A dynamical, collective calculation of supernova neutrino signals

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PRL, **103**, 071101 (2009)

There has been rapid progress over the past few years in the field of supernova neutrinos.

- 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)

Since then:

- density profiles are now taken from multi-d hydro simulations,
- and neutrino self-interaction calculations can now be done with three flavours, CP phase, ...

For a review see Duan & Kneller, JPhG, (2009) [arXiv:0904.0974].

The two lines of development have largely been in parallel.

There have been some attempts at putting them together,

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

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

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

but the two have not been put together consistently.

We need

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

Our Calculation

The parameters are set to:

$$\theta_{12} = 33°, \theta_{13} = 0.573°, \theta_{23} = 45°,$$

$$\delta m^2_{21} = 8 \times 10^{-5}\ eV^2, \delta m^2_{31} = -3 \times 10^{-3}\ eV^2$$

The calculation is done in two steps.

The ν collective effects are calculated from 70 km above the PNS up to r ~ 1000 km using SA approximation but no CP.

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

- The initial spectra are Fermi-Dirac with either equal luminosities $L=10^{52}$ erg/s.
- 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 density profiles are dynamic, inverse power laws, $1 / r^n$.

- The dynamic MSW effects from ~1000 km onwards use a new 3-flavour code.

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

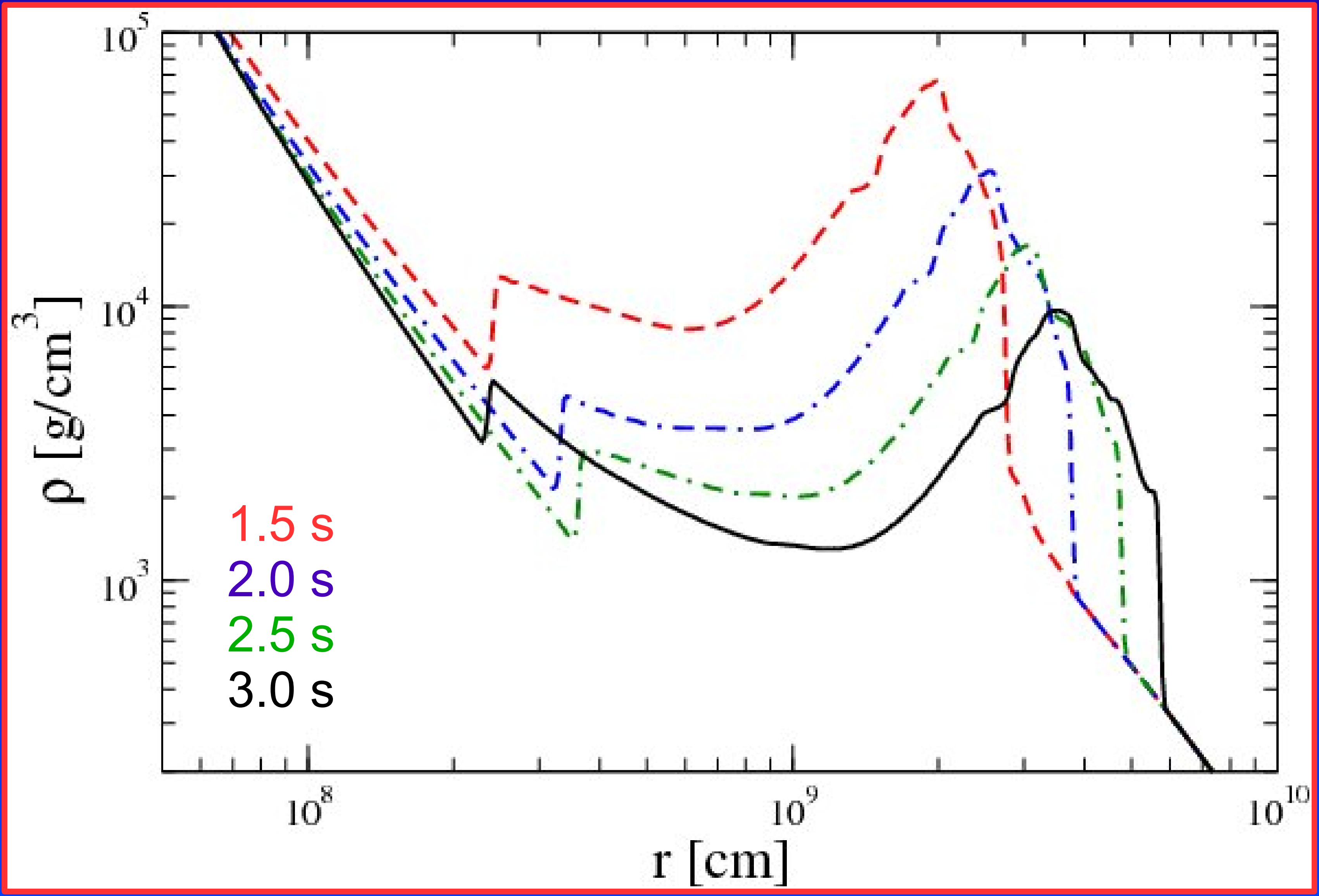
- The density profile is from a 1D hydro, $Q = 3.36 \times 10^{51}$ erg.

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

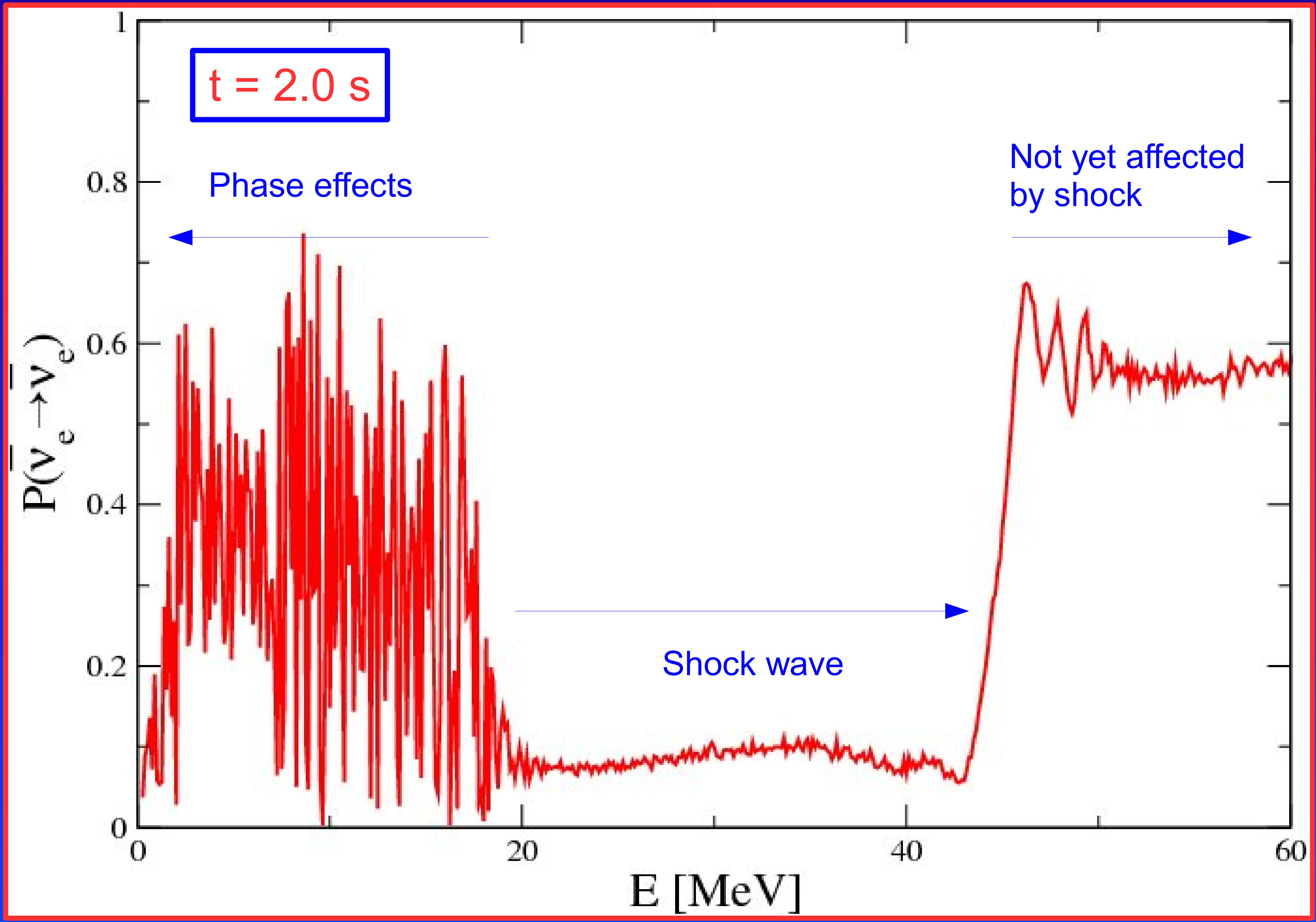
- The inverse power law profile used in the previous step is extrapolated from these profiles.

The density profiles contain both a forward and a reverse shock.

Neutrinos can experience multiple H resonances.



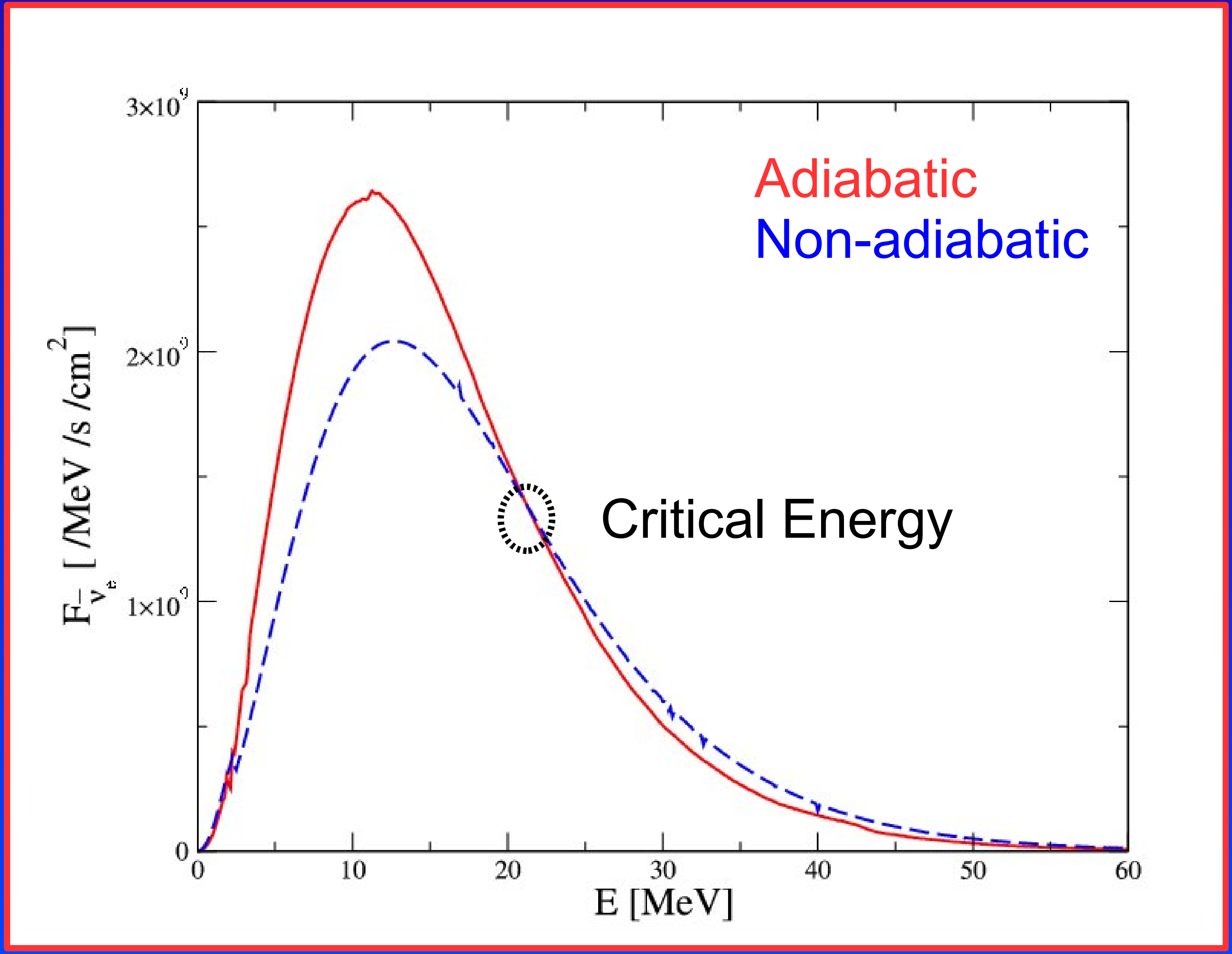
The net result is constructed by multiplying S(E,t) matrices.



The flux at Earth

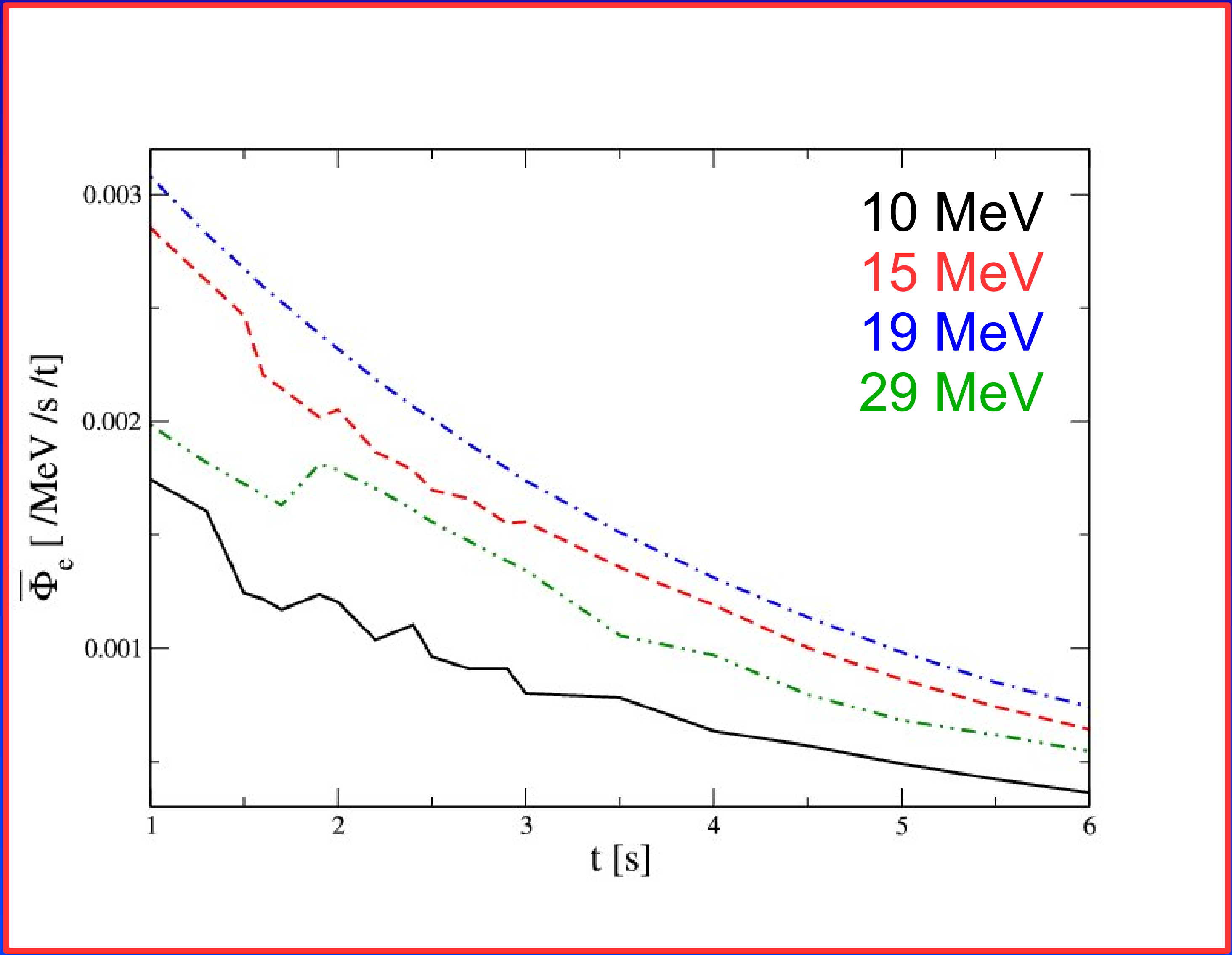
The decoherence on the journey to Earth is accounted for.

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

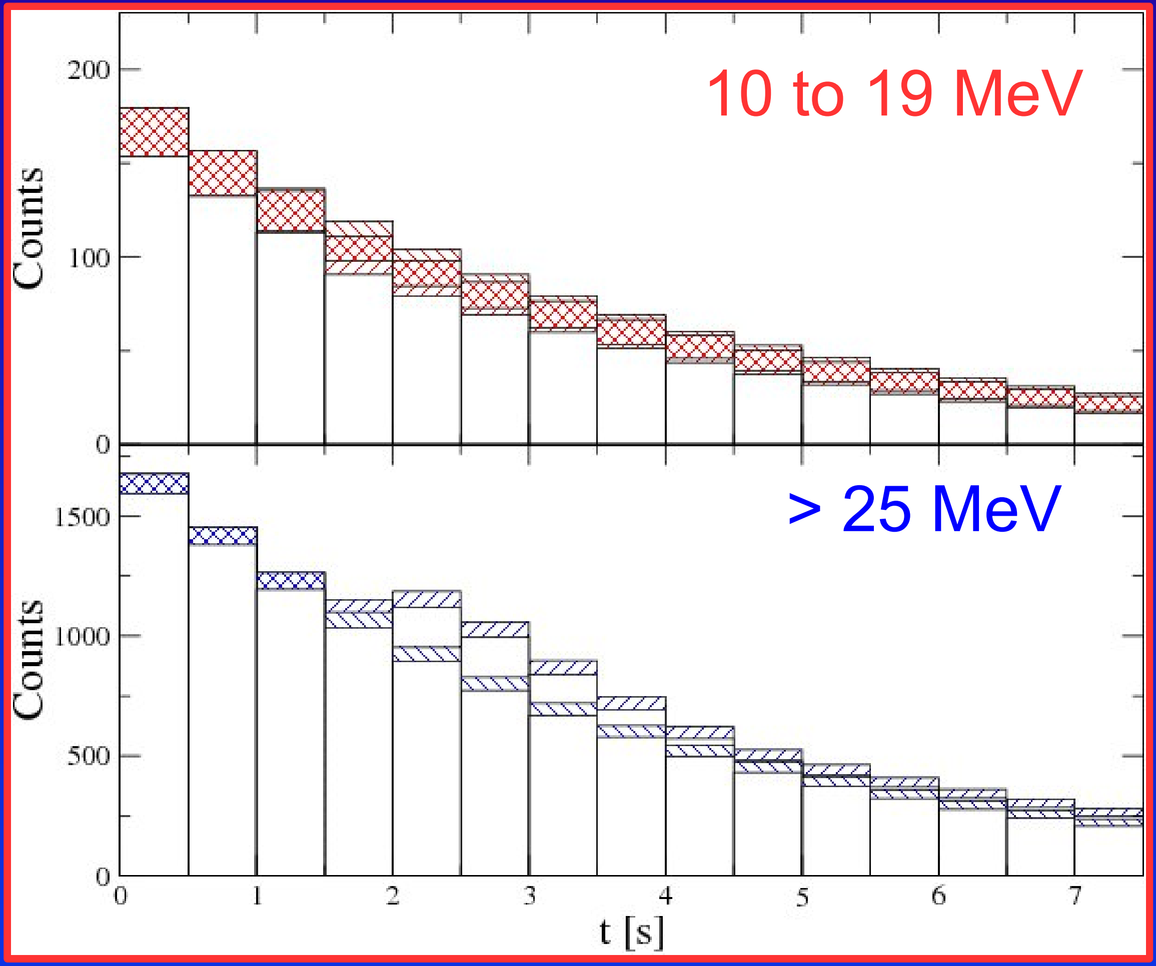


Positron Rate

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



The signal in SuperK

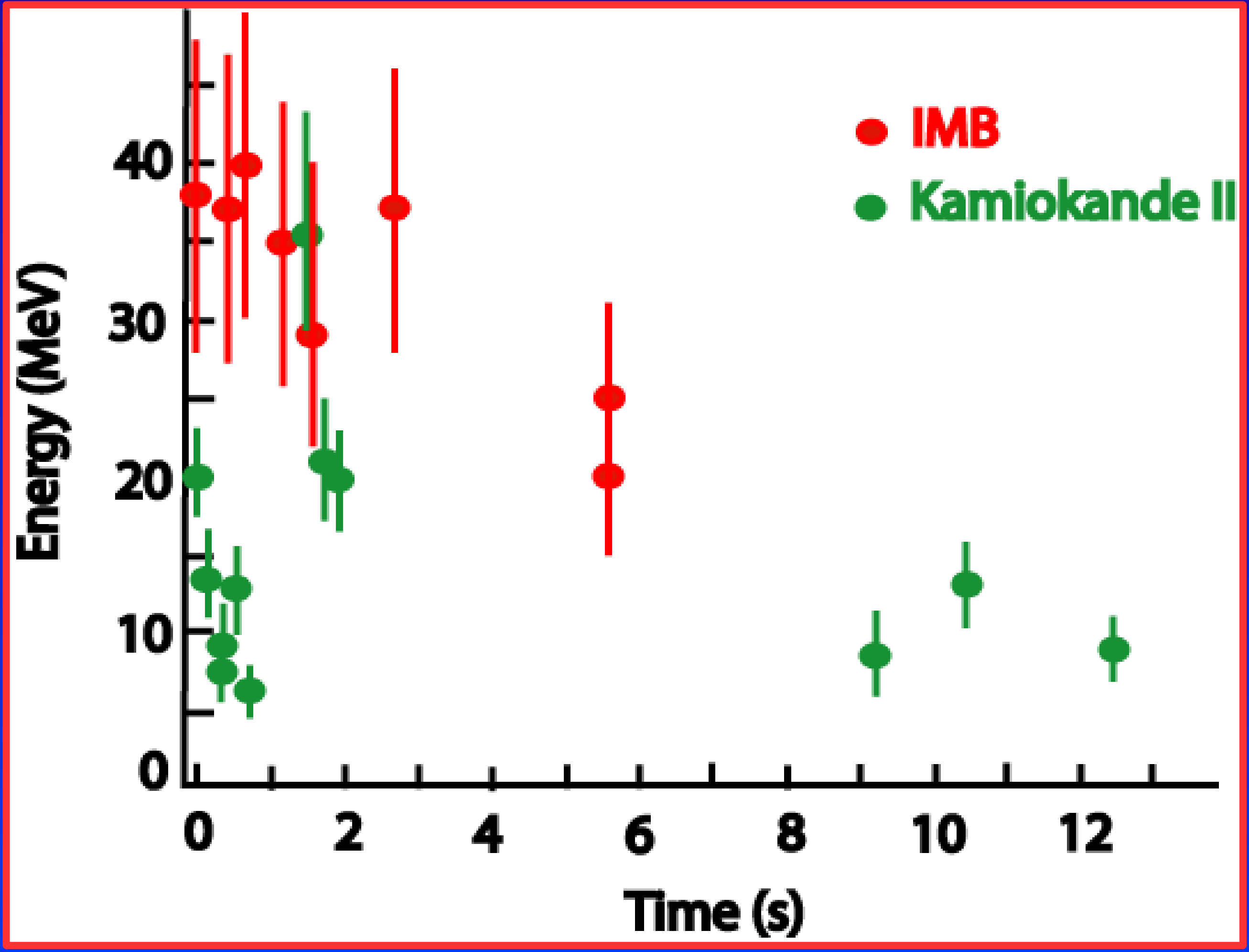


SuperK can detect the shock feature.

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;

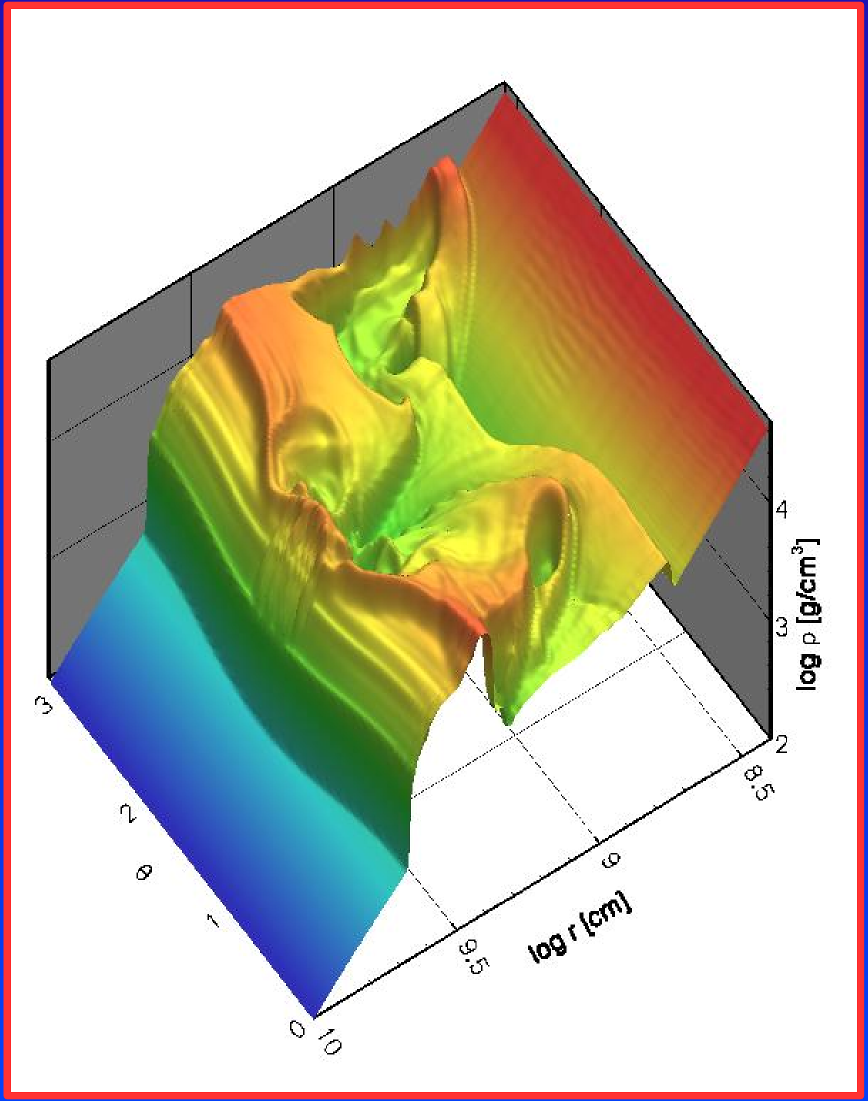


but an emission model with no shock effects is compatible at 5%.

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

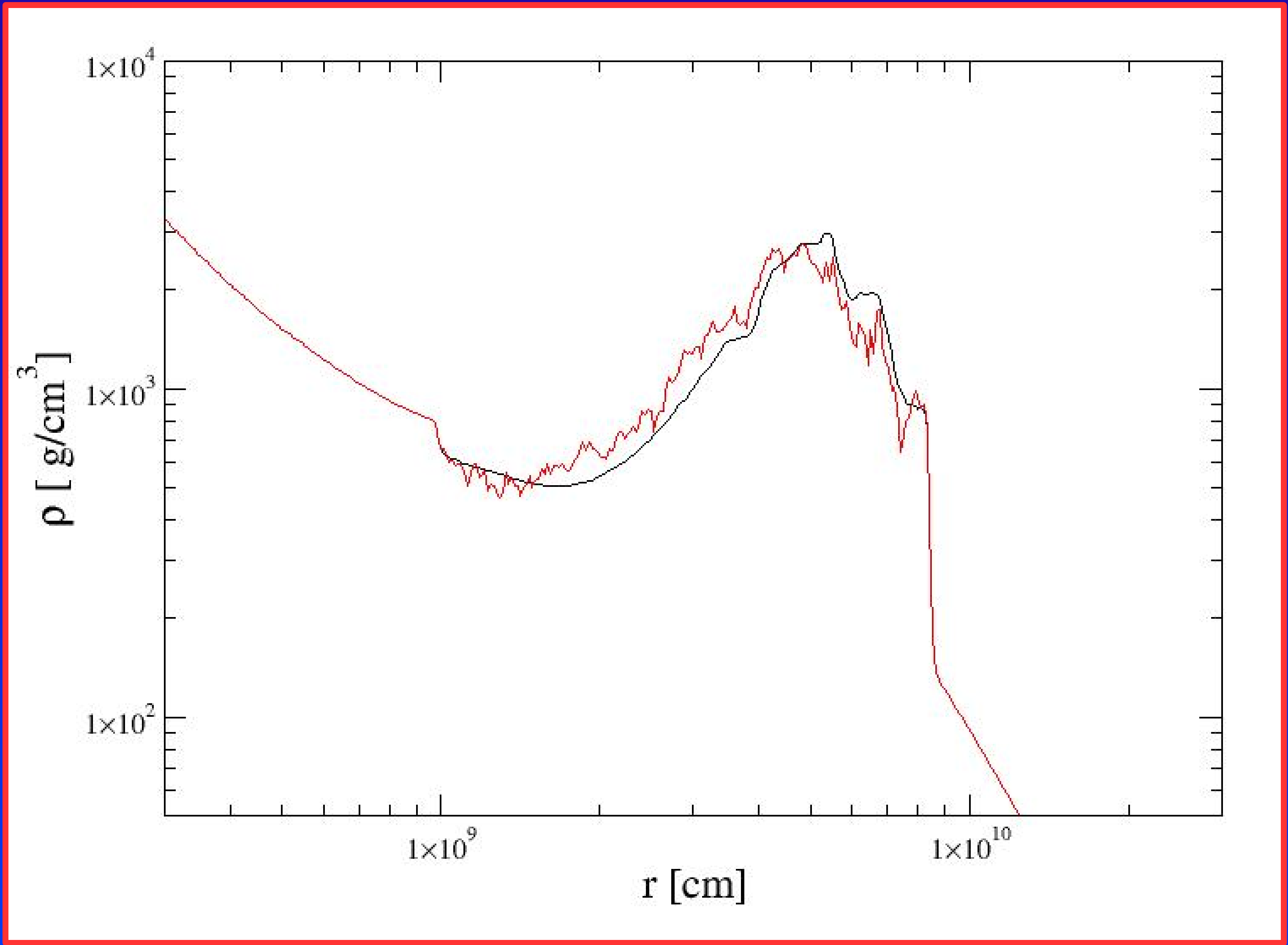
Turbulence

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

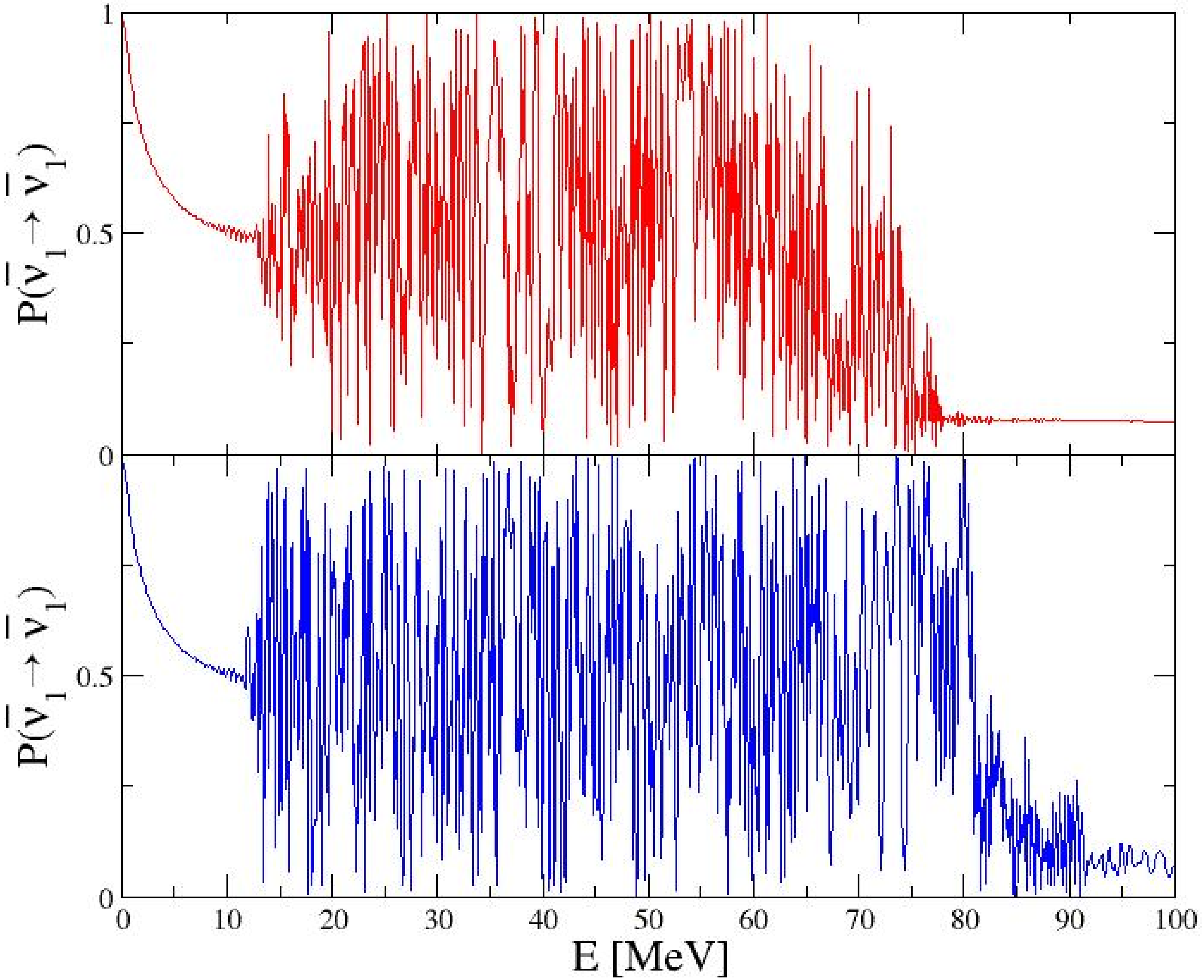


Kneller, McLaughlin & Brockman, PRD, **77**, 045023 (2008)

We can add turbulence to the profiles ...



... and see if there is any change.



Summary

- We have put together, consistently, neutrino self interaction and dynamic MSW calculations.
- 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.
- There is a similarity of the expectations with the gap of low energy events seen in the SN 1987A data.
- Adding turbulence does not change the result significantly.
- Shocks also affect the DSNB: ask Sébastien Galais.