Neutrino-neutrino interactions inside a SN

and their effects on neutrino flavor conversions

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Outline

1. Neutrino interactions inside a SN core
2. Net neutrino flavor conversions
3. Observations at neutrino detectors

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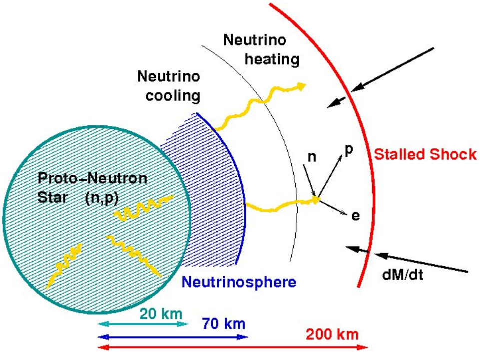
Neutrinos and the SN explosion

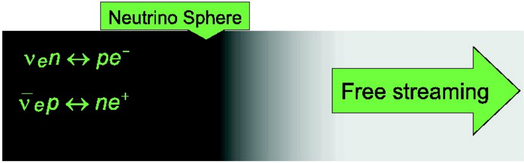


Requirements for a successful explosion

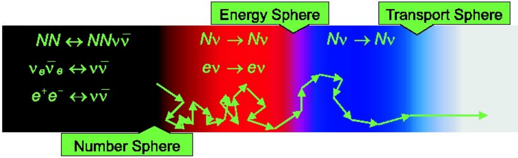
- Neutrinos pushing the shock wave (cross sections)
- Large scale convection ($\geq$ 2 dimensional simulations)
- Hydrodynamic instabilities

Hammer, Janka, Mueller, arXiv:0908.3474 [astro-ph.SR]

Neutrino trapping and free-streaming



$\nu_e, \bar{\nu}_e$

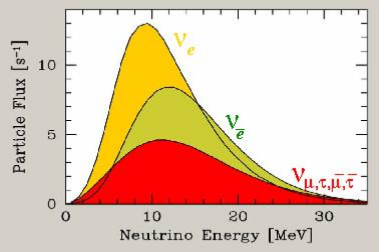


$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

Zeroth approximation: “neutrinospheres”

- Inside ($\rho \gtrsim 10^{10}$g/cc): neutrinos trapped
- Outside ($\rho \lesssim 10^{10}$g/cc): neutrinos free-streaming
- Depend on neutrino flavor and energy

Typical features of the spectra

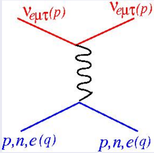


- Average energies:
  $\langle E_0(\nu_e)\rangle \approx$ 10–12 MeV
  $\langle E_0(\bar{\nu}_e)\rangle \approx$ 13–16 MeV
  $\langle E_0(\nu_x)\rangle \approx$ 15–25 MeV
- Energy hierarchy:
  $\langle E_0(\nu_e)\rangle < \langle E_0(\bar{\nu}_e)\rangle < \langle E_0(\nu_x)\rangle = \langle E_0(\nu_y)\rangle$
- Luminosities:
  $L_{\nu_e} \approx L_{\bar{\nu}_e}$
  $L_{\nu_x} \approx (0.5 - 2.0)\ L_{\nu_e}$

Forward scattering for free-streaming neutrinos

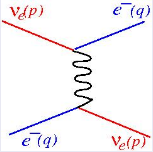
Scattering over protons, neutrons and electrons

NC:



$V^{\nu_\alpha\nu_\alpha}_{NC} = -G_F N_n/\sqrt{2}$

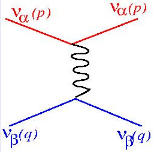
CC:



$V^{\nu_e\nu_e}_{CC} = \sqrt{2}G_F N_e$

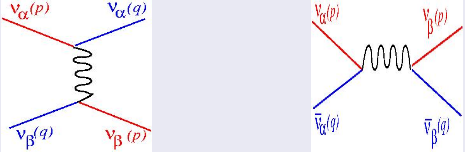
Scattering over neutrinos and antineutrinos:

FC:



$V^{\nu_\alpha\nu_\alpha}_{\nu\nu} = \sqrt{2}G_F N_\nu$

FV: flavour non-diagonal potential



$V^{\nu_\alpha\nu_\beta}_{\nu\nu} = \sqrt{2}G_F\langle\nu^*_\alpha\nu_\beta\rangle$, $V^{\nu_\alpha\nu_\beta}_{\nu\nu} = -\sqrt{2}G_F\langle\bar{\nu}^*_\beta\bar{\nu}_\alpha\rangle$

- Density matrix formalism the most natural (and necessary)

Nonlinear effects due to $\nu - \nu$ coherent interactions

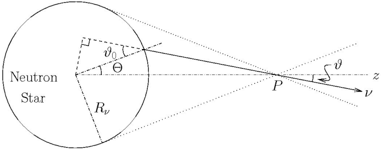
- Large neutrino density ⇒ substantial ν–ν potential

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

$$\begin{aligned} H_{vac}(\vec{p}) &= M^2/(2p) \\ H_{MSW} &= \sqrt{2} G_F N_e diag(1,0,0) \\ H_{\nu\nu}(\vec{p}) &= \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{pq}) (\rho(\vec{q}) - \bar{\rho}(\vec{q})) \end{aligned}$$

- $d\rho/dt = i[H(\rho), \rho]$ ⇒ Nonlinear effects !

Single-angle approximation and multi-angle effects



H.Duan, G.M.Fuller, J.Carlson

Y.-Z. Qian, PRD74, 105014 (2006)

- Multi-angle simulations computationally intensive
- Single angle approximation: Potential calculated by an *a priori* effective averaging over all angles

Multi-angle effects

- Smearing of the spectral features

  Fogli et al., JCAP 0712, 010 (2007)

- "Multi-angle decoherence" suppressed by large ν–$\bar{\nu}$ flux asymmetry, enhanced at extremely high matter densities.

  A. Esteban-Pretel et al., PRD76, 125018 (2007), PRD78, 085012 (2008)

- May affect the onset of neutrino oscillations

  H. Duan, A. Friedland, 2010

“Collective” effects: qualitatively new phenomena

Synchronized oscillations:

ν and $\bar{\nu}$ of all energies oscillate with the same frequency

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

Bipolar/pendular oscillations:

Coherent $\nu_e\bar{\nu}_e \leftrightarrow \nu_y\bar{\nu}_y$ and $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ oscillations even for extremely small θ_{13}

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

Spectral split/swap:

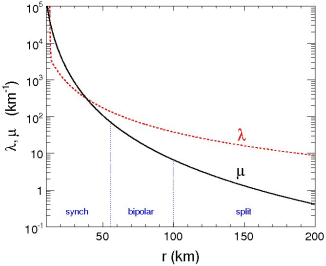
ν_e and ν_y ($\bar{\nu}_e$ and $\bar{\nu}_y$) spectra
interchange completely, but only within certain energy ranges.
Similarly for ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) swaps

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

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL103,051105 (2009)

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

Sequential dominance of phenomena (Fe-core SN)



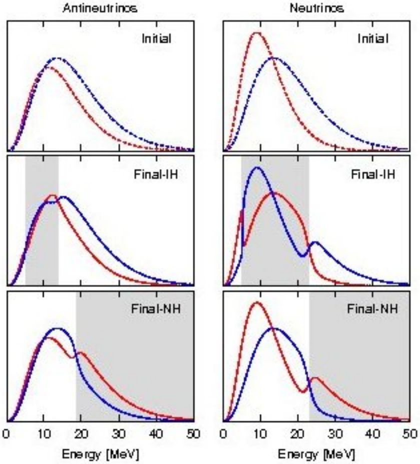
- $\mu \equiv \sqrt{2} G_F (N_\nu + N_{\bar{\nu}})$
- $\lambda \equiv \sqrt{2} G_F N_e$

- $r \lesssim 200$ km: collective effects dominate
- $r \gtrsim 200$ km: standard MSW matter effects dominate

G.L.Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)

Spectral split/swap depend on hierarchy

cooling-phase Garching fluxes



B. Dasgupta, AD, G.Raffelt, A.Smirnov, arXiv:0904.3542 [hep-ph], PRL

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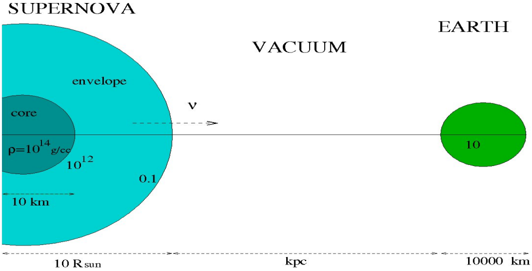
Propagation through matter of varying density



Inside the SN: *flavor conversion*

Collective effects and MSW matter effects

Between the SN and Earth: *no flavor conversion*

Mass eigenstates travel independently

Inside the Earth: *flavor oscillations*

MSW matter effects (*if detector is shadowed by the Earth*)

After collective oscillations, before MSW oscillations

Electron flavor dominance: $L_{\nu_e} \approx L_{\bar{\nu}_e} \gtrsim L_{\nu_x}$ (Phase A)

- No swaps for NH
- $\nu_e \leftrightarrow \nu_y$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$ swaps for IH

Non-electron flavor dominance: $L_{\nu_e} \approx L_{\bar{\nu}_e} \lesssim L_{\nu_x}$ (Phase C)

- $\nu_e \leftrightarrow \nu_y$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$ swaps for NH
- Additional $\nu_e \leftrightarrow \nu_x$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ swaps for IH

NH vs. IH distinction possible even for $\sin^2 2\theta_{13}$ as low as 10^{-10} (and even lower) $\Leftarrow$ Nonlinear instability

After collective oscillations, before MSW oscillations

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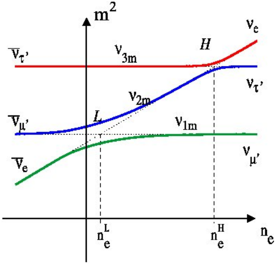
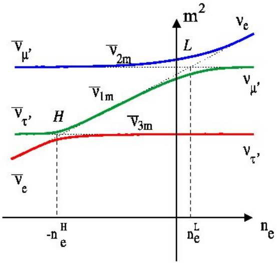
NH vs. IH distinction possible even for $\sin^2 2\theta_{13}$ as low as 10^{-10} (and even lower) $\Leftarrow$ Nonlinear instability

MSW Resonances inside a SN

Normal mass ordering



Inverted mass ordering



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

H resonance: $(\Delta m^2_{\rm atm}, \theta_{13})$, $\rho \sim 10^3$–10^4 g/cc

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

L resonance: $(\Delta m^2_{\odot}, \theta_{\odot})$, $\rho \sim 10$–100 g/cc

- Always adiabatic, always in ν

Fluxes arriving at the Earth

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

p at low, intermediate, high energies

		Phase A ($L_{\nu_e} \gtrsim L_{\nu_x}$)			Phase C ($L_{\nu_e} \gtrsim L_{\nu_x}$)		
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 ($L_{\nu_e} \gtrsim L_{\nu_x}$)		
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)

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

( ), [ ] : non-adiabatic swaps

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Signal expected from a galactic SN (10 kpc)

Water Cherenkov detector: (events at SK)

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

  $$\Delta_{\mathrm{WC}}/\mathrm{MeV} = 0.47\sqrt{E_e/\mathrm{MeV}}$$
- $\nu e^- \to \nu e^-$: $\approx 200 - 300$
- $\nu_e +^{16} O \to X + e^-$: $\approx$ 150–800

Carbon-based scintillation detector:

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

  $$\Delta_{\mathrm{SC}}/\mathrm{MeV} = 0.075\sqrt{E_e/\mathrm{MeV}}$$
- $\nu + {}^{12}C \to \nu + X + \gamma$ (15.11 MeV)

Liquid Argon detector:

- $\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$ ($\sim$ 300 per kt)

  $$\Delta_{\mathrm{LAr}}/\mathrm{MeV} = 0.11\sqrt{E_e/\mathrm{MeV}} + 0.02\, E_e/\mathrm{MeV}$$

Earth matter effects

When neutrinos pass through the Earth

- Oscillations inside the Earth (like day-night effects)
- Total flux / luminosities change
- Oscillating features in the final spectra

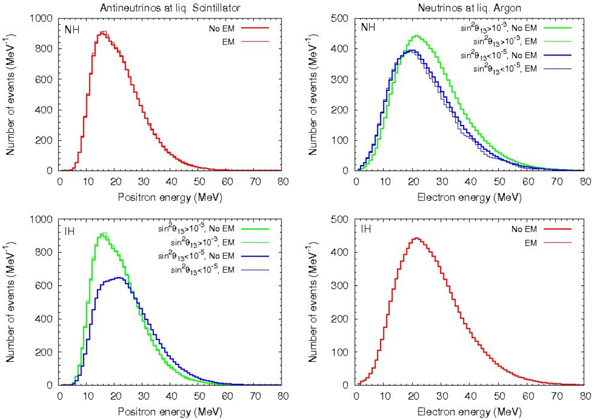
Detection of Earth effects

- Identify oscillations at a single detector (need good energy resolution)
- Compare signal at two large detectors, one of which is “shadowed” by the Earth (e.g. IceCube vs. HK)

Robust experimental signature

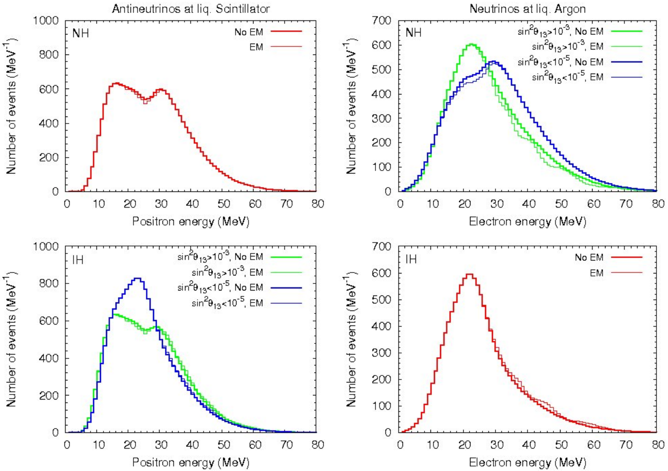
- Earth effects can distinguish hierarchies even for $\theta_{13} \lesssim 10^{-10}$

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

Shock wave effects

When shock wave passes through a resonance

- Adiabatic resonances become temporarily non-adiabatic
- Sharp changes in the final spectra even if the primary spectra change smoothly

Schirato and Fuller, astro-ph/0205390, Fogli et al., PRD 68, 033005 (2003), J. Kneller et al., PRD77, 045023 (2008)

Detection of shock wave effects

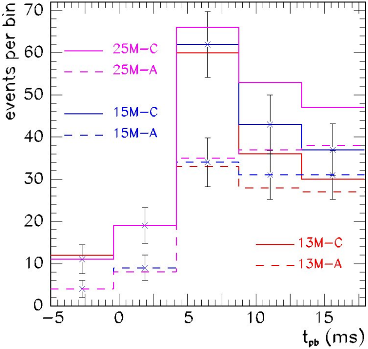
- Time-dependent dip/peak features in $N_{\nu_e,\bar{\nu}_e}(E)$, $\langle E_{\nu_e,\bar{\nu}_e} \rangle$, $\langle E^2_{\nu_e,\bar{\nu}_e} \rangle$, etc.
- Times at which dips/peaks appear show when the shock waves enter the resonance densities $\rho(E) = (m_N \Delta m^2_{atm})/(2\sqrt{2} G_F Y_e E)$

R. Tomas et al., JCAP 0409, 015 (2004)

Identifying mixing scenario

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

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 NH $\oplus \sin^2\theta_{13} \gtrsim 10^{-3}$

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

What should the detectors look for

Spectral splits

Sharp shoulders: difficult to identify

Earth matter effects

- Comparatively easy to identify (if shadowed detector)
- If primary fluxes are similar, identifying Earth effects is hard
- Better results with ν_e spectrum ⇒ Ar detector crucial
- Hierarchy identification even for extremely small θ_{13} values

Shock wave effects

- Easy to spot with time variation of signal
- Presence / absence independent of collective effects
- Hierarchy determination possible for $\theta_{13} \gtrsim 10^{-5}$

Neutronization burst signal

- Robust, but needs Ar detector and good time resolution

Final comments

Open questions in ν–ν interaction effects

- Better analytical understanding of collective effects
- Development of "pendular oscillations"
- Prediction of positions of spectral splits
- Extent of multi-angle effects, decoherence
- Effects of turbulence

Effect of ν–ν interactions on SN astrophysics

- Shock wave propagation
  (Flavor conversions change net $\nu - N$ cross section)
- R-process nucleosynthesis

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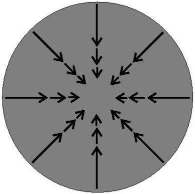
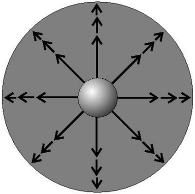
Extra Slides

Core collapse, shock wave, and explosion

Gravitational core collapse ⇒ Shock Wave





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

Cooling through neutrino emission: $\sim 10^{58}$ neutrinos

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ Duration: About 10 sec

Emission of 99% of the SN collapse energy in neutrinos

¿¿¿ Explosion ???

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 → bipolar osc → 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 $\sin^2\theta_{13} \sim 10^{-10}$

Changing paradigm of SN neutrino oscillations

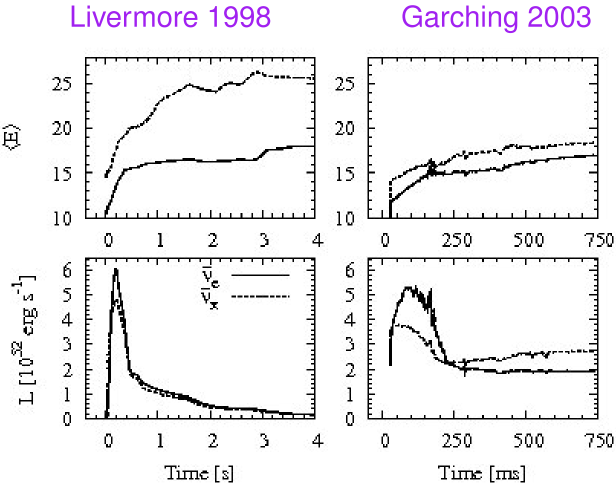
Multiple spectral splits (2009 –)

- "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

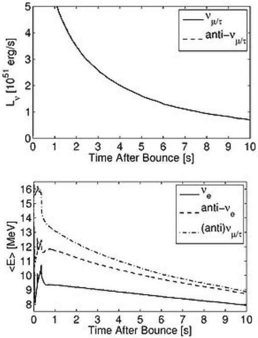
Garching 2003

solid: $\bar{\nu}_e$, dotted: $\bar{\nu}_x$

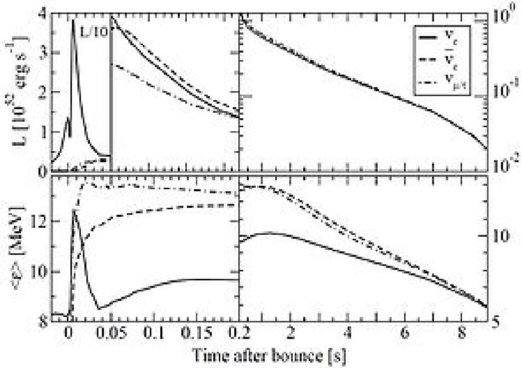
Totani et al., 1998, Raffelt et al., 2003

Recent model preditions for fluxes

Basel 2009



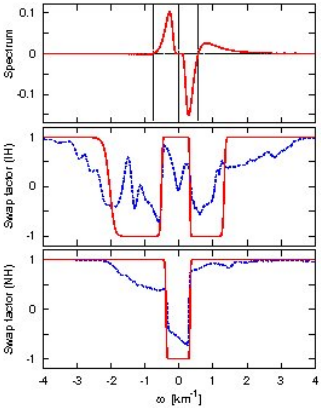
Garching 2009



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)

Mass ordering, spectral crossings, swaps, and splits



- Neutrinos:
  $\omega \equiv 1/E$
- Antineutrinos:
  $\omega \equiv -1/E$
- Spectrum
  $g(|\omega|) = F_{\nu_e}(\omega) - F_{\nu_x}(\omega)$
  $g(-|\omega|) = F_{\bar{\nu}_x}(\omega) - F_{\bar{\nu}_e}(\omega)$
- Swap
  $S(\omega) = \frac{g(\omega)_{final}}{g(\omega)_{initial}}$

Swap $S(\omega) = -1 \Rightarrow$

- Inverted Hierarchy: positive crossing
- Normal Hierarchy: negative crossing
- Nearby swaps may overlap to reduce number of splits

B. Dasgupta, AD, G.Raffelt, A.Smirnov, arXiv:0904.3542 [hep-ph], PRL

Earth matter effects

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

$$F^D_{\nu_e}(L) - F^D_{\nu_e}(0) \;=\; (F_{\nu_2} - F_{\nu_1}) \times \sin 2\theta^{\oplus}_{12} \sin(2\theta^{\oplus}_{12} - 2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{\oplus} L}{4E}\right)$$

(Sign changes for antineutrinos)

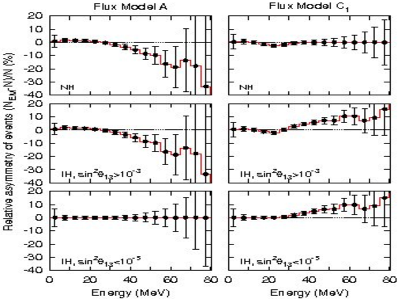
- Nonzero Earth matter effects require
  - Neutrinos: $p \neq 0$
  - Antineutrinos: $\bar{p} \neq 0$
- Can distinguish scenarios depending on Earth effects in different energy regimes
- A more efficient way of detecting split positions

Earth effects: 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



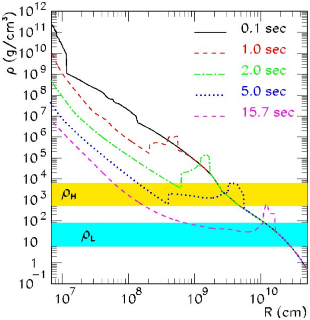
S. Choubey et al., arXiv:1008.0308 [hep-ph]

Robust experimental signature

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

Shock wave effects

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

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

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

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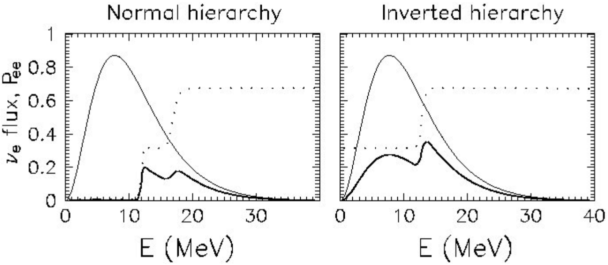
Stepwise spectral split in O-Ne-Mg supernovae



Neutronization burst

- 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 ??