Collective and Dynamic MSW Effects in Supernova Neutrino Signals

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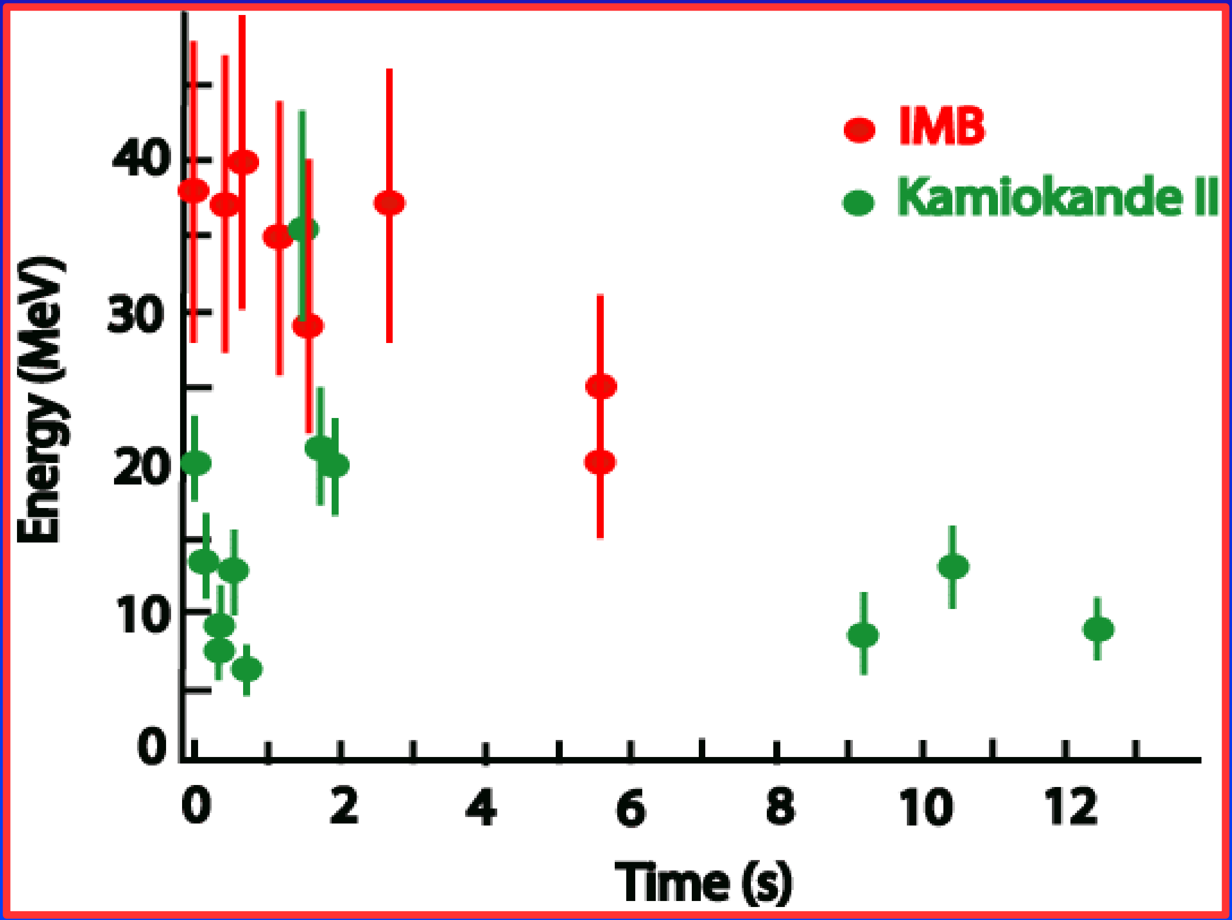
PRL, 103, 071101 (2009)

Neutrinos from Supernovae

99% of the gravitational binding energy is emitted as neutrinos.

~ 10^{57} neutrinos are released over a period of ~ 10 s.

The typical energy is ~ 10 MeV.



Neutrino Oscillations

There is now compelling evidence that υ flavour is not conserved.

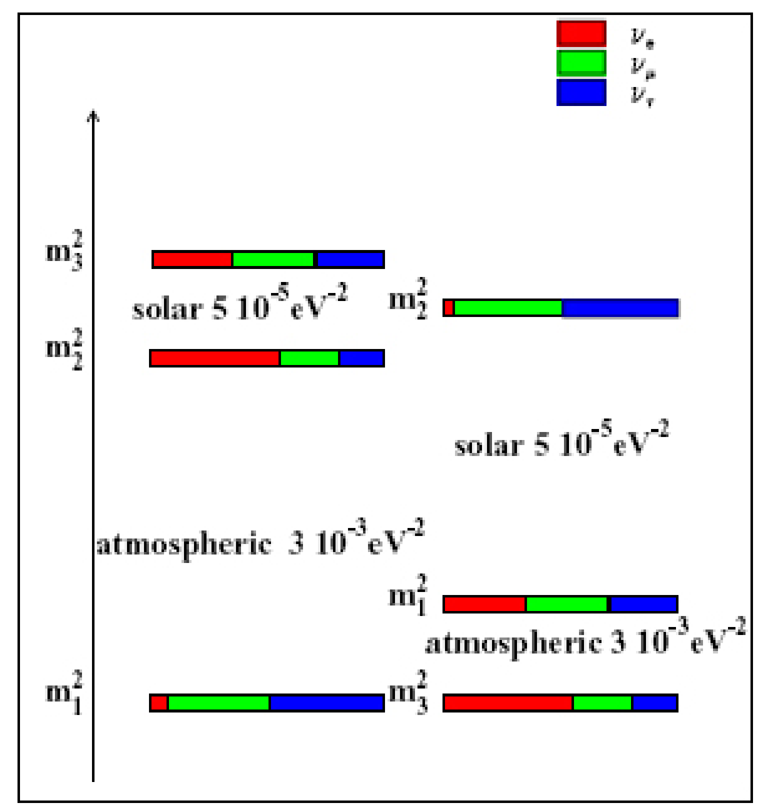
The mass states, m_1, m_2, m_3, are not the same as the flavour states.

The two bases are related by a mixing matrix *U* parameterized by three mixing angles, θ_{12}, θ_{13}, θ_{23} and a CP phase δ.

We know:

- $m_2 > m_1$ and
- $|m_3-m_2| > |m_2-m_1|$ but
- the ordering is unknown,

- θ_{12} and θ_{23} are well-known,
- $\theta_{13} < 9°$,
- δ is unknown.



The Flavour Evolution of Supernova Neutrinos

The flavour content of a neutrino changes as it propagtes from the proto-neutron star to our detectors here on Earth.

It evolves a number of times during the voyage:

- within the first 1000 km due to neutrino self interactions,
- (up to) two times within the rest of the star due to the MSW effect,
- flavour transformation due to turbulence,
- there are vacuum oscillations and decoherence as the neutrino propagates to Earth,
- and then Earth matter effects if the SN is shadowed.

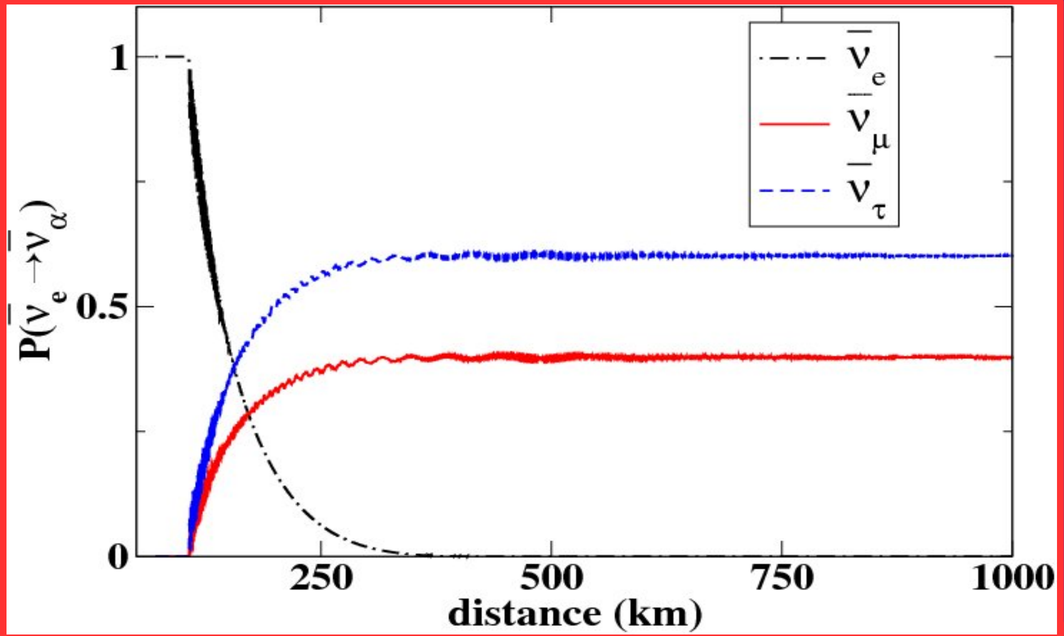
Self-Interaction and the MSW Effect

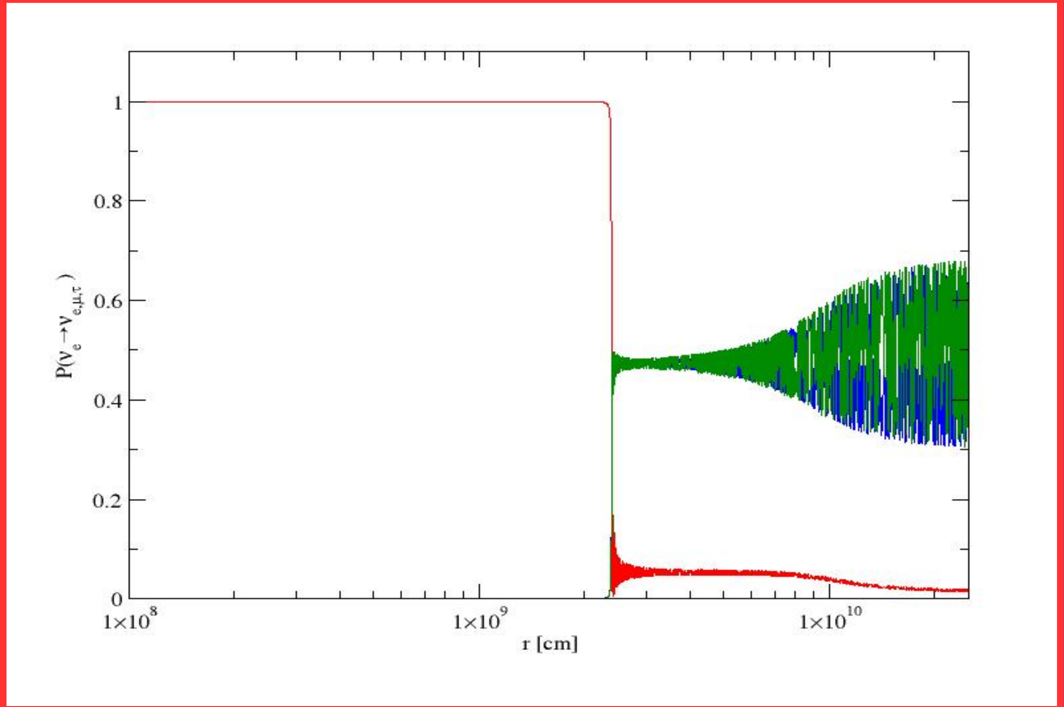
The ν density is so high close to the proto-NS that neutrinos interact with themselves.

Gava & Volpe,
PRD, **78**, 083007 (2008)

MSW effect is name for the effect of matter upon ν 's.

It occurs because e interact with ν_e and ν_e through the CC in addition to the NC.





There has been rapid progress over the past few years in the understanding of how neutrinos propgate through a supernova.

- In 2003 Schirato & Fuller showed that the evolving density profile - aka the explosion - imprints itself on ν through the MSW effect.

Schirato & Fuller, arXiv:astro-ph/0205390

- In 2006 Duan *et al.* solved the multi-angle neutrino self-interaction problem in supernova.

Duan, Fuller, Carlson & Qian, PRL, **97**, 241101 (2006)

Duan, Fuller, Carlson & Qian, PRD, **74**, 105014 (2006)

For a review see Duan & Kneller, JPhG, **36**, 113201(2009).

These developments have largely been in parallel.

There have been some attempts at putting themall together,

Kneller, McLaughlin & Brockman, PRD, **77**, 045023 (2008)

Lunardini, Muller & Janka, PRD, **78**, 023016 (2008)

Chakraborty, Choubey, Dasgupta & Dighe, JCAP, **809**, 013 (2008)

but this has not been done consistently.

We need

- matched density profiles,
- consistent mixing parameters,
- to avoid calculation overlap,
- suturing with S matrices.

Combing the Effects: Our Calculation

We shall consider only an Inverse hierarchy and $\theta_{13} = 0.57°$.

The calculation is done in two steps.

The ν collective effects are calculated up to r ~ 1000 km.

Gava & Volpe, PRD, **78**, 083007 (2008)

- The initial spectra are Fermi-Dirac with equal luminosities.
- Mean energies are $\langle E_e \rangle = 12$ MeV, $\langle E_{\bar{e}} \rangle = 15$ MeV, $\langle E_x \rangle = 18$ MeV and the luminosities decay exponentially with time-scale $\tau = 3.5$ s.

The dynamic MSW effects are calculated from ~1000 km onwards.

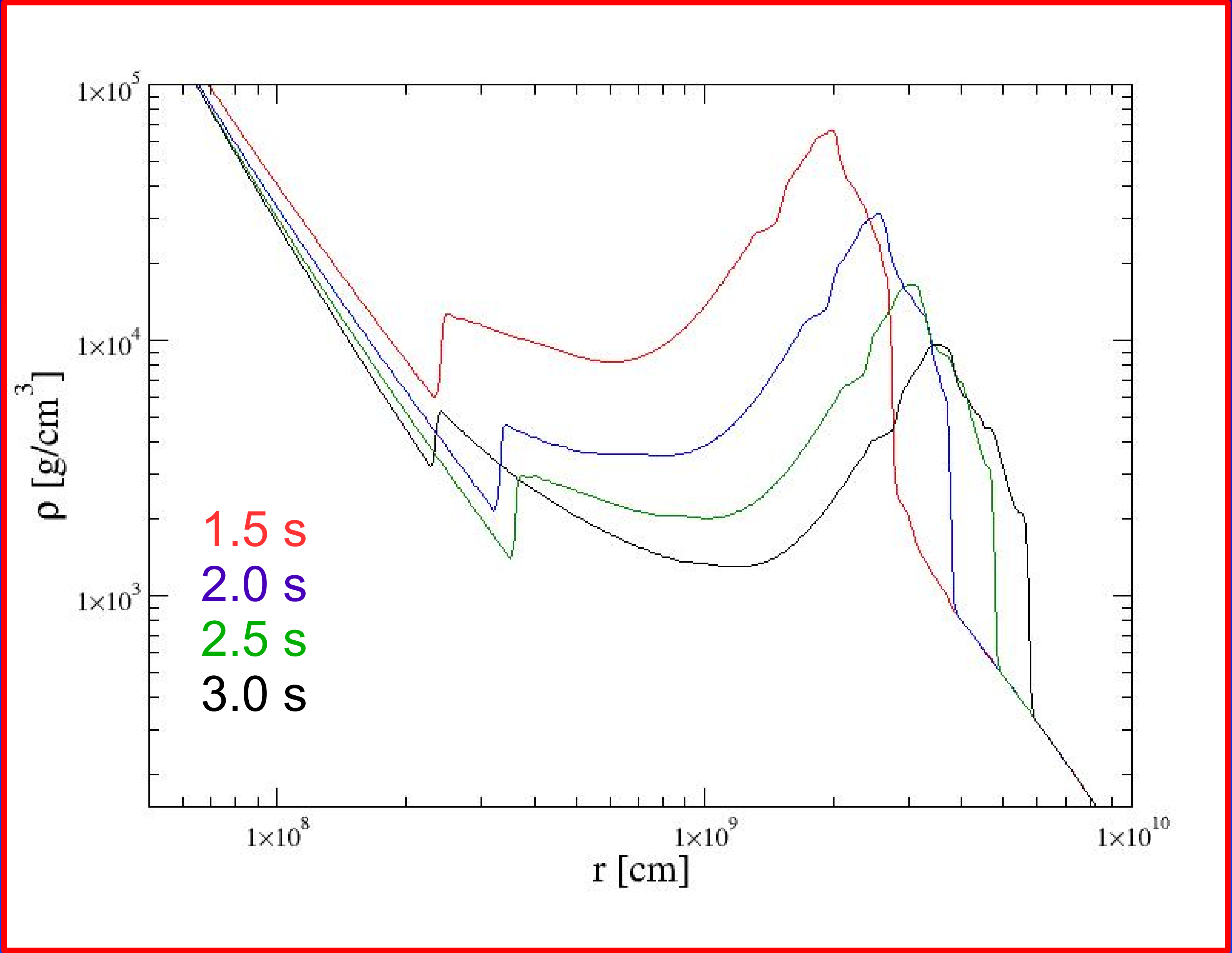
Kneller & McLaughlin, PRD (2009) [arXiv:0904.3823]

- The density profiles are taken from a 1D hydro of a SN.

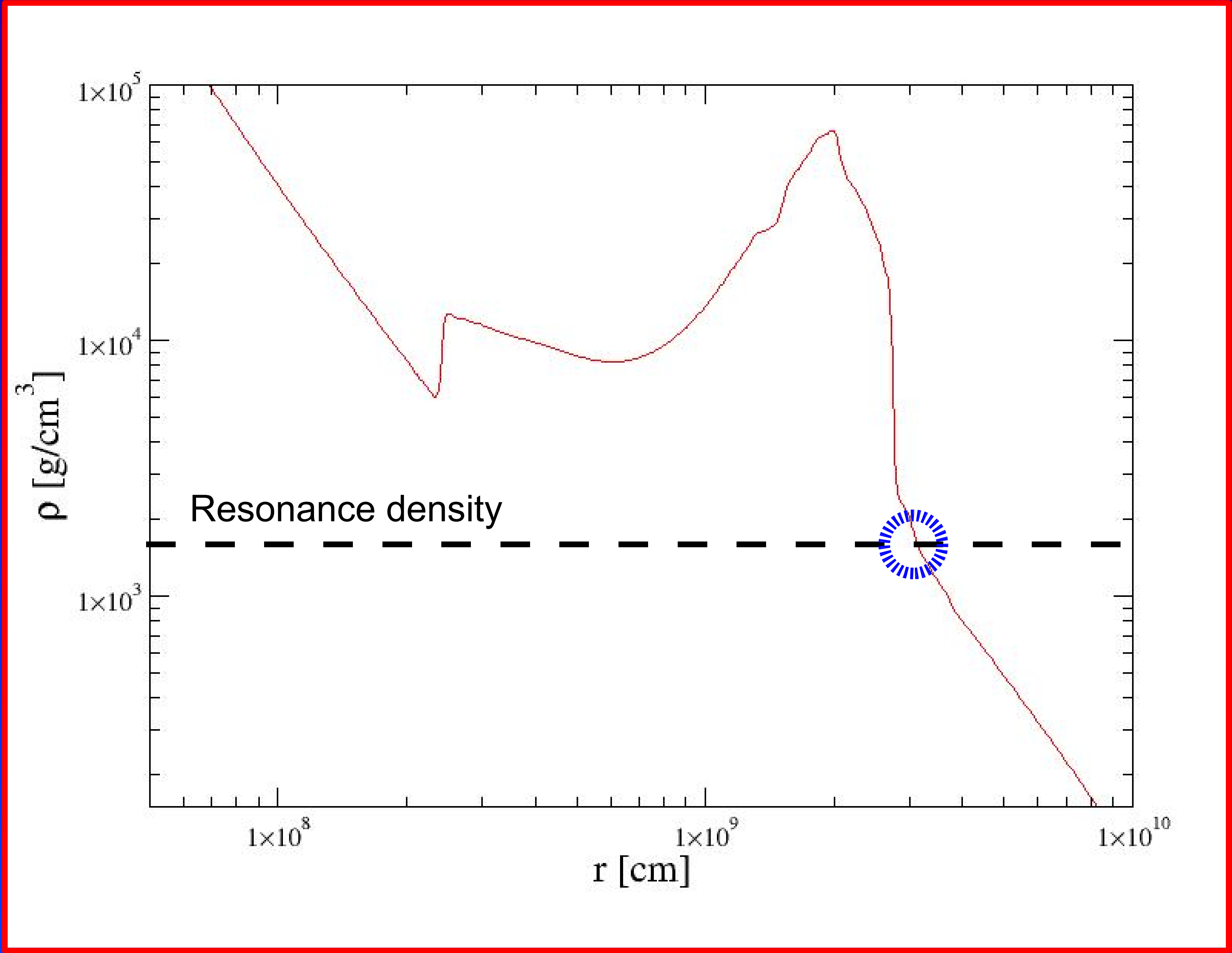
Kneller, McLaughlin & Brockman, PRD, **77**, 045023 (2008)

The density profiles contain a forward and a reverse shock.

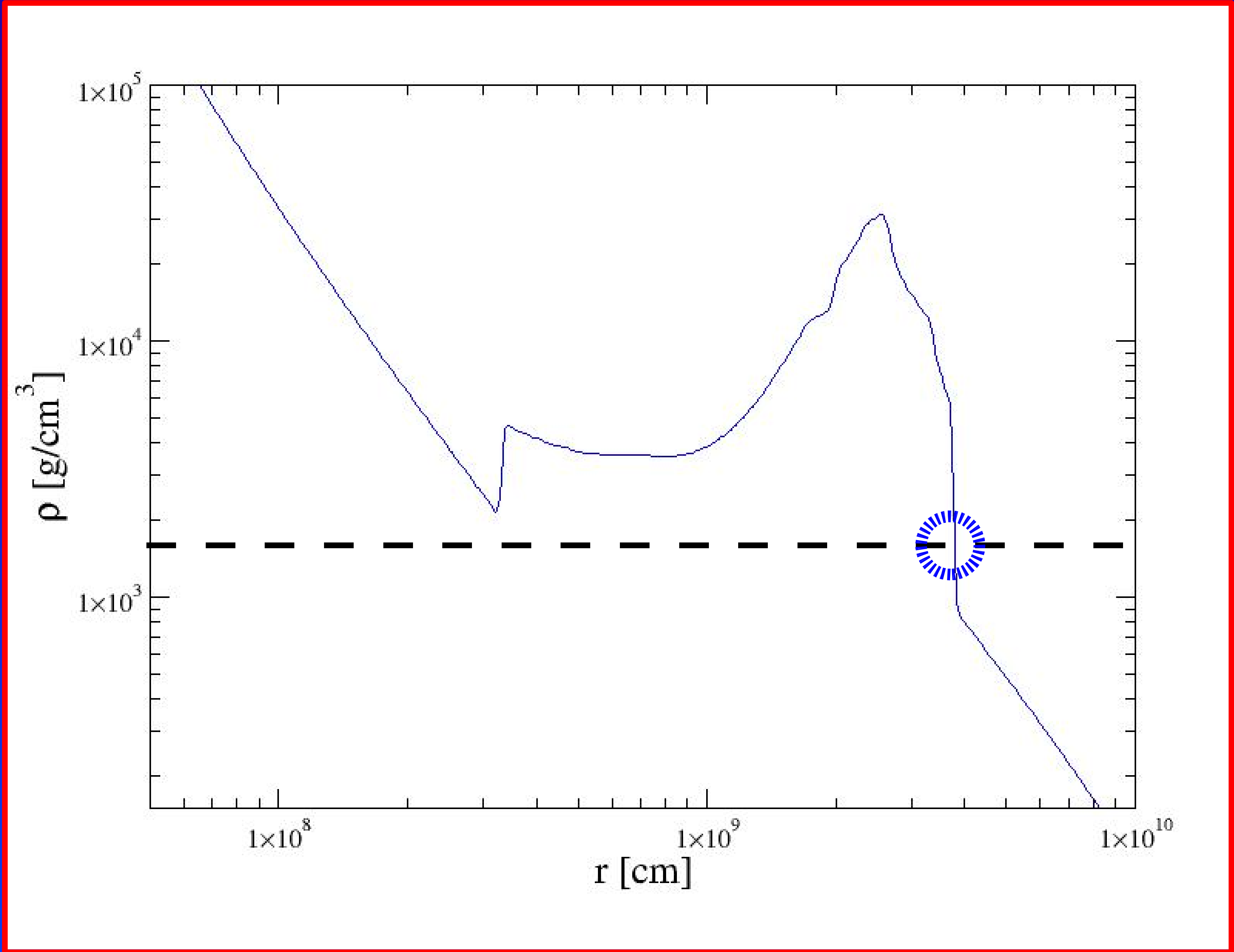
The adiabaticity is controlled by the derivative of the density.



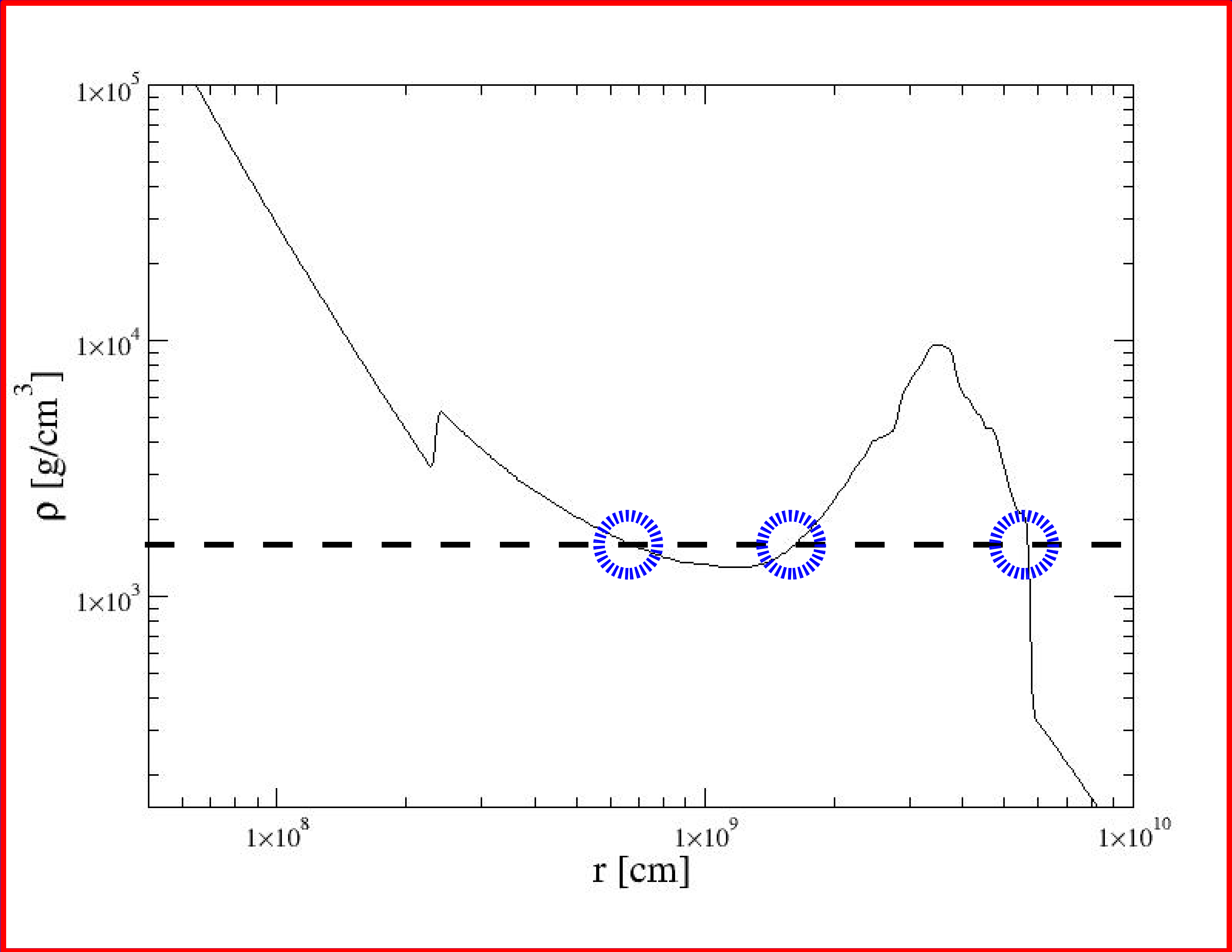
For θ_{13} =0.57° the progenitor profile is adibatic – small dρ/dx.



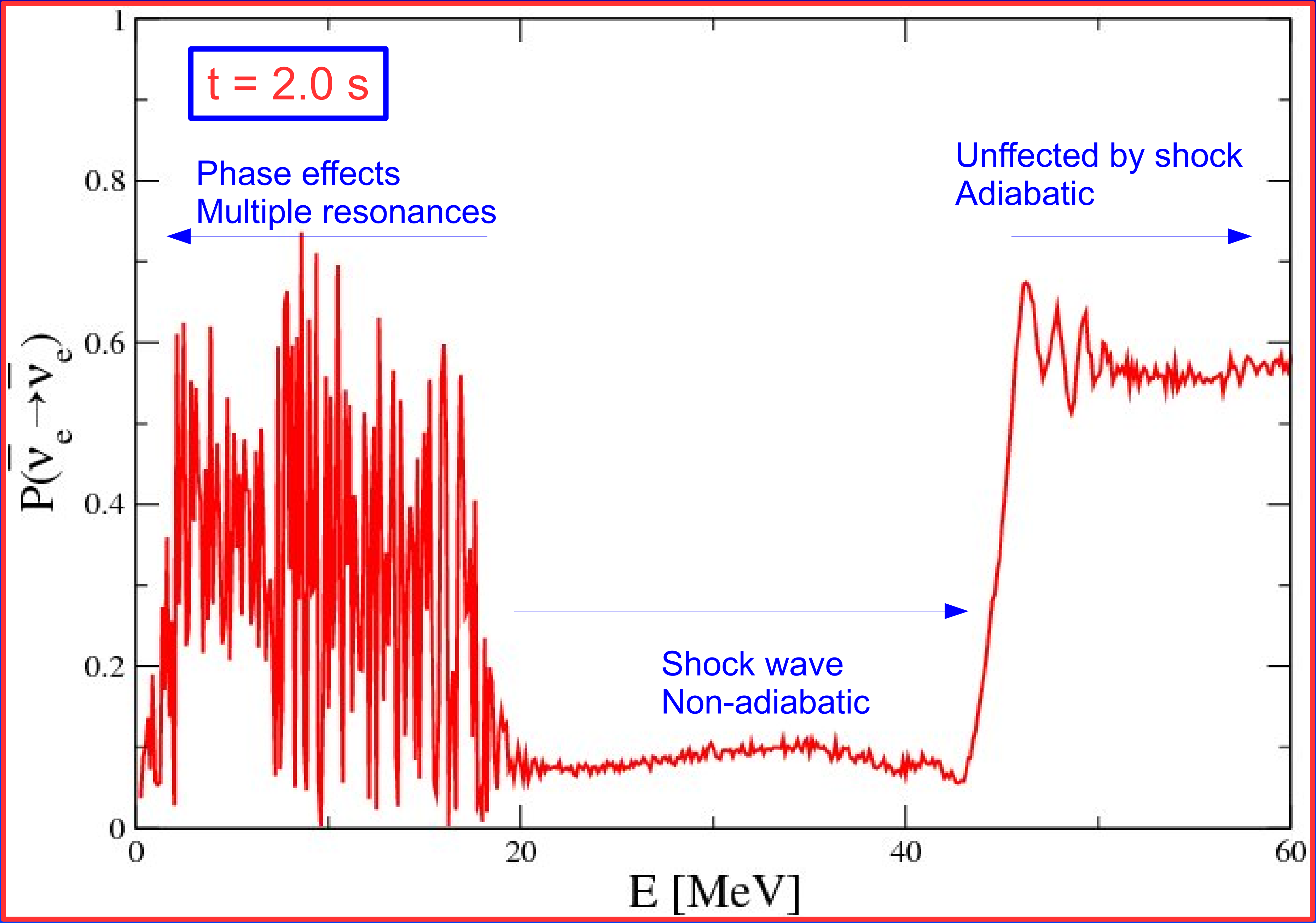
The shock leads to non-adiabatic propgation – large dρ/dx.



Neutrinos can experience multiple resonances.



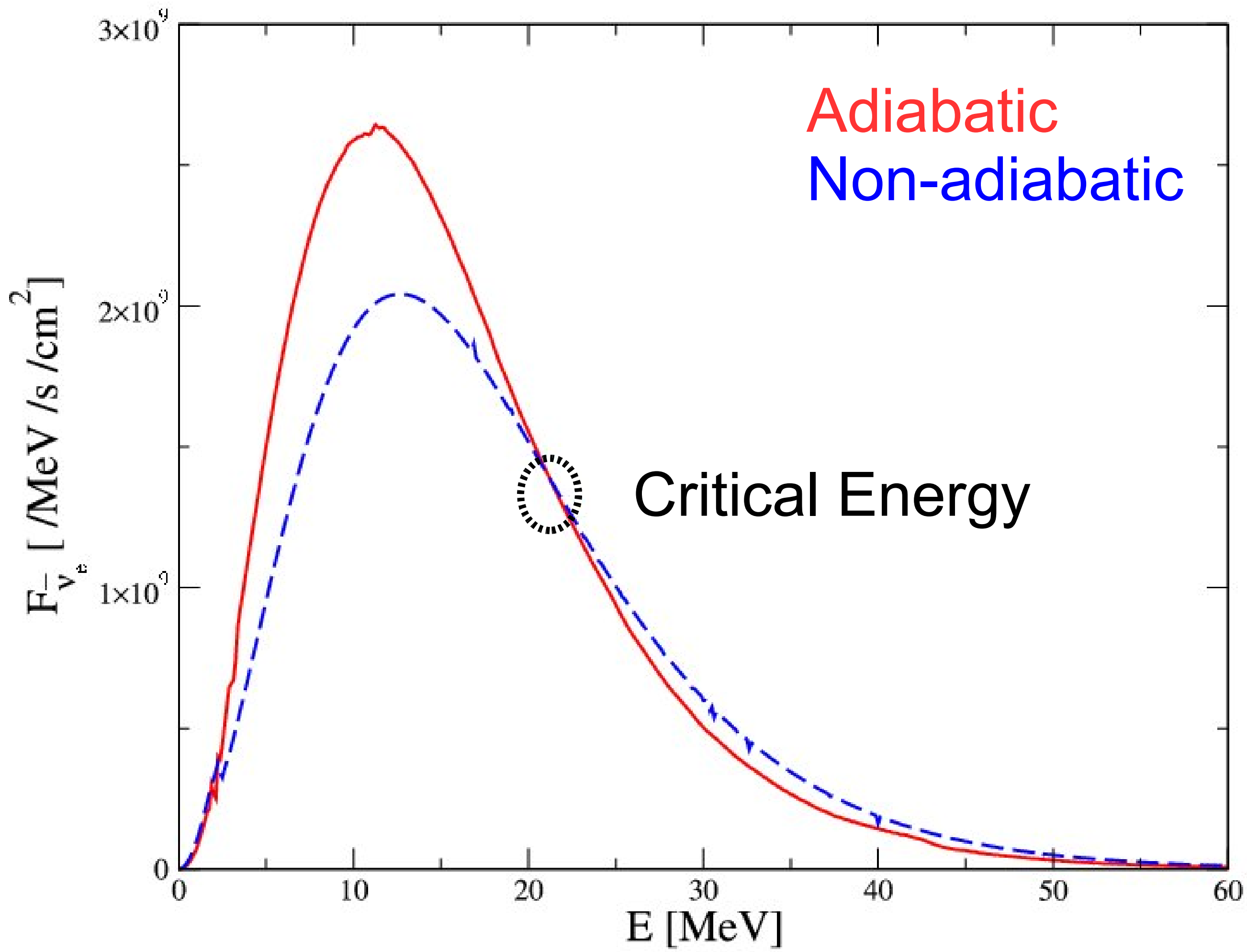
P(t|E) = P(E|t). As a function of energy at some fixed time.



The flux at Earth

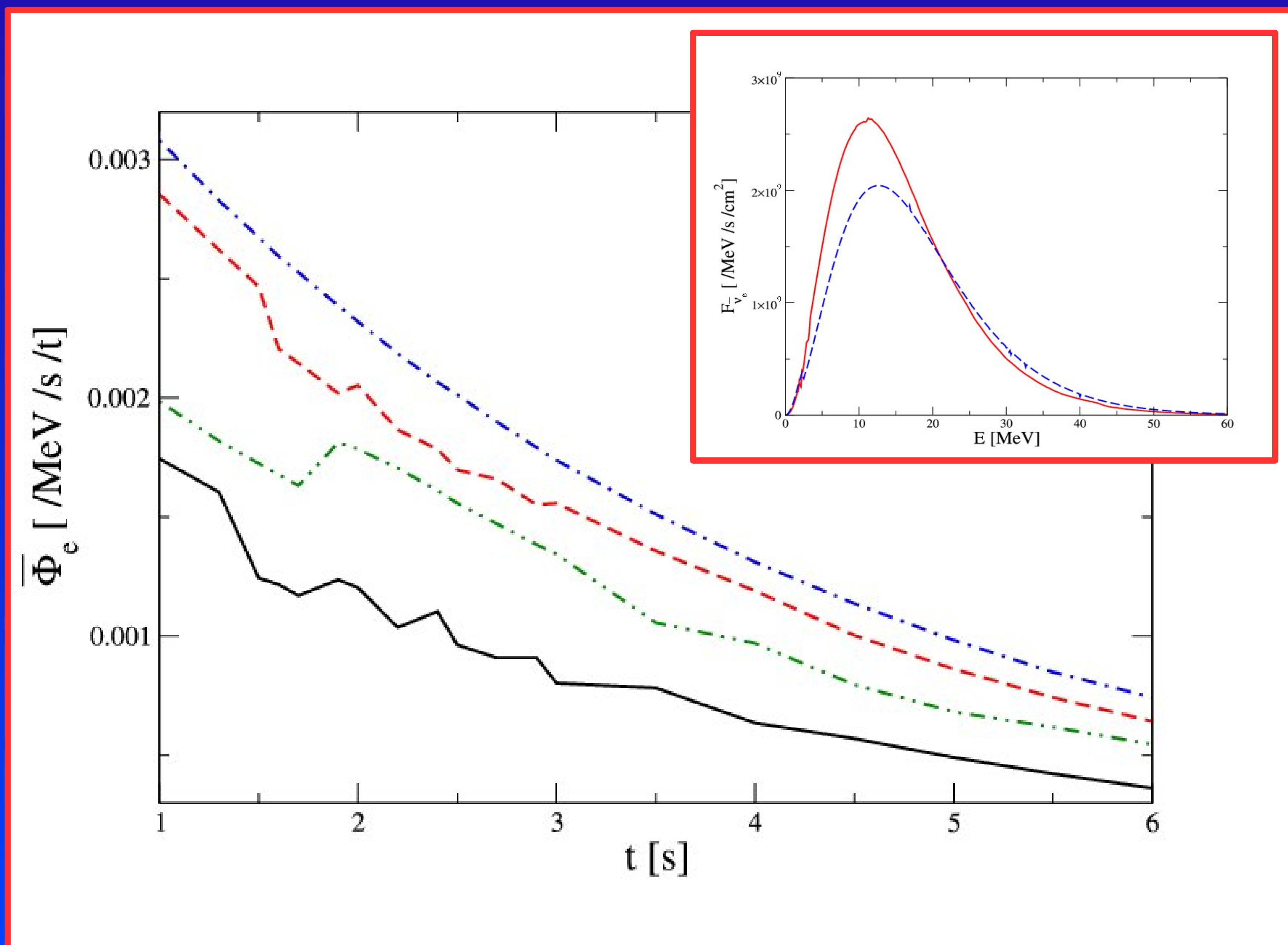
The decoherence on the journey to Earth is accounted for.

Dighe & Smirnov, PRD, **62**, 033007 (2000)



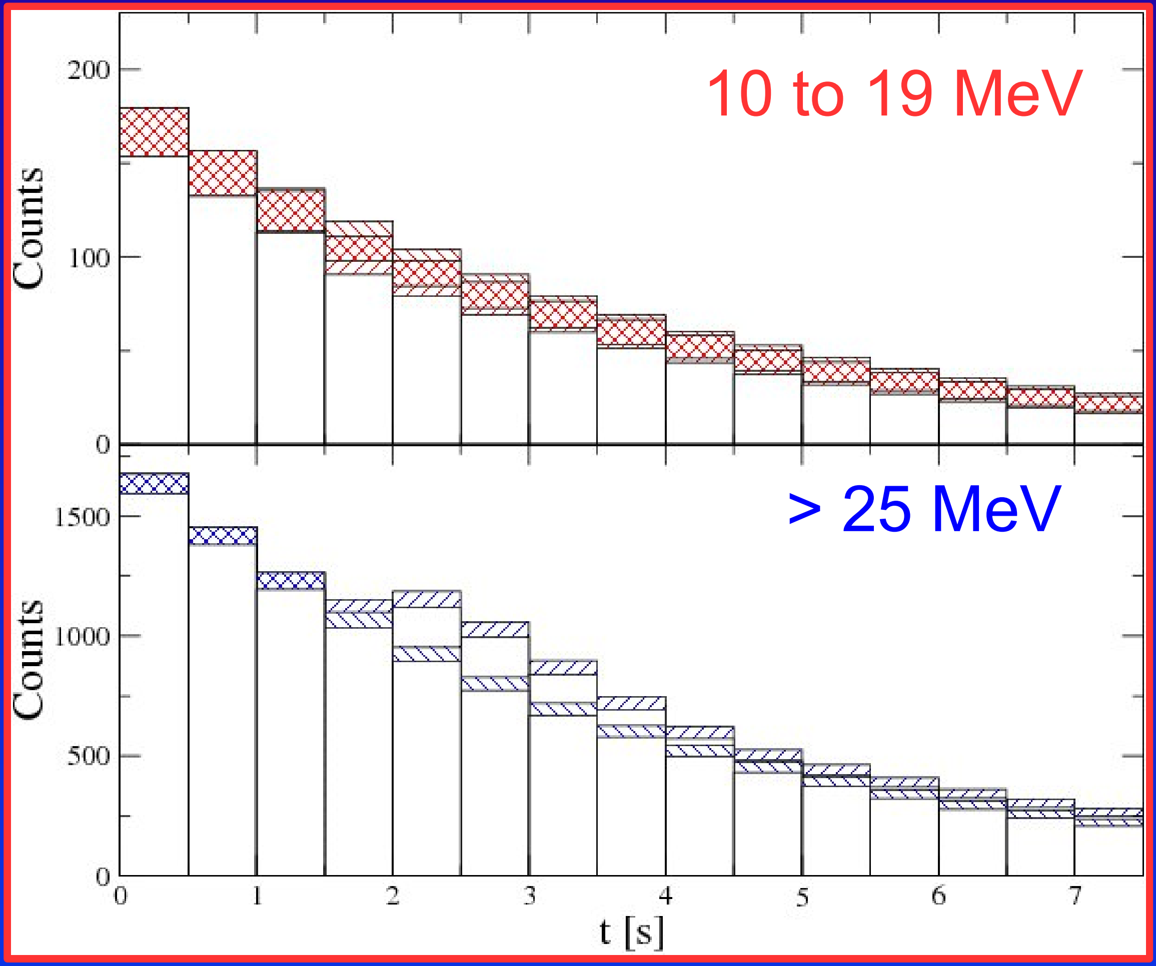
Positron Rate

With the neutrino flux at Earth determined we compute the positron rate in a water Cerenkov detector.



10 MeV
15 MeV
19 MeV
29 MeV

The signal in SuperK

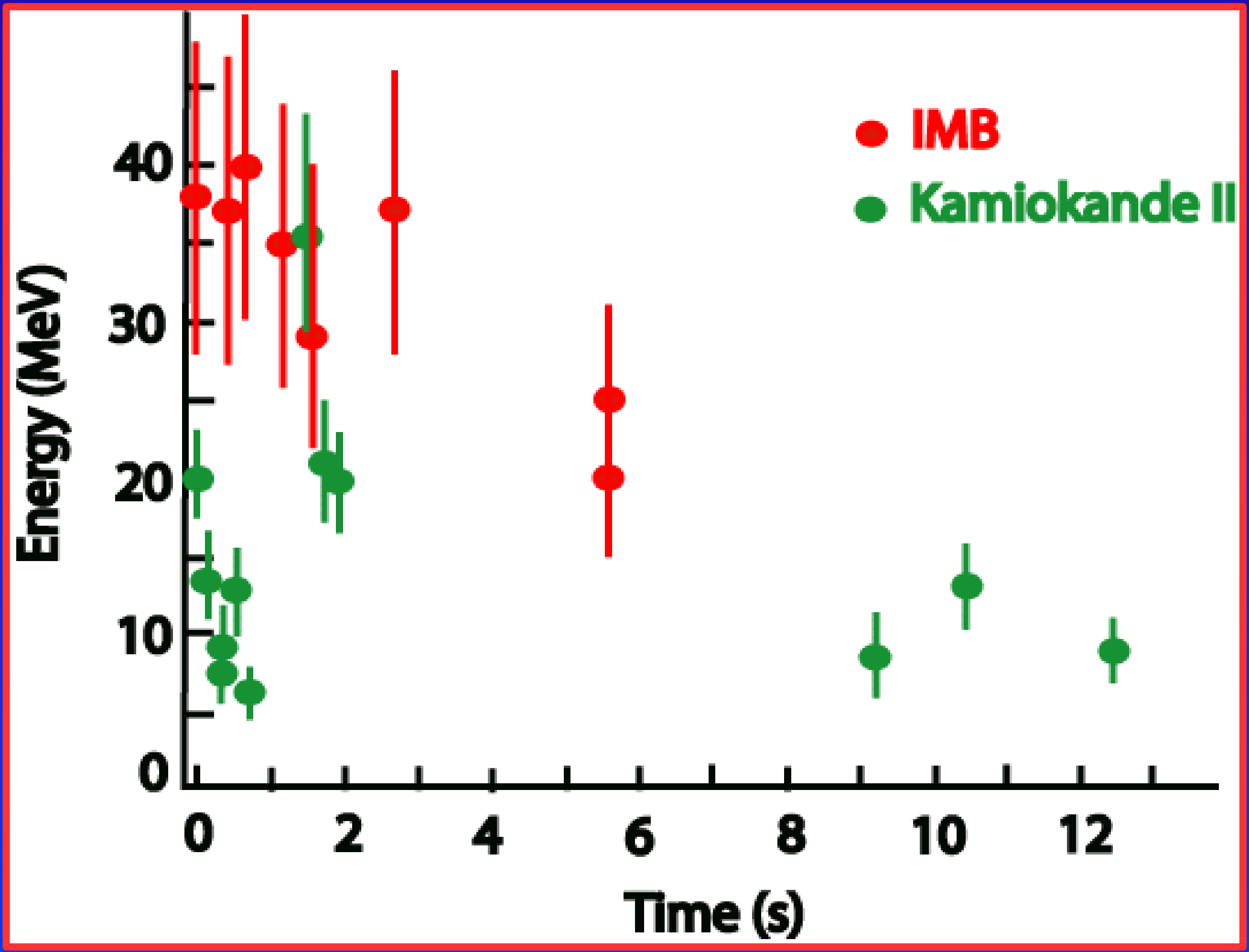


SuperK can detect the shock feature.

At high (low) energy the count rate differs from the exponential decay by ~ 4σ (~ 1σ) for each bin with the assumed source spectra.

Comparison with SN 1987A

Of course there is already some data to compare with;

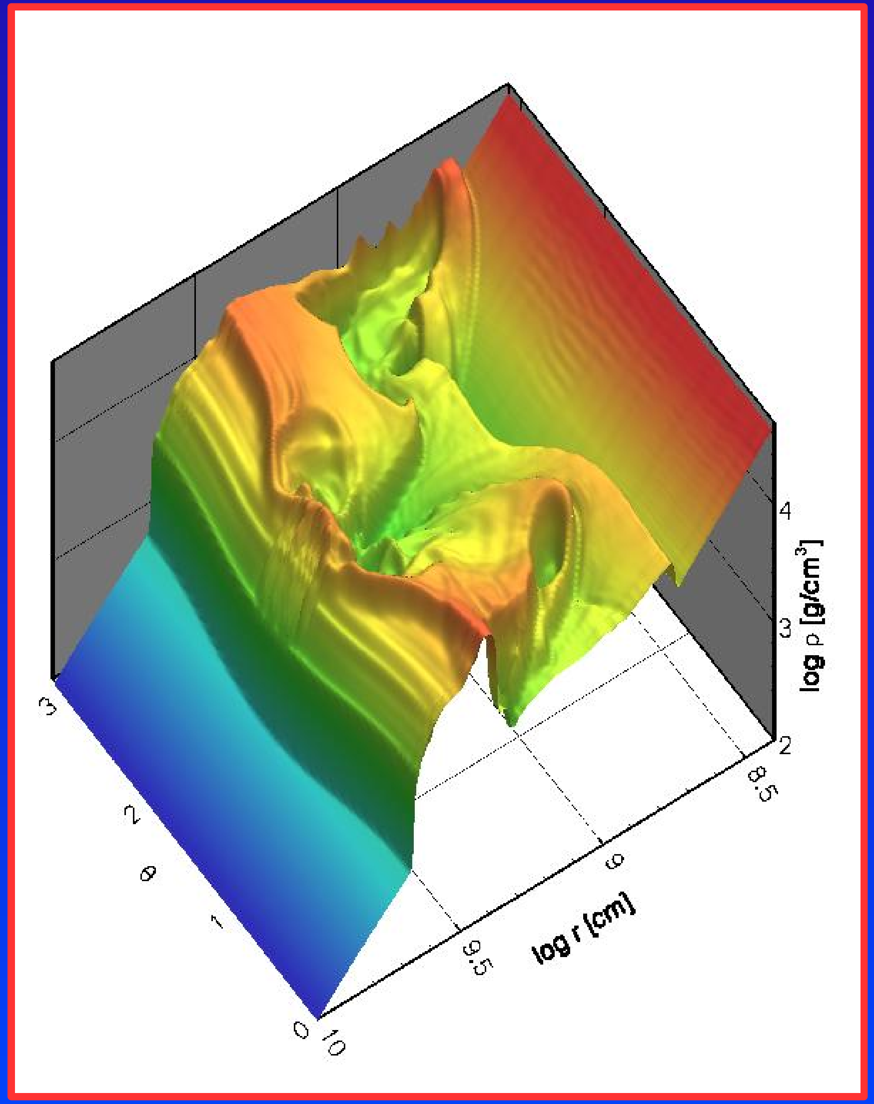


but an emission model with no shock effects is compatible at 5%.

Lattimer & Yahil, ApJ, **340**, 426 (1989)

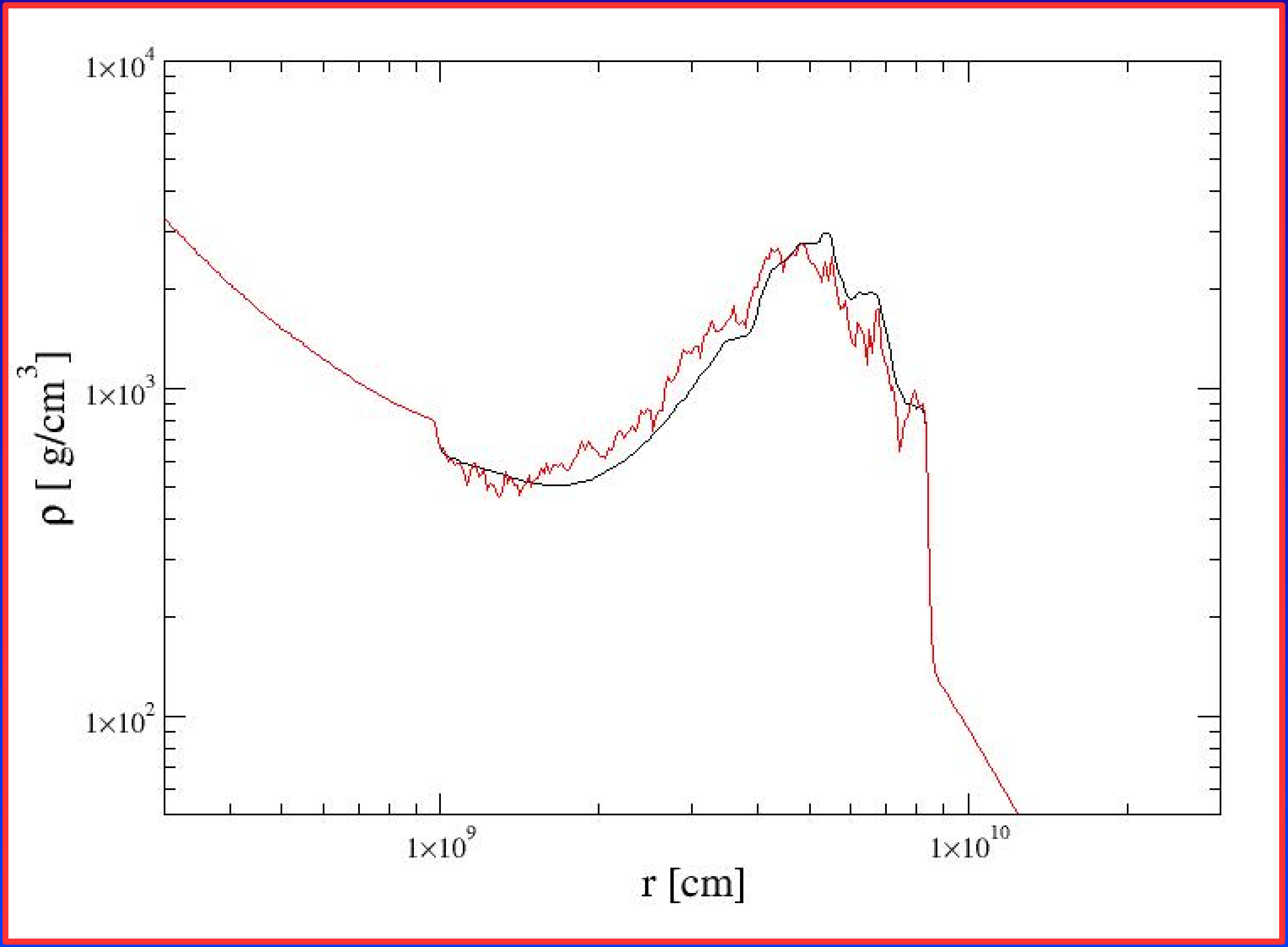
Turbulence

Our profiles lack the small scale features seen in multi-d generated by aspherical flows through distorted shocks etc.



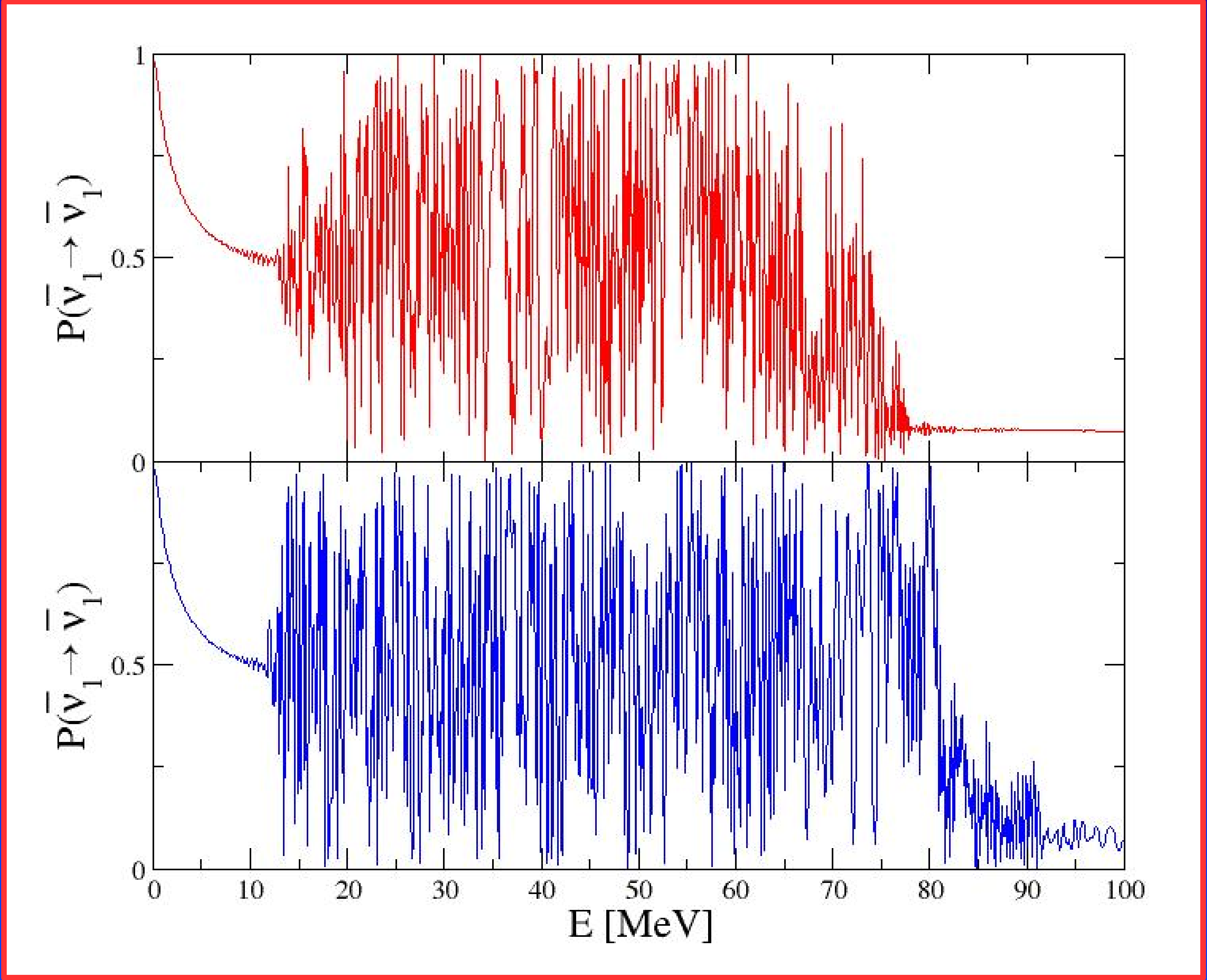
Kneller, McLaughlin & Brockman, PRD, 77, 045023 (2008)

To simulate the effect of turbulence we add noise to our 1-d profiles ...

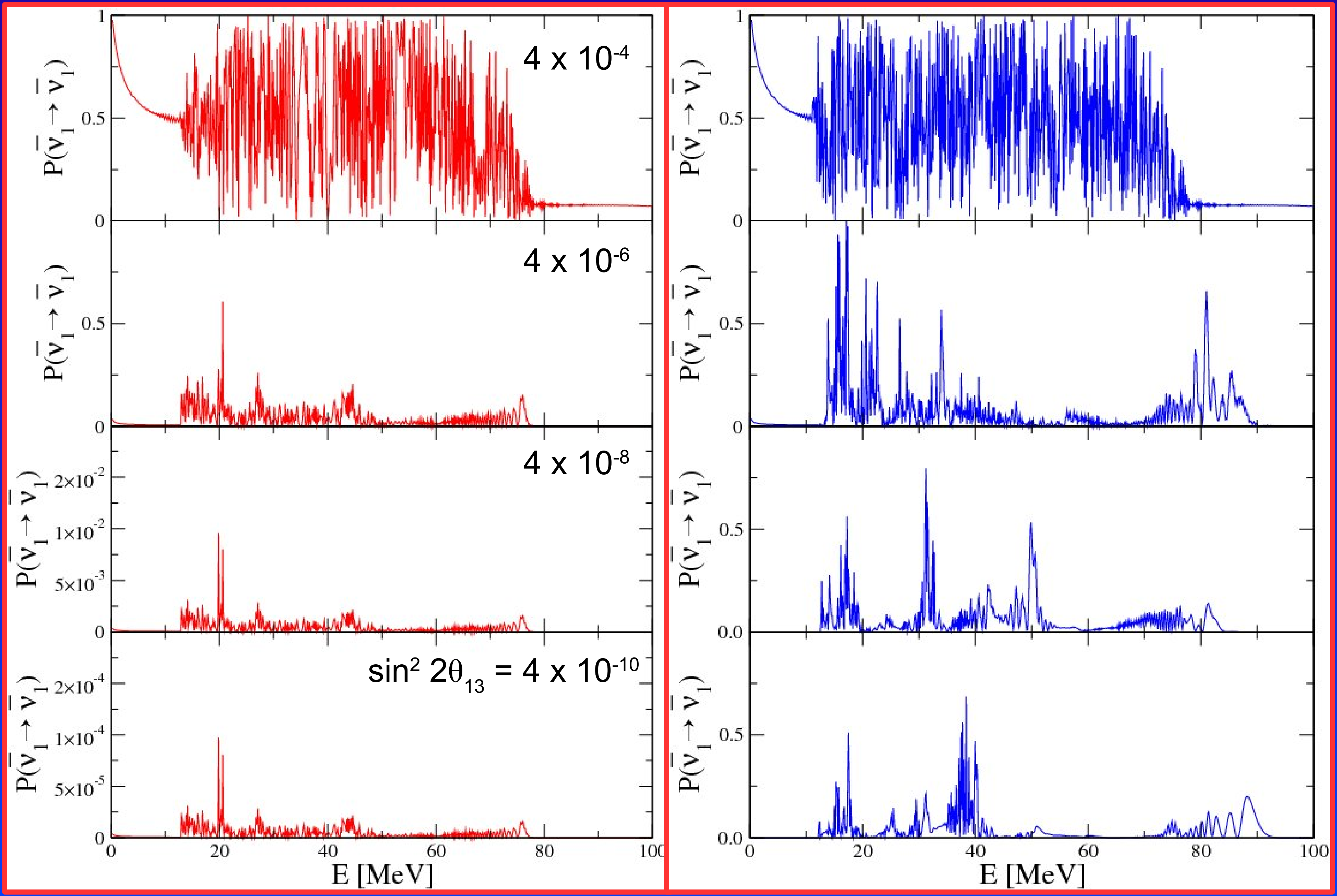


... and see if there is any change.

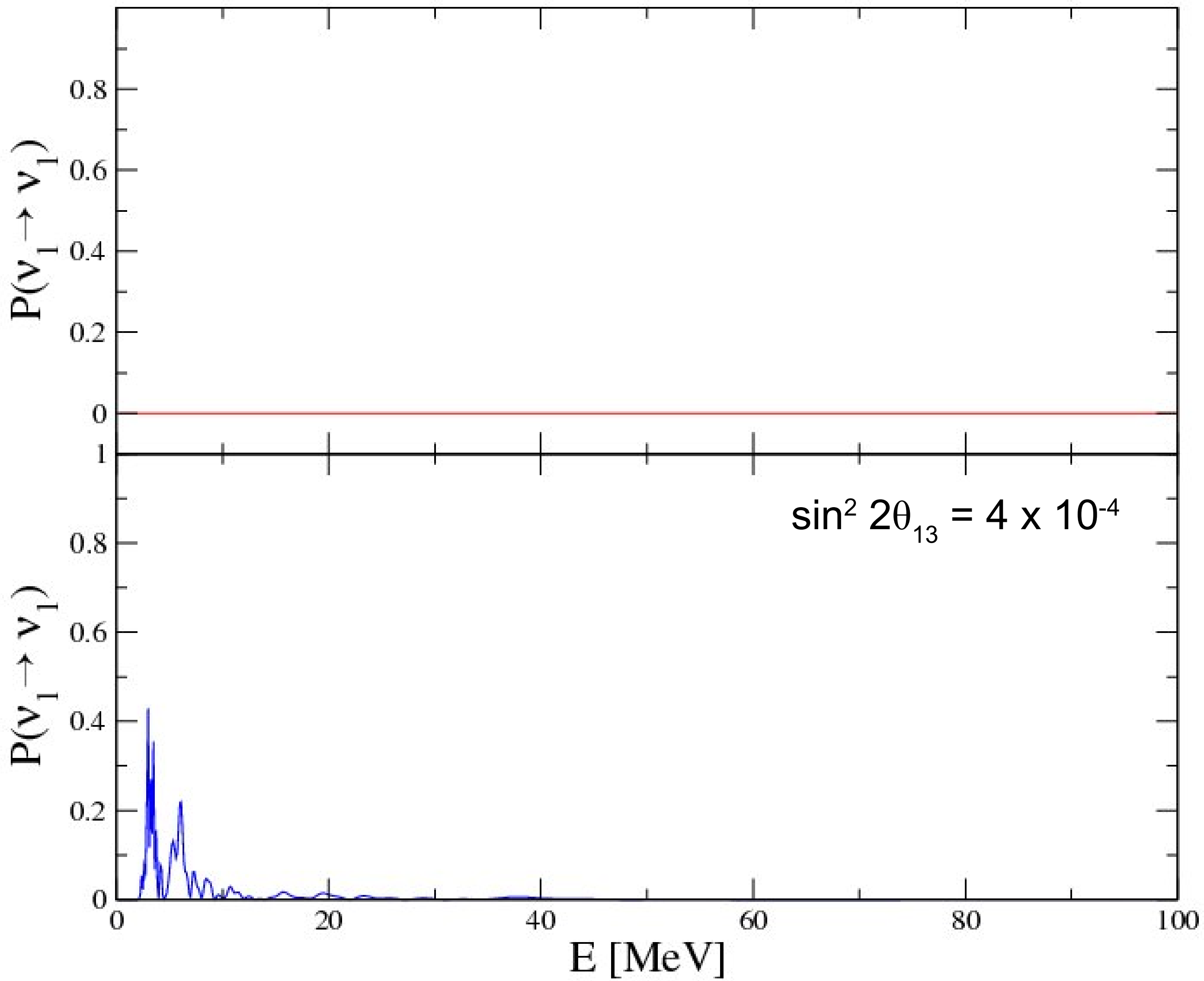
For Inverse hierarchy and θ_{13} = 0.57°



But when we try smaller values of θ_{13} we observe large changes.



And if we look in the neutrinos.



Summary

- There is a lot to be learned from SN neutrino signals.

- For an Inverted Hierarchy and $\theta_{13} > 0.5°$ we expect
  - a decrease in the positron rate for E < 20 MeV,
  - an increase for E > 20 MeV

  midway through the signal.
- SuperK can observe the shock signal for a Galactic SN.
- Adding turbulence does not change this result significantly.
- Turbulence can have considerable effects for much smaller θ_{13} and in the 'wrong' channel.

- Sébastien Galais will give a talk at the next GDR on the effects upon the Diffuse Supernova Neutrino Background