Neutrino Physics: Lecture 17

Supernova neutrinos

Amol Dighe

Department of Theoretical Physics
Tata Institute of Fundamental Research

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Outline

1. Explosion and neutrino emission
2. Neutrino flavour conversions
3. Detection of SN neutrinos

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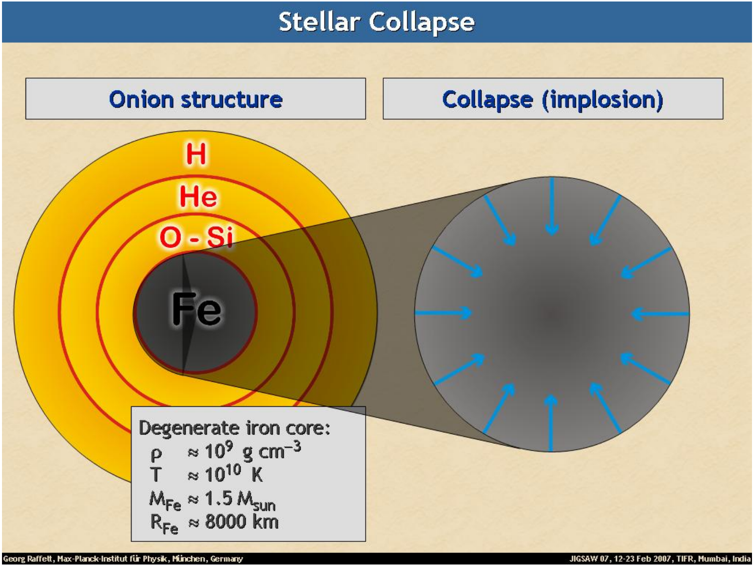
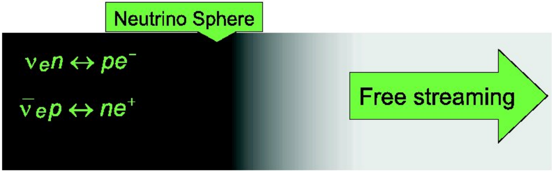
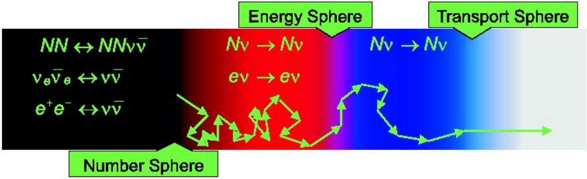
The would-be supernova before the collapse



Trapped neutrinos before the collapse

- Neutrinos trapped inside “neutrinospheres” around $\rho \sim 10^{10}$g/cc.

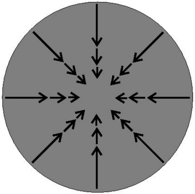


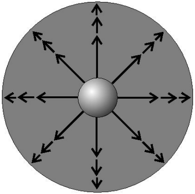


- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

Core collapse and the shock wave

Gravitational core collapse $\Rightarrow$ Shock Wave





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

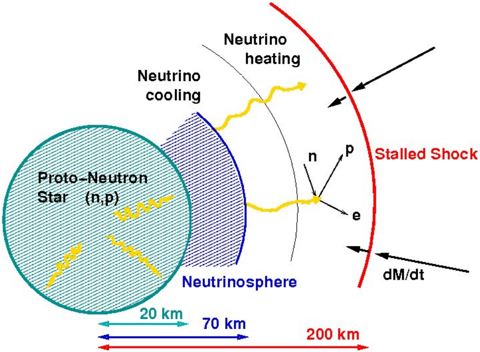
Cooling through neutrino emission: $\sim 10^{58}$ neutrinos

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

Emission of 99% of the SN energy in neutrinos

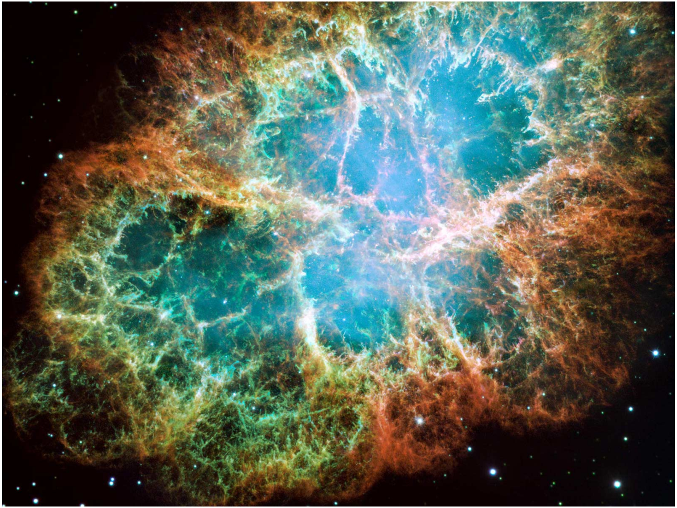
¿¿¿ Explosion ???

Role of neutrinos in explosion



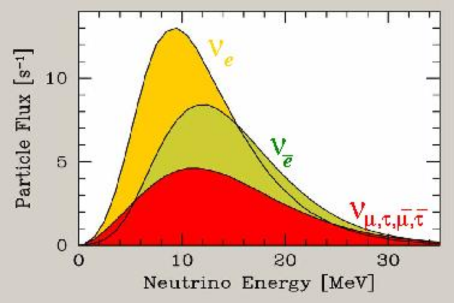
- Neutrino heating needed for pushing the shock wave
- Large scale convection also needed for explosion

The star after explosion



(Crab nebula, supernova seen in 1054)

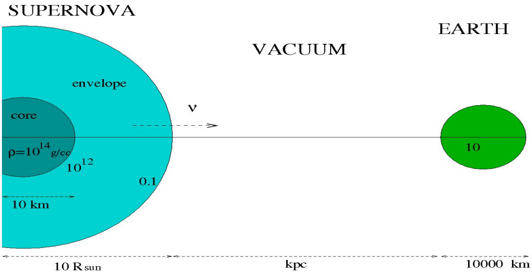
Primary fluxes and spectra



- Almost blackbody spectra, slightly "pinched"
- Energy hierarchy: $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$
- $E_0(\nu_e) \approx$ 10–12 MeV
  $E_0(\bar{\nu}_e) \approx$ 13–16 MeV
  $E_0(\nu_x) \approx$ 15–25 MeV

Outline

Neutrino oscillations in matter of varying density



Inside the SN: ***flavour conversion***

Non-linear "collective" effects and resonant matter effects

Between the SN and Earth: ***no flavour conversion***

Mass eigenstates travel independently

Inside the Earth: ***flavour oscillations***

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

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

- Large neutrino density $\Rightarrow$ substantial ν–ν potential

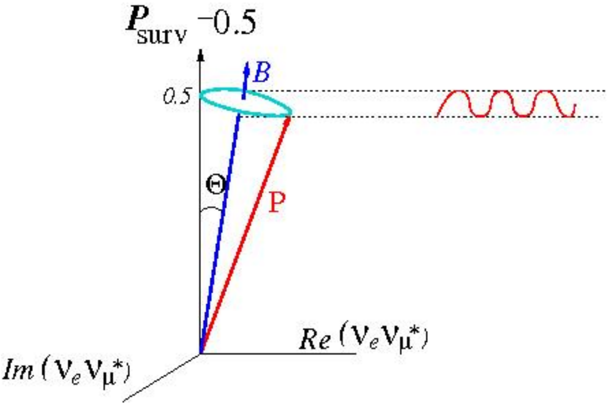
$$H = H_{vac} + H_{MSW} + H_{\nu\nu}$$

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

- $$\frac{d\rho}{dt} = i[H(\rho), \rho] \quad \Rightarrow \quad \text{Nonlinear effects !}$$

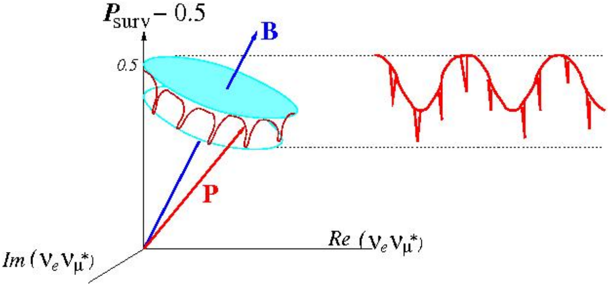
Synchronized osc. $\rightarrow$ Bipolar osc. $\rightarrow$ Spectral split

Synchronized oscillations



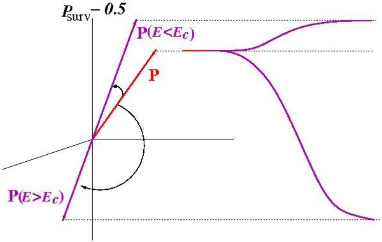
- ν and $\bar{\nu}$ of all energies oscillate with the same frequency
- No significant flavour change since mixing angle is small

Bipolar oscillations

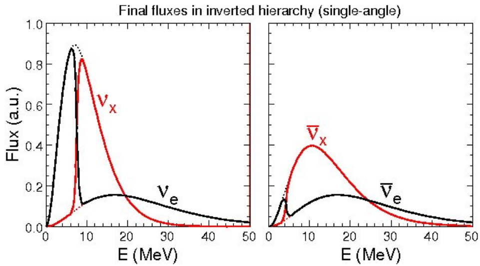


- Coherent $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ oscillations
- A nutating top ??
- Even $\theta_{13} \lesssim 10^{-10}$ OK !
- Prepare neutrinos for the “spectral split”

Spectral split



- $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra interchange completely
- ν_e and ν_x spectra interchange for $E > E_c$



"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 $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ 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_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra interchange completely, only within certain energy ranges.

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

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

Collective effects influencing supernova astrophysics

- Nucleosynthesis of heavy elements (r-process)
- Shock wave propagation

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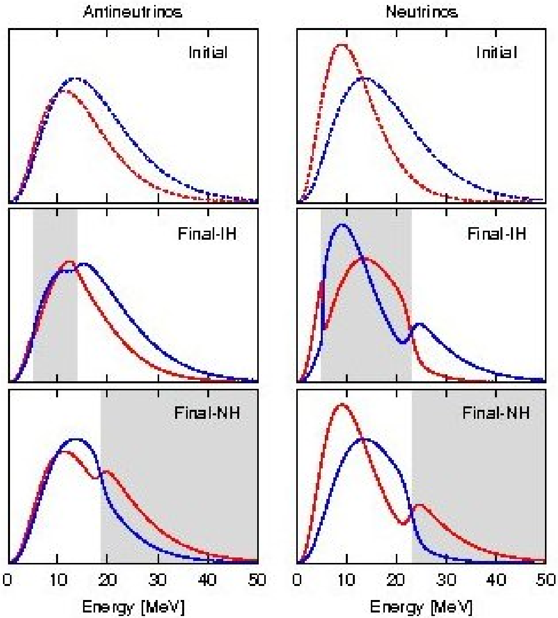
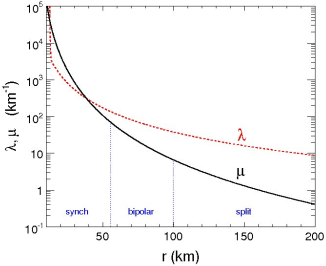
Neutrino spectra after collective effects



red ν_e
blue ν_x

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL 2009

Sequential dominance of phenomena (Fe-core SN)



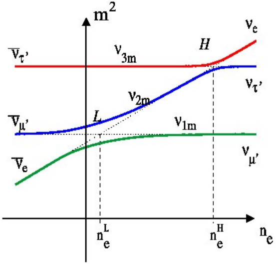
- $\mu \equiv \sqrt{2} G_F (N_\nu + N_{\bar{\nu}})$
- $\lambda \equiv \sqrt{2} G_F N_e$

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

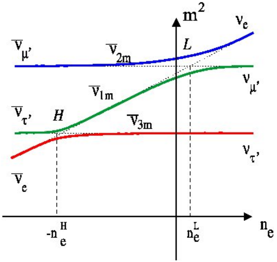
G.L.Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)

MSW Resonances inside a SN

Normal mass ordering



Inverted mass ordering



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

Mixture of initial fluxes:

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

p and $\bar{p}$ in the swapped and unswapped energy regimes (Low-Δm^2 swaps not included)

		Θ_{13}	p unswapped	p swapped	$\bar{p}$ unswapped	$\bar{p}$ swapped
A	NH	Large	0	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$	0
B	IH	Large	$\sin^2\theta_{12}$	0	0	$\cos^2\theta_{12}$
C	NH	small	$\sin^2\theta_{12}$	0	$\cos^2\theta_{12}$	0
D	IH	small	$\sin^2\theta_{12}$	0	$\cos^2\theta_{12}$	0

- "Small": $\sin^2\theta_{13} \lesssim 10^{-5}$, "Large": $\sin^2\theta_{13} \gtrsim 10^{-3}$.

Outline

A recent nearby supernova: SN1987A

(Hubble image)

- 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

Signal expected from a galactic SN (10 kpc)

Water Cherenkov detector:

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

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

Carbon-based scintillation detector:

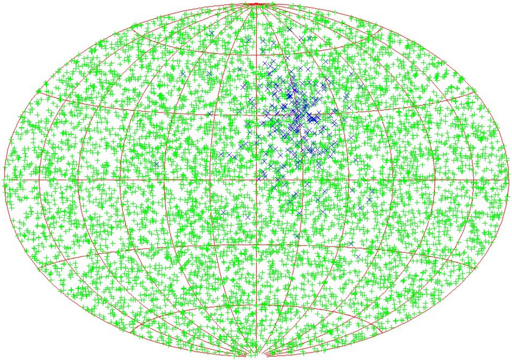
- $\bar{\nu}_e p \rightarrow n e^+$ 300/kt
- $\nu + {}^{12}C \rightarrow \nu + X + \gamma$ (15.11 MeV)

Liquid Argon detector:

- $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$ 30 0/kt

Pointing to the SN in advance

- Neutrinos reach 6-24 hours before the light from SN explosion (SNEWS network)
- $\bar{\nu}_e p \to n e^+$: nearly isotropic background
- $\nu e^- \to \nu e^-$: forward-peaked "signal"
- Background-to-signal ratio: $N_B/N_S \approx 30\text{–}50$
- SN at 10 kpc may be detected within a cone of $\sim 5^\circ$ at SK



Earth matter effects

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

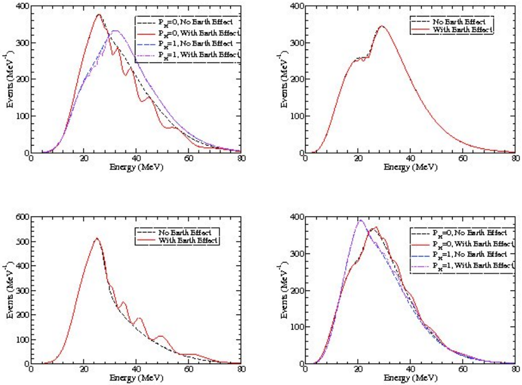
$$F^D_{\nu_e}(L) - F^D_{\nu_e}(0) = (F_{\nu_2} - F_{\nu_1}) \times \sin 2\theta^{\oplus}_{12} \sin(2\theta^{\oplus}_{12} - 2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{\oplus} L}{4E}\right)$$

(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

Event spectra observed at detectors

Neutrinos   Antineutrinos

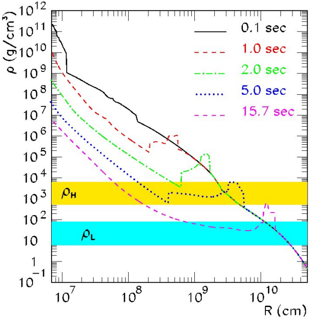


- Identify oscillations at one detector
- Compare total luminosity at two detectors

IceCube: the best luminosity counter

Shock wave and adiabaticity breaking

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

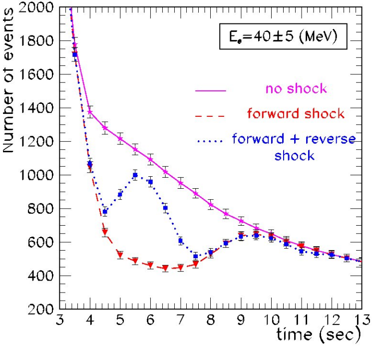


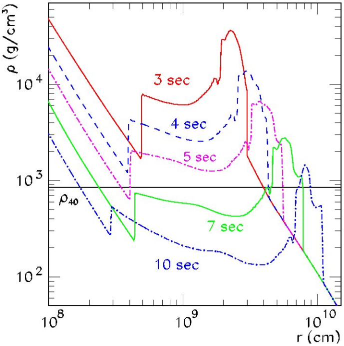
- adiabatic resonances may become momentarily non-adiabatic
- Sharp changes in the final spectra even if the primary spectra change smoothly

R. C. Schirato, G. M. Fuller, astro-ph/0205390

G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi, PRD 68, 033005 (2003)

Tracking the shock fronts





- At $t \approx 4.5$ sec, (reverse) shock at ρ_{40}
- At $t \approx 7.5$ sec, (forward) shock at ρ_{40}
- Multiple energy bins ⇒ the times the shock fronts reach different densities of $\rho \sim 10^2$–10^4 g/cc

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 scenario A
- Shock wave present in $\bar{\nu}_e$ only for scenario B

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What supernova neutrinos can tell us

On neutrino physics

- Information about ν masses and mixings encoded in energy spectra of neutrinos
- Identify neutrino mass ordering: normal or inverted

On supernova astrophysics

- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)

Inverse supernova neutrino problem

Observe the neutrino spectra, deduce neutrino mixing parameters, primary neutrino spectra, shock wave propagation

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