Supernova detection in IceCube
Status and Future

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IceCube

- Km$^3$ instrumented in the Antarctic Ice at the South Pole
- Sensors: 10” photomultipliers housed in pressure resistant spheres: DOMs
  - 86 strings total
  - 5160 DOMs
- DeepCore:
  - Optimized for lower energies
- Physics programme:
  - Neutrino point sources
  - Gamma ray bursts
  - Cosmic-ray anisotropy
  - Neutrino oscillations
  - ...

See IceCube talks at this conference for more details
Main detection channel/events in IceCube

Cherenkov light from the products of the interaction of an individual primary

Different primary and interaction types lead to different hit patterns (hit: recorded photon(s))

Primaries carry enough energy to create a significant number of hits

The large number of hits allows for reconstruction of event (direction, energy, type)

Examples:

Tracks

Up-going (~TeV) muon track from a muon neutrino interaction

Cascades

Sensitive to all neutrino types through neutral current
Supernova detection in IceCube

In contrast, the interaction of a supernova neutrino (~10 MeV) does not produce enough photons to derive the properties

- Main interaction channel (~93%):
  - Inverse beta decay (anti-nue)
- Detection: Cherenkov light from positrons
  - Number of photons proportional to $E$
  - Very small photon detection probability per interaction
Need a large number of interactions to have significant signal!

Supernova within our Galaxy (at 10kpc):

- ~0.3 neutrino interactions/m$^3$/10 seconds uniformly distributed
- ~3x10$^8$ interactions in IceCube volume

Detection by increase of noise rate on top of background
No information on individual interaction (energy/direction)

Luminosity and $<E>$ for 8.8 M SN

Standard Supernova detection: SNdaq

The supernova datastream is separate from the primary datastream
Scaler format
Discriminator threshold: 0.25 p.e.
Binning: 1.6384 ms
Standard supernova detection: background and signal

- DOM noise rates are log-normally distributed
- Rate: 265+-26 Hz after deadtime
- Stable, with 6% seasonal variation
- Re-binned and synchronized in 2ms bins

Supernova detection:

- Search for collective rise over all DOMs in noise ($\Delta \mu$)
  - Rate estimate in 300 s bins
  - Likelihood analysis estimates $\Delta \mu$ and error $\sigma_{\Delta \mu}$
  - Correction for individual DOM characteristics
  - Several bin sizes: 0.5, 1.5, 4, and 10 s

Standard Supernova detection

- Significance: $\xi = \Delta \mu / \sigma_{\Delta \mu}$
- Atmospheric muon background widens significance distribution and is corrected

Supernova triggers:
- $\xi = 6.0$: internal trigger
- $\xi = 7.65$: SNEWS trigger

(SNEWS: Supernova Early Warning System)

- High significance within Milky Way
- Triggers up to Small Magellanic cloud
Standard Supernova detection: Neutrino Oscillations/Hierarchy

Different neutrino hierarchies lead to different detected rates for a given model.

If the emission model is known, hierarchy can be determined for close supernovae.
Beyond Standard SN detection: coincident hits

The luminosity and average energy are entangled, and cannot be distinguished by just measuring the rate!

Flux at detector
\[ \frac{d \tilde{\Phi}_{\nu_e} (E_\nu, d)}{dE_\nu} = \frac{1}{4\pi d^2} \int_0^t \frac{L(t)}{\langle E \rangle (t)} f_{\alpha(t), \langle E \rangle (t)} dt \]

Average energy

Luminosity

Spectral shape

In this talk we use:
\[ f_{\alpha, \langle E \rangle} (E_\nu) = \frac{(1+\alpha)^{1+\alpha}}{\langle E_\nu \rangle \Gamma (1+\alpha)} \left( \frac{E_\nu}{\langle E_\nu \rangle} \right)^\alpha e^{-\frac{(1+\alpha) E_\nu}{\langle E_\nu \rangle}} \]

Average energy

'Shape'

Coincident hits from individual interaction can provide additional information

- Coincidences are sensitive to different parts of the spectrum
  - Probability of coincidence increases with energy
- The more dense the detector, the more powerful this technique
Coincident Hits: Future DAQ improvement: Hit-Spooling

- An improvement to the SNdaq is foreseen: Hit-Spooling
  - All photon hits are stored in a rotating file system
  - Written to permanent storage in case of a SN trigger
- Advantages:
  - Improved timing resolution
  - Additional information can be obtained from coincident hits
  - Background monitoring and reduction
Coincident Hits: Hit modes

Photon hits \(i\) and \(j\), at times \(t_i\) and \(t_j\) are coincident when \(|t_i - t_j| < \delta t\)

Several hit modes:

- Single sensor hit: mode 10 (or “1+0”)
- Two photons detected in the same sensor: mode 20 (or “2+0”)
- A single hit in two sensors: 11 (or “1+1”)
  - Nearest-neighbour (NN)
  - Next-to-nearest-neighbour (NNN)
  - Even farther distance (...)
- Three hits on different sensors: 111 (or “1+1+1”)
  - Same string, NN, NNN or farther
  - Different strings (2 or 3 strings)
- And more ...
Coincident Hits: Denser detector

IceCube: 17 m between sensors
DeepCore: 7 m between sensors

PINGU: projected dense enhancement
The final configuration is not settled, here we assume the particular geometry from ApP 35, 485 (2012) which we call:

Deep and Dense

20 strings
120 sensors/string
3 meter between sensors
4π sensitive sensors
Coincident Hits: Energy

The ratios of the different hit modes (rate2/rate1) show a sensitivity to the average energy.

Plots show the ratios as function of average positron energy, using the Garching model.

Thus, the average energy and luminosity can be disentangled for a given model.

Lines: analytical*, points: simulation

Analytical calculation breaks down for $4\pi$ sensitive modules.

Coincident Hits: Energy resolution

The average energy can be determined from the ratios of hit rates for different modes. Below, the energy resolution obtained for DeepCore and the 11/10 hit ratio using the Garching model. The resolution is determined by the mode with the lowest statistics, thus 11.
Can we determine shape parameters?

Different modes probe different parts of the spectra
They depend differently on energy
Thresholds for higher order coincidences are at higher energies

In an envisaged dense detector, the coincidence rates are sufficiently high to also look at triple coincidences

The following plot is made for the Deep and Dense configuration for the Garching model.
Can we determine shape parameters?

\[ \chi^2 = (\mathbf{r}_{\text{meas}} - \mathbf{r}_{\text{model}})^T \mathbf{V}^{-1} (\mathbf{r}_{\text{meas}} - \mathbf{r}_{\text{model}}) \]

with \[
\mathbf{r} = \begin{pmatrix}
\frac{\text{rate}^{11}}{\text{rate}^{10}} \\
\frac{\text{rate}^{111}}{\text{rate}^{10}} \\
\vdots
\end{pmatrix}
\]

A scan over \( \alpha \) and \(<E>\) assuming the Garching model at 10 kpc

Degeneracy between \( \alpha \) and \(<E>\)
Multiple minima scattered in a narrow 'valley'

true \(<E>\) : 0.01247 GeV
true \(\alpha\) : 2.84
Summary/Outlook

• IceCube/DeepCore is a capable supernova detector

• Coincident hits can provide additional information on galactic supernova properties
  • Average energy and luminosity can be disentangled with IceCube when hitspooling is commissioned

• In dense detectors there is potential for studying finer spectral features
Backup slides
Sources of background

While the coincidental rate is reduced by requiring multiple hits, sources of correlated noise form a background which can be reduced by offline analysis.

- Cosmic-ray induced muons
- Sensor correlated noise (afterpulses*, radioactive decays)
  - Suppressed by narrow time window

Cuts on the number of coincidences and time distribution can reduce atmospheric muon background (under study)

*: NIM, A618 (2010), 139-152
Simulated sample

- Generated \(\sim 2 \times 10^9\) positron interactions
- Non-physical spectrum folded with cross-section
Simulation

- Geant4 based simulation
  - Extends analytic calculation to a full detector
  - All hit modes
- Custom photon tracking
  - Depth dependent ice properties
- Now, only inverse beta decay on protons
  - Other neutrino cross-sections are already implemented

M. Ackermann et al. (2006), Optical properties of deep glacial ice at the South Pole, J. Geophys. Res., 111, D13203
8.8 solar mass electron capture supernova (Garching*)

\[ \frac{d\Phi_{\nu_e}}{dE_{\nu_e}}(E_{\nu_e}, d) = \frac{1}{4 \pi d^2} \int_0^\tau \frac{L(t)}{\langle E \rangle(t)} f_{\alpha(t), \langle E \rangle(t)} dt \]

\[ f_{\alpha, \langle E \rangle}(E_{\nu_e}) = \frac{(1+\alpha)^{1+\alpha}}{\langle E \rangle \Gamma(1+\alpha)} \left( \frac{E_{\nu_e}}{\langle E \rangle} \right)^\alpha e^{-(1+\alpha) \frac{E_{\nu_e}}{\langle E \rangle}} \]

Throughout this work, we use an effective spectrum integrated over \( \tilde{t} = 2.95 \) s

Obtained by optimizing signal over noise with an exponential luminosity decrease and \( \tau = 2.35 \) s. This is conservative as the spectrum is steeper a shorter times.

The integrated luminosity : \( \tilde{L} = 2.13 \cdot 10^{52} \text{erg} \)

The average energy : \( \langle \tilde{E}_{\nu_e} \rangle = 12.5 \text{MeV} \)

\[ \alpha = 2.84 \]

We use as a benchmark distance \( 10 \text{kpc} : \tilde{\Phi} = 0.89 \cdot 10^{15} \text{m}^{-2} \)

Also neutrino spectra with a Fermi-Dirac ("FD") distribution are considered, normalized to have the same luminosity as Garching.

\[ f_{\eta, T}(E_{\nu_e}) = N(\eta, T) \left( \frac{E_{\nu_e}}{T} \right)^2 \frac{1}{1 + e^{E_{\nu_e}/T - \eta}} \]

\[ N(\eta, T) = -(2T \text{Li}_3(-e^{\eta}))^{-1} \]

Used values:

\[ \eta = 0 \quad \langle \tilde{E}_{\nu_e} \rangle_{T=5 \text{MeV}} = 15.8 \text{MeV} \]

\[ \langle \tilde{E}_{\nu_e} \rangle_{T=6.5 \text{MeV}} = 20.5 \text{MeV} \]

Effective volume calculation (analytical) I

Effective volume* for model M (e.g. Garching, FD) and hit mode kk' (k hits in one sensor and k' in another):

\[ V_{\text{eff}}^{M, kk'} = \frac{1}{\rho_e^M (d)} \int \frac{d \rho_e^M}{dE_e} (E_e, d) V_{\text{eff}}^{kk'} (E_e) dE_e \]

Positron energy distribution

(M dropped, implicit from now on)

\[ \frac{d \rho_e}{dE_e} (E_e, d) = \rho_p \int \frac{d \sigma}{dE_e} (E_\nu, E_e) \frac{d \Phi_\nu}{dE_\nu} dE_\nu \]

\[ \rho_e (10\text{kpc}) = \frac{0.074 \text{ m}^{-3}, \text{Garching}}{0.096 \text{ m}^{-3}, T_{\text{FD}}=5 \text{ MeV}} \]
\[ \frac{0.12 \text{ m}^{-3}, T_{\text{FD}}=6.5 \text{ MeV}} \]

Interactions per m\(^3\)

*Effective volume =
(protons in detection volume)*(detected positrons)/(generated positrons)
Effective volume calculation (analytical) II

Now, the positron effective volume:

\[ V_{\text{eff}}^{k k'}(E_e) = 2 \pi \int_{R}^{\infty} r^2 \, dr \int_{-1}^{1} d\cos \theta \times 4 f(k, r, \theta, E_e) f(k', r', \theta', E_e) \]

Probability density of detecting k hits or more
Contains:
- Number of detectable Cherenkov photons emitted by a positron (quantum efficiency taken into account)
- Fraction of sensitive area viewed under angle theta at distance r

10 mode
DDC
DeepCore
IceCube

20 (Thick) and 11 (thin) modes
Making use of coincident photon hits

- Once the enhancements in the data-acquisition in IceCube/DeepCore are implemented, making all photon hits during a SN burst available, space-time correlations between hits can be used to obtain additional information.

- Higher order modes (coincidental hits) have lower rates, but probe spectral features of neutrino emission at higher energies.

- The more dense the detector, the more powerful this technique becomes.

\[ \text{Neutrino (IBD) interaction} \] (\(~2000 \text{ photons at 10MeV positron energy}\)
Hit modes

Photon hits $i$ and $j$, at times $t_i$ and $t_j$ are coincident when $|t_i - t_j| < \delta t$

Several hit modes:

- Single sensor hit: mode 10 (or “1+0”)
- Two photons detected in the same sensor: mode 20 (or “2+0”)
- A single hit in two sensors: 11 (or “1+1”)
  - Nearest-neighbour (NN)
  - Next-to-nearest-neighbour (NNN)
  - Even farther distance (...)
- Three hits on different sensors: 111 (or “1+1+1”)
  - Same string, NN, NNN or farther
  - Different strings (2 or 3 strings)
- And more ...
Can we determine an energy shape parameter?

First simple try: define a $\chi^2$, assuming uncorrelated variables:

$$
\chi^2 = \sum \left( \frac{(r_{\text{meas}}^{20/10} - r_{\text{model}}^{20/10})^2}{\sigma_{20/10}^2} + \frac{(r_{\text{meas}}^{11(NN)/10} - r_{\text{model}}^{11(NN)/10})^2}{\sigma_{11(NN)/10}^2} + \frac{(r_{\text{meas}}^{11(NNN)/10} - r_{\text{model}}^{11(NNN)/10})^2}{\sigma_{11(NNN)/10}^2} + \ldots \right)
$$

Each term is sensitive to different parts of the spectrum.

Two independent data sets
1. The 'measurement' : to get the measured values for the ratios
2. The model(s) : to get the ratios for different parameters and models

Is it sensitive at all? : Scan over parameter space, and study the sensitivity of $\chi^2$
Positron spectra

Positron spectra for interactions leading to different modes

The average energy increases with higher modes

Different modes probe different parts of the spectrum

\[
\begin{align*}
&\langle E_{\text{ana}} \rangle = 20.1 \text{ MeV} \\
&\langle E_{\text{sim}} \rangle = 20.46 \pm 0.01 \\
&\langle E_{\text{ana}} \rangle = 22.85 \text{ MeV} \\
&\langle E_{\text{sim}} \rangle = 22.5 \pm 0.2
\end{align*}
\]

○: simulation
○: analytical*