The Neutrino Signal From Pair Instability Supernovae

Jim Kneller
Carla Fröhlich
Matt Gilmer
Warren Wright

Pair Instability Supernovae

- Pair Instability Supernovae (PISNe) are the disruption of a star due to explosive burning in a CO core that becomes unstable due to electron-positron pair production.
  - the mass of the CO core lies in the range $64 \, M_\odot < M_{\text{CO}} < 133 \, M_\odot$
  

- There has been a revival of interest in PISNe in recent years.
  

- PISNe can occur at non-zero metallicities i.e. the nearby Universe.

- PISNe are an explanation for some superluminous supernovae.
  - Less energetic PISN may be hidden among other classes.
The neutrino signal from PISNe

- The neutrino signal from PISNe differs from other supernovae.

- We start with two GENEC progenitor models: P150 and P250.
  - at the point where pair creation begins the CO core mass of P150 is 65.7 M⊙, the core mass of P250 is 126.7 M⊙

- The explosion is followed using FLASH 4.3 with Aprox19 and the Helmholtz Equation of State (EOS).

- We then post-process the simulations using NuLib to compute the neutrino luminosity and spectra.

- The emission due to thermal processes is straightforward.

- For the weak emission we adopt two approaches:
  - use the composition of the isotopes in Aprox19 and the Helmholtz EOS
  - identify those zones with T > 3 GK and use the SFHo EOS (which assumes Nuclear Statistical Equilibrium)
Most of the emission is due to thermal processes.

The SFHo EOS predicts much more neutrino emission due to weak processes than the Helmholtz EOS.
The spectrum for P250 is ‘hotter’ than for P150.

There is a ‘bump’ in the spectrum at $E \sim 10$ MeV in $\nu_e$ using the SFHo EOS that is not present in the Helmholtz EOS.

- The origin of the spectral feature is electron capture on $^{69}$Cu.
We compute the neutrino flavor evolution as a function of time and energy for both neutrino mass orderings: NMO and IMO

- The shock affects the neutrinos in the P250 model.
- The flavor evolution for the P150 model is very close to adiabatic.
We put the flavor transformation probabilities and the emission spectra together to get the neutrino spectra at Earth.

At Earth most of the electron type neutrinos and antineutrinos have converted to mu and tau flavors.

The flux of electron antineutrinos is ~10 times larger for the NMO than the IMO.
The Signal At Earth

- The neutrino flux at Earth is run through SNOwGLoBES for a representative set of detectors.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass [kt]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperKamiokande (30% PMT coverage)</td>
<td>Water Cerenkov</td>
<td>50</td>
</tr>
<tr>
<td>HyperKamiokande</td>
<td>Water Cerenkov</td>
<td>374</td>
</tr>
<tr>
<td>DUNE</td>
<td>Liquid Argon</td>
<td>40</td>
</tr>
<tr>
<td>JUNO</td>
<td>Scintillator</td>
<td>20</td>
</tr>
</tbody>
</table>

- SuperK, HyperK and JUNO are mainly sensitive to electron antineutrinos; DUNE is mainly sensitive to electron neutrinos.
- The PISN is placed at the standard distance \( d = 10 \text{ kpc} \).
<table>
<thead>
<tr>
<th>Model</th>
<th>Detector</th>
<th>NMO</th>
<th>IMO</th>
<th>Unoscillated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Helm</td>
<td>SFHo</td>
<td>Helm</td>
</tr>
<tr>
<td>P150</td>
<td>HyperK</td>
<td>1.77</td>
<td>1.78</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>SuperK</td>
<td>0.24</td>
<td>0.24</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>DUNE</td>
<td>0.14</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>JUNO</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>P250</td>
<td>HyperK</td>
<td>52.23</td>
<td>50.08</td>
<td>43.32</td>
</tr>
<tr>
<td></td>
<td>SuperK</td>
<td>6.98</td>
<td>6.69</td>
<td>5.79</td>
</tr>
<tr>
<td></td>
<td>DUNE</td>
<td>2.95</td>
<td>2.78</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>JUNO</td>
<td>3.13</td>
<td>3.00</td>
<td>2.48</td>
</tr>
</tbody>
</table>

- At 10 kpc HyperK can detect neutrinos from both P150 and P250.
  - HyperK could detect neutrinos from a P250 PISN in the LMC.
- SuperK, DUNE and JUNO can only detect neutrinos from P250.
- There is ~5% difference between the two EOS’s for P250.
- There is a ~20% difference between the two mass orderings for P250 model.
The number of events for P250 is $\sim 10^2$ larger than for a Type Ia and $\sim 10^3$ smaller than a core-collapse supernova (CCSN).

The signal extends over $\sim 10$ s and peaks midway through.

- the signal from Type Ia lasts (at most) 5 s
- the signal from a CCSN lasts 10 s but decays exponentially.
Nearby Very Massive Stars

- Estimates of the PISN rate compared to the CCSN rate in the local Universe are uncertain but typically get 1:1000.
  - e.g. Langer et al. A&A 475 L19 (2007) assume stars with ZAMS masses between $140 \, M_\odot < M_{ZAMS} < 250 \, M_\odot$ explode as PISN

- There are many stars within the Milky Way and the Large Magellanic Cloud with masses above $100 \, M_\odot$

- $\eta$ Carinae at a distance of $d = 2.3$ kpc, has a ZAMS mass greater than $100 \, M_\odot$

  Clemental et al., MNRAS 447 2445 (2015)
Fifty-One Ergs 2019
Raleigh NC, USA
May 20 – 24 2019

Stellar Evolution
Transient Surveys
Supernova Remnants
Short GRBs / Kilonovae
Core-Collapse Supernovae
Novae and Thermonuclear Supernovae
Neutrinos, Nucleosynthesis, Dust and Chemical Evolution

Carles Badenes
Marica Branchesi
Matteo Cantiello
Carla Fröhlich
Jim Kneller (Chair)
Davide Lazzati
Raffaella Margutti
Takashi Moriya
Enrico Ramirez-Ruiz
Steve Reynolds
Jeno Sokoloski
Summary

- The neutrino signal from a PISN is well understood and found to be very different from Type Ia and CCSN.

- The emission is dominated by thermal processes (pair annihilation), not weak processes.
  - There is little sensitivity to the composition and EOS.

- A PISN within the Milky Way can be seen with Hyper K.
- DUNE, JUNO and SuperK can observe a large PISN in the Milky Way, HyperK can observe a large PISN in the LMC.
- A large PISN has a 20% difference between neutrino mass orderings, a small PISN has almost none.

Thank you
Using the neutrino emission from the P250 model, the PISN would have to be very close in order to observe a statistically significant signal in IceCube.
As the detector thresholds increase we miss events.

- A threshold is worse for the P150 than the P250 model because the P150 spectrum is cooler.