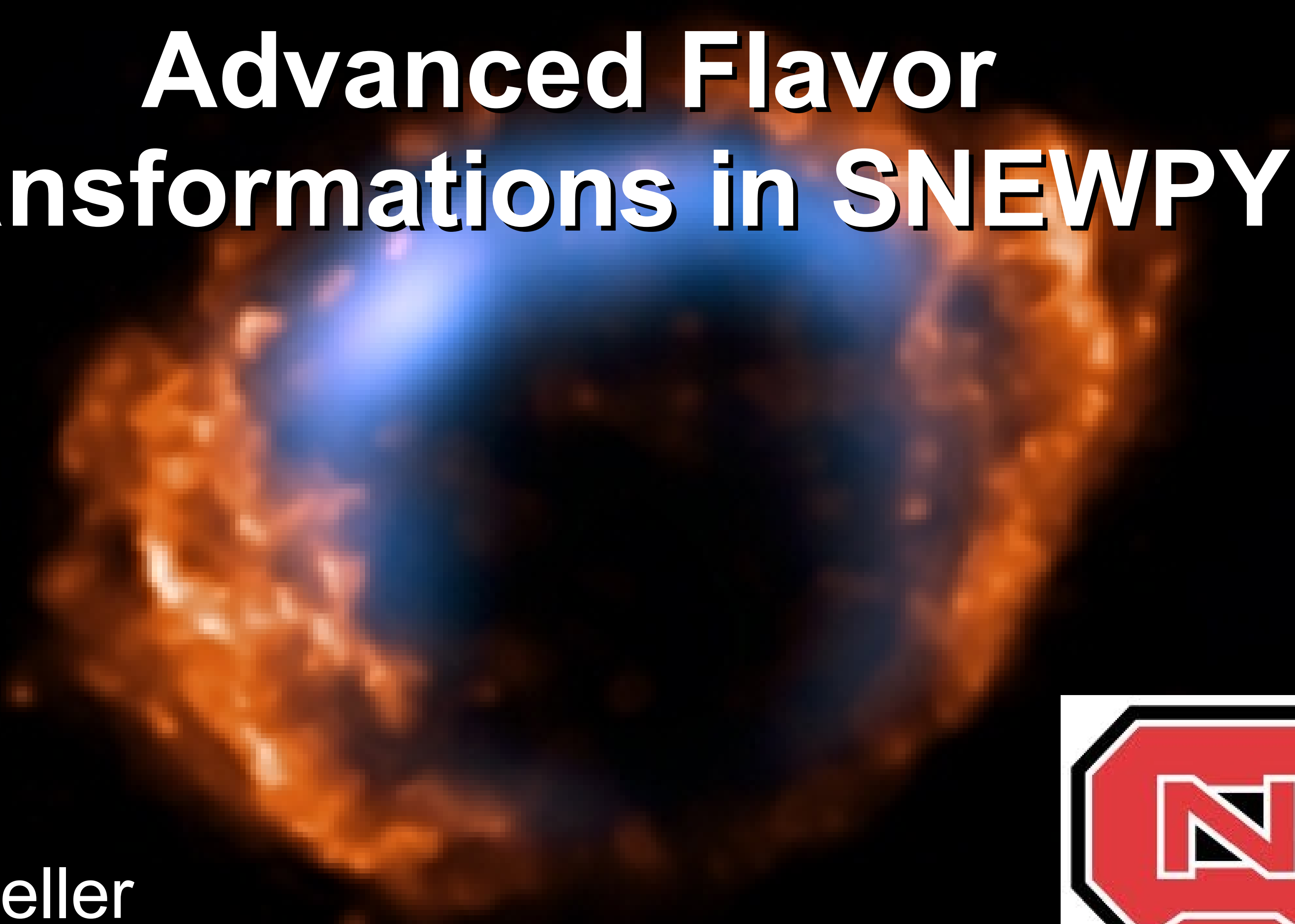
Advanced Flavor Transformations in SNEWPY



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SNEWPY presently has 15 flavor transformation prescriptions.

For three flavors:

- No Oscillations and Complete Exchange
- Adiabatic MSW in both mass orderings
- NonAdiabatic MSW H resonance in both mass orderings
- Two Flavor Decoherence at the H resonance in both mass orderings.
- Three Flavor Decoherence
- Neutrino Decay of the heaviest mass state to the lightest with variable lifetime and neutrino mass, in both mass orderings,

For four flavors:

- Adiabatic MSW of four flavors in both mass orderings
- MSW where the ‘outer’ es resonance is non adiabatic, for both mass orderings.

They are all independent of time and apart from NeutrinoDecay, they all independent of energy.

SNEWPY 2.0

We want to improve the flavor transformation prescriptions in SNEWPY in three ways:

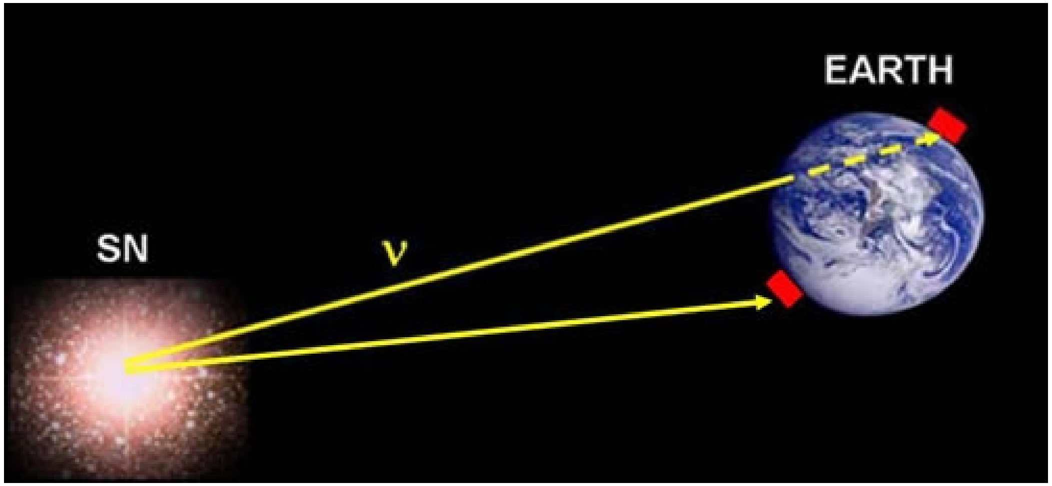
- make them 3 flavor
- add the option to include the Earth-Matter Effect
- find a way to model the Shockwave Effect

The first is straight-forward-ish.

The second two will require quite a bit of work.

Earth Matter Effects

The neutrinos from a supernova may travel through the Earth before reaching a particular neutrino detector.



The passage leaves an imprint on the signal which may be detectable if we have good statistics.

The imprint depends upon the path through the Earth so we might be able to use this effect to say something about the direction of the supernova.

To compute the Earth-Matter Effect we have modified a C++ flavor transformation code called SQA and turned it into a python module.

The code solves the Schrodinger equation for the evolution matrices S and $\bar{S}$.

$$\frac{dS}{d\lambda} = H\,S$$

H is the Hamiltonian – vacuum + matter.

The modules inputs are:

- the neutrino mixing parameters,
- the neutrino energies,
- the Earth density profile (PREM)
- the altitude of the SN.

The module returns the mass to flavor transition probabilities for both neutrinos and antineutrinos.

The module does 1000 neutrino calculations in ~30 seconds.

One present uncertainty is how to distribute the module – any advice would be greatly appreciated.

- It contains a lot of code and needs to be compiled.

We need to modify SNEWPY to get the input data into the module, and then handle the array of probabilities.

A first draft of the necessary changes:

- the altitude of the SN would be computed by the user for a given star location, SN time and detector location.
- the altitude would be an optional argument into the `generate` functions which would pass it on to the SN model classes in `get_transformed_spectra`.
- we will write a new member function for the flavor transformation classes called `get_probabilities`.
- the altitude will be an optional argument into this method. If it is not None, the Earth matter effect is computed.
- `get_probabilities` will return an N x N array of probabilities with N the number of SNEWPY flavors (currently 4).
- the elements of this array replace the `prob_ee` etc. methods used in `get_transformed_spectra`.

```
import numpy as np
from astropy import units as u
from astropy.time import Time
from astropy.coordinates import SkyCoord, EarthLocation, AltAz

# skycoordinates of neutrino source
Betelgeuse = SkyCoord.from_name('Betelgeuse')

# neutrino detector
SuperK = EarthLocation(lat=36.425722*u.deg, lon=137.310306*u.deg, height=389*u.m)
#SuperK = EarthLocation.of_site('Super-Kamiokande')
utcoffset = +9*u.hour

# when the supernova occured
time = Time('2021-5-26 23:14:00') - utcoffset

# altaz of supernovae at detector
SNaltaz = Betelgeuse.transform_to(AltAz(obstime=time,location=SuperK))
```

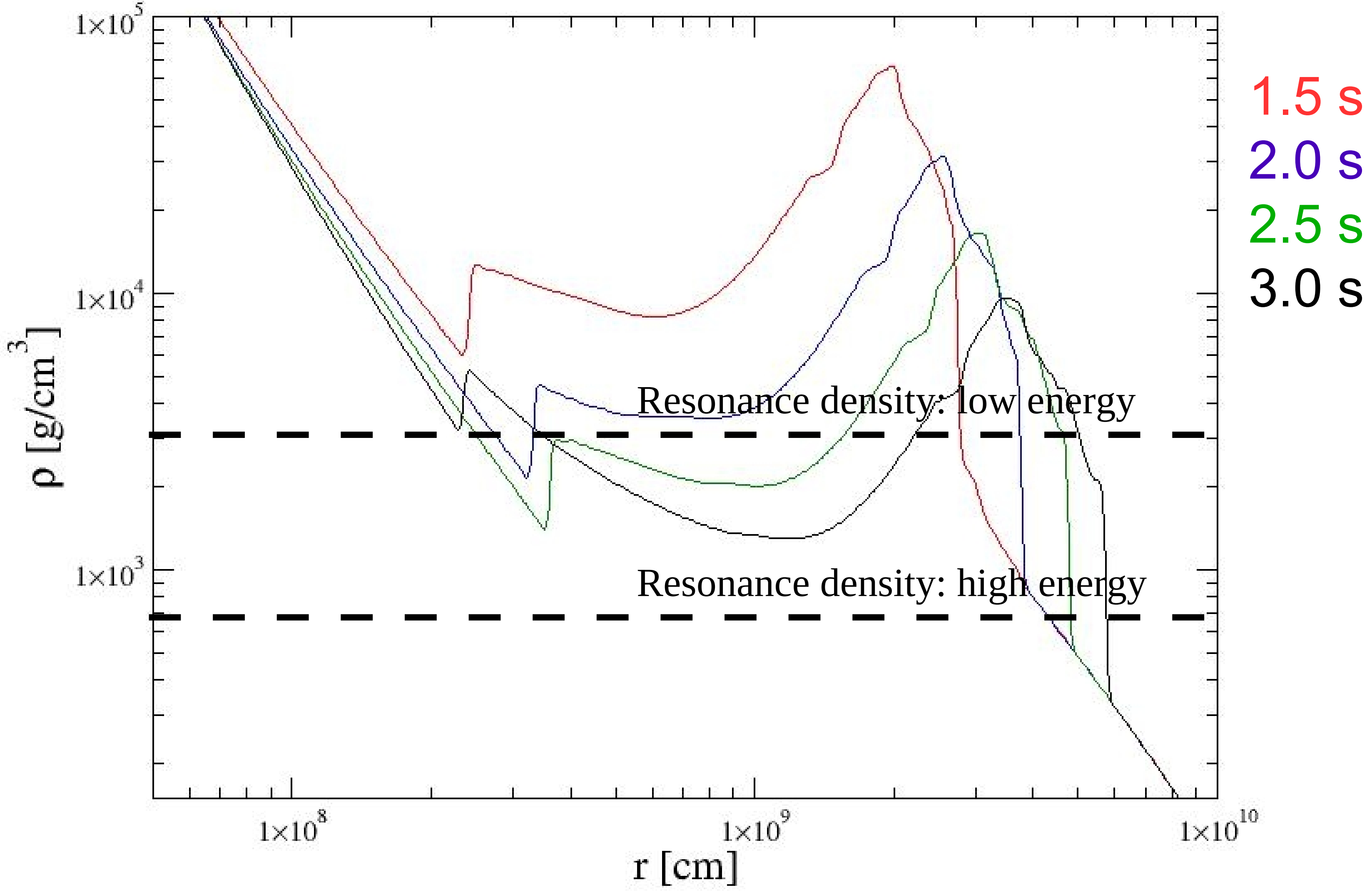
Shockwave Effects

Using the measured mixing angles and typical progenitor density profiles, the neutrino flavor evolution is initially adiabatic through the mantle of the supernova.

For some supernovae, the shock will reach the high-density (H) MSW resonance region while the PNS is emitting neutrinos.

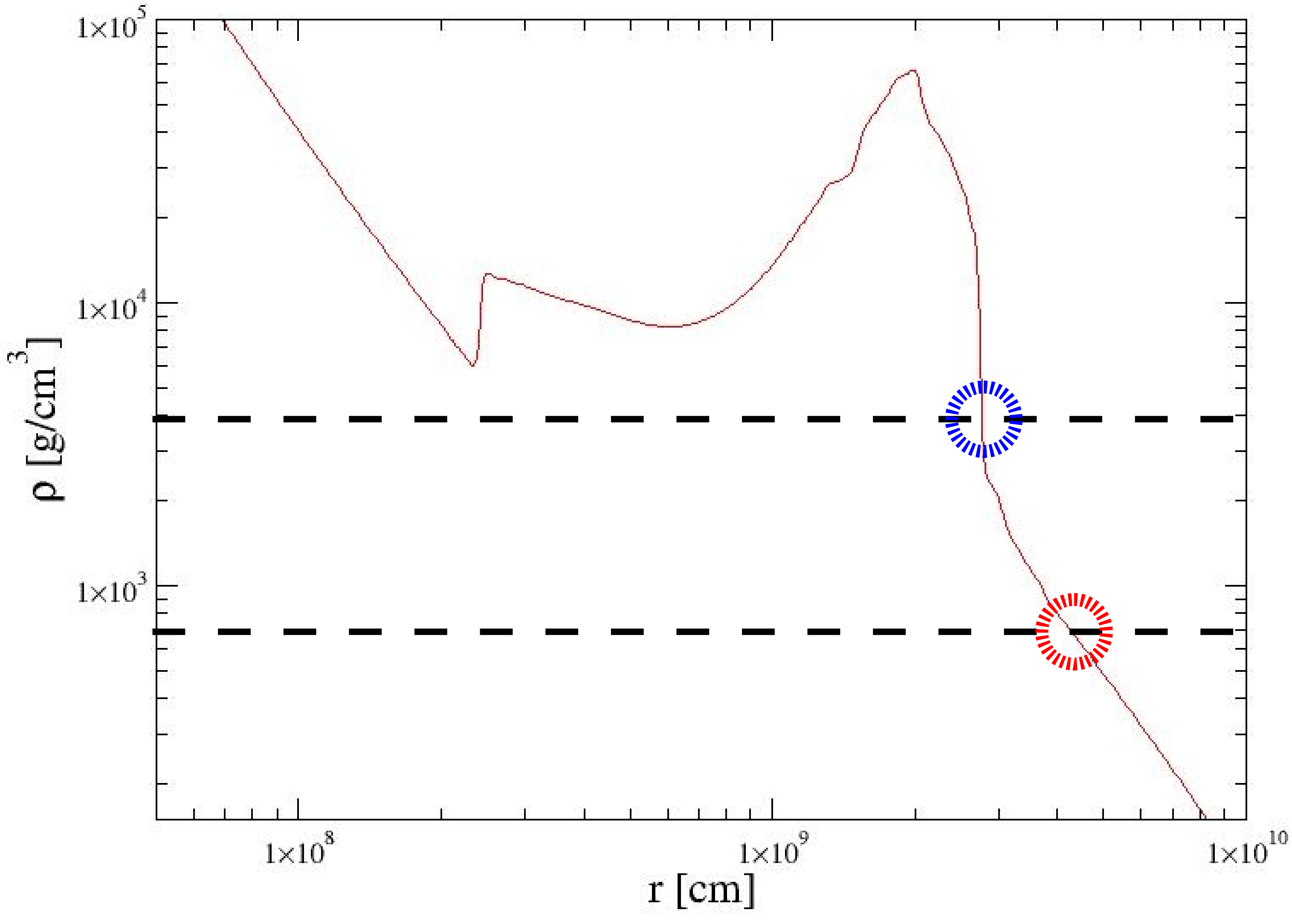
The shock changes the adiabaticity of the H resonance and leaves an imprint in the neutrino signal.

Detecting the shock allows us to measure the shock speed and if we know the progenitor, calculate the time of shock breakout.

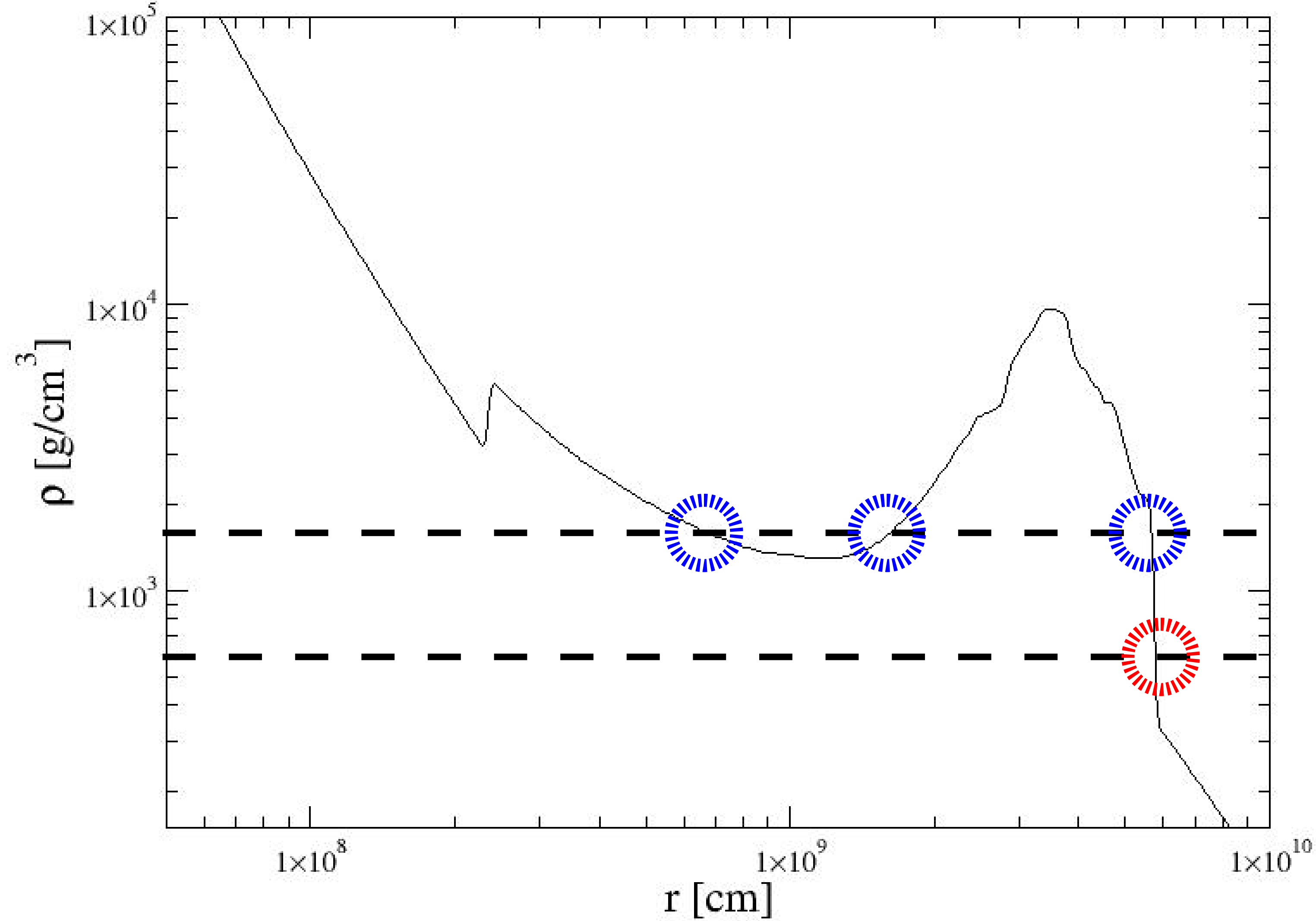


1×10^5
1×10^4
1×10^3
ρ [g/cm^3]
1×10^8
1×10^9
1×10^10
r [cm]
Resonance density: low energy
Resonance density: high energy
1.5 s
2.0 s
2.5 s
3.0 s

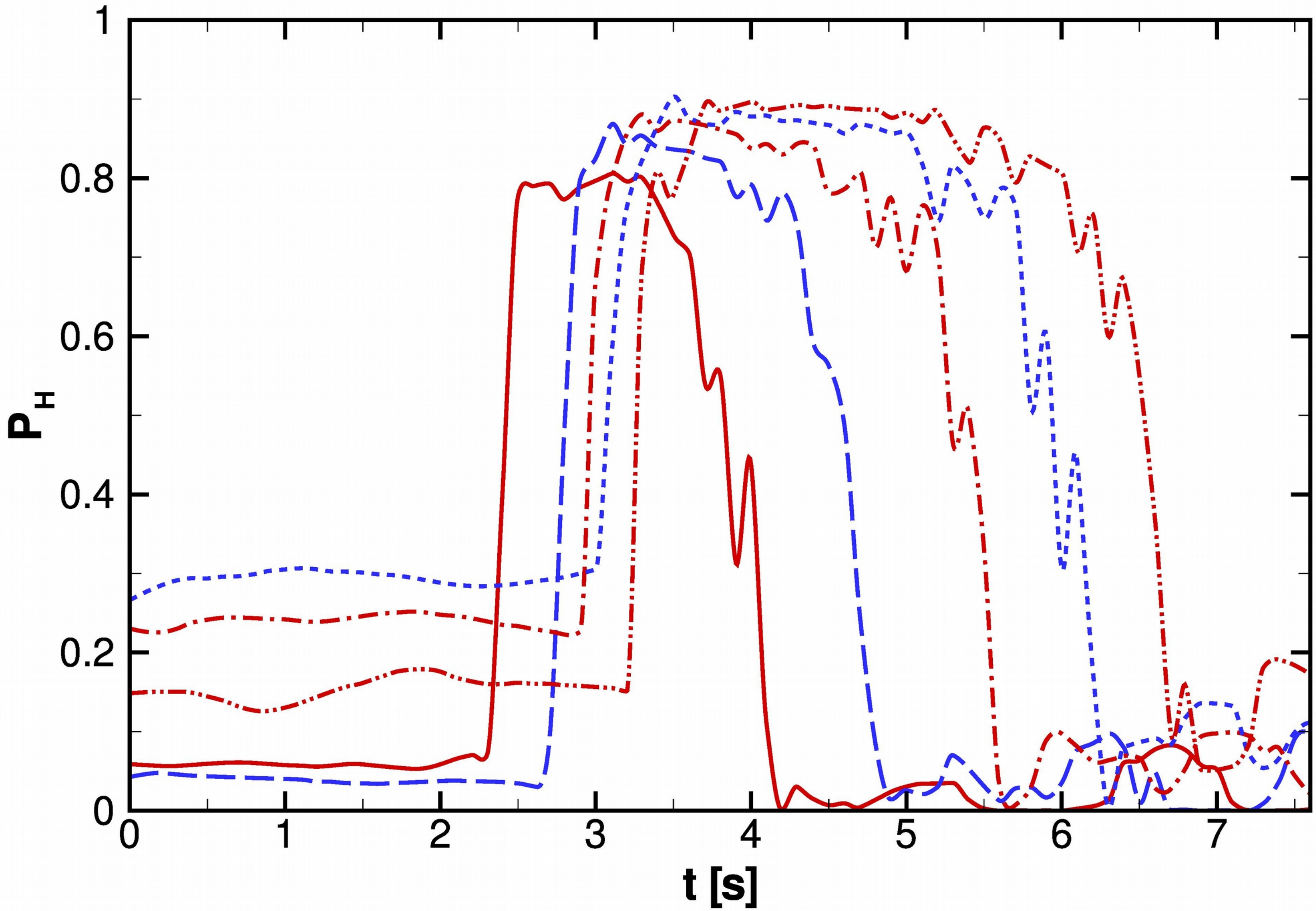
- Small slope → adiabatic evolution → flavor changes.
- Steep slope → diabatic evolution → no flavor change.



- Neutrinos can experience multiple resonances – interference.

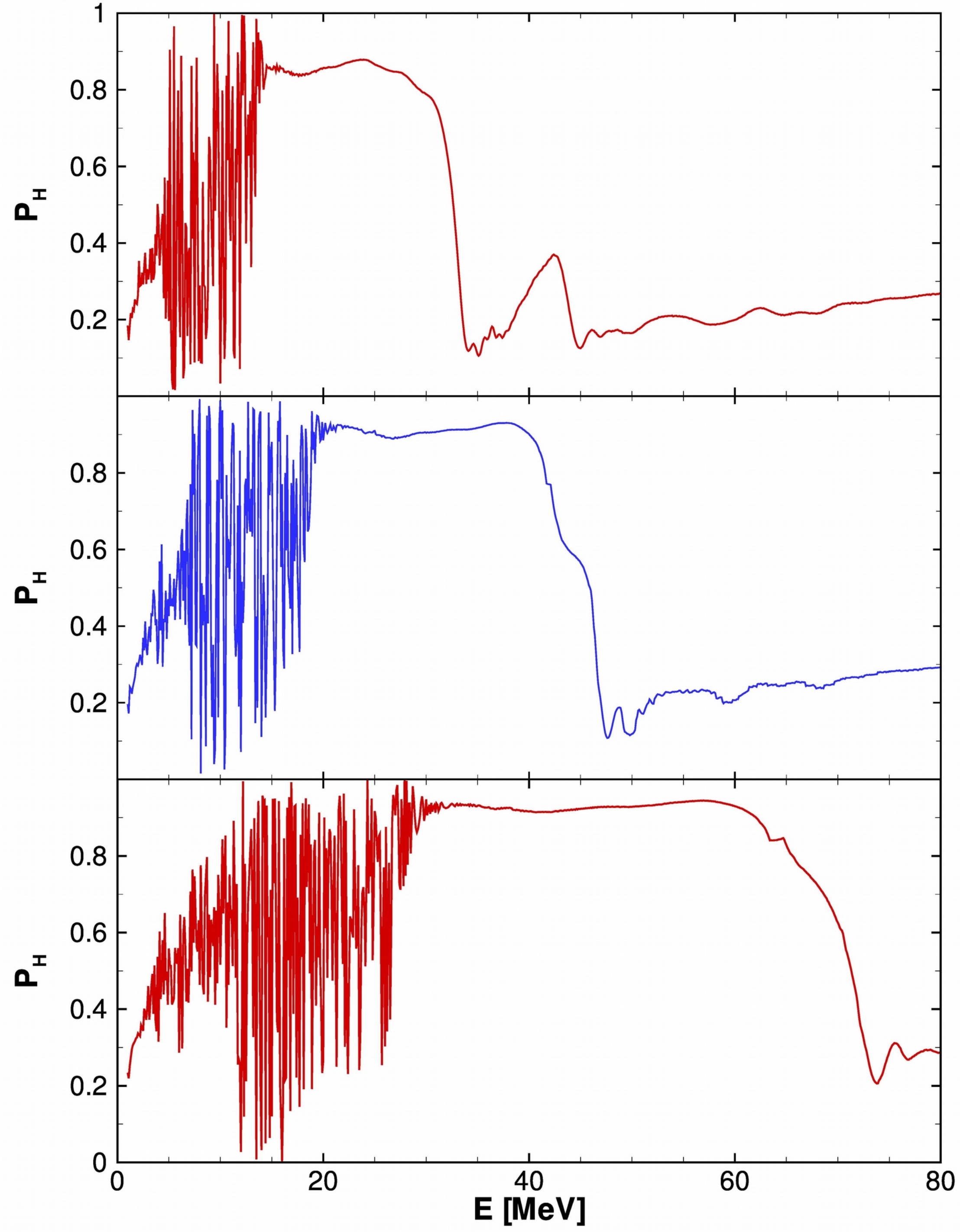


For a fixed energy,



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

For a fixed time,



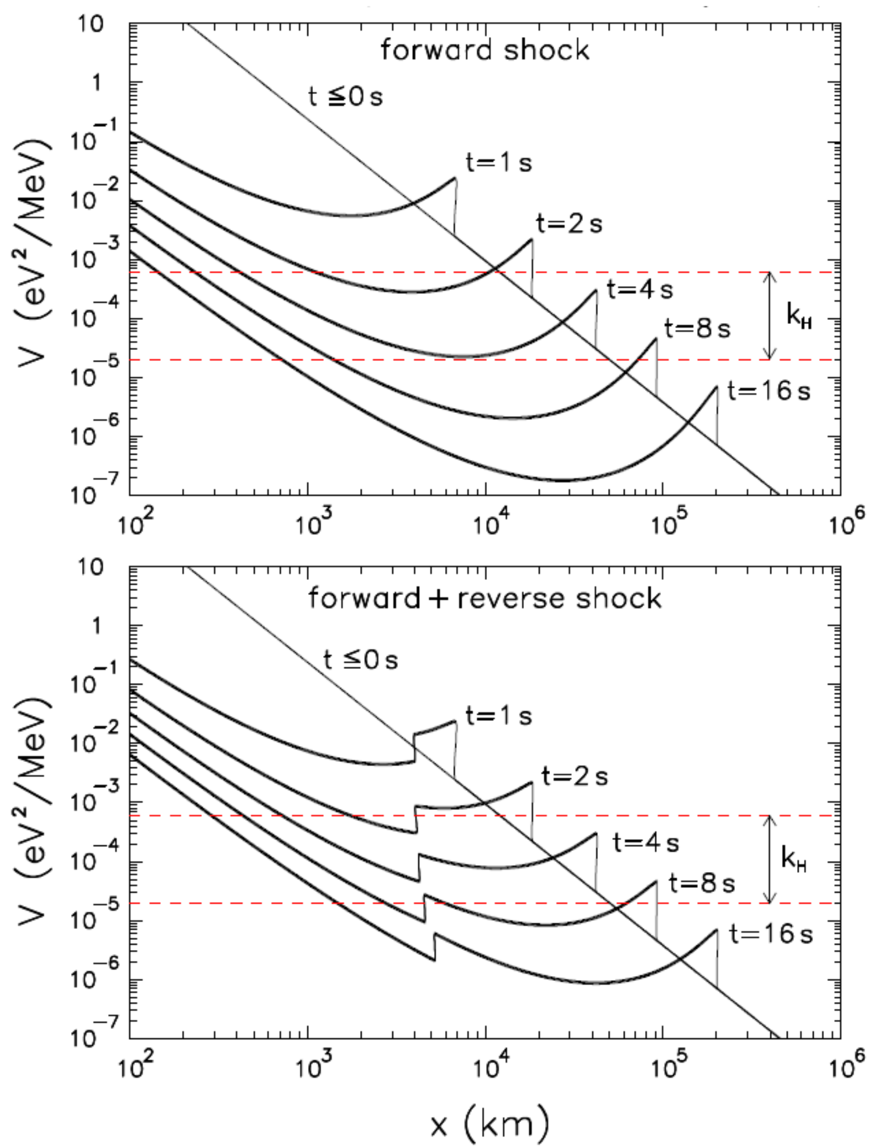
Kneller, McLaughlin & Brockman, PRD **77** 045023 (2008)

Shockwaves are present in simulations but we can’t just plug the density profiles into a flavor oscillation code e.g. SQA.

- the shock in the simulation is usually too soft – the shock is spread over several spatial grid zones and the gradient of the is not steep enough for non-adiabatic evolution.

If we want to include shock effects in SNEWPY, we need a way of producing plausible density profiles for the mantle of the supernova which we can feed into a suitable version of the SQA module.

A possible starting point is the analytic profiles by Fogli et al., JCAP, **6** 12 (2006)



The Fogli profiles are defined by a set of parameters that can be adjusted to fit the progenitor.

The shock speed and density jump can be extracted from simulations.

We can also add turbulence in the region between the two shocks.

Once we have the density profiles we can feed them through a different version of the SQA module.

- the calculation is the same, the output is slightly different because we need the flavor to mass basis transition probabilities

While a plan exists, none of the code is written yet.

Summary

- SNEWPY is a new bridge across the gulf between supernova simulations and detector signals.
- Version 2.0 will include more advanced flavor transformation prescriptions that will vary in energy and time.

- The Earth-Matter Effect is in an advanced stage of development, the Shockwave Effect is yet to be started but there’s a plan.

Thank you