Supernova Neutrinos

Sovan Chakraborty

ICTS, Numerical Relativity, June, 2013
TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS

Production (flavor)
- Simulations of SN
- Initial energy spectra
- Initial time spectra

Propagation (mass, mixing)
- Matter effects: shock wave, turbulences, Earth crossing, ...
- Dense neutrino bkg
- New interactions
- Decays
- ........

Detection (flavor)
- CC & NC interactions
- Different detectors
- Energy spectra
- Angular spectra
- Time spectra

Theory

Phenomenology
Supernova one of the most energetic events in nature.

Terminal phase of a massive star ($M > 8 \sim 10 ~ M_\odot$)

Collapses and ejects the outer mantle in a shock wave driven explosion.

**ENERGY SCALES:** $\sim 10^{53}$ erg : 99% energy is emitted by Neutrinos (Energy $\sim 10$ MeV).

**TIME SCALE:** The duration of the burst lasts $\sim 10$ s.
Neutrino Emission Phases

Neutronization burst
- Shock breakout
- De-leptonization of outer core layers
- Duration $\sim 25 \text{ ms}$

Accretion
- powered by infalling matter
- Stalled shock

Cooling
- Cooling by $\nu$ diffusion

Accretion: $\sim 0.5 \text{ s}$ ; Cooling: $\sim 10 \text{ s}$

[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 $M_{\text{sun}}$ progenitor mass]
Sanduleak –69 202

Supernova 1987A
23 February 1987
What could we see “tomorrow”? SN 20XXA!
Large Detectors for Supernova Neutrinos

In brackets events for a “fiducial SN” at distance 10 kpc:

- MiniBooNE (200)
- LVD (400)
- Borexino (80)
- Super-Kamiokande ($10^4$)
- KamLAND (330)
- IceCube ($10^6$)
Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model.

Accretion phase

Cooling phase
Possible to reconstruct the SN $\nu$ lightcurve with current detectors. Discrimination btw different simulations.
Next-generation large volume detectors might open a new era in SN neutrino detection:

- 0.4 Mton WATER Cherenkov detectors
- 100 kton Liquid Ar TPC
- 50 kton scintillator

See LAGUNA Collaboration, “Large underground, liquid based detectors for astro-particle physics in Europe: Scientific case and prospects,”
Next-generation LAGUNA large-volume detectors might open a new era in SN neutrino detection:

- **0.4 Mton WATER**
- Cherenkov detectors

### Interactions

<table>
<thead>
<tr>
<th>Interaction</th>
<th># of events @ 10 kpc</th>
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<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_e + O \rightarrow X + e^\pm$</td>
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</tr>
<tr>
<td>$\nu + e^- \rightarrow \nu + e^-$</td>
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Golden channel:

Inverse beta decay (IBD) of $\bar{\nu}_e$
• LAGUNA Detectors for Supernova Neutrinos

Next-generation LAGUNA large-volume detectors might open a new era in SN neutrino detection:

• 50 kton scintillator

**Interactions**

\[
\begin{align*}
\bar{\nu}_e + p & \rightarrow n + e^+ \\
\nu + p & \rightarrow \nu + p \\
\bar{\nu}_e + ^{12}C & \rightarrow e^+ + ^{12}B \\
\nu_e + ^{12}C & \rightarrow e + ^{12}N \\
\nu + ^{12}C & \rightarrow \nu + ^{12}C^* \\
\nu + e^- & \rightarrow \nu + e^-
\end{align*}
\]

**# of events at 10 kpc**

\begin{align*}
10^4 & \quad \bar{\nu}_e + p \rightarrow e^+ + n \\
10^3 & \quad \nu + p \rightarrow \nu + p \\
400 & \quad \bar{\nu}_e + ^{12}C \rightarrow e^+ + ^{12}B \\
500 & \quad \nu_e + ^{12}C \rightarrow e + ^{12}N \\
3 \times 10^3 & \quad \nu + ^{12}C \rightarrow \nu + ^{12}C^* \\
600 & \quad \nu + e^- \rightarrow \nu + e^-
\end{align*}

Golden channel:

Inverse beta decay (IBD) of $\nu_e$

Better energy resolution than a water Cherenkov
LAGUNA Detectors for Supernova Neutrinos

Next-generation LAGUNA large-volume detectors might open a new era in SN neutrino detection:

- **100 kton Liquid Ar TPC**

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Golden channel:

$\nu_e$ Ar CC

Complementary to previous techniques
The flavor evolution in matter is described by the non-linear MSW equations:

\[ i \frac{d}{dx} \psi_\nu = \left( H_{\text{vac}} + H_e + H_{\nu\nu} \right) \psi_\nu \]

In the standard 3\(\nu\) framework

- **Kinematical mass-mixing term**
  \[ H_{\text{vac}} = \frac{U M^2 U^\dagger}{2E} \]

- **Dynamical MSW term (in matter)**
  \[ H_e = \sqrt{2} G_F \text{ diag}(N_e, 0, 0) \]

- **Neutrino-neutrino interactions term (non-linear)**
  \[ H_{\nu\nu} = \sqrt{2} G_F \int (1 - \cos \theta_{pq}) \left( \rho_q - \bar{\rho}_q \right) dq \]
3ν FRAMEWORK

- **Mixing parameters:** \( U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \) as for CKM matrix

\[
\begin{pmatrix}
  v_e \\
v_\mu \\
v_\tau
\end{pmatrix} =
\begin{pmatrix}
  1 \\
c_{23} & s_{23} \\
-s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
  c_{13} \\
e^{-i\delta} s_{13} \\
 \end{pmatrix}
\begin{pmatrix}
  e^{-i\delta}s_{13} \\
  c_{12} & s_{12} \\
  s_{12} & c_{12}
\end{pmatrix}
\begin{pmatrix}
  1 \\
  0 \\
  0
\end{pmatrix}
\begin{pmatrix}
  v_1 \\
v_2 \\
v_3
\end{pmatrix}
\]

- \( c_{12} = \cos \theta_{12} \), etc., \( \delta \) CP phase

- **Mass-gap parameters:** \( M^2 = \left( \begin{array}{ccc}
-\frac{\delta m^2}{2} & \pm\frac{\Delta m^2}{2} \\
\frac{\Delta m^2}{2} & \end{array} \right) \)

  - “solar”
  - “atmospheric”

  - **normal hierarchy:**
    - \( v_1 \):
      - +\( \delta m^2/2 \)
    - \( v_2 \):
      - -\( \delta m^2/2 \)
    - \( v_3 \):
      - \( -\Delta m^2 \)

  - **inverted hierarchy:**
    - \( v_1 \):
      - +\( \delta m^2/2 \)
    - \( v_2 \):
      - -\( \delta m^2/2 \)
    - \( v_3 \):
      - +\( \delta m^2 \)
The flavor evolution in matter is described by the non-linear MSW equations:

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- \(H_{\nu\nu} = \sqrt{2}G_F \int (1 - \cos \theta_{pq}) \left( \rho_q - \bar{\rho}_q \right) dq\)

**Kinematical mass-mixing term**

**Dynamical MSW term (in matter)**

**Neutrino-neutrino interactions term (non-linear)**
When neutrinos propagate in a medium they will experience a shift of their energy, similar to photon refraction, due to their coherent interaction with the medium constituents.

The difference of the interaction energy of different flavors gives an effective potential for electron (anti)neutrinos:

\[ V(x) = \sqrt{2} G_F N_e \]

net electron density
The flavor evolution in matter is described by the non-linear MSW equations:

\[ i \frac{d}{dx} \psi_\nu = (H_{\text{vac}} + H_e + H_{\nu\nu}) \psi_\nu \]

In the standard 3\(\nu\) framework:

- \(H_{\text{vac}} = \frac{U M^2 U^\dagger}{2E}\)
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**Kinematical mass-mixing term**

**Dynamical MSW term (in matter)**

**Neutrino-neutrino interactions term (non-linear)**
Two seminal papers in 2006 triggered a torrent of activities:

- Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616
- Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046
SYNCHRONIZED OSCILLATIONS BY NEUTRINO-NEUTRINO INTERACTIONS

Example: evolution of neutrino momenta with a thermal distribution

If neutrino density dominates, synchronized oscillations with a characteristic common oscillation frequency

[Pastor, Raffelt, Semikoz, hep-ph/0109033]
PENDULAR OSCILLATIONS

Equal densities of $\nu_e$ and $\nu_e$

INVERTED HIERARCHY + small $\theta$

In inverted hierarchy: coherent “pair conversions” $\nu_e \nu_e$

With constant $\mu$: periodic behaviour
Neutrino mass hierarchy (and $\theta_{13}$) set initial condition and fate

With only initial $\nu_e$ and $\bar{\nu}_e$:

- **Normal hierarchy**
  
  Pendulum starts in ~ downward (stable) positions and stays nearby. No significant flavor change.

- **Inverted hierarchy**
  
  Pendulum starts in ~ upward (unstable) positions and eventually falls down. Significant flavor changes.

$\theta_{13}$ sets initial misalignment with vertical. Specific value not much relevant.

[Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695, Duan, Carlson, Fuller, Qian, astro-ph/0703776]
SUPERNOVA: **Non-periodic** since $\nu$ density decreases

- Occurs for very small mixing angles
- Preserves the initial excess $\nu_e$ over $\bar{\nu}_e$ (lepton number conservation)

**Complete flavor conversions!**
Spectral Splits in the Accretion Phase

Initial fluxes typical of accretion phase at neutrinosphere ($r \sim 10 \text{ km}$)

$$F_{\nu_e} : F_{\overline{\nu}_e} : F_{\nu_x} = 2.4 : 1.6 : 1.0$$

Inverted mass hierarchy (IH)

Fluxes at the end of collective effects ($r \sim 200 \text{ km}$)

Nothing happens in Normal Hierarchy (NH)
Spectral Splits in the Accretion Phase

Initial fluxes typical of accretion phase at neutrinosphere ($r \sim 10$ km)

$$F_{\nu_e} : F_{\bar{\nu}_e} : F_{\nu_x} = 2.4 : 1.6 : 1.0$$

Inverted mass hierarchy (IH)

Hierarchical sensitive for small $\theta_{13}$

Fluxes at the end of collective effects ($r \sim 200$ km)

Nothing happens in Normal Hierarchy (NH)
Neutrinos emitted from spherical source, travel on different trajectories.
Different oscillation phases for neutrinos traveling in different paths.
Strong $\nu - \nu$ interaction can overcome trajectory dependent dispersion.

Collective conversion requires: $n_e \ll n_\nu$

Collective conversion is matter Suppressed: $n_e \gtrsim n_\nu$

[ Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico & Sigl, arxiv: 0807.0659 ]
Radial Variation of the Ratio ($R$) between $n_e$, $n_\nu$

$R = n_e / (n_\nu - n_e)$

(10.8 Solar Mass)

Dense Matter effect Suppresses Collective Oscillations

$n_e >> n_\nu$

Shock Front

$r$ (km)
Radial Evolution of Survival Probability

Dense Matter effect Suppresses Collective Oscillations

S.C, Fischer, Mirizzi, Saviano & Tomas
PRL 107:151101, 2011
PRD 84:025002, 2011
Similar Results from other Groups

Dasgupta, P. O'Connor, Ott
PRD 85:065008, 2012

[MPA, Garching Group, slide from B.Muller’s talk at Hanse 2011, Hamburg]
Similar Results from Garching Simulations

Contours of instability parameter ‘k’ in the ($\lambda$, $\mu$) plane.
&
SN density profile at 280 ms

Self Induced flavor conversions do not occur

Sarikas, Raffelt, Hüdepohl & Janka
PRL 108:061101, 2012
Oscillation is **not** important for shock revival

- Oscillation **suppressed** by dense matter effect.
- Conversion (Synchronization) radius **larger** than shock radius.

![Graphs showing radial positions over time](image)

**S.C., Fischer, Mirizzi, Saviano & Tomas**

PRL 107:151101, 2011
PRD 84:025002, 2011

Also see,
Dasgupta, P. O'Connor, Ott
PRD 85:065008, 2012
Dense matter ($n_e$) dominates over nu-nu interaction ($n_\nu$).
Suppression of Collective effects

Predictions are robust when collective effects are suppressed, i.e.:

1) Neutronization burst (t < 20 ms)
   - large $\nu_e$ excess and $\nu_x$ deficit

   [Hannestad et al., astro-ph/0608695]

2) Accretion phase (t < 500 ms)
   - Dense matter term dominates over nu-nu interaction term.

   [S.C, Fischer, Mirizzi, Saviano & Tomas
   PRL 107:151101, 2011
   PRD 84:025002, 2011]
Discovery of large $\theta_{13}$

T2K; MINOS; Double Chooz -> Large $\theta_{13}$

Daya Bay -> $\sin^2 2\theta_{13} = 0.092 \pm 0.017$

[Fogli, Lisi, Marrone, Montanino, Palazzo & Rotunno, PRD 86:013012, 2012]
SN neutrino Flux at Earth

Neutronization burst & Accretion Phase:

Normal Hierarchy (NH):

\[ F_{\nu_e} = F_{\nu_x}^0 \]
\[ F_{\bar{\nu}_e} = \cos^2 \vartheta_{12} (F_{\bar{\nu}_e}^0 - F_{\nu_x}^0) + F_{\nu_x}^0 \]

Inverted Hierarchy (IH):

\[ F_{\nu_e} = \sin^2 \vartheta_{12} (F_{\nu_e}^0 - F_{\nu_x}^0) + F_{\nu_x}^0 \]
\[ F_{\bar{\nu}_e} = F_{\nu_x}^0 \]
Removal of axial symmetry

Contours of instability parameter ‘k’ in the ($\lambda$, $\mu$) plane.

&

SN density profile at 280 ms

15 Solar Mass

Sarikas, Raffelt, David arxiv: 1305.7140
Oscillations in the Neutronization Burst

Water Cherenkov ($\nu_{e,x} e^- \rightarrow \nu_{e,x} e^-$)

- Peak is absent \quad \rightarrow \quad \text{NH}

\[
\sin^2 \theta_{13} = 10^{-3}
\]

\[
1 \text{ Mton}
\]

[M.Kachelriess et al, hep-ph/0412082]

Liq Ar TPC $\nu_e^{40}\text{Ar CC}$

- Peak is seen \quad \rightarrow \quad \text{IH}

\[
F_{\nu_e} = \begin{cases} 
F_{\nu_{e,x}}^0 & \text{No oscillation} \\
\sin^2 \vartheta_{12} (F_{\nu_e}^0 - F_{\nu_{x}}^0) + F_{\nu_x}^0 & \text{IH} 
\end{cases}
\]


- Peak is absent \quad \rightarrow \quad \text{NH}

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F_{\nu_e} = \begin{cases} 
F_{\nu_{e,x}}^0 & \text{No oscillation} \\
\sin^2 \vartheta_{12} (F_{\nu_e}^0 - F_{\nu_{x}}^0) + F_{\nu_x}^0 & \text{IH} 
\end{cases}
\]
SN Bounds on Neutrino Velocity

Violation of Lorentz invariance

\[
\frac{\nu - c}{c} = \left( \frac{E}{M_{OG}} \right)^{\alpha}
\]

The signal would be spread out and shifted in time.

\((\nu-c)/c < 10^{-14}\) for linear Lorentz violation

\((\nu-c)/c < 10^{-8}\) for quadratic Lorentz violation

[Ellis et al., 0805.0253 & 1110.4848]

SN neutrino Flux at Earth

Earth Matter Effect:

Identify “wiggles” in a signal (but good E-resolution & high statistics required): Liquid scintillators like LENA?
SN neutrino Flux at Earth

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**SN neutrino Flux at Earth**

**Earth Matter Effect:**

\[
F_{e}^{D} = \sin^2 \theta_{12} F_{\nu_x}^0 + \cos^2 \theta_{12} F_{\bar{\nu}_e}^0 + \Delta F^0 A_\oplus \sin^2 (12.5 \Delta m^2_{\odot} L/E)
\]

**Normal Hierarchy (NH):**

\[
F_{\nu_e} = F_{\nu_x}^0 \quad \text{(No E.M)}
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F_{\bar{\nu}_e} = \cos^2 \theta_{12} (F_{\bar{\nu}_e}^0 - F_{\nu_x}^0) + F_{\nu_x}^0
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[ Dighe, Keil & Raffelt, hep-ph/0304150 ]
SN neutrino Flux at Earth

Earth Matter Effect:

\[ F_{e}^{D} = \sin^2 \theta_{12} F_{\nu x}^0 + \cos^2 \theta_{12} F_{\bar{\nu} e}^0 + \Delta F_{\nu e}^0 A_{\odot} \sin^2 (12.5 \Delta m_{\odot}^2 L/E) \]

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\[ F_{\bar{\nu}_e} = F_{\nu_x}^0 \quad \text{(No E.M)} \]

[ Dighe, Keil & Raffelt, hep-ph/0304150 ]

[ Diagram of power spectrum vs. frequency ]
SN neutrino Flux at Earth

Earth Matter Effect:

\[ F_{\ell e}^D = \sin^2 \theta_{12} F_{\ell e}^0 + \cos^2 \theta_{12} F_{\ell e}^0 + \Delta F^0 \bar{A}_\odot \sin^2 (12.5 \Delta m^2_{\odot} L/E) \]

Normal Hierarchy (NH):

- \( F_{\nu e} = F_{\nu_x}^0 \)
- \( F_{\bar{\nu}_e} = \cos \theta_{12} \)

Inverted Hierarchy (IH):

- \( F_{\nu e} = \sin^2 \theta_{12} \)
- \( F_{\bar{\nu}_e} = F_{\nu_x}^0 \)

Recent simulations with close average energies of different flavors show negligible EM effects.

[ Dighe, Keil & Raffelt, hep-ph/0304150 ]
SN antineutrino Flux at Earth

Earth Matter Effect:

SN neutrino Flux at Earth

Earth Matter Effect:

[ Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012) ]
Rise time Analysis: Hierarchy Determination

15 Solar Mass

$\nu_x$ has only NC, $\bar{\nu}_e$ has both CC+NC.

$\nu_e$ more in equilibrium with environment than $\nu_x$

Flux of $\nu_x$ rises faster than $\bar{\nu}_e$

Flux in IH ($\nu_x$) rises faster than NH ($\nu_x, \bar{\nu}_e$)

[Serpico, S.C, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]
Rise time Analysis: Hierarchy Determination

Garching 15 Solar Mass in Ice-Cube

Flux in IH rises faster than NH

Rise time Analysis: Hierarchy Determination

Garching 15 Solar Mass in Ice-Cube

Normalized Count rate:

10 different models (12 M⊙ - 40 M⊙)

Blue: IH; Red: NH

Flux in IH rises faster than NH

Rise time Analysis: Hierarchy Determination

Garching 15 Solar Mass in Ice-Cube Normalized Count rate: 32 different models

Normalized Count rate:

\[ \begin{array}{cccc}
\nu & \bar{\nu} & \alpha & <\nu^4> \\
\end{array} \]

Flux in IH rises faster than NH

[C.D. Ott et al. Neutrino 2012, Japan]
Diffuse SN Neutrino Background (DSNB)

- Approx. 10 core-collapse/sec in the visible universe
- mostly from redshift \( z \sim 1 \)
- Confirm star formation rate

Window of opportunity bkg less than signal

SK-doped with Gd would detect few clear DSNB-\( \nu \) events/year.

\( \nu \) astronomy at cosmic distances!
Conclusions

• Observing SN neutrinos is the next frontier of low-energy neutrino astronomy.

• Collective effects are suppressed in early SN phases, implying hierarchy sensitivity at large $\theta_{13}$.

• Earth Matter effect: Detectable for Sub-kpc SNe.

• New physics scenarios can be constrained.

• Rise time of SNe signal contains hierarchy information.
LOOKING FORWARD FOR THE NEXT GALACTIC SN!

Thank You!