Supernova Seismology: Shock Waves, Turbulence and Neutrinos

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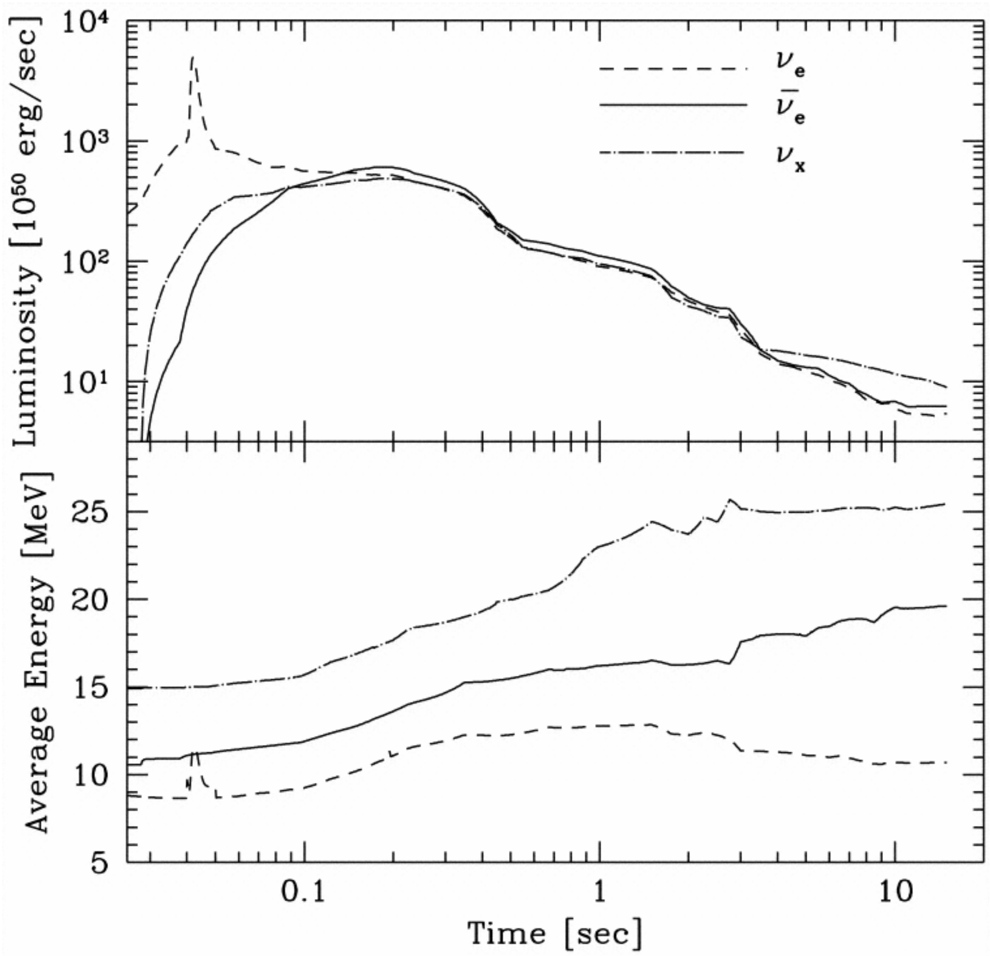
Overview

- Supernova mechanism
- Neutrino oscillations in supernova
- The effect of a shock-wave and turbulence on oscillations
- Predicted signal in a megaton water Cherenkov detector
- Sterile neutrino
- Conclusion

Supernovae

- Stars $M > 8M_\odot$ burn for millions of years and collapse when the core becomes too massive to be supported by thermal or degenerate pressures
- When the core reaches nuclear density the collapse rebounds to form an outward shock
- This shock stalls, then a explosion is triggered by neutrino heating
- Computer simulations predict that a forward and reverse shock forms with a turbulent region behind

Simulations of a supernova



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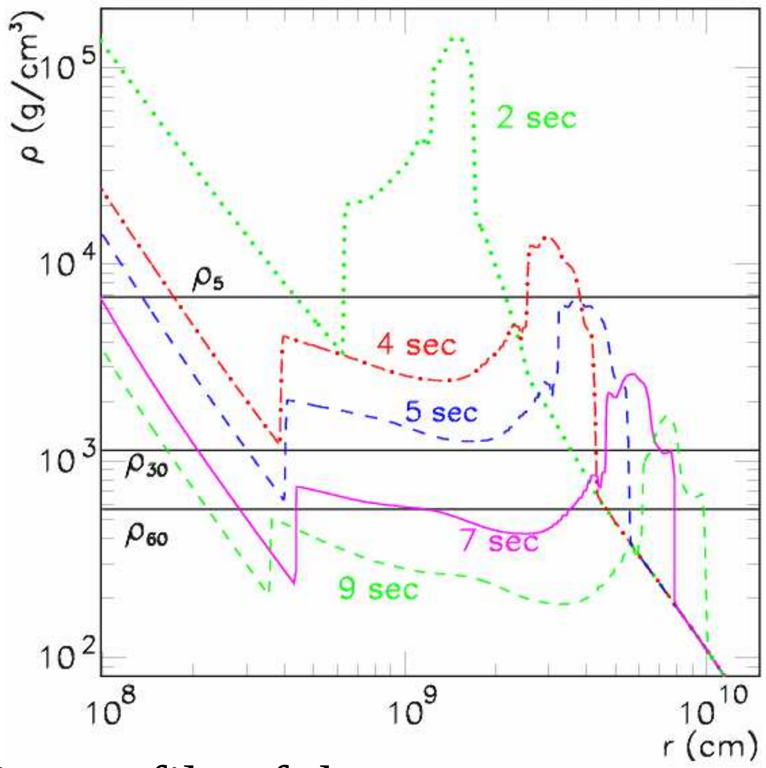
The Lawrence Livermore simulation, full time dependence but all of the interactions were not included(left)



The density profile of the shock-wave (right)

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Neutrino Oscillations

The probability of an oscillation in vacuum is

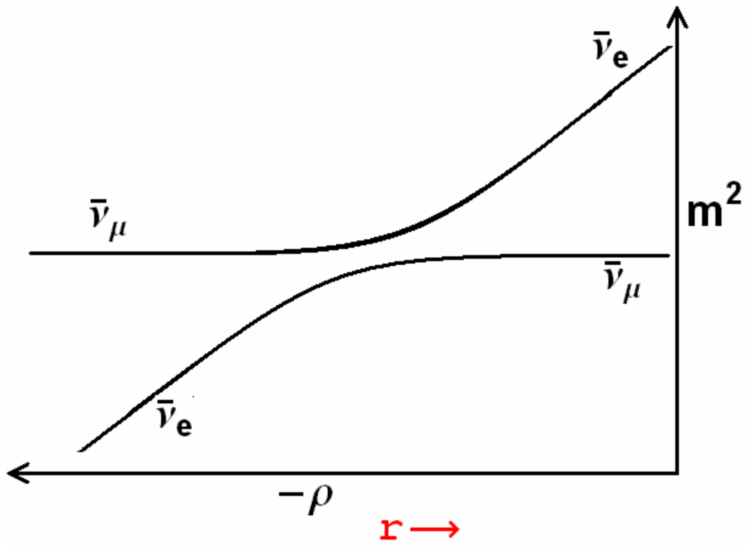
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2(1.27 \Delta m_{21}^2 L/E)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2(1.27 \Delta m_{21}^2 L/E)$$

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

In matter:

$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \frac{A - \Delta m_{21}^2 \cos 2\theta}{4E} & \frac{\Delta m_{21}^2 \sin 2\theta}{4E} \\ \frac{\Delta m_{21}^2 \sin 2\theta}{4E} & -\frac{A - \Delta m_{21}^2 \cos 2\theta}{4E} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$



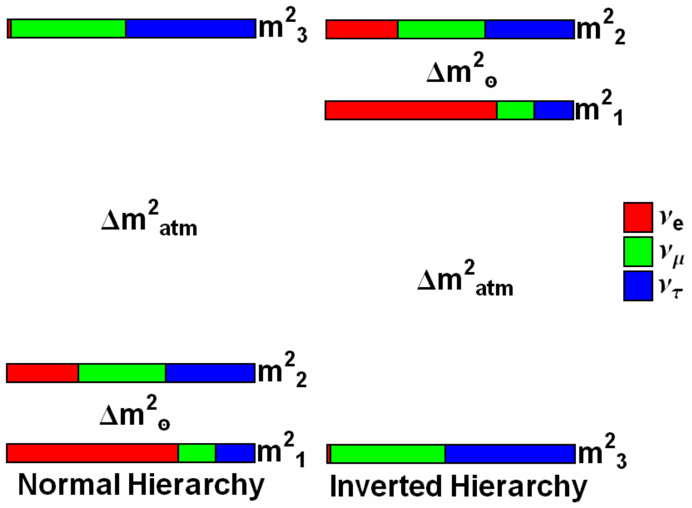
$A \propto \rho$ (neutrino) $A \propto -\rho$ (anti-neutrino)

Resonance when $A = \Delta m_{21}^2 \cos 2\theta$ when the neutrinos are maximally mixed

If $\Delta m^2 > 0$ the resonance is in the neutrino channel

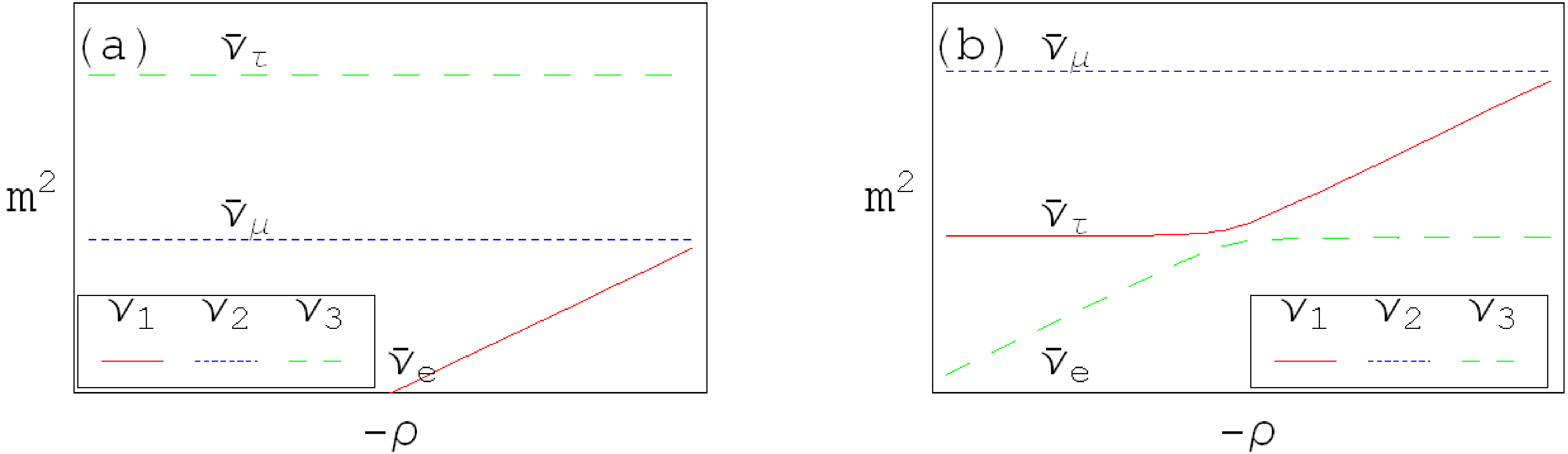
If $\Delta m^2 < 0$ the resonance is in the anti-neutrino channel

Anti-neutrino resonance

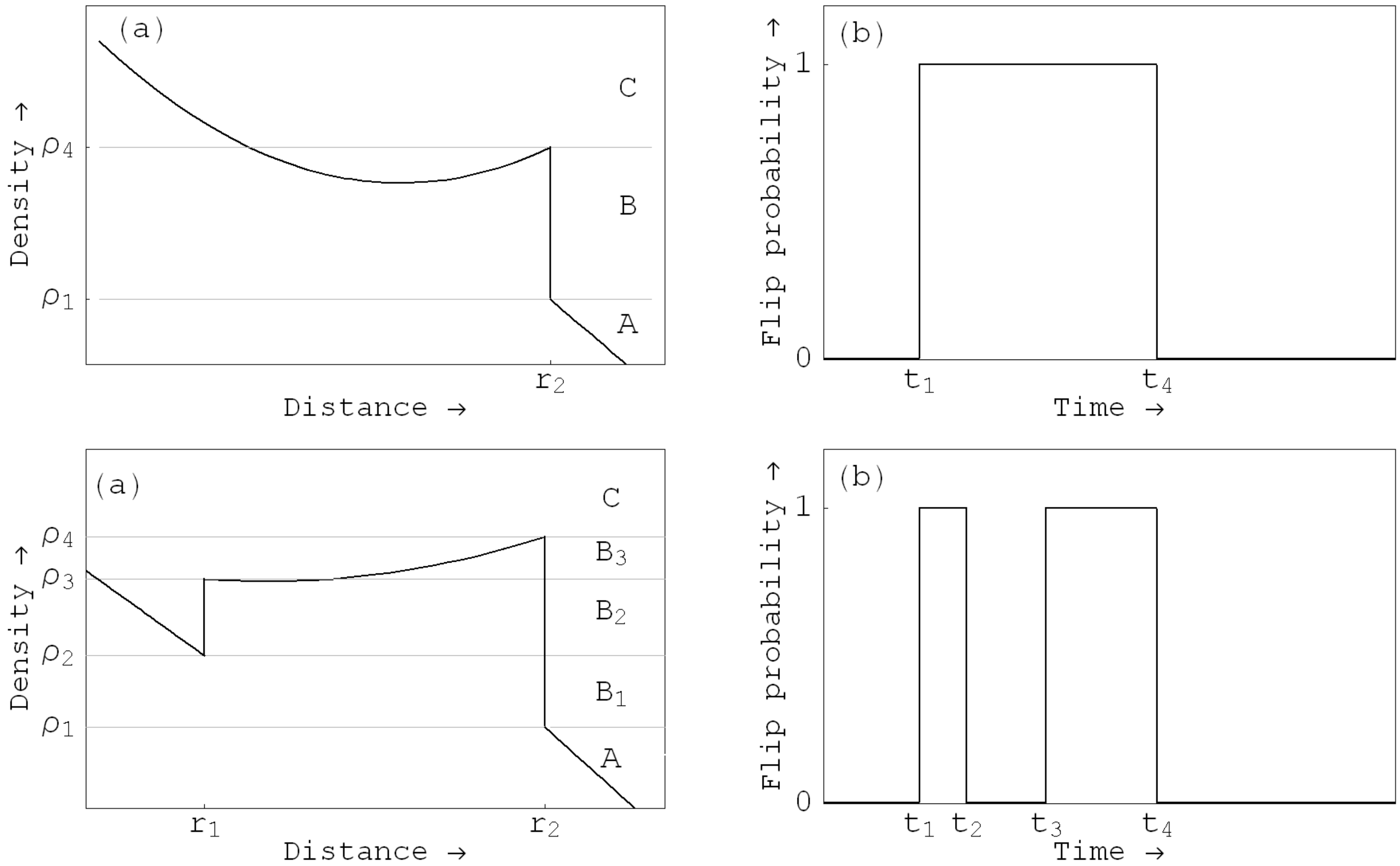


The mass squared difference in matter for the anti-neutrino channel

(a) normal hierarchy
(b) inverted hierarchy



Effect of the shock wave on the oscillations

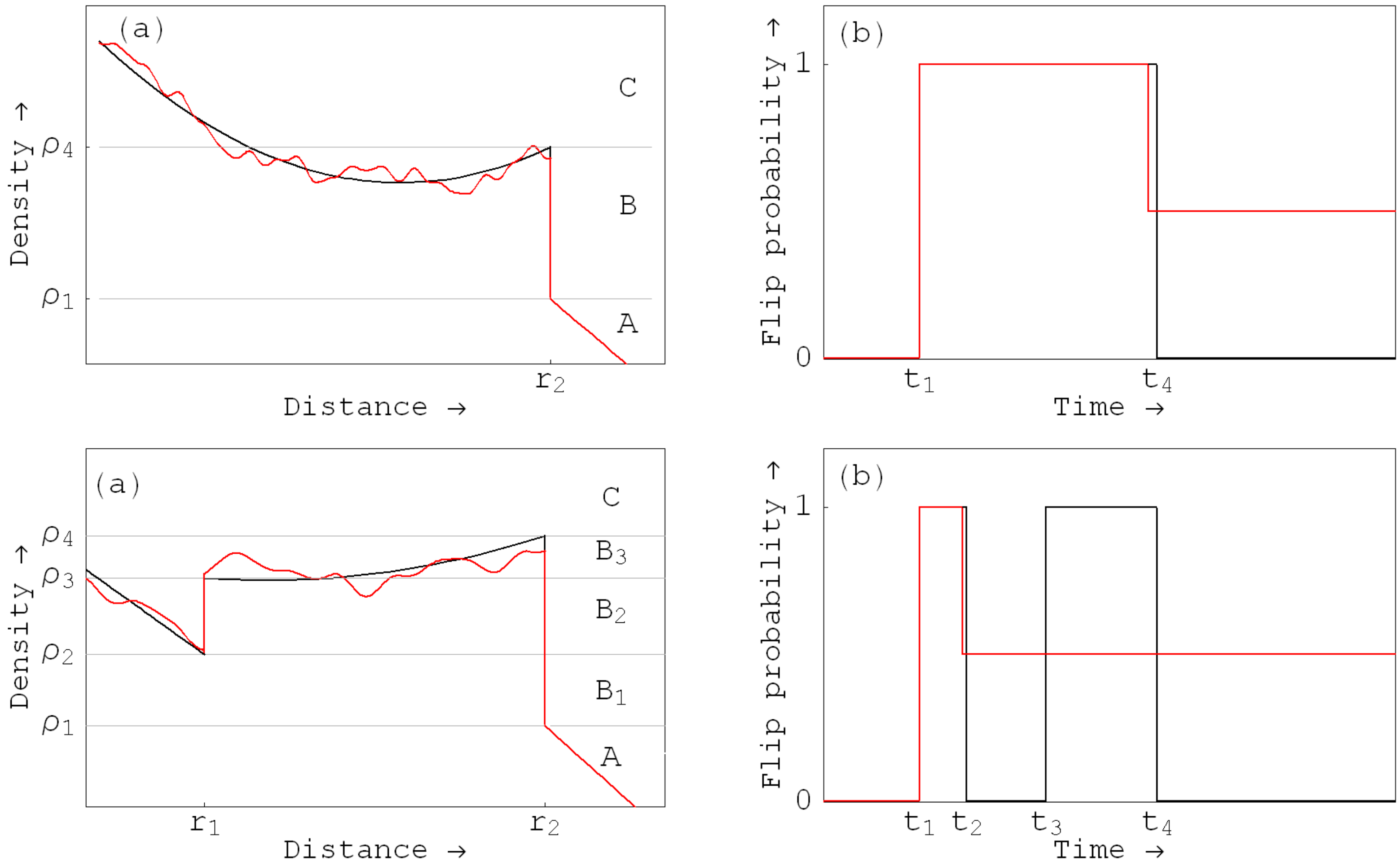


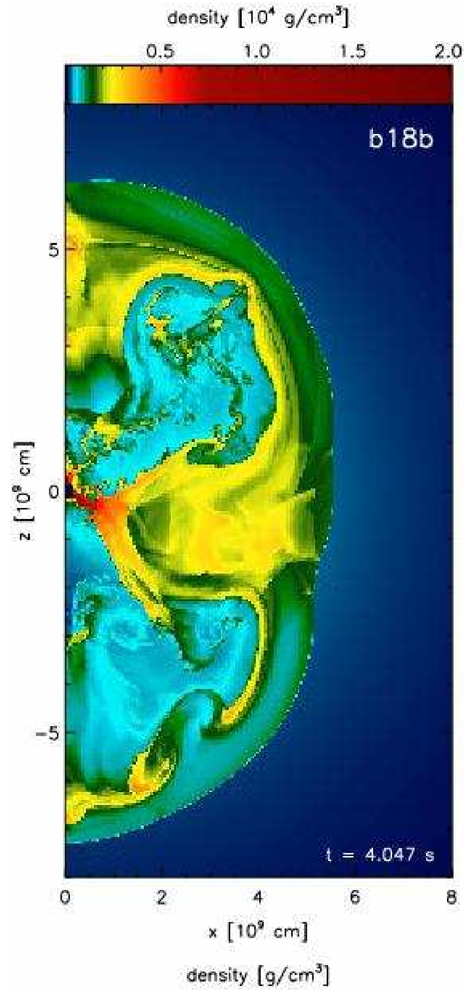
$$P = e^{-\frac{\pi(\Delta m^2 \sin 2\theta)^2}{4EA'}}$$

$$\lim_{|A'|\to 0} P = 0$$

$$\lim_{|A'|\to \infty} P = 1$$

Effect of the turbulence on the oscillations





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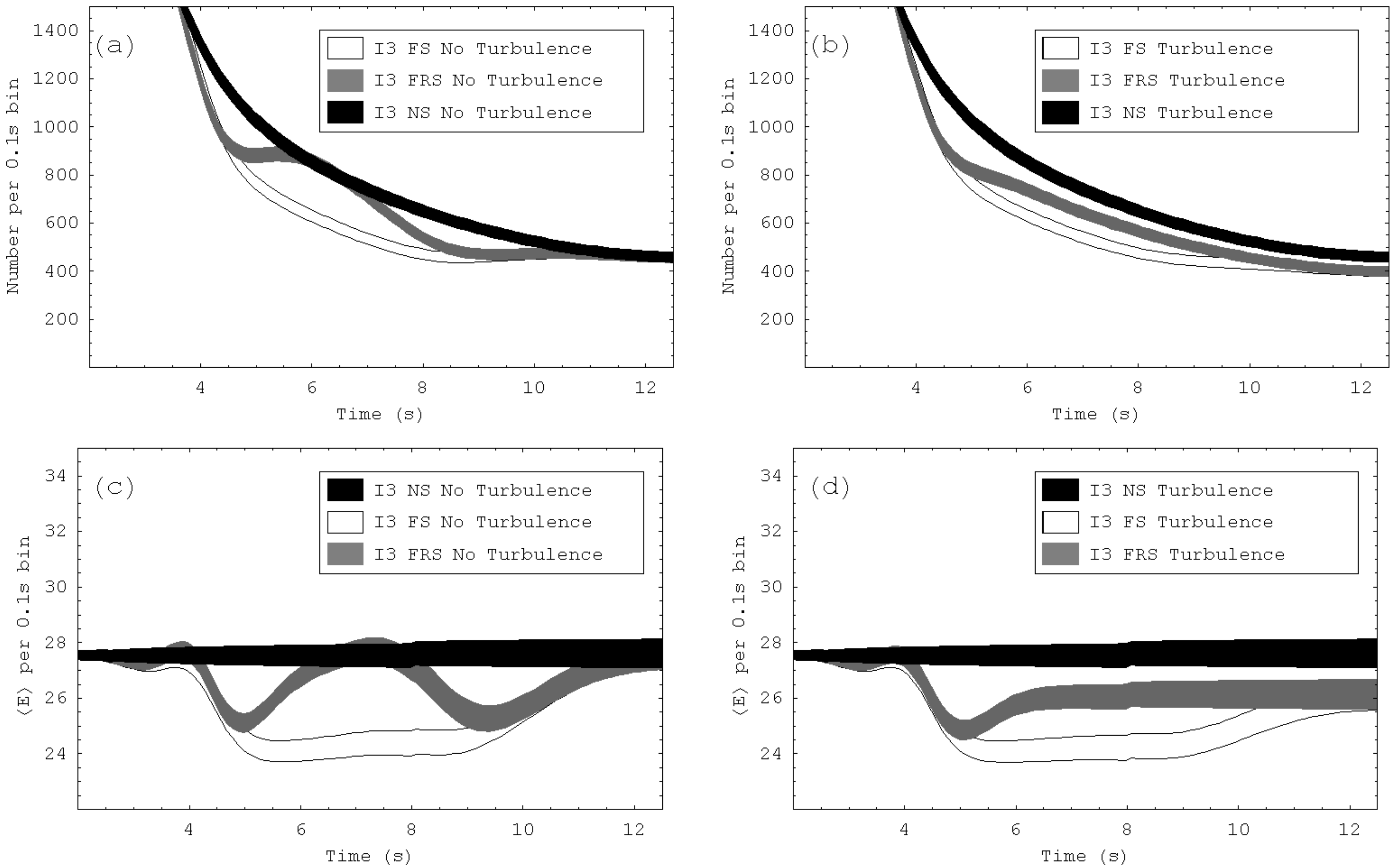
$$P = e^{-\frac{\pi(\Delta m^2 \sin 2\theta)^2}{4EA'}} \qquad \lim_{|A'|\to 0} P = 0 \qquad \lim_{|A'|\to\infty} P = 1$$

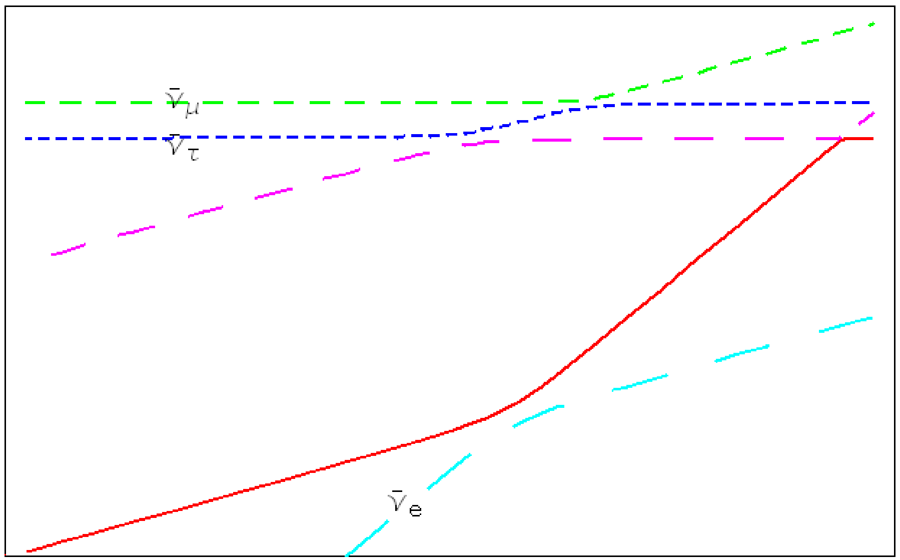
The atmospheric resonance

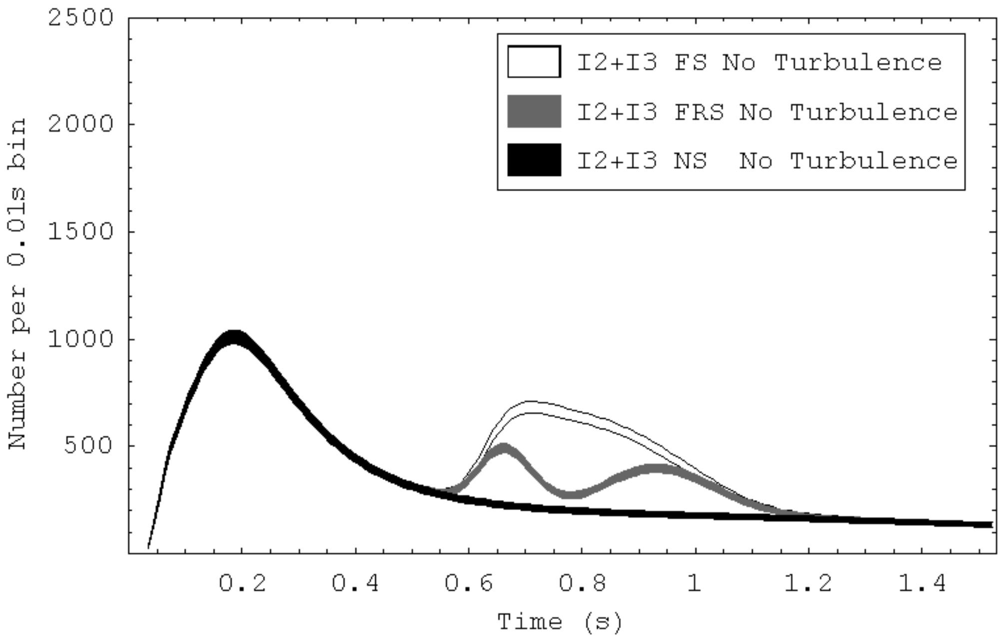


The sterile resonance

The LSND experiment is evidence for a fourth sterile neutrino (unconfirmed)

The modulation in the signal is dominated by oscillations into sterile neutrinos, does not require a difference in the initial energy spectra





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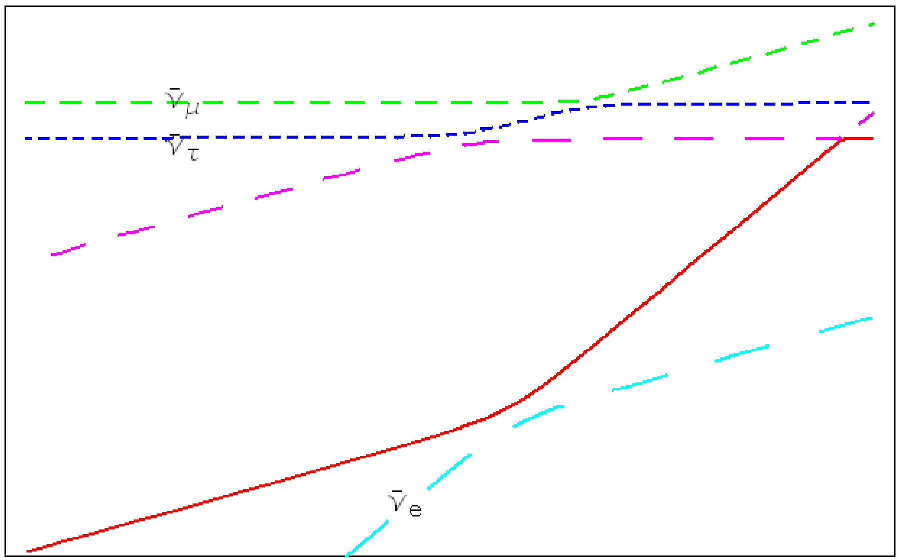

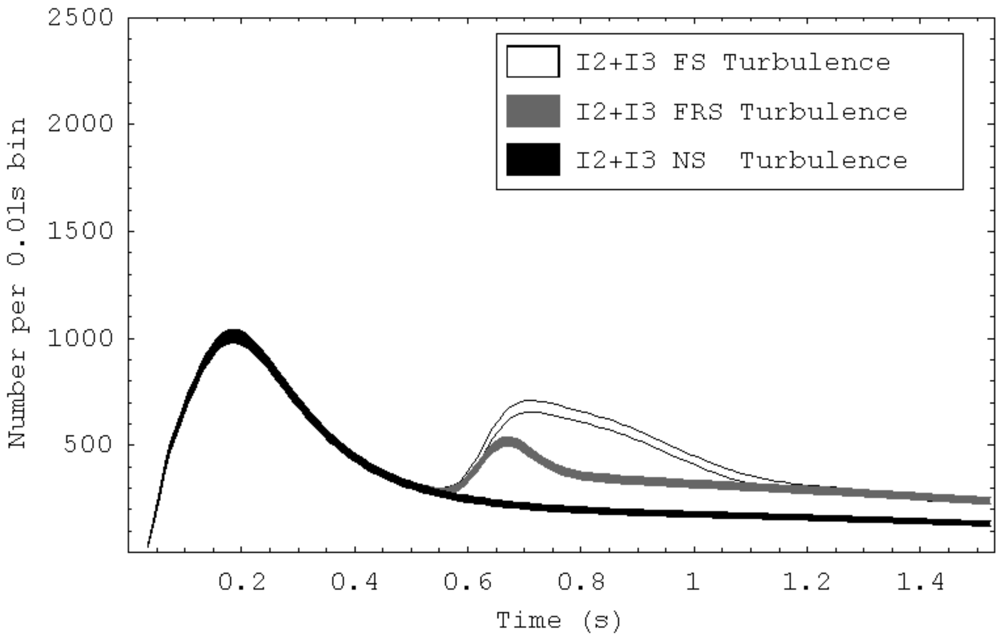

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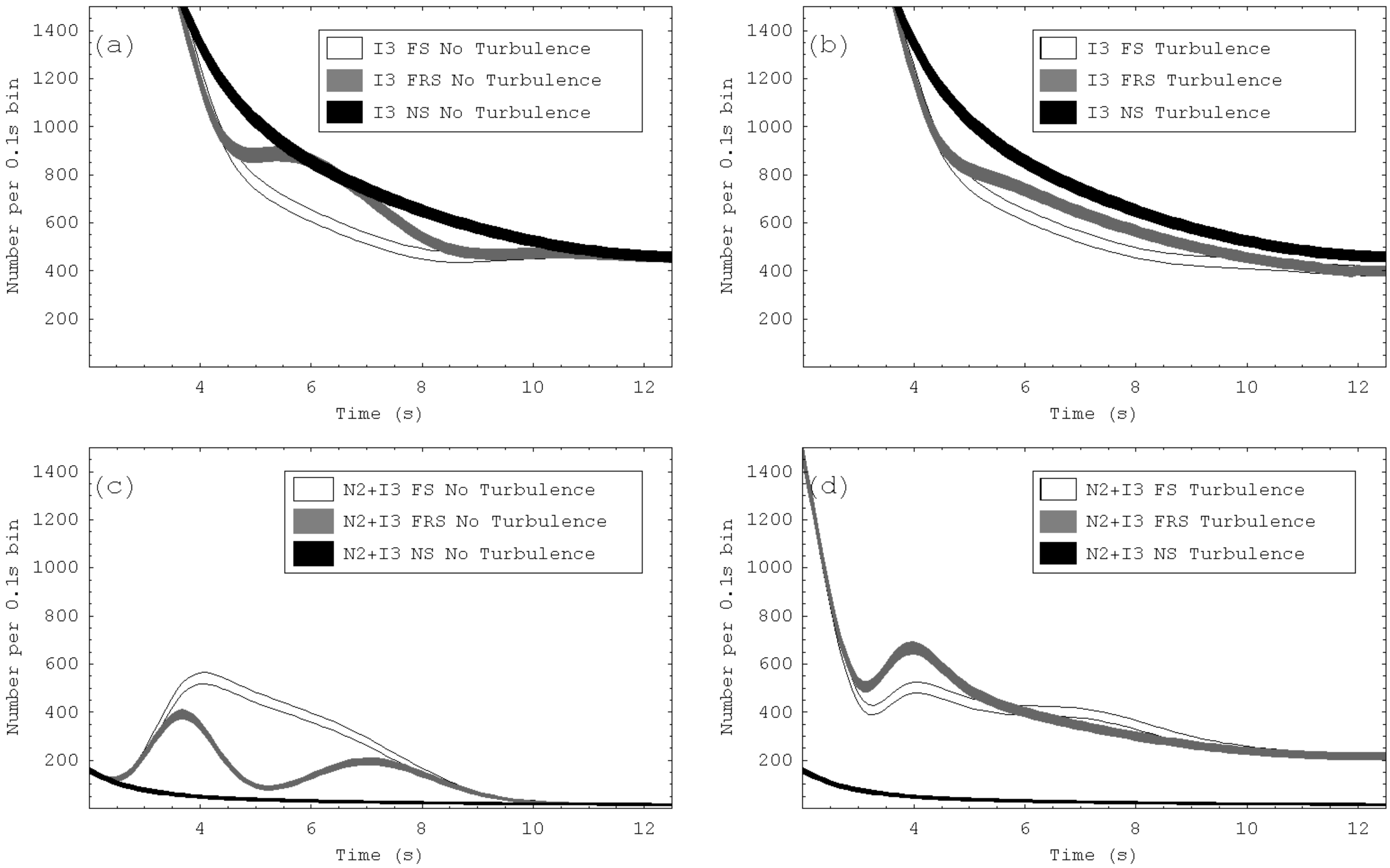

Conclusions

- The shock-wave in a supernova can change the probability of the neutrino oscillations
- Numerical simulations show a highly turbulent region behind the shock-wave, this also changes the probability of the oscillations
- If there are no sterile neutrinos this effect is dependent on a difference in the energy spectra of the neutrinos
- If there are sterile neutrinos the dominant effect does not depend on the energy spectra of neutrinos

Need a supernova!