC
NGC 3603
Close by Supernova

Star Formation Rate: \([0.1, 1000] \, M_\odot \text{yr}^{-1}\)

\(\Delta t_{\text{starburst}} = 10 \, \text{Myr}\)