Towards an extragalactic supernova neutrino detector at the South Pole

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Trends in extragalactic supernova core-collapse supernovae (SNe)

- With today’s neutrino observatories, only Galactic SNe (>2–3 per century) visible
- Need to extend sensitivity to neighboring galaxies (5–10 Mpc) for a routine detection of ~1 SN per year in neutrinos (see Figure 1)
- Physics motivation:
  - Measure the core-collapse SN rate accurately
  - Study the core-collapse mechanism
  - Trigger early optical observations of SNe
  - Probe for optically dark SNe (see below)
  - Set limits on neutrino mass

Neutrinos from extragalactic core-collapse supernovae (SNe)

- Lawrence-Livemore model (LL): One of the few model calculations leading to an explosion
- Thompson-Burrows-Pinto model (TBP): More recent than LL, but does not lead to an explosion.
- Dark SNe: While the collapse of a fast-rotating star with M ≥ 25 Msun leads to a hypernova, a slow-rotating one collapses to a black hole without emitting photons. These “dark” SNe or failed SNe could be detected with a SN v detector.

Simulation

- Probing two different regions for Cherenkov array in South Pole Ice:
  - diffuse ice (750 – 1050 m depth)
  - clear ice (2150 – 2450 m depth)
- 61 strings arranged in hexagonal pattern
- Assuming 300 optical modules on each string with eff.
  - photosensitive area: ~78 cm² in diffuse ice
  - ~312 cm² in clear ice corresponding to 1.4 (5.5) high QE IceCube modules (~57 cm²)
- Photon propagation:
  - diffuse ice: random walk
  - clear ice: Photons
- Event trigger requirement:
  - 5 photon hits anywhere in the detector (no time window applied)
  - SN trigger requirement: ≥ 3 (10) events within 10 s

Backgrounds

- Backgrounds are challenging, require BG rate <4 mHz to get at most 1 fake SN event/year
- Atmospheric muons: Easily recognized if through-going. Need outer veto layers (IceCube) against stopping muons.

Results

- SN detection probability computed for optimal eff. mass (~9 Mton for clear ice).
- Fig. 5 shows probability for Nv=3 as function of SN distance for the three SN models.
- Using Fig. 5 and Fig. 1, we estimate the number of SN detections, taking observed SNe as lower and predicted SNe as upper limit (see table below, backgrounds not considered)

- Number of SN detections per year:

<table>
<thead>
<tr>
<th>Model</th>
<th>Nv ≥ 3</th>
<th>Nv ≥ 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>1.7 – 3.3</td>
<td>0.4 – 0.8</td>
</tr>
<tr>
<td>TBP</td>
<td>0.8 – 1.6</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>Dark SN</td>
<td>1.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* assuming 5% Dark SNe occur at 10% of observed SN rate

Fig. 1: Cumulative number of SNe per 10 Mpc from star formation rate (red) and as observed (black).

Fig. 2: Position spectrum from SN in 1 Mpc distance for 1 Mton effective mass

Fig. 3: Number of detected photons as function of neutrino vertex position in clear ice

Fig. 4: Effective mass for positrons from LL spectrum as function of string spacing

Fig. 5: SN detection probability (clear ice)

Fig. 6: Neutrino fluxes of BG and signal

Fig. 7: Differential event rate