Abstract

A nearby supernova will carry an unprecedented wealth of information about astrophysics, nuclear physics, and particle physics. Because supernova are fundamentally neutrino driven phenomenon, our knowledge about neutrinos – particles that remain quite elusive – will increase dramatically with such a detection. One of the biggest open questions in particle physics is related to the masses of neutrinos. Here we show how a galactic supernova provides information about the masses of each of the three mass eigenstates *individually*, at some precision, and is well probed at JUNO. This information comes from several effects including time delay and the physics within the supernova. The time delay feature is strongest during a sharp change in the flux such as the neutronization burst; additional information may also come from a QCD phase transition in the supernova or if the supernova forms a black hole. We consider both standard cases as dictated by local oscillation experiments as well as new physics motivated scenarios where neutrino masses may differ across the galaxy.

Individual Neutrino Masses From a Supernova

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BNL HET Lunch Discussion

January 10, 2025

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Outline

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1. Introduction
2. Possibility of spatially evolving neutrino masses
3. Neutrinos from a supernova
4. Time delay features
5. Detection
6. Sensitivities
7. Conclusions

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Neutrino Unknowns

- Neutrino oscillations add 7+ parameters to the SM
- Oscillations probe 6: 4 in the mixing matrix, and 2 mass-squared differences
- Absolute neutrino mass scale needs other data
  - Cosmology looks promising: $\sum_{i=1}^{3} m_i$ too good?
  - KATRIN is less sensitive: $\sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$
  - Neutrinoless double beta decay: model dependent, generally less sensitive than cosmology
  - Supernova?

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Possibility of spatially evolving neutrino masses

- Cosmology is pushing down on neutrino masses below the oscillation limit
- Cosmological constraints come dominantly from $10 \lesssim z \lesssim 100$
- Neutrino masses may vary depending on the DM distribution

H. Davoudiasl, G. Mohlabeng, M. Sullivan 1803.00012

S.-F. Ge, H. Murayama 1904.02518

$\vdots$

- Neutrinos could be massless in the vacuum of space $\Rightarrow \sum_{i=1}^{3} m_i = 0$
- Within solar system reproduce oscillation measurements
- Masses may be different through the galaxy

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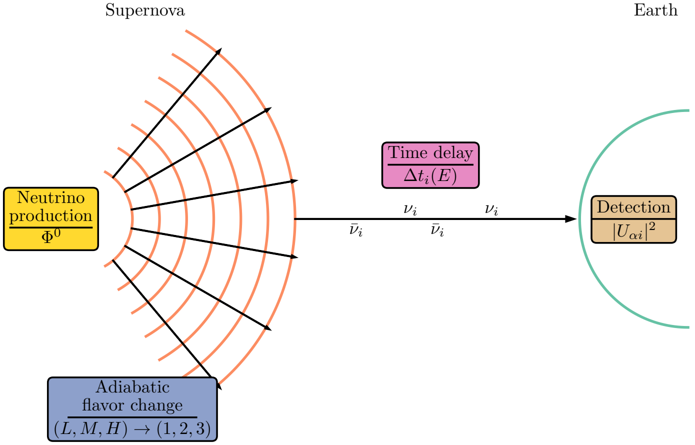
Supernova Neutrinos

- SN1987A confirmed that $\sim 99\%$ of gravitational energy of large stars $\to \nu$'s
- CCSN produce $\sim 10^{58}$ neutrinos with $E_\nu \sim 10$s MeV
- We believe that stars $8 \lesssim M/M_\odot \lesssim 125$ form CCSN
- Larger progenitors form BHs (?) while smaller form NSs
- Neutrino spectrum generally seems to follow a pinched Fermi-Dirac distribution:

$$\phi_{\nu_i}(E_{\nu_i}, t) = \xi_{\nu_i}(t) \left(\frac{E_{\nu_i}}{\langle E_{\nu_i}(t) \rangle} \right)^{\alpha_{\nu_i}(t)} \exp\left(-\frac{(\alpha_{\nu_i}(t)+1)E_{\nu_i}}{\langle E_{\nu_i}(t) \rangle} \right)$$

- Mean energy and pinching parameter time dependence fit to simulations

Schematic



Supernova
Earth
Neutrino production
Φ^0
Time delay
$\Delta t_i(E)$
ν_i
ν_i
$\bar{\nu}_i$
$\bar{\nu}_i$
Detection
$|U_{\alpha i}|^2$
Adiabatic flavor change
$(L, M, H) \to (1, 2, 3)$

Flavor Mixing

NO:

$$\Phi_{\nu_e}(E,t) = s_{13}^2\Phi^0_{\nu_e}(E,t) + c_{13}^2\Phi^0_{\nu_x}(E,t)$$
$$\Phi_{\bar\nu_e}(E,t) = c_{12}^2c_{13}^2\Phi^0_{\bar\nu_e}(E,t) + (1-c_{12}^2c_{13}^2)\Phi^0_{\bar\nu_x}(E,t)$$
$$2\Phi_{\nu_x}(E,t) = c_{13}^2\Phi^0_{\nu_e}(E,t) + (1+s_{13}^2)\Phi^0_{\nu_x}(E,t)$$
$$2\Phi_{\bar\nu_x}(E,t) = (1-c_{12}^2c_{13}^2)\Phi^0_{\bar\nu_e}(E,t) + (1+c_{12}^2c_{13}^2)\Phi^0_{\bar\nu_x}(E,t)$$

IO:

$$\Phi_{\nu_e}(E,t) = s_{12}^2c_{13}^2\Phi^0_{\nu_e}(E,t) + (1-s_{12}^2c_{13}^2)\Phi^0_{\nu_x}(E,t)$$
$$\Phi_{\bar\nu_e}(E,t) = s_{13}^2\Phi^0_{\bar\nu_e}(E,t) + c_{13}^2\Phi^0_{\bar\nu_x}(E,t)$$
$$2\Phi_{\nu_x}(E,t) = (1-s_{12}^2c_{13}^2)\Phi^0_{\nu_e}(E,t) + (1+s_{12}^2c_{13}^2)\Phi^0_{\nu_x}(E,t)$$
$$2\Phi_{\bar\nu_x}(E,t) = (1-s_{13}^2)\Phi^0_{\bar\nu_e}(E,t) + (1+s_{13}^2)\Phi^0_{\bar\nu_x}(E,t)$$

A. Dighe, A. Smirnov hep-ph/9907423

Flavor Mixing

NO:

$$\begin{aligned}
\Phi_{\nu_e}(E,t) &= |U_{e3}|^2\Phi^0_{\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e2}|^2)\Phi^0_{\nu_x}(E,t)\\
\Phi_{\bar\nu_e}(E,t) &= |U_{e1}|^2\Phi^0_{\bar\nu_e}(E,t) + (|U_{e2}|^2 + |U_{e3}|^2)\Phi^0_{\bar\nu_x}(E,t)\\
2\Phi_{\nu_x}(E,t) &= (|U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\nu_e}(E,t) + (|U_{\mu1}|^2 + |U_{\tau1}|^2 + |U_{\mu2}|^2 + |U_{\tau2}|^2)\Phi^0_{\nu_x}(E,t)\\
2\Phi_{\bar\nu_x}(E,t) &= (|U_{\mu1}|^2 + |U_{\tau1}|^2)\Phi^0_{\bar\nu_e}(E,t) + (|U_{\mu2}|^2 + |U_{\tau2}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\bar\nu_x}(E,t)
\end{aligned}$$

IO:

$$\begin{aligned}
\Phi_{\nu_e}(E,t) &= |U_{e2}|^2\Phi^0_{\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e3}|^2)\Phi^0_{\nu_x}(E,t)\\
\Phi_{\bar\nu_e}(E,t) &= |U_{e3}|^2\Phi^0_{\bar\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e2}|^2)\Phi^0_{\bar\nu_x}(E,t)\\
2\Phi_{\nu_x}(E,t) &= (|U_{\mu2}|^2 + |U_{\tau2}|^2)\Phi^0_{\nu_e}(E,t) + (|U_{\mu1}|^2 + |U_{\tau1}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\nu_x}(E,t)\\
2\Phi_{\bar\nu_x}(E,t) &= (|U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\bar\nu_e}(E,t) + (|U_{\mu1}|^2 + |U_{\tau1}|^2 + |U_{\mu2}|^2 + |U_{\tau2}|^2)\Phi^0_{\bar\nu_x}(E,t)
\end{aligned}$$

Mass States

We define the three mass states by the electron neutrino fraction:

$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$

$$0.65 > 0.33 > 0.02$$

New definition:

$$m_H > m_M > m_L$$

NO: $L = 1$, $M = 2$, $H = 3$
IO: $L = 3$, $M = 1$, $H = 2$

Flavor Mixing

Hierarchy independent:

$$\begin{aligned}
\Phi_{\nu_e}(E,t) &= |U_{eH}|^2\Phi^0_{\nu_e}(E,t) + (|U_{eL}|^2 + |U_{eM}|^2)\Phi^0_{\nu_x}(E,t)\\
\Phi_{\bar\nu_e}(E,t) &= |U_{eL}|^2\Phi^0_{\bar\nu_e}(E,t) + (|U_{eM}|^2 + |U_{eH}|^2)\Phi^0_{\bar\nu_x}(E,t)\\
2\Phi_{\nu_x}(E,t) &= (|U_{\mu H}|^2 + |U_{\tau H}|^2)\Phi^0_{\nu_e}(E,t) + (|U_{\mu L}|^2 + |U_{\tau L}|^2 + |U_{\mu M}|^2 + |U_{\tau M}|^2)\Phi^0_{\nu_x}(E,t)\\
2\Phi_{\bar\nu_x}(E,t) &= (|U_{\mu L}|^2 + |U_{\tau L}|^2)\Phi^0_{\bar\nu_e}(E,t) + (|U_{\mu M}|^2 + |U_{\tau M}|^2 + |U_{\mu H}|^2 + |U_{\tau H}|^2)\Phi^0_{\bar\nu_x}(E,t)
\end{aligned}$$

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All of the above assumes neutrinos are produced well above both resonances

Neutrinos decouple at

$$\rho \sim 10^{11} - 10^{12}\ \text{g/cc}$$

Higher resonance is at

$$\rho_{\text{res}} \simeq 10^6\ \text{g/cc} \times \left(\frac{\Delta m^2}{1\ \text{eV}^2}\right)\left(\frac{10\ \text{MeV}}{E}\right)\left(\frac{0.5}{Y_e}\right)\cos 2\theta$$

So neutrinos are produced well above upper resonance for any relevant masses

Jump probabilities

The above discussion assumes neutrinos adiabatically transform from production to the surface

In reality there is a chance of jumping from one eigenvalue to another $\Rightarrow$ vastly complicates the above expressions

Simple picture:

$$P_j = \exp\left(-\frac{\pi}{2}\gamma\right)$$

where the adiabaticity parameter is

$$\gamma = \frac{\Delta m^2}{2E}\frac{s_2^2}{c_2}\frac{1}{\dot{n}_e/n_e|_{\rm res}}$$

For larger angles need to use

$$P_j = \frac{\exp\left(-\frac{\pi}{2}\gamma f\right) - \exp\left(-\frac{\pi}{2}\gamma\frac{f}{s^2}\right)}{1-\exp\left(-\frac{\pi}{2}\gamma\frac{f}{s^2}\right)}$$

Jump probabilities

where s is $\sin\theta$ and

$$f = {}_2F_1\left(1 - \frac{1}{2n}, \frac{n-1}{2n}, 2, -t_2^2\right)$$

which $\to 1$ as $s \to 0$ and $\rho \propto r^n$

A number of additional caveats here as well: multiple jump, off resonance jumps, nearby resonances, ...

Is this small enough?

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For regular Δm^2's, yes

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For arbitrary Δm^2's: probably

Supernova neutrinos

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There are many simulations
Focus on features that are largely simulation independent
Use a 27 $M_\odot$ SN at 10 kpc

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Time delay features

Massive neutrinos lead to time delay relative to light:

$$\Delta t_i(E) = t_{\nu_i} - t_c = D\left(\frac{1}{v_i} - 1\right) \simeq \frac{D}{2}\left(\frac{m_i}{E}\right)^2$$

Modify flavor transformations:

$$|U_{\alpha i}|^2 \Phi^0_{\nu_\beta}(E,t) \to |U_{\alpha i}|^2 \Phi^0_{\nu_\beta}(E, t - \Delta t_i(E))$$

Need a sharp effect in the signal

Time delay features

1. Neutronization burst
   - Has been in all simulations since the early days
   - Lasts ~ 25 ms
   - Highest L_ν, but not the dominant source of neutrinos
   - Turns on/off fairly sharply
   - Depends on true oscillation parameters
2. QCD (quark/hadron) phase transition
   - A FOPT from nuclear to quark matter
   - May restart stalled shocks
   - May produce very sharp enhancement in the neutrino flux
   - Unclear if it happens
3. BH formation
   - Some CCSN form BHs
   - Probably $\mathcal{O}(10\%)$
   - Leads to a sharp truncation of the signal
4. Other things like standing accretion shock instability (SASI)

Detection

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Many current and upcoming detectors that are sensitive to SN neutrinos
Focus on JUNO due to low thresholds, good timing, large volume, and online in ~ 1 year
Cross sections:

- IBD: primary, but threshold $E_\nu > 1.8$ MeV
- eES
- ^{12}C
- ^{13}C
- NC
- pES: uncertain cross section, plus quenching effects, not included

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Benchmarks for Sensitivities

- Oligations:

$$|\Delta m^2_{31}| = 2.5\times10^{-3}\ \text{eV}^2\,,\quad \Delta m^2_{21} = +7.4\times10^{-5}\ \text{eV}^2$$

  Two benchmarks: lightest allowed in NO, IO
- Planck and oscillations only (NO, IO) as other cosmological data is very tight:

$$\sum_i m_i < 0.24\ \text{eV}$$

- KATRIN and oscillations only:

$$m_{\beta\beta} < 0.45\ \text{eV}$$

- High mass scenario (new physics):

$$m_1 = 0.2\ \text{eV}\,,\quad m_2 = 1\ \text{eV}\,,\quad m_3 = 1.8\ \text{eV}$$

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...to conclusions

Caveats

- If DM provides mass to neutrinos, they evolve during propagation
- Terrestrial matter effect may further modify this picture; possible to account for
- Assumes we know the mixing parameters and they are unchanged
  - Can you measure the masses *and* mixing parameters?

Conclusions

- Galactic supernova can probe the absolute neutrino mass scale
- Likely only possible if masses are anomalously large, or cosmology is more complicated
- Multiple possible timing features to leverage
- Combinations of features and of detectors (e.g. DUNE) will improve the numerical results
- Individual neutrino masses can be reconstructed