Neutrinos from Type Ia Supernovae
DDT vs. GCD

Warren Wright
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Motivation
Method
Production
Oscillation
Detection
Conclusion

Collaborators:
- Gautam Nagaraj
- James Kneller
- Kate Scholberg
- Ivo Seitenzahl

Thanks to:
- Evan O'Connor

Papers:
- PRD 94, 025026
- In preparation
Conference focus:

Supernova neutrinos ... carry unique flavor information ... crucial for understanding:

- neutrino oscillations
- explosion mechanism
- Nucleosynthesis
Motivation

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- Supernova neutrinos carry unique flavor information...
  crucial for understanding:
  - neutrino oscillations
  - explosion mechanism
  - Nucleosynthesis

Why Type Ia?

SNela useful for:
- Standard candles
- Universe expansion measurements

We don't know the:
- progenitors
- explosion mechanism

The Galactic SN Ia rate as given by Adams et al.
- $1.4^{+1.4}_{-0.8}$ per century
- and is 30% of the total supernovae rate


SNela neutrinos could give explosion mechanism
Motivation

Why is determining the explosion mechanism hard?

- Pure Detonation: Too little intermediate mass elements
- Pure Deflagration: Hard to explode

Available Explosion Mechanisms

- Delayed-Detonation Transition model (DDT)
- Gravitationally Confined Detonation model (GCD)
- Pure Turbulent Deflagration model (PTD)
- Pulsational (Reverse) Detonation (PD/PRD)
- ...
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INT-16-61W: Flavor Observations with Supernova Neutrinos
Method: Production

Start with

Carbon Oxygen White Dwarf

\[ M = 1.4 \, M_{\text{Sun}} \]
\[ \rho_{\text{center}} = 2.9 \times 10^9 \, \text{g/cm}^3 \]
\[ r = 2 \times 10^8 \, \text{cm} \]
\[ T = 5 \times 10^5 \, \text{K} \]
\[ Y_e = 0.498886 \]

Seed Deflagration

DDT: 100
GCD: 1

Hydro Evolution

Thermonuclear SN code: LEAFS

Detonation Transition

Different for DDT and GCD

NuLib

Seitenzahl et al.
MNRAS.429.1156S (2013)
Production: DDT

Image Credit: http://www.flash.uchicago.edu/site/gallery/stills/Supernovae/DDT/ASCFlashCenter_DDT_8km63_4panel_FLAMEDENS.jpg
Neutrino Production

Assumptions:
- Only cells in NSE (T9>3) produce neutrinos.
- Neutrinos are only produced by:
  - electron or positron capture on nuclei or nucleons (weak)
  - electron positron annihilation (thermal)

NuLib:
- Postprocess simulation to get emissivity spectra.
  - Weak: Effective neutrino spectra with average energy chosen to match tabulated rates
  - Thermal: From Burrows, Reddy and Thompson

Sullivan et al. (1508.07348)
Burrows et al. (astro-ph/0404432)
Production: DDT

N100ν: Total Neutrino Luminosity

Phys. Rev. D 94, 025026
Production: DDT Spectrum

N100ν Total Neutrino Luminosity

$\nu_e$, $\nu_\mu$, $\nu_\tau$, $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$

$E_\nu$ (MeV)

$\nu_\tau$

$\bar{\nu}_\tau$

$\bar{\nu}_e$

$\nu_\mu$

$\bar{\nu}_\mu$

$\nu_e$

erg/s

$10^{48}$ $10^{46}$ $10^{44}$ $10^{42}$ $10^{40}$ $10^{38}$

$0.05s$, $0.3s$, $0.55s$, $0.8s$, $1s$, $1.15s$, $1.3s$, $1.5s$
Production: DDT Spectrum

N100\(\gamma\) at 1.5s: \(\gamma_e\) luminosity from electron capture on nuclei for dominant nuclear species

\[ \text{erg/s} \]

Abs(Sum(Colors)−Gray)/Gray

error

\[ E_\gamma \text{ (MeV)} \]

Ni 51 to 63
Fe 47 to 59
Co 49 to 61
Cu 53 to 65
All Species
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INT-16-61W: Flavor Observations with Supernova Neutrinos
Oscillated Flux

Total Oscillated Neutrino Flux @10kpc with NMO

- $N_\nu$ (cm$^{-2}$ s$^{-1}$ MeV$^{-1}$)
- $E_\nu$ (MeV)

- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

Deflagration Peak
Detonation Peak

- just MSW
- non-adiabatic
- density discontinuities
Main Neutrino Oscillation Effects:
1) Introduce line-of-sight dependence
2) Generally oscillate $\nu_e$ into $\nu_\mu$ & $\nu_\tau$
3) Mix spectral features
4) Non-Adiabatic
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Interaction Events

Using SNOwGLoBES Energy Integrated

GCD Hyper-K
GCD DUNE
DDT Hyper-K
DDT DUNE

1=10kpc
1=1kpc
1=100pc

Shadows are oscillation effects
Error bars are 3σ
Line-of-sight variation

Neutrinos from SNeIa By Warren Wright @ University of Washington, August 15-19, 2016
The Institute for Nuclear Theory: Flavor Observations with Supernova Neutrinos (INT-16-61W)
Interaction Events

The graph shows interaction events over time (t in seconds) for different distances (1 km, 1 kpc, 10 kpc, 100 pc). The graphs are labeled as NMO and IMO, and the lines are color-coded as follows:

- Blue: GCD Hyper-K
- Red: GCD DUNE
- Purple: DDT Hyper-K
- Green: DDT DUNE

Error bars are 3σ and line-of-sight variation is indicated for each data point. Shadows represent oscillation effects.
Detection Summary

DDT vs. GCD:
1) Geometry  ❌
2) Luminosity  ✔
3) Timing  ✔

SNeIa needs D < 1kpc for Hyper-K to classify a SN as GCD or DDT
Conclusion

- Type Ia Supernova are:
  - Universe defining
  - “Frequent” 30%
  - Have an unknown explosion mechanism
- SNeIa neutrinos can help determine the explosion mechanism.
- Discrimination by:
  - Total event rate: SNeIa within 1kpc @ Hyper-K
  - Spectral features: need next^2 gen detectors

Thank you
Result Summary

SNeIa needs D < 1kpc for Hyper-K to classify a SN as GCD or DDT
Method: Production

Start with:

2 Carbon Oxygen White Dwarfs:
• Both with same mass, central density, radius, temperature, composition and electron fraction.
• Both start with seeded deflagration sparks: DDT: 100 & GCD: 1.
• Both hydrodynamically evolved with the thermonuclear supernova code LEAFS, on a $512^3$ spatial grid.

\[
M = 1.4 \, M_{\text{Sun}} \\
\rho_{\text{center}} = 2.9 \times 10^9 \, \text{g/cm}^3 \\
r = 2 \times 10^8 \, \text{cm} \\
T = 5 \times 10^5 \, \text{K} \\
Y_e = 0.498886
\]

Seitenzahl et al.
MNRAS.429.1156S (2013)

Different transition to detonation
Production: GCD Spectrum

GCD Total Neutrino Luminosity

- \( \nu_e \)
- \( \nu_\mu \)
- \( \nu_\tau \)
- \( \bar{\nu}_e \)
- \( \bar{\nu}_\mu \)
- \( \bar{\nu}_\tau \)

\( E_\nu \) (MeV)

\( \text{erg/s} \)

- 2.5s
- 2.7s
- 2.9s
- 3.1s
- 3.3s
| Model | Deflagration | | Detonation | | | Total |
|-------|--------------|----------------|--------------|----------------|----------------|
|       | time  | erg/s  | time  | erg/s  | time  | erg/s  | erg   |
| DDT   | 0.53 s | $5.1 \times 10^{49}$ | 1.32 s | $2.3 \times 10^{47}$ | | 2.0 $\times 10^{49}$ |
| GCD   | 0.45 s | $2.3 \times 10^{48}$ | 2.82 s | $1.8 \times 10^{48}$ | | 1.2 $\times 10^{48}$ |

**DDT vs. GCD:**
1) Geometry
2) Luminosity
3) Timing
Method: Oscillation

- Using hydro simulation data, retrieve density and electron fraction trajectories, (8 for DDT and 10 for GCD).
- Insert discontinuities at deflagration and detonation flame edges.
- Numerically calculate oscillation probabilities by solving the Schrödinger equation without assuming adiabatic evolution.
Oscillation

GCD Density profile raw data for various $(\theta, \phi)$ directions

$(\theta, \phi) = (45^\circ, 0^\circ)$

$(\theta, \phi) = (-135^\circ, 180^\circ)$

$\rho \text{ (g/cm}^3)\text{)}$

$10^9$

$10^7$

$10^5$

$10^3$

$10^1$

$10^{-1}$

$10^{-3}$

$10^{-5}$

$10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $r \text{ (cm)}$

$10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $r \text{ (cm)}$
Oscillation Phenomenology

- $P_{33}^{(m)}(r=\text{edge}, \theta=45^\circ, \phi=54.7^\circ, t=0.05\text{s})$
- $P_{33}^{(m)}(r=\text{edge}, \theta=-135^\circ, \phi=54.7^\circ, t=1.3\text{s})$
- $P_{22}^{(m)}(r=\text{edge}, \theta=45^\circ, \phi=54.7^\circ, t=1.5\text{s})$

$E_\nu (\text{MeV})$
Oscillation Phenomenology

\( \rho \text{ (g/cm}^3\text{)} \)

\( P_{33}^{(m)}(r,E_\nu) \text{ NMO} \)

\( P_{33}^{(m)}(r=\text{edge},E_\nu) \text{ NMO} \)

\( (\theta,\phi) = (-135^\circ, 54.7^\circ) \)

N100v@1.3s
Oscillation Phenomenology

\( (\theta, \phi) = (45^\circ, 54.7^\circ) \)

\( N100v@1.5s \)

Neutrinos from SNeIa

By Warren Wright

@ University of Washington, August 15-19, 2016

The Institute for Nuclear Theory: Flavor Observations with Supernova Neutrinos (INT-16-61W)
Oscillation Phenomenology

\(\rho (\text{g/cm}^3)\)

\((\theta, \phi) = (45^\circ, 54.7^\circ)\)

N100v@1.5s

\(P_{22}^{(m)}(r, E_\nu)\) NMO

\(P_{22}^{(m)}(r=\text{edge}, E_\nu)\) NMO
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Detection

- Fold oscillation probabilities with luminosities to get the time, line-of-sight, energy, mass ordering, and flavor dependent neutrino flux on Earth.

- Use SNOwGLOBES to calculate the event rates in JUNO, Super-K, Hyper-K, and DUNE.

- Use the flux and calculate the low-energy event rate in IceCube and compare to background.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-Kamiokande like: 30%</td>
<td>Water Cherenkov</td>
<td>50</td>
</tr>
<tr>
<td>Hyper-Kamiokande like</td>
<td>Water Cherenkov</td>
<td>560</td>
</tr>
<tr>
<td>DUNE like detector</td>
<td>Liquid Ar</td>
<td>40</td>
</tr>
<tr>
<td>JUNO like detector</td>
<td>Scintillator</td>
<td>20</td>
</tr>
<tr>
<td>IceCube</td>
<td>Water Cherenkov</td>
<td>3500*</td>
</tr>
</tbody>
</table>
## Interaction Events

<table>
<thead>
<tr>
<th>Detector</th>
<th>NMO</th>
<th>IMO</th>
<th>Unoscillated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K</td>
<td>0.034</td>
<td>0.076</td>
<td>0.154</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>0.378</td>
<td>0.868</td>
<td>1.725</td>
</tr>
<tr>
<td>DUNE</td>
<td>0.025</td>
<td>0.066</td>
<td>0.138</td>
</tr>
<tr>
<td>JUNO</td>
<td>0.014</td>
<td>0.032</td>
<td>0.063</td>
</tr>
<tr>
<td>IceCube*</td>
<td>0.286</td>
<td>0.660</td>
<td>1.320</td>
</tr>
</tbody>
</table>

### DDT

<table>
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<th>IMO</th>
<th>Unoscillated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K</td>
<td>0.002</td>
<td>0.004</td>
<td>0.009</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>0.027</td>
<td>0.048</td>
<td>0.100</td>
</tr>
<tr>
<td>DUNE</td>
<td>0.002</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>JUNO</td>
<td>0.001</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>IceCube*</td>
<td>0.021</td>
<td>0.033</td>
<td>0.069</td>
</tr>
</tbody>
</table>

* Note that the numbers of interactions quoted for IceCube are after background subtraction
Interaction Events

- Deflagration Peak
- Detonation Peak

$N_\nu / \text{MeV/s}$ vs. $E_\nu \ (\text{MeV})$

Graphs showing interaction events with different scales and peak categories.
Detector Events

N100v Events at IceCube (IBD & $\nu e^-$ per 145ms)

- NMO
  - 100pc
  - 75pc
  - 50pc

- IMO
  - 25pc
  - 10pc
  - 6pc

Background

$10^5$ events per 145ms

$2.115 - 2.11$ range

$t (s)$ range from $0.2$ to $1.4$