

Supernova neutrinos

Collective and matter effects at large detectors

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Changing paradigm of SN neutrino oscillations

Neutrino-electron forward scattering: MSW effects (1999 –)

- Flavour conversions mainly in MSW resonance regions :
($\rho \sim 10^{3-4}$ g/cc, 1–10 g/cc)
- Sensitivity to $\sin^2 \theta_{13} \gtrsim 10^{-5}$ and mass hierarchy

Neutrino-neutrino forward scattering: Collective effects (2006 –)

- Significant flavour conversions near the neutrinosphere :
($\rho \sim 10^{6-10}$ g/cc)
- Synchronized osc \rightarrow bipolar osc \rightarrow spectral split
- Single spectral split: In IH,
 $\bar{\nu}_e$ and $\bar{\nu}_\mu$ spectra swap completely
 ν_e and ν_μ spectra swap for $E > E_c$
- Sensitivity even to $\sin^2 \theta_{13} \sim 10^{-10}$

Multiple spectral splits (2009 –)

- “Single spectral split” valid only when $L_{\nu_e} \approx L_{\bar{\nu}_e} \gtrsim L_{\nu_\mu}$
- In general, both $\nu_e \leftrightarrow \nu_y$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$ swaps take place, in sharply separated energy regions

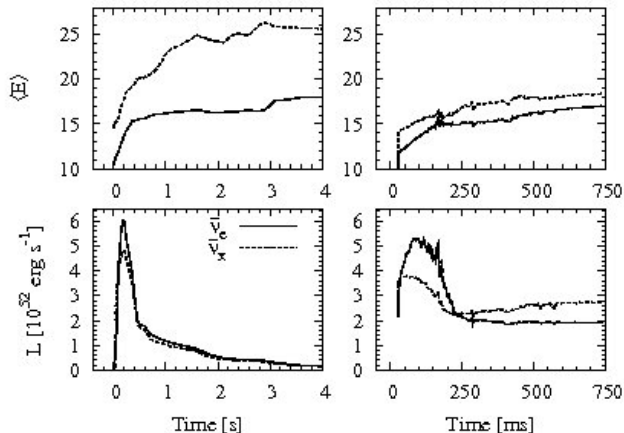
$$\begin{pmatrix} \nu_x \\ \nu_y \end{pmatrix} = \begin{pmatrix} \cos \theta_{23} & \sin \theta_{23} \\ -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}$$

- **Three flavour effects:** even $\nu_e \leftrightarrow \nu_x$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ swaps take place, in sharply separated energy regions
- **The swapped / unswapped energy regions depend on primary fluxes and mass hierarchy**

Primary neutrino fluxes: a lot of model dependence

Livermore 1998

Garching 2003

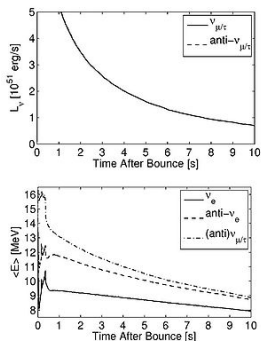


solid: $\bar{\nu}_e$, dotted: $\bar{\nu}_\mu$

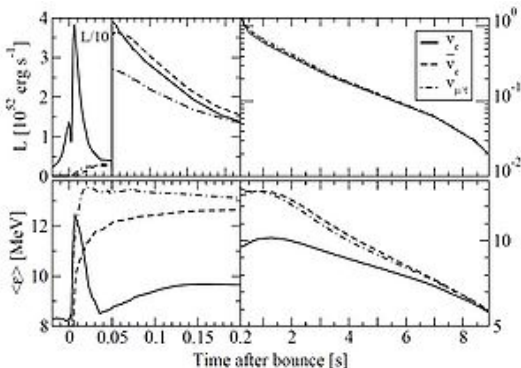
Totani et al., 1998, Raffelt et al., 2003

Recent model predictions for fluxes

Basel 2009



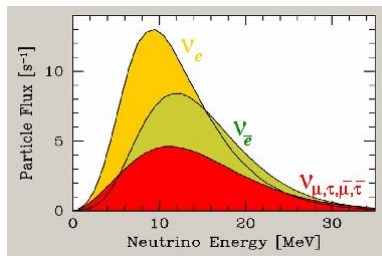
Garching 2009



Fischer et al, 2009; Hüdepohl et al, 2009

- Average energies slightly smaller
- $\sim 20\%$ differences in average energies and fluxes (especially during the accretion phase; more for neutrinos)

Typical features of the spectra



- Average energies:

$$\langle E_0(\nu_e) \rangle \approx 10\text{--}12 \text{ MeV}$$

$$\langle E_0(\bar{\nu}_e) \rangle \approx 13\text{--}16 \text{ MeV}$$

$$\langle E_0(\nu_x) \rangle \approx 15\text{--}25 \text{ MeV}$$

- Energy hierarchy:

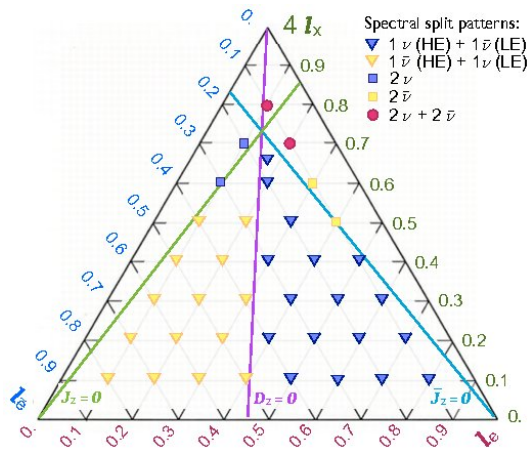
$$\langle E_0(\nu_e) \rangle < \langle E_0(\bar{\nu}_e) \rangle < \langle E_0(\nu_x) \rangle = \langle E_0(\nu_y) \rangle$$

- Luminosities:

$$L_{\nu_e} \approx L_{\bar{\nu}_e}$$

$$L_{\nu_x} \approx (0.5 - 2.0) L_{\nu_e}$$

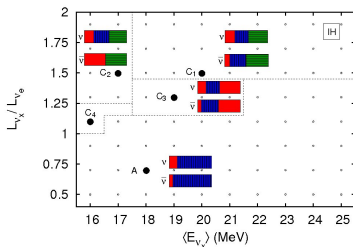
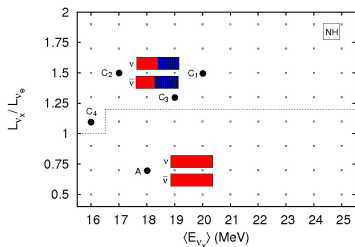
Number and position of splits: is there a pattern ?



(Inverted hierarchy, $\nu_e \leftrightarrow \nu_y$ split)

G.Fogli, E.Lisi, A.Marrone, I.Tamborra, JCAP 0910:002 (2009)

Split patterns with $\langle E_{\nu_\mu} \rangle$ and L_{ν_μ} : two “phases”



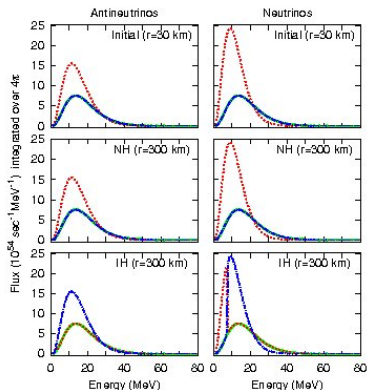
No swap, $e \leftrightarrow y$ swap, $e \leftrightarrow x$ swap

S. Choubey, B. Dasgupta, AD, A. Mirizzi, arXiv:1008.0308 [hep-ph]

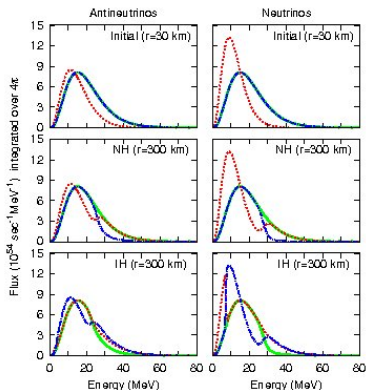
- $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV
- $L_{\nu_e} = L_{\bar{\nu}_e}$
- For lower $\langle E_{\nu_e} \rangle$, scale $\langle E_{\nu_\mu} \rangle$ appropriately

Multiple splits in different phases

Phase A



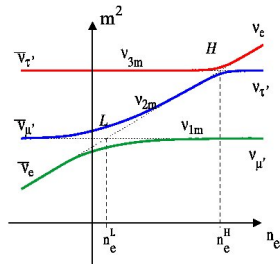
Phase C



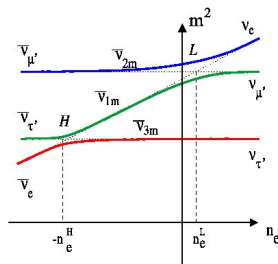
Flavours: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

MSW Resonances inside a SN

Normal mass ordering



Inverted mass ordering



AD, A.Smirnov, PRD62, 033007 (2000)

H resonance: $(\Delta m_{\text{atm}}^2, \theta_{13}), \rho \sim 10^3\text{--}10^4 \text{ g/cc}$

- In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
- Adiabatic (non-adiabatic) for $\sin^2 \theta_{13} \gtrsim 10^{-3} (\lesssim 10^{-5})$

L resonance: $(\Delta m_{\odot}^2, \theta_{\odot}), \rho \sim 10\text{--}100 \text{ g/cc}$

- Always adiabatic, always in ν

Fluxes arriving at the Earth

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

p at low, intermediate, high energies

		Phase A ($L_{\nu_e} \gtrsim L_{\nu_x}$)			Phase C ($L_{\nu_e} \lesssim L_{\nu_x}$)		
NH	$\sin^2 \theta_{13} \gtrsim 10^{-3}$	0	0	0	0	0	s^2
	$\sin^2 \theta_{13} \lesssim 10^{-5}$	s^2	s^2	s^2	s^2	s^2	0
IH	$\sin^2 \theta_{13} \gtrsim 10^{-3}$	s^2	0	0	s^2	0	$c^2 (s^2)$
	$\sin^2 \theta_{13} \lesssim 10^{-5}$	s^2	0	0	s^2	0	$c^2 (s^2)$

\bar{p} at low, intermediate, high energies

		Phase A ($L_{\nu_e} \gtrsim L_{\nu_x}$)			Phase C ($L_{\nu_e} \lesssim L_{\nu_x}$)		
NH	$\sin^2 \theta_{13} \gtrsim 10^{-3}$	c^2	c^2	c^2	c^2	c^2	0
	$\sin^2 \theta_{13} \lesssim 10^{-5}$	c^2	c^2	c^2	c^2	c^2	0
IH	$\sin^2 \theta_{13} \gtrsim 10^{-3}$	0	c^2	c^2	0	$c^2 [0]$	$s^2 (0)$
	$\sin^2 \theta_{13} \lesssim 10^{-5}$	c^2	0	0	c^2	0 [c^2]	$s^2 (c^2)$

$$s^2 \equiv \sin^2 \theta_{12}, \quad c^2 \equiv \cos^2 \theta_{12}$$

$$(C_3, C_4), [C_2, C_4]$$

Signal expected from a galactic SN (10 kpc)

Water Cherenkov detector: (events at SK)

- $\bar{\nu}_e p \rightarrow n e^+$: $\approx 7000 - 12000$

$$\Delta_{\text{WC}}/\text{MeV} = 0.47 \sqrt{E_e/\text{MeV}}$$

- $\nu e^- \rightarrow \nu e^-$: $\approx 200 - 300$

- $\nu_e + {}^{16}\text{O} \rightarrow X + e^-$: $\approx 150 - 800$

Carbon-based scintillation detector:

- $\bar{\nu}_e p \rightarrow n e^+$ (~ 300 per kt)

$$\Delta_{\text{SC}}/\text{MeV} = 0.075 \sqrt{E_e/\text{MeV}}$$

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

Liquid Argon detector:

- $\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$ (~ 300 per kt)

$$\Delta_{\text{LAR}}/\text{MeV} = 0.11 \sqrt{E_e/\text{MeV}} + 0.02 E_e/\text{MeV}$$

Earth matter effects

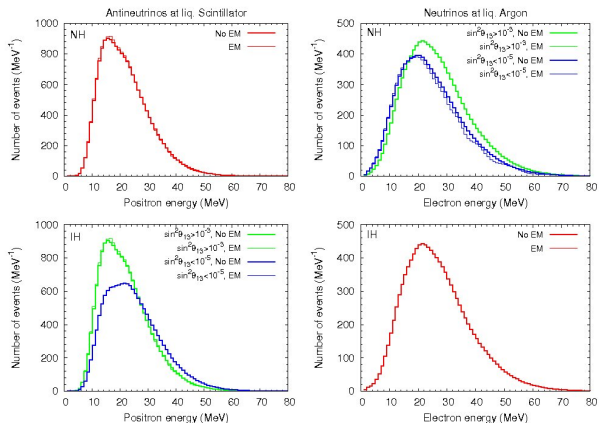
- If F_{ν_1} and F_{ν_2} reach the earth,

$$F_{\nu_e}^D(L) - F_{\nu_e}^D(0) = (F_{\nu_2} - F_{\nu_1}) \times \sin 2\theta_{12}^{\oplus} \sin(2\theta_{12}^{\oplus} - 2\theta_{12}) \sin^2 \left(\frac{\Delta m_{\oplus}^2 L}{4E} \right)$$

(Sign changes for antineutrinos)

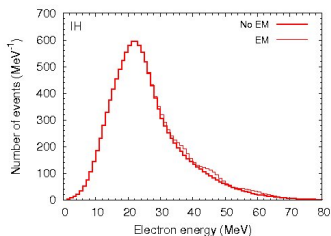
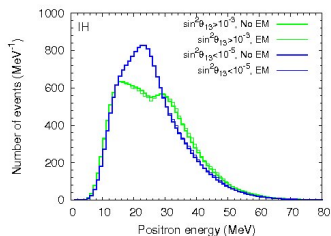
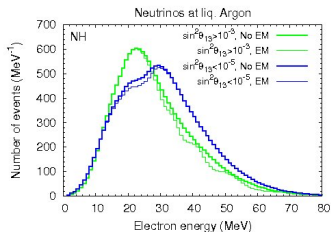
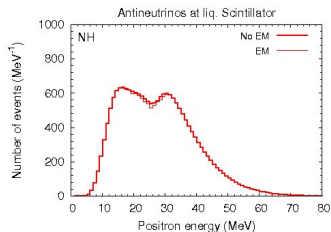
- Nonzero Earth matter effects require
 - Neutrinos: $p \neq 0$
 - Antineutrinos: $\bar{p} \neq 0$
- Can distinguish scenarios depending on Earth effects in different energy regimes
- A more efficient way of detecting split positions

Spectra at detectors with Earth effects: phase A



- Spectral splits not visible
- Earth effects possibly visible in neutrinos

Spectra at detectors with Earth effects: phase C

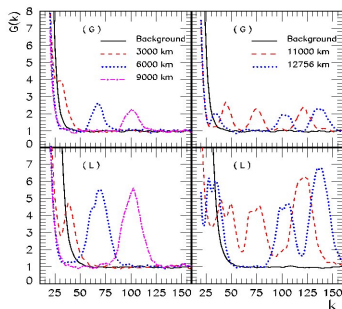


- Spectral split may be visible as “shoulders”
- Earth effects possibly visible, more prominent in ν_e

Earth effects: oscillations at a single detector

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

- Peak positions model independent, at known frequencies



AD, M. Kachelrieß, G. Raffelt,

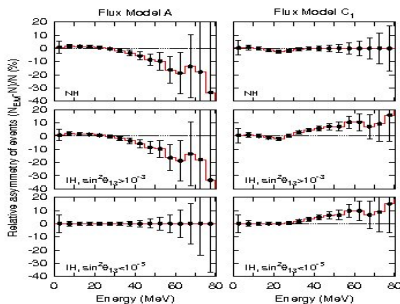
R. Tomàs, JCAP 0401:004 (2004)

Comparison between two detectors

- Ratio of luminosities at IceCube and a megaton water Cherenkov, as a function of time

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

- Comparing spectra at two 400 kt water Cherenkovs



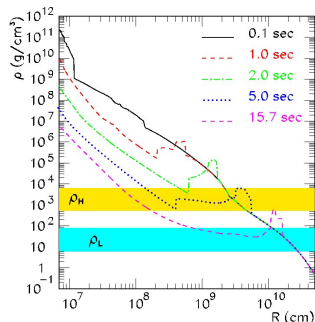
S. Choubey et al., arXiv:1008.0308 [hep-ph]

Robust experimental signature

- Earth effects can distinguish hierarchies even for $\theta_{13} \lesssim 10^{-10}$

Shock wave and adiabaticity breaking

When shock wave passes through a resonance region (density ρ_H or ρ_L):



- adiabatic resonances may become momentarily non-adiabatic
- 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)

J.P.Kneller, G.C.Mclaughlin, J.Brockman, PRD77, 045023 (2008)

Shock signals at a megaton water Cherenkov

- Time-dependent dip/peak features in $N_{\nu_e, \bar{\nu}_e}(E)$, $\langle E_{\nu_e, \bar{\nu}_e} \rangle$, $\langle E_{\nu_e, \bar{\nu}_e}^2 \rangle$, etc.
- Times at which dips/peaks appear in $N_{\bar{\nu}_e}(E)$ are the times at which the shock waves enter the densities

$$\rho(E) = \frac{m_N \Delta m_{atm}^2}{2\sqrt{2} G_F Y_e E}$$

- \Rightarrow Tracking of shock wave while it is still inside the mantle

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

Identifying mixing scenario

- Shock wave present in ν_e only for $\text{NH} \oplus \sin^2 \theta_{13} \gtrsim 10^{-5}$
- Shock wave present in $\bar{\nu}_e$ only for $\text{IH} \oplus \sin^2 \theta_{13} \gtrsim 10^{-5}$

Shock signals at a megaton water Cherenkov

- Time-dependent dip/peak features in $N_{\nu_e, \bar{\nu}_e}(E)$, $\langle E_{\nu_e, \bar{\nu}_e} \rangle$, $\langle E_{\nu_e, \bar{\nu}_e}^2 \rangle$, etc.
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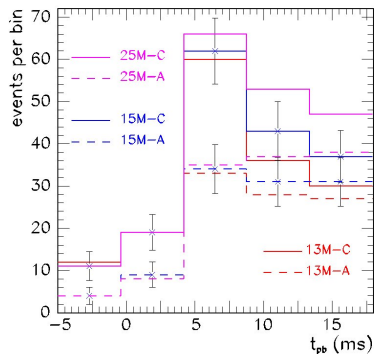
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Vanishing neutronization (ν_e) burst

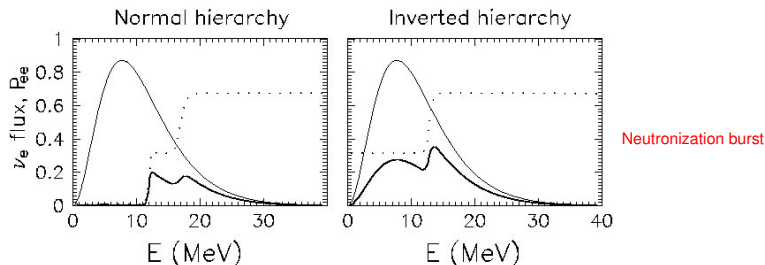


M. Kachelriess, R. Tomas, R. Buras,
H. T. Janka, A. Marek and M. Rampp
PRD 71, 063003 (2005)

- Time resolution of the detector crucial for separating ν_e burst from the accretion phase signal

Burst signal vanishes for $\text{NH} \oplus \sin^2 \theta_{13} \gtrsim 10^{-3}$

Stepwise spectral split in O-Ne-Mg supernovae



- MSW resonances deep inside collective regions

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

C. Lunardini, B. Mueller, H. T. Janka, arXiv:0712.3000

- “MSW-prepared” spectral splits: two for IH, one for NH

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, PRD77, 1130007 (2008)

- ν_e suppression more at low energy: Ar detector crucial
- Identification of O-Ne-Mg supernova ??

Inverse SN neutrino problem

Multiple independent signals

	Earth Matter Effects				Shock effects		ν_e burst vanishing
	ν_e		$\bar{\nu}_e$		ν_e	$\bar{\nu}_e$	
	Peak	Tail	Peak	Tail			
NH, $\sin^2 \theta_{13} \gtrsim 10^{-3}$							
Phase A	X	X	✓	✓	✓	X	✓
Phase C	X	✓	✓	X	✓	X	✓
NH, $\sin^2 \theta_{13} \lesssim 10^{-5}$							
Phase A	✓	✓	✓	✓	X	X	X
Phase C	✓	X	✓	X	X	X	X
IH, $\sin^2 \theta_{13} \gtrsim 10^{-3}$							
Phase A	X	X	✓	✓	X	✓	X
Phase C	X	✓	✓	✓	X	✓	X
IH, $\sin^2 \theta_{13} \lesssim 10^{-5}$							
Phase A	X	X	X	X	X	X	X
Phase C	X	✓	X	✓	X	X	X

Smoking gun signals and caveats

Earth matter effects

- Hierarchy identification even for extremely small θ_{13} values
- If primary fluxes are similar, identifying Earth effects is hard
- Multi-angle effects still to be understood (should not affect in accretion phase)
- Better results with ν_e spectrum \Rightarrow **Ar detector crucial**

S.Choubey et al., 2010

Shock wave effects

- Presence / absence independent of collective effects
- Stochastic density fluctuations: may partly erase the shock wave imprint
- Turbulent convections behind the shock wave: gradual depolarization effects

G. Fogli et al, 2003

A. Friedland et al., 2006; J. Kneller et al, 2008, 2010,

Neutronization burst signal

- **Robust**, but needs Ar detector with good time resolution