Physics Potential of Future Supernova Neutrino Observations

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Mumbai, India

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Supernova for neutrino physics and astrophysics

SN for neutrino oscillation phenomenology
- Detection of nonzero angle *you-know-who*
- Normal vs. inverted mass ordering (both possible even if $\theta_{13} \rightarrow 0$)

Neutrino detection for SN astrophysics
- Pointing to the SN in advance
- Tracking SN shock wave in neutrinos
- Diffuse SN neutrino background

The flavour of this talk
- Only standard three-neutrino mixing
- Only standard SN explosion scenario
- Concentrate on the exciting developments in the last two years: “neutrino refraction / collective effects”
Supernova for neutrino physics and astrophysics

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   - Neutrino emission and primary spectra
   - Detection of a galactic supernova

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   - Matter effects inside the star: collective and MSW
   - Earth matter effects
   - Shock wave effects

3. Smoking gun signals
   - During neutronization burst
   - During the accretion and cooling phase

4. Concluding remarks
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Neutrino emission

Gravitational core collapse $\Rightarrow$ Shock Wave

Neutronization burst:
$\nu_e$ emitted for $\sim 10$ ms

Cooling through neutrino emission: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
Duration: About 10 sec
Emission of 99% of the SN energy in neutrinos

??? Explosion ???
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Explosion
Primary fluxes and spectra

Neutrino fluxes:

\[ F_{\nu_i}^0 = N_i E^\alpha \exp \left[ -(\alpha + 1) \frac{E}{E_0} \right] \]

\( E_0, \alpha \): in general time dependent

- Energy hierarchy: \( E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x) \)

\( E_0(\nu_e) \approx 10–12 \text{ MeV} \)
\( E_0(\bar{\nu}_e) \approx 13–16 \text{ MeV} \)
\( E_0(\nu_x) \approx 15–25 \text{ MeV} \)
\( \alpha_{\nu_i} \approx 2–4 \)
Flavor-dependence of neutrino fluxes

\[
\langle E \rangle_0 \left( \nu_e \right) \quad \langle E \rangle_0 \left( \bar{\nu}_e \right) \quad \langle E \rangle_0 \left( \nu_x \right) \quad \frac{\Phi_0 \left( \nu_e \right)}{\Phi_0 \left( \nu_x \right)} \quad \frac{\Phi_0 \left( \bar{\nu}_e \right)}{\Phi_0 \left( \nu_x \right)}
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>\langle E_0 (\nu_e) \rangle</th>
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<td>Garching (G)</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Livermore (L)</td>
<td>12</td>
<td>15</td>
<td>24</td>
<td>2.0</td>
<td>1.6</td>
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Confirmed the **SN cooling mechanism** through neutrinos

*Number of events too small* to say anything concrete about neutrino mixing

Some constraints on **SN parameters** obtained

(Hubble image)
Signal expected from a galactic SN (10 kpc)

Water Cherenkov detector:

- $\bar{\nu}_e p \rightarrow ne^+: \approx 7000 - 12000^*$
- $\nu e^- \rightarrow \nu e^-: \approx 200 - 300^*$
- $\nu_e + ^{16}O \rightarrow X + e^-: \approx 150-800^*$

* Events expected at Super-Kamiokande with a galactic SN at 10 kpc

Carbon-based scintillation detector:

- $\bar{\nu}_e p \rightarrow ne^+$
- $\nu + ^{12}C \rightarrow \nu + X + \gamma (15.11 \text{ MeV})$

Liquid Argon detector:

- $\nu_e + ^{40}Ar \rightarrow ^{40}K^* + e^-$
Neutrinos reach 6-24 hours before the light from SN explosion (SNEWS network)

$\bar{\nu}_e p \rightarrow ne^+$: nearly isotropic background

$\nu e^- \rightarrow \nu e^-$: forward-peaked “signal”

Background-to-signal ratio: $N_B/N_S \approx 30–50$

SN at 10 kpc may be detected within a cone of $\sim 5^\circ$ at SK

J. Beacom and P. Vogel, PRD 60, 033007 (1999)

Neutron tagging with Gd improves the pointing accuracy 2–3 times

R. Tomàs et al., PRD 68, 093013 (2003). GADZOOKS

Within reach of HK, easier if Gd added

“Invisible muon” background needs to be taken care of

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Propagation through matter of varying density

Inside the SN: *flavour conversion*
Collective effects and MSW matter effects

Between the SN and Earth: *no flavour conversion*
Mass eigenstates travel independently

Inside the Earth: *flavour conversion*
MSW matter effects (*if detector is on the other side*)
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Nonlinear effects due to $\nu - \nu$ coherent interactions

- Large neutrino density $\Rightarrow$ substantial $\nu-\nu$ potential
  \[ H = H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu} \]

\[
H_{\text{vac}}(\bar{\rho}) = M^2/(2p) \\
H_{\text{MSW}} = \sqrt{2}G_F n_e - \text{diag}(1, 0, 0) \\
H_{\nu\nu}(\bar{\rho}) = \sqrt{2}G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos \theta_{pq})(\rho(\bar{q}) - \bar{\rho}(\bar{q}))
\]

- Coherent scattering and nonlinear effects

  General formalism:

  Numerical simulations in SN context:
  H. Duan, G. Fuller, J. Carlson, Y. Qian, et al. (2006-2008)
Nonlinear effects due to $\nu - \nu$ coherent interactions

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- Coherent scattering and nonlinear effects

  \textit{General formalism:}
  

  \textit{Numerical simulations in SN context:}
  
Multi-angle effects

“Multi-angle decoherence” during collective oscillations suppressed by $\nu - \bar{\nu}$ asymmetry

“Single-angle” evolution along lines of neutrino flux works even for non-spherical geometries, as long as coherence is maintained
“Collective” effects: analytical understanding

Synchronized oscillations:
\( \nu \) and \( \bar{\nu} \) of all energies oscillate with the same frequency

Bipolar oscillations:
Coherent \( \nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x \) pairwise conversions even for extremely small \( \theta_{13} \) (in IH)

Spectral split:
In inverted hierarchy, \( \bar{\nu}_e \) and \( \bar{\nu}_x \) spectra interchange completely. \( \nu_e \) and \( \nu_x \) spectra interchange only above a certain critical energy.
Collective effects: some insights

- Synchronized oscillations ⇒ No significant flavour changes
- Bipolar oscillations ⇒ preparation for spectral split

- Multi-angle effects only smear the spectra to some extent

Collective effects vs. MSW effects (two-flavor)

\[ \mu \equiv \sqrt{2}G_F(N_\nu + N_{\bar{\nu}}) \]

\[ \lambda \equiv \sqrt{2}G_FN_e \]

- \( r \lesssim 200 \text{ km} \): collective effects dominate
- \( r \gtrsim 200 \text{ km} \): standard MSW matter effects dominate

O-Ne-Mg supernovae

- MSW resonances occur while collective effects are still dominant
- All neutrinos resonate together, the same adiabaticity for all
- Interesting spectral split features

H. Duan, G. M. Fuller, J. Carlson
Y.Z. Qian, PRL100, 021101 (2008)

C. Lunardini, B. Mueller and
Three-flavor collective effects

Three-flavor results by combining two-flavor ones

- Factorization in two two-flavor evolutions possible
- Pictorial understanding through “flavour triangle” diagrams

B.Dasgupta and AD, arXiv:0712.3798, PRD

New three-flavor effects

- In early accretion phase, large $\mu-\tau$ matter potential causes interference between MSW and collective effects, sensitive to deviation of $\theta_{23}$ from maximality


- Spectral splits develop at two energies, in a stepwise process

H.Duan, G.M.Fuller and Y.Z.Qian, arXiv:0801.1363
**MSW Resonances inside a SN**

**Normal mass ordering**

- **$H$ resonance:** $(\Delta m_{\text{atm}}^2, \theta_{13})$, $\rho \sim 10^3 – 10^4$ g/cc
  - In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
  - Adiabatic (non-adiabatic) for $\sin^2 \theta_{13} \gtrsim 10^{-3}$ ($\lesssim 10^{-5}$)

**Inverted mass ordering**

- **$L$ resonance:** $(\Delta m_{\odot}^2, \theta_{\odot})$, $\rho \sim 10 – 100$ g/cc
  - Always adiabatic, always in $\nu$

---

Fluxes arriving at the Earth

Mixture of initial fluxes:

$$F_{\nu_e} = p F_{\nu_e}^0 + (1 - p) F_{\nu_x}^0,$$
$$F_{\bar{\nu}_e} = \bar{p} F_{\bar{\nu}_e}^0 + (1 - \bar{p}) F_{\nu_x}^0,$$
$$4F_{\nu_x} = (1 - p) F_{\nu_e}^0 + (1 - \bar{p}) F_{\bar{\nu}_e}^0 + (2 + p + \bar{p}) F_{\nu_x}^0.$$

Survival probabilities in different scenarios:

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<tr>
<th>Hierarchy</th>
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<th>$p$</th>
<th>$\bar{p}$</th>
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<tr>
<td>A Normal</td>
<td>Large</td>
<td>0</td>
<td>$\sin^2 \theta_{13}$</td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
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<td>Small</td>
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“Small”: $\sin^2 \theta_{13} \lesssim 10^{-5}$, “Large”: $\sin^2 \theta_{13} \gtrsim 10^{-3}$.

All four scenarios separable in principle !!

Final spectra for inverted hierarchy

Neutrinos

Antineutrinos

Small $\theta_{13}$

Large $\theta_{13}$

Survival probabilities in different scenarios:

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- Spectral split in **neutrinos** present for IH, absent for NH.

- Earth matter effects in **antineutrinos** present in IH, absent for NH.

- Valid even for \( \sin^2 \theta_{13} \lesssim 10^{-10} \) !!
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Earth matter effects

Neutrinos

(\(\nu_e, \nu_x, \text{mixed } \nu\))

- Total number of events change
- “Earth effect” oscillations are introduced

Antineutrinos

(\(\bar{\nu}_e, \bar{\nu}_x, \text{mixed } \bar{\nu}\))

Presence or absence of Earth matter effects:

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<th>(\bar{\nu}_e)</th>
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<td>X</td>
<td>√</td>
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IceCube as a co-detector with HK

- **Total Cherenkov count in IceCube** increases beyond statistical background fluctuations during a SN burst. 

- This signal can be determined to a statistical accuracy of $\sim 0.25\%$ for a SN at 10 kpc.

- The extent of Earth effects changes by 3–4 % between the accretion phase (first 0.5 sec) and the cooling phase.

- Absolute calibration not essential

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Collective effects will change the ratio
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Collective effects will change the ratio

Earth effects through Fourier Transform

Power spectrum: \( G_N(k) = \frac{1}{N} \left| \sum_{\text{events}} e^{iky} \right|^2 \)

(\( y \equiv 25 \text{ MeV}/E \))

- Model independence of peak positions at a scintillator:


Collective effects will not change peak positions
Earth effects through Fourier Transform

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(\( y \equiv 25 \text{ MeV}/E \))

- Model independence of peak positions at a scintillator:

Collective effects will not change peak positions

Earth matter effects from two Water Cherenkovs

\[ R \equiv \frac{N(\text{shadowed}) - N(\text{unshadowed})}{N(\text{unshadowed})} \]

Robust experimental signature, thanks to Collective Effects

- Earth effects can distinguish hierarchies even for \( \theta_{13} \rightarrow 0 \)

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When shock wave passes through a resonance region (density $\rho_H$ or $\rho_L$):

- adiabatic resonances may become momentarily non-adiabatic
- scenario A $\rightarrow$ scenario C
- scenario B $\rightarrow$ scenario D
- Sharp changes in the final spectra even if the primary spectra change smoothly

R. C. Schirato, G. M. Fuller, astro-ph/0205390
Time dependent spectral evolution

Double/single dip at a megaton water Cherenkov

Single (Double) dip in $\langle E_e \rangle$
Single (Double) peak in $\langle E_e^2 \rangle/\langle E_e \rangle^2$

for Forward (+ Reverse) shock

Double/single dip
- robust under monotonically decreasing average energy
- In $\nu_e$ ($\bar{\nu}_e$) for normal (inverted) hierarchy for $\sin^2 \theta_{13} \gtrsim 10^{-5}$


JCAP 0409, 015 (2004)
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JCAP 0409, 015 (2004)

Collective effects $\Rightarrow$ dip $\leftrightarrow$ peak
Tracking the shock fronts

At \( t \approx 4.5 \text{ sec} \), (reverse) shock at \( \rho_{40} \)

At \( t \approx 7.5 \text{ sec} \), (forward) shock at \( \rho_{40} \)

Multiple energy bins \( \Rightarrow \) the times the shock fronts reach different densities of \( \rho \sim 10^2\text{--}10^4 \text{ g/cc} \)
Shock wave giving rise to neutrino oscillations

F: Forward shock
A: Accretion region
C: Contact discontinuity
B: Low density “bubble”
R: Reverse shock
T: tail of the shock

- Oscillations smeared out at a water Cherenkov
- At a scintillator, $\mathcal{O}(10^5)$ events needed in a time bin

# Shock wave signals

Presence or absence of shock wave signal:

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>sin²θ₁₃</th>
<th>νₑ</th>
<th>\bar{ν}_ₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Normal</td>
<td>Large</td>
<td>✓</td>
</tr>
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</tr>
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</table>

Shock wave signal may be diluted by:

- Stochastic density fluctuations: may partly erase the shock wave imprint
  

- Turbulent convections behind the shock wave: gradual depolarization effects
  
  A. Friedland and A. Gruzinov, astro-ph/0607244
  
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Vanishing $\nu_e$ burst

Time resolution of the detector crucial for separating $\nu_e$ burst from the accretion phase signal

Burst signal vanishes for Normal hierarchy $\oplus$ large $\theta_{13}$

M. Kachelriess, R. Tomas, R. Buras, H. T. Janka, A. Marek and M. Rampp
PRD 71, 063003 (2005)
Stepwise spectral split in O-Ne-Mg supernovae

- MSW resonances deep inside collective regions
- “MSW-prepared” spectral splits: two for NH, one for IH
  
  H. Duan, G. Fuller, Y. Z. Qian, PRD77, 085016 (2008)

- Positions of splits fixed by initial spectra
  

Stepwise $\nu_e$ suppression much more at low energy

- Identification of O-Ne-Mg supernova ??
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Spectral split in $\nu_e$

- Happens only in **inverted hierarchy**
- Takes place at **low energies (5-10 MeV)**
- Needs **liquid Ar detector** with a low threshold
- Signal at a detector almost washed out due to the difference in $E_{\nu_e}$ and $E_{e^-}$ and detector resolution
Shock wave effects

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<td>✓</td>
</tr>
<tr>
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<td>Small</td>
<td>X</td>
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<tr>
<td>D Inverted</td>
<td>Small</td>
<td>X</td>
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</table>

- **Time dependent spectral evolution**

- Dips / peaks in $\langle E^n \rangle$
Earth matter effects

### Presence or absence of Earth matter effects:

<table>
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<th></th>
<th>Hierarchy</th>
<th>(\sin^2 \theta_{13} )</th>
<th>(\nu_e)</th>
<th>(\bar{\nu}_e)</th>
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<td>Inverted</td>
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- **Comparison of IceCube/HK luminosities** during accretion and cooling phases
- **Earth effect oscillations** through Fourier transforms of neutrino spectra
- **Energy dependent ratio of events at shadowed/unshadowed detectors**
1. Neutrino production and detection
   - Neutrino emission and primary spectra
   - Detection of a galactic supernova

2. Neutrino propagation and flavor conversions
   - Matter effects inside the star: collective and MSW
   - Earth matter effects
   - Shock wave effects

3. Smoking gun signals
   - During neutronization burst
   - During the accretion and cooling phase

4. Concluding remarks
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- Supernova neutrinos probe neutrino mass hierarchy and \( \theta_{13} \) range, even for \( \theta_{13} \rightarrow 0 \), thanks to collective effects and MSW resonances inside the star.

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  - Neutronization burst suppression
  - Time variation of signal during shock wave propagation
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- Implications for SN astrophysics:
  - Pointing to the SN in advance
  - Diffuse supernova neutrino background
  - Tracking the shock wave while still inside mantle

A rare event is a lifetime opportunity

– Anon
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