Probing neutrino properties with supernovae

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Outline

- Neutrino astronomy: detection of SN neutrinos
- What can we learn on neutrinos?
  - Neutrino mass
  - Oscillation parameters
  - Exotica: non-standard interactions, …
Neutrino astronomy
Detection methods

- **Capture on nuclei:**
  - e-flavor exclusive
  - Energy sensitivity

  $\nu_e + \frac{N}{K} A \rightarrow \frac{N}{K+1} X^* + e^-;$

  $\bar{\nu}_e + \frac{N}{K} A \rightarrow \frac{N}{K-1} Y^* + e^+$

- **Scattering**
  - All flavors

  $\nu + \frac{N}{K} A \rightarrow \nu + \frac{N}{K} A;$

  $\nu + \frac{N}{K} A \rightarrow \nu + \frac{N}{M} B + \frac{N}{K-M} C ;$

  $\nu + e^- \rightarrow \nu + e^-$

- **Choice:** cost + practicality + high cross section + low threshold
Neutrino telescopes

Numbers of CC events (D=10 kpc)

What can we learn?

Neutrino mass

Flavor structure
Neutrino mass: time-of-flight tests

- Energy-arrival time correlation: the colder the slower
  - Look for features in time distribution
  - Need: timing, energy resolution, low energy threshold

\[ \Delta t = 0.0051 \text{ s} \left( \frac{D}{10 \text{ kpc}} \right) \left( \frac{10 \text{ MeV}}{E} \right)^2 \left( \frac{m_{\nu}}{\text{eV}} \right)^2 \]

- Future galactic supernova: \( m_{\nu} \sim 1-3 \text{ eV} \) (Totani, PRL80, 1998, Beacom, Boyd & Mezzacappa, PRD63, 2001, Nardi & Zuluaga, PRD69, 2004)
  (Tritium \( \beta \)-decay limit: 2.8 eV (95% C.L., Mainz))
Neutrino flavor oscillations

- Oscillations established from solar and atmospheric neutrinos

- *will* affect observed SN signal (spectra), must be taken into account for data interpretation
The unknowns: $\theta_{13}$ and mass hierarchy

$(\sin^2 2 \theta_{13} < 0.15, \text{CHOOZ})$
Why interesting?

- $\theta_{13}$ key to study violation of CP symmetry in lepton sector
- Impact on direct searches of neutrino mass
- Important element of the puzzle for physics beyond the Standard Model (Grand Unification, Supersymmetry,...)
$\theta_{13}$ as a conversion "switch"

adiabatic case: $\sin^2 \theta_{13} > 10^{-4}$

High density, matter eigenstates

MSW resonance

Low density, vacuum eigenstates

Observed $\bar{\nu}_e$ have hard spectrum!
Non-adiabatic case: $\sin^2 \theta_{13} < 10^{-5}$

- High density, matter eigenstates
- Low density, vacuum eigenstates

Hard

Soft

Hard

Soft

MSW resonance

Observed $\bar{\nu}_e$ have composite spectrum!
The transition probability

$$P_H \propto \text{Exp} \left[ -\text{const} \cdot \sin^2 \theta_{13} \left( \frac{\Delta m^2_{31}}{E} \right)^{2/3} \right]$$

C.L. & A.Y. Smirnov, JCAP 2003
SN-model-independent test: oscillations in the Earth

Adiabatic: $P_H \sim 0$

Non-adiabatic: $P_H \sim 1$

- Unambiguous: no confusion with astrophysics
### combinations of results

<table>
<thead>
<tr>
<th>$\bar{\nu}_e$</th>
<th>$\nu_e$</th>
<th>Conclusion</th>
</tr>
</thead>
</table>
| **YES**       | **YES** | $P_H \sim 1$
|               |         | Hierarchy unknown, different fluxes |
| **YES**       | **NO**  | $P_H \sim 0$
|               |         | Normal hierarchy, different fluxes |
| **NO**        | **YES** | $P_H \sim 0$, inverted hierarchy
|               |         | OR $P_H \sim 1$, similar fluxes |
| **NO**        | **NO**  | Similar fluxes |

Non-standard interactions (NSI)
New neutrino-matter interactions

- Possible in theories beyond the Standard Model of particle physics

- Neutral current interactions of neutrinos are poorly constrained in the \( e^- \tau \) sector:
  \[ G_e^\tau \leq G_F \]
  (Davidson et al., JHEP0303, 2003, Berezhiani & Rossi, PLB535, 2002)
Example of large effect with tiny NSI: \( \theta_{13} \) – NSI degeneracy

- Assume small flavor changing NSI in the Hamiltonian:

\[
H_m = \frac{\sqrt{2} G_F N_e}{2} \begin{pmatrix} 1 & 2\epsilon \\ 2\epsilon & -1 \end{pmatrix} \\
\equiv \frac{\sqrt{2} G_F N_e}{2} \xi \begin{pmatrix} \cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha \end{pmatrix}
\]
Transition probability

Even a small $\alpha$ can cancel a small $\theta_{13}$!
Large difference in the probability $P_H$

$$P_H \propto \exp\left[ -\text{const} \cdot \sin^2 (\theta_{13} - \alpha) \left( \frac{\Delta m^2_{31}}{E} \right)^{2/3} \right]$$

NSI effects on neutrino production/transport?
Summary

- Testing neutrino properties with a galactic supernova and existing detectors is feasible

- *Unique* conditions of matter density allow unique tests of oscillation parameters

- Degeneracies with astrophysical effects can be resolved