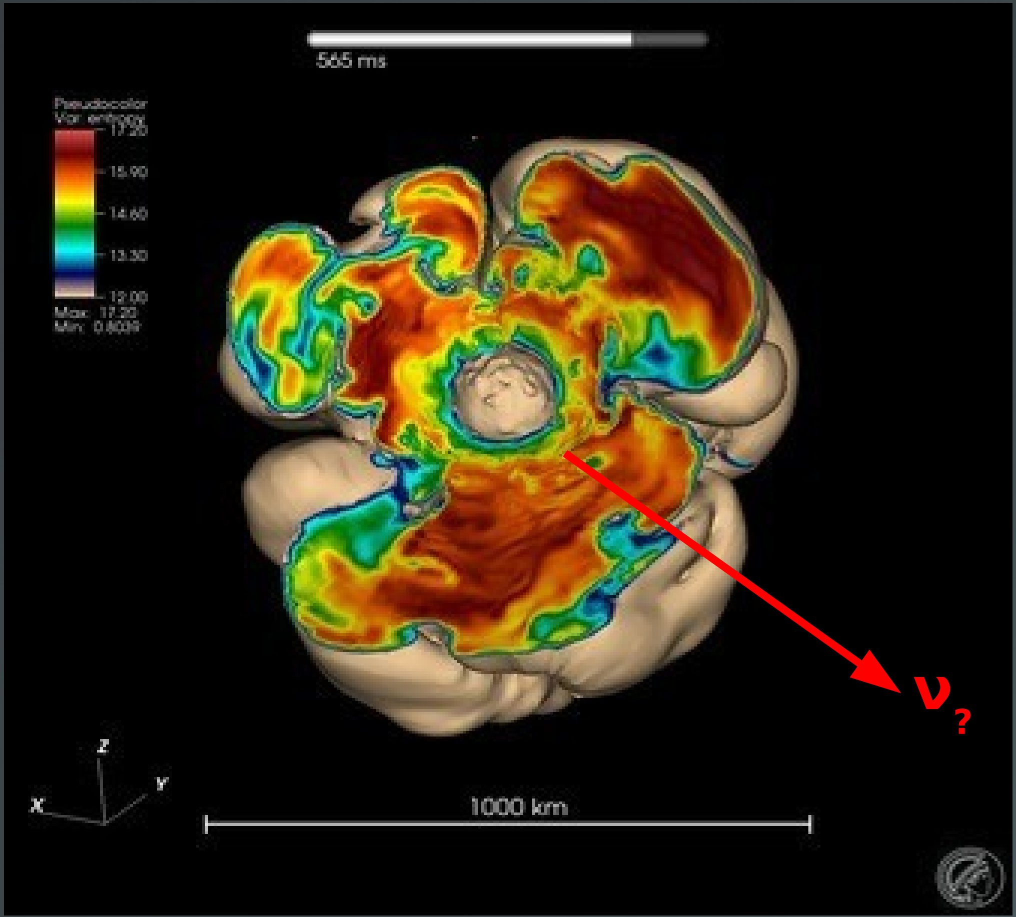
Traveling through turbulence



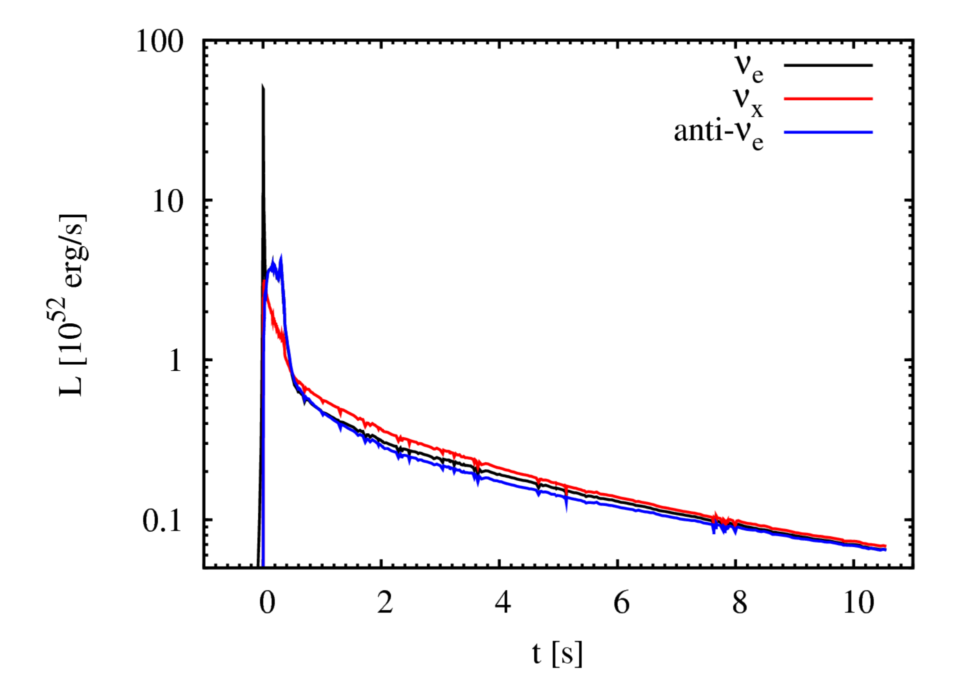
Tina Lund and Jim Kneller, NCSU

INT Program 12-2a ”Core-Collapse Supernovae: Models and Observable Signals ”

July 16th – July 20th, 2012

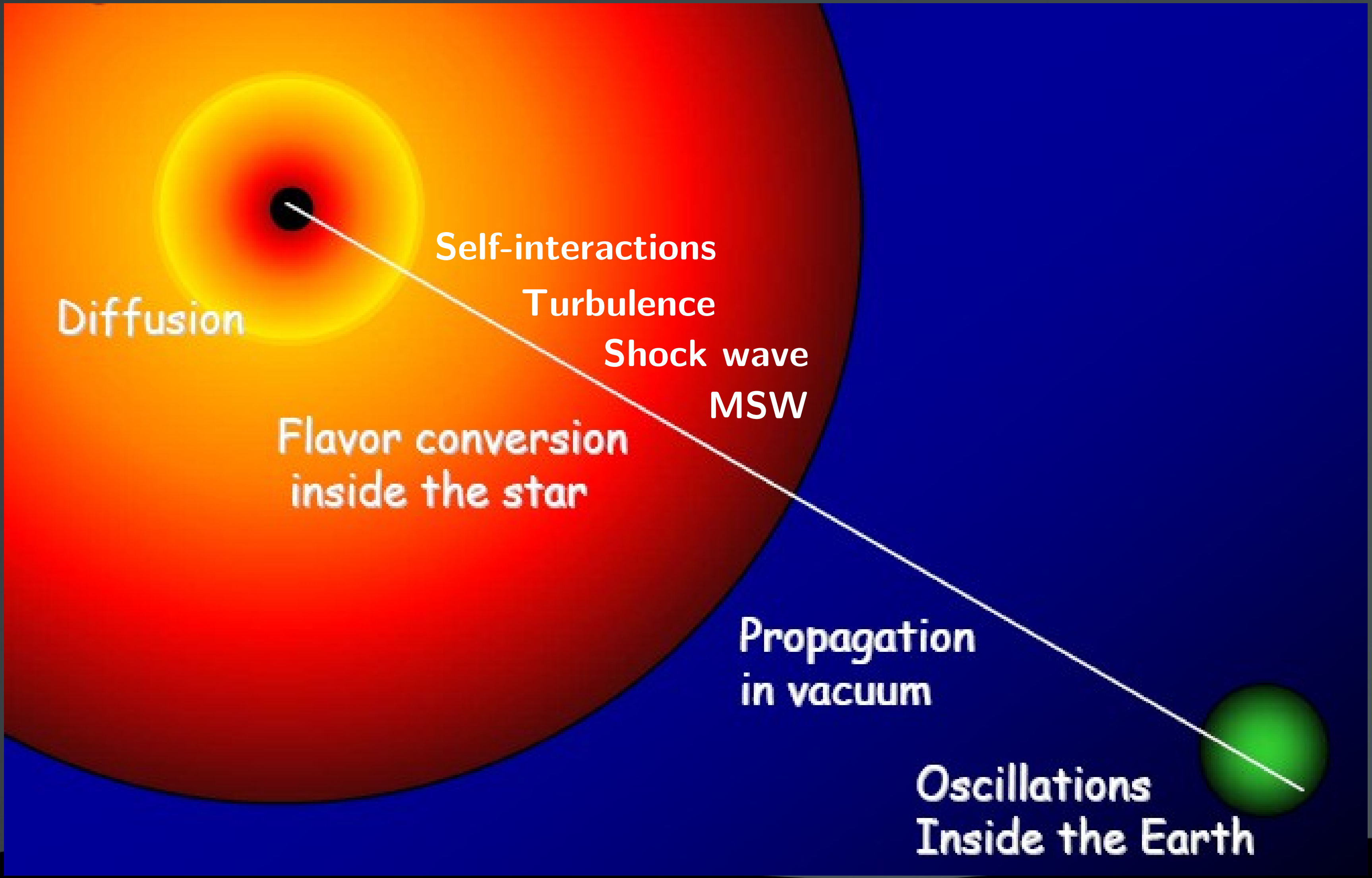
Neutrino emission from ccSN

- Neutrinos produced at PNS surface.
- Amount and energies varies during accretion and cooling phases.
- Correct interpretation of observed neutrinos → Need to know all about ν's.



[Fischer et al., 2010]

Effects affecting neutrinos



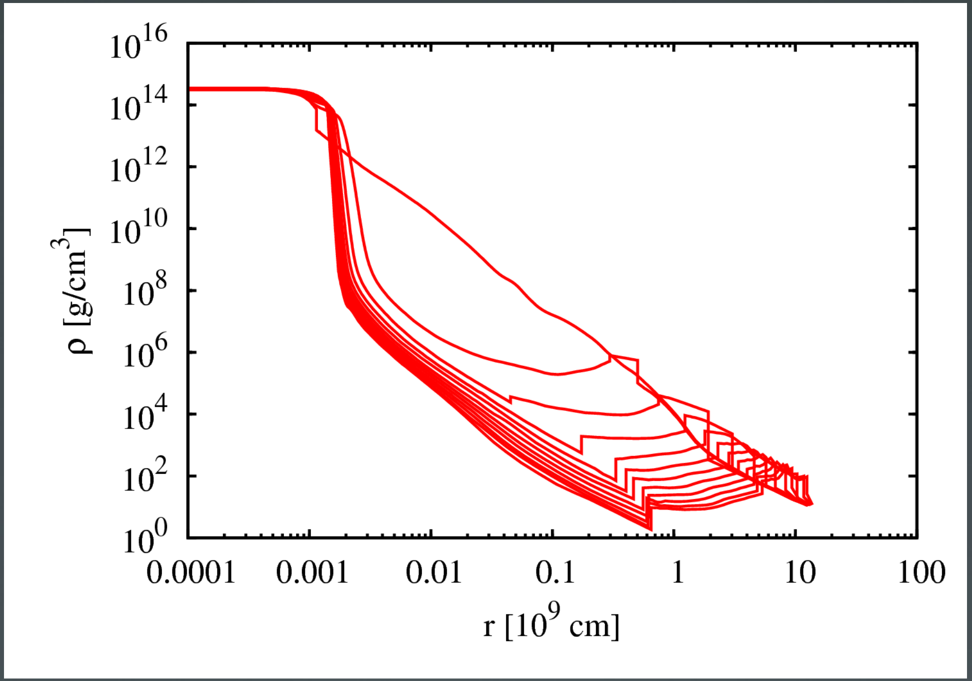
Focus of this project

[www.particlezoo.net]

- Interplay of MSW, $\nu\nu$ self-interaction and turbulence.
- Impact of turbulence - 2 regions.
- Investigate shock hitting MSW L resonance.
- Use numerically realistic density profiles.

Density profiles

- Ideally multi-D simulations, but does not go long enough.
- 1D simulation of 10.8 $M_\odot$ progenitor, (8.8 and 18.0 $M_\odot$).
- Provided by Basel group.
- 10.7 s post bounce duration.
- Develop contact discontinuity, forward and reverse shocks.



MSW resonances

- Neutino flavor changes at two resonance densities:

$$\rho_{res} \sim 1.4 \times 10^6 \text{ g/cc} \left(\frac{\Delta m^2}{1 \text{ eV}^2}\right) \left(\frac{10 \text{ MeV}}{E}\right) \left(\frac{0.5}{Y_e}\right) \cos 2\theta$$

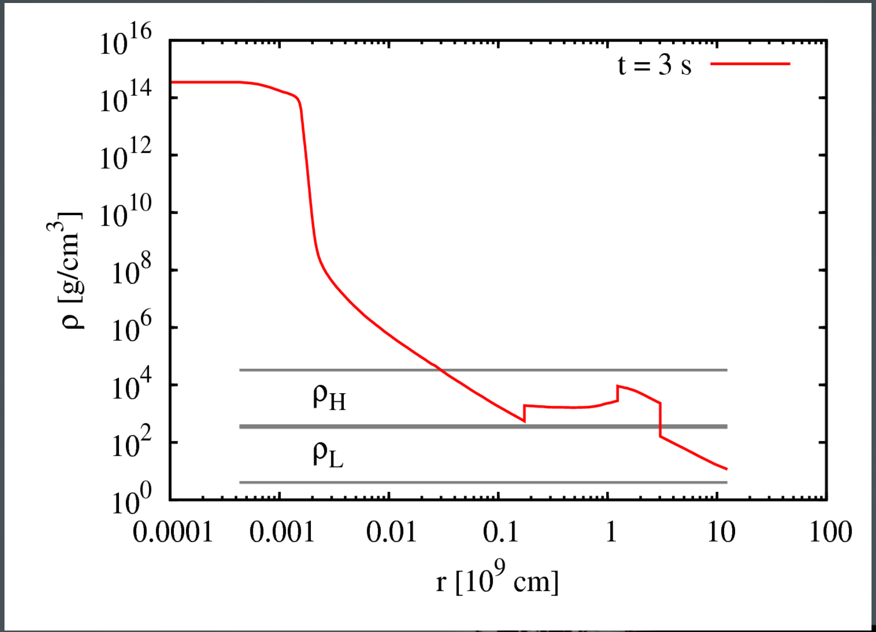
- ρ_H corresponding to

$\Delta m_{13}^{\ 2} \approx 2.43 \cdot 10^{-3}$ eV^2 and $\theta_{13} = 9°$

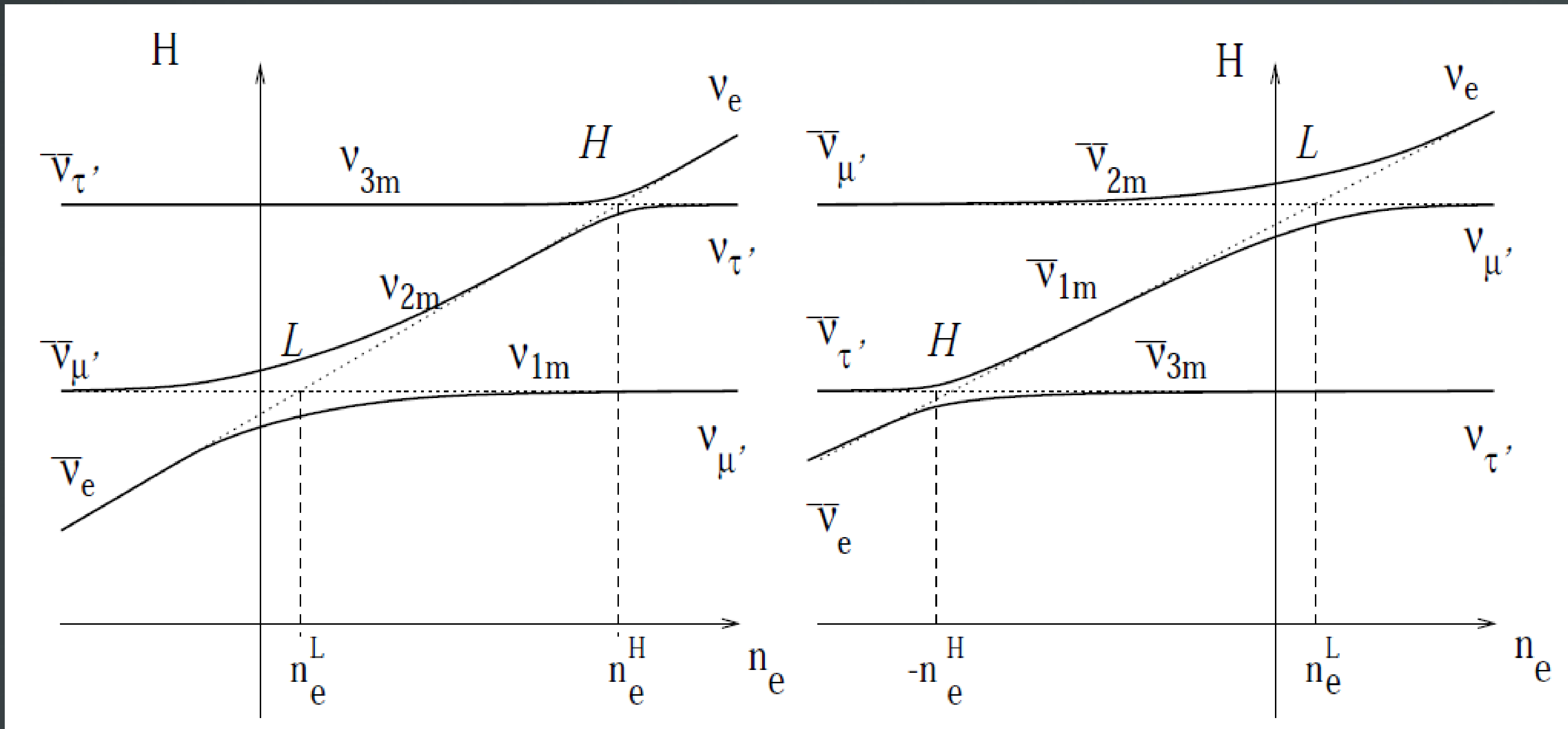
- ρ_L corresponding to

$\Delta m_{12}^{\ 2} = 7.56 \cdot 10^{-5}$ eV^2 and $\theta_{12} = 34°$

- Position of ρ_{res} and derivative of density there important.



Resonance transitions

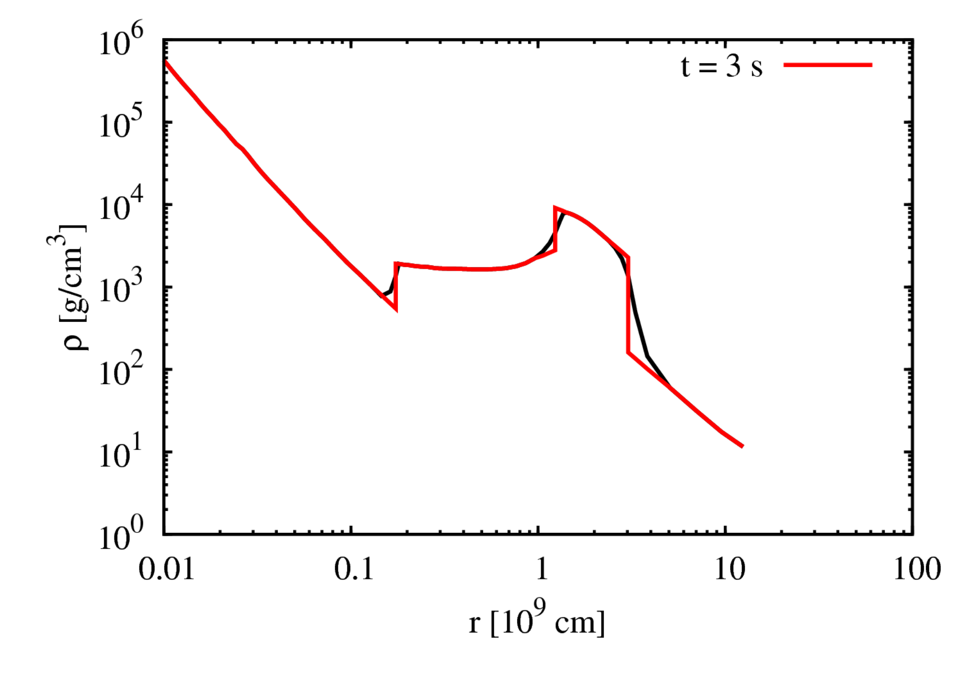


[Dighe & Smirnov, 2000]

- General propagation is adiabatic.
- Need diabatic at shock.

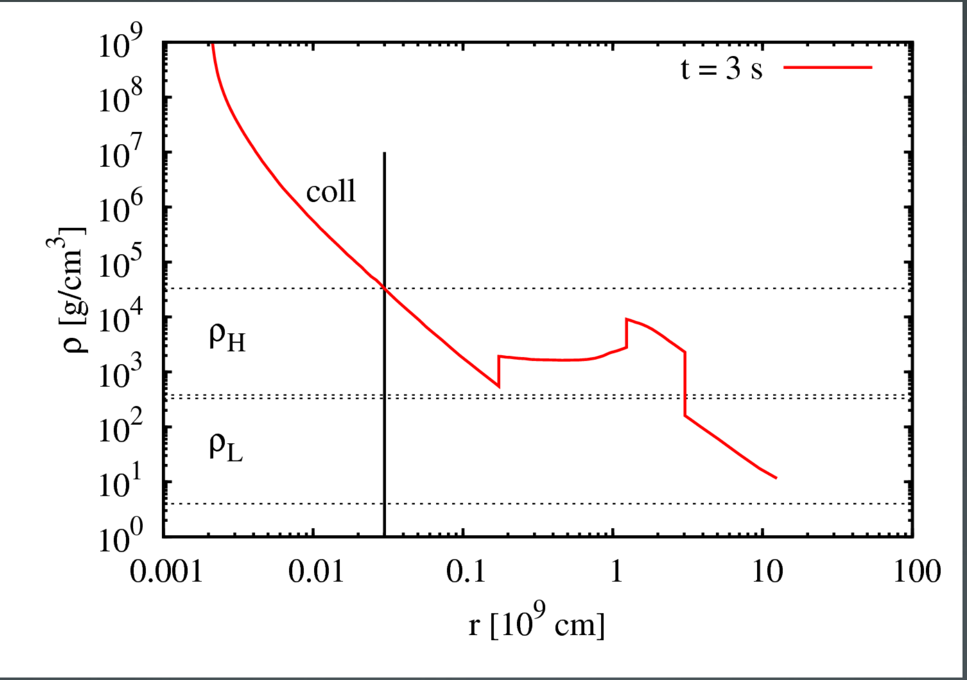
Shock morphology

- Numerical soft shocks.
- When θ_{13} is big, only adiabatic transitions happens: $\gamma >> 1$, $\gamma \propto n_e / (dn_e / dr)$
- Need diabatic at shock.
- Partially steepend by hand.



Collective effects

- Flavor changes from background neutrinos.
- When n_ν is high enough.
- Usually before MSW and turbulence.



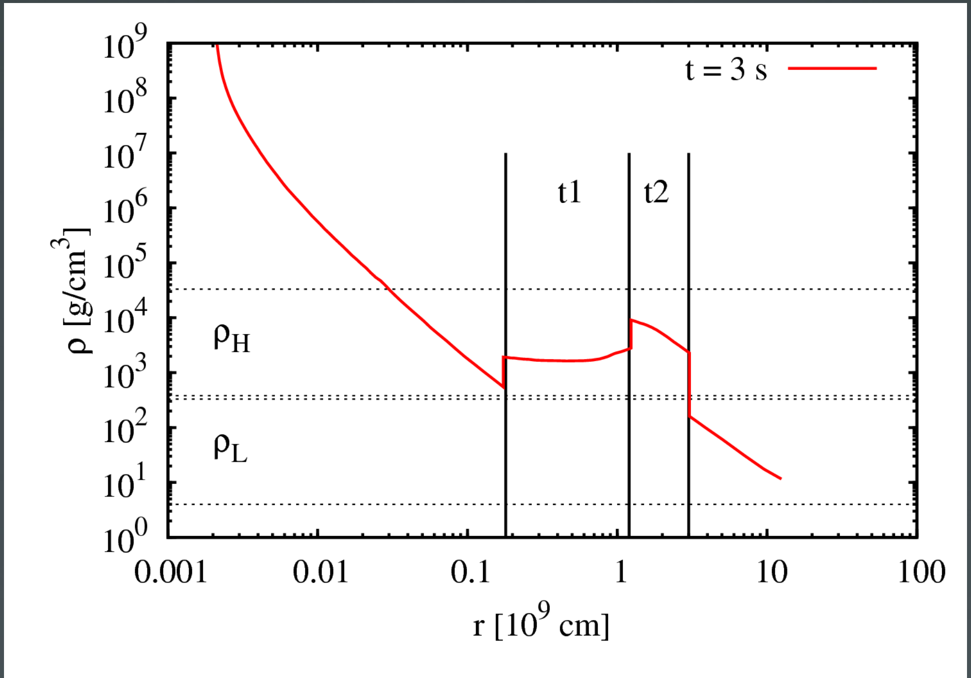
Turbulence

- Turbulence by hand on 1D.
- 2 different turbulence areas.
- From Kneller & Volpe, we have the equations for adding turbulence:

$$V(r) = (1 + F(r))\,\langle V\rangle(r)$$

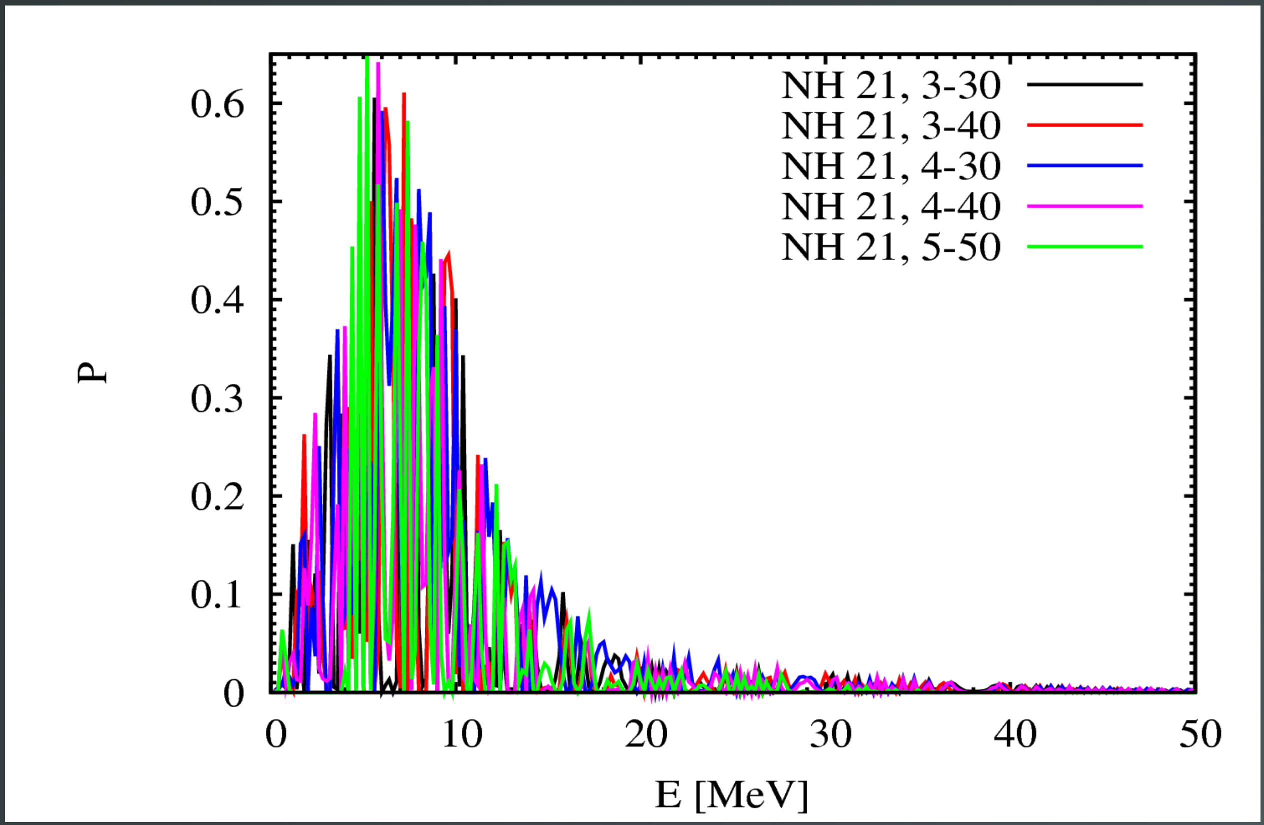
- Where F(r) is given by:

$$F(r) = \frac{C_\star}{\sqrt{N_k}} \tanh\left(\frac{r - r_r}{\lambda}\right) \tanh\left(\frac{r_s - r}{\lambda}\right) \times \sum_{n=1}^{N_k} \left\{A_n \cos\left[k_n\left(r - r_r\right)\right] + B_n \sin\left[k_n\left(r - r_r\right)\right]\right\}$$



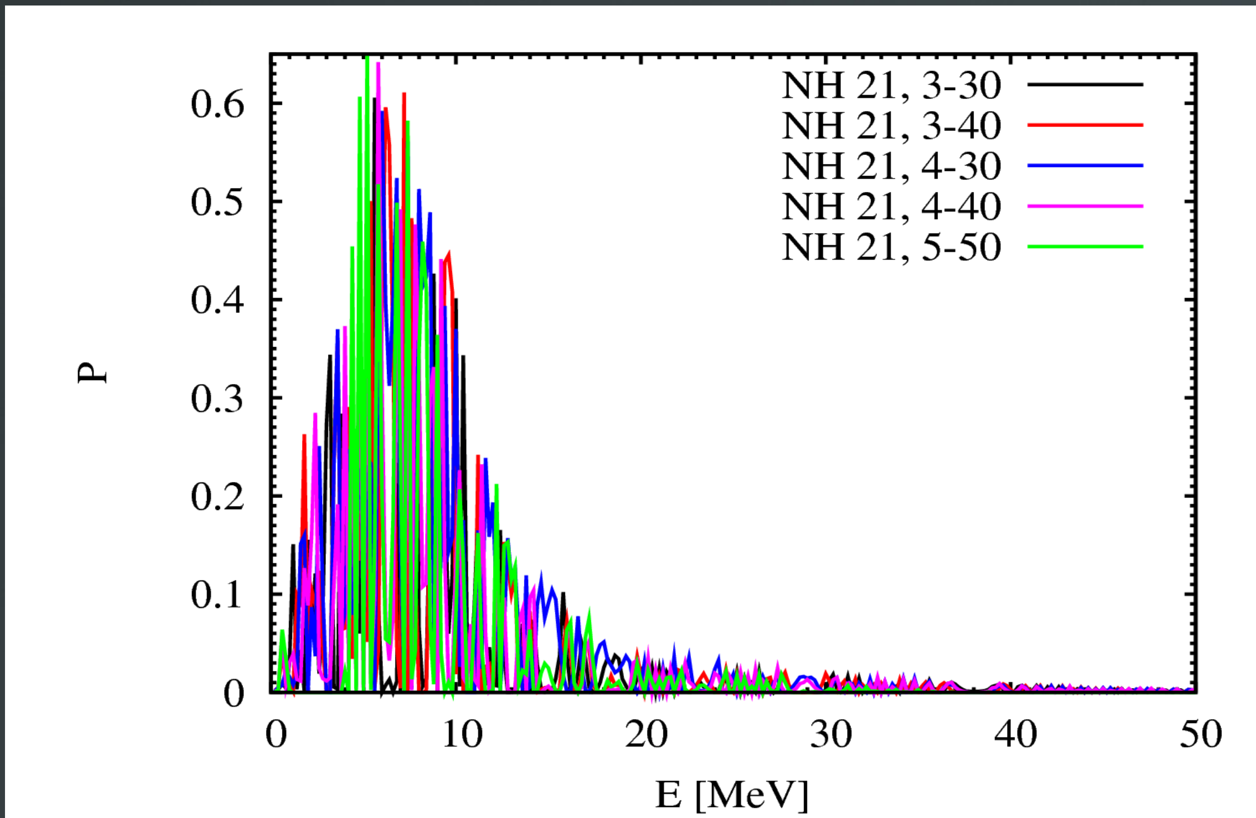
- $C_* = 0.03$
- $N_k = 10^3$

Tests



- Kolmogorov spectrum.
- Decades and number of wave modes.

Tests



- Results reported in the following will be for
- $C_* = 0.03$
- $N_k = 10^3$

- Kolmogorov spectrum.
- Decades and number of wave modes.

Results for t = 9 s

- MSW:

  H: $\nu_3 \leftrightarrow \nu_2$, NH

  $\bar{\nu}_1 \leftrightarrow \bar{\nu}_3$, IH

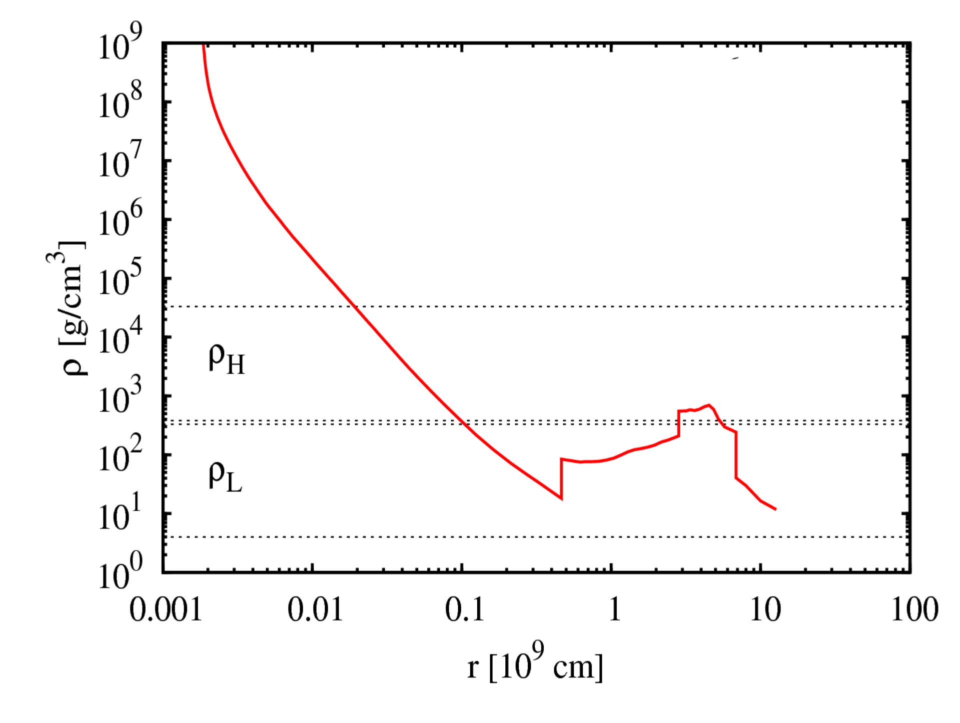
  L: $\nu_1 \leftrightarrow \nu_2$, both

- Collective:

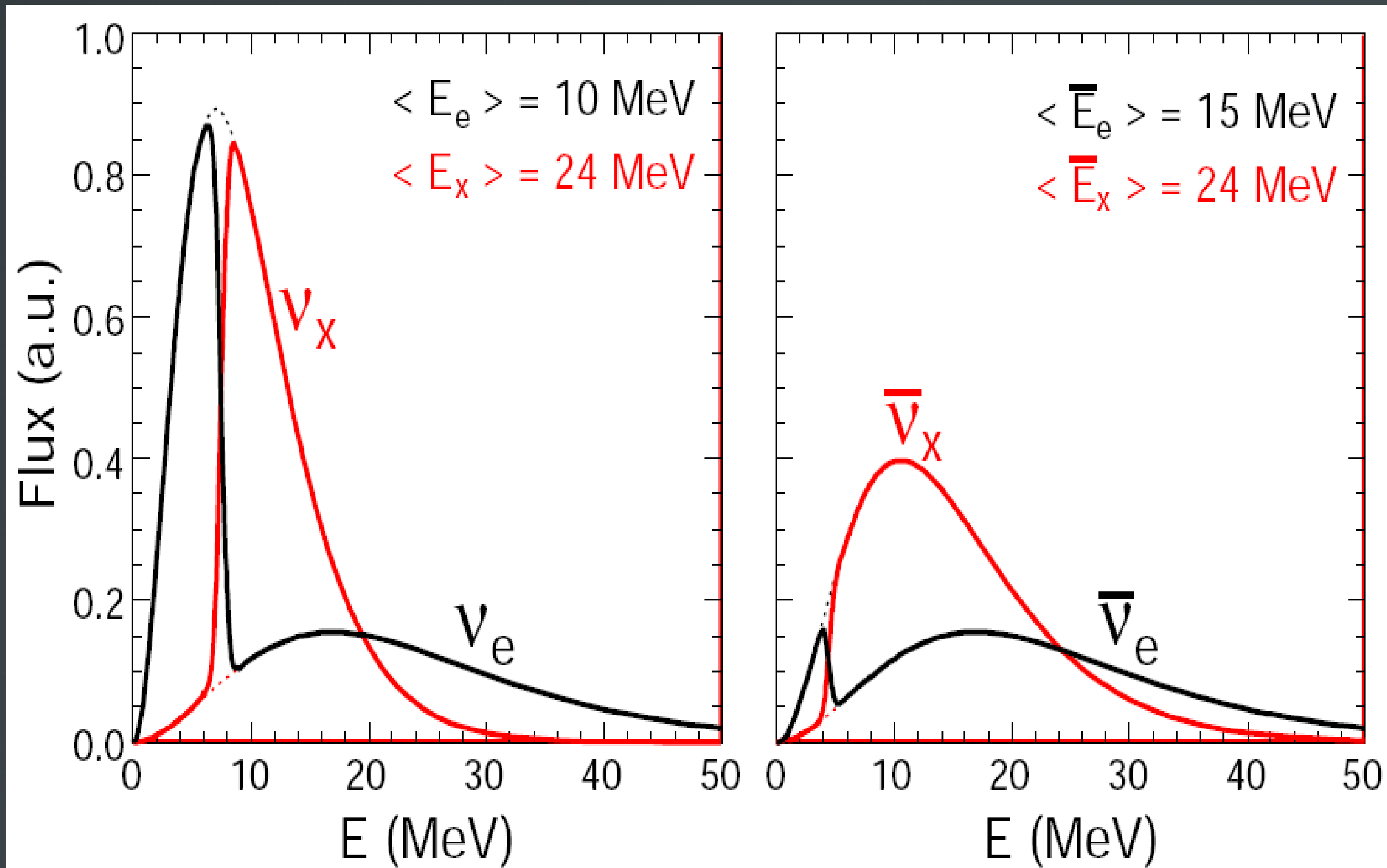
  NH: nothing

  IH: $\nu_3 \leftrightarrow \nu_{1,2}$, split

  IH: $\bar{\nu}_3 \leftrightarrow \bar{\nu}_{1,2}$, swap

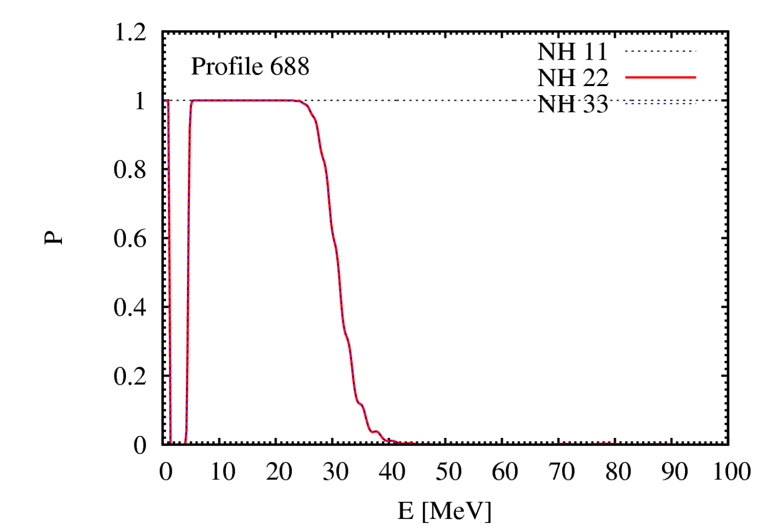


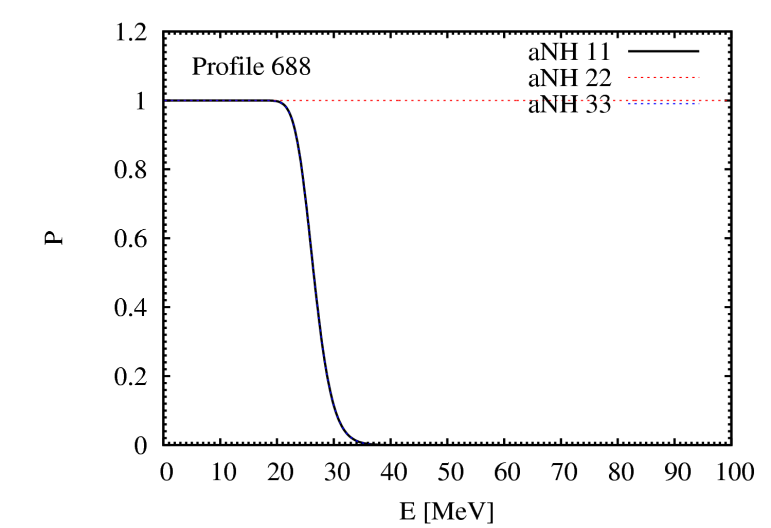
Collective effects



[Fogli et al., 2003, 2006]

Comment on collective effects only

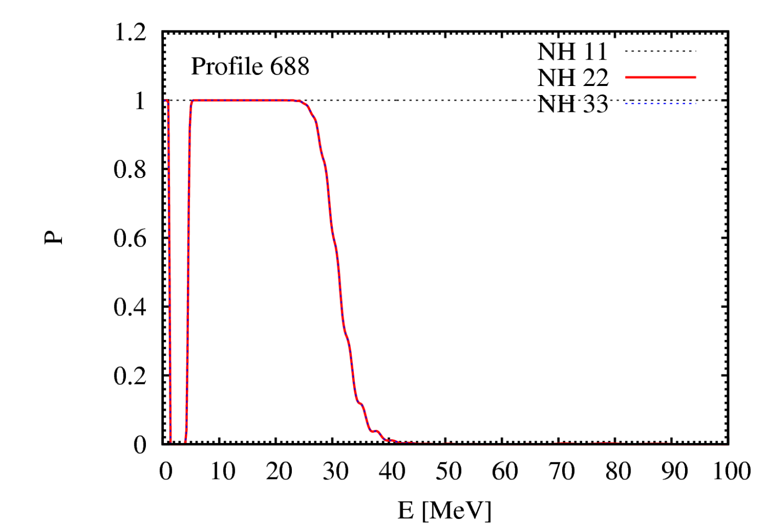




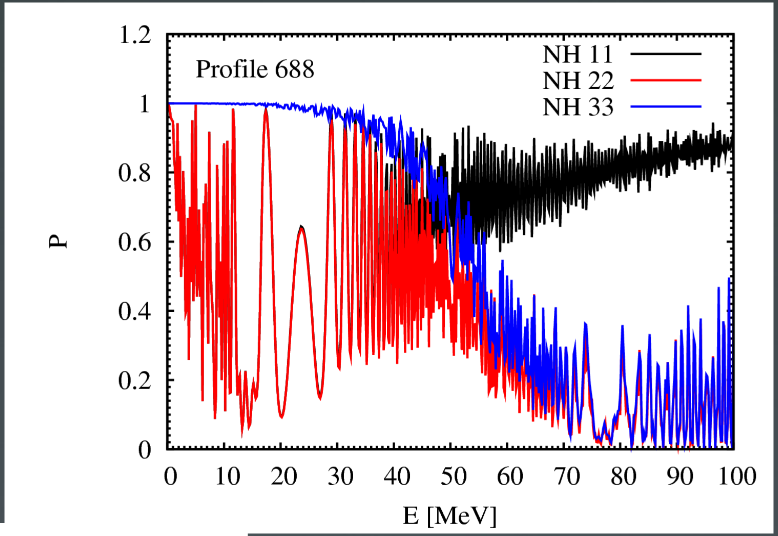
- Cooling phase, so $L_x \geq L_e$
- 70 – 1000 km.
- Previously investigated by, e.g.

  Choubey et al, 2010 [1008.0308]
  Dasgupta et al, 2010 [1002.2943]
  Friedland, 2010 [1001.0996]
  Duan et al, 2006 [astro-ph/0606616]
- Multiple splits observed.
- No exact match.
- Highly non-linear problem.

MSW and $\nu\nu$ – NH and ν's

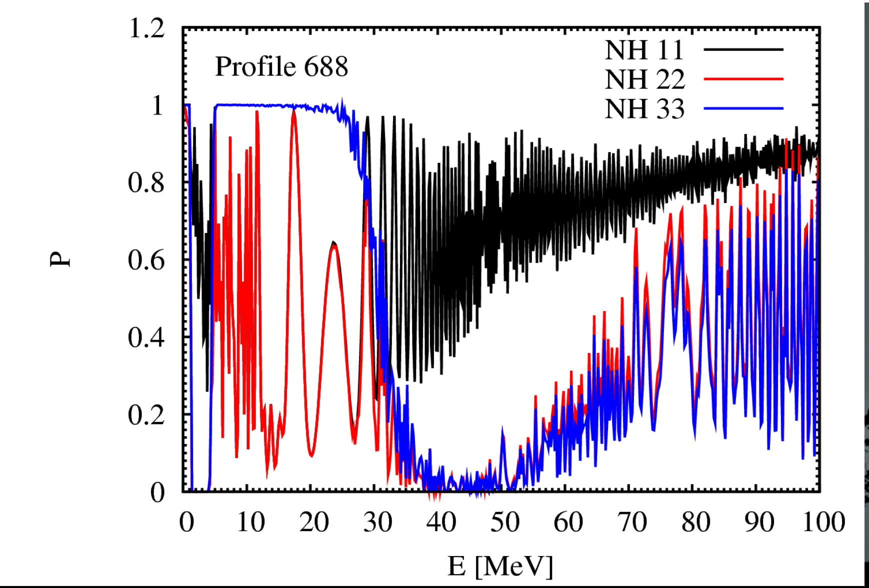


Collective only

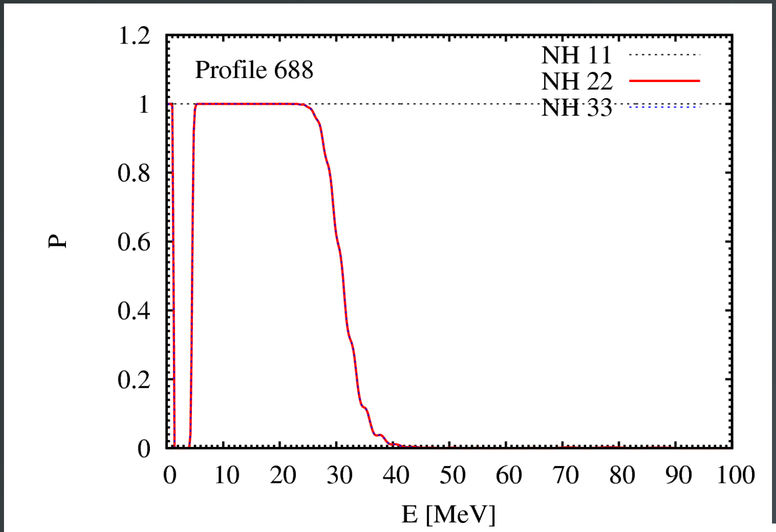


MSW only

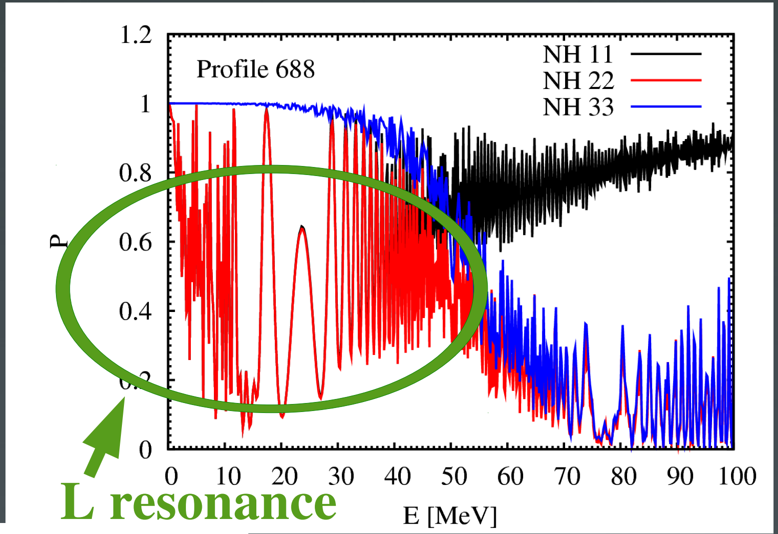
Collective and MSW



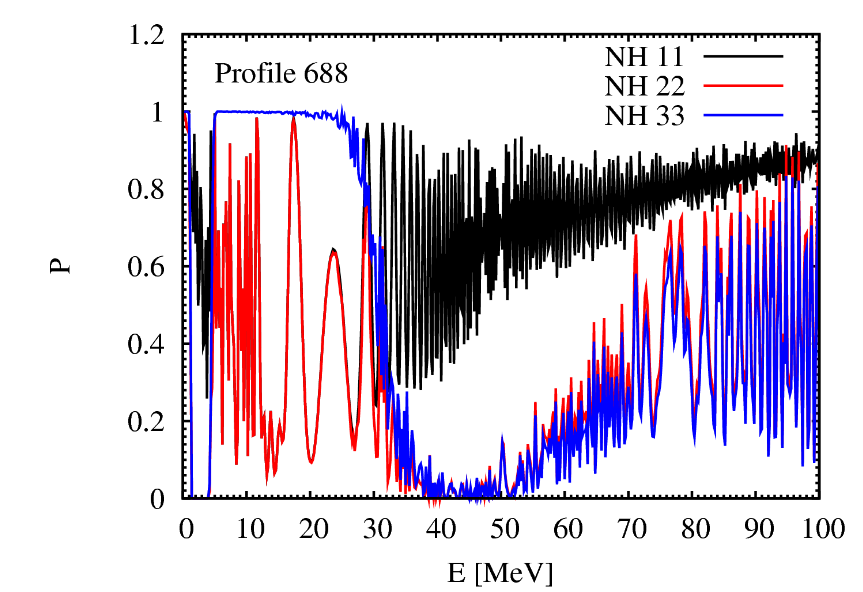
MSW and $\nu\nu$ – NH and ν's



Collective only

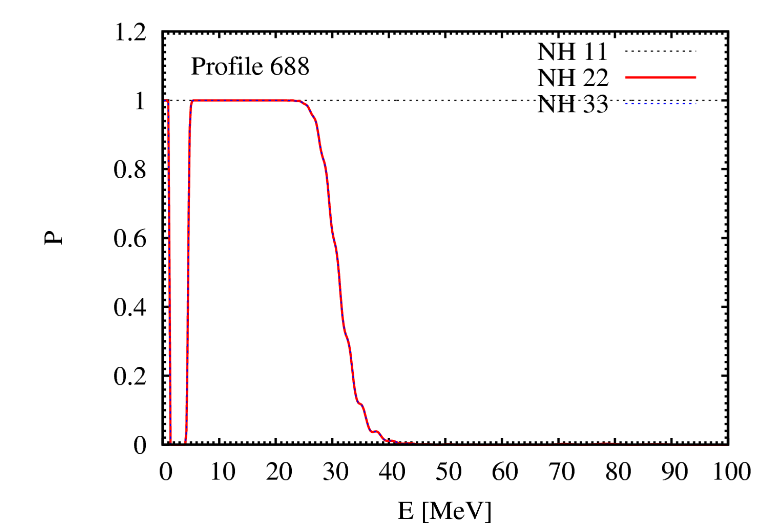


MSW only

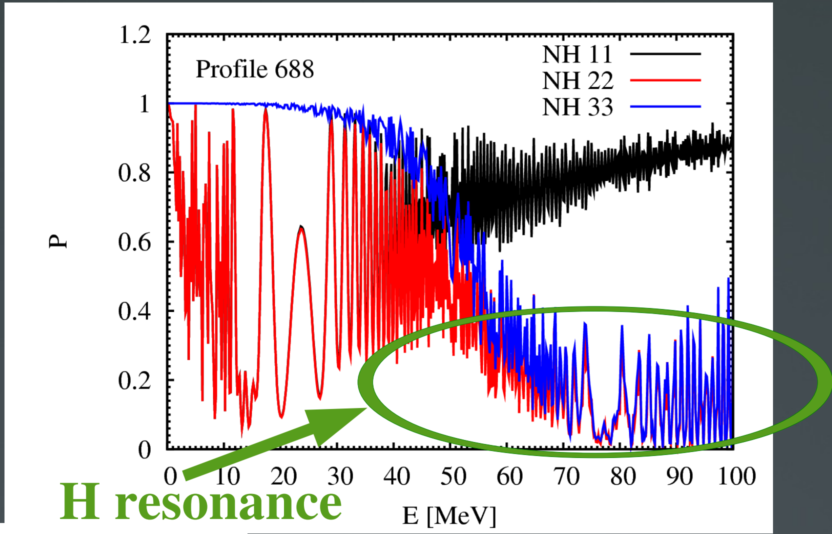


Collective and MSW

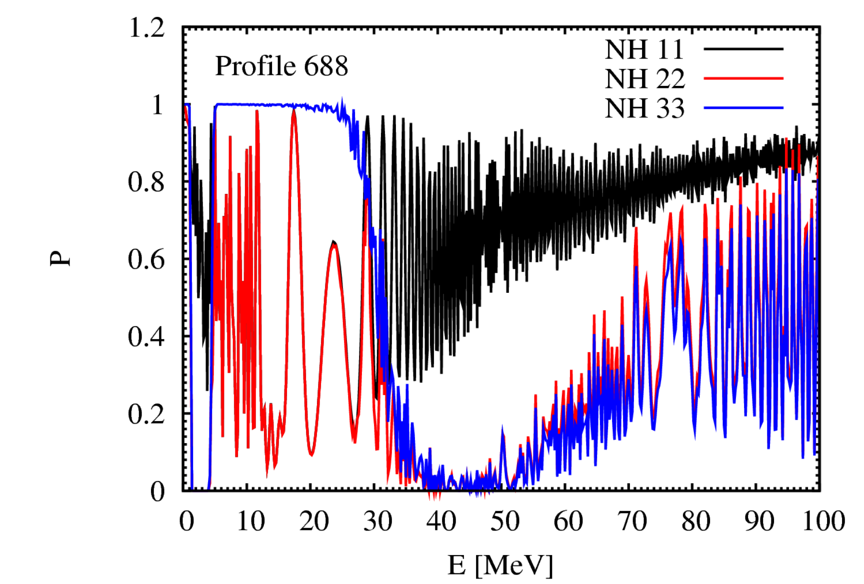
MSW and $\nu\nu$ – NH and ν's



Collective only

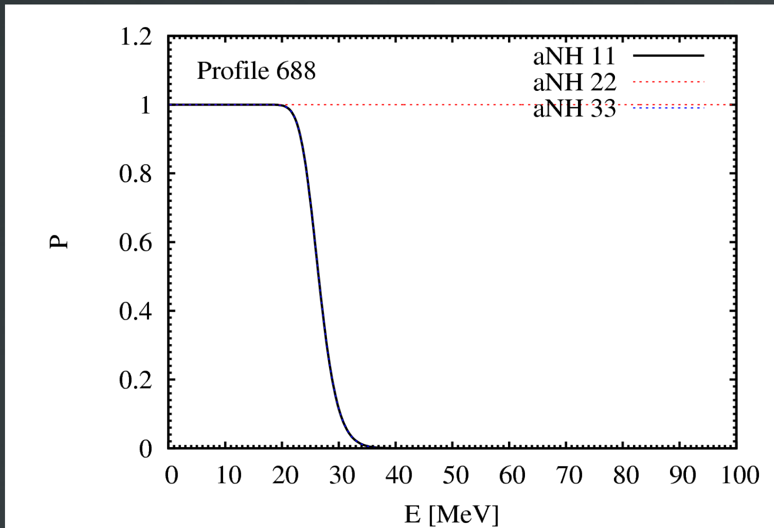


MSW only

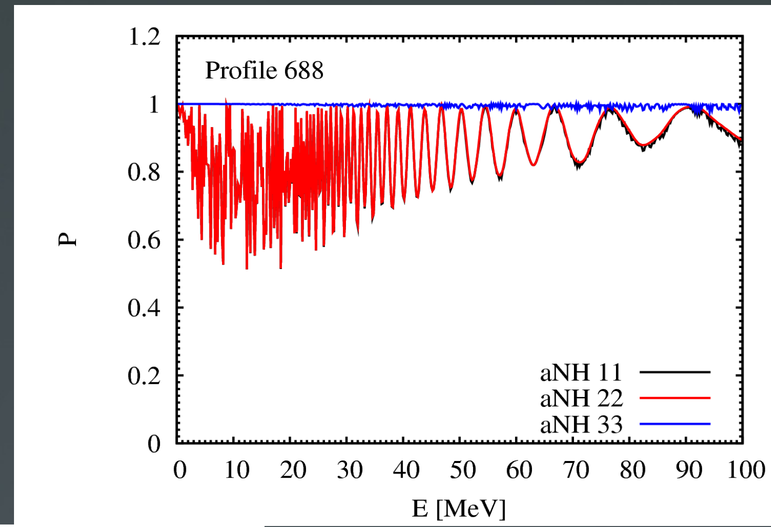


Collective and MSW

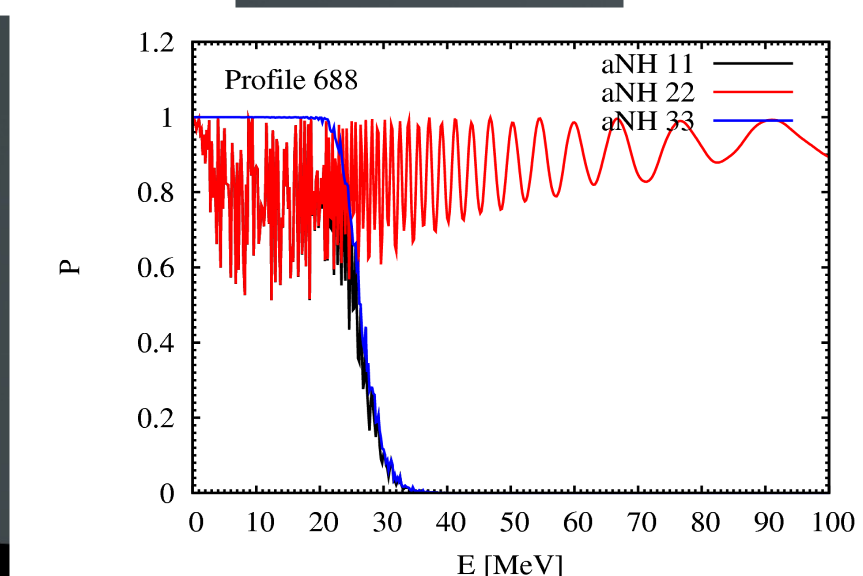
MSW and $\nu\nu$ – NH and $\bar{\nu}$'s



Collective only

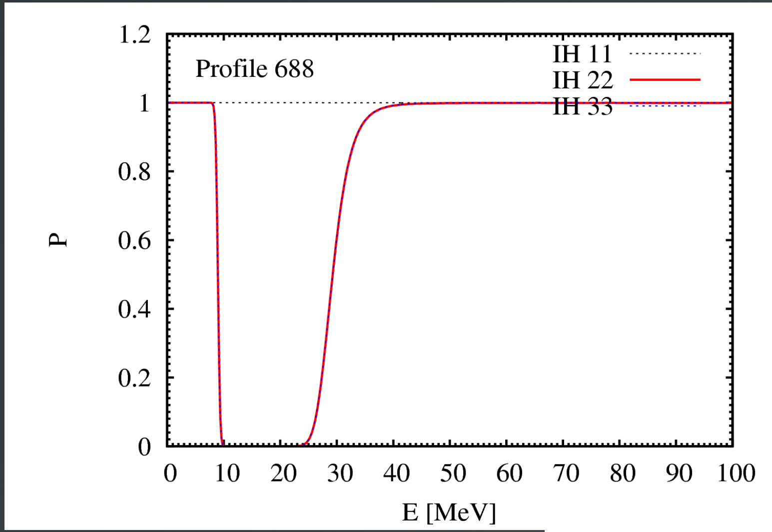


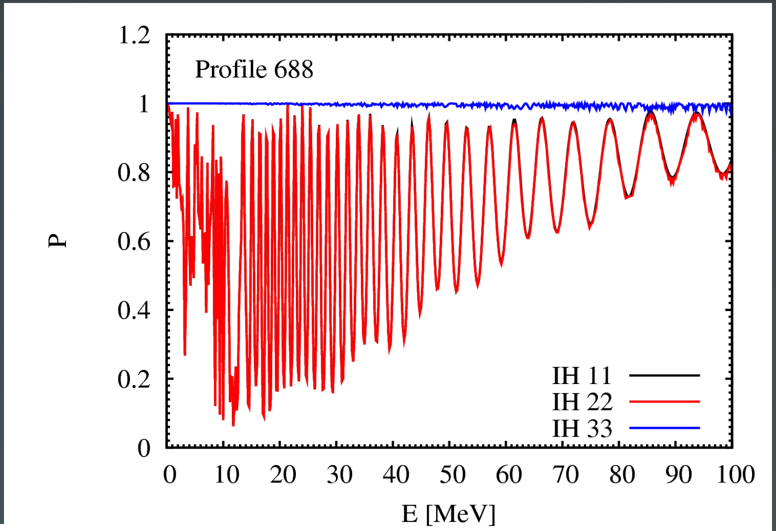
MSW only



Collective and MSW

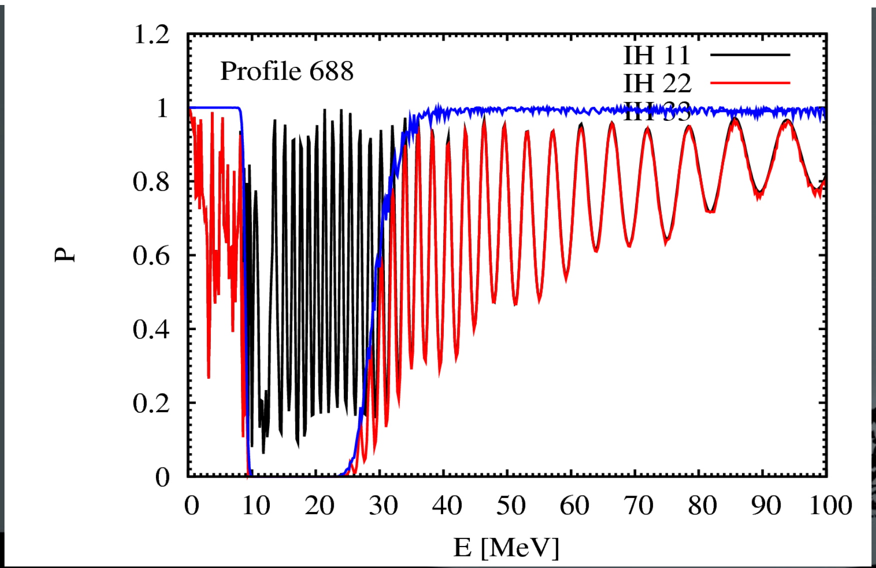
MSW and $\nu\nu$ – IH and ν's





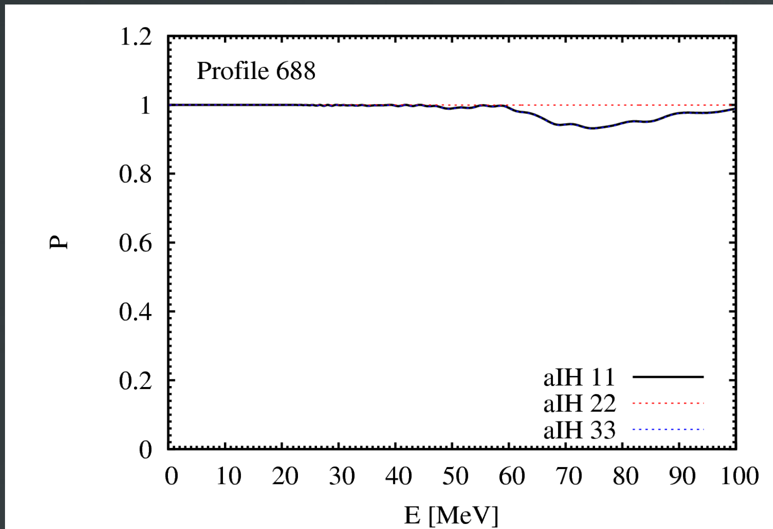
Collective only

MSW only

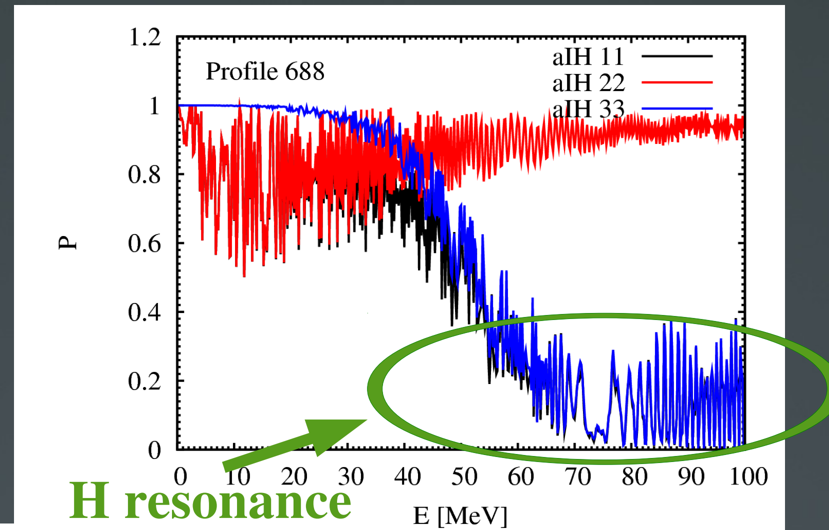


Collective and MSW

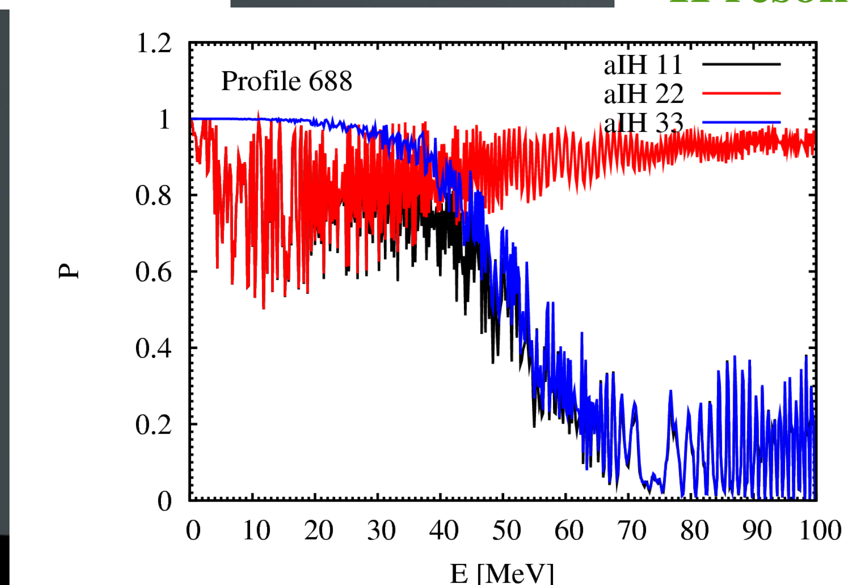
MSW and $\nu\nu$ – IH and $\overline{\nu}$'s



Collective only

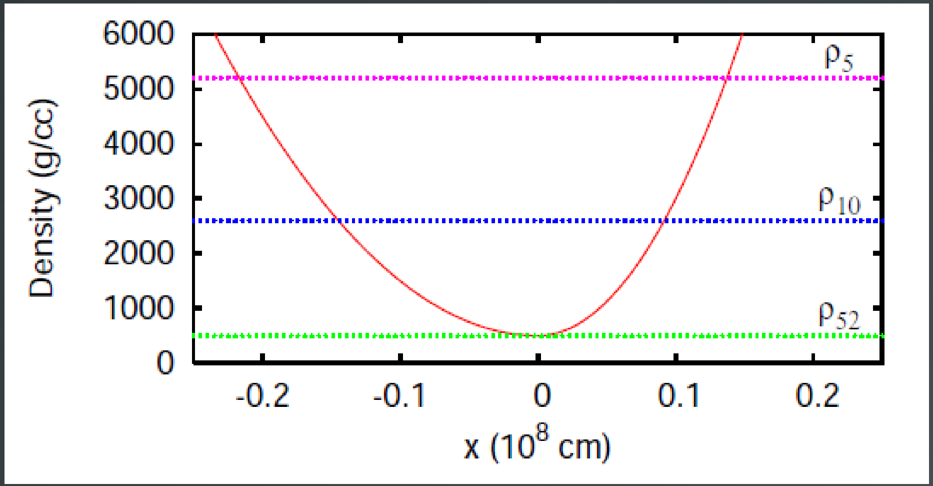


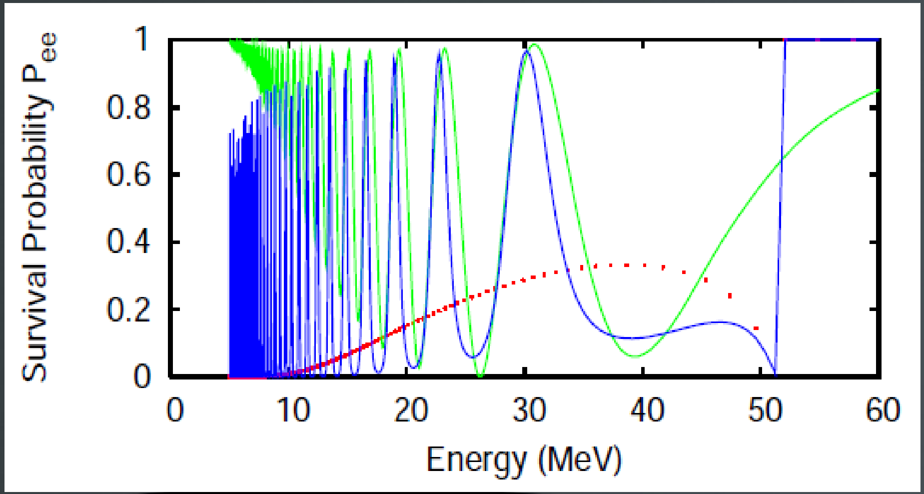
MSW only



Collective and MSW

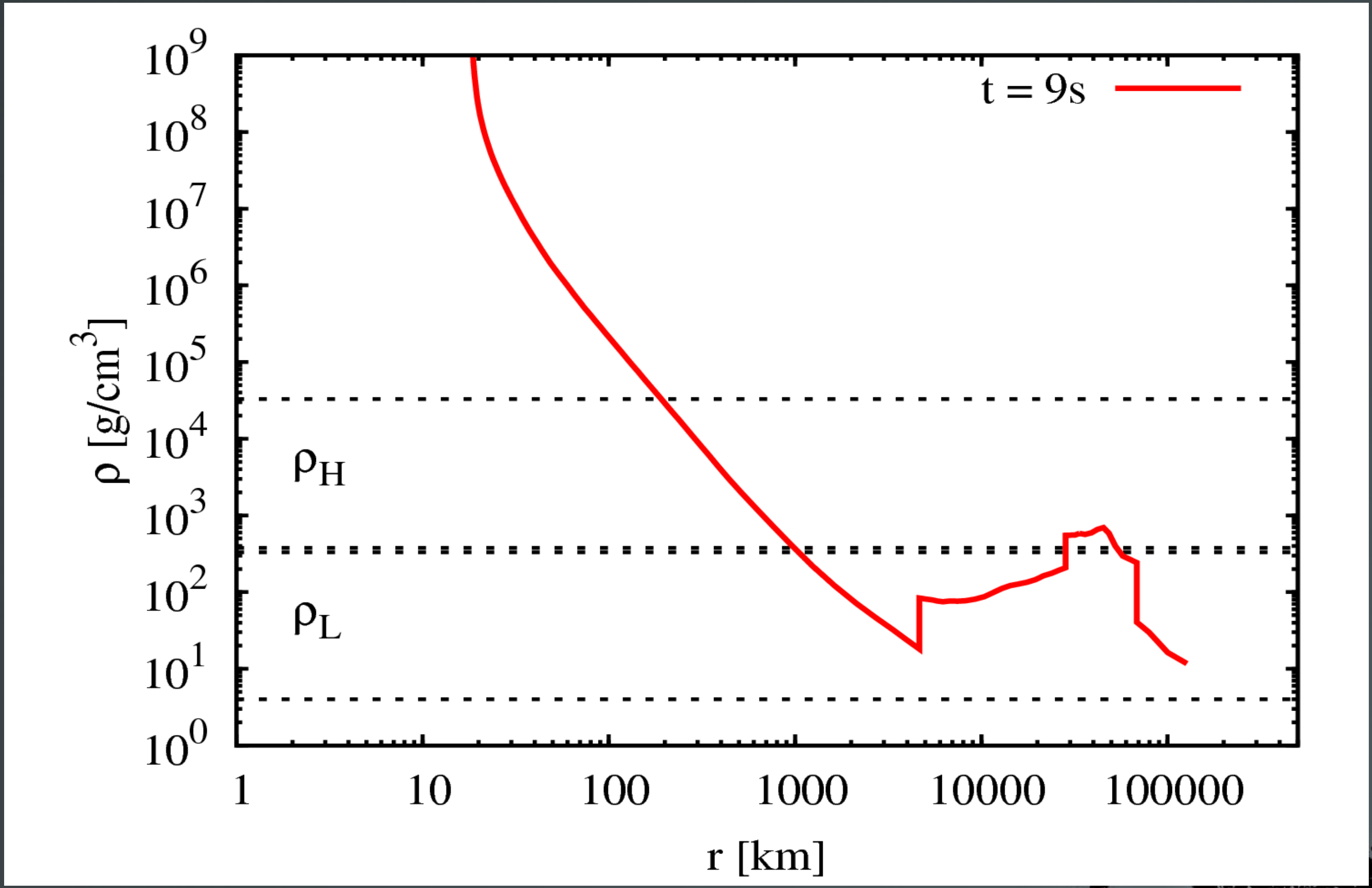
Phase effects



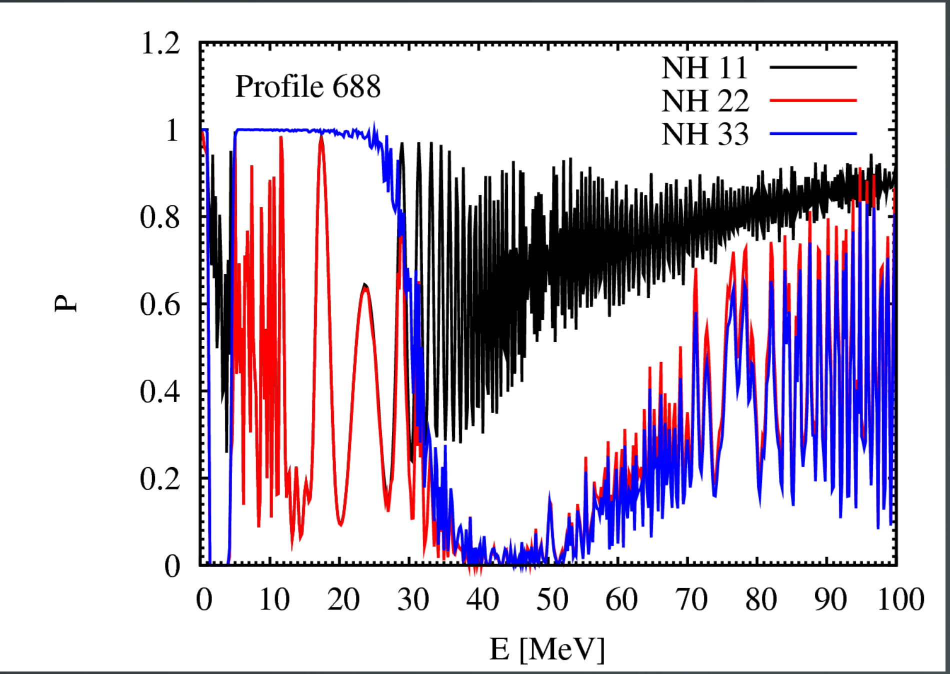


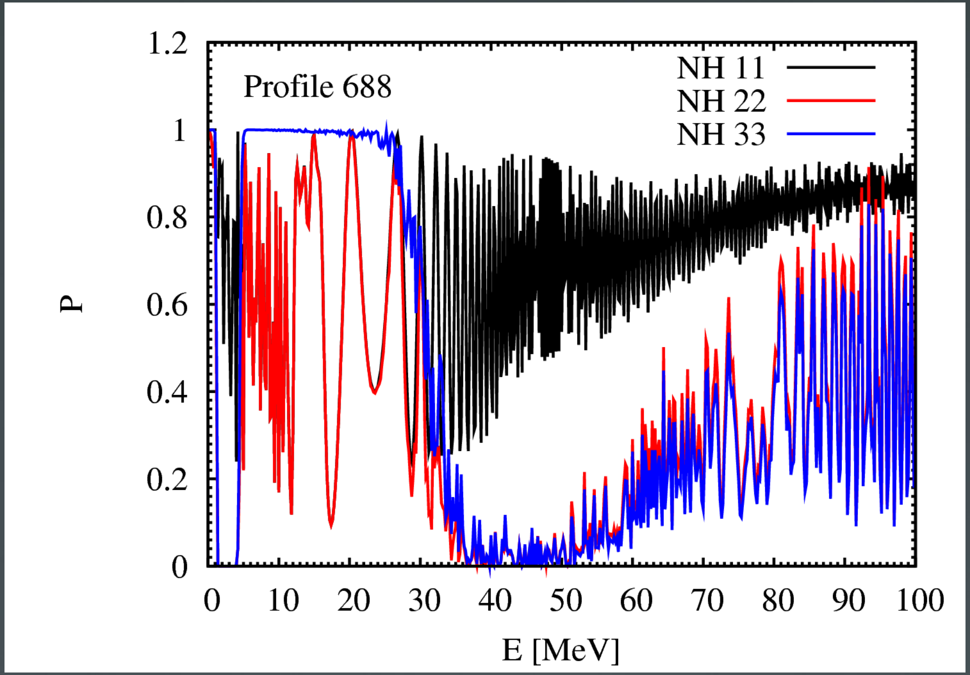
- Oscillations due to phase effects.
- Distance between 2 MSW resonans points depends on neutrino energy.
- Discussed by Dasgupta and Dighe 2007 [arXiv:hep-ph/0510219].
- $\theta_{13} \approx 5.7^\circ$.

Multiple passings



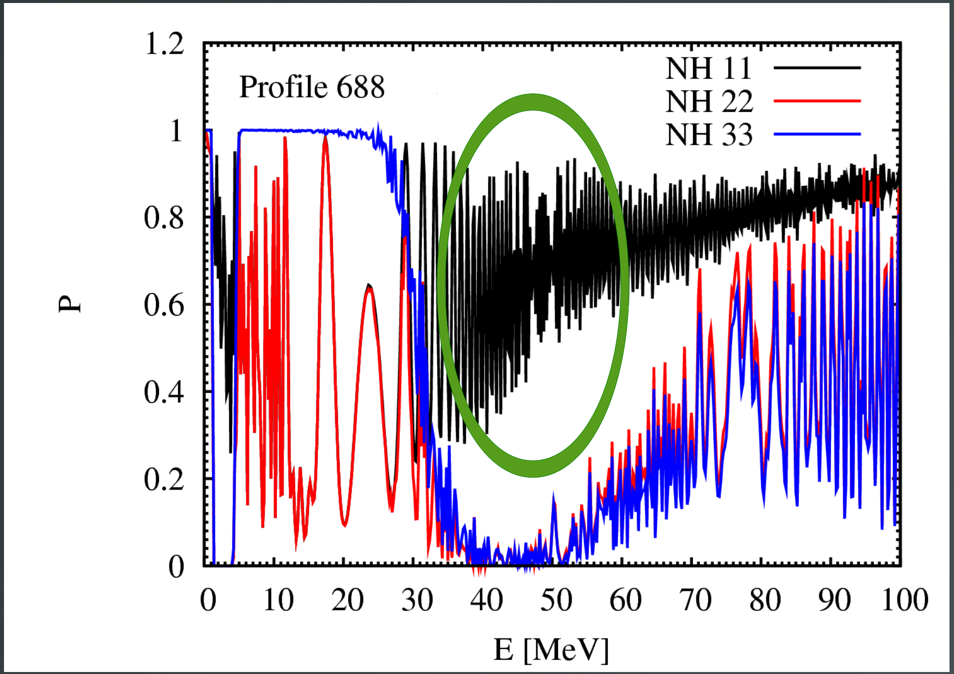
Adding turbulence – NH and ν's

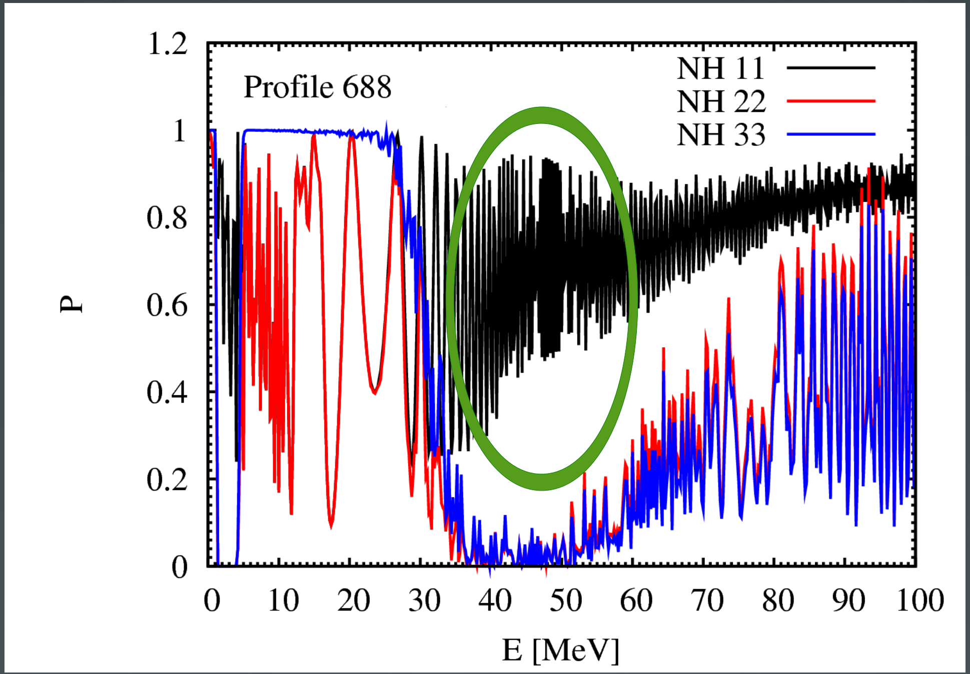




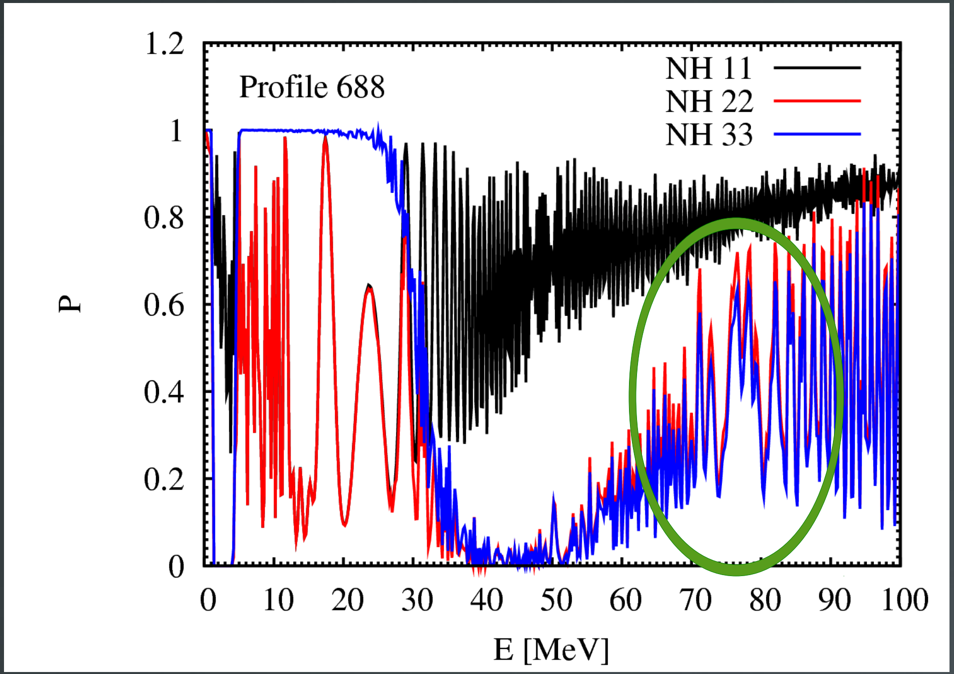
- Detailed differences.

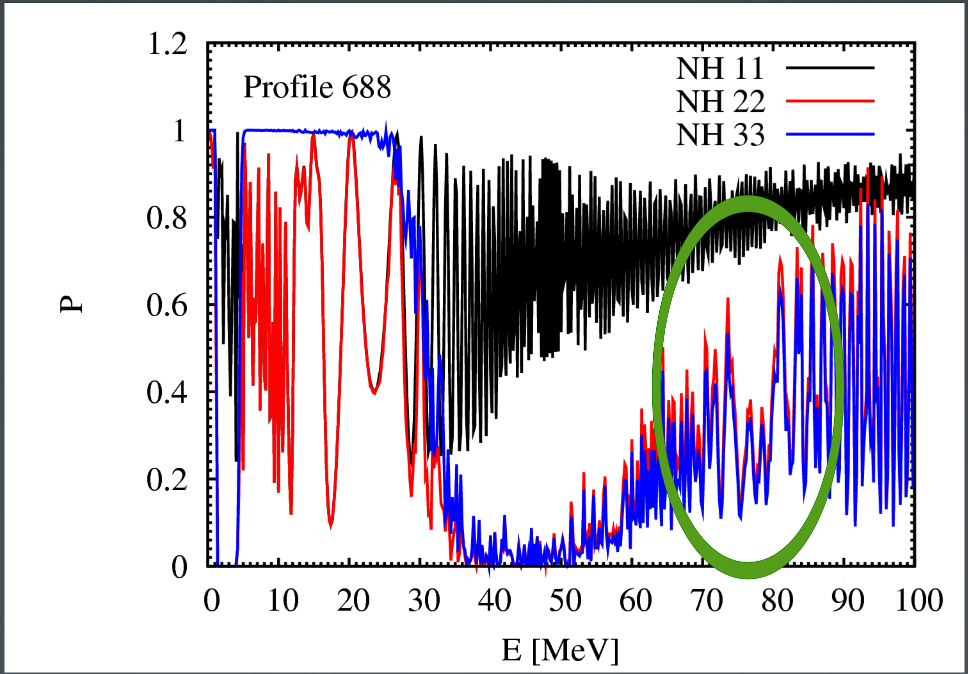
Adding turbulence – NH and ν's



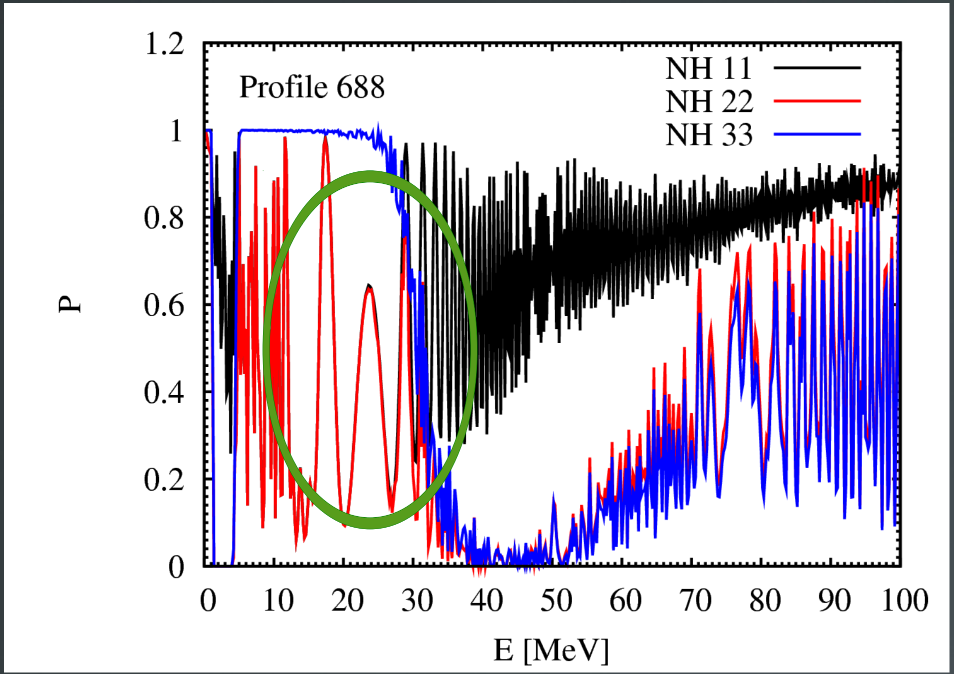


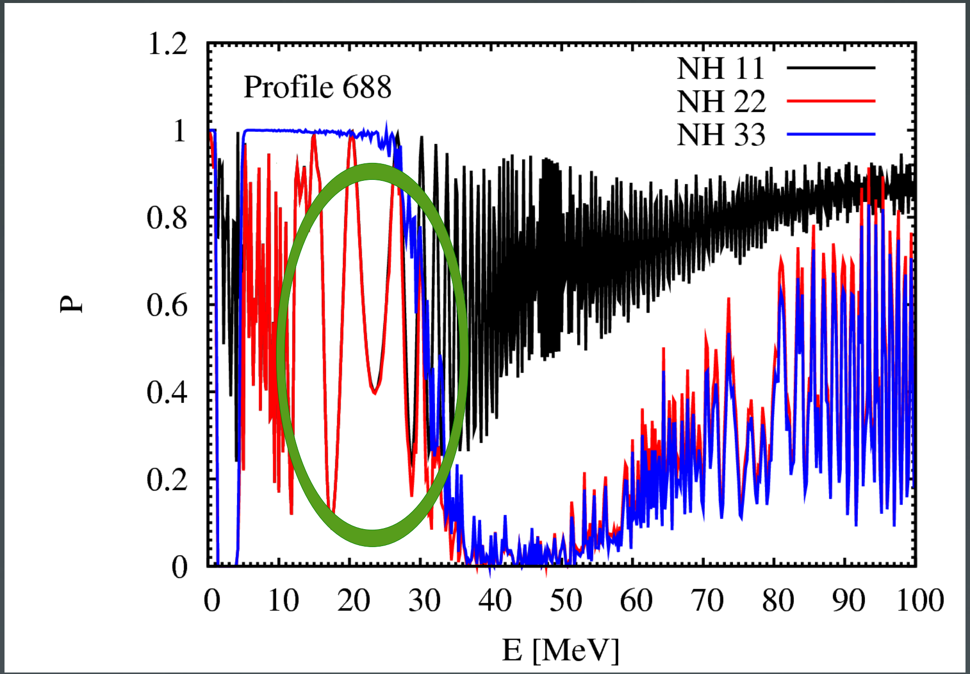
Adding turbulence – NH and ν's





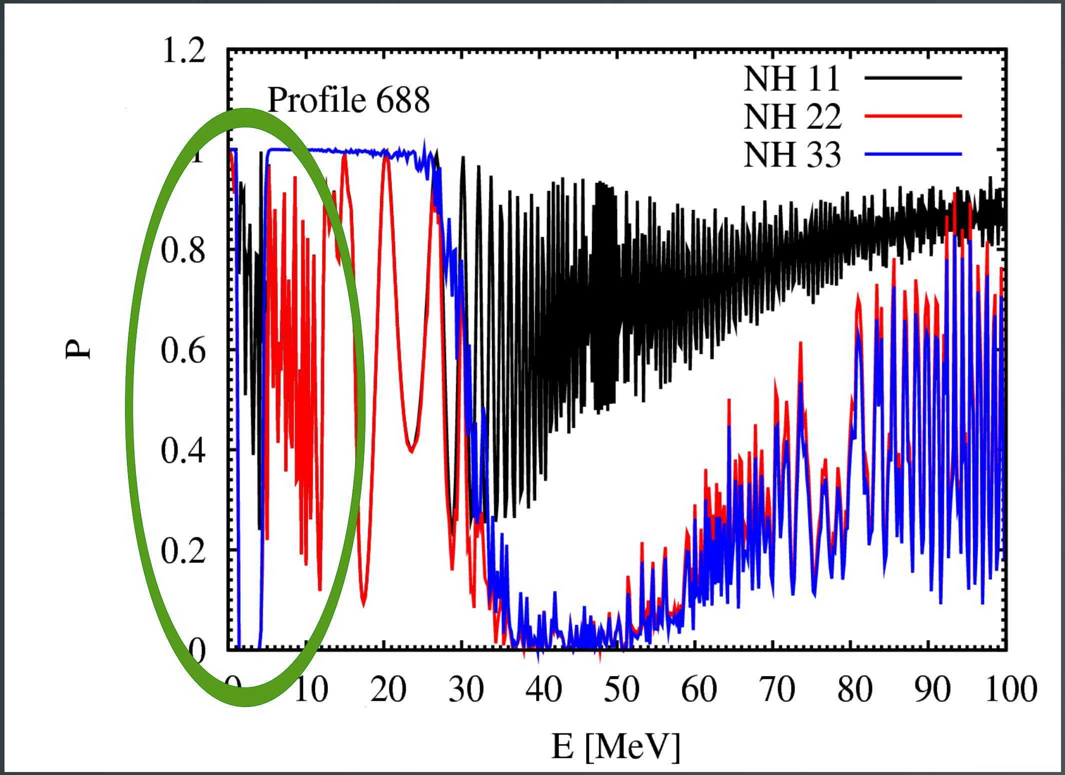
Adding turbulence – NH and ν's





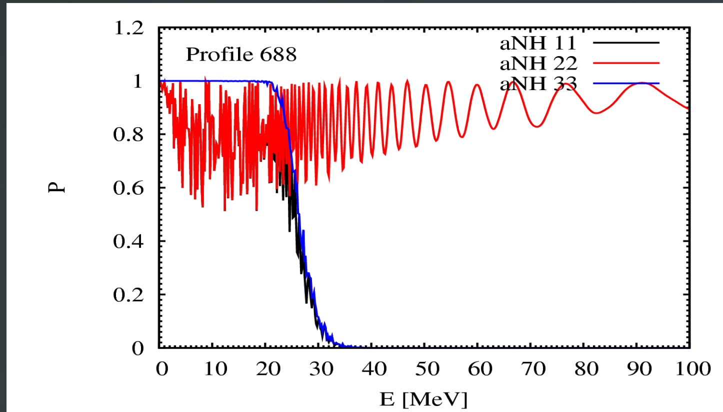
- Detailed differences.
- Multiple realisations.
- Bigger amplitudes.
- Collective and MSW features survive.

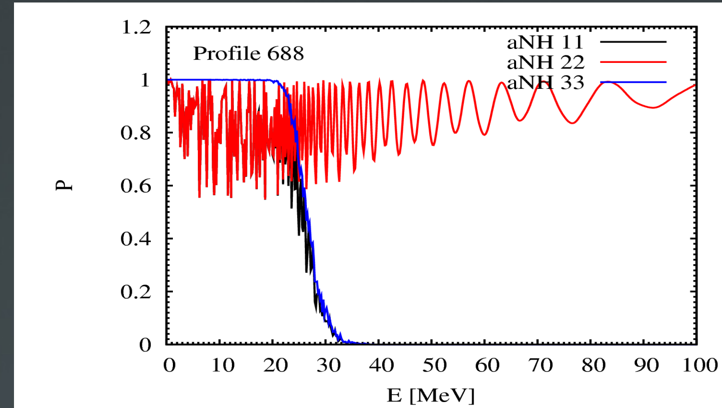
Adding turbulence – NH and ν's

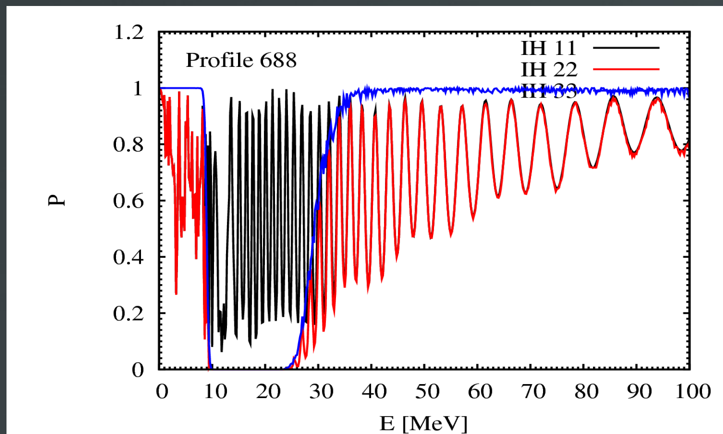


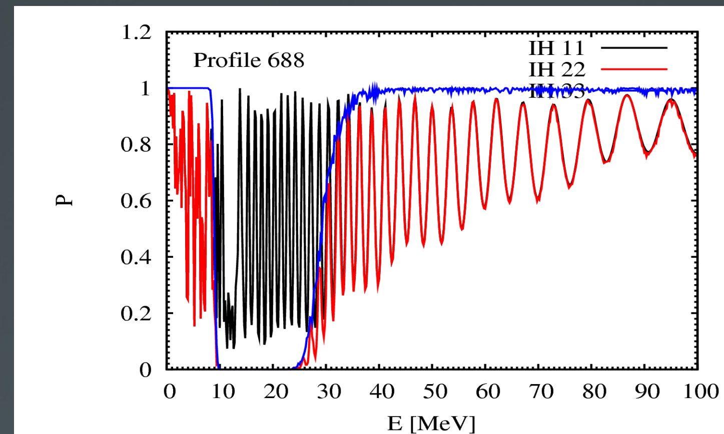
- Wash out by energy resolution of detectors.
- Some collective and MSW features survive – future work.

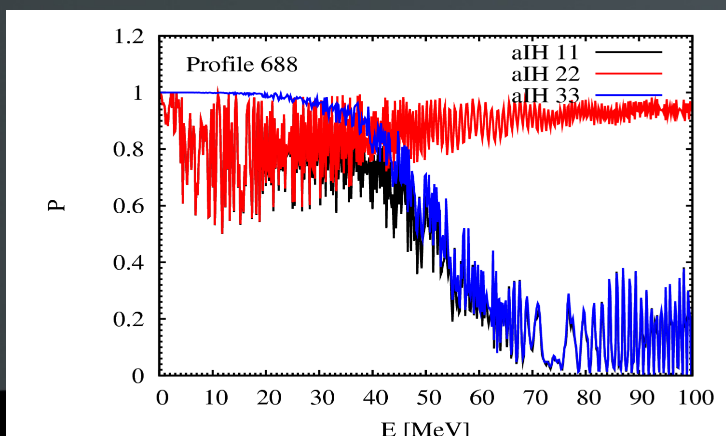
Adding turbulence

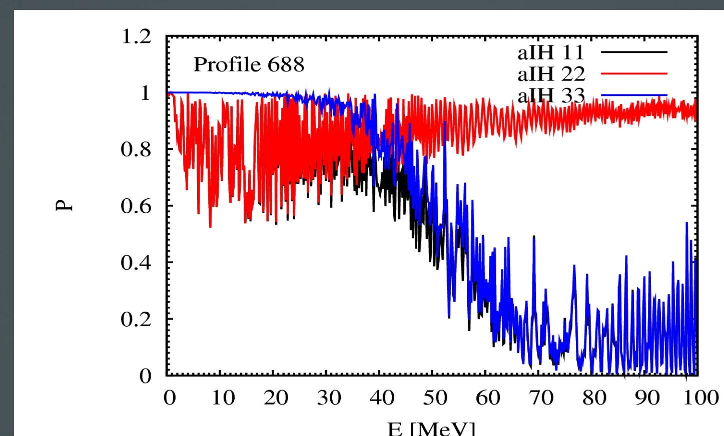




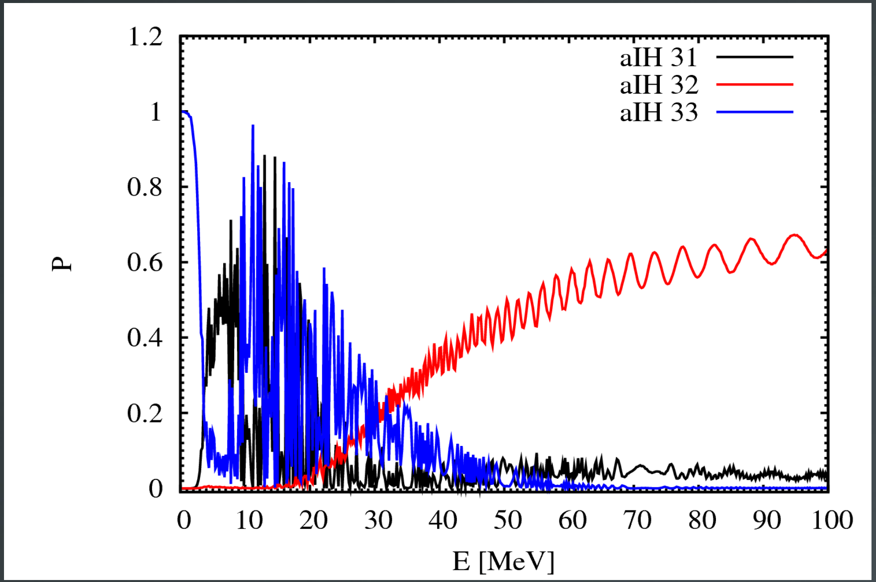


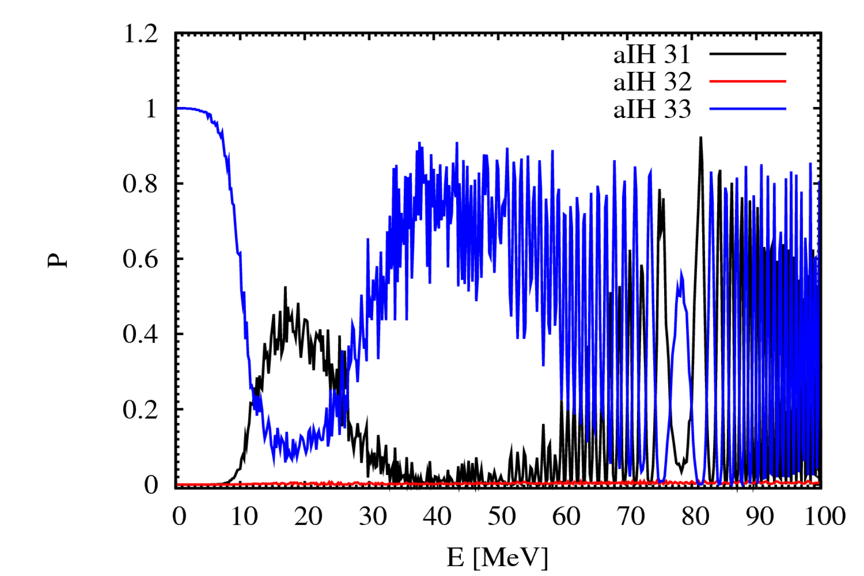


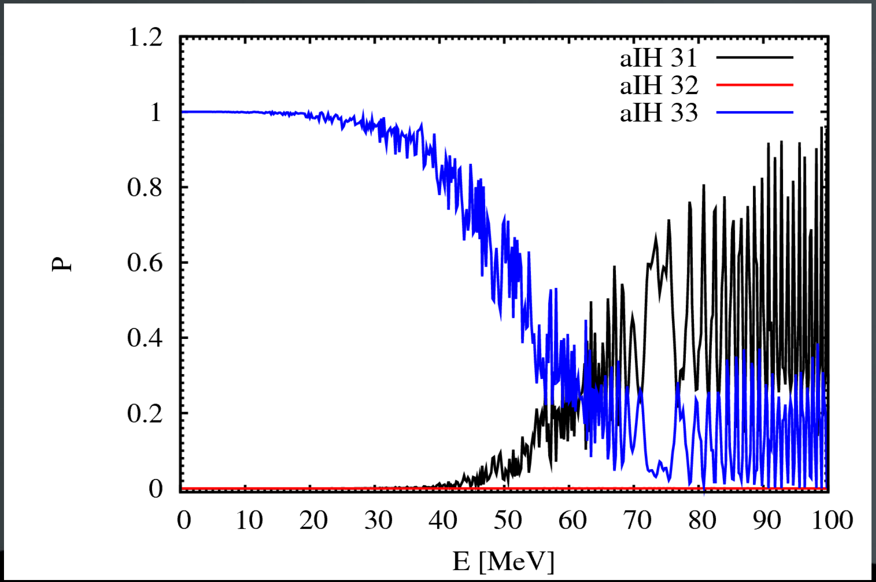


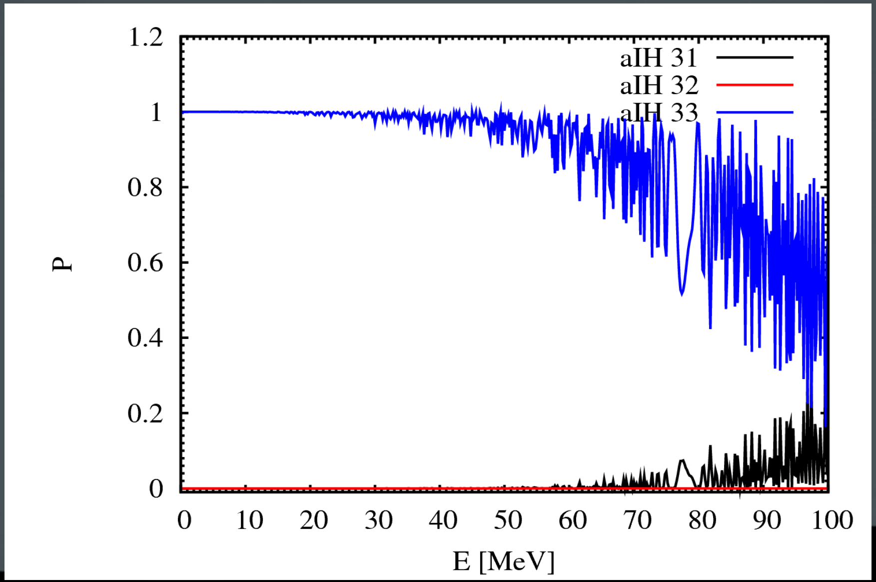


Time dependent probabilities

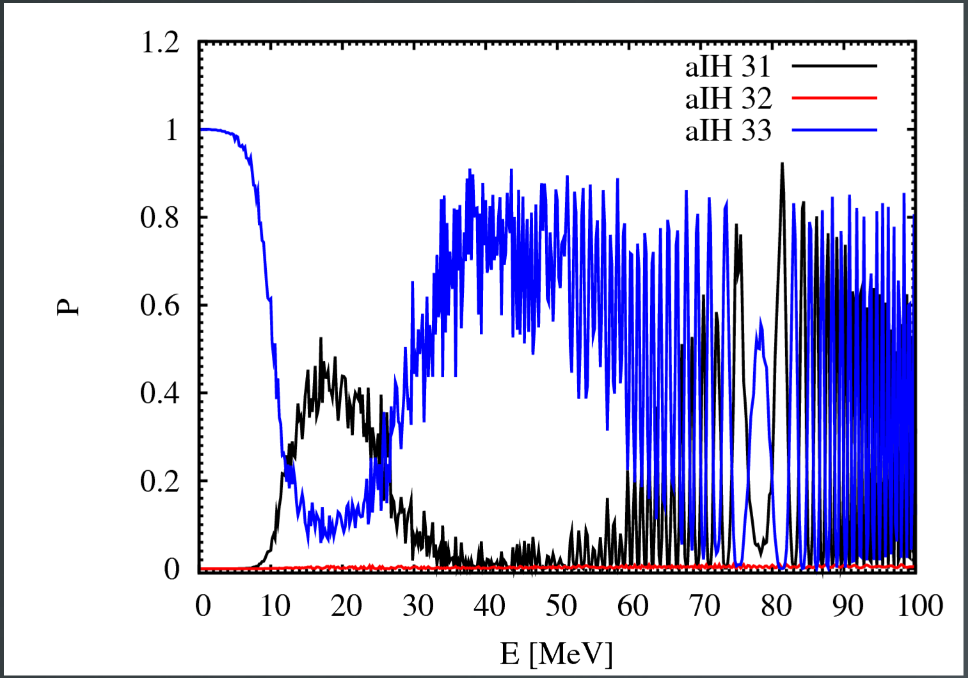


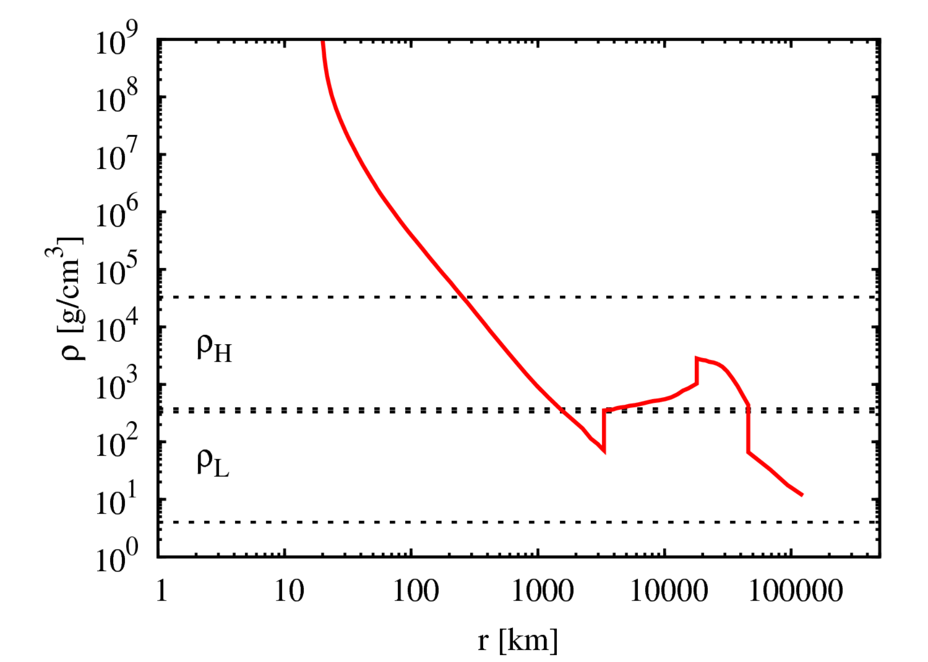






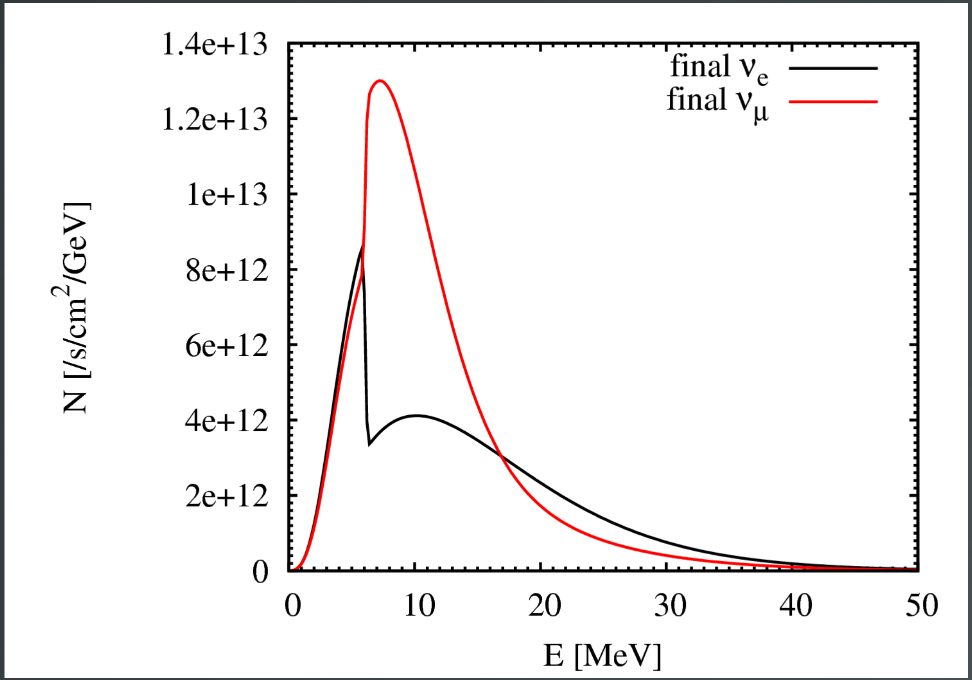
Case of t = 4 s

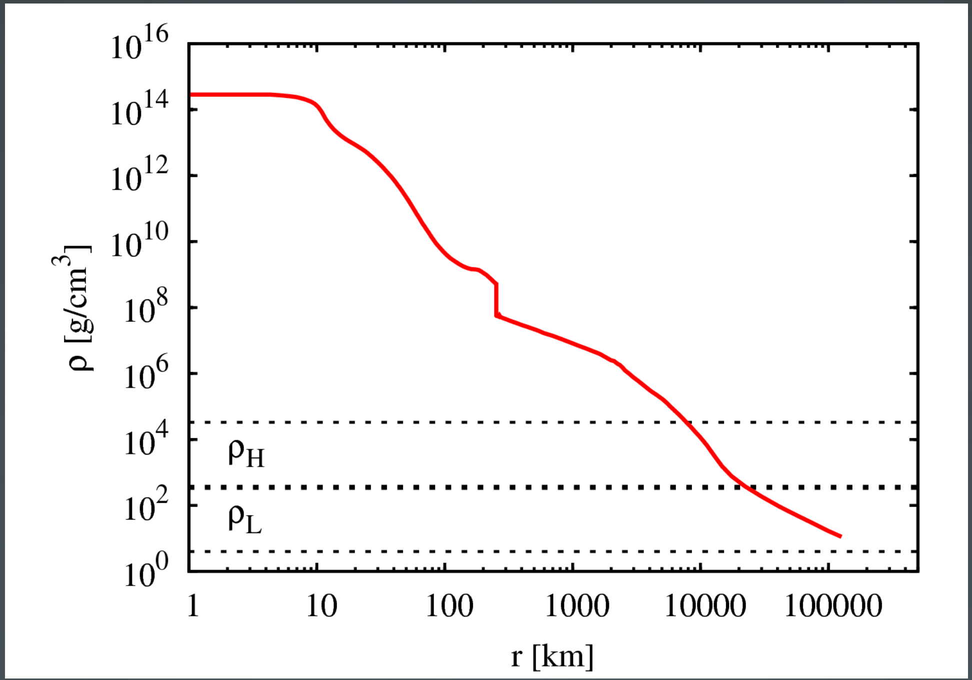




- Low E one pass of H, high E multiple passes.
- Transition probabilities for L resonance not shown.

Accretion phase 93 ms





- Collective effects only.
- Adiabatic transversal of H and L.

Conclusions and future challenges

- Features not washed out by turbulence.
- Need both anti-ν and ν detectors.
- Energy resolution.

Future:

- Better understanding of collective effects.
- Ensemble averages.
- More profiles and progenitors.
- Observability in detectors.