Physics Potential of Future Supernova Neutrino Observations

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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 $\theta_{13} \to 0$)

#### 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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Outline

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
1. Neutrino production and detection
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4 Concluding remarks
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???
Neutrino emission

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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 ???
Primary fluxes and spectra

Neutrino fluxes:

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

\( E_0, \alpha \): 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

Garching (G) 12 15 18 0.8 0.8
Livermore (L) 12 15 24 2.0 1.6

G. G. Raffelt, M. T. Keil, R. Buras, H. T. Janka and M. Rampp, astro-ph/0303226
T. Totani, K. Sato, H. E. Dalhed and J. R. Wilson, Astrophys. J. 496, 216 (1998)
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SN1987A

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

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

**Carbon-based scintillation detector:**
- $\bar{\nu}_e p \rightarrow n e^+$
- $\nu + ^{12}C \rightarrow \nu + X + \gamma (15.11 \text{ MeV})$

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

$\bar{\nu}_e p \rightarrow n e^+$: 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

J. Beacom and M. Vagins, PRL 93, 171101 (2004)
Diffuse SN neutrino background

- Within reach of HK, easier if Gd added
- “Invisible muon” background needs to be taken care of

S. Ando and K. Sato, New J. Phys. 6, 170 (2004)
S. Chakraborti, B. Dasgupta, S. Choubey, K. Kar, arXiv:0805.xxxx
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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

$$H = H_{\text{vac}} + H_{\text{MSW}} + H_{\nu \nu}$$

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

- Coherent scattering and nonlinear effects

**General formalism:**

J. Pantaleone, M. Thomson, B. McKellar, V.A. Kostelecky, S. Samuel, G. Sigl, G. G. Raffelt, *et al.*, (1992-1998)

**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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**Numerical simulations in SN context:**

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“Multi-angle decoherence” during collective oscillations suppressed by $\nu - \bar{\nu}$ asymmetry
A. Esteban-Pretel, S. Pastor, R. Tomas, G. Raffelt, G. Sigl, PRD76, 125018 (2007)

“Single-angle” evolution along lines of neutrino flux works even for non-spherical geometries, as long as coherence is maintained
B. Dasgupta, AD, A. Mirizzi, G. Raffelt, arXiv:0805.xxxx
“Collective” effects: analytical understanding

Synchronized oscillations:

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

S. Pastor, G. Raffelt and D. Semikoz, PRD65, 053011 (2002)

Bipolar oscillations:

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

S. Hannestad, G. Raffelt, G. Sigl, Y. Wong, PRD74, 105010 (2006)

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.

G. Raffelt, A. Smirnov, PRD76, 081301 (2007), PRD76, 125008 (2007)
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

G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)
Collective effects vs. MSW effects (two-flavor)

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

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

G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)
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
H. T. Janka, arXiv:0712.3000
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

Poster by B. Dasgupta

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

A. Esteban-Pretel, S. Pastor, R. Tomas, G. Raffelt, G. Sigl, PRD77, 065024 (2008)

Poster by S. Pastor

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

H. Duan, G. M. Fuller and Y. Z. Qian, arXiv:0801.1363

B. Dasgupta, AD, A. Mirizzi and G. G. Raffelt, arXiv:0801.1660
MSW Resonances inside a SN

Normal mass ordering

\[ (\Delta m_{\text{atm}}^2, \theta_{13}), \rho \sim 10^3 - 10^4 \text{ g/cc} \]
- 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

\[ (\Delta m_{\odot}^2, \theta_{\odot}), \rho \sim 10 - 100 \text{ g/cc} \]
- Always adiabatic, always in \( \nu \)
Fluxes arriving at the Earth

Mixture of initial fluxes:

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

Survival probabilities in different scenarios:

| Hierarchy | \( \sin^2 \theta_{13} \) | \( \rho \) | \( \bar{\rho} \) |
|-----------|-----------------|---------|---------|
| A Normal  | Large           | 0       | \( \sin^2 \theta_{13} \) |
| B Inverted| Large           | \( \cos^2 \theta_{13} \) | 0 | \( \cos^2 \theta_{13} \) |
| C Normal  | Small           | \( \sin^2 \theta_{13} \) | \( \cos^2 \theta_{13} \) |
| D Inverted| Small           | \( \cos^2 \theta_{13} \) | 0 | 0 |

- “Small”: \( \sin^2 \theta_{13} \lesssim 10^{-5} \), “Large”: \( \sin^2 \theta_{13} \gtrsim 10^{-3} \).
- All four scenarios separable in principle !!

B. Dasgupta, AD, arXiv:0712.3798, PRD
Final spectra for inverted hierarchy

[Graphs showing flux vs energy for neutrinos and antineutrinos for small and large $\theta_{13}$ values]

B. Dasgupta, AD, arXiv:0712.3798, PRD
Normal vs. inverted hierarchy even when $\theta_{13} \to 0$ ??

| Hierarchy | $\sin^2 \theta_{13}$ | $p$ | $\bar{p}$ |
|-----------|----------------------|-----|----------|
| A Normal  | Large                | 0   | $\sin^2 \theta_{13}$ |
| B Inverted| Large                | $\cos^2 \theta_{13}$ | $0$ | $\cos^2 \theta_{13}$ |
| C Normal  | Small                | $\sin^2 \theta_{13}$ | $\cos^2 \theta_{13}$ |
| D Inverted| Small                | $\cos^2 \theta_{13}$ | $0$ | 0 |

- Spectral split in **neutrinos** present for IH, absent for NH  
  H.Duan, G.M.Fuller, J.Carlson and Y.Q.Zhong, PRL 99, 241802 (2007)
- Earth matter effects in **antineutrinos** present in IH, absent for NH.  
  B.Dasgupta, AD, A.Mirizzi, arXiv:0802.1481
- Valid even for $\sin^2 \theta_{13} \lesssim 10^{-10}$ !!
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Earth matter effects

Neutrinos

Antineutrinos

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

- Total number of events change
- "Earth effect" oscillations are introduced

Presence or absence of Earth matter effects:

| Hierarchy | \( \sin^2 \theta_{13} \) | \( \nu_e \) | \( \bar{\nu}_e \) |
|-----------|-----------------|-------------|-------------|
| A Normal  | Large \( \times \) | \( \checkmark \) | \( \times \) |
| B Inverted| Large \( \times \) | \( \checkmark \) | \( \checkmark \) |
| C Normal  | Small \( \checkmark \) | \( \checkmark \) | \( \checkmark \) |
| D Inverted| Small \( \times \) | \( \times \) | \( \times \) |
IceCube as a co-detector with HK

- **Total Cherenkov count in IceCube** increases beyond statistical background fluctuations during a SN burst
  
  F. Halzen, J. Jacobsen, E. Zas, PRD53, 7359 (1996)

- 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

AD, M. Keil, G. Raffelt, JCAP 0306:005 (2003)

Collective effects will change the ratio
IceCube as a co-detector with HK

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Collective effects will change the ratio.

AD, M. Keil, G. Raffelt, JCAP 0306:005 (2003)
Earth effects through Fourier Transform

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

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

- Model independence of peak positions at a scintillator:

AD, M. Kachelrieß, G. Raffelt, R. Tomàs, JCAP 0401:004 (2004)

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

Power spectrum: \( G_N(k) = \frac{1}{N} |\sum_{\text{events}} e^{iky}|^2 \) 
\( (y \equiv 25 \text{ MeV}/E) \)

- 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 \( \theta_{13} \rightarrow 0 \)

B. Dasgupta, AD, A. Mirizzi, arXiv:0802.1481
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4 Concluding remarks
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
G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi, PRD 68, 033005 (2003)
Time dependent spectral evolution

J.P.Kneller, G.C.Mclaughlin, J.Brockman, PRD77, 045023 (2008)
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 $\sin^2 \theta_{13} \gtrsim 10^{-5}$

R. Tomas, M. Kachelriess, G. Raffelt, AD, H. T. Janka and L. Scheck
JCAP 0409, 015 (2004)

Collective effects $\Rightarrow$ dip $\leftrightarrow$ peak
Double/single dip at a megaton water Cherenkov

Single (Double) dip in $\langle E_e \rangle$
Single (Double) peak in $\langle E_e^2 \rangle / \langle E_e \rangle^2$ \quad \text{for Forward (+ Reverse) shock}

Double/single dip

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

R. Tomas, M. Kachelriess, G. Raffelt, AD, H. T. Janka and L. Scheck
\textit{JCAP 0409}, 015 (2004)

Collective effects $\Rightarrow$ dip $\leftrightarrow$ peak
At \( t \approx 4.5 \) sec, (reverse) shock at \( \rho_{40} \)

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

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

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

B. Dasgupta, AD, PRD 75, 093002 (2007)
## Shock wave signals

### Presence or absence of shock wave signal:

| Hierarchy  | sin$^2 \theta_{13}$ | $\nu_e$ | $\bar{\nu}_e$ |
|------------|---------------------|---------|----------------|
| A Normal   | Large               | ✓       | ✓              |
| B Inverted | Large               | X       | ✓              |
| C Normal   | Small               | X       | X              |
| D Inverted | Small               | X       | X              |

Shock wave signal may be diluted by:

- Stochastic density fluctuations: may partly erase the shock wave imprint  
  G. Fogli, E. Lisi, A. Mirizzi and D. Montanino, JCAP 0606, 012 (2006)
- Turbulent convections behind the shock wave: gradual depolarization effects  
  A. Friedland and A. Gruzinov, astro-ph/0607244  
  S. Choubey, N. Harries, G. G. Ross, PRD76, 073013 (2007)
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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 $\Theta_{13}$ large
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
  - B.Dasgupta, AD, A. Mirizzi, G.G.Raffelt, arXiv:0801.1660, PRD

Stepwise $\nu_e$ suppression much more at low energy

- Identification of O-Ne-Mg supernova ??
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4. Concluding remarks
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

Presence or absence of shock wave signal:

| Hierarchy  | $\sin^2 \theta_{13}$ | $\nu_e$ | $\bar{\nu}_e$ |
|------------|-------------------|--------|-------------|
| A Normal   | Large             | √      | √           |
| B Inverted | Large             | X      | √           |
| C Normal   | Small             | X      | X           |
| D Inverted | Small             | X      | X           |

- Time dependent spectral evolution

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

### Presence or absence of Earth matter effects:

| Hierarchy | $\sin^2 \theta_{13}$ | $\nu_e$ | $\bar{\nu}_e$ |
|-----------|----------------------|---------|---------------|
| A Normal  | Large                | X       | √             |
| B Inverted| Large                | X       | √             |
| C Normal  | Small                | √       | √             |
| D Inverted| Small                | X       | X             |

- **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**
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  - Neutronization burst suppression
  - Time variation of signal during shock wave propagation
  - Earth matter effects

- Implications for SN astrophysics:
  - Pointing to the SN in advance
  - Diffuse supernova neutrino background
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