The Supernova Neutrino Burst

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Overview

- Review of Supernova explosions a.k.a. gravity powered neutrino bombs.
- Selected physical processes which produce neutrinos or have consequences for flavor transformation.
- Issues extracting physics from test supernova neutrino burst signals.
How our Story Begins

As the core contracts isothermally:

\[ \rho_{\text{core}} \leq 4 \times 10^9 \text{ g cm}^{-3} \]

\[ T_{\text{core}} \leq 2.5 \times 10^9 \text{ K} \]

As the core contracts isothermally:

\[ k_B T_{\text{core}} \ll E_F \]
Core Collapse

Collapse releases $0.14 M_\odot$ of gravitational binding energy, 99% of which is trapped as thermal energy in the core. This thermal energy is then re-radiated as neutrinos of all flavors.
What does it take to blow up a star?

- About one Bethe of energy. 
  \[ 1 \text{ B} = 10^{51} \text{ erg} \]

- The initial shock has this much energy, but is stalled by photodissociation.

- The thermal energy trapped in the core is huge! 
  \[ \sim 300B \]
Shock Reheating

- Thermal energy of the PNS emerges as neutrinos of all flavors.

\[ \tau_{\text{diff}} \sim O(1 \text{ ms}) \quad L_\nu \sim 10^{51} - 10^{53} \text{ erg s}^{-1} \]

\[ \sim 10^{58} \nu' s \]

- Neutrino cross sections are just too small to effectively heat the shocked region alone. Large scale convection is necessary to increase the efficiency of the neutrino heating.
Standing Accretion Shock Instability

Neutrino heating and cooling work very differently:

**Heating:** \( H \propto \frac{L_\nu \langle E^2 \rangle}{r^2} \)

**Cooling:**
\[
C \sim 1.4 \times 10^{20} \left( \frac{T}{2 \text{ MeV}} \right)^6 \text{ erg g}^{-1} \text{ s}^{-1}
\]
Neutrino eyes?

Neutrinos can see through to the heart of the explosion.
The sun, in neutrinos (via Super-K)

Evolution of the Neutrino Burst

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

Image courtesy of B. Messer
Progenitor Importance

Compactness

High density EOS

Based on Nakamura, et al. (2015)

Neutrino luminosity ($\bar{\nu}_e$) and Spectrogram Analysis

⇒ SASI-induced modulation is visible in the luminosity.
⇒ Confirmation of Tamborra, Hanka, Mueller, Janka, Raffelt (2013, 2014)) by 3D-GR simulations (Kuroda et al. in prep.)
⇒ Detectable by IceCube and Hyper-K out to Galactic events.

Slide and Data Courtesy of: Kei Kotake, INT Workshop INT-16-61W
Flavor Observations with Supernova Neutrinos
Matter Effects

“Adiabatic”

Matter effects via the MSW mechanism:

Adiabatic Transformation

“Non-Adiabatic”

Shock induced flavor transformation

Turbulence driven flavor decoherence
Evolution of Matter Effects

Schirato and Fuller (2002)
Friedland and Gruzinov, astro-ph/0607244
Collective Neutrino Effects

Two seemingly distinct limits contribute:

Coherent neutrino forward scattering

\[ H_{\nu\nu}, i = \sqrt{2} G_F \sum_j (1 - \cos \theta_{ij}) n_{\nu, j} |\psi_j \rangle \langle \psi_j | \]
\[ -\sqrt{2} G_F \sum_j (1 - \cos \theta_{ij}) n_{\bar{\nu}, j} |\bar{\psi}_j \rangle \langle \bar{\psi}_j | \]

Boltzmann transport of neutrinos

\[ r \gg R_{\nu} \Rightarrow \langle 1 - \cos \theta_{ij} \rangle \propto \left( \frac{R_{\nu}}{r} \right)^2 \]
\[ \langle 1 - \cos \theta_{ik} \rangle \approx 1 \]

\[ \sim 10^{-3} \text{ of all } \nu' \text{s} \]

Spectral Swaps

First reported in:
Duan, Fuller, Carlson, Qian (2006)

J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko,

J. F. Cherry, et al. (2010), 1006.2175.

J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko,
Cooling Phase
Nucleosynthesis

As the PNS cools, its neutrino radiation powers a low density wind of protons and neutrons left over from the explosion.

\[ U_G \approx 0.1 \times \frac{m_p}{n} \sim 100 \text{ MeV} \]

\(~ 10\) CC captures to gain enough energy to be ejected

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

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

Duan, Friedland, McLaughlin & Surman (2011)
Cartoon Supernova Environment

The diagram shows the density in grams per cubic centimeter (g/cm³) as a function of radius in centimeters (cm). The axes are labeled with logarithmic scales, indicating a range from $10^0$ to $10^{12}$ for density and from $10^6$ to $10^{10}$ for radius.

Key features include:
- A v-sphere region indicating a high-density area.
- A collective region with labels for $v_e$, $v_\mu$, $v_\tau$, $\bar{v}_e$, $\bar{v}_\mu$, $\bar{v}_\tau$, and turbulence.
- Front shock and "regular MSW" annotations at the bottom right.

The graph also includes a line indicating the evolution over time, with 1.0 s marked on the right side.
Reconstruction: it is not enough to look at static spectra

- Supernova are dynamical!
- The neutrino emission evolves rapidly with time, so we must establish a time series of different spectra for each model.
- Space snapshots roughly evenly in terms of neutrino fluence and stitch them together with curve fitting for fine time resolution.
Stitch Snapshots Together

Roberts spectra, $\nu_e$ Flux

Roberts spectra, $\bar{\nu}_e$ Flux

Roberts spectra (collective + shocked), $\nu_e$ Flux

Roberts spectra (collective + shocked), $\bar{\nu}_e$ Flux
SNOwGLoBES

• Software tool designed to model neutrino events from core-collapse supernovae in terrestrial neutrino detectors.

• Developed by:

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Single experiments lack discrimination power.

Due primarily to:
Rapid time variability.

Lack of simultaneous $\nu_e/\bar{\nu}_e$ sensitivity.
Exploit detector complementarity

- Need to fit all spectral components to get at neutronization fluence.

\[
\frac{F_{\nu_e}}{F_{\bar{\nu}_e}}, \frac{F_{E_{\nu_e}}}{F_{E_{\nu_x}}}, \frac{E_{\nu_e}, E_{\bar{\nu}_e}, E_{\nu_x}}{E_{\nu_e}, E_{\bar{\nu}_e}, E_{\nu_x}}
\]

- Complicated structure, but initially we simply want the \( \nu_e/\bar{\nu}_e \) fit.

Normal mass hierarchy, \( t = 96 \text{ ms}, d = 10 \text{ kpc}, \) DUNE+Hyper-K.

Cherry, J., Horiuchi, S., in preparation
A segregated parameter space rife with local minima

- Deterministic, steepest descent methods take infeasible lengths of time to finish due to the density of L. M.
- Some non-deterministic minimization methods also fail (MCMC) due to large potential barriers $(\Delta \chi^2)$ between L. M.
- Requires non-deterministic, diffusion-like methods, e.g. genetic algorithms, nested MCMC.

Computationally Intensive!
3 Generations

Normal mass hierarchy,
\( t = 0 \) ms, \( d = 10 \) kpc,
DUNE+Hyper-K.

Cherry, J., Horiuchi, S., in preparation
20 Generations

Normal mass hierarchy, 
$t = 0$ ms, $d = 10$ kpc,
DUNE+Hyper-K.

Cherry, J., Horiuchi, S., in preparation
Success?

Fits to the neutronization burst signal, modeling deleptonization and accretion.

Cherry, J., Horiuchi, S., in preparation
Comparing Mass Hierarchies

Good news: at 10 kpc we are beginning to be able to distinguish EOS’s

Cherry, J., Horiuchi, S., in preparation
Conclusions

- There is a treasure trove of observable physics in the Supernova Neutrino burst signal.
- Take advantage of known physics in constructing statistical tests. In this case we learned that detector complementarity is indispensable.
- Great care must be taken in fitting the emission spectra.
- Fitting the neutrino burst can be done!
Revenge of $\theta_{13}$

$\nu_3$

NMH  IMH

$\nu_e$  $\bar{\nu}_e$

2% Survival probability

Upside: any exotic phenomena from supernova dynamics or collective oscillations come with a large signal enhancement.
Where are the accretion $\nu_e$'s?

$Y_e \sim 0.5$ \quad $\dot{M} \sim 1 M_\odot s^{-1}$

$P_{ee}^{nm} = 0.02$, $P_{ee}^{im} = 0.31$

Energetics of accretion:

$E_{dep} \sim 0.1 \times m_p/m_n \sim 100\,\text{MeV} \sim 10\nu/\text{nucleon}$

$\implies 5\%$ of accretion neutrinos carry lepton number

$\sim 2\%$ of that survives as electron flavor, accretion may end early when the shock is launched.
Normal mass hierarchy,
$t = 48$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
Normal mass hierarchy,
\[ t = 80 \text{ ms}, \quad d = 10 \text{ kpc}, \]
DUNE+Hyper-K.
Normal mass hierarchy, \( t = 104 \) ms, \( d = 10 \) kpc, DUNE+Hyper-K.
Normal mass hierarchy,
$t = 136$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
Reconstruction fraught with systematics!

\[ E_{\text{excess}} = 2.2 \times 10^{52} \pm 0.3 \times 10^{52} \text{ erg} \]
The SASI modulation appears more clearly in 3D-GR model with best EOS available!

The modulation freq. from the SASI and rapid rotation: in the range (100 – 200 Hz). So... how to tell the difference?